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Performance evaluation of generic flexible manufacturing systems

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Performance evaluation of generic
flexible manufacturing systems

by

Mohammad Shakil-ur Rahman

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of the
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I. STATEMENT OF PROBLEM

A. Introduction

This research presents an approach for evaluating the performance of Flexible Manufacturing Systems (FMSs). There are several ways to evaluate a system but, performance is the most critical factor that should be considered for evaluating an FMS, since system performance is inter-related with reliability, maintainability, schedule, cost, etc.

System effectiveness is a measure to evaluate the performance of systems. Adequate evaluation serves as a guide to optimum design and operations. In addition, proper maintenance policy and production strategy can be determined as results of the performance modeling.

The system effectiveness describes the overall capability of a system. It adequately evaluates the success of meeting an operational demand within a given time under specified conditions. Another way of defining system effectiveness is: a measure of the degree to which an item can be expected to achieve a set of mission requirements, which may be expressed as a function of a availability, utilization, and production rate. Among system's effectiveness measure, availability has received the most

attention, while utilization and production rate have often been employed as an appropriate measure for capacity planning or production schedule planning.

The availability of a system or equipment is defined as the probability that it is operating satisfactorily at any point in time when used under stated conditions, where total time considered includes operating time, active repair time, administration time, and logistic time.

System effectiveness models are normally expressed in a variety of ways according to each user's requirements and its application. This research defines the system effectiveness as the probability measure of the achievement of a specific mission goal.

B. Needs for the Study

Most of the previous studies concerning FMS performance were concentrated towards simulation based models for evaluating performance of scheduling rules in the FMS environment, determining system performance for different operating conditions to different configurations, and employing closed network of queue with multiple components that are subject to failure to determine optimal capacities for repair facilities, utilization, queue length, waiting time, etc. in FMS. Moreover, a few researchers used cost to

benefit ratio as a performance measure for determination of an FMS acquisition decision.

Almost, all of the present FMS models for FMSs are treated as an entirety, not split into sub-systems. Also, current models find difficulties in evaluating a system which consists of many subsystems, each performing its specific function, and limiting themselves to a system which is confined to a local region. These two drawbacks rule out applications to many commercial FMSs which are formed in modules.

As modern technology advances, many sophisticated FMSs are becoming larger, complexer, and modular. Study of such performance modeling and justifying these modeling techniques theoretically and practically are important and timely goals.

C. Study Goals

- To study the FMSs thoroughly and find a generic FMS layout.
- To investigate realistic performance models.
- To justify these modeling techniques theoretically and practically.

- To solve certain types of modeling problems which arise during the research.
- To evaluate system effectiveness for a system consisting of subsystems.
- To define and to evaluate performance measure for a centralized storage and selecting optimal storage policy for the subsystems.
- To conduct sensitivity analysis on the results of an heuristic approach and determine the critical input parameters to the system's operations.

D. Methodology

In this study, probability is to be used to evaluate the system effectiveness of a generic flexible manufacturing system (FMS) consisting of subsystems. Stochastic process will be used to define the Markovian model and resulting probabilities will be employed to describe the storage performance measure, to evaluate the system availability and consequently the system effectiveness. Once the functional form of the measure is available, a heuristic programming is proposed to determine the optimal spares level for each subsystem, subject to given performance requirement.

Due to numerical complexities and iterative procedures of the method, three programs in FORTRAN will be designed. Two out of three programs will be used to determine system effectiveness (performance measure) of an FMS with and without having centralized storage, steady-state probabilities, and optimal spares level for subsystems. The final program is coded to perform sensitivity analysis of the system's input parameters.

II. FLEXIBLE MANUFACTURING SYSTEM

A. Introduction

The recent advances in manufacturing processes, including the generation of cheap and powerful computers, permits the integration of many previously distinct manufacturing concepts. Today the highest hierarchical level in computer controlled manufacturing plants contain Flexible Manufacturing System (FMS). FMS is a production unit capable of producing a range of discrete products with a minimum of manual intervention.

A flexible manufacturing system has been defined in several contexts through different terminologies but all come close to each other in identifying the characteristics common to most of these systems.

Phillips (51) has defined FMSs as follows:

Flexible Manufacturing Systems are engineered, computer controlled manufacturing process that can adapt automatically to random changes in product design configurations, models or styles. The system will always strive to optimize production output and work-in-process inventory.

From the above definition one can realize that :

- Automatic material handling between the machines
- Numerical Control (NC) and CNC machines
- Computer control over material handling system and direct numerical control (DNC)
- Medium size production volume

- Group technology principles

are main aspects of FMSs. A sample FMS layout is shown in Figure 1.

In FMSs human labor is used to carry out the following function to support the operations of FMSs.

- Load raw work-parts onto the system.
- Unload finished parts from the system.
- Change tools and tool settings.
- Equipments maintenance and repair.

B. Classification of FMSs

FMSs can be classified according to the level of automation, volume produced, parts per family, flow of work-parts, configurations of the system, scheduling techniques, etc. Various research groups from different institutes have investigated operations of FMS and claimed that automation and flexibility are the key concepts of FMSs. By referring to above statement, one can classify a FMS based on the level of automation used, after proving that the system satisfies the basic characteristics.

Moreover, a FMS can also be classified based on the volume and degree of variability of manufactured parts. This category of classification was also examined by

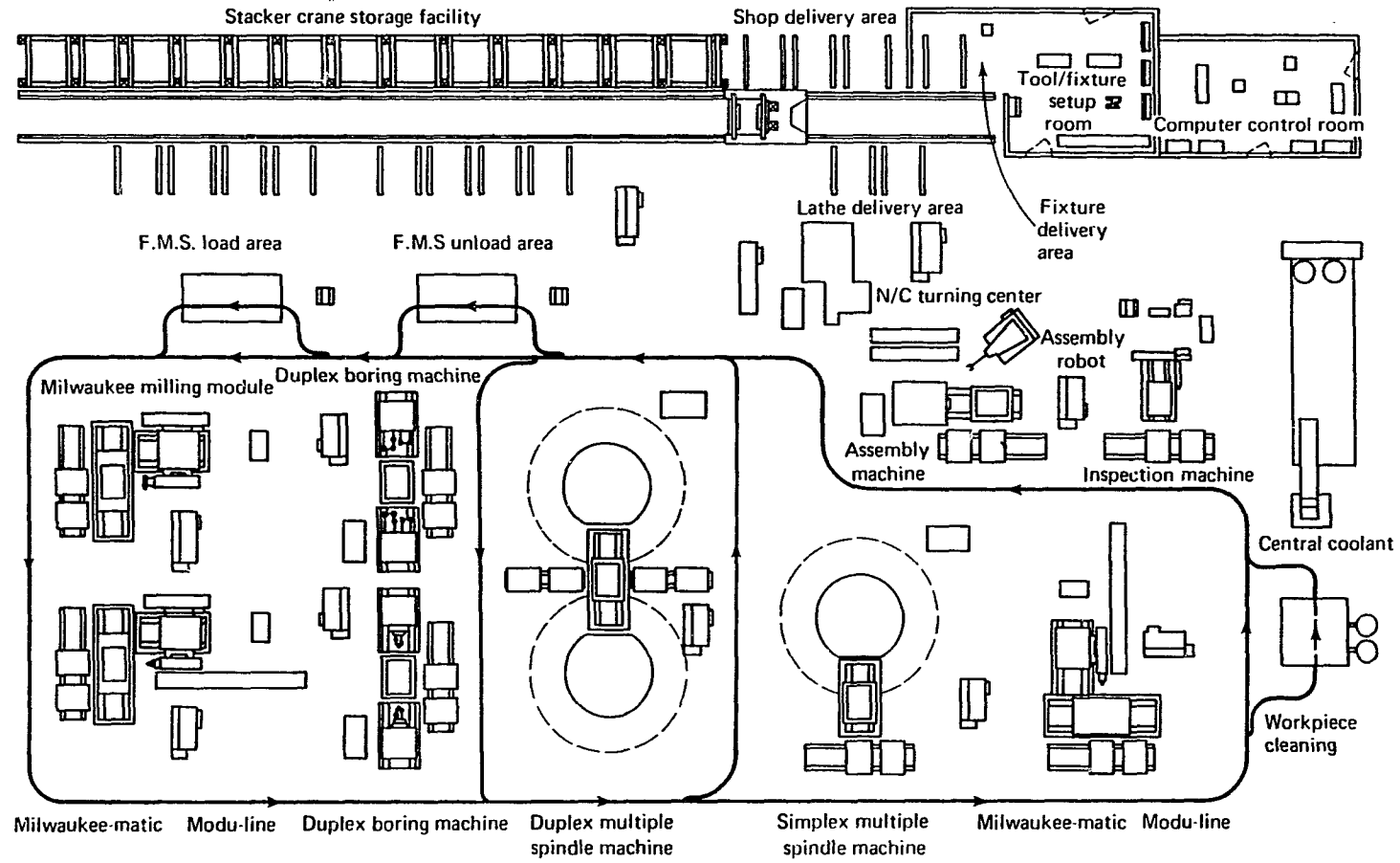


FIGURE 1. A sample FMS layout

Hutchinson, at University of Wisconsin Milwaukee (22). He has developed a Table 1, which shows a general classification of certain manufacturing systems.

TABLE 1. General classification of manufacturing systems

Degree of flexibility. Type of manuf. system	Number of parts in a family	Average quantity per batch
Low Transfer line	1 - 2	7,000 - up
Medium Dedicated FMSs	3 - 10	1,000 - 10,000
Sequential or random FMSs	4 - 50	50 - 2,000
Manufacturing cell	30 - 500	20 - 500
High Stand alone NC machines	200 - up	1 - 50

The transfer line represents high-volume production where the diversity of parts are limited and therefore flexibility is low. Stand alone NC machine represents low-volume production, but a large variety of parts, hence flexibility is high. Obviously, flexible manufacturing system (FMS) falls in the middle where flexibility is medium and is further classified into three categories discussed below.

In dedicated FMSs, highly specialized machines are devoted to a narrow range of parts. Sequential and random FMSs are referred according to the order of flow of parts through machines, and the manufacturing cell (MC) alludes to a cluster of numerically controlled machines served by robot.

Browne et al. (9) identified four types in classifying FMSs, based on equipment arrangements and associated scheduling techniques. These types cover all FMS configurations, from the simplest to the most intricate layouts.

The first of these types is referred to as Flexible Machining Cell (FMC). This type alludes to the simplest and the most flexible system. It generally consists of one general purpose CNC machine tool serviced by automated material handling components that are capable of loading or unloading, transporting, storing, etc. Although a FMC contains only one machine tool, it can still be considered a FMS since it has all the characteristics of an FMS.

Type II FMS is called Flexible Machining System. It consists of different FMCs that provide a variety of metal removing operations. This type, also, allows multiple routes for work-parts with each having a small volume of production. Other options of this type include system

dependent priority scheduling and on-line control of parts production.

Flexible Transfer Line (FLT) is labeled type III. In this system each operation is assigned to, and performed on only one machine. This results in fixed route for each part through the system. The layout is process driven and hence ordered layout. Material handling is usually accomplished using a conveyor or a carousel and storage is located at each machine station. However, this system has less flexibility and is less capable of handling breakdowns.

Finally, type IV FMS is an interconnection of multiple type III FMS and, therefore, called flexible transfer multi-line. The main advantage of such a system is its maneuverability in a breakdown situation. It is also an attempt to achieve the best of type II and type III FMSs.

In classifying FMSs, nothing is absolute. No matter how many classification methods are developed, there will always be some exceptions. Each system design is unique and depends on the nature of the work-parts to be processed through the system. The versatility of the FMS concept makes it impossible to standardize. There is general trade-off between versatility and capacity.

C. FMS Components

A flexible manufacturing system is a fully automated, computer controlled system that provides the control of parts from receiving, storing, processing, packaging, and shipping or for further processing. A typical FMS is divided into five components for analytical purposes. These components are listed bellow:

- Machine Tool
- Tools
- Material Handling
- Storage and Warehousing
- Computer Control System

The first four components mentioned above incorporate some kind of automated design. The last component is the brain of FMS that controls and monitors all of the operations of the system. These FMS components will be examined in this section.

1. Machine Tool

The machine tools selection for a FMS depends on the nature of operations to be performed, volume of production, and variability in operations. Based on processing requirement, Grover (28) has distinguished two different types of FMSs:

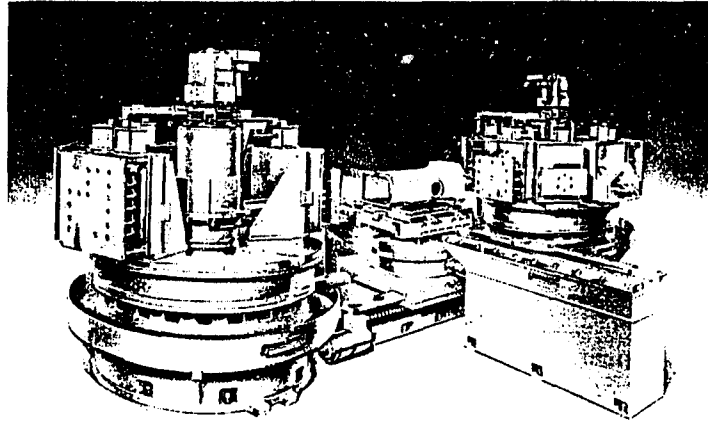
1. Dedicated FMS

2. Random FMS

The dedicated FMS is referred to a high volume, limited variety, and specialized machining of parts. He used the Army contract to Chrysler Corporation for XM-1 tank as an example. This contract resulted in requirements of pre-determined machining applications along with specialized tools.

The random FMS is designed to handle a variety of parts in random sequence. This system allows the processing of new parts. Flexibility is a significant characteristic of machine tools utilized. Standard NC machines are used to handle the product mix. Four and five axis machines would be a typical choice. These machines are designed to perform a wide variety of machining operations on a variety of work-part geometries.

Nordstrom (42) has stated that FMSs are usually designed for two main configurations, prismatic and rotational, of parts. Machines are determined relevant to these configurations. Automatic machines are an inherent aspect in each of the above categories. Therefore, NC or CNC machines are inevitable in the design of any FMS. And Duplex multiple spindle head indexer is usually used as modules on FMS, shown in Figure 2.



Duplex multiple spindle head indexer used as module on FMS
Courtesy Kearney & Trecker Corp.



Machine tool modules and in-floor towline cart transfer system
combined into FMS concept. (Courtesy Kearney & Trecker Corp.)

FIGURE 2. Machine tool module on FMS

2. Tooling

High-tech tool changing is an essential feature in FMSs. The level of automation is analyzed and fixed by the degree of flexibility required in the system. Another aspect of the tooling is flexibility in workpiece fixture. For this reason, Modular Fixturing Systems (71) are usually employed. It provides a secure assembly of elements, and accurate positioning of workpieces. In addition, the elements that make up the system are fast and easy to assemble and capable of handling enough configurations.

A complete tool changing system should provide the following (71):

- Tool magazine
- Tool holders
- Tool locking mechanism
- Tool gauging and changing
- Tool monitoring

A tool magazine stores a variety of tools needed at each machining cell. Generally, it carries from 24 to 120 types. Tool holders are designed to accommodate different tools that may be used for processing certain parts. These tool holders come with an automatic locking mechanism. A tool gauge is provide for checking tool wear via sensitive

probes. These probes emit signals which compare the actual value with the nominal one.

Finally, tool monitoring is necessary mainly for breakage detection and also for the tool life monitoring. The objectives of this function are to protect the machine and its components, to permit the unmanned operation over extended periods, and to ensure efficient tool utilization.

3. Material Handling System

Material handling system in an FMS has been realized to be the most critical component in term of design. To satisfy design requirements, work-part handling systems adaptable to the FMS concept include power roller conveyors, power and free overhead conveyors, shuttle conveyors, floor tow-line systems, and automated guided vehicle systems (AGVS).

The AGVS is the most common feature in FMSs as the driverless cart for physically transporting the workpieces. The movement of the cart is controlled by certain signals and objects. These signals are usually received when an operation such as loading, unloading, machine ready or occupied is to be performed. The reception of signals can be accomplished either through wires or wireless devices such as infrared, radio-frequency, chemicals, and vision concepts (49).

Tow-line is another material handling method that is being used in operating FMSs. This method consists of a straight fixed line that runs through the central part of the system on which a transport cart is operated. The flexibility of the system is degraded by using tow-line but the gain is the ease of integration with the overall system. Figure 3 illustrates the difference between AGVS and tow-line system.

The loading and unloading of the carts can be performed in several ways. The simplest being the assignment of human operators at each station, and the most complex being the installation of a mini-robot aboard the cart itself. One factor must be taken into account when utilizing robots is its weight handling capability. Another device that can be used for transportation of workpieces is an automatic conveyor system, shown in Figure 4. The state of the workpiece is an important factor that should be considered in deciding a service system.

Grover (28) has suggested some guidelines for the designs of FMS material handling system.

1. Workpieces handled should be palletized and their movement should be random and independent.
2. Convenient access for loading and unloading work-parts.
3. Provision for temporary storage of work-parts.

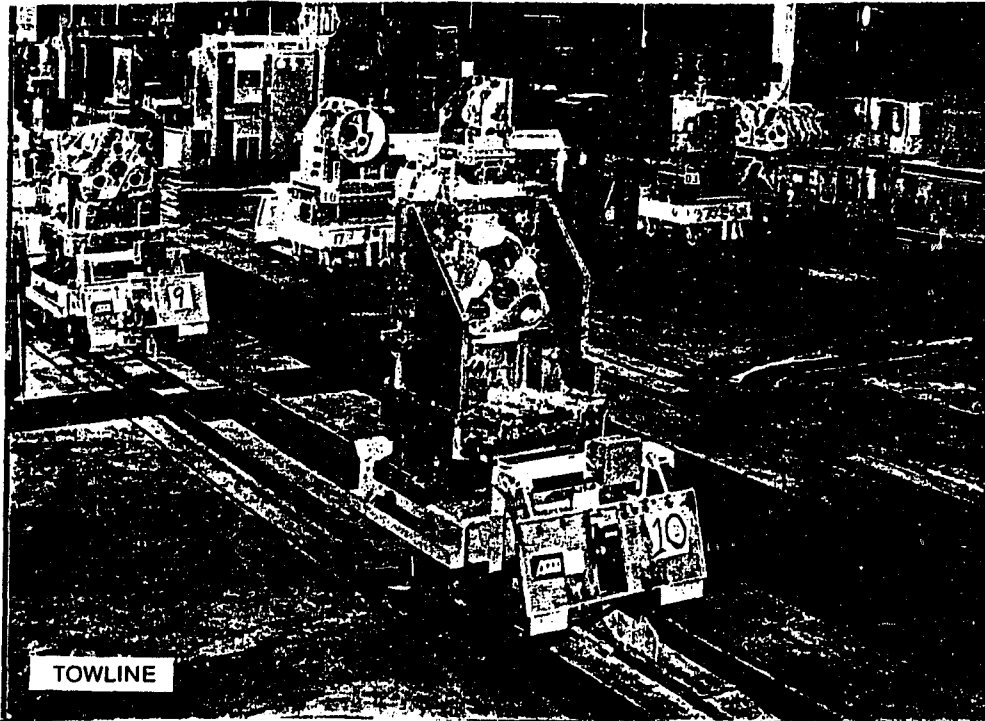
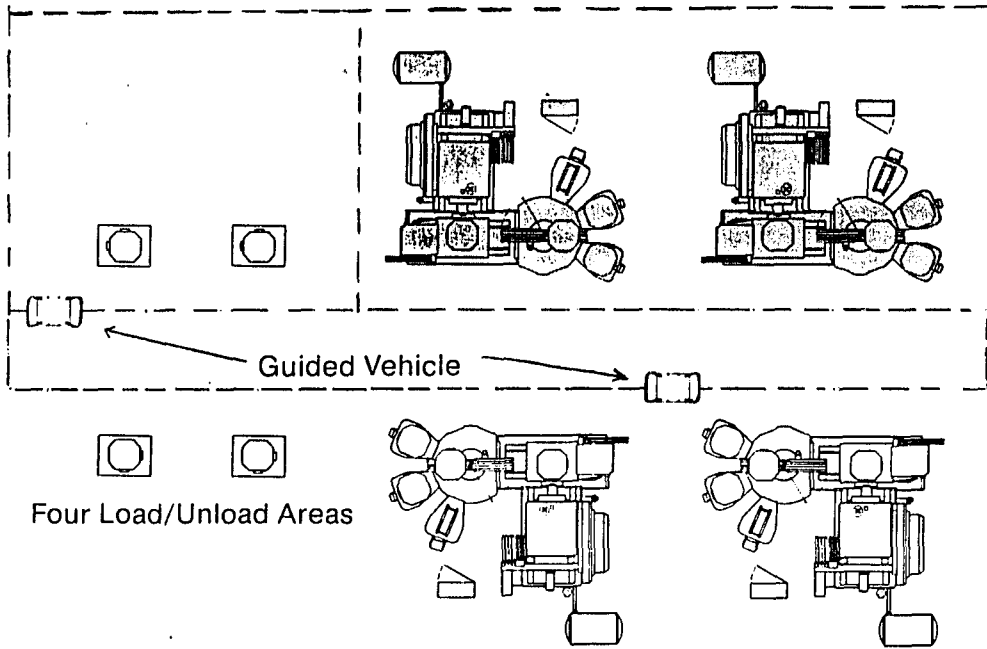


FIGURE 3. AGVS versus tow-line

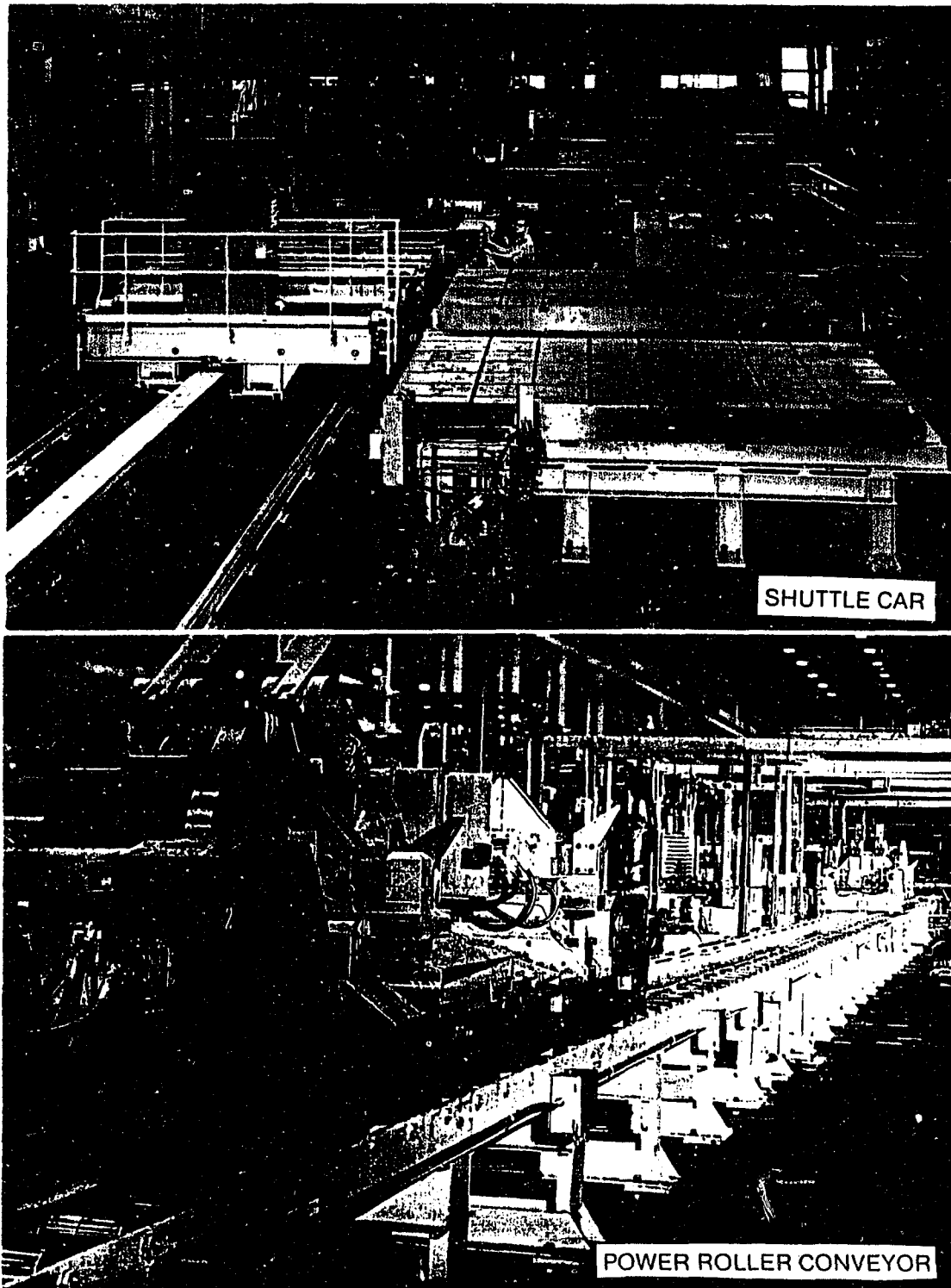


FIGURE 4. Power conveyor and shuttle car

4. Compatibility with computer control.
5. Provision for future expansion.
6. Accessibility to machine tool along with reliability of operation in shop environment

Finally, the material handling system should adhere all applicable industrial codes such as safety, temperature, noise, etc.

4. Warehousing and Storage

Warehousing of finished parts, work-in-process, and storage for raw materials are designed in coordination with the automated material manipulators. This mechanism is provided to adapt to the material handling system.

Buzacott and Shantikumar (12) point out that central storage along with buffer storage for one or two workpieces at each station is superior to local storage. This scheme reduces machine idle time while maintaining efficient use of storage facilities. For designing storage and delivery system, automation is the deriving force of the construction of such subsystem. Among many options and levels of automation, Automated Storage and Retrieval System (AS/RS) is one of the best known system.

AS/RS, see Figure 5, is usually implemented for the raw materials and finished parts, as well as for work-in-process

at machining cells. For the raw materials and processed parts, an automatic carrier with axial movement racks is the mean by which materials are transferred and stored. But for work-in-process buffer storage, centralized or decentralized, can be used. There are other conventional storage designs that could be installed as a part of an FMS, but the effects of such methods will converge on the flexibility of the whole system. Thus, automation is imperative.

5. Computer Control System

The computer system is the brain of any flexible manufacturing system. Success hinges on the ability of the computer hardware and software to do the job. In this subsection, the various functions of the computer including the data files needed to carry out these function, and various types of reports which FMS computer can be programmed to prepare, have been discussed (28).

The FMS computer system can be grouped according to the function performed into eight categories.

1. NC part program storage
2. Distribution of the part programs to the individual machine tool
3. Production control
4. Traffic control

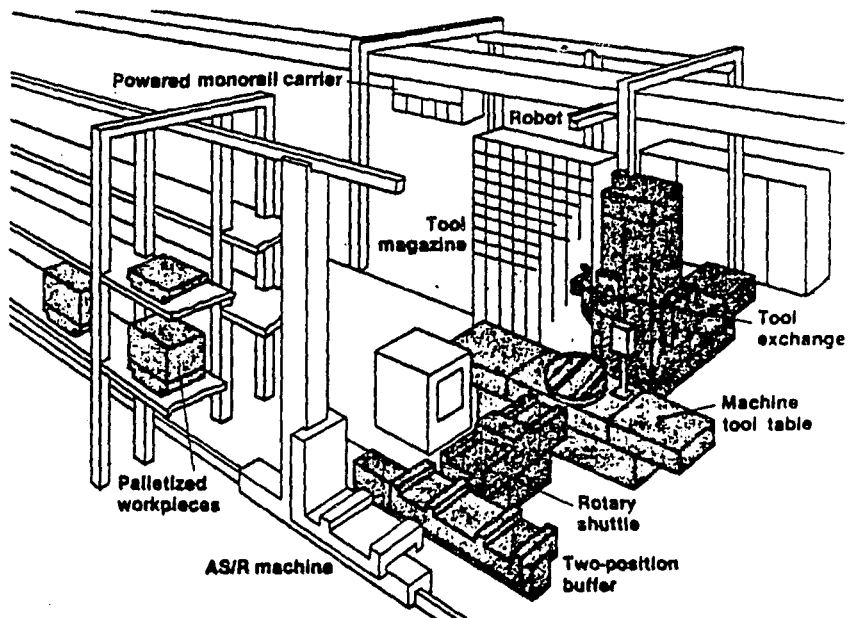


FIGURE 5. AS/RS storing and delivering parts to machines

5. Shuttle control
6. Work handling system monitoring
7. Tool control
8. System performance, monitoring, and reporting

To exercise control over the FMS, the computer relies on the data in files. The principal data files required for a flexible manufacturing system are the following six types.

1. Part file
2. Route file
3. Part production file
4. Pallet reference file
5. Station tool file
6. Tool-life file

Data collected during monitoring of FMS can be summarized for the system's performance reports, such as:

- Utilization report
- Production report
- Status report

Figure 6 illustrates how a computer hierarchy can be organized in a given FMS. The system is divided into three levels. The lowest one is the production level, where equipments are directly controlled by microcomputers and programmable controllers which take instruction from the mid-level. At mid-level, scheduling and logic decision

making are set forth for all the operations. This level is controlled by plant management. The top level is used by management to determine and to analyze various status of the plant operations.

No one package has proven to be the most efficient due to the numerous possible designs of FMS and their implications. Computer software engineering in FMS is the most critical stage of design and operation procedures. Having finalized production objectives and physical requirements for an FMS; the last major step will have to be the construction of a suitable computer control hierarchy, which should maximize the over all performance.

D. Methodologies for Justifying FMS

Objectives which can be used to justify an FMS may be related to economic, production, output quality, and flexibility. For example:

- The maximization of investment and operation costs
- Maximization of throughput time
- Improving product quality
- Flexibility of production

A primary difficulty involved in justifying an FMS is quantifying the intangible benefits. In many cases inherent

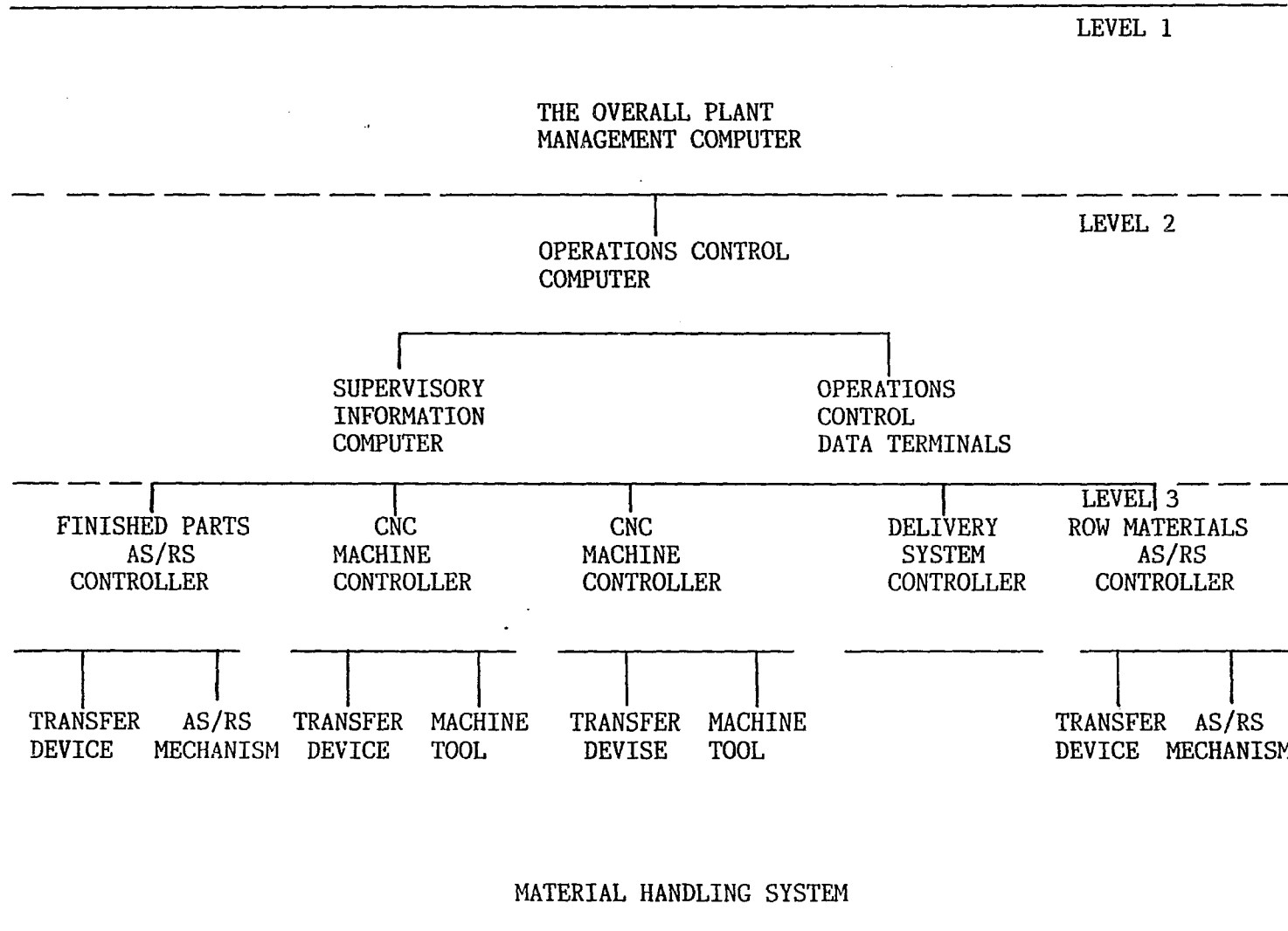


FIGURE 6. FMS computer hierarchy

efficiency of the FMS makes a compelling case for the justification.

1. Economic Justification

Popular engineering economy methods which are being used for economical justifications are payback period, rate of return, discount cash flow, net present value, and life cycle costing. A recent survey of 67 U.S. manufacturing firms indicate that 65% used the payback period, 26% used the rate of return methods, 5% used the net present value method, and 4% used other methods (14).

The popularity of payback is its ease of use. However, payback period does not account the time value of money. The popularity of the rate of return method is the ease of comparing the rate of return of the investment projects. Each method of the above treats only certain aspects of the project under consideration. However, additional factors must be considered to enhance the accuracy for the justification of project. The worthy consideration with FMS project is the effect of indirect factors on the over all system integration which leads to indirect cost reductions in work tracking, in-process inspection, transportation, tool control, production control, etc.

The direct cost reduction emerges from the elimination of most of direct labor that would be needed in a conventional system. This has been a proven fact that FMS technology reduces direct labor cost by 30% to 65%. This reduction in turn diminishes the errors caused by manual operation and eliminates scrap. The elimination of scrap implies direct material saving.

An FMS is a sophisticated combination of many elements operating as a single unit. A sound economical analysis of such system requires considerable efforts and should cover the planning, installing, and operating phases of the project.

2. Productivity

The second big cost saving by implementing FMS concepts is associated with productivity improvement through increasing machine utilization, reducing levels of work-in-process (WIP), and shortening the production cycle time.

The manufacturing lead time is reduced due to the possible elimination of its non-productive time components such as work-part handling time, tool handling time, machine set-up time, etc. This reduction leads to better utilization of machines as work-parts spend more time on the machines than in between. Therefore, work-parts are

processed at a faster rate, only few remain unfinished. This resulted in lowering in-process inventory. The empirical analysis at the University of Central Florida shows a reduction of about 81% in inventory carrying cost is nominal due to FMS application.

Although, preventive maintenance cost can be higher for a FMS than for a conventional system, but corrective maintenance cost is lower because of rerouting of parts. Consequences of this are lower indirect labor and material costs.

3. Quality Improvement

The level of automation offers improved quality of output and productivity which leads to a better utilization of expensive raw materials. Since, improved quality is associated with decrease in cost due to decrease in the number of defectives as humans are more prone to make mistakes than machines. The product quality is determined by the procedures, systems and paperwork which document how a product is made, and what inspections are carried out. The poor quality costs money and that a high level of quality therefore always pays because (23):

- Poor quality means rejects and costs money

- Maintaining of large numbers of people and machines who do nothing but repair, rectify and inspects also costs money
- Poor quality also means faulty products in the field, leading to lost of customers and high service costs
- Poor quality means breakdowns and these cost money

In other words, not making mistakes means increase in efficiency and productivity hence big returns.

4. Flexibility

Flexibility gives rise to many of the relative advantages of an FMS. Since machine tools are computer controlled, the system is flexible to produce a variety of parts by a simple change of software. During operations, the system can respond flexibly to unforeseen events, such as machine breakdown and temporary overloads, by rerouting workpieces to alleviate potential bottlenecks. Flexible machining centers in an FMS allow multiple operations to be performed on a workpiece. The wide acceptance of FMSs around industries today may be attributed solely to the flexibility that they carry.

Browne et al. (9) have classified flexible manufacturing systems according to the following types of

the flexibilities which cover all features of a manufacturing system.

- Machine flexibility
- Process flexibility
- Product flexibility
- Routing flexibility
- Volume flexibility
- Expansion flexibility
- Operation flexibility
- Production flexibility

The ideal FMS is one that possesses all of these flexibilities. A planner must be careful about the effects of acquiring one flexibility on the others. For instance, volume flexibility can be achieved through the most advance machine tools which may imply specialization. This would affect process, product, and production flexibilities in a negative way.

E. An Overview of Applications

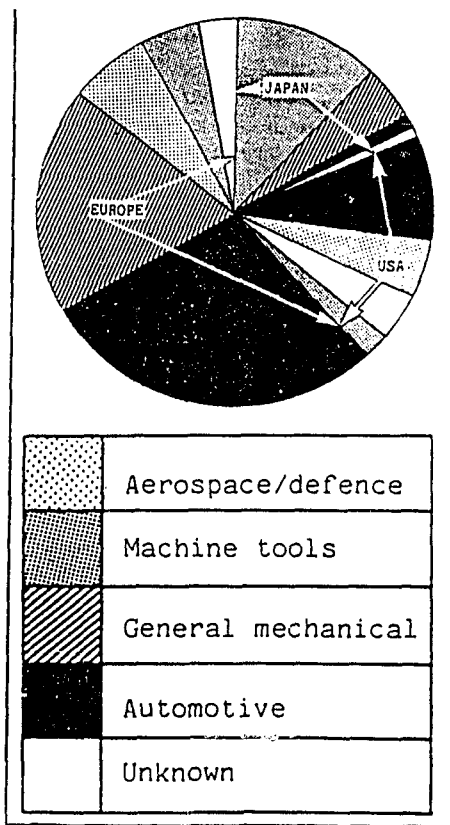
The distribution of the FMS installations in each country is shown in Figure 7. Since the concept of FMS has evolved around metal working industries, and therefore, has been applied solely in the manufacturing of metallic

components. The automotive industry is the main user in both Europe and USA, in Japan it is the smallest with the machine tool industry building the largest number of systems. The automotive industry accounts for 38.5% of the FMS user. Next comes general mechanical industry with 27.9% and machine tools with 18.3%. Finally some 11.5% are in aerospace or defense industries. The remaining 3.8% are either in educational establishments or unknown destinations. But if one examines FMS concept, he/she can realize the diversity of possible applications in various types of operations (14).

Plastic can be easily processed through some kind of a FMS in the same manner as metals are. The only difference would be in the type of machining used. A slight difference would also be in the material handling system because of lower weight capacity specifications. Woods, foods, chemicals, and other materials can utilize some FMS designs in certain processing operations. The level of automation with respect to personnel requirements may vary from one application to another, but FMS concept can be embedded.

Regarding FMS, Gettelman (24) has identified three broad aspects where it must be given deep consideration. The first is the need for constantly introducing new products, as it is easier to incorporate new product

APPLICATIONS OF AN FMS



- * 38.5% Automotive Industries
- * 27.9% Mechanical Industries
- * 18.3% Machine Tools
- * 11.5% Aerospace OR Defence
- * 3.8% Educational Establishments or Unknown

FIGURE 7. FMS application industries-worldwide

requirements in FMS than in conventional systems. The second is capacity expansion. An efficiently designed FMS provides anywhere from two to five times as much manufacturing capacity per unit of floor space as traditional plant floor organization. Finally modernization, this aspect maintains certain levels of technology which is capable of meeting all competitive challenges. A FMS is the one way of achieving them.

F. Generic Flexible Manufacturing System

The purpose of this thorough study was not only to understand concepts of flexible manufacturing system, or to comprehend the terminology of FMSs but also to find generic FMS layout or layouts which can be used for the development of performance evaluation model and must have all the characteristics of an FMS. Figures 8 and 9 are the findings of the intensive literature search. These are simple layouts but have all the necessary characteristics for claiming to be an FMS.

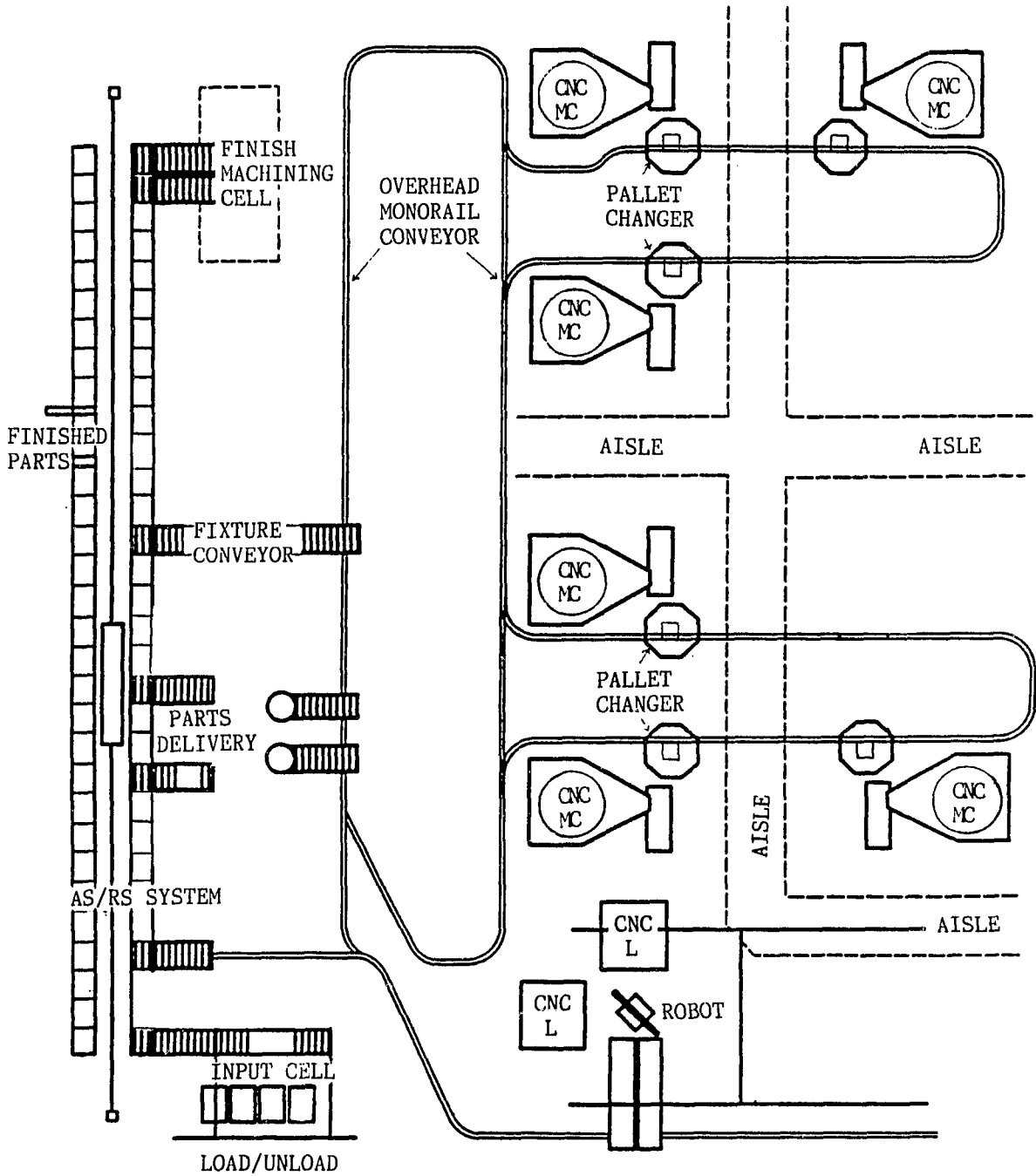


FIGURE 8. A conceptual FMS layout

MACHINING CENTER

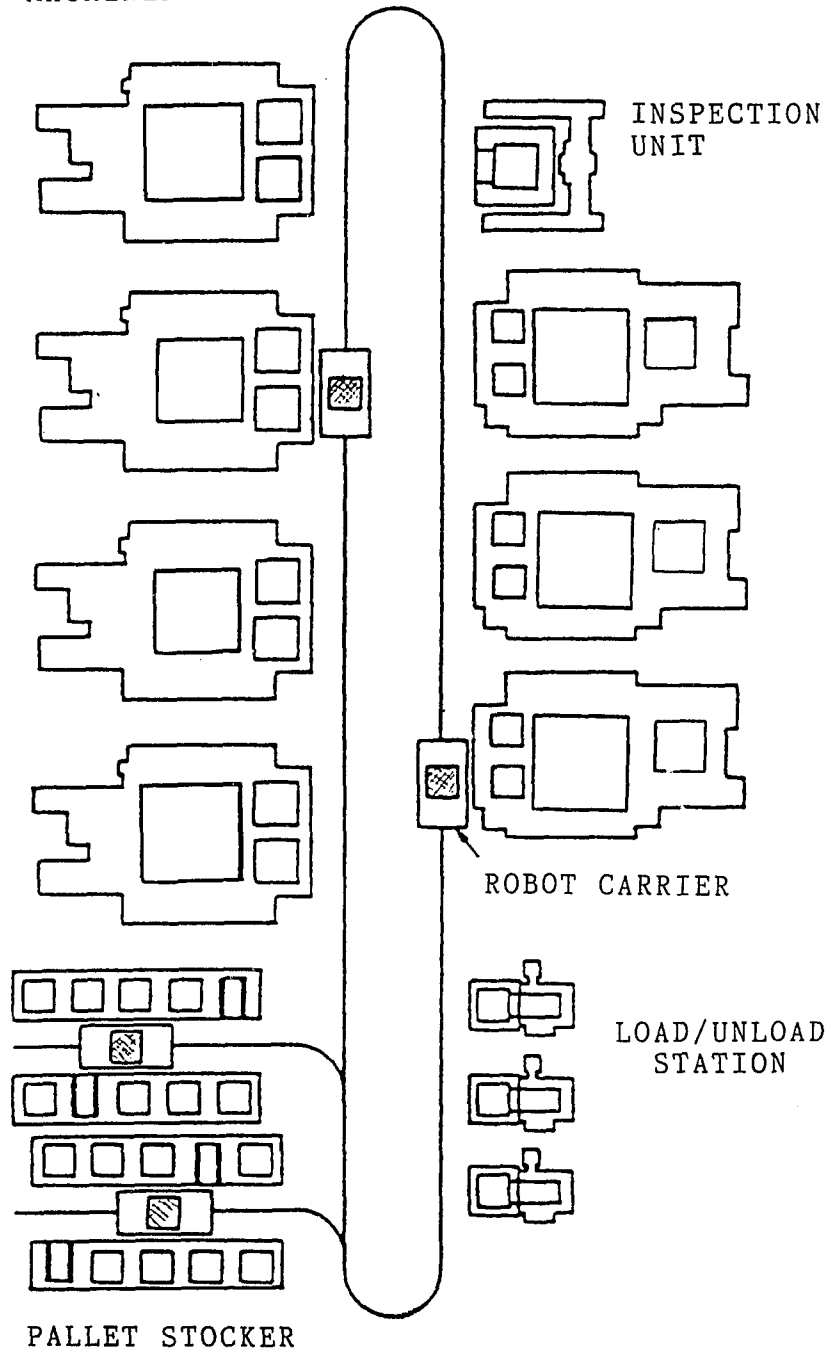


FIGURE 9. A generic FMS layout

III. TYPICAL PERFORMANCE MEASURES

A. Introduction

The overall objectives of a particular system are usually complex, very wide, and depend on specific requirements. Simple one-word answers such as performance, reliability, utilization, or cost alone are not sufficient. Other factors which are usually considered are schedule, maintainability, and life expectancy. Depending upon the application and the requirements, some system may stress on performance, others on reliability, others on schedule, others on cost, etc. (19).

System performance, reliability, schedule, cost, maintainability, and life expectancy are all inter-related system functions. The system performance improvement can usually be obtained if the schedule and cost factors are increased. On the other hand, the cost of the system can be decreased at the expense of poor performance and reliability.

This inter-relationship implies that performance is the most critical factor that should be considered for evaluating a system. Typical measures of performance for a system are availability, throughput and response time, production rate, component utilization, and system effectiveness.

B. Availability

Availability deals with both the failure and repair, whereas reliability is a measure of system quality for only failure event and maintainability measures restoration to service after a failure. Therefore, combination can be objectively evaluated only in terms of availability. The availability 'A(t)' is the ratio of the actual operating time to the schedule, excluding the preventive maintenance. Also, one can define availability as the probability of being in service during a scheduled operating period. Mathematically system availability at time, 't', is;

$$A(t) = \frac{MTBF}{MTBF + MDT}$$

where MTBF = Mean time between failure

MDT = Mean down time

or

The sum of the probabilities that corresponds to operating states at time t.

$$A(t) = \sum_{i \in Q_0} P(t)$$

where Q = State space

Q₀ = Operational state

Q_f = Failure state

P(t) = State probabilities at time t

The availability measure is important when the main penalty of system failures depend on the duration of failures. The term availability is used differently in the different situations. If one is to impose an availability figure of merit as a design requirement for a given equipment, then A_i (inherent availability) or A_a (achieved availability) might be the appropriate figures of merit against which equipment can be properly assessed. Since the supplier has no control over operational surrounding in which it is to function. If one is to assess a system or equipment in a operational environment, then A_o (operational availability) is a preferred figure of merit to employ for assessment purposes. Further, the term availability may be applied at any time in the overall mission profile representing a point estimate or may be more appropriately related to a specific segment of the mission where the requirements are different from other segments. Thus, one must be precise about meaning and the application of availability.

The availability can be applied to a single or multiple components in series but in case of parallel or parallel/series network its application is limited to two components due to difficulty of applying Laplace transformation theory to a large number of states.

C. Throughput and Response Time

Throughput is a measure of the rate at which the system does its work. Put another way, it is a measure of the quantity of function executions that the system can perform per unit time. Most systems can easily handle the throughput load generated by a single workstation, as the number of active work-stations increases, the peak throughput capacity can quickly be reached. When operating close to the peak throughput, the readiness of a system to accept further work diminishes and its response to operator requests for action slows down. This reduction in response time is the system's way of metering its work flow to match its throughput and prevent overloads (24).

However, the slowed response drastically reduces the productivity of the operator. Thus, system throughput is an especially important factor in multi-work-station because of its bearing on average work-station productivity. In some systems, a fast, partial response to operator action is made, even at peak throughput capacity. These requests are queued, then executed when the required capacity becomes available. This smooths some peaks in throughput demand; however, it is not effective for all functions or situations where a high rate of work-station requests are maintained for any length of time. Thus, the required throughput

capacity is set by what is deemed an acceptable work-station response time. Also, work-station response time should be evaluated in terms of its effects on operator productivity.

D. Utilization

Utilization is an important performance measure for an individual component. It can be defined in many ways. Most commonly it is defined as the fraction of time, over the long run, that a component is busy. For the system having multiple components, the utilization per component can be obtained by taking average of the fraction of time that each component is busy. The average utilization of parallel components can be determined by the total production rate of the parallel components divided by system output capacity (CAPOUT).

$$\text{Utilization} = \frac{P \cdot N}{\text{CAPOUT}}$$

where P = Production rate of each component
 N = Total number of component

E. Production Rate

Production rate is the number of finished parts per unit time, and is denoted by "P". The average production rate of each component is the reciprocal of the average production time, " t_p ".

$$P = 1/t_p$$

The net production rate of the system depends on the various kinds of stoppages such as tool failures, maintenance, control provisions, breakdowns of machines and material handling, and the effect of these factors on the entire system. Assuming that the work load of the system is shared equally, operating in the same conditions and consequently having same failures and repair rates for different modes of failure, and if all components are working at their production rate which is less than or equal to their capacity output. If F be the number of failed components, and Pr be the expected production rate at any time t. Therefore,

1) For n series components,

$$Pr(t) = P_O(t) \cdot P$$

where $P = \min \{P_1, \dots, P_n\}$

$P_O(t)$ = Operational probability at time t

or

$$Pr(t) = A(t) \cdot P$$

2) For parallel components,

When all N components in a group are operational then

$$\text{Production output} = T = P \cdot N$$

When F out of N components fail then

$$T(F) = P \cdot (N - F)$$

For a group of parallel components production rate is

$$\text{Pr}(t) = \sum_{i=0}^{N-1} P_i(t) \cdot T_i(F)$$

where $T_i(F)$ = Corresponding production rate for each failure state

$P_i(t)$ = State probability at time t

3) For combined system, components in each series represent a group and these groups behave like parallel components. Therefore, using parallel components technique one can find production rate.

F. System Effectiveness

The system effectiveness, E , is used to describe the overall capability of a system. It is defined as "the probability that a system can successfully meet an overall operational demand within a given time when operated under specified conditions (G. Salvendy)". The effectiveness is influenced by the way the system is designed, manufactured,

used, and maintained. Thus the effectiveness of a system is a function of a several attributes, such as performance measures, reliability, quality, producibility, and maintainability (72).

It is impossible to consider all parameters in constructing effectiveness function. Therefore, the parameters selection depend on the specific application and their significance to outcome. In this study the system effectiveness "E" is

$$\begin{aligned} E &= f(\text{performance measures}) \\ &= f(A_0, U, Pr) \end{aligned}$$

The A_0 , U , and Pr are inter-related parameters and can be measured on a single scale. The aim is to maximize the function which can be achieved by improving availability. This research defines the system effectiveness as the probability measure of the achievement of a specific mission goal.

IV. PERFORMANCE EVALUATION OF FLEXIBLE MANUFACTURING SYSTEMS

A. Introduction

In this chapter an approach has been presented for evaluating the performance (system effectiveness) of Generic Flexible Manufacturing Systems (FMSs) for which material is extracted from Kuo (37). There are several ways to evaluate a system but, performance is the most critical factor that should be considered for evaluating an FMS, since system performance is inter-related with reliability, maintainability, schedule, cost, etc.

System effectiveness is a measure to evaluate performance of systems. Adequate evaluation serves as a guide to optimum design and operations. In addition, proper maintenance policy and production strategy can be determined as a result of performance modeling. The system effectiveness adequately evaluates the success of meeting an operational demand within a given time under specified conditions. Another way of defining system effectiveness is "a measure of the degree to which an item can be expected to achieve a set of mission requirements and which may be expressed as a function of a availability, utilization, and

production rate". Among system effectiveness measure, availability has received the most attention, while utilization and production rate have often been employed as an appropriate measure for capacity planning or production schedule planning.

The availability of a system or equipment is "the probability that it is operating satisfactorily at any point in time when used under stated conditions, where total time considered includes operating time, active repair time, administration time, and logistic time".

System effectiveness models are normally expressed in a variety of ways according to user's requirements and its applications. This research describes the system effectiveness as a function of system availability and the probability measure of the achievement of a specific mission goal.

B. Performance Measure for a Generic FMS and Its Description

This research refers to system effectiveness as the performance measure of a Generic Flexible Manufacturing System which is in a compact form may consist of one or more than one subsystems, and is to perform a single functional purpose. Such stated subsystems are viewed as local systems

in this study. If an environment consists of several local systems which may or may not be of the same kind, then we extend the definition of system effectiveness such that the performance measure for the collection of local systems is defined in terms of the local system effectiveness. If FMS contains several local systems, each serving one kind of customer, then the needs of all kinds of customers should be considered when evaluating the performance of the whole FMS.

An FMS contains many local systems and shared central storage. Spares for the components of local systems are equipped in the central storage. Each local system is independently working, unless it requires spare parts from the central storage. Performance measure for such a system is determined by the local system effectiveness and the sparing policy. System effectiveness for a local system is a special case of our definition of performance measure for an FMS system.

A generic FMS contains M distinct local systems. Each local system contains N identical units as shown in Figure 10. Fulfillment of the requirements that all M local systems function properly is of interest to the system engineers. Physical link exist among local systems. In the case that a fraction of M local systems work properly while the others are down for repairs, partial credit is granted to the overall environment.

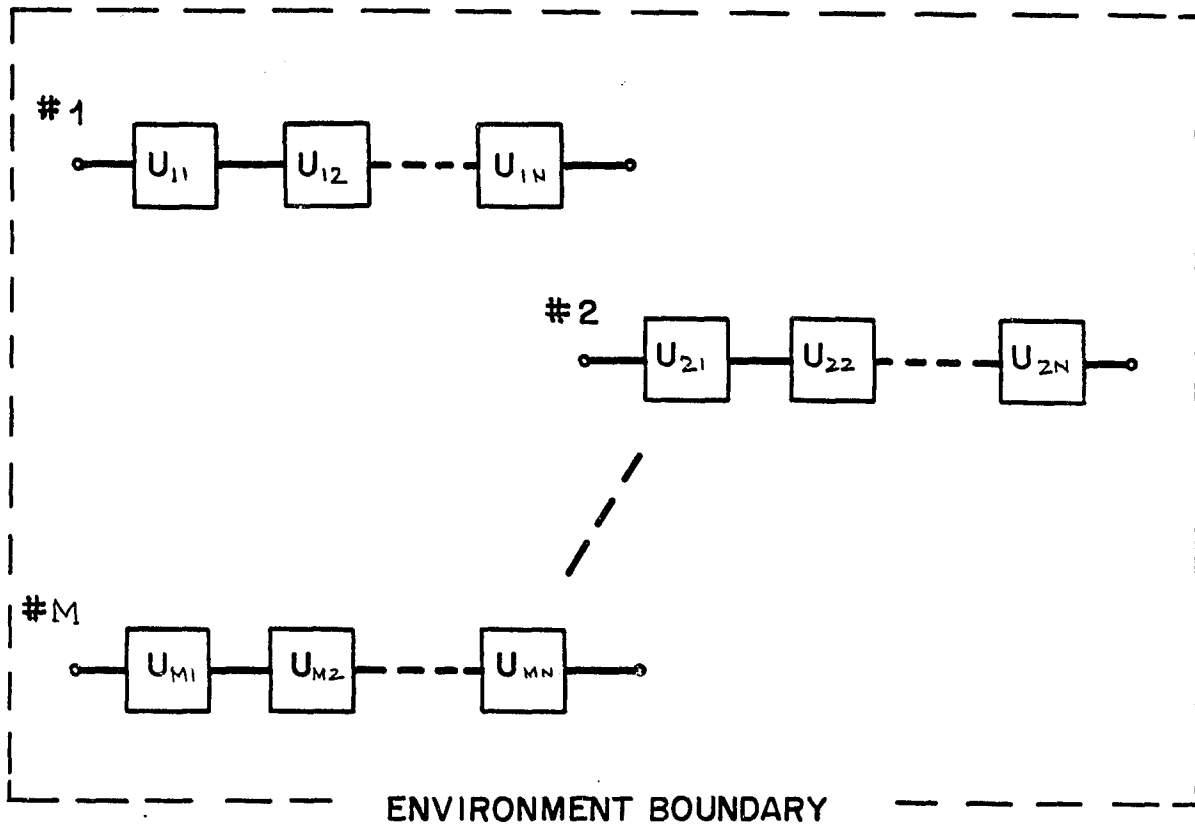


FIGURE 10. Diagram of a generic FMS containing M distinct systems

Failures are repaired at the central storage area. The central storage has a limited number of various kind of spare parts. Failed unit may be routed through the central storage area to factory for repairing if needed. Repaired units are shipped from central storage area to replenish a down system.

Another way to redraw such a system is to assume M sites environment where each contains N identical units as in Figure 11. Failures of the units are sent to the central storage to obtain a good spare, if it exists, and wait for a period of down time during the replenishment duration. If the central storage area has no spares, there is a longer interval until a repair is completed in the factory and routed to the site through the central storage area.

Units at the same site are also referred to as the same equipment type. The central storage area is located at a distance accessible to every local system. The original storage level of the k^{th} part at the central storage is x_k . The primary concern of this study is to evaluate and fulfill the environment requirements so that a certain degree of overall environment performance can be met. A proposed weighted availability, along with a stochastic process approach, serves this evaluation purpose.

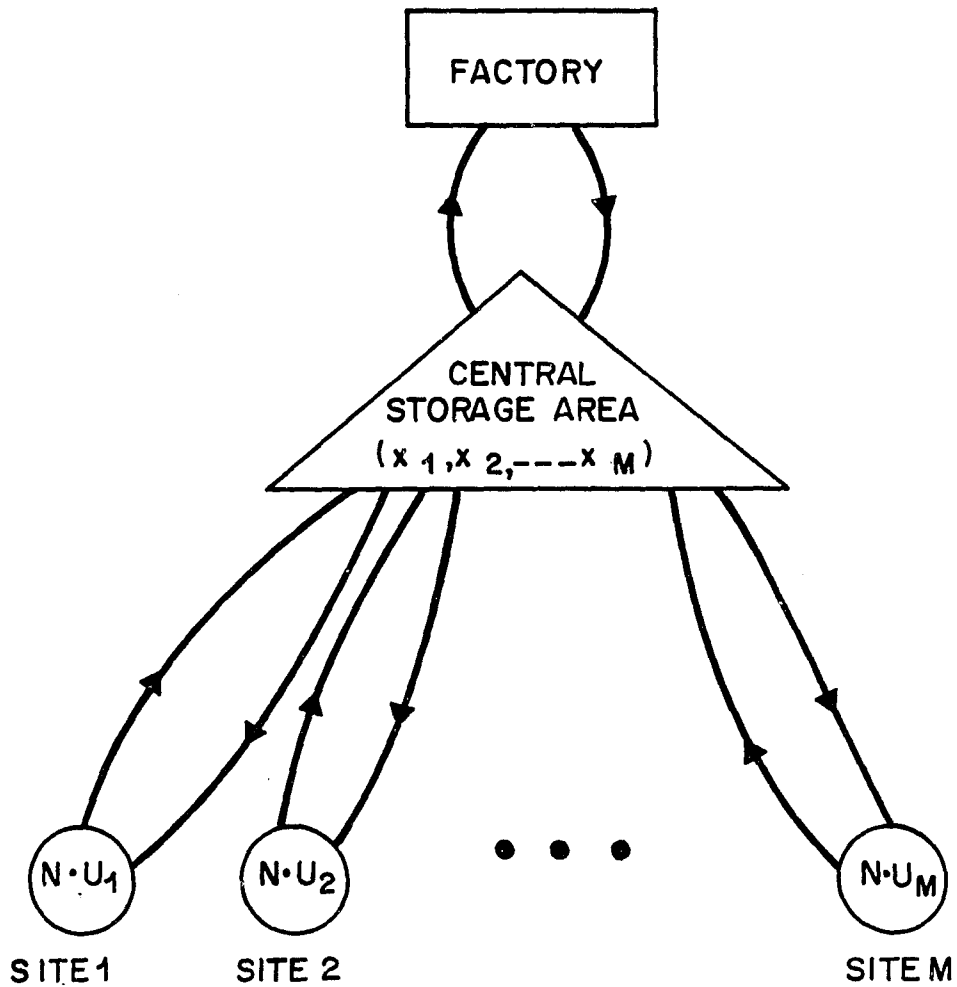


FIGURE 11. An environment of M distinct equipment types. Failures of any equipment types are sent to the central storage area, then routed to the factory for repair

C. Markov Modeling

1. Notation

n_i	number of working units in state $(i,0)$
(i,j)	i represents number of units of a certain type currently in the repair process and j tracks additional failed unit to be replaced
p	probability that a selected spare works
$P_k(i,j)$	the $(i,j)^{\text{th}}$ state probability of the k^{th} equipment type
n_{max}	maximum number of the units in the repair process
U_k	the k^{th} equipment type in a given local system, $k = 1,2,\dots,M$
x_k	number of allocated spares for the k^{th} equipment type, $k = 1,2,\dots,M$
x	number of allocated spares for one equipment type, a shorthand notation for x_k in later sections
\bar{x}	$(x_1, x_2, \dots, x_k, \dots, x_n)$
λ_i	transitional probability from $(i,0)$ to $(i,1)$ for one type of equipment
μ_i	transitional probability from $(i+1,0)$ to $(i,0)$ for one type of equipment
β_i	transitional probability from $(i,1)$ to $(i+1,0)$ for one equipment type
$\beta_{ii'}$	transitional probability from $(i,1)$ to $(i',1)$ $i \neq i'$ for one type of equipment

2. Markov Modeling for One Type of Equipment

A Flexible Manufacturing System may or may not consist of many different types of equipment. However, one can easily define an FMS into subsystems or local systems. Each of the local system comprises of one kind of equipment functioning independently. It is realistic to assume that the failures of various types of equipment occur independently and hence the Markov approach can be utilized to analyze each equipment type separately. This results in a separate application of the mathematical model for each type of equipment. The effect of an equipment type on the operation of FMS is characterized by the states of the model. Solving for steady-state probabilities gives the percentage time that the local system spends in each state. These probabilities are used to drive the steady state availability of an FMS based on one type.

Consider Figure 12 which depicts events of failure, replacement (response), and repair for one type of equipment on the site. Events in the interval (t_0, t_9) are outlined below.

- t_0 ---all equipment types functioning
- t_1 ---failure of one working unit
- t_2 ---replacement of failed unit with working spare
- t_3 ---failure of the second working unit
- t_4 ---replacement of failed unit with working spare

t_5 ---failure of the third working unit

t_6 ---replacement of failed unit with working spare
after first spare was found defective

t_7 ---repaired unit is returned to stock as spares

t_8 ---another repaired unit is returned to stock as spares

The overall effect, on the equipment type at the site of operation during the time interval (t_0, t_9) , is an increase from 0 unit to 2 units in the repair process.

Two state variables (i, j) characterize the Markov model. The variable i tracks the number of units (given type) currently in the repair process. And additional units yet to be replaced are reported by the variable j . To illustrate state variable, the events given in Figure 12 indicate the following one to one correspondence.

t_0 ---(0,0)

t_1 ---(0,1)

t_2 ---(1,0)

t_3 ---(1,1)

t_4 ---(2,0)

t_5 ---(2,1)

t_6 ---(4,0)

t_7 ---(3,0)

t_8 ---(2,0)

t_9 ---(2,0)

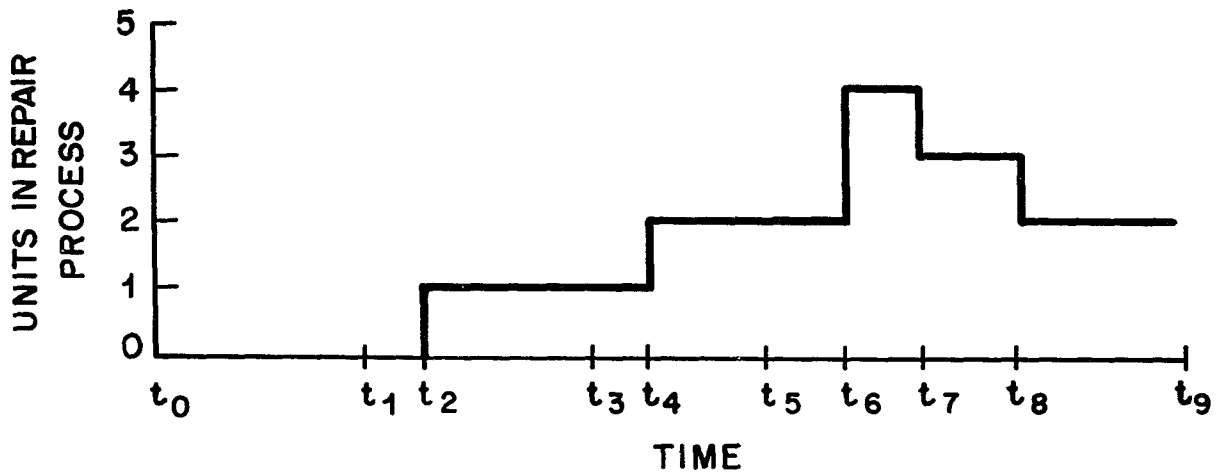


FIGURE 12. Units in the repair process during time interval (t_0, t_9)

Implicit in the Markov model is the concept of random failures of FMS equipments. Statistically, random failures correspond to postulating an exponential distribution for the time between failures (inter-failure distribution).

In Figure 12, failure of working units occur at times t_1 , t_3 , and t_5 . It is assumed that the working units are operating in the post infant mortality, constant failure rate region. Some spare parts are defective when they are installed. These spares may be broken in shipment or they may deteriorate in storage. Notice in Figure 12 that a failed spare is discovered at the time t_6 . Clearly, the spare has failed during the interval (t_0, t_6) , but generally no more information is known concerning this spare. This situation is modeled by simply assuming a constant probability that a spare unit will work. Once a working spare replaces a failed unit, this spare is treated as a working unit and thus is assumed to operate in the constant failure rate region.

Replacement rates of working units rather than failure rates are used in the Markov model since units that are replaced often haven't necessarily failed. For example, system diagnostics may isolate a a problem to three parts of different types. To expedite the restoral of service, all three units may be replaced even though only one might have

failed. The replacement rate is determined from the failure rate and specification of a constant ratio of the rate of replacement to failure.

Replacement of a failed unit in the plant is not assumed to be immediate. The concept of replacement (or response) interval is the time taken to reach a failed item and replace it with working spare is introduced.

Replacement interval involves time to (1) diagnose the failure, (2) travel to the site (from a central storage to an unattended equipment site), and (3) insert spares until a repair is completed. Replacement intervals shown in Figure 12 are (t_1, t_2) , (t_3, t_4) , and (t_5, t_6) .

Spare repair interval is the time required to replenish the stock of spare units with a repaired or new unit. It involves transportation time to and from the factory and time spent at the factory either for repairs or to obtain a new unit. The spare repair interval in Figure 12 are (t_2, t_7) and (t_4, t_8) . A unit in the spare repair interval is described in figure 12 as being in the repair process.

The Markov model is applied separately to each equipment type under the following assumptions.

- 1) Failure time, replacement time, and spare repair time are distributed exponentially with different parameters.
- 2) Each spare has constant working probability.
- 3) The system starts at a working state.

- 4) Replacements come from spares of identical age as the failing units.
- 5) M local systems function statistically independent.
- 6) N units in a local system function statistically independent.
- 7) Repairing two or more spare units simultaneously is impossible.
- 8) Work-pieces in each fixture are independent.

The equations for the steady-state probability are set up and solved from a continuous time, discrete state, Markov model. Solving the simultaneous equations yields the steady-state probabilities which determine spares allocation and system availability.

Let $Z(t)$ be the stochastic process defined by the state variables (i,j) and indexed by time t . The observed value of $Z(t)$ at time t_n is denoted by Z_n . A set of random variables $\{Z(t)\}$ forms a Markov chain. The transitions between states for a continuous time Markov chain may take place at any time. These transitions are indexed by $t_0, t_1, \dots, t_n, \dots$.

Recall that the system is assumed to be in steady-state equilibrium. Figure 13 shows the state space and the state transitional diagram for the Markov model. Let $P(i,j)$ denote the steady-state probability associated with state

(i,j) ; $i = 0, 1, \dots, n_{\max}$, $j = 0, 1$. By the definition of steady-state, the transition rate out of a given state equals the rate into that state. Thus, the following equations are written using Figure 13.

$$\textcircled{A} \quad \lambda_0 P(0,0) = \mu_1 P(1,0) \quad (1)$$

$$\textcircled{B} \quad (\lambda_i + \mu_i) = p\beta_{i-1}P(i-1,1) + \mu_{i+1}P(i+1,0) \quad (2)$$

for $i = 1, 2, \dots, x$

$$\textcircled{H} \quad (\lambda_i + \mu_i) = \beta_{i-1}P(i-1,1) + \mu_{i+1}P(i+1,0) \quad (3)$$

for $i = x+1, \dots, n_{\max}-1$

$$\textcircled{E} \quad \mu_{n_{\max}}P(n_{\max},0) = \beta_{n_{\max}-1}P(n_{\max}-1,1) \quad (4)$$

$$\textcircled{C} \quad p\beta_0P(0,1) + \sum_{i'=1}^x \beta_{0i'}P(0,1) = \lambda_0P(0,0) \quad (5)$$

$$\textcircled{D} \quad p\beta_iP(i,1) + \sum_{i'=i+1}^x \beta_{ii'}P(i,1) = \lambda_iP(i,0) + \sum_{i'=0}^{i-1} \beta_{i'i}P(i',1) \quad (6)$$

for $i = 1, 2, \dots, x-1$

$$\textcircled{F} \quad \beta_xP(x,1) = \lambda_xP(x,0) + \sum_{i'=0}^{x-1} \beta_{i'x}P(i',1) \quad (7)$$

$$\textcircled{G} \quad \beta_iP(i,1) = \lambda_iP(i,0) \quad (8)$$

for $i = x+1, x+2, \dots, n_{\max}$

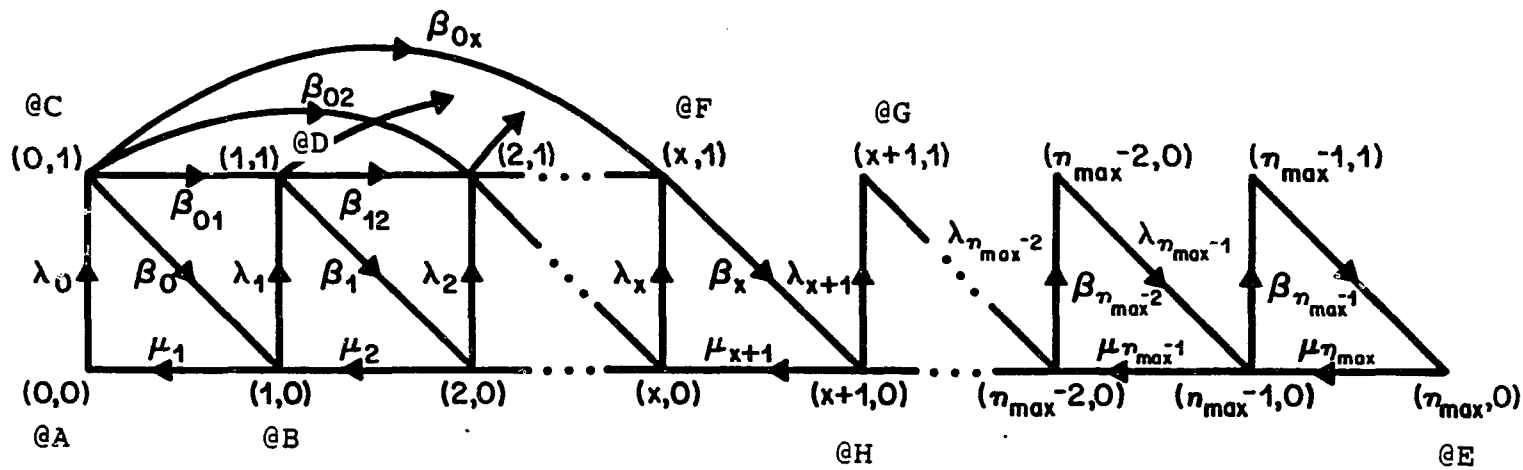


FIGURE 13. State space and transition rate

From the axioms of probability theory, the following equation also holds since the state space in Figure 13 is assumed to be exhaustive.

$$\sum_{i=0}^{n_{\max}} P(i,0) + \sum_{i=0}^{n_{\max}-1} P(i,1) = 1 \quad (9)$$

Solving equations (1) to (8), along with the normality condition of equation (9), a set of solutions for $P(i,j)$ where $i = 0, 1, \dots, n_{\max}$, $j = 0, 1$ can be obtained.

D. Evaluation of FMS Performance Measure

The final goal is to optimally allocate $\bar{X} = (x_1, x_2, \dots, x_M)$ so that local systems of an FMS in a given environment meet certain performance standards. The performance requirements include the following:

1. All subsystems are properly functioning
2. Some of the subsystems are functioning while some are not, given that one equipment type is down
3. Some of the subsystems are functioning while some are not, given that more than one equipment type is down

The first performance requirement is a conventional way to treat the effectiveness of the systems, i.e., system

regarded as an entirety unit. Partial fulfillment of the requirements in the system deserve partial credits, which is important when each unit/subsystem is an independent identity. Thus, the second one accounts for partial credit which may be granted to the overall performance. Since all "N" pieces of equipment within each "M" local system are identical, it would be immaterial to assign partial credit to any specific unit; only a weight assigned to the overall effectiveness is important. The third performance requirement also accounts for some partial credit granted to the overall performance. Since more than one equipment type is down, these failing equipment types are spread over several subsystems. The probability that a specific event occurs might affect the weighting factor to the overall system performance.

1. Effectiveness Evaluation

Consider a k^{th} type of an FMS equipment, all of the k^{th} type units function properly as long as the number of units in the repair process is less than x_k . Let $P_k(0,0)$ be the probability that all of the k^{th} type of equipments are working properly in the environment without any failure in the repairing process. Similarly, $P_k[(i,0) | i \leq x_k]$ is the

probability that all of the k^{th} type of equipments are functioning properly in the environment given that i units are in the repairing process, where $i \leq x_k$.

Traditionally, the availability of the k^{th} type of equipment is

$$\sum_{i=0}^{x_k} P_k[(i,0) | i \leq x_k]$$

Hence, the availability of a given system can be expressed as

$$A_0 = \prod_{k=1}^M \sum_{i=0}^{x_k} P_k[(i,0) | i \leq x_k] \quad (10)$$

which is also the probability that the environment is under proper working condition.

In case that the k^{th} equipment is in the state $(x_k+1,0)$ with probability $P_k(x_k + 1,0)$ while all the other equipment types are in the state $(i,0)$ where $i \leq x_i$ for $i \neq k$, then we can assume that (1) one of the M sub-systems is in partially down or down state because of the unavailability of a good spare for the k^{th} type of equipment and (2) the other $M-1$ sub-systems are functioning properly. The probability associated with events (1) and (2) guarantees $M-1$ systems function and can be written as

$$A_{11}^k = P_k(x_k + 1, 0) \prod_{\substack{k'=1 \\ k' \neq k}}^M \sum_{i=1}^{x_{k'}} P_{k'}[(i, 0) | i \leq x_{k'}] \quad (11)$$

If the k^{th} equipment type is in the state $(x_k+1, 0)$ and, simultaneously, the ℓ^{th} equipment is in the state $(x_\ell+1, 0)$ while all the other types of equipment are in the state $(i, 0)$ where $i \leq x_i$ for $i \neq k$ and $i \neq \ell$, then one can imagine that (1) two of the M sub-systems are in the partially down or down state because of unavailability of good spares for the k^{th} equipment type in one system and for the ℓ^{th} equipment type in the other system while remaining $M-2$ are functioning properly. Therefore, probability associated with event (1) is written as

$$A_{11}^{k\ell} = P_k(x_k + 1, 0) P_\ell(x_\ell + 1, 0) \prod_{\substack{k'=1 \\ k' \neq k \\ k' \neq \ell}}^M \sum_{i=0}^{x_{k'}} P_{k'}[(i, 0) | i \leq x_{k'}] \quad (12)$$

The probability that at least one sub-system is working properly can similarly be calculated. Unless all M equipment types are in the state $(x_i+1, 0)$, for all $i = 1, 2, \dots, M$, there exists a positive probability that some of the local systems will function properly, and hence credit should be granted as partial attributes to the overall environment performance measurement.

For example, if the k^{th} equipment is in the state $(x_k+2,0)$ with probability $P_k(x_k+2,0)$ while the other equipment types are in the state $(i,0)$ where $i \leq x_i$ for $i \neq k$, then we can assume that (1) one of the M sub-systems are in the partially down or down state because of the inability of getting good spares for the k^{th} equipment type and (2) the $M-1$ sub-systems are functioning properly. The probability associated with such events can be written as

$$A_2^k = P_k(x_k + 2, 0) \prod_{\substack{k'=1 \\ k' \neq k}}^M \sum_{i=0}^{x_{k'}} P_{k'}[(i, 0) | i \leq x_{k'}] \quad (13)$$

In case that the k^{th} equipment type is in the state $(x_k+2,0)$ and, simultaneously, the ℓ^{th} equipment type is in the state $(x_\ell+2,0)$ while all the other equipment types are in the state $(i,0)$ where $i \leq x_i$ for $i \neq k$ and $i \neq \ell$, then we can assume that (1) two of the M sub-systems are in the partially down or down state and the other $M-2$ local systems are functioning properly. The probability associated with the above event is

$$A_{22}^{k\ell} = P_k(x_k + 2, 0) P_\ell(x_\ell + 2, 0) \prod_{\substack{k'=1 \\ k' \neq k \\ k' \neq \ell}}^M \sum_{i=0}^{x_{k'}} P_{k'}[(i, 0) | i \leq x_{k'}] \quad (14)$$

In general, if the k_1^{th} type is in the state $(x_{k_1}+a_1,0)$, the k_2^{th} type is in the state $(x_{k_2}+a_2,0)$, ..., the k_m^{th} type is in the state $(x_{k_m}+a_m,0)$, and $a_i < N$, $\forall i$ and $m < M$, then there exists a positive probability that at least one system is functional. The probability associated with the events is

$$\begin{aligned}
 & \begin{matrix} k_1 & k_2 & \dots & k_m \\ A & & & \\ a_1 & a_2 & \dots & a_m \end{matrix} = \\
 & \prod_{j=1}^m P_{k_j}(x_{k_j} + a_j) \prod_{\substack{k'=1 \\ k' \neq k_j}}^M \sum_{i=0}^{x_{k'}} P_{k'}[(i,0) | i \leq x_{k'}] \quad (15) \\
 & \quad \forall j=1, 2, \dots, m
 \end{aligned}$$

2. Assignment of Weights to the Effectiveness

Since all "N" units in each of M local systems are identical to one another, it is realistic to regard each unit and each subsystem equally important to overall system effectiveness. Therefore, the frequency of failures occurring in a specific system follows the combination law. The relative weight given to the environment effectiveness under various failures in the repairing process can be readily evaluated. If $i \leq x_k$, the weight of unity is assigned to availability, otherwise a fraction will be assigned.

For the k^{th} equipment type in the state $(x_{k+1}, 0)$ and all the other types of equipment in the state $(i, 0)$ where $i \leq x_i$ for $i \neq k$, the down state can appear in any one of the M local systems with equal probability. Therefore, the weighting factor to be assigned to A_1^k is

$$w_1^k = (N - 1)/N \quad (16)$$

For the k^{th} equipment type in the state $(x_{k+1}, 0)$, and simultaneously, the ℓ^{th} equipment in the state $(x_{\ell+1}, 0)$, while all the other equipment types are in the state $(i, 0)$ where $i \leq x_i$ for $i \neq k$ and $i \neq \ell$, the weighting factor of

$$\begin{aligned} w_{11}^{k\ell} &= (N - 1)/N \cdot (N - 1)/N \\ &= [(N - 1)/N]^2 \end{aligned} \quad (17)$$

should be assigned to $A_{11}^{k\ell}$.

For the k^{th} equipment type in the state $(x_{k+2}, 0)$ while other equipment types in the state $(i, 0)$ where $i \leq x_i$ for $i \neq k$, the two down units are distributed uniformly among the N local units. Therefore, the weighting factor assigned to A_2^k is

$$w_2^k = (N - 2)/N \quad (18)$$

For the k^{th} equipment types in the state $(x_{k+1}, 0)$ and, simultaneously, the ℓ^{th} equipment in the state $(x_{\ell+2}, 0)$

while all the other equipment types in the state $(i,0)$ where $i \leq x_i$ for $i \neq k$ and $i \neq \ell$ implies that there are two local systems in down state. Hence, the weighting factor is

$$\begin{aligned} w_{12}^{k1} &= (N - 1)/N \cdot (N - 2)/N \\ &= (N - 1)(N - 2)/N^2 \end{aligned} \quad (19)$$

For the k^{th} equipment types in the state $(x_{k+2},0)$ and, simultaneously, the ℓ^{th} equipment in the state $(x_{\ell+2},0)$ while all the other equipment types in the state $(i,0)$ where $i \leq x_i$ for $i \neq k$ and $i \neq \ell$ implies that there are two local systems in down state.

$$\begin{aligned} w_{22}^{k1} &= (N - 2)/N \cdot (N - 2)/N \\ &= [(N - 2)/N]^2 \end{aligned} \quad (20)$$

For the k^{th} equipment types in the state $(x_{k+1},0)$, the ℓ^{th} equipment in the state $(x_{\ell+2},0)$, and the m^{th} equipment types in the state $(x_{m+3},0)$ while all the other equipment types in the state $(i,0)$ where $i \leq x_i$ for $i \neq k$, $i \neq \ell$, and $i \neq m$ implies that three local systems are in partially down or down state. We denote the weighting factor by

$$\begin{aligned} w_{123}^{klm} &= (N - 1)/N \cdot (N - 2)/N \cdot (N - 3)/N \\ &= (N - 1)(N - 2)(N - 3)/N^3 \end{aligned} \quad (21)$$

In general, if the k_1^{th} equipment type is in the state $(x_{k_1} + a_1, 0)$, the k_2^{th} equipment type is in the state $(x_{k_2} + a_2, 0)$, ..., the k_m^{th} equipment type is in the state $(x_{k_m} + a_m, 0)$, also $a_i < N$, $\forall i$ and $m < M$, the weighting factor is denoted by

$$W_{a_1 a_2 \dots a_m}^{k_1 k_2 \dots k_m} = \prod_{i=1}^m (N - a_i) / N \quad (22)$$

3. FMS Performance Measurement

To adequately model the performance measurement for all the local systems in an environment, a weighted availability measure is formulated which includes the following:

1. A_0 where all the systems are operating properly, either no failure occurs or the failures do not exceed the storage level.
2. $W_1^k A_1^k$ for k^{th} types of equipment, $k = 1, 2, \dots, M$ where exactly one local system is in the partially down or down state.
3. $W_2^k A_2^k$ for k^{th} types of equipment, $k = 1, 2, \dots, M$ where exactly two equipment in a local system is in the partially down or down state.

•

•

•

4. $W_{a_1 a_2 \dots a_m}^{k_1 k_2 \dots k_m}$ where the k_1 th equipment type is in the state $(x_{k_1} + a_1, 0)$, the k_2 th equipment type is in the state $(x_{k_2} + a_2, 0)$, ..., the k_m th equipment type is in the state $(x_{k_m} + a_m, 0)$, as long as $a_i < N, \forall i$. A summation of the above attributes forms the performance measurement.

$$P = A_0 + \sum_{k=1}^M W_1^k A_1^k + \sum_{k=1}^M W_2^k A_2^k + \dots + \sum_{k=1}^M W_{N-1}^k A_{N-1}^k$$

$$+ \sum_{\ell=1}^M \sum_{k=1}^M W_{11}^{k\ell} A_{11}^{k\ell} + \sum_{\ell=1}^M \sum_{k=1}^M W_{22}^{k\ell} A_{22}^{k\ell} + \dots$$

$$+ \sum_{\ell=1}^M \sum_{k=1}^M W_{N-1}^{k\ell} A_{N-1}^{k\ell} + \sum_{\ell=1}^M \sum_{k=1}^M W_{12}^{k\ell} A_{12}^{k\ell} + \dots$$

$$+ \sum_{k_1=1}^M \sum_{k_2=1}^M \dots \sum_{k_m=1}^M W_{N-1}^{k_1 k_2 \dots k_m} A_{N-1}^{k_1 k_2 \dots k_m}$$

$$= A_0 + \sum_{a_1=1}^{N-1} \sum_{k=1}^M W_{a_1}^k A_{a_1}^k + \sum_{a_1=1}^{N-1} \sum_{a_2=1}^{N-1} \sum_{k_1=1}^M \sum_{k_2=1}^M \dots$$

$$W_{a_1 a_2}^{k_1 k_2} A_{a_1 a_2}^{k_1 k_2} + \dots + \sum_{a_1=1}^{N-1} \sum_{a_2=1}^{N-1} \dots \sum_{a_m=1}^{N-1} \sum_{k_1=1}^M \sum_{k_2=1}^M \dots \sum_{k_m=1}^M$$

$$\cdot W \begin{matrix} k_1 & k_2 & \dots & k_m \\ a_1 & a_2 & \dots & a_m \end{matrix} \quad A \begin{matrix} k_1 & k_2 & \dots & k_m \\ a_1 & a_2 & \dots & a_m \end{matrix}$$

$$\begin{aligned}
P &= A_0 + \sum_{a_1=1}^{N-1} [(N - a_1)/N] \sum_{k=1}^M A_{a_1}^k \\
&+ \sum_{a_1=1}^{N-1} \sum_{a_2=1}^{N-1} [(N - a_1)/N][(N - a_2)/N] \sum_{k_1=1}^M \sum_{k_2=1}^M A_{a_1 a_2}^{k_1 k_2} \\
&+ \dots \dots \dots + \dots \dots \dots + \dots \dots \\
&+ \sum_{a_1=1}^{N-1} \sum_{a_2=1}^{N-1} \dots \sum_{a_m=1}^{N-1} [(N - a_1)/N] [(N - a_2)/N] \dots \\
&\dots [(N - a_m)/N] \sum_{k_1=1}^M \sum_{k_2=1}^M \dots \sum_{k_m=1}^M A_{a_1 a_2 \dots a_m}^{k_1 k_2 \dots k_m}
\end{aligned} \tag{23}$$

Equation (23) is a realization of performance measure of a system consisting of one or more subsystems. The first term on the right hand side is a regular estimate for effectiveness. The other terms are the effectiveness contributed by the down states.

E. Optimal Storage Policy

In this section author discusses the storage level for each subsystem. The maximum storage level for any local system will not likely to exceed the number of that kind of equipment in the environment. To determine the optimal storage level for each subsystem subjected to a given performance measure, a functional form of the performance measure for the centralized storage of flexible manufacturing system is derived, i.e., equation (23). A heuristic programming (discussed later) is performed for the optimization, after examining the functional properties of the equation (23). The optimization problem is to minimize

$$\begin{aligned} Z &= C(\bar{X}) \\ &= C(x_1, x_2, x_3, \dots, x_m) \end{aligned}$$

s.t.

$$\begin{aligned} g_1 &= P(\bar{X}) \geq P_{\min} \\ g_2 &= A_0(\bar{X}) \geq A_{0,\min} \\ \bar{X} &\geq 0 \end{aligned}$$

where

$C(\bar{X})$ is the cost function

P_{\min} is the minimum performance requirement

$A_{0 \min}$ is the minimum system's availability

$P(\bar{X})$ and $A_0(\bar{X})$ are given by the equation (23) and equation (14) respectively.

1. Heuristic Approach

This heuristic approach is based on the concept that a spare is added to the central storage to the equipment type where its addition produces the greatest ratio of "product of increments increase in the performance" to "incremental increase in the system cost". The ratio is defined by

$$F_k(X_k) = \frac{\prod_{i=1}^2 \Delta_k g_i(\bar{X})}{\Delta_k Z(\bar{X})}$$

where

$$\Delta_k g_i(\bar{X}) = P(x_1, x_2, \dots, x_{k+1}, \dots, x_m) - P(x_1, x_2, \dots, x_k, \dots, x_m)$$

$$\Delta_k Z(\bar{X}) = C(x_1, x_2, \dots, x_{k+1}, \dots, x_m) - C(x_1, x_2, \dots, x_k, \dots, x_m)$$

$F_k(X_k)$ is the function of k as well as x_k ; hence in the computation it keeps changing even for a fixed k . A flow diagram of the heuristic algorithm is shown in Figure 14 and the computational procedure is as follows:

Step 1. Let $\bar{X} = (x_1, x_2, x_3, \dots, x_m) = (1, 1, 1, \dots, 1)$

Step 2. a) Calculate $F_k(X_k)$ for all k , $k = 1, 2, \dots, M$.

b) Select the subsystem having highest $F_k(X_k)$ A spare

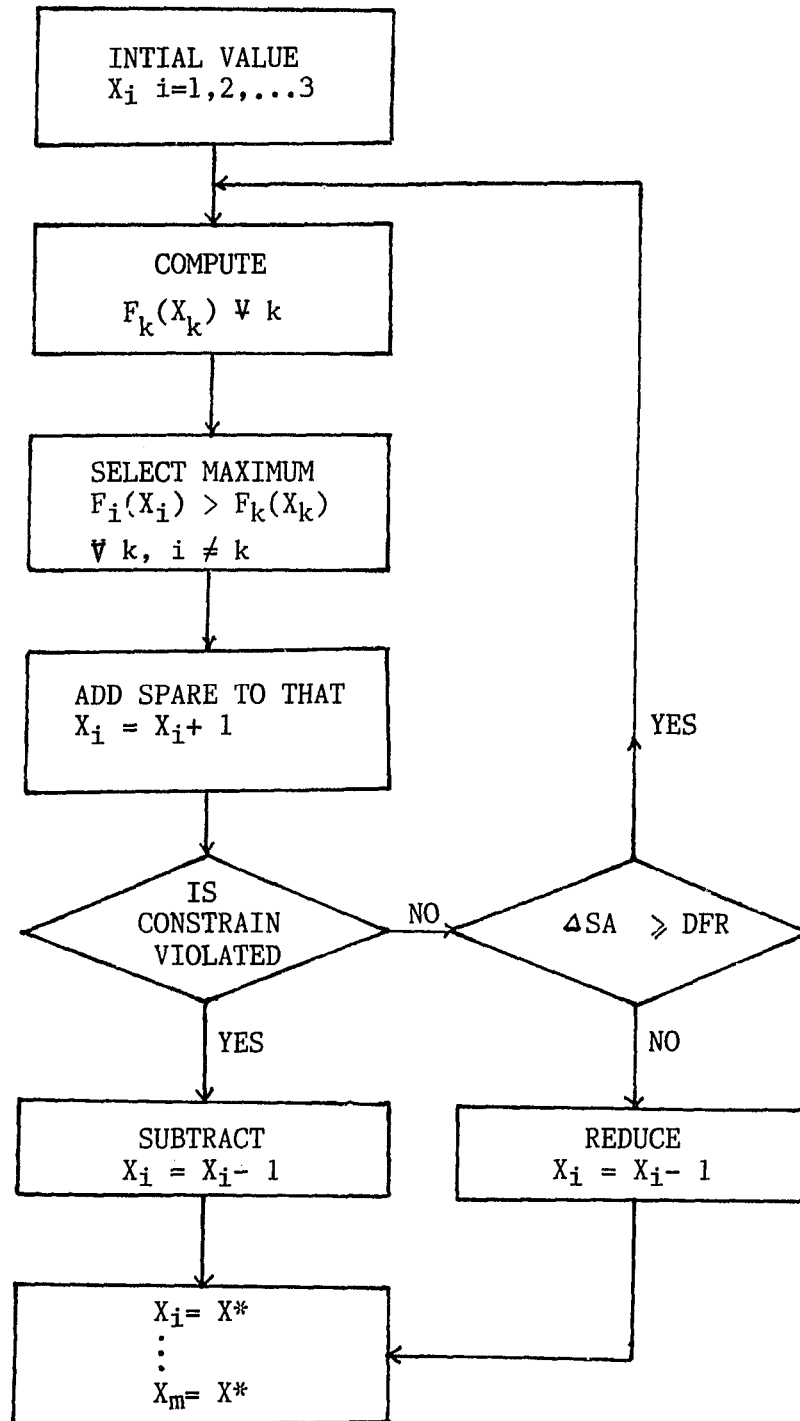


FIGURE 14. A flow diagram of heuristic approach

component is proposed to be added.

Step 3. Check to see if the constraints are violated.

- a) If solution is still feasible, add one spare component to that subsystem having highest $F_k(X_k)$. Check increase in system performance \geq DFR and hence go to step 2.
- b) If increase in system performance $<$ DFR, remove that stage from further consideration and repeat step 2. When all the subsystems are exhausted from consideration the current value of \bar{X} is optimum configuration.

Where: DFR is a desirability factor ratio. It is defined as percentage increase in system availability to percentage increase of corresponding cost due to spares. Its value depends on application, cost, and desirability to increase system's availability. This research assumes DRF = 0.0005.

2. Summary and Results

This newly developed heuristic procedure is carried out by a algorithm to determine, if not optimal, close to optimal storage level for each sub-system. The algorithm

involves a sequence of iteration each of which allows a higher degree of system availability.

Unlike traditional approach there are two goals to be achieved for the heuristic approach. First for each type, accounting for partial credits from environment viewpoint if only some local systems are partially available. Secondly, the implicit enumeration algorithm determines the optimal cost effective storage policy by exploiting the monotonous property of constraints.

With the integration of above mentioned goals, it has been found that the heuristic approach generates storage policy level that maximizes the system performance measure for generic FMS systems. Two representative examples have been run using the heuristic approach whose data and results are tabulated in Tables 2 and 3 for analysis.

TABLE 2. Heuristic approach: Example-I

DATA:

	TYPE#1	TYPE#2	TYPE#3
MTTF:	1000	2000	1500
MTTR:	10	12	15
MTR :	4	6	8
N :	4	4	4

PROBABILITY A SPARE WORKS=.99

DESIRABILITY FACTOR RATIO =.0003

SPARE COMPONENTS FOR			SUBSYSTEM SELECTION FACTOR			SYS AVAIL
TYPE# 1	TYPE# 2	TYPE# 3	F(X)# 1	F(X)# 2	F(X)# 3	
0	0	0	-	-	-	0.907606
1	1	1	.990738	.993023	.987189	0.986773
1	1	2	.990738	.993023	.988979	0.987198

TABLE 3. Heuristic approach: Example-II

DATA:

	TYPE#1	TYPE#2	TYPE#3	TYPE#4
MTTF:	300	650	500	400
MTTR:	10	12	15	20
MTR :	4	6	8	5
N :	5	6	4	6

PROBABILITY A SPARE WORKS=.99
 DESIRABILITY FACTOR RATIO =.0005

SPARE COMPONENTS FOR				SUB-SYSTEM SELECTION FACTOR				SYS AVAIL
TYPE# 1	TYPE# 2	TYPE# 3	TYPE# 4	F(X)# 1	F(X)# 2	F(X)# 3	F(X)# 4	
0	0	0	0	-	-	-	-	0.602784
1	1	1	1	.967494	.978302	.960282	.962444	0.944565
1	1	2	1	.967494	.978302	.966633	.962444	0.946197
1	1	2	2	.967494	.978302	.966633	.972044	0.947727
2	1	2	2	.972533	.978302	.966633	.972044	0.948514

F. Sensitivity Analysis

This section discusses the sensitivity of performance due to changes in a particular parameter or parameters. Moreover, optimal values of spare-components are used for conducting sensitivity analysis since optimization of a system depends to a great extent upon the system's behavior. It is often true that the solution one obtains in solving a model is the solution that is optimal only with respect to the model and not necessarily with respect to the actual problem. As in constructing such model we have employed certain simplifying assumptions that may or may not affect the validity of the derived solution.

Another reason to look beyond the initial solution is that, in most real-life situations, the solution is only part of information that is really needed or desired. Quite often, more important than model solutions is any information that will enable us to improve the system itself, such as, information regarding:

- The parameter or parameters principally responsible for specific behavior.
- What facility and/or product may be discontinued.
- What may be gained from, and how much one should pay for additional gain.

- What will be the impact of increase or decrease in parameter of interest.

Sensitivity analysis provides a systematic procedure for analyzing all the aspects listed above and, as such, can well be the most important phase in the total decision making framework. In addition, sensitivity analysis provides information that establishes the limitations, characteristics and capabilities of a system.

This research particularly investigates the analysis of discrete changes only. The types of discrete changes in the parameter or parameters that the research investigates are:

1. MTTF: Mean time to failure
2. MTTR: Mean time to repair
3. MTR: Mean time to replacement

These parametric changes influence the formulas that are obtained by utilizing the markov process. These formulas for a typical equipment type having N equal to 4, x equal to 1 and including all parametric variations are:

$$P(1,0) = \frac{\lambda_0 + \Delta\lambda_0}{\mu_1 + \Delta\mu_1} P(0,0)$$

$$P(0,1) = \frac{\lambda_0 + \Delta\lambda_0}{p(\beta_0 + \Delta\beta_0) + \beta_{01}} P(0,0)$$

$$P(i+1,0) = \frac{1}{\mu_{i+1} + \Delta\mu_{i+1}} \{ [(\lambda_i + \Delta\lambda_i) + (\mu_i + \Delta\mu_i)] P(i,0) - (\beta_{i-1} + \Delta\beta_{i-1}) P(i-1,1) \}$$

for $i = 1, 2, \dots, 4$

$$P(5,0) = \frac{\beta_4 + \Delta\beta_4}{\mu_5 + \Delta\mu_5} P(4,1)$$

$$P(i,1) = \frac{\lambda_i + \Delta\lambda_i}{\mu_i + \Delta\mu_i} P(i,0)$$

for $i = 2, 3, 4$

$$P(1,1) = \frac{1}{\beta_1 + \Delta\beta_1} [(\lambda_1 + \Delta\lambda_1) P(1,0) + \beta_{01} P(0,1)]$$

Under the normality condition

$$\sum_{i=0}^5 P(i,0) + \sum_{i=0}^4 P(i,1) = 1$$

For the response of a system against the parametric changes, each parameter individually and with certain possible combination with other parameters are considered. These discrete changes in the parameter or parameters and their effect on the system performance are discussed in the following section.

1. Procedure and Comments

Recognizing changes in the system performance due to variations in parameters is of great importance in engineering analysis and design. The parameter perturbation may represent uncertainty in manufacturing tolerance, or iterative improvement of control parameters during the optimization stage. One often asks "What if questions such as "What's the smallest acceptable value of specific parameter, or What's the best value for this ?". To answer all of the above mentioned what if questions, it is necessary to simulate large changes in the value of one or more parameters and immediately examine the resulting effect on the system performance. The following five cases illustrate possible individual or combinatorial parametric variations. Each variation is in a certain amount or percentage.

Case-A

$$MTTF_i \longrightarrow MTTF_i + \Delta MTTF_i \quad i = 1, 2, \dots, m$$

Case-B

$$MTTR_i \longrightarrow MTTR_i + \Delta MTTR_i \quad i = 1, 2, \dots, m$$

Case-C

$$MTR_i \longrightarrow MTR_i + \Delta MTR_i \quad i = 1, 2, \dots, m$$

Case-D

$$\begin{aligned}
 \text{MTTF}_1 + \text{MTTF}_2 + \dots + \text{MTTF}_m &\longrightarrow \text{MTTF}_1 + \Delta\text{MTTF}_1 \\
 &+ \text{MTTF}_2 + \Delta\text{MTTF}_2 \\
 &+ \dots \quad \dots \quad \dots \\
 &+ \text{MTTF}_m + \Delta\text{MTTF}_m
 \end{aligned}$$

$$\begin{aligned}
 \text{MTTR}_1 + \text{MTTR}_2 + \dots + \text{MTTR}_m &\longrightarrow \text{MTTR}_1 + \Delta\text{MTTR}_1 \\
 &+ \text{MTTR}_2 + \Delta\text{MTTR}_2 \\
 &+ \dots \quad \dots \quad \dots \\
 &+ \text{MTTR}_m + \Delta\text{MTTR}_m
 \end{aligned}$$

$$\begin{aligned}
 \text{MTR}_1 + \text{MTR}_2 + \dots + \text{MTR}_m &\longrightarrow \text{MTR}_1 + \Delta\text{MTR}_1 \\
 &+ \text{MTR}_2 + \Delta\text{MTR}_2 \\
 &+ \dots \quad \dots \quad \dots \\
 &+ \text{MTR}_m + \Delta\text{MTR}_m
 \end{aligned}$$

Case-E

$$\begin{aligned}
 \text{MTTF}_i + \text{MTTR}_i + \text{MTR}_i &\longrightarrow \text{MTTF}_i + \Delta\text{MTTF}_i \\
 &+ \text{MTTR}_i + \Delta\text{MTTR}_i \\
 &+ \text{MTR}_i + \Delta\text{MTR}_i \\
 &i = 1, 2, \dots, m
 \end{aligned}$$

Where ΔMTTF_i , ΔMTTR_i , and ΔMTR_i denote the amount of variation in that parameter. Two typical FMS examples have been selected for the sensitivity analysis. The initial value of the parameters for example one are listed in Table 4 and for example two, see Appendix B for the initial value of the parameters and results of the analysis.

TABLE 4. Parameters' initial value:
Example-I

Parameter	Type 1	Type 2	type 3
MTTF	1000	2000	1500
MTTR	10	12	15
MTR	4	6	8
x^a	1	1	2

^a x is not a parameter. The given values of x are the optimum values obtained by using heuristic approach.

a. Change in $MTTF_i$ The first discrete variation to be considered is a change in value of $MTTF_i$ (Mean time to failure) by an amount $\Delta MTTF_i$ (100 hours) considering any one equipment type (type $i = 1, 2, \dots, m$) at a time. The range of change for type 1 is from 800 to 2600 hours, for type 2 is from 800 to 3000 hours, and for type 3 is from 800 to 2600 hours. The effect of each change is summarized in Table 5 and presented graphically in Figures 15, 16, and 17 respectively. These figures show that initially the system availability increases as $MTTF_i$ increases but after reaching a certain point (critical point) increase in system availability is not significant as compare to increase in $MTTF_i$.

TABLE 5. Variations in MTTF for each equipment type

Type #1	Mean time to failure	System Availability
	800	0.986063
	1000	0.987138
	1200	0.987851
	1400	0.988357
	1600	0.988739
	1800	0.989045
	2000	0.989270
	2200	0.989462
	2400	0.989623
	2500	0.989693
Type #2	Mean time to failure	System Availability
	800	0.982307
	1000	0.983926
	1300	0.985413
	1600	0.986338
	1800	0.986783
	2000	0.987138
	2300	0.987555
	2500	0.987777
	2700	0.987866
	2900	0.988129
Type #3	Mean time to failure	System Availability
	800	0.982424
	1000	0.984445
	1300	0.986310
	1500	0.987138
	1600	0.987772
	1800	0.988035
	2000	0.988484
	2200	0.988851
	2300	0.989011
	2500	0.989292

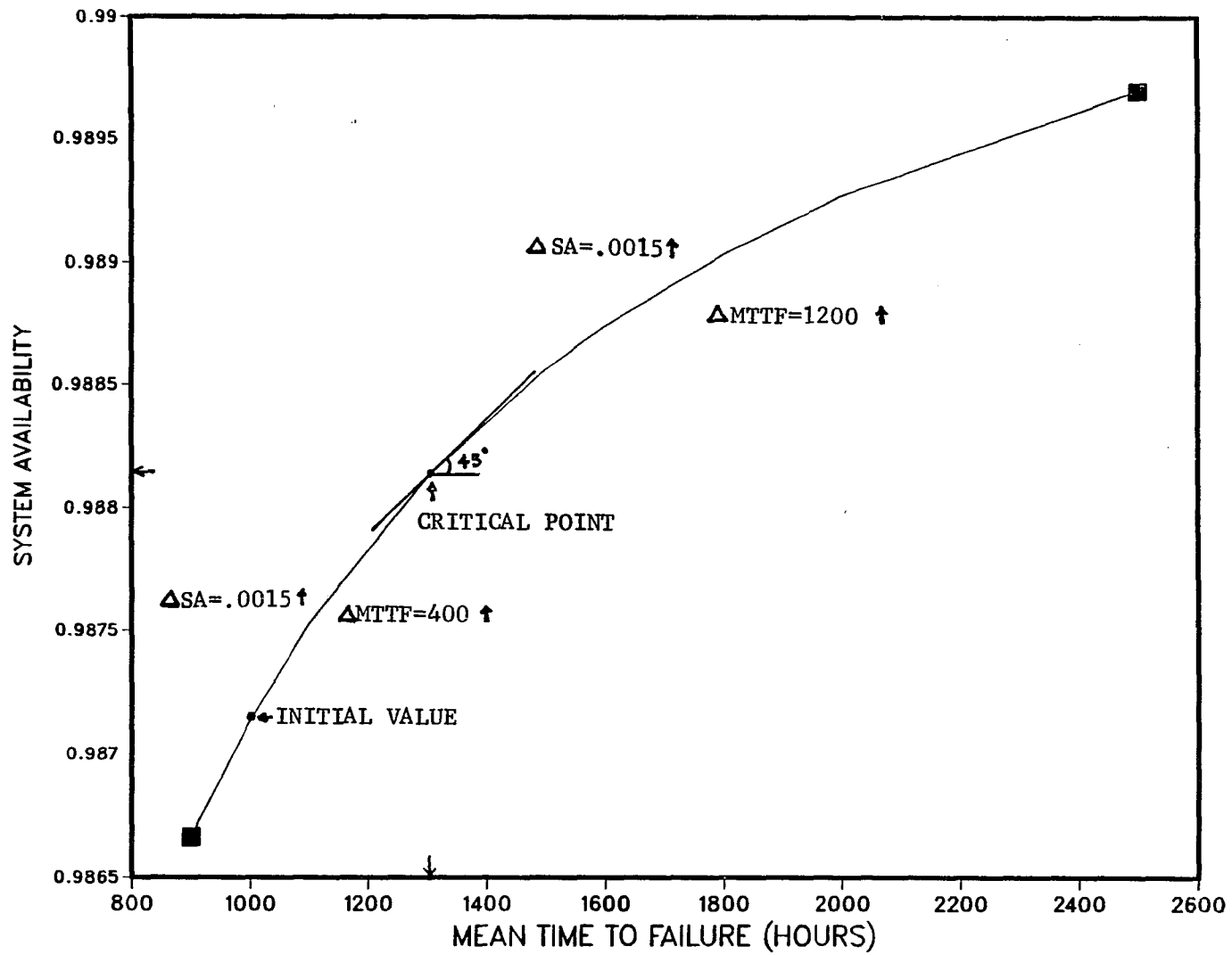


FIGURE 15. Sensitivity analysis: Change in MTTF for equipment type #1

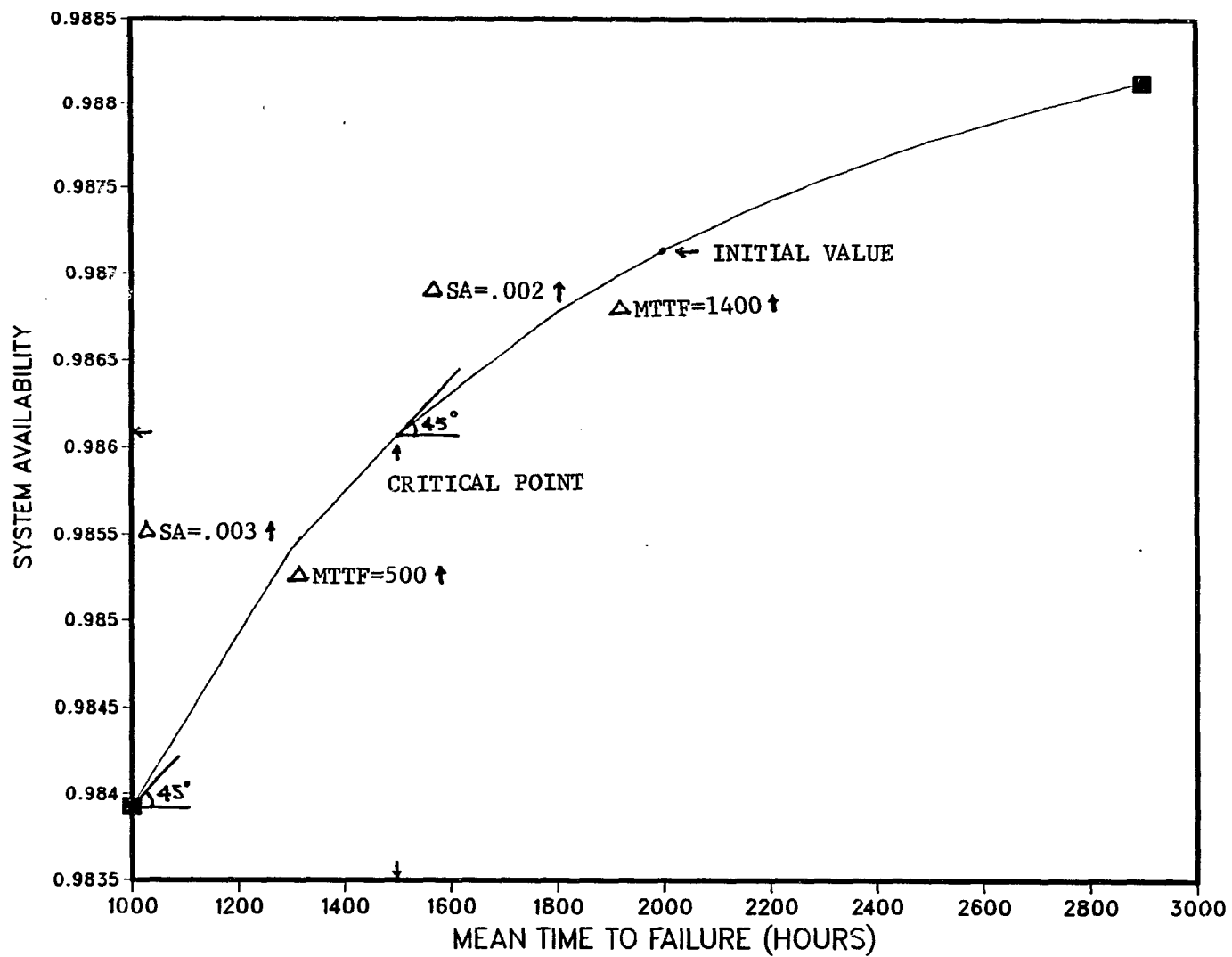


FIGURE 16. Sensitivity analysis: Change in MTTF for equipment type #2

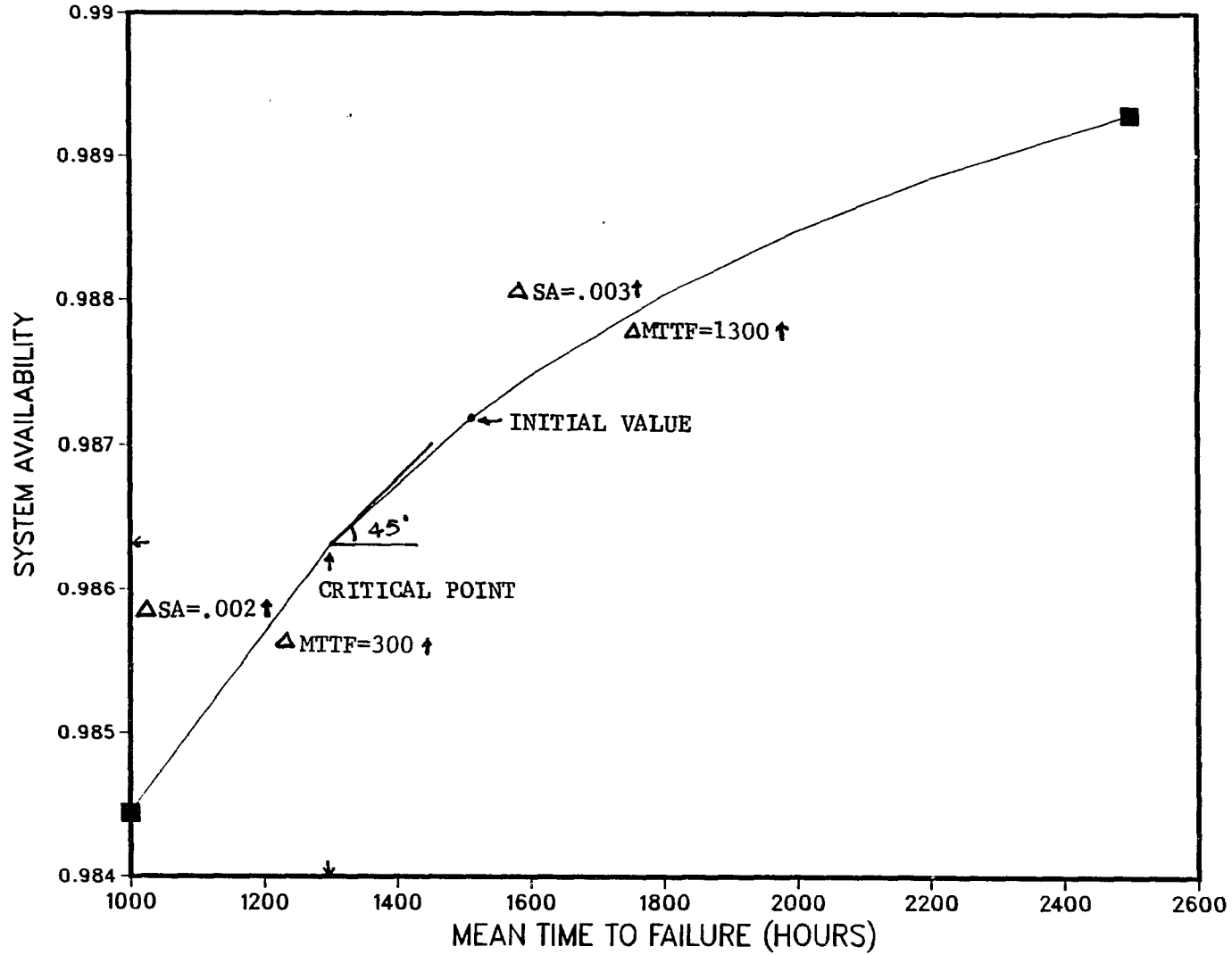


FIGURE 17. Sensitivity analysis: Change in MTTF for equipment type #3

b. Change in $MTTR_i$ The next discrete change to be made is in the value of $MTTR_i$ (Mean time to repair) by an amount $\Delta MTTR_i$ (2 hours) considering any one type of equipment (type $i = 1, 2, \dots, m$) at a time. The range of changes for type 1, type 2, and type 3 are from eight to thirty hours. The effect of these parametric changes are listed in Table 6 and shown in Figures 18, 19, and 20. These figures show that the system availability declines slowly as $MTTR_i$ increases but after crossing a certain point (critical point) the system availability diminishes rather sharply as $MTTR_i$ increases.

c. Change in MTR_i The third discrete variation is considered in the value of MTR_i (Mean time replacement) by an amount ΔMTR_i (2 hours) taking any one type of equipment (type $i = 1, 2, \dots, m$) at a time. The range of changes for type 1, type 2, and type 3 are from one to twenty hours. The effect of such changes are condensed in Table 7 and depicted in Figures 21, 19, and 23, which show that the system performance measure decreases proportionally with increase in MTR_i .

d. Change in MTTF or MTTR or MTR of all Equipment Types

Variation in any one of the parameter's value mentioned above, considering all equipment types simultaneously, is

TABLE 6. Variations in MTTR for each equipment type

Type #1	Mean time to repair	System Availability
	8	0.987199
	10	0.987138
	12	0.987072
	14	0.987000
	16	0.986922
	18	0.986838
	21	0.986700
	25	0.986483
	30	0.986194
Type #2	Mean time to repair	System Availability
	8	0.987207
	10	0.987173
	12	0.987138
	14	0.987101
	17	0.987044
	19	0.987004
	21	0.986962
	25	0.986874
	30	0.986756
Type #3	Mean time to repair	System Availability
	8	0.987176
	10	0.987167
	12	0.987156
	15	0.987138
	17	0.987125
	19	0.987111
	21	0.987095
	25	0.987060
	30	0.987009

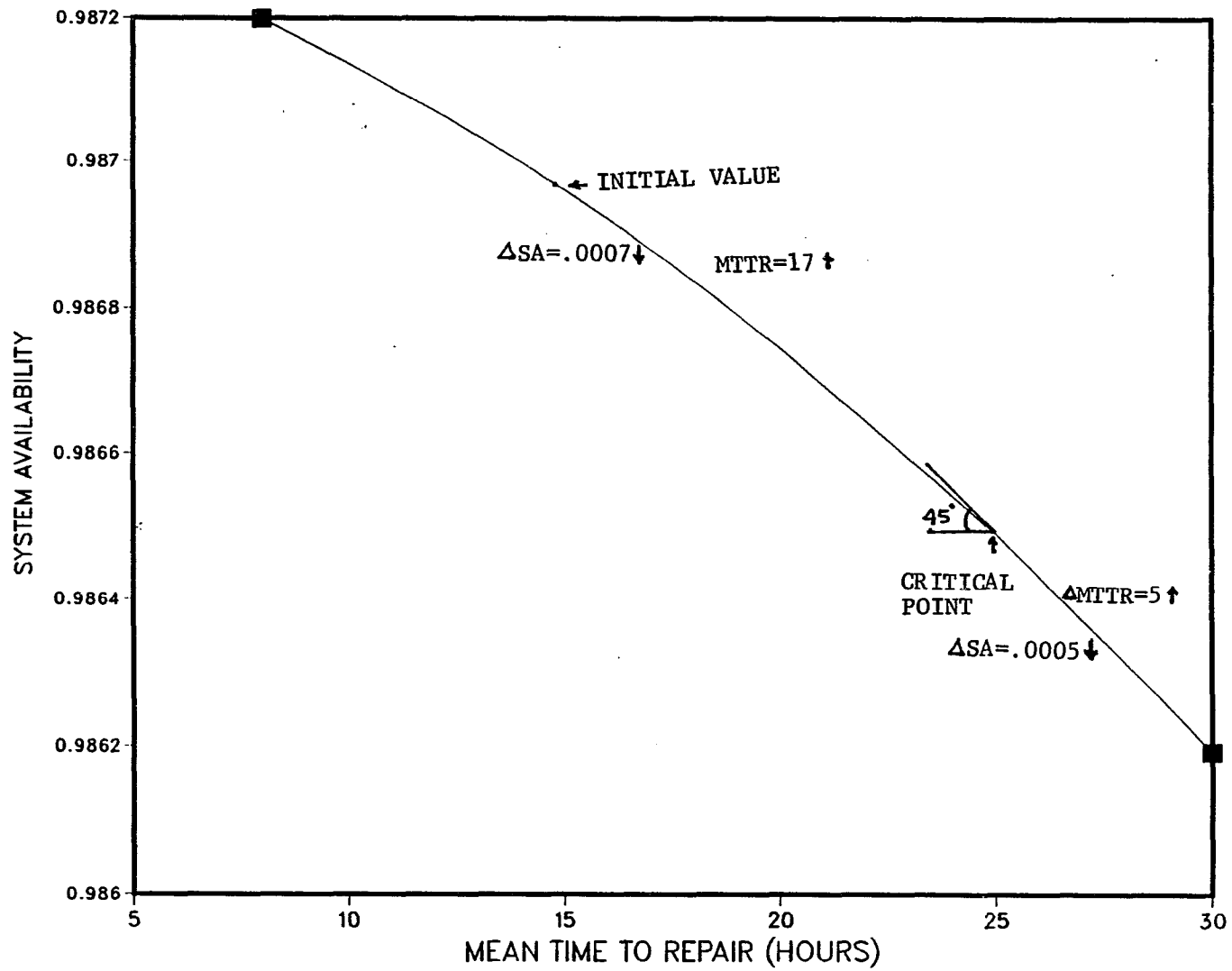


FIGURE 18. Sensitivity analysis: Change in MTRR for equipment type #1

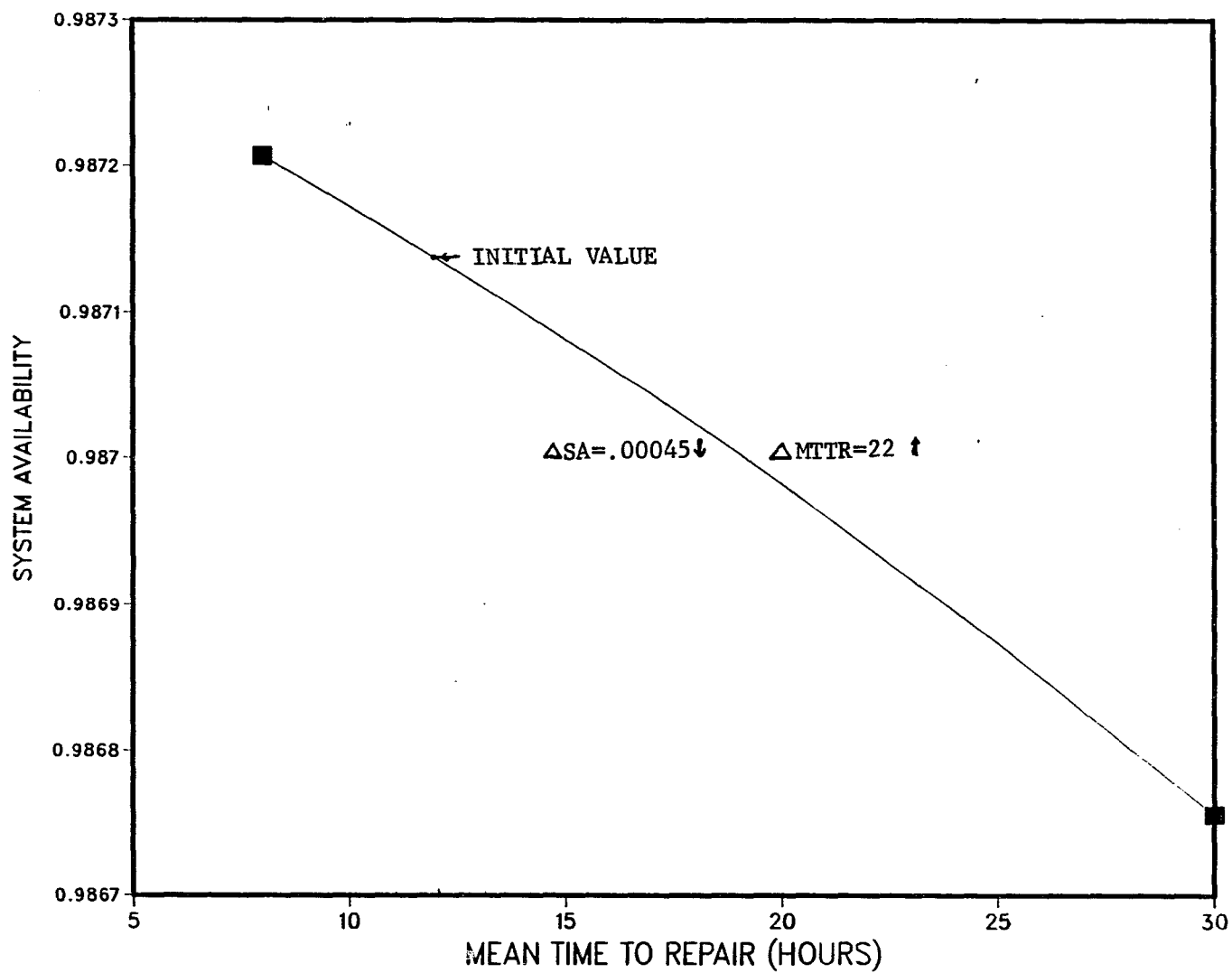


FIGURE 19. Sensitivity analysis: Change in MTTR for equipment type #2

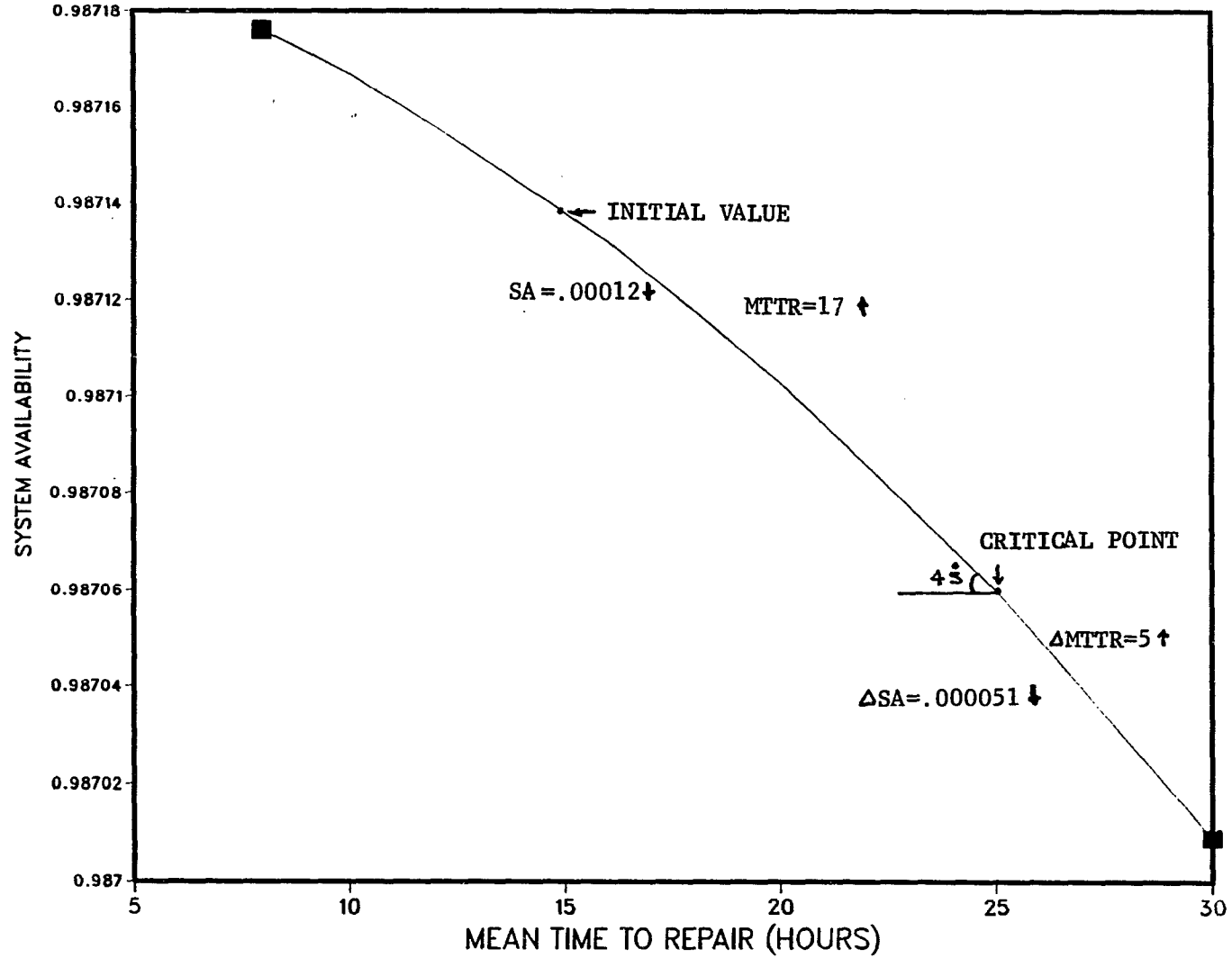


FIGURE 20. Sensitivity analysis: Change in MTRR for equipment type #3

TABLE 7. Variations in MTR for each equipment type

Type #1	Mean time to response	System Availability
	1	0.990274
	3	0.988180
	6	0.985064
	8	0.983002
	10	0.980952
	12	0.978915
	15	0.975880
	18	0.972871
	20	0.970878
Type #2	Mean time to response	System Availability
	1	0.989771
	3	0.988714
	6	0.987138
	8	0.986093
	10	0.985052
	12	0.984016
	15	0.982469
	18	0.980930
	20	0.979909
Type #3	Mean time to response	System Availability
	1	0.991852
	3	0.990506
	6	0.988486
	8	0.987138
	10	0.985790
	12	0.984443
	15	0.982424
	18	0.980408
	20	0.979067

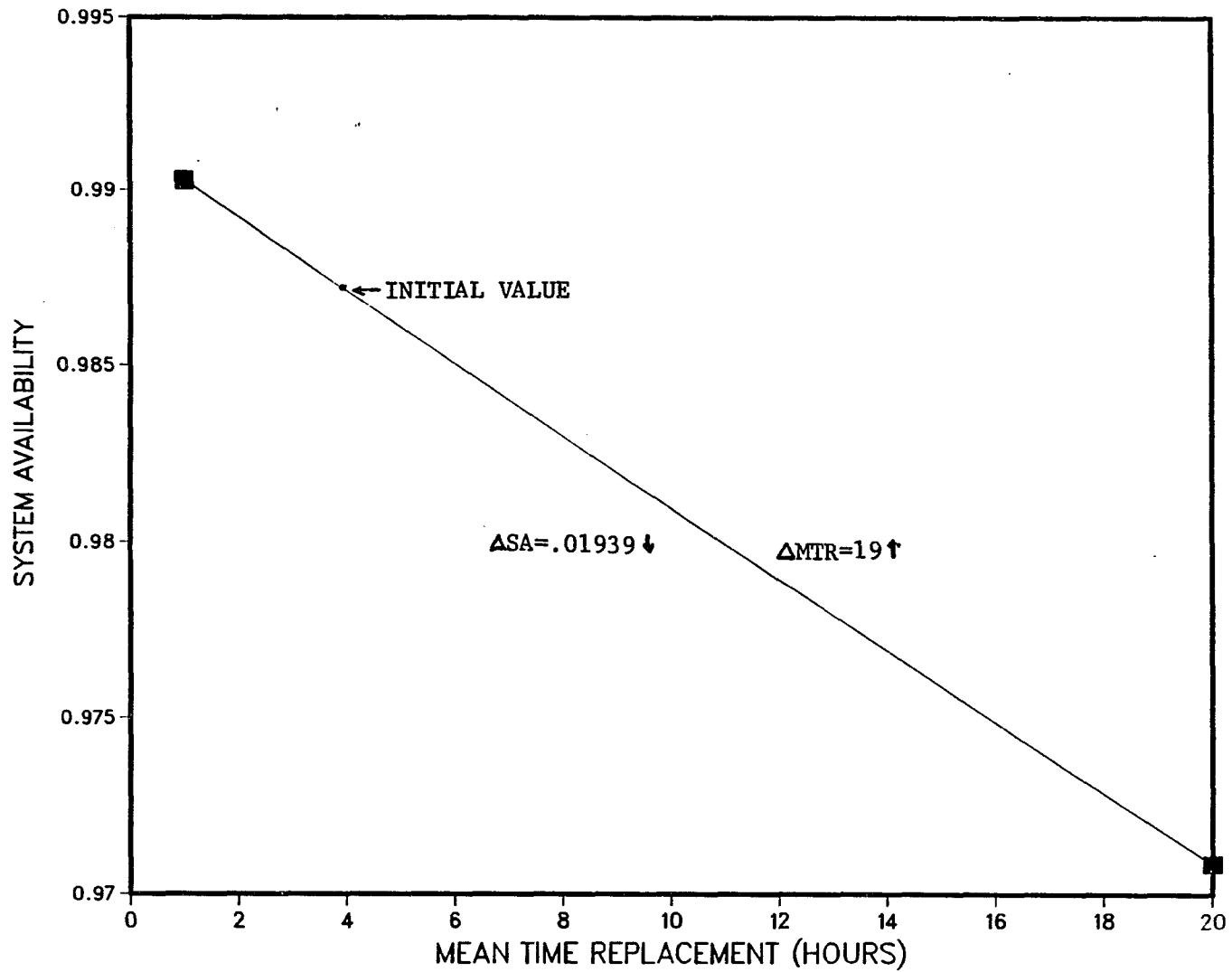


FIGURE 21. Sensitivity analysis: Change in MTR for equipment type #1

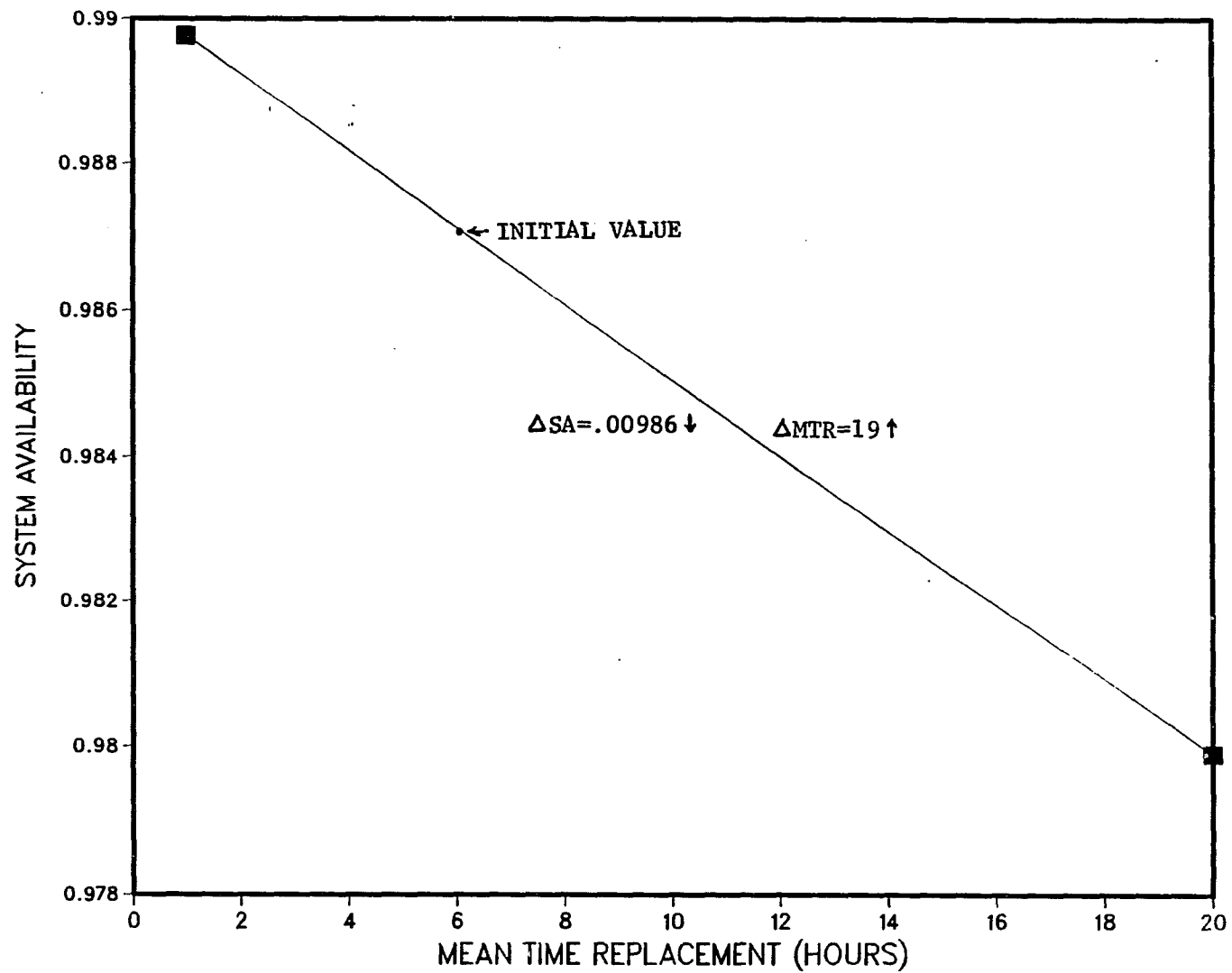


FIGURE 22. Sensitivity analysis: Change in MTR for equipment type #2

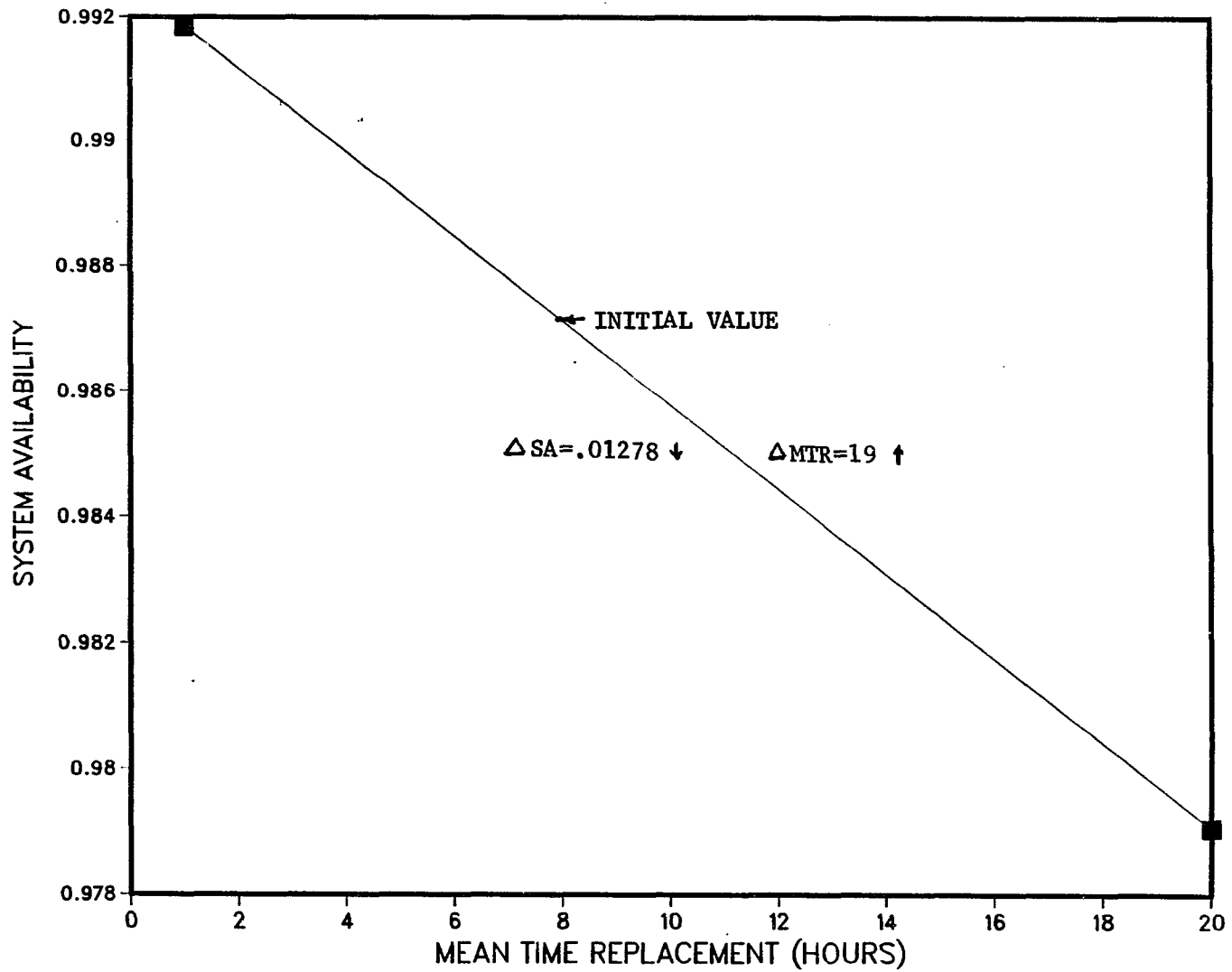


FIGURE 23. Sensitivity analysis: Change in MTR for equipment type #3

not feasible in a fixed amount because of inconsistencies in their range of values. The only way of varying any one parameter's value in all equipment types is by applying percentile-change. Therefore, a discrete percentage change in a parameter's (MTTF, or MTTR, or MTR) value is made by an amount of ten percent taking into account all equipment types at a time. Table 8 and Figures 24, 25, and 26 portrayed the effect of these changes on the system performance. The percentage increase in MTTF does not make an appreciable improvement in the system performance beyond the initial value of MTTF. Whereas MTTR and MTR percentage variations do produce proportional changes in the system availability.

e. Simultaneous Changes in $MTTF_i$, $MTTR_i$, and MTR_i

The discrete percentile-changes in the values of all parameters ($MTTF_i$, $MTTR_i$, and MTR_i), considering any one type of equipment (type $i = 1, 2, \dots, m$) at a time, by a value of ten percent is made to observe the effect on system performance. The resulting effect is abbreviated in Table 9 and displayed in Figures 27, 28, and 29. These variations do produce linear changes in the system performance, however, the size of an overall change in performance measure is of negative-fourth degree (very very small) compare to the overall change in values of parameters.

TABLE 8. Variations of any one parameter for all equipment types

MEAN TIME TO FAILURE				
Percent Increase	Type #1	Type #2	Type #3	System Availability
0.5	500	1000	750	0.974249
0.6	600	1200	900	0.978551
0.8	800	1600	1200	0.983920
1.0	1000	2000	1500	0.987138
1.2	1200	2400	1800	0.989282
1.4	1400	2800	2100	0.990814
1.6	1600	3200	2400	0.991962
1.7	1700	3400	2559	0.992435
1.8	1800	3600	2800	0.993138

MEAN TIME TO REPAIR				
Percent Increase	Type #1	Type #2	Type #3	System Availability
0.5	5	6.0	7.5	0.987422
0.7	7	8.4	10.5	0.987316
0.9	9	10.8	13.5	0.987200
1.0	10	12.0	15.0	0.987138
1.2	12	14.4	18.0	0.987007
1.4	14	16.8	21.0	0.986866
1.6	16	19.2	24.0	0.986715
1.8	18	21.6	27.0	0.986552
2.0	20	24.0	30.0	0.986377

MEAN TIME TO RESPONSE				
Percent Increase	Type #1	Type #2	Type #3	System Availability
0.4	1.6	2.4	3.2	0.994790
0.6	2.4	3.6	4.8	0.992231
0.8	3.2	4.8	6.4	0.989681
1.0	4.0	6.0	8.0	0.987138
1.3	5.2	7.8	10.4	0.983339
1.5	6.0	9.0	12.0	0.980816
1.7	6.8	10.2	13.6	0.978301
1.9	7.6	11.4	15.2	0.975795
2.1	8.4	12.6	16.8	0.970808

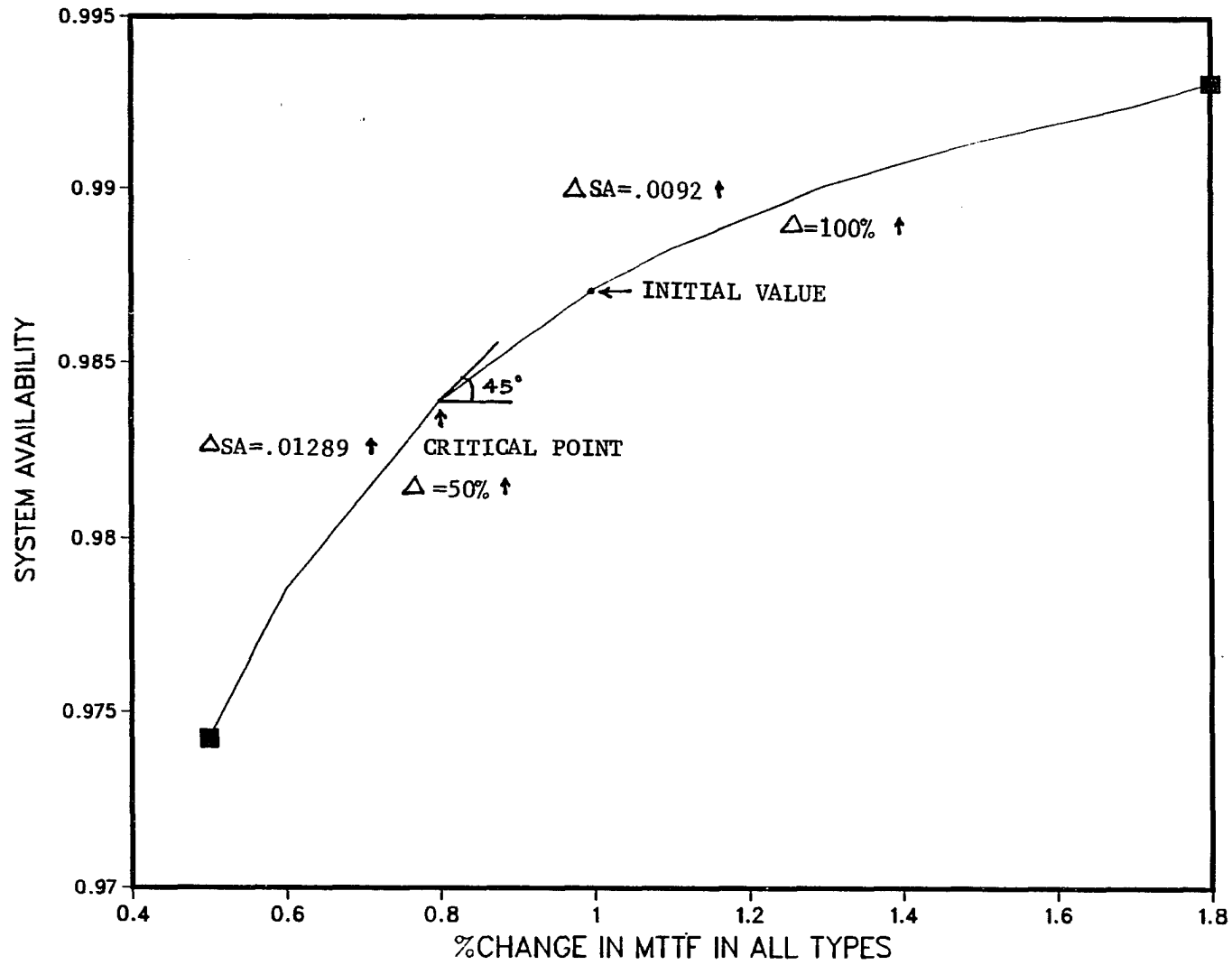


FIGURE 24. Sensitivity analysis: Change in MTF for all equipment types

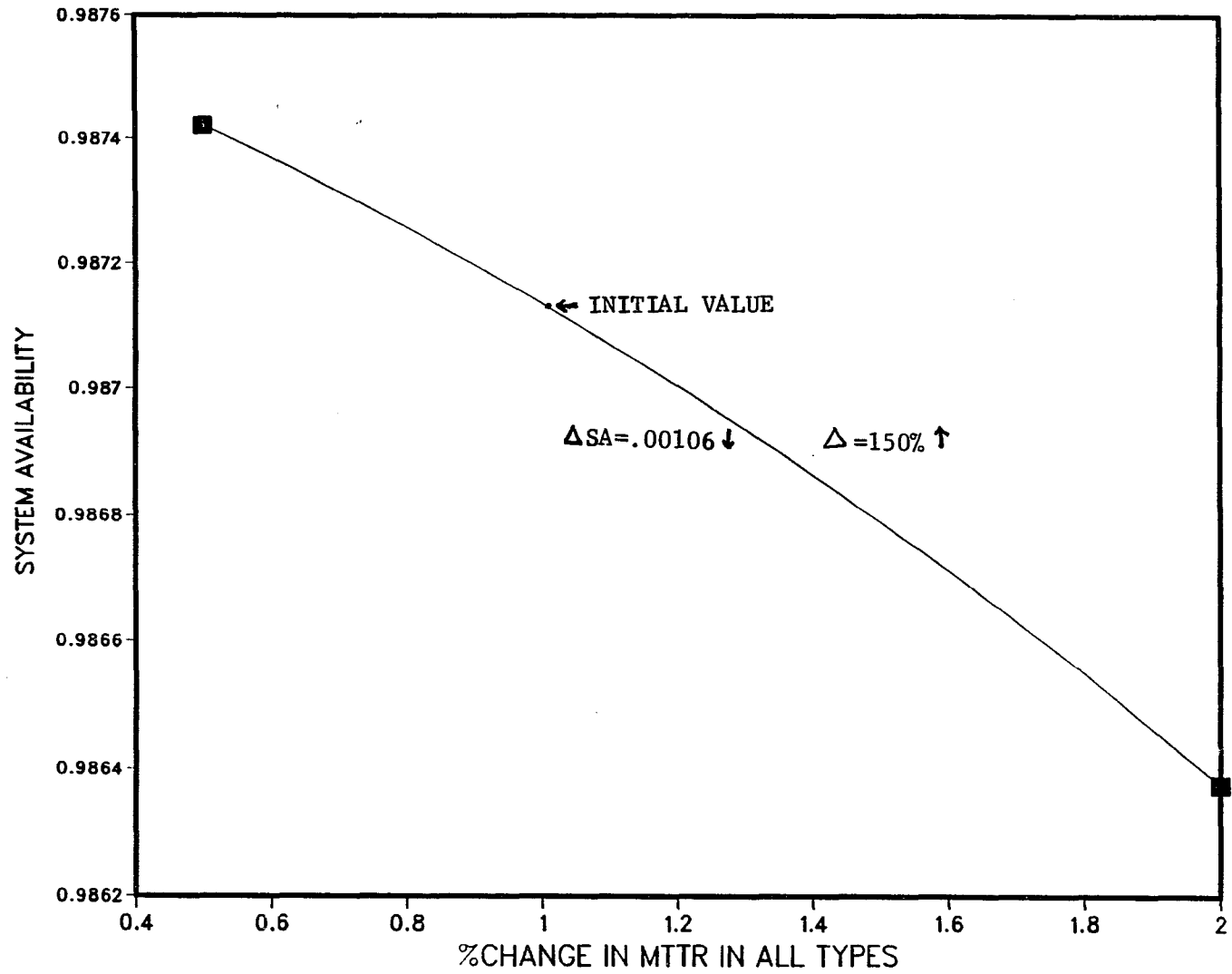


FIGURE 25. Sensitivity analysis: Change in MTTR for all equipment types

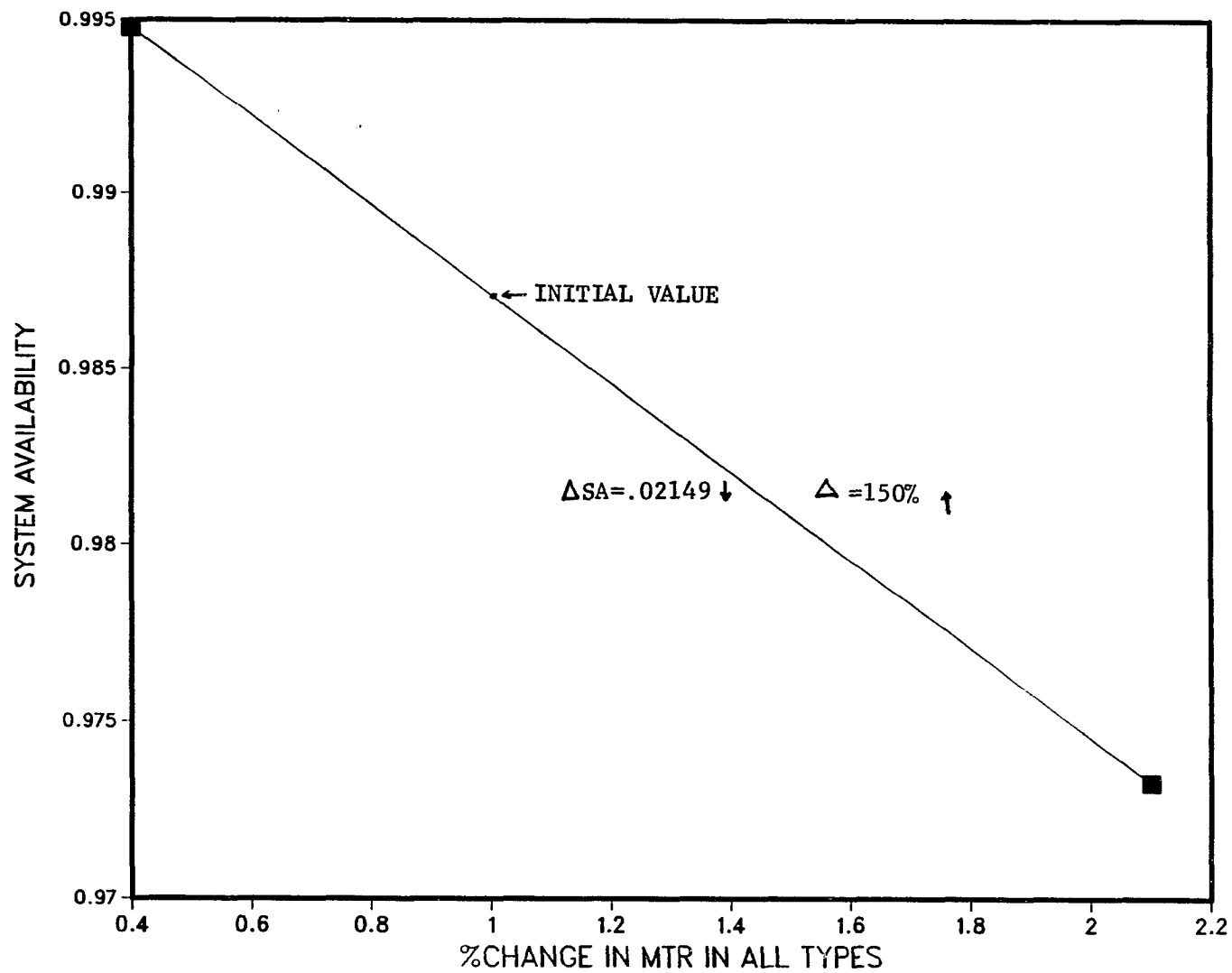


FIGURE 26. Sensitivity analysis: Change in MTR for all equipment types

TABLE 9. Variations of all parameters for any one equipment type

Percent Increase	Type #1 Mean time to failure	Type #1 Mean time to repair	Type #1 Mean time to response	System Availability
0.3	300	3	1.2	0.987275
0.5	500	5	2.0	0.987235
0.7	700	7	2.8	0.987196
0.9	900	9	3.6	0.987157
1.1	1100	11	4.4	0.987119
1.3	1300	13	5.2	0.987082
1.5	1500	15	6.0	0.987045
1.7	1700	17	6.8	0.987008
1.9	1900	19	7.6	0.986972
Percent Increase	Type #2 Mean time to failure	Type #2 Mean time to repair	Type #2 Mean time to response	System Availability
0.1	300	1.2	0.6	0.987292
0.3	600	3.6	1.8	0.987256
0.5	1000	6.0	3.0	0.987221
0.7	1400	8.4	4.2	0.987187
0.9	1800	10.8	5.4	0.987154
1.1	2200	13.2	6.6	0.987122
1.3	2600	15.6	7.8	0.987090
1.5	3000	18.0	9.0	0.987060
1.7	3400	20.4	10.2	0.987029
Percent Increase	Type #3 Mean time to failure	Type #3 Mean time to repair	Type #3 Mean time to response	System Availability
0.2	300	3.0	1.6	0.987198
0.4	600	6.0	3.2	0.987188
0.6	900	9.0	4.8	0.987174
0.9	900	12.0	6.4	0.987157
1.1	1650	16.5	8.8	0.987128
1.3	1950	19.5	10.4	0.987105
1.5	2250	22.5	12.0	0.987080
1.7	2550	25.5	13.6	0.987054
1.9	2850	28.5	15.2	0.987026

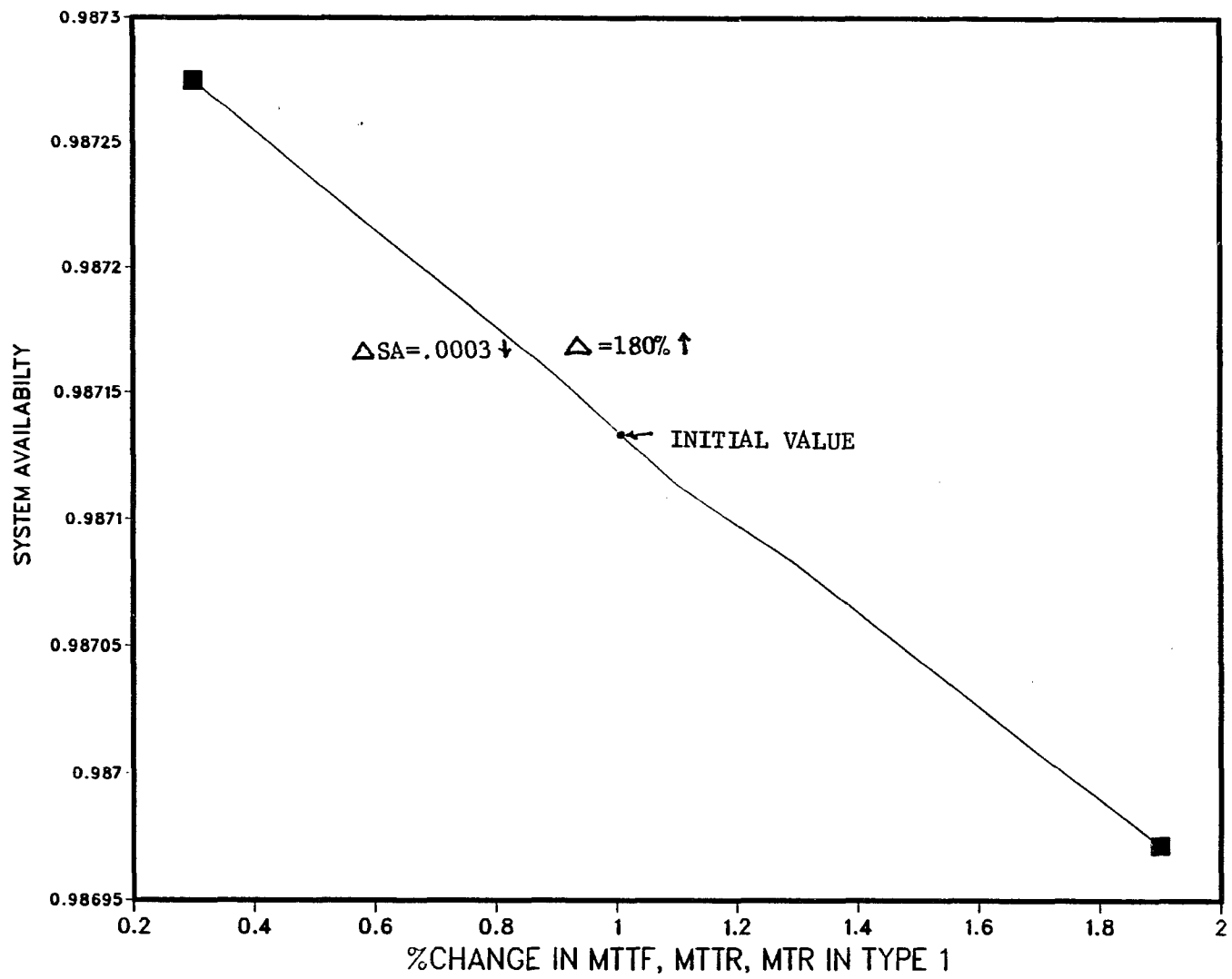


FIGURE 27. Sensitivity analysis: Changes in MTTF, MTTR, and MTR for type #1

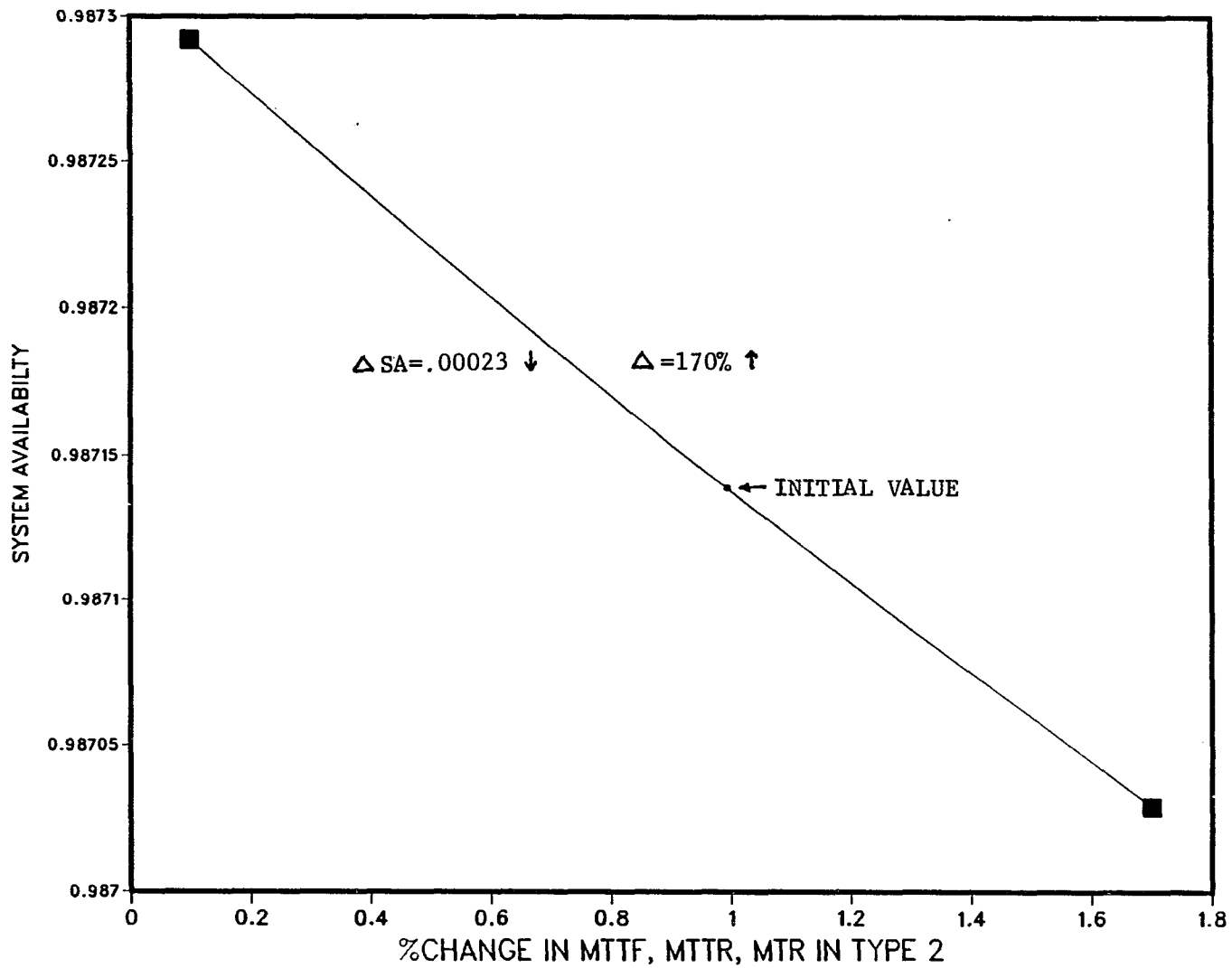


FIGURE 28. Sensitivity analysis: Changes in MTF, MTR, and MTR for type #2

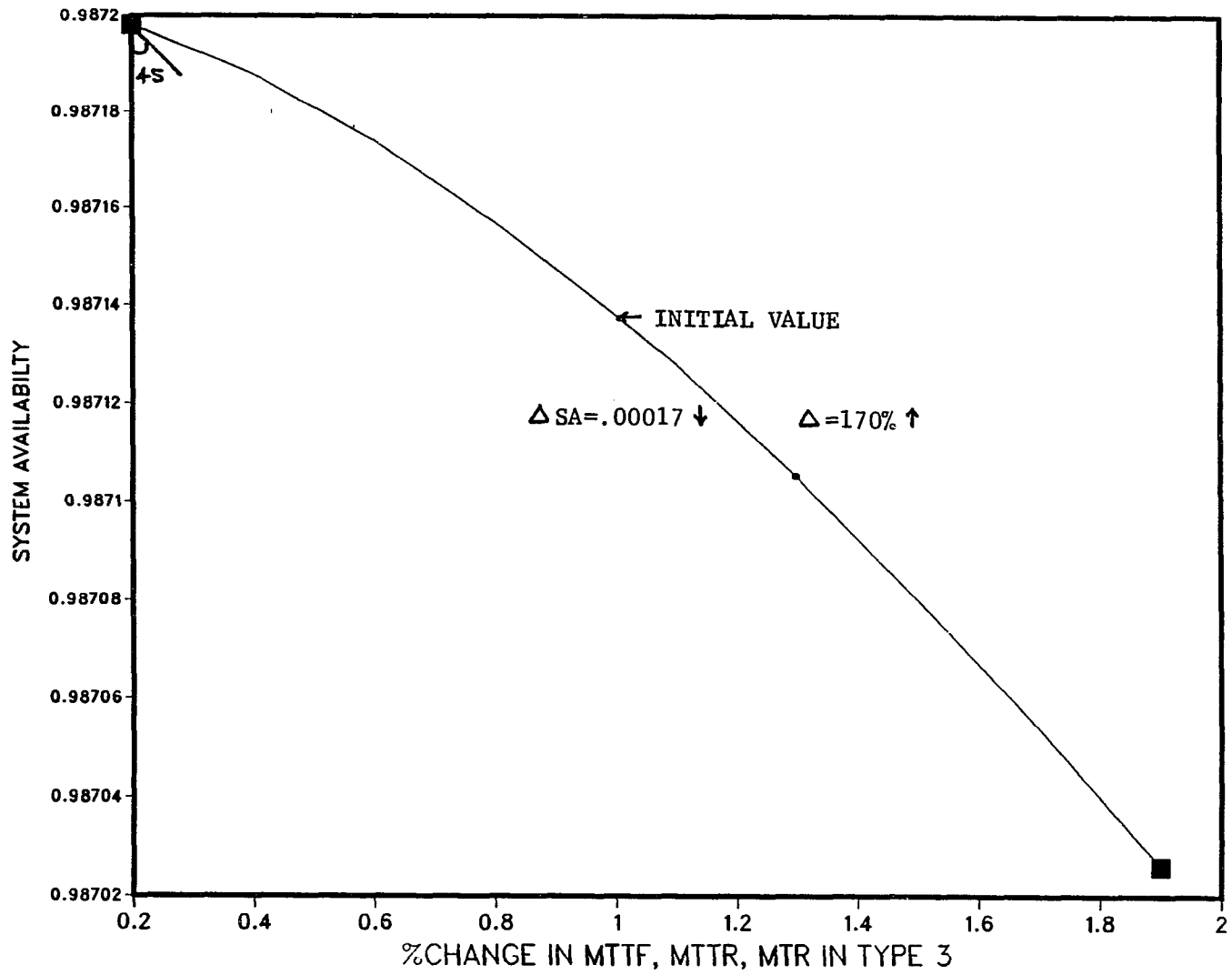


FIGURE 29. Sensitivity analysis: Changes in MTTF, MTTR, and MTR for type #3

Finally, these procedures provide a convenient way of conducting sensitivity analysis systematically. A computer code (algorithms) has been developed which supplies the result and effect of changes in parameter or parameters on system performance measure (system availability). Graphs of these changes have been plotted for a quick overview.

2. Summary and Results

It is imperative that the sensitivity and optimization should be combined, since optimization involves changes in component values and sensitivity analysis has as its objective the prediction of the effect of changes. Therefore, several different possible combinatorial parametric changes are made to test the effect on system availability which is treated solely as a performance measure. Knowledge of the effect of small variations in parameter within a system provide an indication of those parameters which might usefully be adjusted to improve performance. The outputs of each change are tabulated and plotted, as shown in Figures 15 through 29, for overview.

The effect of change in $MTTF_i$ on system availability, taking into account only one equipment type at a time, is small. The overall improvement in system performance

measure is 0.005 due to increase in MTTF from 800 to 2600 hours. By looking at the graphs of MTTF, it is quite obvious that the improvement in performance is high for equipments having initially low MTTF. But after reaching a critical point (Critical point is that point where slope of curve become less than 45 degree) growth is not pronounced as compared to the tremendous increase in MTTF.

The increase in $MTTR_i$ reduces system availability. Initially, decrease in system availability is slow compared to the increase in $MTTR$. This may be because of available spare(s). However, it drops rather sharply as $MTTR$ crosses the 25 hours mark, but the overall magnitude of the system performance impairment is little.

Increasing the value of MTR_i , taking one type at a time, declines the system availability proportionally. The size of change in the system availability is quite distinguishable related to the previous two parametric variations. The reason of this prominent effect on performance could be strong association of MTR with $MTTR$. Since the repair can not be initiated until the problem is diagnosed. Thus, the longer the problem finding time, the later the repair begins, and the greater the detrimental effect on the system performance measure.

The effect of percentage variations in $MTTF$, considering all types of equipment at a time, on the system availability is almost equal to the sum of the effects on system availability, when changes in $MTTF_i$ are made separately in each type. The impact of percentile $MTTR$ changes made simultaneously in all types of equipment on performance is not the same as the sum of effects on the performance due to changes in $MTTR_i$ when considering only one equipment type at a time. But the overall reduction in the system availability due to increment in $MTTR$ is very small, therefore, it is not very critical to worry about. On the other hand, changes in MTR made simultaneously in all equipment types have a prominent effect on the system performance, though it is of half the magnitude of sum of effects due to all individual equipment MTR_i changes. Hence $MTTF$ and MTR are critical parameters to be controlled for the performance improvement.

Finally, the effect of simultaneous variations, considering any one equipment type, in $MTTF_i$, $MTTR_i$, and MTR_i on the system availability is of very little magnitude or one can say almost negligible effect, although graphs appear to be linear. Justification of this behavior is that the influence of changes in $MTTF$ is nullified by the Changes in $MTTR$ and MTR . Thus improvement in system performance due

to increase in MTTF is neutralized by impairment of performance due to increase in MTTR and MTR. The net effect is nearly the same performance of system.

From the above discussion, it is quite obvious that MTTF and MTR are crucial parameters to be controlled. As equipment gets older, the MTTF decreases thus resulting in declining system availability. This can be overcome by decreasing MTR and MTTR which improve the system availability. Also, MTR and MTTR are in the control of an engineer or mechanic whereas MTTF is hard to control.

V. APPLICATION AND VALIDATION OF MODEL

A. Introduction

There are two major facets of this chapter. The first is called numerical illustration. In this section a typical flexible manufacturing system's example is considered for which Kuo (37) is used as a guideline. The model developed in this research is employed for evaluating the performance measure with and without having centralized storage for spares. Since each subsystem of an FMS behaves independently, therefore appropriate credits are assigned for partial availability of subsystems. To make sure that, the new researchers can understand the model's terminology and apply it to an FMS conveniently, every aspect of the model is analyzed, expanded, and explained numerically.

The second facet is called case study, in which the model developed is used for investigating the performance and setting the storage policy for the state-of-the-art FMS for a manufacturer in the state of Iowa. For these, computer algorithms are used, which determine the performance measure of a system with and without having centralized storage for spares and take into account credits for partially available local systems. Moreover, it also

utilizes the heuristic approach, discussed in the Chapter IV, for determining optimal storage level for each subsystem.

B. Numerical Illustration (37)

1. Description of System and Terminology

An ISU company maintains a system in Flexible Manufacturing environment which can be broken down into four local systems or sub-systems. The first, second, third, and fourth local systems are formed by five units, six units, four units, and six units (equipments of same type) respectively. As each subsystem is necessary for production operation, therefore, it is reasonable to assume that each sub-system is equally important to the company.

A previous study showed that the ISU company served by local systems would be satisfied with the service if the average down time of the system was less than six percent of the total operating time.

It is known from historical data that the first equipment type has mean time to failure (MTTF) of 300 hours and mean time to repair (MTTR) of 10 hours, the second equipment type has MTTF of 650 hours and MTTR of 12 hours, the third equipment type has MTTF of 500 hours and MTTR of

15 hours, and the fourth equipment type has MTTF of 400 hours and MTTR of 20 hours. The steady-state availability of such system is

$$\begin{aligned} & \prod_{i=1}^{M=4} \left(\frac{\text{MTTF}_i}{\text{MTTF}_i + \text{MTTR}_i} \right) \\ &= \frac{300}{310} \cdot \frac{650}{662} \cdot \frac{500}{515} \cdot \frac{400}{420} \\ &= 0.878594 \end{aligned}$$

Therefore, traditionally the probability that all the local systems in FMS environment are available is

$$\begin{aligned} & \left(\frac{300}{310} \right)^5 \left(\frac{650}{662} \right)^6 \left(\frac{500}{515} \right)^4 \left(\frac{400}{420} \right)^6 \\ &= 0.504249 \end{aligned}$$

Neither 0.878594 nor 0.504249 satisfies the maximum six percent down time restriction. Since each sub-system is very expensive and it is really not necessary to achieve the extraordinary high availability at the expense of very high cost, a redundant system configuration is not recommended. A central storage area, in which one spare for each equipment type is stored, can be utilized for achieving high availability.

2. Performance Evaluation Using Weighted Factors Without Spares

Traditionally no partial credits were accounted for partial operational units. Since this research is assigning partial credits if some of its sub-systems are operational, therefore the availability of 0.504249 is underestimated. Applying equation (23) and substituting values of $x_1 = x_2 = x_3 = x_4 = 0$

$$P = [P_1(0,0) \ P_2(0,0) \ P_3(0,0) \ P_4(0,0)]$$

In the state of (1,0)

$$\begin{aligned} &+ [(4/5)P_1(1,0) \ P_2(0,0) \ P_3(0,0) \ P_4(0,0)] \\ &+ [P_1(0,0) \ (5/6)P_2(1,0) \ P_3(0,0) \ P_4(0,0)] \\ &+ [P_1(0,0) \ P_2(0,0) \ (3/4)P_3(1,0) \ P_4(0,0)] \\ &+ [P_1(0,0) \ P_2(0,0) \ P_3(0,0) \ (5/6)P_4(1,0)] \end{aligned}$$

In the state of (2,0)

$$\begin{aligned} &+ [(3/5)P_1(2,0) \ P_2(0,0) \ P_3(0,0) \ P_4(0,0)] \\ &+ [P_1(0,0) \ (4/6)P_2(2,0) \ P_3(0,0) \ P_4(0,0)] \\ &+ [P_1(0,0) \ P_2(0,0) \ (2/4)P_3(2,0) \ P_4(0,0)] \\ &+ [P_1(0,0) \ P_2(0,0) \ P_3(0,0) \ (4/6)P_4(2,0)] \end{aligned}$$

In the state of (1,0) and (1,0)

$$\begin{aligned} &+ [(4/5)P_1(1,0) \ (5/6)P_2(1,0) \ P_3(0,0) \ P_4(0,0)] \\ &+ [(4/5)P_1(1,0) \ P_2(0,0) \ (3/4)P_3(1,0) \ P_4(0,0)] \\ &+ [(4/5)P_1(1,0) \ P_2(0,0) \ P_3(0,0) \ (5/6)P_4(1,0)] \end{aligned}$$

$$\begin{aligned}
& + [P_1(0,0) (5/6)P_2(1,0) (3/4)P_3(1,0) P_4(0,0)] \\
& + [P_1(0,0) (5/6)P_2(1,0) P_3(0,0) (5/6)P_4(1,0)] \\
& + [P_1(0,0) P_2(0,0) (3/4)P_3(1,0) (5/6)P_4(1,0)]
\end{aligned}$$

In the state of (3,0)

$$\begin{aligned}
& + [(2/5)P_1(3,0) P_2(0,0) P_3(0,0) P_4(0,0)] \\
& + [P_1(0,0) (3/6)P_2(3,0) P_3(0,0) P_4(0,0)] \\
& + [P_1(0,0) P_2(0,0) (1/4)P_3(3,0) P_4(0,0)] \\
& + [P_1(0,0) P_2(0,0) P_3(0,0) (3/6)P_4(3,0)]
\end{aligned}$$

In the states of (1,0) and (2,0)

$$\begin{aligned}
& + [(4/5)P_1(1,0) (4/6)P_2(2,0) P_3(0,0) P_4(0,0)] \\
& + [(4/5)P_1(1,0) P_2(0,0) (2/4)P_3(2,0) P_4(0,0)] \\
& + [(4/5)P_1(1,0) P_2(0,0) P_3(0,0) (4/6)P_4(2,0)] \\
& + [(3/5)P_1(2,0) (5/6)P_2(1,0) P_3(1,0) P_4(0,0)] \\
& + [P_1(0,0) (5/6)P_2(1,0) (2/4)P_3(2,0) P_4(0,0)] \\
& + [P_1(0,0) (5/6)P_2(1,0) P_3(0,0) (4/6)P_4(2,0)] \\
& + [(3/5)P_1(2,0) P_2(0,0) (3/4)P_3(1,0) P_4(0,0)] \\
& + [P_1(0,0) (4/6)P_2(2,0) (3/4)P_3(1,0) P_4(0,0)] \\
& + [P_1(0,0) P_2(0,0) (3/4)P_3(1,0) (4/6)P_4(2,0)] \\
& + [(2/5)P_1(2,0) P_2(0,0) P_3(0,0) (5/6)P_4(1,0)] \\
& + [P_1(0,0) (4/6)P_2(2,0) P_3(0,0) (5/6)P_4(1,0)] \\
& + [P_1(0,0) P_2(0,0) (2/4)P_3(2,0) (5/6)P_4(1,0)]
\end{aligned}$$

In the state of (4,0)

$$\begin{aligned}
& + [(1/5)P_1(4,0) P_2(0,0) P_3(0,0) P_4(0,0)] \\
& + [P_1(0,0) (2/6)P_2(4,0) P_3(0,0) P_4(0,0)]
\end{aligned}$$

$$+ [P_1(0,0) P_2(0,0) P_3(0,0) (2/6)P_4(4,0)]$$

$$+ \dots \dots \dots + \dots \dots \dots$$

In the states of (5,0),(6,0),(4,0),and (6,0)

$$+ [(1/5)P_1(4,0) (1/6)P_2(5,0) (1/4)P_3(3,0) P_4(5,0)]$$

$$P = \left(\frac{300}{310} \right)^5 \left(\frac{650}{662} \right)^6 \left(\frac{500}{515} \right)^4 \left(\frac{400}{420} \right)^6$$

Any one equipment type in (1,0) state

$$+ \frac{4}{5} \left(\frac{10}{310} \right) \left(\frac{300}{310} \right)^4 \left(\frac{650}{662} \right)^6 \left(\frac{500}{515} \right)^4 \left(\frac{400}{420} \right)^6$$

$$+ \frac{5}{6} \left(\frac{12}{662} \right) \left(\frac{650}{662} \right)^5 \left(\frac{300}{310} \right)^5 \left(\frac{500}{515} \right)^4 \left(\frac{600}{420} \right)^6$$

$$+ \frac{3}{4} \left(\frac{15}{515} \right) \left(\frac{500}{515} \right)^3 \left(\frac{300}{310} \right)^5 \left(\frac{650}{662} \right)^6 \left(\frac{400}{420} \right)^6$$

$$+ \frac{5}{6} \left(\frac{20}{420} \right) \left(\frac{400}{420} \right)^5 \left(\frac{300}{310} \right)^5 \left(\frac{650}{662} \right)^6 \left(\frac{500}{515} \right)^4$$

Any one equipment type in (2,0) state

$$+ \frac{3}{5} \left(\frac{10}{310} \right)^2 \left(\frac{300}{310} \right)^3 \left(\frac{650}{662} \right)^6 \left(\frac{500}{515} \right)^4 \left(\frac{400}{420} \right)^6$$

$$+ \frac{4}{6} \left(\frac{12}{662} \right)^2 \left(\frac{650}{662} \right)^4 \left(\frac{300}{310} \right)^5 \left(\frac{500}{515} \right)^4 \left(\frac{400}{420} \right)^6$$

$$+ \frac{2}{4} \left(\frac{15}{515} \right)^2 \left(\frac{500}{515} \right)^2 \left(\frac{300}{310} \right)^5 \left(\frac{650}{662} \right)^6 \left(\frac{400}{420} \right)^6$$

$$+ \frac{4}{6} \left(\frac{20}{420} \right)^2 \left(\frac{400}{420} \right)^4 \left(\frac{300}{310} \right)^5 \left(\frac{650}{662} \right)^6 \left(\frac{500}{515} \right)^4$$

Any two equipment types in (1,0) and (1,0) states

$$+ \frac{4}{5} \frac{5}{6} \left(\frac{10}{310} \right) \left(\frac{300}{310} \right)^4 \left(\frac{12}{662} \right) \left(\frac{650}{662} \right)^5 \left(\frac{500}{515} \right)^4 \left(\frac{400}{420} \right)^6$$

$$+ \frac{4}{5} \frac{3}{4} \left(\frac{10}{310} \right) \left(\frac{300}{310} \right)^4 \left(\frac{15}{515} \right) \left(\frac{500}{515} \right)^3 \left(\frac{650}{662} \right)^6 \left(\frac{400}{420} \right)^6$$

$$+ \frac{4}{5} \frac{5}{6} \left(\frac{10}{310} \right) \left(\frac{300}{310} \right)^4 \left(\frac{20}{420} \right) \left(\frac{400}{420} \right)^5 \left(\frac{650}{650} \right)^6 \left(\frac{500}{515} \right)^4$$

$$+ \frac{5}{6} \frac{3}{4} \left(\frac{12}{662} \right) \left(\frac{650}{662} \right)^5 \left(\frac{15}{515} \right) \left(\frac{500}{515} \right)^3 \left(\frac{300}{310} \right)^5 \left(\frac{400}{420} \right)^6$$

$$+ \frac{5}{6} \frac{5}{6} \left(\frac{12}{662} \right) \left(\frac{650}{662} \right)^5 \left(\frac{20}{420} \right) \left(\frac{400}{420} \right)^5 \left(\frac{300}{310} \right)^5 \left(\frac{500}{515} \right)^4$$

$$+ \frac{3}{4} \frac{5}{6} \left(\frac{15}{515} \right) \left(\frac{500}{515} \right)^3 \left(\frac{20}{420} \right) \left(\frac{400}{420} \right)^5 \left(\frac{300}{310} \right)^5 \left(\frac{650}{662} \right)^6$$

Any one equipment type in (3,0) state

$$+ \frac{2}{5} \left(\frac{10}{310} \right)^3 \left(\frac{300}{310} \right)^2 \left(\frac{650}{662} \right)^6 \left(\frac{500}{515} \right)^4 \left(\frac{400}{420} \right)^6$$

$$+ \frac{3}{6} \left(\frac{12}{662} \right)^3 \left(\frac{650}{662} \right)^3 \left(\frac{300}{310} \right)^5 \left(\frac{500}{515} \right)^4 \left(\frac{600}{420} \right)^6$$

$$+ \frac{1}{4} \left(\frac{15}{515} \right)^3 \left(\frac{500}{515} \right)^1 \left(\frac{300}{310} \right)^5 \left(\frac{650}{662} \right)^6 \left(\frac{400}{420} \right)^6$$

$$+ \frac{3}{6} \left(\frac{20}{420} \right)^3 \left(\frac{400}{420} \right)^3 \left(\frac{300}{310} \right)^5 \left(\frac{650}{662} \right)^6 \left(\frac{500}{515} \right)^4$$

Any two equipment types in (1,0) and (2,0) states

$$\begin{aligned}
 & + \frac{4}{5} \frac{4}{6} \left(\frac{10}{310} \right)^1 \left(\frac{300}{310} \right)^4 \left(\frac{12}{662} \right)^2 \left(\frac{650}{662} \right)^4 \left(\frac{500}{515} \right)^4 \left(\frac{400}{420} \right)^6 \\
 & + \frac{4}{5} \frac{2}{4} \left(\frac{10}{310} \right)^1 \left(\frac{300}{310} \right)^4 \left(\frac{15}{515} \right)^2 \left(\frac{500}{515} \right)^2 \left(\frac{650}{662} \right)^6 \left(\frac{400}{420} \right)^6 \\
 & + \frac{4}{5} \frac{4}{6} \left(\frac{10}{310} \right)^1 \left(\frac{300}{310} \right)^4 \left(\frac{20}{420} \right)^2 \left(\frac{400}{420} \right)^4 \left(\frac{650}{662} \right)^6 \left(\frac{500}{515} \right)^4 \\
 & + \frac{3}{5} \frac{5}{6} \left(\frac{10}{310} \right)^2 \left(\frac{300}{310} \right)^3 \left(\frac{12}{662} \right)^1 \left(\frac{650}{662} \right)^5 \left(\frac{500}{515} \right)^4 \left(\frac{400}{420} \right)^6 \\
 & + \frac{5}{6} \frac{2}{4} \left(\frac{12}{662} \right)^1 \left(\frac{650}{662} \right)^5 \left(\frac{15}{515} \right)^2 \left(\frac{500}{515} \right)^2 \left(\frac{300}{310} \right)^5 \left(\frac{400}{420} \right)^6 \\
 & + \frac{5}{6} \frac{4}{6} \left(\frac{12}{662} \right)^1 \left(\frac{650}{662} \right)^5 \left(\frac{20}{420} \right)^2 \left(\frac{400}{420} \right)^4 \left(\frac{300}{310} \right)^5 \left(\frac{500}{515} \right)^4 \\
 & + \frac{3}{5} \frac{3}{4} \left(\frac{10}{310} \right)^2 \left(\frac{300}{310} \right)^3 \left(\frac{15}{515} \right)^1 \left(\frac{500}{515} \right)^3 \left(\frac{650}{662} \right)^6 \left(\frac{400}{420} \right)^6 \\
 & + \frac{4}{6} \frac{3}{4} \left(\frac{12}{662} \right)^2 \left(\frac{650}{662} \right)^4 \left(\frac{15}{515} \right)^1 \left(\frac{500}{515} \right)^3 \left(\frac{300}{310} \right)^5 \left(\frac{400}{420} \right)^6 \\
 & + \frac{3}{4} \frac{4}{6} \left(\frac{15}{515} \right)^1 \left(\frac{500}{515} \right)^3 \left(\frac{20}{420} \right)^2 \left(\frac{400}{420} \right)^4 \left(\frac{300}{310} \right)^5 \left(\frac{650}{662} \right)^6 \\
 & + \frac{3}{5} \frac{5}{6} \left(\frac{10}{310} \right)^2 \left(\frac{300}{310} \right)^3 \left(\frac{20}{420} \right)^1 \left(\frac{400}{420} \right)^5 \left(\frac{650}{662} \right)^6 \left(\frac{500}{515} \right)^4 \\
 & + \frac{4}{6} \frac{5}{6} \left(\frac{12}{662} \right)^2 \left(\frac{650}{662} \right)^4 \left(\frac{20}{420} \right)^1 \left(\frac{400}{420} \right)^5 \left(\frac{300}{310} \right)^5 \left(\frac{500}{515} \right)^4 \\
 & + \frac{2}{4} \frac{5}{6} \left(\frac{15}{515} \right)^2 \left(\frac{500}{515} \right)^2 \left(\frac{20}{420} \right)^1 \left(\frac{400}{420} \right)^5 \left(\frac{300}{310} \right)^5 \left(\frac{650}{662} \right)^6
 \end{aligned}$$

Any one equipment type in (4,0) state

$$\begin{aligned}
 & + \frac{1}{5} \left(\frac{10}{310} \right)^4 \left(\frac{300}{310} \right)^1 \left(\frac{650}{662} \right)^6 \left(\frac{500}{515} \right)^4 \left(\frac{400}{420} \right)^6 \\
 & + \frac{2}{6} \left(\frac{12}{662} \right)^4 \left(\frac{650}{662} \right)^2 \left(\frac{300}{310} \right)^5 \left(\frac{500}{515} \right)^4 \left(\frac{600}{420} \right)^6 \\
 & + \frac{2}{6} \left(\frac{20}{420} \right)^4 \left(\frac{400}{420} \right)^2 \left(\frac{300}{310} \right)^5 \left(\frac{650}{662} \right)^6 \left(\frac{500}{515} \right)^4 \\
 & + \dots \quad \dots \quad \dots \quad \dots + \dots \quad \dots \quad \dots \quad \dots + \dots
 \end{aligned}$$

All four types in (5,0), (6,0), (4,0), (6,0) states

$$+ \left(\frac{10}{310} \right)^5 \left(\frac{12}{662} \right)^6 \left(\frac{15}{515} \right)^4 \left(\frac{20}{420} \right)^6$$

$$= 0.504249 + 0.053561 + 0.001541$$

$$+ 0.002040 + 0.000035 + o(10^{-7})$$

$$= 0.561426$$

3. Achieving High Availability by a Central Storage Area

Suppose that a central area is provided which is stocked with x_1 spares of equipment type 1, x_2 spares of equipment type 2, x_3 spares of equipment type 3, and x_4 spares of equipment type 4. Mean time to replacement (MTR) is four hours for the equipment type 1, six hours for type 2, eight hours for type 3, and five hours for type 4. It is

given by the vendor that the probability of a spare failing is one percent. A summary of the numerical data of the parameters is listed in Table 10.

TABLE 10. Numerical data of the parameters

Parameters	Transition Rate			
	Equipment Type 1	Equipment Type 2	Equipment Type 3	Equipment Type 4
λ_i $i = 0, 1, \dots, N_i$	1/300	1/650	1/500	1/400
μ_i $i = 1, 2, \dots, n_{\max_i}$	1/10i	1/12i	1/15i	1/20
β_i $i = 0, 1, \dots, N_i$	1/4	1/6	1/8	1/5
β_{01}	1-P	1-P	1-P	1-P
N_i	5	6	4	6
x_i	1	1	1	1
n_{\max_i}	6	7	5	7
$M = 4, P=0.99$				

Each equipment type is treated as statistically independent to each other, and the Markov Process of a typical equipment type, having N equal to 4, is depicted in Figure 30. The formulas describing the transitional

probabilities of Figure 30 resulting from equations (1) through (9) are:

$$P(1,0) = \frac{\lambda_0}{\mu_1} P(0,0)$$

$$P(0,1) = \frac{\lambda_0}{\rho\beta_0 + \beta_{01}} P(0,0)$$

$$P(i+1,0) = \frac{1}{\mu_{i+1}} [(\lambda_i + \mu_i) P(i,0) - \beta_{i-1} P(i-1,1)]$$

for $i = 1, 2, \dots, 4$

$$P(5,0) = \frac{\beta_4}{\mu_5} P(4,1)$$

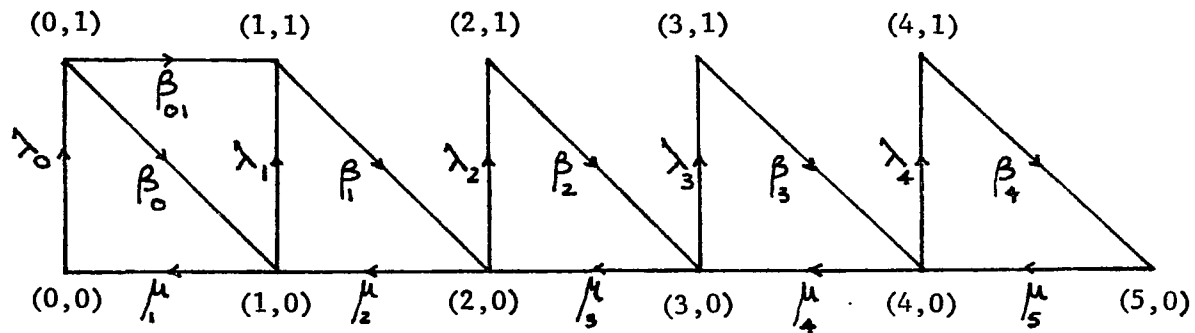
$$P(i,1) = \frac{\lambda_i}{\mu_i} P(i,0)$$

for $i = 2, 3, 4$

$$P(1,1) = \frac{1}{\beta_1} [\lambda_1 P(1,0) + \beta_{01} P(0,1)]$$

Under the normality condition

$$\sum_{i=0}^5 P(i,0) + \sum_{i=0}^4 P(i,1) = 1$$



For: $N=4$
 $X=1$
 $N_{\max}=5$

FIGURE 30. Transition rate diagram for the example

Similarly, Markov Process for the other three types of equipment are considered and the formulas resulting from the transitional probabilities give similar equations as above. The state probabilities are computed and listed in Table 11 for all four equipment types. Using Table 11, the traditional availability becomes

$$A_0 = \prod_{i=1}^4 [P_i(0,0) + P_i(x_i,0)]$$

Since it is given that $x_1 = x_2 = x_3 = x_4 = 1$, therefore,

$$\begin{aligned} A_0 &= \prod_{i=1}^4 [P_i(0,0) + P_i(1,0)] \\ &= (0.949980 + 0.031666) \cdot (0.970012 + 0.017908) \\ &\quad \cdot (0.949106 + 0.028473) \cdot (0.930222 + 0.046511) \\ &= 0.981646 \times 0.987920 \times 0.977579 \times 0.976733 \\ &= 0.925986 \end{aligned}$$

which is lot better than 0.561426 when the central storage area is not installed. To account for the partial credits from the environment viewpoint, consider the states one by one and assign partial credits for partial availability of the manufacturing subsystem.

1) Any one equipment type in failure states

a) Only one equipment type in the state $(x+1,0) = (2,0)$

$$\sum_{k=1}^4 W_1^k A_1^k = 4/5 A_1^1 + 5/6 A_1^2 + 3/4 A_1^3 + 5/6 A_1^4$$

TABLE 11. State probabilities of the numerical illustration

State Probabilities				
State	Equipment Type 1	Equipment Type 2	Equipment Type 3	Equipment Type 4
	$P_1(i, j)$	$P_2(i, j)$	$P_3(i, j)$	$P_4(i, j)$
(0,0)	0.949980	0.970012	0.949106	0.930222
(0,1)	1.230×10^{-2}	8.532×10^{-3}	1.420×10^{-2}	1.119×10^{-2}
(1,0)	3.167×10^{-2}	1.791×10^{-2}	2.847×10^{-2}	4.651×10^{-2}
(1,1)	9.094×10^{-4}	6.721×10^{-4}	1.580×10^{-3}	1.135×10^{-3}
(2,0)	4.547×10^{-3}	2.688×10^{-3}	5.927×10^{-3}	9.081×10^{-3}
(2,1)	6.063×10^{-5}	2.482×10^{-5}	9.483×10^{-5}	1.135×10^{-4}
(3,0)	4.547×10^{-4}	1.489×10^{-4}	5.334×10^{-4}	1.362×10^{-3}
(3,1)	6.063×10^{-6}	1.375×10^{-6}	8.534×10^{-6}	1.703×10^{-5}
(4,0)	6.062×10^{-5}	1.099×10^{-5}	6.400×10^{-5}	2.724×10^{-4}
(4,1)	8.083×10^{-7}	1.015×10^{-7}	1.024×10^{-6}	3.405×10^{-6}
(5,0)	1.010×10^{-5}	1.017×10^{-6}	9.600×10^{-6}	6.811×10^{-5}
(5,1)	1.346×10^{-7}	9.386×10^{-9}	-	8.514×10^{-7}
(6,0)	2.020×10^{-6}	1.147×10^{-7}	-	2.044×10^{-5}
(6,1)	-	1.059×10^{-9}	-	2.555×10^{-7}
(7,0)	-	1.482×10^{-8}	-	7.154×10^{-6}

$$\begin{aligned}
&= 4/5 \{P_1(2,0) [P_2(0,0)+P_2(1,0)] \\
&\quad [P_3(0,0)+P_3(1,0)] [P_4(0,0)+P_4(1,0)]\} \\
&+ 5/6 \{P_2(2,0) [P_1(0,0)+P_1(1,0)] \\
&\quad [P_3(0,0)+P_3(1,0)] [P_4(0,0)+P_4(1,0)]\} \\
&+ 3/4 \{P_3(2,0) [P_1(0,0)+P_1(1,0)] \\
&\quad [P_2(0,0)+P_2(1,0)] [P_4(0,0)+P_4(1,0)]\} \\
&+ 5/6 \{P_4(2,0) [P_1(0,0)+P_1(1,0)] \\
&\quad [P_2(0,0)+P_2(1,0)] [P_3(0,0)+P_3(1,0)]\} \\
&= 0.003431 + 0.002100 + 0.004210 + 0.007174 \\
&= 0.0169158
\end{aligned}$$

b) Only one equipment type in the state $(x+2,0) = (3,0)$

$$\begin{aligned}
\sum_{k=1}^4 w_2^k A_2^k &= 3/5 A_2^1 + 4/6 A_2^2 + 2/4 A_2^3 + 4/6 A_2^4 \\
&= 3/5 \{P_1(3,0) [P_2(0,0)+P_2(1,0)] \\
&\quad [P_3(0,0)+P_3(1,0)] [P_4(0,0)+P_4(1,0)]\} \\
&+ 4/6 \{P_2(3,0) [P_1(0,0)+P_1(1,0)] \\
&\quad [P_3(0,0)+P_3(1,0)] [P_4(0,0)+P_4(1,0)]\} \\
&+ 2/4 \{P_3(3,0) [P_1(0,0)+P_1(1,0)] \\
&\quad [P_2(0,0)+P_2(1,0)] [P_4(0,0)+P_4(1,0)]\} \\
&+ 4/6 \{P_4(3,0) [P_1(0,0)+P_1(1,0)] \\
&\quad [P_2(0,0)+P_2(1,0)] [P_3(0,0)+P_3(1,0)]\} \\
&= 1.4639E-3 \quad \text{or} \quad 0.001464
\end{aligned}$$

c) Only one equipment type in the state $(x+3,0) = (4,0)$

$$\begin{aligned}
\sum_{k=1}^4 W_3^k A_3^k &= 2/5 A_3^1 + 3/6 A_3^2 + 1/4 A_3^3 + 3/6 A_3^4 \\
&= 2/5 \{P_1(4,0) [P_2(0,0)+P_2(1,0)] \\
&\quad [P_3(0,0)+P_3(1,0)] [P_4(0,0)+P_4(1,0)]\} \\
&+ 3/6 \{P_2(4,0) [P_1(0,0)+P_1(1,0)] \\
&\quad [P_3(0,0)+P_3(1,0)] [P_4(0,0)+P_4(1,0)]\} \\
&+ 1/4 \{P_3(4,0) [P_1(0,0)+P_1(1,0)] \\
&\quad [P_2(0,0)+P_2(1,0)] [P_4(0,0)+P_4(1,0)]\} \\
&+ 3/6 \{P_4(4,0) [P_1(0,0)+P_1(1,0)] \\
&\quad [P_2(0,0)+P_2(1,0)] [P_3(0,0)+P_3(1,0)]\} \\
&= 1.723E-4 \quad \text{or} \quad 0.000172
\end{aligned}$$

d) Only one equipment type in the state $(x+4,0) = (5,0)$

$$\begin{aligned}
\sum_{k=1}^4 W_4^k A_4^k &= 1/5 A_4^1 + 2/6 A_4^2 + 2/6 A_4^4 \\
&= 1/5 \{P_1(5,0) [P_2(0,0)+P_2(1,0)] \\
&\quad [P_3(0,0)+P_3(1,0)] [P_4(0,0)+P_4(1,0)]\} \\
&+ 2/6 \{P_2(5,0) [P_1(0,0)+P_1(1,0)] \\
&\quad [P_3(0,0)+P_3(1,0)] [P_4(0,0)+P_4(1,0)]\} \\
&+ 2/6 \{P_4(5,0) [P_1(0,0)+P_1(1,0)] \\
&\quad [P_2(0,0)+P_2(1,0)] [P_3(0,0)+P_3(1,0)]\} \\
&= 2.37E-5 \quad \text{or} \quad 0.000024
\end{aligned}$$

e) Only one equipment type in the state $(x+5,0) = (6,0)$

$$\begin{aligned}
\sum_{k=1}^4 W_5^k A_5^k &= 1/6 A_5^2 + 1/6 A_5^4 \\
&+ 1/6 \{P_2(6,0) [P_1(0,0)+P_1(1,0)] \\
&\quad [P_3(0,0)+P_3(1,0)] [P_4(0,0)+P_4(1,0)]\} \\
&+ 1/6 \{P_4(6,0) [P_1(0,0)+P_1(1,0)] \\
&\quad [P_2(0,0)+P_2(1,0)] [P_3(0,0)+P_3(1,0)]\} \\
&= 3.30E-6 \quad \text{or} \quad 0.000003
\end{aligned}$$

2) Two or more equipment types in failure states

a) Any two equipment types in the state $(x+1,0) = (2,0)$

$$\begin{aligned}
\sum_{\substack{l=1 \\ l \neq k}}^4 \sum_{k=1}^4 W_{11}^{kl} A_{11}^{kl} &= 4/5 (5/6 A_{11}^{12} + 3/4 A_{11}^{13} + 5/6 A_{11}^{14}) \\
&+ 5/6 (3/4 A_{11}^{23} + 5/6 A_{11}^{24}) + 3/4 \cdot 5/6 A_{11}^{34} \\
&= 2/3 \{P_1(2,0) P_2(2,0) \\
&\quad [P_3(0,0)+P_3(1,0)] [P_4(0,0)+P_4(1,0)]\} \\
&+ 3/5 \{P_1(2,0) P_3(2,0) \\
&\quad [P_2(0,0)+P_2(1,0)] [P_4(0,0)+P_4(1,0)]\} \\
&+ 2/3 \{P_1(2,0) P_4(2,0) \\
&\quad [P_2(0,0)+P_2(1,0)] [P_3(0,0)+P_3(1,0)]\} \\
&+ 5/8 \{P_2(2,0) P_3(2,0) \\
&\quad [P_1(0,0)+P_1(1,0)] [P_4(0,0)+P_4(1,0)]\} \\
&+ 25/36 \{P_2(2,0) P_4(2,0) \\
&\quad [P_1(0,0)+P_1(1,0)] [P_3(0,0)+P_3(1,0)]\} \\
&+ 5/8 \{P_3(2,0) P_4(2,0) \\
&\quad [P_2(0,0)+P_2(1,0)] [P_3(0,0)+P_3(1,0)]\}
\end{aligned}$$

$$\begin{aligned}
&= 0.000008 + 0.000016 + 0.000026 \\
&+ 0.000009 + 0.000016 + 0.000032 \\
&= 0.000107
\end{aligned}$$

b) Other terms given in equation (23) have numerical values much smaller than 10^{-7} .

Finally, the proposed performance measure is the summation of A_0 and the above mentioned points including their subsections which are equal to following

$$\begin{aligned}
&= 0.925986 + 0.018578 + 0.000107 + o(10^{-7}) \\
&= 0.944672
\end{aligned}$$

C. Case Study

1. Description of System

In this case study, the model developed in chapter IV will be implemented to analyze and predict the performance of the state-of-the-art FMS for a manufacturer in the state of Iowa (1). The FMS consists of a total of sixteen machine tools. Six of these are head indexers and ten are machining centers. An integrated tow-line conveyor system is utilized for loading/unloading which is controlled by the D.E.C. PDP 11-44 host computer. There are four load/unload stations

located near head indexers. Infrared machines and personal computers are employed for monitoring the quality of output.

The precision boring and multi-spindle drilling and tapping operations are made possible by the use of horizontal 2-axis head indexers (H.I.). The horizontal 2-axis head indexers use as many as seven different spindles per operation. The milling, drilling, boring, and tapping operations are performed by the use of vertical 3-axis CNC machining centers (M.C.) each having a sixty nine tool capacity magazine. The vertical 3-axis CNC machining centers use ten to twenty three tools per operation. The computer controlled tow-line conveyor is employed for identifying codes on pallets to control the routing of parts to the specific machine tool. The machine tools layout as shown in Figure 31 displays two interconnected tow-line loops that serve all the machine tools.

The load/unload station is arranged to accept one pallet at a time from the tow-line carts. Each load/unload station has one CRT terminal and a pallet reader for parts guidance.

2. FMS Operation

The finished products of this system are a family of heavy casting which are used in drive-train assemblies.

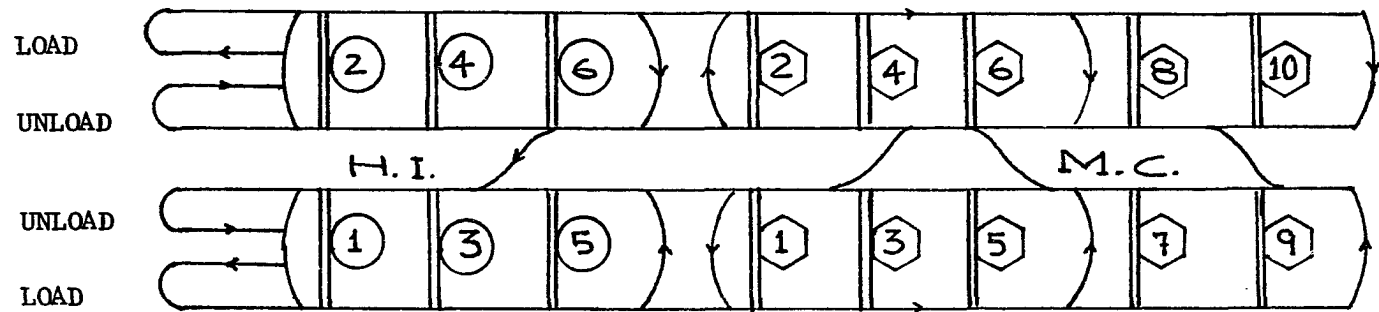


FIGURE 31. Case study: State-of-the-art FMS layout

Unfinished castings are brought to the load/unload stations by fork lift trucks. The tow-line carts arrive carrying fixtures on machining pallets then workers load the parts on the fixtures, report part number and pallet codes at the CRT terminal, and release the carts to the tow-line. These metal pallets stay on the carts until the finished parts are removed from the machine. Computer then routes the parts to the machine and downloads the NC program to the machine accordingly.

To transfer a part to or from a machine, a stop mechanism disengages the cart's tow pin from the in-floor conveyor chain and holds the cart in proper alignment for the transfer. A shuttle mounted hydraulic cylinder actuates the transfer device that unloads and reloads a tow-line cart when the palletized part arrives at the machine.

The computer directs a part from one machine to the next available one. The selection of machine tool occurs at random. Once machining is completed, carts pass through each machine for pick up and carry parts to the next machine or to the load/unload station. It is possible to machine all types of parts at once with different operations being performed on all sixteen machines.

3. Failure Data Analysis

An analysis of breakdown data is done in attempt to define the types of failure associated with machine tools. Electrical and electronic, mechanical and hydraulic are combined and considered as electrical and mechanical failures respectively. Overall, breakdowns are classified into three categories which are 1) electrical, 2) mechanical, and 3) tool failures. The data needed for this analysis is given in Table 12 and Table 13. This data is acquired from the local flexible manufacturing system through courtesy of "Dr. John Even".

TABLE 12. Summary of the Machine Center data

Failure Mode	No. of Failures	Rate of Failure	Average Response time	Average Repair time
Electrical	114	0.013	2.43	11.28
Mechanical	45	0.005	5.82	18.22
Tool	16	0.008	4.92	25.38

It is evident that the electrical failure is more frequent than the other two failures, and it is also responsible for a large share of downtime of the vertical

TABLE 13. Summary of the Head Indexer data

Failure Mode	No. of Failures	Rate of Failure	Average Response time	Average Repair time
Electrical	149	0.018	1.46	4.97
Mechanical	49	0.006	2.12	6.53
Tool	11	0.004	2.50	7.17

machining center. However, average downtime for the three failure types of the head indexer are relatively close. Based on this analysis, further analyses are unfolded to re-define or make the data compatible with model usage.

4. Application to Model

To put on the mathematical model developed in this research for the performance evaluation of an FMS, it is necessary to rearrange the data and to re-define FMS in modules or sub-systems. The FMS debated in this case study can be divided into two sub-systems, that is $M = 2$. The first type of sub-system consists of six units of head indexer, that is $N_1 = 6$ and the second type of sub-system has ten machine centers, that is $N_2 = 10$.

This research emphasizes on failures which are totally independent of modes of failure. Thus, it is necessary to combine all three modes of failure together and treat them as general failures of an equipment. This can be achieved by taking either simple average of all modes of failure rates or the weighted average of all modes of failure rates. The weighted average is recommended when the modes of failure rates and frequencies of failure are not reasonably close. The failure data analysis of the given FMS shows that electrical, mechanical, and tool failures have remarkably different frequencies as well as rates of breakdown. Hence the weighted average is a better choice for computing the mean time to failure, the mean time to repair, and the mean time to replacement. Table 14 displays the transformed values of arrival, repair, and replacement (response) times.

TABLE 14. Summary of transformed data

Equipment Type	Mean time to failures	Mean time to repair	Mean time to response
Head Indexer	69.20	5.36	1.61
Machine Center	95.38	13.25	3.02

This transformed data along with certain realistic assumption are used for developing input value of the parameters for the computer model usage. A summary of input data is displayed in Table 15.

TABLE 15. The input parameters' data: Case study

Parameters	Transition Rate	
	Sub-system Type #1	Sub-system Type #2
λ_i $i = 0, 1, \dots N_i$	1/69.20	1/95.38
μ_i $i = 1, 2, \dots n_{\max i}$	1/5.36i	1/13.25i
β_i $i = 0, 1, \dots N_i$	1/1.61	1/3.02
β_{01}	1-P	1-P
N_i	6	10
x_i^a	1	1
$n_{\max i}$	7	11
$M = 2, P=0.99$		

^aThese are the values of subsystems' spares before applying heuristic optimization.

Each equipment type is statistically independent of each other. Therefore, the Markovian process is employed

for generating a series of necessary equations. These equations describe the transitional probabilities of a sub-system and coded in computer. By entering the values of parameters into the computer the state probabilities are obtained and shown in Table 16 for both types of the sub-system.

5. Computer Model Usage

The computer procedures for the model have been coded in FORTRAN. There are three parts of the program. The first part determines the performance measure of a flexible manufacturing system without having a central storage for spares. Second part computes the performance measure of an FMS when a central storage is provided for spares. It also generates the system state probabilities and optimizes the storage level for the sub-systems using heuristic approach. The third and the final part is utilized for sensitivity of performance measure having optimal storage level.

The output of programs "PEWOS", and "PEWS" contain information concerning the state probabilities of the system, the storage level of each sub-system and the corresponding system availability. In addition, it provides optimum values of spares and the maximum achievable system availability with cost efficiency.

TABLE 16. State probabilities of the case study

State Probabilities		
State	Sub-system Type #1	Sub-system Type #2
	$P_1(i,j)$	$P_2(i,j)$
(0,0)	8.907×10^{-1}	7.569×10^{-1}
(0,1)	2.059×10^{-2}	3.349×10^{-2}
(1,0)	6.898×10^{-2}	1.052×10^{-2}
(1,1)	1.933×10^{-3}	4.032×10^{-3}
(2,0)	1.287×10^{-2}	3.538×10^{-2}
(2,1)	2.995×10^{-4}	1.120×10^{-3}
(3,0)	2.991×10^{-3}	1.474×10^{-2}
(3,1)	6.959×10^{-5}	4.668×10^{-4}
(4,0)	9.268×10^{-4}	8.193×10^{-3}
(4,1)	2.156×10^{-5}	2.594×10^{-4}
(5,0)	3.589×10^{-4}	5.691×10^{-3}
(5,1)	8.351×10^{-6}	1.802×10^{-4}
(6,0)	1.668×10^{-4}	4.744×10^{-3}
(6,1)	3.881×10^{-6}	1.502×10^{-4}
(7,0)	9.044×10^{-5}	4.613×10^{-3}
(7,1)	-	1.461×10^{-4}
(8,0)	-	5.126×10^{-3}
(8,1)	-	1.623×10^{-4}

TABLE 16. (Continued)

State Probabilities		
State	Sub-system Type #1	Sub-system Type #2
(9,0)	-	6.409×10^{-3}
(9,1)	-	2.029×10^{-4}
(10,0)	-	8.904×10^{-3}
(10,1)	-	2.819×10^{-4}
(11,0)	-	1.360×10^{-5}

6. Summary and Results

The case study indicates that a performance measure can be explored with the aid of markovian process and probabilistic model of a generic flexible production system. To organize the data compatible with the model developed in this research requires a general understanding of the model and basic engineering background.

It is apparent from this analysis that the sub-system with high repair and response times requires more spares than the sub-system with low repair and response times, not considering the effect of different number of units in the each sub-system and various mean time to failures of equipment.

The outcome of the case study is depicted in the Table 17. It is obvious from the table that 92 percent of the time system is available when the system has optimum level of spares. The Table 17 also displays maximum achievable system availability at cost efficient expenses. If one tries to improve the system availability beyond this it won't be cost efficient.

The results show that conducting the analysis, developed in this research, provides significant insight regarding system performance. The designer can use this information for improving and redesigning the parameters of

the sub-systems that consist of one or more units of same or similar types.

TABLE 17. Case study: Data and result

DATA:

	TYPE#1	TYPE#2
MTTF:	69.20	95.36
MTTR:	5.36	13.25
MTR :	1.61	3.02
N :	6	10

PROBABILITY A SPARE WORKS =.99

DESIRABILITY FACTOR RATIO =.0005

SPARE COMPONENTS FOR		SUBSYSTEM SELECTION FACTOR		SYS AVAIL
TYPE# 1	TYPE# 2	F(X)# 1	F(X)# 2	
0	0	-	-	0.312502
1	1	.933735	.795296	0.896958
1	2	.933735	.821431	0.907752
1	3	.933735	.839171	0.916727

VI. CONCLUSION

Throughout the extensive literature associated with flexible manufacturing systems (FMSs), a constant repeating problems stated, namely the inability of companies to determine analytically whether such system's implementation is viable. Conceptually, it is extremely difficult to evaluate an FMS comprehensively. This research provides a useful tool that can help in predicting system performance, in the initial design and operation of FMSs, on the basis of both conventional design parameters and other factors, including the use of Markov process under certain assumptions.

This approach is from a system viewpoint to enhance the performance modelling capability of modern large and complex FMS. Although in the past, availability was the popular performance measure, this study proves it underestimates the performance. To compensate or overcome this, credits are granted even only if some of the local systems are functional. When a central storage area is installed, the performance of an FMS is enhanced. The heuristic programming is performed to set up optimal spare allocation policy. Finally sensitivity analysis is conducted to see how parameters of interest affect system performance and what measures one can take to improve or maintain the system

performance. It is found from the sensitivity analysis that mean time to response (replacement) is the most critical factor to be controlled.

The computer programs, developed in this work, evaluate the system performance with or without having a central storage area for spares. The third program conducts sensitivity analysis by varying the value of one or more than one parameter of interest. All outputs are generated in tabular form giving value of performance measure due to each change in value(s) of parameter(s).

The model of this study is independent of foreign change i.e. demand, supply, etc. Hence analyst can figure out up-time of a system and a way to improve it. Before making decision to implement FMS, management can get a general idea of system's availability using designed values of mean time to failure, mean time to repair, meant time to response (replace), and other factors. Thus the managers of FMS should therefore have planning decisions that ensure system demand within the capacity of the system.

This performance measurement technique is likely to be very useful for most real life FMS planning and implementing decisions. The model is tested for a wide range of applications.

VII. REFERENCES

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IX. APPENDIX A. JUST-IN-TIME AND FLEXIBLE MANUFACTURING
SYSTEMS

The Just-in-Time Environment

Just-in-Time (JIT) is a production philosophy which attempts to incorporate all aspects of the production process (from incoming deliveries to actual manufacturing), into a "continued commitment to the pursuit of excellence in all phases of manufacturing" (33). In simple term JIT aims at the production of the required quantity of the required goods at the required time.

The JIT system was developed at the Toyota Motor Company two decades ago. The introduction of JIT has affected many production management functions. Among these are production planning, work methods and processes, man power skills and deployment, quality and production control. It is essential that the system should possess flexibility and synchronization to ensure a smooth and continuous work flow.

In view of the enormous repercussions associated with the implementation of this new system, management will naturally seek firm and reliable indicators before making a commitment to it. In some instances pilot projects have been used as test cases. A better alternative approach is the application of computer simulation. With a comprehensive model it is possible to obtain an accurate portrayal of the proposed JIT system and to investigate the likely outcome of various options.

The present study reviews some major features of the JIT system (Kanban). Kanban is the production control as realized by Toyota Motor Company. Actual meaning of Kanban in Japanese is card (48). The JIT principle aims at the production of parts, sub-assemblies and assemblies only as and when required. Considerable planning and reorganization have to to be done in order to meet the JIT. Some of the features are outlined below.

Facilities layout:

To ensure a smooth and continuous work flow from the raw material stage to finished products it is necessary to adopt a product flow approach rather than a functional or process layout. Furthermore, to improve the movement of items between processes and to match the "supply and demand" between them, there is an advantage in placing the stations in close proximity and, if possible, within visual range. The stations should be connected by conveyors or similar despatching devices as these not only prevent the building up in-process inventory but also enforce the expeditious transfer of work to succeeding stations.

To ensure the flexibility required for JIT, operators should possess multiple skills so that they are able to attend to parts from station to station. Moreover, this will be useful when it is necessary to smooth out production

when imbalances between processes arise due to machine breakdowns, unexpectedly high defect rates or other contingencies.

Set-Up Times:

Shorter set-up times facilitate smaller batch production and reduce product lead times. Set-up times are often regarded as a necessary evil and a common measure to try to render them proportionately insignificant by increasing the batch size. This results in the generation of excessive stock and work-in-process and the eventually choking up the production system. A better approach is to address the set-up time directly by examining the possibility of reducing it or even achieving its elimination. This can be done through the standardization and rationalization of parts design, process planning, jig and fixtures design, and the introduction of composite set-ups and tool pre-setting.

The automation of machine tools has also assisted in the reduction of set-up times. Computer numerical control machines allow a quick turnover of parts and automated insertion machines permit different circuit boards to be handled easily due to the short reprogramming times.

Quality control:

A principal function of the quality control department is to ensure that the level of defects of parts leaving the shop-floor department falls within specified levels, the more important objective is to be able to detect the defects at source as soon as they arise. This is because the counter-productive nature of poor quality control is far more insidious than commonly recognized. The value of the scrapped item is often the least costly factor. Of more importance is the adverse effect on work flow, production planning and plant capacity when short-falls in quality occur.

One means of overcoming the problem is to do away with centralized inspection stations and substitute patrolling inspectors. Alternatively, operators should be assigned the responsibility for the quality of their work before despatching to the next station. The term "automation" was coined at Toyota to identify the process of autonomous and, in some cases, automatic identification of defects in the production process. Basically, this requires each work station to be solely responsible for its own quality control which must, as far as possible, avoid passing on defective parts to subsequent stations. A complementary feature is the installation of a set of different colored lights which

are used to summon assistance from the operators of other stations in the event that the a particular station is running behind schedule. This prevents the transfer of faulty parts resulting from the pressure of not being able to cope.

Production Planning and Control:

For the realization of JIT, all facets of the system must be well timed and synchronized. Logistics and smooth work flow are imperative. MRP method is more suitable for longer-term schedules -- such as the master or monthly -- rather than for short-term schedules. The JIT usually have a general one-year rough-cut master schedule, a one or two-month detailed production schedule, a ten-day schedule, and a daily schedule. The ten days schedule is 99 percent reliable while the daily schedule is prepared on the previous day. Naturally, the prompt delivery of purchased items is a key factor. Often, the arrangement is that the vendor's truck driver checks the status of the Kanban tickets, restocks the delivery area, updates the transaction in both the vendor's and customer's records, and carries the requisition Kanban tickets back to his firm. The vendor's inventory is seen to be an extension of the customer's inventory.

With JIT there is a preference for the use of Kanban over computerized control. This provides greater responsiveness; bottlenecks can be quickly identified and the appropriate remedies applied. It is advantageous if operators have multi-function abilities as they can then act as mobile production smoothers. It is also recommended that operators should maintain their respective machines and equipment to minimize machine down-times.

Relationship between JIT and FMS:

The relationship between JIT and FMS showed agreement on the assertion that both concepts are closely connected. The Toyota production system is a natural way to attain FMS in repetitive manufacturing; as more technical components for flexible automated assembly systems become available. These components can easily be integrated. The FMS-developments in components manufacturing will eventually make small lot-sizes economically feasible in the job-shop. JIT production may improve the quality control system by a very fast feedback of the consuming facility to the producing facility.

X. APPENDIX B. OUTPUT TABLES AND GRAPHS OF SENSITIVITY
ANALYSIS

TABLE 18. Parameters' initial value: Example-II

Parameter	Type 1	Type 2	type 3	Type 4
MTTF	300	650	500	400
MTTR	10	12	15	20
MTR	4	6	8	5
N	5	6	4	6
x^a	2	1	2	2

^a x is not a parameter. The given values of x are the optimum values obtained by using heuristic approach.

TABLE 19. Variations in MTTF for each equipment

Type #1	Mean time to failure	System Availability
	100	0.918711
	300	0.948425
	500	0.953627
	700	0.955847
	900	0.957080
	1200	0.958159
	1500	0.958807
	1800	0.959239
Type #2	Mean time to failure	System Availability
	100	0.884938
	300	0.937265
	500	0.945591
	650	0.948425
	900	0.951033
	1200	0.952721
	1500	0.953731
	1800	0.954404
Type #3	Mean time to failure	System Availability
	100	0.859209
	300	0.937673
	500	0.948425
	700	0.952939
	900	0.955436
	1200	0.957617
	1500	0.958925
	1800	0.959797
Type #4	Mean time to failure	System Availability
	100	0.753568
	200	0.931674
	400	0.948425
	600	0.952737
	900	0.955512
	1200	0.956883
	1500	0.957702
	1800	0.958247

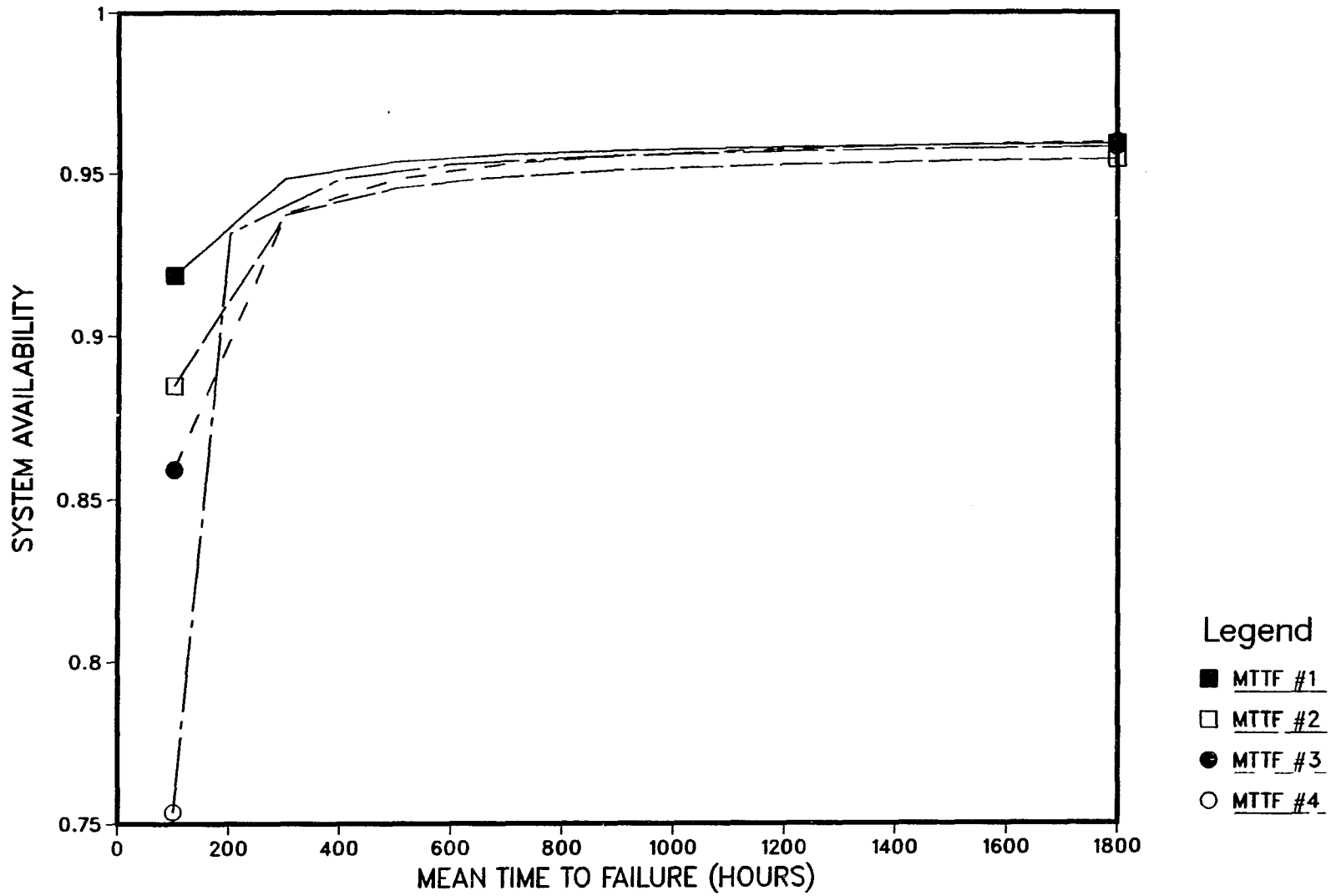


FIGURE 32. Sensitivity analysis: Change in MTTF for equipment type #1/#2/#3/#4

TABLE 20. Variations in MTTR for each equipment

Type #1	Mean time to repair	System Availability
	4	0.948593
	6	0.948558
	8	0.948504
	10	0.948425
	12	0.948313
	15	0.948062
	18	0.947670
	22	0.946820
Type #2	Mean time to repair	System Availability
	4	0.948787
	6	0.948710
	8	0.948625
	10	0.948530
	12	0.948425
	15	0.948248
	18	0.948045
	22	0.947729
Type #3	Mean time to repair	System Availability
	4	0.948775
	6	0.948738
	8	0.948692
	10	.0948663
	12	0.948562
	15	0.948425
	18	0.948246
	22	0.947927
Type #4	Mean time to repair	System Availability
	4	0.948959
	8	0.948910
	10	0.948871
	12	.0948820
	15	0.948713
	18	0.948560
	20	0.948425
	22	0.948256

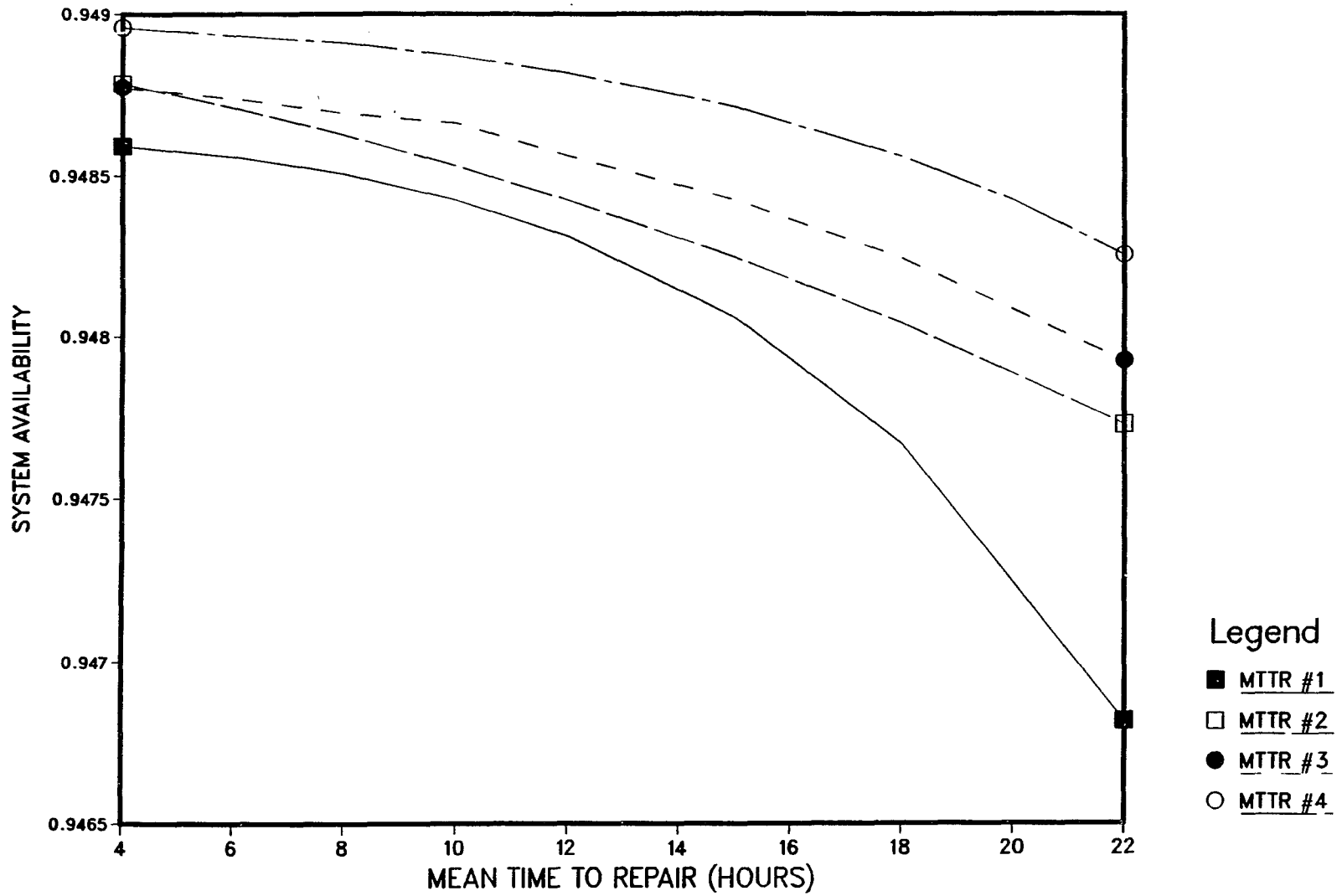


FIGURE 33. Sensitivity analysis: Change in MTTR for equipment type #1/#2/#3/#4

TABLE 21. Variations in MTR for each equipment

Type #1	Mean time to response	System Availability
	2	0.954849
	4	0.948425
	6	0.942073
	8	0.935794
	10	0.929586
	12	0.923455
	15	0.914384
	18	0.905479
Type #2	Mean time to response	System Availability
	2	0.954540
	4	0.951470
	6	0.948425
	8	0.945404
	10	0.942407
	12	0.939433
	15	0.935014
	18	0.930645
Type #3	Mean time to response	System Availability
	2	0.960164
	4	0.956234
	6	0.952320
	8	0.948425
	10	0.944550
	12	0.940696
	15	0.934958
	18	0.929272
Type #4	Mean time to response	System Availability
	2	0.955814
	4	0.948425
	6	0.943541
	8	0.938691
	10	0.933877
	12	0.929100
	15	0.924361
	18	0.917328

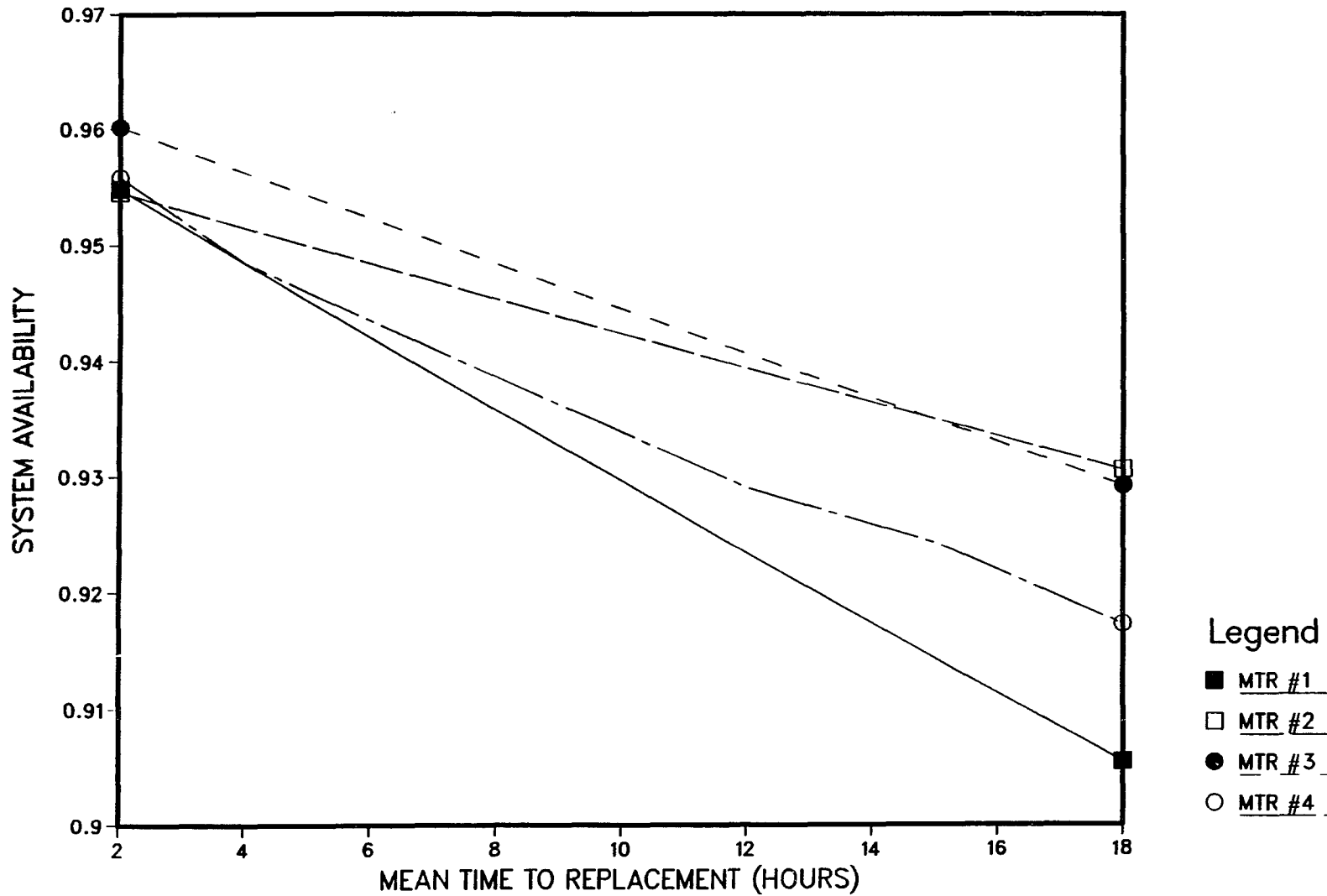


FIGURE 34. Sensitivity analysis: Change in MTR for equipment type #1/#2/#3/#4

TABLE 22. Variations of any one parameter for all equipment types

Percent Increase	MEAN TIME TO FAILURE				System Availability
	Type #1	Type #2	Type #3	Type #4	
0.4	120	260	200	160	0.858541
0.6	180	390	300	240	0.912905
0.8	240	520	400	320	0.935410
1.0	300	650	500	400	0.948425
1.2	360	780	600	480	0.957015
1.4	420	910	700	560	0.963131
1.6	480	1040	800	840	0.967716
1.8	540	1170	900	720	0.971282
2.0	600	1300	1000	800	0.974137

Percent Increase	MEAN TIME TO REPAIR				System Availability
	Type #1	Type #2	Type #3	Type #4	
0.4	4	4.8	6	8	0.949716
0.6	6	7.2	9	12	0.949423
0.8	8	9.6	12	16	0.949007
1.0	10	12.0	15	20	0.948425
1.2	12	14.4	18	24	0.947614
1.4	14	16.8	21	28	0.946485
1.6	16	19.2	24	32	0.944913
1.8	18	21.6	27	36	0.942722
2.0	20	24.0	30	40	0.939669

Percent Increase	MEAN TIME TO RESPONSE				System Availability
	Type #1	Type #2	Type #3	Type #4	
0.4	1.6	2.4	3.2	2	0.978757
0.6	2.4	3.6	4.8	3	0.968528
0.8	3.2	4.8	6.4	4	0.958418
1.0	4.0	6.0	8.0	5	0.948425
1.2	4.8	7.2	9.6	6	0.938550
1.4	5.6	8.4	11.2	7	0.928792
1.6	6.4	9.6	12.8	8	0.919151
1.8	7.2	10.8	14.4	9	0.909625
2.0	8.0	12.0	16.0	10	0.900213

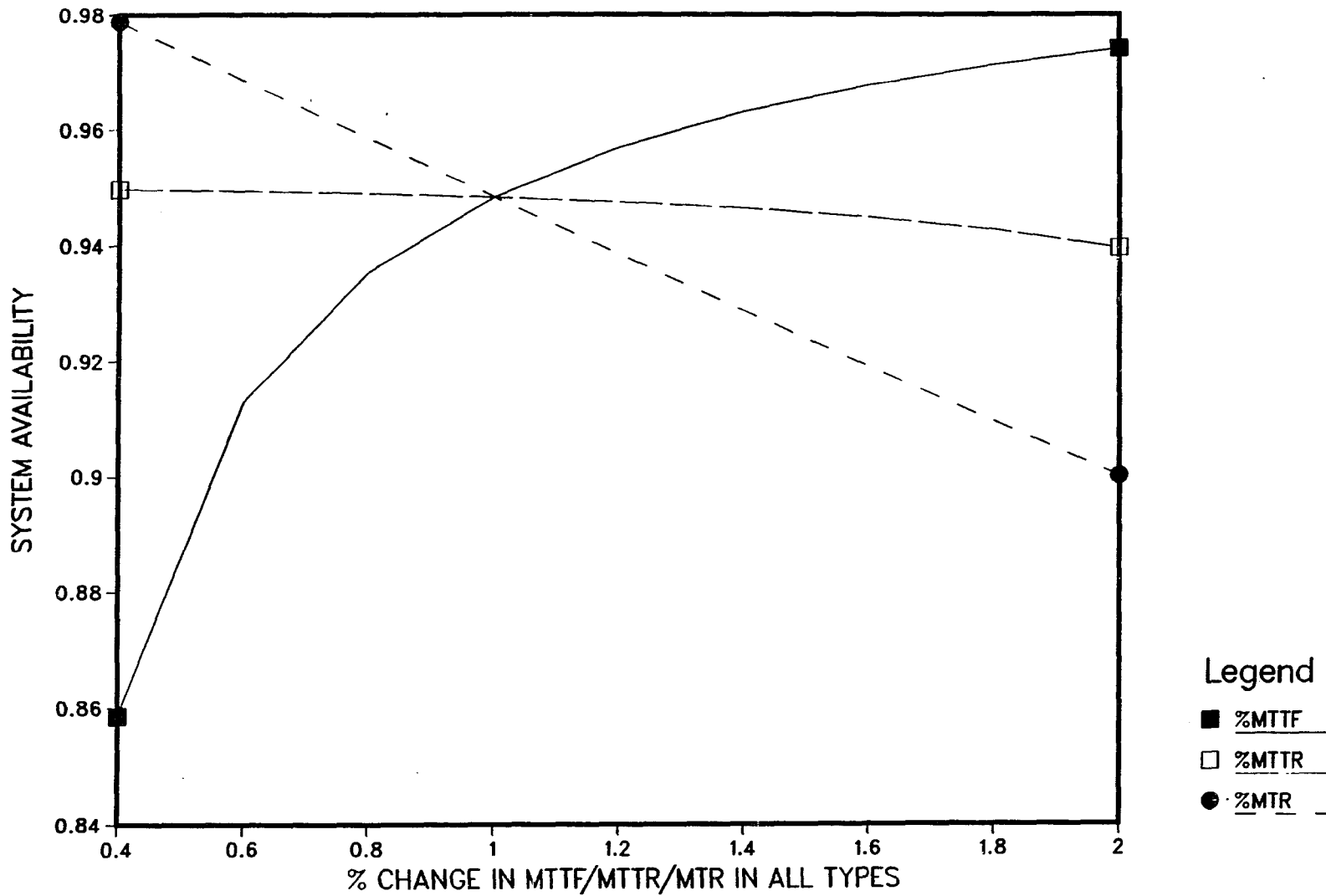


FIGURE 35. Sensitivity analysis: Change in MTF/MTR/MTR for all equipment types

TABLE 23. Variations of all parameters for any one equipment type

Percent Increase	Type #1 Mean time to failure	Type #1 Mean time to repair	Type #1 Mean time to response	System Availability
0.3	90	3	1.2	0.948532
0.5	150	5	2.0	0.948505
0.7	210	7	2.8	0.948475
0.9	270	9	3.6	0.948442
1.0	300	10	4.0	0.948425
1.1	330	11	4.4	0.948408
1.3	390	13	5.2	0.948371
1.5	450	15	6.0	0.948332
1.9	570	19	7.6	0.948249

Percent Increase	Type #2 Mean time to failure	Type #2 Mean time to repair	Type #2 Mean time to response	System Availability
0.3	195	3.6	1.8	0.948676
0.5	325	6.0	3.0	0.948620
0.7	455	8.4	4.2	0.948530
0.9	585	10.8	5.4	0.948460
1.0	650	12.0	6.0	0.948425
1.1	715	13.2	6.6	0.948391
1.3	845	15.6	7.8	0.948324
1.5	975	18.0	9.0	0.948258
1.9	1235	22.8	11.4	0.948131

Percent Increase	Type #3 Mean time to failure	Type #3 Mean time to repair	Type #3 Mean time to response	System Availability
0.3	150	4.5	2.4	0.948696
0.5	250	7.5	4.0	0.948630
0.7	350	10.5	5.6	0.948554
0.9	450	13.5	7.2	0.948470
1.0	500	15.0	8.0	0.948425
1.1	550	16.5	8.8	0.948378
1.3	650	19.5	10.4	0.948280
1.5	750	22.5	12.0	0.948175
1.9	950	28.5	15.2	0.947950

TABLE 23. Continued

Percent Increase	Type #4 Mean time to failure	Type #4 Mean time to repair	Type #4 Mean time to response	System Availability
0.3	120	6	1.5	0.948697
0.5	200	10	2.5	0.948625
0.7	280	14	3.5	0.948549
0.9	360	18	4.5	0.948467
1.0	400	20	5.0	0.948425
1.1	440	22	5.5	0.948382
1.3	520	26	6.5	0.948292
1.5	600	30	7.5	0.948198
1.9	760	38	9.5	0.948001

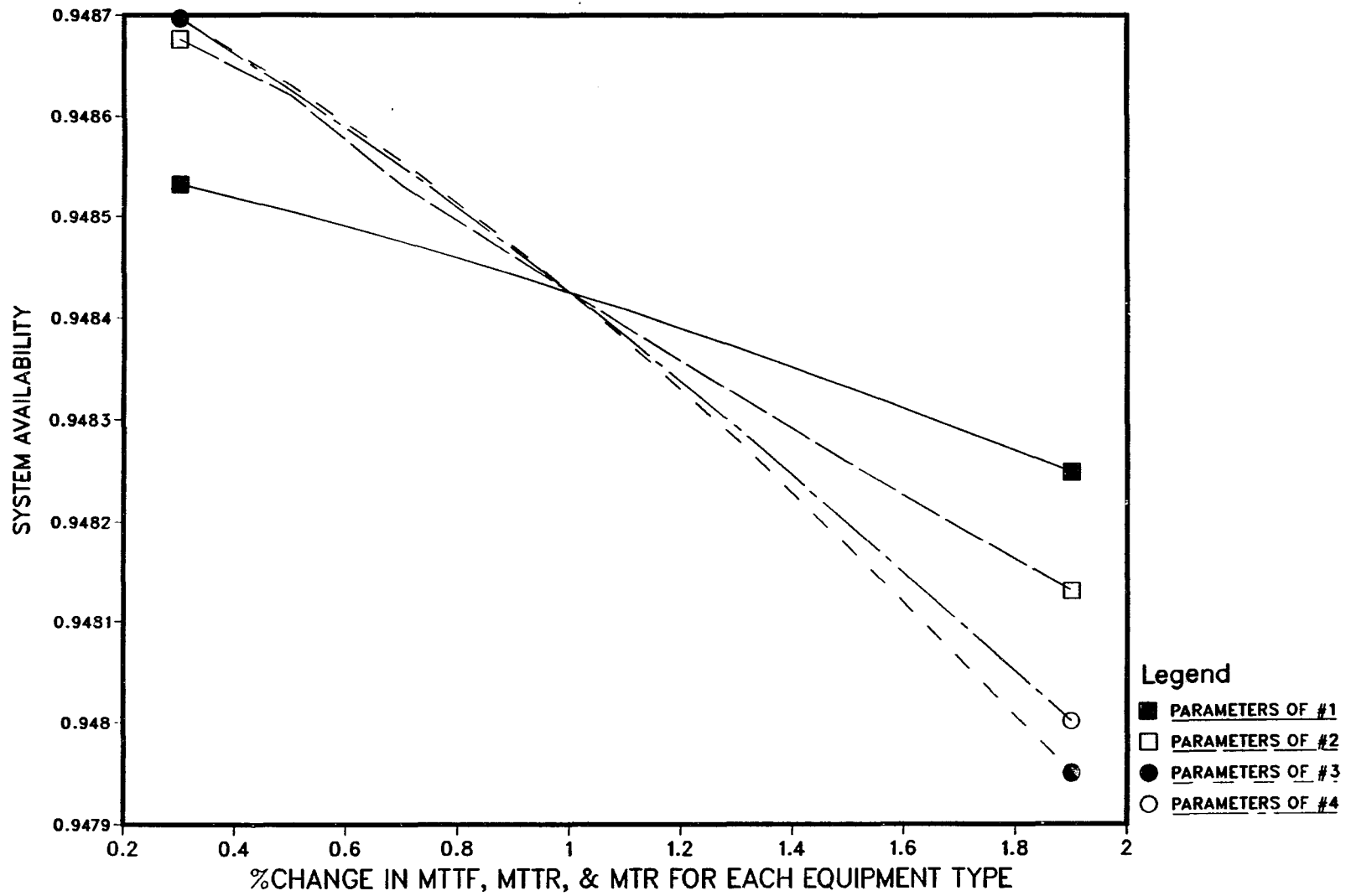


FIGURE 36. Sensitivity analysis: Changes in MTF, MTTR, & MTR for each equipment

XI. APPENDIX C. PROGRAM FOR MEASURING SYSTEM AVAILABILITY
WITHOUT HAVING SPARES FOR EQUIPMENT

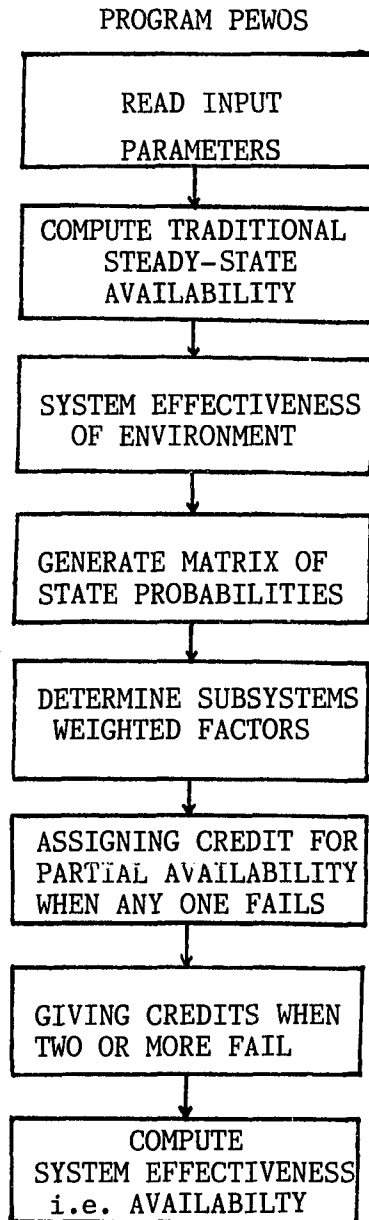


FIGURE 37. Flow chart of computer program PEWOS

```

1 PROGRAM PEWOS
2*****
3*
4* PURPOSE: 1.THIS PROGRAM EVALUATES THE PERFORMANCE USING
5* WEIGHTED FACTORS FOR A GENERIC FLEXIBLE
6* MANUFACTURING SYSTEM WITHOUT HAVING SPARES
6* FOR FAILING EQUIPMENT
7* 2.TAKES INTO ACCOUNT PARTIAL CREDIT FOR
8* PARTIAL AVAILABILITY
9*
10* INPUT: INTEGER,
11* >M: M IS THE TYPES OF EQUIPMENT IN AN FMS
12* >N: N IS THE NUMBER OF EACH TYPE OF
13* EQUIPMENT IN FMS ENVIRONMENT
14* REAL,
15* >MTTF: MTTF IS THE MEAN TIME TO FAILURE
16* >MTTR: MTTR IS THE MEAN TIME TO REPAIR
17*
18* LIMITATION:
19* >M: M CANNOT BE GREATER THEN 10
20* >N: N CANNOT BE GREATER THEN 10
21*
22* OUTPUT:
23* >S.S-A STEADY-STATE AVAILABILITY
24* >SYS-A SYSTEM'S OVERALL AVAILABILITY
25*
26*****
27*
28 REAL MTTR(10),MTTF(10)
29 INTEGER M,A1,A2,A3,A4,A5,A6,A7,A8,A9,A10,N(10)
30 DOUBLEPRECISION P1(0:9,0:0),P2(0:9,0:0),P3(0:9,0:0),
31 :P4(0:9,0:0),P5(0:9,0:0),P6(0:9,0:0),P7(0:9,0:0),P8(0:9,0:0),
32 :P9(0:9,0:0),P10(0:9,0:0),ATRAD,SSAVAL,P0,PA1,PA1A2
33*
34* INITIALIZE DATA
35*
36 DATA N/10*1/
37 DATA P1(0,0),P2(0,0),P3(0,0),P4(0,0),P5(0,0),P6(0,0),P7(0,0),
38 :P8(0,0),P9(0,0),P10(0,0)/1.,1.,1.,1.,1.,1.,1.,1.,1.,1./
39*
40* INTERACTIVE DATA INPUT
41*
42 WRITE(6,'(X,A)')'PLEASE SUPPLY THE VALUE OF "M"; WHERE'
43 WRITE(6,'(X,A)')'M IS THE TYPES OF EQUIPMENT IN FMS'
44 WRITE(6,*)
45 READ *, M
46 WRITE(6,*)
47 WRITE(6,'(X,A)')'PLEASE SUPPLY THE VALUE OF "N"; WHERE'
48 WRITE(6,'(X,A)')'N IS THE # OF EACH TYPE OF EQUIPMENT IN FMS'
49 WRITE(6,*)
50 DO I=1,M

```

```

51     WRITE(6, '(X,A,I2,A)') 'SUPPLY NOW THE VALUE OF "N" FOR
52 : TYPE#,I, ' ONLY'
53     WRITE(6,*)
54     READ*,N(I)
55     ENDDO
56     DO I=1,M
57     WRITE(6, '(X,A,I2,A)') 'SUPPLY VALUES OF "MTTF" AND "MTTR"
58 : FOR THE EQUIPMENT TYPE #,I, ' ONLY'
59     WRITE(6, '(X,A,I2)') 'WHERE MTTF IS THE MEAN TIME TO FAILURE
60 : FOR TYPE #,I, ' ONLY'
61     WRITE(6, '(X,A,I2)') 'WHERE MTTR IS THE MEAN TIME TO REPAIR
62 : FOR TYPE #,I, ' ONLY'
63     WRITE(6,*)
64     READ*,MTTF(I),MTTR(I)
65     WRITE(6,*)
66     ENDDO
67     ATRAD = 1.0D0
68*
69*           DETERMINING STEADY-STATE AVAILABILITY
70*
71     DO J = 1,M
72     SSAVAL= (MTTF(J)/( MTTF(J) + MTTR(J) ))
73     ATRAD=ATRAD*SSAVAL**N(J)
74     ENDDO
75     PRINT*
76     PRINT '(X,A,F9.6)', 'STEADY-STATE AVAILABILITY =',ATRAD
77     PRINT*
78*
79*           PROBABILITY OF FAILURE FOR TYPE #1
80*
81     DO A1 = 0,N(1)-1
82     D1 = MTTR(1) + MTTF(1)
83     P1(A1,0) = (MTTR(1)/D1)**A1 * (MTTF(1)/D1)**(N(1)-A1)
84     ENDDO
85*
86*           PROBABILITY OF FAILURE FOR TYPE #2
87*
88     IF ( M .GE. 2 ) THEN
89     DO A2 = 0,N(2)-1
90     D2 = MTTR(2) + MTTF(2)
91     P2(A2,0) = (MTTR(2)/D2)**A2 * (MTTF(2)/D2)**(N(2)-A2)
92     ENDDO
93     ENDIF
94*
95*           PROBABILITY OF FAILURE FOR TYPE #3
96*
97     IF ( M .GE. 3 ) THEN
98     DO A3 = 0,N(3)-1
99     D3 = MTTR(3) + MTTF(3)
100    P3(A3,0) = (MTTR(3)/D3)**A3 * (MTTF(3)/D3)**(N(3)-A3)
101    ENDDO

```

```

102      ENDIF
103*
104*          PROBABILITY OF FAILURE FOR TYPE #4
105*
106      IF ( M .GE. 4 ) THEN
107          DO A4 = 0,N(4)-1
108              D4 = MTTR(4) + MTF(4)
109              P4(A4,0) = (MTTR(4)/D4)**A4 * (MTTF(4)/D4)**(N(4)-A4)
110          ENDDO
111      ENDIF
112*
113*          PROBABILITY OF FAILURE FOR TYPE #5
114*
115      IF ( M .GE. 5 ) THEN
116          DO A5 = 0,N(5)-1
117              D5 = MTTR(5) + MTF(5)
118              P5(A5,0) = (MTTR(5)/D5)**A5 * (MTTF(5)/D5)**(N(5)-A5)
119          ENDDO
120      ENDIF
121*
122*          PROBABILITY OF FAILURE FOR TYPE #6
123*
124      IF ( M .GE. 6 ) THEN
125          DO A6 = 0,N(6)-1
126              D6 = MTTR(6) + MTF(6)
127              P6(A6,0) = (MTTR(6)/D6)**A6 * (MTTF(6)/D6)**(N(6)-A6)
128          ENDDO
129      ENDIF
130*
131*          PROBABILITY OF FAILURE FOR TYPE #7
132*
133      IF ( M .GE. 7 ) THEN
134          DO A7 = 0,N(7)-1
135              D7 = MTTR(7) + MTF(7)
136              P7(A7,0) = (MTTR(7)/D7)**A7 * (MTTF(7)/D7)**(N(7)-A7)
137          ENDDO
138      ENDIF
139*
140*          PROBABILITY OF FAILURE FOR TYPE #8
141*
142      IF ( M .GE. 8 ) THEN
143          DO A8 = 0,N(8)-1
144              D8 = MTTR(8) + MTF(8)
145              P8(A8,0) = (MTTR(8)/D8)**A8 * (MTTF(8)/D8)**(N(8)-A8)
146          ENDDO
147      ENDIF
148*
149*          PROBABILITY OF FAILURE FOR TYPE #9
150*
151      IF ( M .GE. 9 ) THEN
152          DO A9 = 0,N(9)-1
153              D9 = MTTR(9) + MTF(9)
154              P9(A9,0) = (MTTR(9)/D9)**A9 * (MTTF(9)/D9)**(N(9)-A9)
155          ENDDO
156      ENDIF
157*
158*          PROBABILITY OF FAILURE FOR TYPE #10
159*
160      IF ( M .GE. 10 ) THEN
161          DO A10 = 0,N(10)-1
162              D10 = MTTR(10) + MTF(10)
163              P10(A10,0) = (MTTR(10)/D10)**A10 * (MTTF(10)/D10)**(N(10)-A10)
164          ENDDO
165      ENDIF

```

```

153         P10(A10,0)=(MTTR(10)/D10)**A10*(MTTF(10)/D10)**(N(10)-A10)
154     ENDDO
155     ENDIF
156*
157*             NO FAILURE
158*
159     PO = P1(0,0)*P2(0,0)*P3(0,0)*P4(0,0)*P5(0,0)*P6(0,0)*P7(0,0)*
160     :     P8(0,0)*P9(0,0)*P10(0,0)
161*
162*             ONE OR MORE FAILURES
163*
164     CALL FAIL1 (N,M,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PA1)
165     CALL FAIL2 (N,M,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PA1A2)
166     PRINT*
167     PRINT '(X,A,F9.6)', 'SYSTEM AVAILABILITY=',PO+PA1+PA1A2
168     PRINT*
169     STOP
170     END
171*****
172*
173*     PURPOSE: 1.ACCOUNTING FOR PARTIAL CREDITS FOR PARTIAL
174*             AVAILABILITY
175*             2.WHEN ANY ONE TYPE OF EQUIPMENT IN THE FAILURE
176*             STATE
177*
178*     INPUT:
179*             >M :TYPES OF EQUIPMENT IN FMS
180*             >N :NUMBER OF EACH TYPE IN FMS
181*             >P's :STATE PROBABILITIES
182*
183*     OUTPUT:
184*             >PA1 :PARTIAL CREDITS FROM ENVIRONMENT VIEWPOINT
185*             IF ONLY SOME LOCAL SYSTEMS ARE AVAILABLE
186*
187*****
188*
189     SUBROUTINE FAIL1 (N,M,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PA1)
190     INTEGER N(10),A1,A2,A3,A4,A5,A6,A7,A8,A9,A10
191     DOUBLEPRECISION P1(0:N(1)-1,0:0),P2(0:N(2)-1,0:0),
192     :P3(0:N(3)-1,0:0),P4(0:N(4)-1,0:0),P5(0:N(5)-1,0:0),
193     :P6(0:N(6)-1,0:0),P7(0:N(7)-1,0:0),P8(0:N(8)-1,0:0),
194     :P9(0:N(9)-1,0:0),P10(0:N(10)-1,0:0),PA1,PK(10)
195     REAL Z(10)
196*
197*             INITIALIZATION
198*
199     DATA PK/10*0.0D0/
200     PA1 = 0.0D0
201     DO I=1,M
202         Z(I)=N(I)
203     ENDDO

```

```

204     NMAX=MAX(N(1),N(2),N(3),N(4),N(5),N(6),N(7),N(8),N(9),N(10))
205
206*
207*           ACCOUNTING FOR PARTIAL CREDITS
208*
209     DO A1 = 1,NMAX-1
210         DO I = 1,M
211             PK(I) = 0.0
212         ENDDO
213         DO K = 1,M
214             IF ( K .EQ. 1 .AND. A1 .LT. N(1) ) THEN
215                 WA1=((N(1)-A1)/Z(1))
216                 PK(1)=P1(A1,0)*P2(0,0)*P3(0,0)*P4(0,0)*P5(0,0)*P6(0,0)*
217             :           P7(0,0)*P8(0,0)*P9(0,0)*P10(0,0)*WA1
218                 ELSEIF ( K .EQ. 2 .AND. A1 .LT. N(2) ) THEN
219                     A2 = A1
220                     WA2=((N(2)-A1)/Z(2))
221                     PK(2)=P1(0,0)*P2(A2,0)*P3(0,0)*P4(0,0)*P5(0,0)*P6(0,0)*
222             :           P7(0,0)*P8(0,0)*P9(0,0)*P10(0,0)*WA2
223                     ELSEIF ( K .EQ. 3 .AND. A1 .LT. N(3) ) THEN
224                         A3 = A1
225                         WA3=((N(3)-A1)/Z(3))
226                         PK(3)=P1(0,0)*P2(0,0)*P3(A3,0)*P4(0,0)*P5(0,0)*P6(0,0)*
227             :           P7(0,0)*P8(0,0)*P9(0,0)*P10(0,0)*WA3
228                     ELSEIF ( K .EQ. 4 .AND. A1 .LT. N(4) ) THEN
229                         A4 = A1
230                         WA4=((N(4)-A1)/Z(4))
231                         PK(4)=P1(0,0)*P2(0,0)*P3(0,0)*P4(A4,0)*P5(0,0)*P6(0,0)*
232             :           P7(0,0)*P8(0,0)*P9(0,0)*P10(0,0)*WA4
233                     ELSEIF ( K .EQ. 5 .AND. A1 .LT. N(5) ) THEN
234                         A5 = A1
235                         WA5=((N(5)-A1)/Z(5))
236                         PK(5)=P1(0,0)*P2(0,0)*P3(0,0)*P4(0,0)*P5(A5,0)*P6(0,0)*
237             :           P7(0,0)*P8(0,0)*P9(0,0)*P10(0,0)*WA5
238                     ELSEIF ( K .EQ. 6 .AND. A1 .LT. N(6) ) THEN
239                         A6 = A1
240                         WA6=((N(6)-A1)/Z(6))
241                         PK(6)=P1(0,0)*P2(0,0)*P3(0,0)*P4(0,0)*P5(0,0)*P6(A6,0)*
242             :           P7(0,0)*P8(0,0)*P9(0,0)*P10(0,0)*WA6
243                     ELSEIF ( K .EQ. 7 .AND. A1 .LT. N(7) ) THEN
244                         A7 = A1
245                         WA7=((N(7)-A1)/Z(7))
246                         PK(7)=P1(0,0)*P2(0,0)*P3(0,0)*P4(0,0)*P5(0,0)*P6(0,0)*
247             :           P7(A7,0)*P8(0,0)*P9(0,0)*P10(0,0)*WA7
248                     ELSEIF ( K .EQ. 8 .AND. A1 .LT. N(8) ) THEN
249                         A8 = A1
250                         WA8=((N(8)-A1)/Z(8))
251                         PK(8)=P1(0,0)*P2(0,0)*P3(0,0)*P4(0,0)*P5(0,0)*P6(0,0)*
252             :           P7(0,0)*P8(A8,0)*P9(0,0)*P10(0,0)*WA8
253                     ELSEIF ( K .EQ. 9 .AND. A1 .LT. N(9) ) THEN
254                         A9 = A1

```



```

255      WA9=((N(9)-A1)/Z(9))
256      PK(9)=P1(0,0)*P2(0,0)*P3(0,0)*P4(0,0)*P5(0,0)*P6(0,0)*
257 :      P7(0,0)*P8(0,0)*P9(A9,0)*P10(0,0)*WA9
258      ELSEIF ( K .EQ. 10 .AND. A1 .LT. N(10) ) THEN
259      A10 = A1
260      WA10=((N(10)-A1)/Z(10))
261      PK(10)=P1(0,0)*P2(0,0)*P3(0,0)*P4(0,0)*P5(0,0)*P6(0,0)*
262 :      P7(0,0)*P8(0,0)*P9(0,0)*P10(10,0)*WA10
263      ENDIF
264      ENDDO
265      PA1=PA1+(PK(1)+PK(2)+
266 :      PK(3)+PK(4)+PK(5)+PK(6)+PK(7)+PK(8)+PK(9)+PK(10))
267      ENDDO
268      END
268*****
269* :
269* PURPOSE: 1.ACCOUNTING FOR PARTIAL CREDITS FOR PARTIAL :
270* AVAILABILITY :
270* 2.WHEN ANY TWO TYPES OF EQUIPMENT IN THE FAILURE :
271* STATE :
271* :
272* INPUT: :
272* >M :TYPES OF EQUIPMENT IN FMS :
273* >N :NUMBER OF EACH TYPE IN FMS :
273* >P's :STATE PROBABILITIES :
274* :
274* OUTPUT: :
275* >PALA2:PARTIAL CREDITS FROM ENVIRONMENT VIEWPOINT :
275* IF ONLY SOME LOCAL SYSTEMS ARE AVAILABLE :
276* :
276*****
277*
278      SUBROUTINE FAIL2 (N,M,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PALA2)
279      INTEGER N(10),M,K1,K2,A(10),AA1,AA2
280      DOUBLEPRECISION P1(0:N(1)-1,0:0),P2(0:N(2)-1,0:0),
281 :P3(0:N(3)-1,0:0),P4(0:N(4)-1,0:0),P5(0:N(5)-1,0:0),
282 :P6(0:N(6)-1,0:0),P7(0:N(7)-1,0:0),P8(0:N(8)-1,0:0),ALEA2,
283 :P9(0:N(9)-1,0:0),P10(0:N(10)-1,0:0),ALNEA2,PALA2,PK1K2(10)
284      REAL Z(10),WA1(10)
285*
286*          INITIALIZATION
287*
288      DATA PK1K2/10*0.0D0/
289      PALA2 = 0.0D0
290      ALEA2 = 0.0D0
291      ALNEA2 = 0.0D0
292      DO I=1,M
293          Z(I)=N(I)
294      ENDDO
295      NMAX=MAX(N(1),N(2),N(3),N(4),N(5),N(6),N(7),N(8),N(9),N(10))
296*

```

```

297*           ACCOUNTING FOR PARTIAL CREDITS
298*
299 DO AA1 = 1,NMAX-1
300 DO I = 1,M
301     WA1(I) = 0.0
302 ENDDO
303 DO AA2 = AA1,NMAX-1
304 DO K1 = 1,M
305 DO I =1,M
306     PK1K2(I) = 0.0D0
307 ENDDO
308 DO K2 = 1,M
309 DO I=1,10
310     A(I)=0.0
311 ENDDO
312 IF ( K1 .EQ. 1 .AND. AA1 .LT. N(1) ) THEN
313     A(1)=AA1
314     WA1(1)=((N(1)-AA1)/Z(1))
315 ELSEIF ( K1 .EQ. 2 .AND. AA1 .LT. N(2) ) THEN
316     A(2)=AA1
317     WA1(2)=((N(2)-AA1)/Z(2))
318 ELSEIF ( K1 .EQ. 3 .AND. AA1 .LT. N(3) ) THEN
319     A(3)=AA1
320     WA1(3)=((N(3)-AA1)/Z(3))
321 ELSEIF ( K1 .EQ. 4 .AND. AA1 .LT. N(4) ) THEN
322     A(4)=AA1
323     WA1(4)=((N(4)-AA1)/Z(4))
324 ELSEIF ( K1 .EQ. 5 .AND. AA1 .LT. N(5) ) THEN
325     A(5)=AA1
326     WA1(5)=((N(5)-AA1)/Z(5))
327 ELSEIF ( K1 .EQ. 6 .AND. AA1 .LT. N(6) ) THEN
328     A(6)=AA1
329     WA1(6)=((N(6)-AA1)/Z(6))
330 ELSEIF ( K1 .EQ. 7 .AND. AA1 .LT. N(7) ) THEN
331     A(7)=AA1
332     WA1(7)=((N(7)-AA1)/Z(7))
333 ELSEIF ( K1 .EQ. 8 .AND. AA1 .LT. N(8) ) THEN
334     A(8)=AA1
335     WA1(8)=((N(8)-AA1)/Z(8))
336 ELSEIF ( K1 .EQ. 9 .AND. AA1 .LT. N(9) ) THEN
337     A(9)=AA1
338     WA1(9)=((N(9)-AA1)/Z(9))
339 ELSEIF ( K1 .EQ. 10 .AND. AA1 .LT. N(10) ) THEN
340     A(10)=AA1
341     WA1(10)=((N(10)-AA1)/Z(10))
342 ENDIF
343 IF ( K2 .NE. K1 ) THEN
344 IF ( K2 .EQ. 1 .AND. AA2 .LT. N(1) ) THEN
345     A(1)=AA2
346     WA21=((N(1)-AA2)/Z(1))
347     PK1K2(1)=P1(A(1),0)*P2(A(2),0)*P3(A(3),0)*P4(A(4),0)*

```

```

348      :           P5(A(5),0)*P6(A(6),0)*P7(A(7),0)*P8(A(8),0)*
349      :           P9(A(9),0)*P10(A(10),0)*WA1(K1)*WA21
350      ELSEIF ( K2 .EQ. 2 .AND. AA2 .LT. N(2) ) THEN
351      A(2)=AA2
352      WA22=((N(2)-AA2)/Z(2))
353      PK1K2(2)=P1(A(1),0)*P2(A(2),0)*P3(A(3),0)*P4(A(4),0)*
354      :           P5(A(5),0)*P6(A(6),0)*P7(A(7),0)*P8(A(8),0)*
355      :           P9(A(9),0)*P10(A(10),0)*WA1(K1)*WA22
356      ELSEIF ( K2 .EQ. 3 .AND. AA2 .LT. N(3) ) THEN
357      A(3)=AA2
358      WA23=((N(3)-AA2)/Z(3))
359      PK1K2(3)=P1(A(1),0)*P2(A(2),0)*P3(A(3),0)*P4(A(4),0)*
360      :           P5(A(5),0)*P6(A(6),0)*P7(A(7),0)*P8(A(8),0)*
361      :           P9(A(9),0)*P10(A(10),0)*WA1(K1)*WA23
362      ELSEIF ( K2 .EQ. 4 .AND. AA2 .LT. N(4) ) THEN
363      A(4)=AA2
364      WA24=((N(4)-AA2)/Z(4))
365      PK1K2(4)=P1(A(1),0)*P2(A(2),0)*P3(A(3),0)*P4(A(4),0)*
366      :           P5(A(5),0)*P6(A(6),0)*P7(A(7),0)*P8(A(8),0)*
367      :           P9(A(9),0)*P10(A(10),0)*WA1(K1)*WA24
368      ELSEIF ( K2 .EQ. 5 .AND. AA2 .LT. N(5) ) THEN
369      A(5)=AA2
370      WA25=((N(5)-AA2)/Z(5))
371      PK1K2(5)=P1(A(1),0)*P2(A(2),0)*P3(A(3),0)*P4(A(4),0)*
372      :           P5(A(5),0)*P6(A(6),0)*P7(A(7),0)*P8(A(8),0)*
373      :           P9(A(9),0)*P10(A(10),0)*WA1(K1)*WA25
374      ELSEIF ( K2 .EQ. 6 .AND. AA2 .LT. N(6) ) THEN
375      A(6)=AA2
376      WA26=((N(6)-AA2)/Z(6))
377      PK1K2(6)=P1(A(1),0)*P2(A(2),0)*P3(A(3),0)*P4(A(4),0)*
378      :           P5(A(5),0)*P6(A(6),0)*P7(A(7),0)*P8(A(8),0)*
379      :           P9(A(9),0)*P10(A(10),0)*WA1(K1)*WA26
380      ELSEIF ( K2 .EQ. 7 .AND. AA2 .LT. N(7) ) THEN
381      A(7)=AA2
382      WA27=((N(7)-AA2)/Z(7))
383      PK1K2(7)=P1(A(1),0)*P2(A(2),0)*P3(A(3),0)*P4(A(4),0)*
384      :           P5(A(5),0)*P6(A(6),0)*P7(A(7),0)*P8(A(8),0)*
385      :           P9(A(9),0)*P10(A(10),0)*WA1(K1)*WA27
386      ELSEIF ( K2 .EQ. 8 .AND. AA2 .LT. N(8) ) THEN
387      A(8)=AA2
388      WA28=((N(8)-AA2)/Z(8))
389      PK1K2(8)=P1(A(1),0)*P2(A(2),0)*P3(A(3),0)*P4(A(4),0)*
390      :           P5(A(5),0)*P6(A(6),0)*P7(A(7),0)*P8(A(8),0)*
391      :           P9(A(9),0)*P10(A(10),0)*WA1(K1)*WA28
392      ELSEIF ( K2 .EQ. 9 .AND. AA2 .LT. N(9) ) THEN
393      A(9)=AA2
394      WA29=((N(9)-AA2)/Z(9))
395      PK1K2(9)=P1(A(1),0)*P2(A(2),0)*P3(A(3),0)*P4(A(4),0)*
396      :           P5(A(5),0)*P6(A(6),0)*P7(A(7),0)*P8(A(8),0)*
397      :           P9(A(9),0)*P10(A(10),0)*WA1(K1)*WA29
398      ELSEIF ( K2 .EQ. 10 .AND. AA2 .LT. N(10) ) THEN

```

```

399         A(10)=AA2
400         WA210=((N(10)-AA2)/Z(10))
401         PK1K2(10)=P1(A(1),0)*P2(A(2),0)*P3(A(3),0)*P4(A(4),0)
402         :           *P5(A(5),0)*P6(A(6),0)*P7(A(7),0)*P8(A(8),0)*
403         :           P9(A(9),0)*P10(A(10),0)*WA1(K1)*WA210
404         ENDIF
405         ENDIF
406         ENDDO
407         IF ( AA1 .EQ. AA2 ) THEN
408             A1EA2=0.5*(PK1K2(1)+PK1K2(2)+PK1K2(3)+PK1K2(4)+
409             :       PK1K2(5)+PK1K2(6)+PK1K2(7)+PK1K2(8)+PK1K2(9)+PK1K2(10))
410             A1NEA2=0.0DO
411         ELSE
412             A1NEA2=(PK1K2(1)+PK1K2(2)+PK1K2(3)+PK1K2(4)+
413             :       PK1K2(5)+PK1K2(6)+PK1K2(7)+PK1K2(8)+PK1K2(9)+PK1K2(10))
414             A1EA2=0.0DO
415         ENDIF
416         PALA2 = PA1A2 + A1EA2 + A1NEA2
417         ENDDO
418         ENDDO
419         ENDDO
420         END

```

XII. APPENDIX D. PROGRAM FOR MEASURING SYSTEM AVAILABILITY
HAVING CENTRAL STORAGE, OPTIMIZE HEURISTICALLY, FOR SPARES

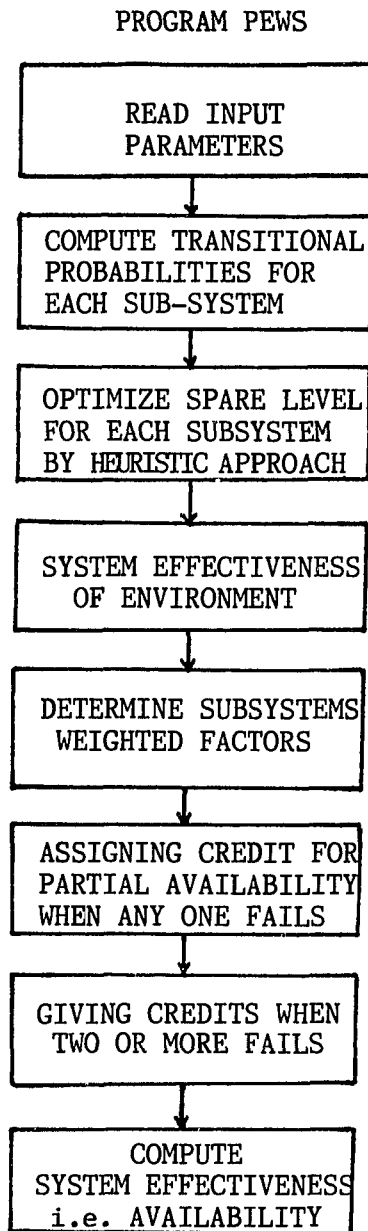


FIGURE 38. Flow chart of computer program PEWS

```

1      PROGRAM PEWS
2*****
3*
4*      PURPOSE: 1.HEURISTIC PROGRAMMING FOR OPTIMIZING THE
5*                SPARES-STORAGE LEVEL OF GENERIC FLEXIBLE
6*                MANUFACTURING SYSTEMS
7*                2.EVALUATES THE PERFORMANCE USING WEIGHTED
8*                FACTORS FOR AN FMS HAVING A CENTRALIZED
9*                STORAGE FOR SPARES
10*               3.TAKES INTO ACCOUNT PARTIAL CREDITS ONLY
10*                IF SOME SYSTEMS FUNCTION
11*
12*      INPUT:  INTEGER,
13*              >M:   WHERE M IS THE TYPES OF EQUIPMENT IN FMS
14*              >N:   WHERE N IS THE NUMBER OF EACH TYPE OF
15*                    EQUIPMENT IN FMS ENVIRONMENT
16*              REAL,
17*              >P:   WHERE IS THE PROBABILITY THAT A SELECTED
18*                    SPARE WORKS
19*              >DFR: WHERE DFR IS A DESIRABILITY FACTOR RATIO
20*              >MTR  WHERE MTR IS THE MEAN TIME REPLACEMENT
21*              >MTTF: WHERE MTTF IS THE MEAN TIME TO FAILURE
22*              >MTTR: WHERE MTTR IS THE MEAN TIME TO REPAIR
23*
24*      LIMITATION:
25*              >M:   M CANNOT BE GREATER THEN 10
26*              >N:   N CANNOT BE GREATER THEN 10
27*
28*      OUTPUT: TABULATED FORM
29*              >TYPE# SPARE COMPONENTS REQUIRED FOR EACH TYPE
30*              >F(X)# SUB-SYSTEM SELECTION FACTOR
31*              >SYS-A SYSTEM AVAILABILITY AT GIVEN NUMBER OF
32*                    OF SPARE FOR EACH TYPE OF EQUIPMENT
33*              >OPTIMUM NUMBER OF SPARES
34*
35*****
36      INTEGER N,M,X,IX(10),IN(10),NMX(10),IXP(10)
37      REAL MTTR(10),MTTF(10),MTR(10),BETAI(0:14),LAM(0:14),MEU(15)
38      DOUBLEPRECISION P1(0:15,0:1),P2(0:15,0:1),P3(0:15,0:1),
39      :P4(0:15,0:1),P5(0:15,0:1),P6(0:15,0:1),P7(0:15,0:1),P8(0:15,0:1),
40      :P9(0:15,0:1),P10(0:15,0:1),TP(0:15,0:1),AVL(10),TRDA(10),ASTOR(2),
41      :CHECK(10),AVLMIN,DFR,PROB
42:
43:              INTERACTIVE DATA INPUT
44:
45      DATA IX/10*1./
46      DATA IXP/10*1/
47      WRITE(6,'(X,A)')'PLEASE SUPPLY THE VALUE OF "M"; WHERE '
48      WRITE(6,'(X,A)')'M IS THE TYPES OF EQUIPMENT IN FMS ENVIRONMENT'
49      WRITE(6,*)
50      READ *, M

```

```

51  WRITE(6,*)
52  WRITE(6,'(X,A)')'PLEASE SUPPLY THE VALUE OF "N"; WHERE'
53  WRITE(6,'(X,A)')'N IS THE # OF EACH TYPE OF EQUIPMENT'
54  DO I=1,M
55      WRITE(6,*)
56      WRITE(6,'(X,A,I2,A)')'SUPPLY NOW THE VALUE OF N FOR TYPE #',I,
57  : ' ONLY'
58      WRITE(6,*)
59      READ*,IN(I)
60  ENDDO
61  DO I=1,M
62      NMX(I)=IN(I)+IX(I)
63  ENDDO
64  WRITE(6,'(X,A)')'PLEASE SUPPLY THE VALUE OF "P"; WHERE'
65  WRITE(6,'(X,A)')'P IS THE PROBABILITY THAT A SELECTED SPARE WORKS'
66  WRITE(6,*)
67  READ *, PROB
68  DO I = 1,M
69      WRITE(6,'(X,A,I2,A)')'SUPPLY VALUES OF "MTTF", "MTTR" & "MTR"
70  : FOR THE EQUIPMENT TYPE #',I,' ONLY'
71      WRITE(6,*)
72      WRITE(6,'(X,A,I2)')'WHERE MTTF IS THE MEAN TIME TO FAILURE FOR
73  : TYPE #',I
74      WRITE(6,'(X,A,I2)')'WHERE MTTR IS THE MEAN TIME TO REPAIR FOR
75  : TYPE #',I
76      WRITE(6,'(X,A,I2)')'WHERE MTR IS THE MEAN TIME TO REPLACEMENT FOR
77  : TYPE #',I
78      WRITE(6,*)
79      READ *, MTTF(I),MTTR(I),MTR(I)
80  ENDDO
81  DO I=1,10
82      AVL(I)=1.0D5
83      CHECK(I)=0.0D0
84  ENDDO
85  WRITE(6,'(X,A)')'PLEASE SUPPLY THE VALUE OF "DFR"; WHERE'
86  WRITE(6,'(X,A)')'DFR IS THE DESIRABILITY FACTOR RATIO'
87  WRITE(6,*)
88  READ*, DFR
89  INDEX = 0.0
90:
91:      DETERMINE SUB-SYSTEM SELECTION FUNCTION VALUE
92:
93  DO WHILE ( INDEX .LT. M )
94      INDEX = INDEX+1
95      IF ( INDEX .NE. 1 )THEN
96 111      CONTINUE
97          DO I = 1,M
98              IX(I)=IXP(I)
99          ENDDO
100         DO I = 1,10
101             NMX(I) = IX(I) + IN(I)

```



```

102         ENDDO
103     ENDIF
104     DO JJ = 1,M
105         DO I = 0,NMX(JJ)-1
106             LAM(I) = 1/MTTF(JJ)
107             K = I + 1
108             MEU(K) = 1/(MTTR(JJ) * K)
109             BETAI(I) = 1/MTR(JJ)
110         ENDDO
111         IF ( JJ .EQ. 1 ) THEN
112             X=IX(JJ)
113             N=IN(JJ)
114             NMAX=N+X
115:
116:         TRANSITION PROBABILITY FOR EQUIPMENT TYPE #1
117:
118         CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
119         DO I = 0,NMAX
120             IF ( I .LE. 7 ) THEN
121                 P1(I,0) = TP(2*I,0)
122                 P1(I,1) = TP(2*I+1,0)
123             ELSE
124                 P1(I,0) = TP(2*I-16,1)
125                 P1(I,1) = TP(2*I-15,1)
126             ENDIF
127         ENDDO
128:
129:         DETERMINATION OF SUB-SYSTEM #1 SELECTION FACTOR
130:
131         CALL TAVAIL(JJ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TAVAL)
132         CALL SFAIL1(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL1)
133         CALL SFAIL2(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL2)
134         TRDA(1) = TAVAL
135         PERF(1) = TAVAL+FAIL1+FAIL2
136         AVL(1) = TRDA(1)*PERF(1)
137         ELSEIF ( JJ .EQ. 2 ) THEN
138             X=IX(JJ)
139             N=IN(JJ)
140             NMAX=N+X
141:
142:         TRANSITION PROBABILITY FOR EQUIPMENT TYPE #2
143:
144         CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
145         DO I = 0,NMAX
146             IF ( I .LE. 7 ) THEN
147                 P2(I,0) = TP(2*I,0)
148                 P2(I,1) = TP(2*I+1,0)
149             ELSE
150                 P2(I,0) = TP(2*I-16,1)
151                 P2(I,1) = TP(2*I-15,1)
152             ENDIF

```

```

153          ENDDO
154:
155:          DETERMINATION OF SUB-SYSTEM #2 SELECTION FACTOR
156:
157          CALL TAVAIL(JJ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TAVAL)
158          CALL SFMAIL(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL1)
159          CALL SFMAIL2(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL2)
160          TRDA(2) = TAVAL
161          PERF(2) = TAVAL+FAIL1+FAIL2
162          AVL(2) = TRDA(2)*PERF(2)
163          ELSEIF ( JJ .EQ. 3 ) THEN
164              X=IX(JJ)
165              N=IN(JJ)
166              NMAX=N+X
167:
168:          TRANSITION PROBABILITY FOR EQUIPMENT TYPE #3
169:
170          CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
171          DO I = 0,NMAX
172              IF ( I .LE. 7 ) THEN
173                  P3(I,0) = TP(2*I,0)
174                  P3(I,1) = TP(2*I+1,0)
175              ELSE
176                  P3(I,0) = TP(2*I-16,1)
177                  P3(I,1) = TP(2*I-15,1)
178              ENDIF
179          ENDDO
180:
181:          DETERMINATION OF SUB-SYSTEM #3 SELECTION FACTOR
182:
183          CALL TAVAIL(JJ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TAVAL)
184          CALL SFMAIL(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL1)
185          CALL SFMAIL2(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL2)
186          TRDA(3) = TAVAL
187          PERF(3) = TAVAL+FAIL1+FAIL2
188          AVL(3) = TRDA(3)*PERF(3)
189          ELSEIF ( JJ .EQ. 4 ) THEN
190              X=IX(JJ)
191              N=IN(JJ)
192              NMAX=N+X
193:
194:          TRANSITION PROBABILITY FOR EQUIPMENT TYPE #4
195:
196          CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
197          DO I = 0,NMAX
198              IF ( I .LE. 7 ) THEN
199                  P4(I,0) = TP(2*I,0)
200                  P4(I,1) = TP(2*I+1,0)
201              ELSE
202                  P4(I,0) = TP(2*I-16,1)
203                  P4(I,1) = TP(2*I-15,1)

```

```

204             ENDIF
205             ENDDO
206:
207:             DETERMINATION OF SUB-SYSTEM #4 SELECTION FACTOR
208:
209             CALL TAVAIL(JJ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TAVAL)
210             CALL SFAIL1(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL1)
211             CALL SFAIL2(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL2)
212             TRDA(4) = TAVAL
213             PERF(4) = TAVAL+FAIL1+FAIL2
214             AVL(4) = TRDA(4)*PERF(4)
215             ELSEIF ( JJ .EQ. 5 ) THEN
216                 X=IX(JJ)
217                 N=IN(JJ)
218                 NMAX=N+X
219:
220:             TRANSITION PROBABILITY FOR EQUIPMENT TYPE #5
221:
222             CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
223             DO I = 0,NMAX
224                 IF ( I .LE. 7 ) THEN
225                     P5(I,0) = TP(2*I,0)
226                     P5(I,1) = TP(2*I+1,0)
227                 ELSE
228                     P5(I,0) = TP(2*I-16,1)
229                     P5(I,1) = TP(2*I-15,1)
230             ENDIF
231             ENDDO
232:
233:             DETERMINATION OF SUB-SYSTEM #5 SELECTION FACTOR
234:
235             CALL TAVAIL(JJ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TAVAL)
236             CALL SFAIL1(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL1)
237             CALL SFAIL2(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL2)
238             TRDA(5) = TAVAL
239             PERF(5) = TAVAL+FAIL1+FAIL2
240             AVL(5) = TRDA(5)*PERF(5)
241             ELSEIF ( JJ .EQ. 6 ) THEN
242                 X=IX(JJ)
243                 N=IN(JJ)
244                 NMAX=N+X
245:             TRANSITION PROBABILITY FOR EQUIPMENT TYPE #6
246             CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
247             DO I = 0,NMAX
248                 IF ( I .LE. 7 ) THEN
249                     P6(I,0) = TP(2*I,0)
250                     P6(I,1) = TP(2*I+1,0)
251                 ELSE
252                     P6(I,0) = TP(2*I-16,1)
253                     P6(I,1) = TP(2*I-15,1)
254             ENDIF

```

```

255         ENDDO
256:        DETERMINATION OF SUB-SYSTEM #6 SELECTION FACTOR
257        CALL TAVAIL(JJ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TAVAL)
258        CALL SFAIL1(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL1)
259        CALL SFAIL2(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL2)
260        TRDA(6) = TAVAL
261        PERF(6) = TAVAL+FAIL1+FAIL2
262        AVL(6) = TRDA(6)*PERF(6)
263        ELSEIF ( JJ .EQ. 7 ) THEN
264            X=IX(JJ)
265            N=IN(JJ)
266            NMAX=N+X
267:        TRANSITION PROBABILITY FOR EQUIPMENT TYPE #7
268        CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
269        DO I = 0,NMAX
270            IF ( I .LE. 7 ) THEN
271                P7(I,0) = TP(2*I,0)
272                P7(I,1) = TP(2*I+1,0)
273            ELSE
274                P7(I,0) = TP(2*I-16,1)
275                P7(I,1) = TP(2*I-15,1)
276            ENDIF
277        ENDDO
278:        DETERMINATION OF SUB-SYSTEM #7 SELECTION FACTOR
279        CALL TAVAIL(JJ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TAVAL)
280        CALL SFAIL1(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL1)
281        CALL SFAIL2(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL2)
282        TRDA(7) = TAVAL
283        PERF(7) = TAVAL+FAIL1+FAIL2
284        AVL(7) = TRDA(7)*PERF(7)
285        ELSEIF ( JJ .EQ. 8 ) THEN
286            X=IX(JJ)
287            N=IN(JJ)
288            NMAX=N+X
289:        TRANSITION PROBABILITY FOR EQUIPMENT TYPE #8
290        CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
291        DO I = 0,NMAX
292            IF ( I .LE. 7 ) THEN
293                P8(I,0) = TP(2*I,0)
294                P8(I,1) = TP(2*I+1,0)
295            ELSE
296                P8(I,0) = TP(2*I-16,1)
297                P8(I,1) = TP(2*I-15,1)
298            ENDIF
299        ENDDO
300:        DETERMINATION OF SUB-SYSTEM #8 SELECTION FACTOR
301        CALL TAVAIL(JJ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TAVAL)
302        CALL SFAIL1(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL1)
303        CALL SFAIL2(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL2)
304        TRDA(8) = TAVAL
305        PERF(8) = TAVAL+FAIL1+FAIL2

```

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306     AVL(8) = TRDA(8)*PERF(8)
307     ELSEIF ( JJ .EQ. 9 ) THEN
308         X=IX(JJ)
309         N=IN(JJ)
310         NMAX=N+X
311:     TRANSITION PROBABILITY FOR EQUIPMENT TYPE #9
312     CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
313     DO I = 0,NMAX
314         IF ( I .LE. 7 ) THEN
315             P9(I,0) = TP(2*I,0)
316             P9(I,1) = TP(2*I+1,0)
317         ELSE
318             P9(I,0) = TP(2*I-16,1)
319             P9(I,1) = TP(2*I-15,1)
320         ENDIF
321     ENDDO
322:     DETERMINATION OF SUB-SYSTEM #9 SELECTION FACTOR
323     CALL TAVAIL(JJ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TAVAL)
324     CALL SFAIL1(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL1)
325     CALL SFAIL2(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL2)
326     TRDA(9) = TAVAL
327     PERF(9) = TAVAL+FAIL1+FAIL2
328     AVL(9) = TRDA(9)*PERF(9)
329     ELSEIF ( JJ .EQ. 10 ) THEN
330         X=IX(JJ)
331         N=IN(JJ)
332         NMAX=N+X
333:     TRANSITION PROBABILITY FOR EQUIPMENT TYPE #10
334     CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
335     DO I = 0,NMAX
336         IF ( I .LE. 7 ) THEN
337             P10(I,0) = TP(2*I,0)
338             P10(I,1) = TP(2*I+1,0)
339         ELSE
340             P10(I,0) = TP(2*I-16,1)
341             P10(I,1) = TP(2*I-15,1)
342         ENDIF
343     ENDDO
344:     DETERMINATION OF SUB-SYSTEM #10 SELECTION FACTOR
345     CALL TAVAIL(JJ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TAVAL)
346     CALL SFAIL1(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL1)
347     CALL SFAIL2(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL2)
348     TRDA(10) = TAVAL
349     PERF(10) = TAVAL+FAIL1+FAIL2
350     AVL(10) = TRDA(10)*PERF(10)
351     ENDIF
352     ENDDO
353     MAXX = MAX(IX(1),IX(2),IX(3),IX(4),
354:             IX(5),IX(6),IX(7),IX(8),IX(9),IX(10))
355:
356:     DELIVERING SOLUTION

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357:
358   IF ( MAXX .EQ. 1 .AND. INDEX .EQ. 1 ) THEN
359     JJZ=0
360     CALL TAVAIL(JJZ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TAVAL)
361     CALL SFAIL1(JJZ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL1)
362     CALL SFAIL2(JJZ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL2)
363     ASTOR(1)=TAVAL+FAIL1+FAIL2
364     PRINT '(XM>(I4,4X),XM>(F7.6,2X),2X,F9.6)',
365     : ((IX(I),I=1,M),(AVL(I),I=1,M),ASTOR(1))
366     ENDIF
367     IF ( MAXX .NE. 1 .AND. IFLAG .EQ. 1 ) THEN
368       PRINT '(XM>(I4,4X),XM>(F7.6,2X),2X,F9.6)',
369       : ((IX(I),I=1,M),(AVL(I),I=1,M),ASTOR(1))
370     ENDIF
371:
372:     CHECK MAXIMUM/MINIMUM VALUE OF SELECTION FACTOR F(X)'S
373:
374     AVLMIN=MIN((AVL(1)+CHECK(1)),(AVL(2)+CHECK(2)),(AVL(3)+CHECK(3)),
375     :          (AVL(4)+CHECK(4)),(AVL(5)+CHECK(5)),(AVL(6)+CHECK(6)),
376     :          (AVL(7)+CHECK(7)),(AVL(8)+CHECK(8)),(AVL(9)+CHECK(9)),
377     :          (AVL(10)+CHECK(10)))
378:
379:     ADDING ONE SPARE TO SUB-SYSTEM HAVING REQUIRED BEST F(X)
380:
381     IF ( ((AVL(1)+CHECK(1)) .EQ. AVLMIN ) THEN
382       IX(1)=IX(1)+1
383     ELSEIF ( ((AVL(2)+CHECK(2)) .EQ. AVLMIN ) THEN
384       IX(2)=IX(2)+1
385     ELSEIF ( ((AVL(3)+CHECK(3)) .EQ. AVLMIN ) THEN
386       IX(3)=IX(3)+1
387     ELSEIF ( ((AVL(4)+CHECK(4)) .EQ. AVLMIN ) THEN
388       IX(4)=IX(4)+1
389     ELSEIF ( ((AVL(5)+CHECK(5)) .EQ. AVLMIN ) THEN
390       IX(5)=IX(5)+1
391     ELSEIF ( ((AVL(6)+CHECK(6)) .EQ. AVLMIN ) THEN
392       IX(6)=IX(6)+1
393     ELSEIF ( ((AVL(7)+CHECK(7)) .EQ. AVLMIN ) THEN
394       IX(7)=IX(7)+1
395     ELSEIF ( ((AVL(8)+CHECK(8)) .EQ. AVLMIN ) THEN
396       IX(8)=IX(8)+1
397     ELSEIF ( ((AVL(9)+CHECK(9)) .EQ. AVLMIN ) THEN
398       IX(9)=IX(9)+1
399     ELSEIF ( ((AVL(10)+CHECK(10)) .EQ. AVLMIN ) THEN
400       IX(10)=IX(10)+1
401     ENDIF
402     DO I = 1,M
403       IXP(I) = IX(I)
404     ENDDO
405     DO I = 1,10
406       NMX(I) = IX(I) + IN(I)
407     ENDDO

```

```

408      JJZ=0
409      CALL TAVAIL(JJZ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TAVAL)
410      CALL SFAIL1(JJZ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL1)
411      CALL SFAIL2(JJZ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL2)
412      ASTOR(2)=TAVAL+FAIL1+FAIL2
413:
414:          COMPARING FEASIBILITY OF ONE SPARE ADDITION
415:
416      IF ( (ASTOR(2)-ASTOR(1)) .GE. DFR ) THEN
417          IFLAG = 1.0
418          ASTOR(1)=ASTOR(2)
419          GO TO 111
420      ELSE
421          IFLAG = 0.0
422          IF ( ((AVL(1)+CHECK(1)) .EQ. AVLMIN ) THEN
423              IX(1)=IX(1)-1
424          ELSEIF ( ((AVL(2)+CHECK(2)) .EQ. AVLMIN ) THEN
425              IX(2)=IX(2)-1
426          ELSEIF ( ((AVL(3)+CHECK(3)) .EQ. AVLMIN ) THEN
427              IX(3)=IX(3)-1
428          ELSEIF ( ((AVL(4)+CHECK(4)) .EQ. AVLMIN ) THEN
429              IX(4)=IX(4)-1
430          ELSEIF ( ((AVL(5)+CHECK(5)) .EQ. AVLMIN ) THEN
431              IX(5)=IX(5)-1
432          ELSEIF ( ((AVL(6)+CHECK(6)) .EQ. AVLMIN ) THEN
433              IX(6)=IX(6)-1
434          ELSEIF ( ((AVL(7)+CHECK(7)) .EQ. AVLMIN ) THEN
435              IX(7)=IX(7)-1
436          ELSEIF ( ((AVL(8)+CHECK(8)) .EQ. AVLMIN ) THEN
437              IX(8)=IX(8)-1
438          ELSEIF ( ((AVL(9)+CHECK(9)) .EQ. AVLMIN ) THEN
439              IX(9)=IX(9)-1
440          ELSEIF ( ((AVL(10)+CHECK(10)) .EQ. AVLMIN ) THEN
441              IX(10)=IX(10)-1
442      ENDIF
443      DO I = 1,M
444          IXP(I) = IX(I)
445      ENDDO
446      DO I = 1,10
447          NMX(I) = IX(I) + IN(I)
448      ENDDO
449:
450:          ASSIGNING HIGH VALUE TO DISCARD SUB-SYSTEM FROM
451:          FURTHER CONSIDERATION
452:
453      DO I = 1,M
454          IF ( ((AVL(I)+CHECK(I)) .EQ. AVLMIN ) THEN
455              CHECK(I)=1.0D5
456              GO TO 222
457          ENDIF
458      ENDDO

```

```

459     ENDIF
460 222 CONTINUE
461     ENDDO
462     STOP
463     END
464*****
465:
466:   PURPOSE:SUBROUTINE FOR CALCULATING TRANSITIONAL PROBABILITY :
467:         USING THE MARKOVIAN STEADY-STATE EQUATIONS           :
468:
469:   INPUT:
470:         >M       :TYPES OF EQUIPMENT                       :
471:         >N       :NUMBER OF EACH TYPE                     :
472:         >X       :NUMBER OF EACH TYPE OF SPARE           :
473:         >P       :PROBABILITY A SPARE WORKS              :
474:         >BI      :RECIPROCAL OF MTR                      :
475:         >MEU     :RECIPROCAL OF MTTR                     :
476:         >NMAX    :SUM OF N AND X FOR EACH TYPE           :
477:         >LAMBDA  :RECIPROCAL OF MTTF                     :
478:   OUTPUT:
479:         >TP      TRANSITIONAL PROBABILITY VECTOR         :
480:
481*****
482   SUBROUTINE TPROB(N,M,X,NMAX,PROB,LAM,MEU,BI,TP)
483   INTEGER X
484   REAL LAM(0:NMAX-1),MEU(NMAX),BI(0:NMAX-1)
485   DOUBLEPRECISION TP(0:NMAX,0:1),A(31,31),RHS(31),
486   :B(0:4,1:5),BX,BIIP,PROB
487:
488:           INITIALIZE MATRICES
489:
490   DO I = 1,NMAX*2+1
491     DO J = 1,NMAX*2+1
492       A(I,J) = 0.0
493     ENDDO
494   ENDDO
495   DO I = 0,NMAX
496     DO J = 0,1
497       TP(I,J)=0.0
498     ENDDO
499   ENDDO
500:
501:   CALCULATING TRANSITION PROBABILITY FROM (i,1) to (i',1)
502:   FOR ONE EQUIPMENT TYPE; WHERE i IS NOT EQUAL TO i'
503:
504   DO K = 0,X-1
505     IF ( K .EQ. 0 ) THEN
506       IF ( X .EQ. 1 ) THEN
507         B(K,1)=(1-PROB)*PROB
508       ELSEIF ( X .EQ. 2 )THEN
509         B(K,1)=(1-PROB)*PROB

```



```

510         B(K,2)=(1-PROB)**2*PROB
511     ELSEIF ( X .EQ. 3 ) THEN
512         B(K,1)=(1-PROB)*PROB
513         B(K,2)=(1-PROB)**2*PROB
514         B(K,3)=(1-PROB)**3*PROB
515     ELSEIF ( X .EQ. 4 ) THEN
516         B(K,1)=(1-PROB)*PROB
517         B(K,2)=(1-PROB)**2*PROB
518         B(K,3)=(1-PROB)**3*PROB
519         B(K,4)=(1-PROB)**4*PROB
520     ELSEIF ( X .EQ. 5 ) THEN
521         B(K,1)=(1-PROB)*PROB
522         B(K,2)=(1-PROB)**2*PROB
523         B(K,3)=(1-PROB)**3*PROB
524         B(K,4)=(1-PROB)**4*PROB
525         B(K,5)=(1-PROB)**5*PROB
526     ENDIF
527 ELSEIF ( K .EQ. 1 ) THEN
528     IF ( X .EQ. 2 ) THEN
529         B(K,2)=(1-PROB)*PROB
530     ELSEIF ( X .EQ. 3 ) THEN
531         B(K,2)=(1-PROB)*PROB
532         B(K,3)=(1-PROB)**2*PROB
533     ELSEIF ( X .EQ. 4 ) THEN
534         B(K,2)=(1-PROB)*PROB
535         B(K,3)=(1-PROB)**2*PROB
536         B(K,4)=(1-PROB)**3*PROB
537     ELSEIF ( X .EQ. 5 ) THEN
538         B(K,2)=(1-PROB)*PROB
539         B(K,3)=(1-PROB)**2*PROB
540         B(K,4)=(1-PROB)**3*PROB
541         B(K,5)=(1-PROB)**4*PROB
542     ENDIF
543 ELSEIF ( K .EQ. 2 ) THEN
544     IF ( X .EQ. 3 ) THEN
545         B(K,3)=(1-PROB)*PROB
546     ELSEIF ( X .EQ. 4 ) THEN
547         B(K,3)=(1-PROB)*PROB
548         B(K,4)=(1-PROB)**2*PROB
549     ELSEIF ( X .EQ. 5 ) THEN
550         B(K,3)=(1-PROB)*PROB
551         B(K,4)=(1-PROB)**2*PROB
552         B(K,5)=(1-PROB)**3*PROB
553     ENDIF
554 ELSEIF ( K .EQ. 3 ) THEN
555     IF ( X .EQ. 4 ) THEN
556         B(K,4)=(1-PROB)*PROB
557     ELSEIF ( X .EQ. 5 ) THEN
558         B(K,4)=(1-PROB)*PROB
559         B(K,5)=(1-PROB)**2*PROB
560     ENDIF

```

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561     ELSEIF ( K .EQ. 4 ) THEN
562     IF ( X .EQ. 5 ) THEN
563         B(K,5)=(1-PROB)*PROB
564     ENDIF
565     ENDDO
566
567C    EQUATION #1
568C
569C
570:    LAM(0)*TP(0,0) = MEU(1)*TP(1,0)
571    A(1,1) = -LAM(0)
572    A(1,3) = MEU(1)
573C
574C    EQUATION #2A
575C
576:    (LAM(I)+MEU(I))*TP(I,0) = PROB*BI(I-1)*TP(I-1,1)+MEU(I+1)*TP(I+1,0)
577    DO I = 1,X
578        A(I+1,2*I+1) = LAM(I)+MEU(I)
579        A(I+1,2*I)   = -PROB*BI(I-1)
580        A(I+1,2*I+3) = -MEU(I+1)
581    ENDDO
582C
583C    EQUATION #2B
584C
585:    (LAM(I)+MEU(I))*TP(I,0) = BI(I-1)*TP(I-1,1)+MEU(I+1)*TP(I+1,0)
586    DO I = X+1,NMAX-2
587        A(I+1,2*I+1) = LAM(I)+MEU(I)
588        A(I+1,2*I)   = -BI(I-1)
589        A(I+1,2*I+3) = -MEU(I+1)
590    ENDDO
591C
592C    EQUATION #3
593C
594:    MEU(NMAX)*TP(NMAX,0) = BI(NMAX-1)*TP(NMAX-1,1)
595    A(NMAX,NMAX*2+1) = MEU(NMAX)
596    A(NMAX,NMAX*2) = -BI(NMAX-1)
597C
598C    EQUATION #4
599C
600    BX = 0.0D0
601    DO IP = 1,X
602        BX = BX + B(0,IP)
603    ENDDO
604:    PROB*BI(0)*TP(0,1)+BX*TP(0,1) = LAM(0)*TP(0,0)
605    A(NMAX+1,2) = PROB*BI(0)+BX
606    A(NMAX+1,1) = -LAM(0)
607C
608C    EQUATION #6
609C
610:    BIPX = 0.0
611:    DO IP = 0,X-1

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612:      BIPX = BIPX + B(IP,X)*TP(IP,1)
613:      ENDDO
614:      BI(X)*TP(X,1) = LAM(X)*TP(X,0) + BIPX
615:      IF ( X .EQ. 1 ) THEN
616:          A(NMAX+2,2*X+2) = -BI(X)
617:          A(NMAX+2,2*X+1) = LAM(X)
618:          A(NMAX+2,2*X) = B(0,X)
619:      ELSEIF ( X .EQ. 2 ) THEN
620:          A(NMAX+2,2*X+2) = -BI(X)
621:          A(NMAX+2,2*X+1) = LAM(X)
622:          A(NMAX+2,2*X-2) = B(0,X)
623:          A(NMAX+2,2*X) = B(1,X)
624:      ELSEIF ( X .EQ. 3 ) THEN
625:          A(NMAX+2,2*X+2) = -BI(X)
626:          A(NMAX+2,2*X+1) = LAM(X)
627:          A(NMAX+2,2*X-4) = B(0,X)
628:          A(NMAX+2,2*X-2) = B(1,X)
629:          A(NMAX+2,2*X) = B(2,X)
630:      ELSEIF ( X .EQ. 4 ) THEN
631:          A(NMAX+2,2*X+2) = -BI(X)
632:          A(NMAX+2,2*X+1) = LAM(X)
633:          A(NMAX+2,2*X-6) = B(0,X)
634:          A(NMAX+2,2*X-4) = B(1,X)
635:          A(NMAX+2,2*X-2) = B(2,X)
636:          A(NMAX+2,2*X) = B(3,X)
637:      ELSEIF ( X .EQ. 5 ) THEN
638:          A(NMAX+2,2*X+2) = -BI(X)
639:          A(NMAX+2,2*X+1) = LAM(X)
640:          A(NMAX+2,2*X-8) = B(0,X)
641:          A(NMAX+2,2*X-6) = B(1,X)
642:          A(NMAX+2,2*X-4) = B(2,X)
643:          A(NMAX+2,2*X-2) = B(3,X)
644:          A(NMAX+2,2*X) = B(4,X)
645:      ENDIF
646C
647C      EQUATION #7
648C
649      DO I = X+1,NMAX-1
650:          BI(I)*TP(I,1) = LAM(I)*TP(I,0)
651:          A(NMAX+2+I-X,2*I+2) = BI(I)
652:          A(NMAX+2+I-X,2*I+1) = -LAM(I)
653:      ENDDO
654C
655C      EQUATION #8
656C
657      PIO=0
658      PII=0
659      DO I =0,NMAX
660:          PIO = PIO + TP(I,0)
661:          A(NMAX+2+N,2*I+1) = 1.
662:          IF ( I .NE. NMAX ) THEN

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663:         P11 = P11 + TP(I,1)
664:         A(NMAX+2+N,2*I+2) = 1.
665:     ENDIF
666: ENDDO
667:     PIO + P11 = 1
668C
669C EQUATION #5
670C
671: DO I = 1,X-1,1
672:     BIIP = 0.0DO
673:     DO IP = I+1,X
674:         BIIP = BIIP + B(I,IP)
675:     ENDDO
676:     BIPI = 0
677:     DO IP = 0,I-1
678:         BIPI = BIPI + B(IP,I)*TP(IP,1)
679:     ENDDO
680:     PROB*BI(I)*TP(I,1)+BIIP*TP(I,1)=LAM(I)*TP(I,0)+BIPI
681:     IF ( I .EQ. 1 ) THEN
682:         A(NMAX+N+2+I,2*I+2) =-PROB*BI(I)-BIIP
683:         A(NMAX+N+2+I,2*I+1) = LAM(I)
684:         A(NMAX+N+2+I,2*I) = B(0,1)
685:     ELSEIF ( I .EQ. 2 ) THEN
686:         A(NMAX+N+2+I,2*I+2) =-PROB*BI(I)-BIIP
687:         A(NMAX+N+2+I,2*I+1) = LAM(I)
688:         A(NMAX+N+2+I,2*I) = B(1,2)
689:         A(NMAX+N+2+I,2*I-2) = B(0,2)
690:     ELSEIF ( I .EQ. 3 ) THEN
691:         A(NMAX+N+2+I,2*I+2) =-PROB*BI(I)-BIIP
692:         A(NMAX+N+2+I,2*I+1) = LAM(I)
693:         A(NMAX+N+2+I,2*I) = B(2,3)
694:         A(NMAX+N+2+I,2*I-2) = B(1,3)
695:         A(NMAX+N+2+I,2*I-4) = B(0,3)
696:     ELSEIF ( I .EQ. 4 ) THEN
697:         A(NMAX+N+2+I,2*I+2) =-PROB*BI(I)-BIIP
698:         A(NMAX+N+2+I,2*I+1) = LAM(I)
699:         A(NMAX+N+2+I,2*I) = B(3,4)
700:         A(NMAX+N+2+I,2*I-2) = B(2,4)
701:         A(NMAX+N+2+I,2*I-4) = B(1,4)
702:         A(NMAX+N+2+I,2*I-6) = B(0,4)
703:     ENDIF
704: ENDDO
705:
706:     SOLUTION OF MATRIX "A" USING PORTLIB
707:     GIVES TRANSITION PROBABILITY
708:
709: DO I = 1,NMAX*2+1
710:     RHS(I) = 0.0DO
711: ENDDO
712:     RHS(NMAX+N+2) = 1.0DO
713:     NB = 1.0DO

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714      CALL DLSTSQ(31,31,NMAX*2+1,NMAX*2+1,A,RHS,NB,TP)
715      END
716*****
717:
718:      PURPOSE: CALCULATES TRADITIONAL AVAILABILITY WHEN NUMBER IN :
719:      REPAIR PROCESS IS LESS OR EQUAL TO SPARE AVAILABLE :
720:
721:      INPUT: :
722:      >M      :TYPES OF EQUIPMENT IN FMS :
723:      >IX     :SPARE FOR EACH TYPE :
724:      >JJ     :COMPUTATION CONTROLLING INDEX :
725:      >P's    :TRANSITIONAL PROBABILITIES :
726:      OUTPUT: :
727:      >AO    :TRADITIONAL AVAILABILITY OF :
728:      A SYSTEM :
729:
730*****
731      SUBROUTINE TAVAIL(JJ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,AO)
732      INTEGER S,IX(10)
733      DOUBLEPRECISION P1(0:IX(1),0:0),P2(0:IX(2),0:0),P3(0:IX(3),0:0),
734      :P4(0:IX(4),0:0),P5(0:IX(5),0:0),P6(0:IX(6),0:0),P7(0:IX(7),0:0),
735      :P8(0:IX(8),0:0),P9(0:IX(9),0:0),P10(0:IX(10),0:0),PP(10),AO
736:
737:      INITIALIZATION
738:
739      DO I=1,10
740      PP(I) = 1.0D0
741      ENDDO
742      DO I = 1,M
743      IF ( (I .EQ. 1 .AND. JJ .EQ. 1) .OR.
744      (I .EQ. 1 .AND. JJ .EQ. 0) ) THEN
745      PP(1)=0.0D0
746      DO S = 0,IX(1)
747      PP(1) = PP(1) + P1(S,0)
748      ENDDO
749      ELSEIF ( (I .EQ. 2 .AND. JJ .EQ. 2) .OR.
750      (I .EQ. 2 .AND. JJ .EQ. 0) ) THEN
751      PP(2)=0.0D0
752      DO S = 0,IX(2)
753      PP(2) = PP(2) + P2(S,0)
754      ENDDO
755      ELSEIF ( (I .EQ. 3 .AND. JJ .EQ. 3) .OR.
756      (I .EQ. 3 .AND. JJ .EQ. 0) ) THEN
757      PP(3)=0.0D0
758      DO S = 0,IX(3)
759      PP(3) = PP(3) + P3(S,0)
760      ENDDO
761      ELSEIF ( (I .EQ. 4 .AND. JJ .EQ. 4) .OR.
762      (I .EQ. 4 .AND. JJ .EQ. 0) ) THEN
763      PP(4)=0.0D0
764      DO S = 0,IX(4)

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765         PP(4) = PP(4) + P4(S,0)
766     ENDDO
767     ELSEIF ( (I .EQ. 5 .AND. JJ .EQ. 5) .OR.
768         (I .EQ. 5 .AND. JJ .EQ. 0) ) THEN
769         PP(5)=0.0DO
770         DO S = 0,IX(5)
771             PP(5) = PP(5) + P5(S,0)
772         ENDDO
773     ELSEIF ( (I .EQ. 6 .AND. JJ .EQ. 6) .OR.
774         (I .EQ. 6 .AND. JJ .EQ. 0) ) THEN
775         PP(6)=0.0DO
776         DO S = 0,IX(6)
777             PP(6) = PP(6) + P6(S,0)
778         ENDDO
779     ELSEIF ( (I .EQ. 7 .AND. JJ .EQ. 7) .OR.
780         (I .EQ. 7 .AND. JJ .EQ. 0) ) THEN
781         PP(7)=0.0DO
782         DO S = 0,IX(7)
783             PP(7) = PP(7) + P7(S,0)
784         ENDDO
785     ELSEIF ( (I .EQ. 8 .AND. JJ .EQ. 8) .OR.
786         (I .EQ. 8 .AND. JJ .EQ. 0) ) THEN
787         PP(8)=0.0DO
788         DO S = 0,IX(8)
789             PP(8) = PP(8) + P8(S,0)
790         ENDDO
791     ELSEIF ( (I .EQ. 9 .AND. JJ .EQ. 9) .OR.
792         (I .EQ. 9 .AND. JJ .EQ. 0) ) THEN
793         PP(9)=0.0DO
794         DO S = 0,IX(9)
795             PP(9) = PP(9) + P9(S,0)
796         ENDDO
797     ELSEIF ( (I .EQ. 10 .AND. JJ .EQ. 10) .OR.
798         (I .EQ. 10 .AND. JJ .EQ. 0) ) THEN
799         PP(10)=0.0DO
800         DO S = 0,IX(10)
801             PP(10) = PP(10) + P10(S,0)
802         ENDDO
803     ENDIF
804 ENDDO
805:
806: COMPUTING OVER ALL SYSTEM TRADITIONAL AVAILABILITY
807:
808     AO=PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
809     END
810*****
811:
812: PURPOSE: 1.WHEN ONLY ANY ONE EQUIPMENT TYPE IN THE STATE
813:           OF (X+1,0)
814:           2.TAKES INTO ACCOUNT PARTIAL CREDITS FOR THE
815:           PARTIAL AVAILABILITY OF SUBSYSTEMS

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      INPUT:      > M, IN, JJ, NMX, P's, (EXPLAINED EARLIER)
      OUTPUT:    > PAAX: PARTIAL CREDITS FROM ENVIRONMENT VIEWPOINT
                  IF ONLY SOME LOCAL SYSTEMS ARE AVAILABLE
*****
SUBROUTINE
:SFAIL1(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PAAX)
INTEGER X,S,AAL,NMX(10),IX(10),IN(M)
DOUBLEPRECISION P1(0:NMX(1),0:1),P2(0:NMX(2),0:1),
:P3(0:NMX(3),0:1),P4(0:NMX(4),0:1),P5(0:NMX(5),0:1),
:P6(0:NMX(6),0:1),P7(0:NMX(7),0:1),P8(0:NMX(8),0:1),
:P9(0:NMX(9),0:1),P10(0:NMX(10),0:1),PP(10),PAA(10),
:WAA(10),PAAX
REAL Z(10)

      INITIALIZE

DO I=1,10
  PP(I) = 1.0D0
ENDDO
DO I = 1,M
  IF ( ( I .EQ. 1 .AND. JJ .EQ. 1 ) .OR.
      ( I .EQ. 1 .AND. JJ .EQ. 0 ) ) THEN
    PP(1)=0.0D0
    DO S = 0,IX(1)
      PP(1) = PP(1) + P1(S,0)
    ENDDO
  ELSEIF ( ( I .EQ. 2 .AND. JJ .EQ. 2 ) .OR.
          ( I .EQ. 2 .AND. JJ .EQ. 0 ) ) THEN
    PP(2)=0.0D0
    DO S = 0,IX(2)
      PP(2) = PP(2) + P2(S,0)
    ENDDO
  ELSEIF ( ( I .EQ. 3 .AND. JJ .EQ. 3 ) .OR.
          ( I .EQ. 3 .AND. JJ .EQ. 0 ) ) THEN
    PP(3)=0.0D0
    DO S = 0,IX(3)
      PP(3) = PP(3) + P3(S,0)
    ENDDO
  ELSEIF ( ( I .EQ. 4 .AND. JJ .EQ. 4 ) .OR.
          ( I .EQ. 4 .AND. JJ .EQ. 0 ) ) THEN
    PP(4)=0.0D0
    DO S = 0,IX(4)
      PP(4) = PP(4) + P4(S,0)
    ENDDO
  ELSEIF ( ( I .EQ. 5 .AND. JJ .EQ. 5 ) .OR.
          ( I .EQ. 5 .AND. JJ .EQ. 0 ) ) THEN

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867         PP(5)=0.0DO
868         DO S = 0,IX(5)
869             PP(5) = PP(5) + P5(S,0)
870         ENDDO
871     ELSEIF ( (I .EQ. 6 .AND. JJ .EQ. 6) .OR.
872             (I .EQ. 6 .AND. JJ .EQ. 0) ) THEN
873         PP(6)=0.0DO
874         DO S = 0,IX(6)
875             PP(6) = PP(6) + P6(S,0)
876         ENDDO
877     ELSEIF ( (I .EQ. 7 .AND. JJ .EQ. 7) .OR.
878             (I .EQ. 7 .AND. JJ .EQ. 0) ) THEN
879         PP(7)=0.0DO
880         DO S = 0,IX(7)
881             PP(7) = PP(7) + P7(S,0)
882         ENDDO
883     ELSEIF ( (I .EQ. 8 .AND. JJ .EQ. 8) .OR.
884             (I .EQ. 8 .AND. JJ .EQ. 0) ) THEN
885         PP(8)=0.0DO
886         DO S = 0,IX(8)
887             PP(8) = PP(8) + P8(S,0)
888         ENDDO
889     ELSEIF ( (I .EQ. 9 .AND. JJ .EQ. 9) .OR.
890             (I .EQ. 9 .AND. JJ .EQ. 0) ) THEN
891         PP(9)=0.0DO
892         DO S = 0,IX(9)
893             PP(9) = PP(9) + P9(S,0)
894         ENDDO
895     ELSEIF ( (I .EQ. 10 .AND. JJ .EQ. 10) .OR.
896             (I .EQ. 10 .AND. JJ .EQ. 0) ) THEN
897         PP(10)=0.0DO
898         DO S = 0,IX(10)
899             PP(10) = PP(10) + P10(S,0)
900         ENDDO
901     ENDIF
902     ENDDO
903     DO I=1,M
904         Z(I)=IN(I)
905     ENDDO
906     PAAX = 0.0
907     X=MIN(IX(1),IX(2),IX(3),IX(4),IX(5),
908 :        IX(6),IX(7),IX(8),IX(9),IX(10))
909     NMAX=MAX(NMX(1),NMX(2),NMX(3),NMX(4),NMX(5),
910 :        NMX(6),NMX(7),NMX(8),NMX(9),NMX(10))
911:
912:         ACCOUNTING FOR PARTIAL CREDITS
913:
914     DO AA1 = X+1,NMAX-1
915         DO I = 1,10
916             PAA(I)=0.0DO
917             WAA(I)=0.0DO

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918 ENDDO
919 DO K = 1,M
920   IF ( (K .EQ. 1 .AND. IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1
921   :     .AND. JJ .EQ. 1) .OR. (K .EQ. 1 .AND. IX(1) .LT. AA1
922   :     .AND. NMX(1) .GT. AA1 .AND. JJ .EQ. 0) )THEN
923     WAA1 = ((NMX(1)-AA1)/Z(1))
924     PAA(1)=P1(AA1,0)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*
925   :     PP(8)*PP(9)*PP(10)*WAA1
926   ELSEIF ( (K .EQ. 2 .AND. IX(2) .LT. AA1 .AND. NMX(2) .GT.
927   :     AA1 .AND. JJ .EQ. 2) .OR. (K .EQ. 2 .AND. IX(2) .LT.
928   :     AA1 .AND. NMX(2) .GT. AA1 .AND. JJ .EQ. 0) )THEN
929     WAA2 = ((NMX(2)-AA1)/Z(2))
930     PAA(2)=P2(AA1,0)*PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*
931   :     PP(8)*PP(9)*PP(10)*WAA2
932   ELSEIF ( (K .EQ. 3 .AND. IX(3) .LT. AA1 .AND. NMX(3) .GT.
933   :     AA1 .AND. JJ .EQ. 3) .OR. (K .EQ. 3 .AND. IX(3) .LT.
934   :     AA1 .AND. NMX(3) .GT. AA1 .AND. JJ .EQ. 0) )THEN
935     WAA3 = ((NMX(3)-AA1)/Z(3))
936     PAA(3)=P3(AA1,0)*PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*
937   :     PP(8)*PP(9)*PP(10)*WAA3
938   ELSEIF ( (K .EQ. 4 .AND. IX(4) .LT. AA1 .AND. NMX(4) .GT.
939   :     AA1 .AND. JJ .EQ. 4) .OR. (K .EQ. 4 .AND. IX(4) .LT.
940   :     AA1 .AND. NMX(4) .GT. AA1 .AND. JJ .EQ. 0) )THEN
941     WAA4 = ((NMX(4)-AA1)/Z(4))
942     PAA(4)=P4(AA1,0)*PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*
943   :     PP(8)*PP(9)*PP(10)*WAA4
944   ELSEIF ( (K .EQ. 5 .AND. IX(5) .LT. AA1 .AND. NMX(5) .GT.
945   :     AA1 .AND. JJ .EQ. 5) .OR. (K .EQ. 5 .AND. IX(5) .LT.
946   :     AA1 .AND. NMX(5) .GT. AA1 .AND. JJ .EQ. 0) )THEN
947     WAA5 = ((NMX(5)-AA1)/Z(5))
948     PAA(5)=P5(AA1,0)*PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*
949   :     PP(8)*PP(9)*PP(10)*WAA5
950   ELSEIF ( (K .EQ. 6 .AND. IX(6) .LT. AA1 .AND. NMX(6) .GT.
951   :     AA1 .AND. JJ .EQ. 6) .OR. (K .EQ. 6 .AND. IX(6) .LT.
952   :     AA1 .AND. NMX(6) .GT. AA1 .AND. JJ .EQ. 0) )THEN
953     WAA6 = ((NMX(6)-AA1)/Z(6))
954     PAA(6)=P6(AA1,0)*PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*
955   :     PP(8)*PP(9)*PP(10)*WAA6
956   ELSEIF ( (K .EQ. 7 .AND. IX(7) .LT. AA1 .AND. NMX(7) .GT.
957   :     AA1 .AND. JJ .EQ. 7) .OR. (K .EQ. 7 .AND. IX(7) .LT.
958   :     AA1 .AND. NMX(7) .GT. AA1 .AND. JJ .EQ. 0) )THEN
959     WAA7 = ((NMX(7)-AA1)/Z(7))
960     PAA(7)=P7(AA1,0)*PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*
961   :     PP(8)*PP(9)*PP(10)*WAA7
962   ELSEIF ( (K .EQ. 8 .AND. IX(8) .LT. AA1 .AND. NMX(8) .GT.
963   :     AA1 .AND. JJ .EQ. 8) .OR. (K .EQ. 8 .AND. IX(8) .LT.
964   :     AA1 .AND. NMX(8) .GT. AA1 .AND. JJ .EQ. 0) )THEN
965     WAA8 = ((NMX(8)-AA1)/Z(8))
966     PAA(8)=P8(AA1,0)*PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*
967   :     PP(7)*PP(9)*PP(10)*WAA8
968   ELSEIF ( (K .EQ. 9 .AND. IX(9) .LT. AA1 .AND. NMX(9) .GT.

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969 :      AAL .AND. JJ .EQ. 9) .OR. (K .EQ. 9 .AND. IX(9) .LT.
970 :      AAL .AND. NMX(9) .GT. AAL .AND. JJ .EQ. 0) )THEN
971 :      WAA9 = ((NMX(9)-AAL)/Z(9))
972 :      PAA(9)=P9(AAL,0)*PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*
973 :      PP(7)*PP(8)*PP(10)*WAA9
974 :      ELSEIF ((K .EQ. 10 .AND. IX(10) .LT. AAL .AND. NMX(10) .GT.
975 :      AAL .AND. JJ .EQ. 10) .OR. (K .EQ. 10 .AND. IX(10) .LT.
976 :      AAL .AND. NMX(10) .GT. AAL .AND. JJ .EQ. 0) )THEN
977 :      WAA10 = ((NMX(10)-AAL)/Z(10))
978 :      PAA(10)=P10(AAL,0)*PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*
979 :      PP(7)*PP(8)*PP(9)*WAA10
980 :      ENDIF
981 :      ENDDO
982 :      PAAX = PAAX+(PAA(1)+PAA(2)+PAA3+PAA(4)+PAA(5)+PAA(6)+
983 :      PAA(7)+PAA(8)+PAA(9)+PAA(10))
984 :      ENDDO
985 :      END
986 :*****
987 :
988 :      PURPOSE: 1.WHEN ANY TWO EQUIPMENT TYPES IN THE STATE
989 :      OF (X+1,0)
990 :      2.TAKES INTO ACCOUNT PARTIAL CREDITS FOR
991 :      PARTIAL AVAILABILITY
992 :
993 :      INPUT:
994 :      >      : M, IN, IX, JJ, P's, NMX,
995 :      ( EXPLAINED EARLIER )
996 :
997 :      OUTPUT:
998 :      >PLKX: PARTIAL CREDITS FOR PARTIAL
999 :      AVAILABILITY
1000 :*****
1001 :      SUBROUTINE
1002 :      SFAIL2(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PLKX)
1003 :      INTEGER X,S,AAL,AA2,A1,A2,A3,A4,A5,A6,A7,A8,A9,A10
1004 :      INTEGER IX(10),IN(M),NMX(10)
1005 :      DOUBLEPRECISION P1(0:NMX(1),0:1),P2(0:NMX(2),0:1),
1006 :      P3(0:NMX(3),0:1),P4(0:NMX(4),0:1),P5(0:NMX(5),0:1),
1007 :      P6(0:NMX(6),0:1),P7(0:NMX(7),0:1),P8(0:NMX(8),0:1),
1008 :      P9(0:NMX(9),0:1),P10(0:NMX(10),0:1),PP(10),PLKE,PLKNE,
1009 :      PLKX,PLK(10),PLK1(10),PLK2(10),PLK3(10),PLK4(10),PLK5(10),
1010 :      PLK6(10),PLK7(10),PLK8(10),PLK9(10),PLK10(10)
1011 :      REAL Z(10)
1012 :
1013 :      INITIALIZE
1014 :
1015 :      DO I=1,10
1016 :      PP(I) =1.0D0
1017 :      PLK(I) =0.0D0
1018 :      PLK1(I) =0.0D0
1019 :      PLK2(I) =0.0D0

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1020 PLK3(I) =0.0D0
1021 PLK4(I) =0.0D0
1022 PLK5(I) =0.0D0
1023 PLK6(I) =0.0D0
1024 PLK7(I) =0.0D0
1025 PLK8(I) =0.0D0
1026 PLK9(I) =0.0D0
1027 PLK10(I)=0.0D0
1028 ENDDO
1029 DO I = 1,M
1030 IF ( (I .EQ. 1 .AND. JJ .EQ. 1) .OR.
1031 (I .EQ. 1 .AND. JJ .EQ. 0) ) THEN
1032 PP(1)=0.0D0
1033 DO S = 0,IX(1)
1034 PP(1) = PP(1) + P1(S,0)
1035 ENDDO
1036 ELSEIF ( (I .EQ. 2 .AND. JJ .EQ. 2) .OR.
1037 (I .EQ. 2 .AND. JJ .EQ. 0) ) THEN
1038 PP(2)=0.0D0
1039 DO S = 0,IX(2)
1040 PP(2) = PP(2) + P2(S,0)
1041 ENDDO
1042 ELSEIF ( (I .EQ. 3 .AND. JJ .EQ. 3) .OR.
1043 (I .EQ. 3 .AND. JJ .EQ. 0) ) THEN
1044 PP(3)=0.0D0
1045 DO S = 0,IX(3)
1046 PP(3) = PP(3) + P3(S,0)
1047 ENDDO
1048 ELSEIF ( (I .EQ. 4 .AND. JJ .EQ. 4) .OR.
1049 (I .EQ. 4 .AND. JJ .EQ. 0) ) THEN
1050 PP(4)=0.0D0
1051 DO S = 0,IX(4)
1052 PP(4) = PP(4) + P4(S,0)
1053 ENDDO
1054 ELSEIF ( (I .EQ. 5 .AND. JJ .EQ. 5) .OR.
1055 (I .EQ. 5 .AND. JJ .EQ. 0) ) THEN
1056 PP(5)=0.0D0
1057 DO S = 0,IX(5)
1058 PP(5) = PP(5) + P5(S,0)
1059 ENDDO
1060 ELSEIF ( (I .EQ. 6 .AND. JJ .EQ. 6) .OR.
1061 (I .EQ. 6 .AND. JJ .EQ. 0) ) THEN
1062 PP(6)=0.0D0
1063 DO S = 0,IX(6)
1064 PP(6) = PP(6) + P6(S,0)
1065 ENDDO
1066 ELSEIF ( (I .EQ. 7 .AND. JJ .EQ. 7) .OR.
1067 (I .EQ. 7 .AND. JJ .EQ. 0) ) THEN
1068 PP(7)=0.0D0
1069 DO S = 0,IX(7)
1070 PP(7) = PP(7) + P7(S,0)

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1071         ENDDO
1072     ELSEIF ( (I .EQ. 8 .AND. JJ .EQ. 8) .OR.
1073             (I .EQ. 8 .AND. JJ .EQ. 0) ) THEN
1074         PP(8)=0.0D0
1075         DO S = 0,IX(8)
1076             PP(8) = PP(8) + P8(S,0)
1077         ENDDO
1078     ELSEIF ( (I .EQ. 9 .AND. JJ .EQ. 9) .OR.
1079             (I .EQ. 9 .AND. JJ .EQ. 0) ) THEN
1080         PP(9)=0.0D0
1081         DO S = 0,IX(9)
1082             PP(9) = PP(9) + P9(S,0)
1083         ENDDO
1084     ELSEIF ( (I .EQ. 10 .AND. JJ .EQ. 10) .OR.
1085             (I .EQ. 10 .AND. JJ .EQ. 0) ) THEN
1086         PP(10)=0.0D0
1087         DO S = 0,IX(10)
1088             PP(10) = PP(10) + P10(S,0)
1089         ENDDO
1090     ENDIF
1091     ENDDO
1092     DO I=1,M
1093         Z(I)=IN(I)
1094     ENDDO
1095     X=MIN(IX(1),IX(2),IX(3),IX(4),IX(5),
1096 :        IX(6),IX(7),IX(8),IX(9),IX(10))
1097     NMAX=MAX(NMX(1),NMX(2),NMX(3),NMX(4),NMX(5),
1098 :        NMX(6),NMX(7),NMX(8),NMX(9),NMX(10))
1099     PLKE = 0.0D0
1100     PLKNE = 0.0D0
1101     PLKX = 0.0D0
1102:
1103:         ACCOUNTING FOR PARTIAL CREDITS
1104:
1105     DO AA1 = X+1,NMAX-1
1106         DO AA2 = X+1,NMAX-1
1107             DO L = 1,M
1108                 IF ( L .EQ. 1 ) THEN
1109                     A1 = AA1
1110                     WA11 = ((NMX(1)-AA1)/Z(1))
1111                 ELSEIF ( L .EQ. 2 ) THEN
1112                     A2 = AA1
1113                     WA12 = ((NMX(2)-AA1)/Z(2))
1114                 ELSEIF ( L .EQ. 3 ) THEN
1115                     A3 = AA1
1116                     WA13 = ((NMX(3)-AA1)/Z(3))
1117                 ELSEIF ( L .EQ. 4 ) THEN
1118                     A4 = AA1
1119                     WA14 = ((NMX(4)-AA1)/Z(4))
1120                 ELSEIF ( L .EQ. 5 ) THEN
1121                     A5 = AA1

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1173      :      PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
1174      :      ELSEIF ( L .EQ. 9 .AND.
1175      :      IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
1176      :      PLK1(9)=P1(A1,0)*P9(A9,0)*WA19*WA21*
1177      :      PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
1178      :      ELSEIF ( L .EQ. 10 .AND.
1179      :      IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
1180      :      PLK1(10)=P1(A1,0)*P10(A10,0)*WA110*WA21*
1181      :      PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
1182      :      ENDIF
1183      :      ELSEIF ((K .EQ. 2 .AND. IX(2) .LT. AA2 .AND. NMX(2)
1184      :      .GT. AA2 .AND. JJ .EQ. 2) .OR. (K .EQ. 2 .AND. IX(2)
1185      :      .LT. AA2 .AND. NMX(2) .GT. AA2 .AND. JJ .EQ. 0))THEN
1186      :      WA22 = ((NMX(2)-AA2)/Z(2))
1187      :      A2=AA2
1188      :      IF ( L .EQ. 1 .AND.
1189      :      IX(1) .LT. AA1 .AND. NMXN1) .GT. AA1) THEN
1190      :      PLK2(1)=P1(A1,0)*P2(A2,0)*WA11*WA22*
1191      :      PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
1192      :      ELSEIF ( L .EQ. 3 .AND.
1193      :      IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
1194      :      PLK2(3)=P2(A2,0)*P3(A3,0)*WA13*WA22*
1195      :      PP(1)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
1196      :      ELSEIF ( L .EQ. 4 .AND.
1197      :      IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
1198      :      PLK2(4)=P2(A2,0)*P4(A4,0)*WA14*WA22*
1199      :      PP(1)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
1200      :      ELSEIF ( L .EQ. 5 .AND.
1201      :      IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
1202      :      PLK2(5)=P2(A2,0)*P5(A5,0)*WA15*WA22*
1203      :      PP(1)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
1204      :      ELSEIF ( L .EQ. 6 .AND.
1205      :      IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
1206      :      PLK2(6)=P2(A2,0)*P6(A6,0)*WA16*WA22*
1207      :      PP(1)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
1208      :      ELSEIF ( L .EQ. 7 .AND.
1209      :      IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
1210      :      PLK2(7)=P2(A2,0)*P7(A7,0)*WA17*WA22*
1211      :      PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
1212      :      ELSEIF ( L .EQ. 8 .AND.
1213      :      IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
1214      :      PLK2(8)=P2(A2,0)*P8(A8,0)*WA18*WA22*
1215      :      PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
1216      :      ELSEIF ( L .EQ. 9 .AND.
1217      :      IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
1218      :      PLK2(9)=P2(A2,0)*P9(A9,0)*WA19*WA22*
1219      :      PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
1220      :      ELSEIF ( L .EQ. 10 .AND.
1221      :      IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
1222      :      PLK2(10)=P2(A2,0)*P10(A10,0)*WA110*WA22*
1223      :      PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)

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1224         ENDIF
1225     ELSEIF ((K .EQ. 3 .AND. IX(3) .LT. AA2 .AND. NMX(3)
1226 :         .GT. AA2 .AND. JJ .EQ. 3) .OR. (K .EQ. 3 .AND. IX(3)
1227 :         .LT. AA2 .AND. NMX(3) .GT. AA2 .AND. JJ .EQ. 0))THEN
1228         WA23 = ((NMX(3)-AA2)/Z(3))
1229         A3=AA2
1230         IF ( L .EQ. 1 .AND.
1231 :         IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
1232             PLK3(1)=P1(A1,0)*P3(A3,0)*WA11*WA23*
1233 :         PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
1234         ELSEIF ( L .EQ. 2 .AND.
1235 :         IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
1236             PLK3(2)=P2(A2,0)*P3(A3,0)*WA12*WA23*
1237 :         PP(1)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
1238         ELSEIF ( L .EQ. 4 .AND.
1239 :         IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
1240             PLK3(4)=P3(A3,0)*P4(A4,0)*WA14*WA23*
1241 :         PP(1)*PP(2)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
1242         ELSEIF ( L .EQ. 5 .AND.
1243 :         IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
1244             PLK3(5)=P3(A3,0)*P5(A5,0)*WA15*WA23*
1245 :         PP(1)*PP(2)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
1246         ELSEIF ( L .EQ. 6 .AND.
1247 :         IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
1248             PLK3(6)=P3(A3,0)*P6(A6,0)*WA16*WA23*
1249 :         PP(1)*PP(2)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
1250         ELSEIF ( L .EQ. 7 .AND.
1251 :         IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
1252             PLK3(7)=P3(A3,0)*P7(A7,0)*WA17*WA23*
1253 :         PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
1254         ELSEIF ( L .EQ. 8 .AND.
1255 :         IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
1256             PLK3(8)=P3(A3,0)*P8(A8,0)*WA18*WA23*
1257 :         PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
1258         ELSEIF ( L .EQ. 9 .AND.
1259 :         IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
1260             PLK3(9)=P3(A3,0)*P9(A9,0)*WA19*WA23*
1261 :         PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
1262         ELSEIF ( L .EQ. 10 .AND.
1263 :         IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
1264             PLK3(10)=P3(A3,0)*P10(A10,0)*WA110*WA23*
1265 :         PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
1266         ENDIF
1267     ELSEIF ((K .EQ. 4 .AND. IX(4) .LT. AA2 .AND. NMX(4)
1268 :         .GT. AA2 .AND. JJ .EQ. 4) .OR. (K .EQ. 4 .AND. IX(4)
1269 :         .LT. AA2 .AND. NMX(4) .GT. AA2 .AND. JJ .EQ. 0))THEN
1270         WA24 = ((NMX(4)-AA2)/Z(4))
1271         A4=AA2
1272         IF ( L .EQ. 1 .AND.
1273 :         IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
1274             PLK4(1)=P1(A1,0)*P4(A4,0)*WA11*WA24*

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1275      :          PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
1276      ELSEIF ( L .EQ. 2 .AND.
1277      :          IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
1278      PLK4(2)=P2(A2,0)*P4(A4,0)*WA12*WA24*
1279      :          PP(1)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
1280      ELSEIF ( L .EQ. 3 .AND.
1281      :          IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
1282      PLK4(3)=P3(A3,0)*P4(A4,0)*WA13*WA24*
1283      :          PP(1)*PP(2)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
1284      ELSEIF ( L .EQ. 5 .AND.
1285      :          IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
1286      PLK4(5)=P4(A4,0)*P5(A5,0)*WA15*WA24*
1287      :          PP(1)*PP(2)*PP(3)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
1288      ELSEIF ( L .EQ. 6 .AND.
1289      :          IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
1290      PLK4(6)=P4(A4,0)*P6(A6,0)*WA16*WA24*
1291      :          PP(1)*PP(2)*PP(3)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
1292      ELSEIF ( L .EQ. 7 .AND.
1293      :          IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
1294      PLK4(7)=P4(A4,0)*P7(A7,0)*WA17*WA24*
1295      :          PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
1296      ELSEIF ( L .EQ. 8 .AND.
1297      :          IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
1298      PLK4(8)=P4(A4,0)*P8(A8,0)*WA18*WA24*
1299      :          PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
1300      ELSEIF ( L .EQ. 9 .AND.
1301      :          IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
1302      PLK4(9)=P4(A4,0)*P9(A9,0)*WA19*WA24*
1303      :          PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
1304      ELSEIF ( L .EQ. 10 .AND.
1305      :          IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
1306      PLK4(10)=P4(A4,0)*P10(A10,0)*WA110*WA24*
1307      :          PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
1308      ENDIF
1309      ELSEIF ((K .EQ. 5 .AND. IX(5) .LT. AA2 .AND. NMX(5)
1310      :          .GT. AA2 .AND. JJ .EQ. 5) .OR. (K .EQ. 5 .AND. IX(5)
1311      :          .LT. AA2 .AND. NMX(5) .GT. AA2 .AND. JJ .EQ. 0))THEN
1312      WA25 = ((NMX(5)-AA2)/Z(5))
1313      A5=AA2
1314      IF ( L .EQ. 1 .AND.
1315      :          IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
1316      PLK5(1)=P1(A1,0)*P5(A5,0)*WA11*WA25*
1317      :          PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
1318      ELSEIF ( L .EQ. 2 .AND.
1319      :          IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
1320      PLK5(2)=P2(A2,0)*P5(A5,0)*WA12*WA25*
1321      :          PP(1)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
1322      ELSEIF ( L .EQ. 3 .AND.
1323      :          IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
1324      PLK5(3)=P3(A3,0)*P5(A5,0)*WA13*WA25*
1325      :          PP(1)*PP(2)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)

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1326      ELSEIF ( L .EQ. 4 .AND.
1327 :      IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
1328      PLK5(4)=P4(A4,0)*P5(A5,0)*WA14*WA25*
1329 :      PP(1)*PP(2)*PP(3)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
1330      ELSEIF ( L .EQ. 6 .AND.
1331 :      IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
1332      PLK5(6)=P5(A5,0)*P6(A6,0)*WA16*WA25*
1333 :      PP(1)*PP(2)*PP(3)*PP(4)*PP(7)*PP(8)*PP(9)*PP(10)
1334      ELSEIF ( L .EQ. 7 .AND.
1335 :      IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
1336      PLK5(7)=P5(A5,0)*P7(A7,0)*WA17*WA25*
1337 :      PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(8)*PP(9)*PP(10)
1338      ELSEIF ( L .EQ. 8 .AND.
1339 :      IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
1340      PLK5(8)=P5(A5,0)*P8(A8,0)*WA18*WA25*
1341 :      PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(9)*PP(10)
1342      ELSEIF ( L .EQ. 9 .AND.
1343 :      IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
1344      PLK5(9)=P5(A5,0)*P9(A9,0)*WA19*WA25*
1345 :      PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(10)
1346      ELSEIF ( L .EQ. 10 .AND.
1347 :      IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
1348      PLK5(10)=P5(A5,0)*P10(A10,0)*WA110*WA25*
1349 :      PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)
1350      ENDIF
1351      ELSEIF ((K .EQ. 6 .AND. IX(6) .LT. AA2 .AND. NMX(6)
1352 :      .GT. AA2 .AND. JJ .EQ. 6) .OR. (K .EQ. 6 .AND. IX(6)
1353 :      .LT. AA2 .AND. NMX(6) .GT. AA2 .AND. JJ .EQ. 0))THEN
1354      WA26 = ((NMX(6)-AA2)/Z(6))
1355      A6=AA2
1356      IF ( L .EQ. 1 .AND.
1357 :      IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
1358      PLK6(1)=P1(A1,0)*P6(A6,0)*WA11*WA26*
1359 :      PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
1360      ELSEIF ( L .EQ. 2 .AND.
1361 :      IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
1362      PLK6(2)=P2(A2,0)*P6(A6,0)*WA12*WA26*
1363 :      PP(1)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
1364      ELSEIF ( L .EQ. 3 .AND.
1365 :      IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
1366      PLK6(3)=P3(A3,0)*P6(A6,0)*WA13*WA26*
1367 :      PP(1)*PP(2)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
1368      ELSEIF ( L .EQ. 4 .AND.
1369 :      IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
1370      PLK6(4)=P4(A4,0)*P6(A6,0)*WA14*WA26*
1371 :      PP(1)*PP(2)*PP(3)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
1372      ELSEIF ( L .EQ. 5 .AND.
1373 :      IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
1374      PLK6(5)=P5(A5,0)*P6(A6,0)*WA15*WA26*
1375 :      PP(1)*PP(2)*PP(3)*PP(4)*PP(7)*PP(8)*PP(9)*PP(10)
1376      ELSEIF ( L .EQ. 7 .AND.

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1377 :           IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
1378 :           PLK6(7)=P6(A6,0)*P7(A7,0)*WA17*WA26*
1379 :           PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(8)*PP(9)*PP(10)
1380 :           ELSEIF ( L .EQ. 8 .AND.
1381 :           IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
1382 :           PLK6(8)=P6(A6,0)*P8(A8,0)*WA18*WA26*
1383 :           PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(9)*PP(10)
1384 :           ELSEIF ( L .EQ. 9 .AND.
1385 :           IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
1386 :           PLK6(9)=P6(A6,0)*P9(A9,0)*WA19*WA26*
1387 :           PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(10)
1388 :           ELSEIF ( L .EQ. 10 .AND.
1389 :           IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
1390 :           PLK6(10)=P6(A6,0)*P10(A10,0)*WA110*WA26*
1391 :           PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)
1392 :           ENDIF
1393 :           ELSEIF ((K .EQ. 7 .AND. IX(7) .LT. AA2 .AND. NMX(7)
1394 :           .GT. AA2 .AND. JJ .EQ. 7) .OR. (K .EQ. 7 .AND. IX(7)
1395 :           .LT. AA2 .AND. NMX(7) .GT. AA2 .AND. JJ .EQ. 0))THEN
1396 :           WA27 = ((NMX(7)-AA2)/Z(7))
1397 :           A7=AA2
1398 :           IF ( L .EQ. 1 .AND.
1399 :           IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
1400 :           PLK7(1)=P1(A1,0)*P7(A7,0)*WA11*WA27*
1401 :           PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
1402 :           ELSEIF ( L .EQ. 2 .AND.
1403 :           IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
1404 :           PLK7(2)=P2(A2,0)*P7(A7,0)*WA12*WA27*
1405 :           PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
1406 :           ELSEIF ( L .EQ. 3 .AND.
1407 :           IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
1408 :           PLK7(3)=P3(A3,0)*P7(A7,0)*WA13*WA27*
1409 :           PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
1410 :           ELSEIF ( L .EQ. 4 .AND.
1411 :           IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
1412 :           PLK7(4)=P4(A4,0)*P7(A7,0)*WA14*WA27*
1413 :           PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
1414 :           ELSEIF ( L .EQ. 5 .AND.
1415 :           IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
1416 :           PLK7(5)=P5(A5,0)*P7(A7,0)*WA15*WA27*
1417 :           PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(8)*PP(9)*PP(10)
1418 :           ELSEIF ( L .EQ. 6 .AND.
1419 :           IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
1420 :           PLK7(6)=P6(A6,0)*P7(A7,0)*WA16*WA27*
1421 :           PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(8)*PP(9)*PP(10)
1422 :           ELSEIF ( L .EQ. 8 .AND.
1423 :           IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
1424 :           PLK7(8)=P7(A7,0)*P8(A8,0)*WA18*WA27*
1425 :           PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(9)*PP(10)
1426 :           ELSEIF ( L .EQ. 9 .AND.
1427 :           IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN

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1428          PLK7(9)=P7(A7,0)*P9(A9,0)*WA19*WA27*
1429      :      PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(10)
1430      ELSEIF ( L .EQ. 10 .AND.
1431      :      IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
1432          PLK7(10)=P7(A7,0)*P10(A10,0)*WA110*WA27*
1433      :      PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)
1434      ENDIF
1435      ELSEIF ((K .EQ. 8 .AND. IX(8) .LT. AA2 .AND. NMX(8)
1436      :      .GT. AA2 .AND. JJ .EQ. 8) .OR. (K .EQ. 8 .AND. IX(8)
1437      :      .LT. AA2 .AND. NMX(8) .GT. AA2 .AND. JJ .EQ. 0))THEN
1438          WA28 = ((NMX(8)-AA2)/Z(8))
1439          A8=AA2
1440          IF ( L .EQ. 1 .AND.
1441      :      IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
1442          PLK8(1)=P1(A1,0)*P8(A8,0)*WA11*WA28*
1443      :      PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
1444      ELSEIF ( L .EQ. 2 .AND.
1445      :      IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
1446          PLK8(2)=P2(A2,0)*P8(A8,0)*WA12*WA28*
1447      :      PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
1448      ELSEIF ( L .EQ. 3 .AND.
1449      :      IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
1450          PLK8(3)=P3(A3,0)*P8(A8,0)*WA13*WA28*
1451      :      PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
1452      ELSEIF ( L .EQ. 4 .AND.
1453      :      IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
1454          PLK8(4)=P4(A4,0)*P8(A8,0)*WA14*WA28*
1455      :      PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
1456      ELSEIF ( L .EQ. 5 .AND.
1457      :      IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
1458          PLK8(5)=P5(A5,0)*P8(A8,0)*WA15*WA28*
1459      :      PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(9)*PP(10)
1460      ELSEIF ( L .EQ. 6 .AND.
1461      :      IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
1462          PLK8(6)=P6(A6,0)*P8(A8,0)*WA16*WA28*
1463      :      PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(9)*PP(10)
1464      ELSEIF ( L .EQ. 7 .AND.
1465      :      IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
1466          PLK8(7)=P7(A7,0)*P8(A8,0)*WA17*WA28*
1467      :      PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(9)*PP(10)
1468      ELSEIF ( L .EQ. 9 .AND.
1469      :      IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
1470          PLK8(9)=P8(A8,0)*P9(A9,0)*WA19*WA28*
1471      :      PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(10)
1472      ELSEIF ( L .EQ. 10 .AND.
1473      :      IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
1474          PLK8(10)=P8(A8,0)*P10(A10,0)*WA110*WA28*
1475      :      PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)
1476      ENDIF
1477      ELSEIF ((K .EQ. 9 .AND. IX(9) .LT. AA2 .AND. NMX(9)
1478      :      .GT. AA2 .AND. JJ .EQ. 9) .OR. (K .EQ. 9 .AND. IX(9)

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1479 : .LT. AA2 .AND. NMX(9) .GT. AA2 .AND. JJ .EQ. 0))THEN
1480 WA29 = ((NMX(9)-AA2)/Z(9))
1481 A9=AA2
1482 IF ( L .EQ. 1 .AND.
1483 : IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
1484 PLK9(1)=P1(A1,0)*P9(A9,0)*WA11*WA29*
1485 : PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
1486 ELSEIF ( L .EQ. 2 .AND.
1487 : IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
1488 PLK9(2)=P2(A2,0)*P9(A9,0)*WA12*WA29*
1489 : PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
1490 ELSEIF ( L .EQ. 3 .AND.
1491 : IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
1492 PLK9(3)=P3(A3,0)*P9(A9,0)*WA13*WA29*
1493 : PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
1494 ELSEIF ( L .EQ. 4 .AND.
1495 : IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
1496 PLK9(4)=P4(A4,0)*P9(A9,0)*WA14*WA29*
1497 : PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
1498 ELSEIF ( L .EQ. 5 .AND.
1499 : IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
1500 PLK9(5)=P5(A5,0)*P9(A9,0)*WA15*WA29*
1501 : PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(10)
1502 ELSEIF ( L .EQ. 6 .AND.
1503 : IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
1504 PLK9(6)=P6(A6,0)*P9(A9,0)*WA16*WA29*
1505 : PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(10)
1506 ELSEIF ( L .EQ. 7 .AND.
1507 : IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
1508 PLK9(7)=P7(A7,0)*P9(A9,0)*WA17*WA29*
1509 : PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(10)
1510 ELSEIF ( L .EQ. 8 .AND.
1511 : IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
1512 PLK9(8)=P8(A8,0)*P9(A9,0)*WA18*WA29*
1513 : PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(10)
1514 ELSEIF ( L .EQ. 10 .AND.
1515 : IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
1516 PLK9(10)=P9(A9,0)*P10(A10,0)*WA110*WA29*
1517 : PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)
1518 ENDIF
1519 ELSEIF ((K .EQ. 10 .AND. IX(10) .LT. AA2 .AND. NMX(10)
1520 : .GT. AA2 .AND. JJ .EQ. 10).OR.(K .EQ. 10 .AND. IX(10)
1521 : .LT. AA2 .AND. NMX(10) .GT. AA2 .AND. JJ .EQ. 0))THEN
1522 WA210 = ((NMX(10)-AA2)/Z(10))
1523 A10=AA2
1524 IF ( L .EQ. 1 .AND.
1525 : IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
1526 PLK10(1)=P1(A1,0)*P10(A10,0)*WA11*WA210*
1527 : PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
1528 ELSEIF ( L .EQ. 2 .AND.
1529 : IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN

```

```

1530          PLK10(2)=P2(A2,0)*P10(A10,0)*WA12*WA210*
1531      :      PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
1532      ELSEIF ( L .EQ. 3 .AND.
1533      :      IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
1534          PLK10(3)=P3(A3,0)*P10(A10,0)*WA13*WA210*
1535      :      PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
1536      ELSEIF ( L .EQ. 4 .AND.
1537      :      IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
1538          PLK10(4)=P4(A4,0)*P10(A10,0)*WA14*WA210*
1539      :      PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
1540      ELSEIF ( L .EQ. 5 .AND.
1541      :      IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
1542          PLK10(5)=P5(A5,0)*P10(A10,0)*WA15*WA210*
1543      :      PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)
1544      ELSEIF ( L .EQ. 6 .AND.
1545      :      IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
1546          PLK10(6)=P6(A6,0)*P10(A10,0)*WA16*WA210*
1547      :      PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)
1548      ELSEIF ( L .EQ. 7 .AND.
1549      :      IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
1550          PLK10(7)=P7(A7,0)*P10(A10,0)*WA17*WA210*
1551      :      PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)
1552      ELSEIF ( L .EQ. 8 .AND.
1553      :      IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
1554          PLK10(8)=P8(A8,0)*P10(A10,0)*WA17*WA210*
1555      :      PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)
1556      ELSEIF ( L .EQ. 9 .AND.
1557      :      IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
1558          PLK10(9)=P9(A9,0)*P10(A10,0)*WA19*WA210*
1559      :      PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)
1560      ENDIF
1561      ENDIF
1562      ENDIF
1563      ENDDO
1564      ENDDO
1565      PLK(1)=PLK1(2)+PLK1(3)+PLK1(4)+PLK1(5)+PLK1(6)+PLK1(7)
1566      :      +PLK1(8)+PLK1(9)+PLK1(10)
1567      PLK(2)=PLK2(1)+PLK2(3)+PLK2(4)+PLK2(5)+PLK2(6)+PLK2(7)
1568      :      +PLK2(8)+PLK2(9)+PLK2(10)
1569      PLK(3)=PLK3(1)+PLK3(2)+PLK3(4)+PLK3(5)+PLK3(6)+PLK3(7)
1570      :      +PLK3(8)+PLK3(9)+PLK3(10)
1571      PLK(4)=PLK4(1)+PLK4(2)+PLK4(3)+PLK4(5)+PLK4(6)+PLK4(7)
1572      :      +PLK4(8)+PLK4(9)+PLK4(10)
1573      PLK(5)=PLK5(1)+PLK5(2)+PLK5(3)+PLK5(4)+PLK5(6)+PLK5(7)
1574      :      +PLK5(8)+PLK5(9)+PLK5(10)
1575      PLK(6)=PLK6(1)+PLK6(2)+PLK6(3)+PLK6(4)+PLK6(5)+PLK6(7)
1576      :      +PLK6(8)+PLK6(9)+PLK6(10)
1577      PLK(7)=PLK7(1)+PLK7(2)+PLK7(3)+PLK7(4)+PLK7(5)+PLK7(6)
1578      :      +PLK7(8)+PLK7(9)+PLK7(10)
1579      PLK(8)=PLK8(1)+PLK8(2)+PLK8(3)+PLK8(4)+PLK8(5)+PLK8(6)
1580      :      +PLK8(7)+PLK8(9)+PLK8(10)

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```
1581      PLK(9)=PLK9(1)+PLK9(2)+PLK9(3)+PLK9(4)+PLK9(5)+PLK9(6)
1582      :      +PLK9(7)+PLK9(8)+PLK9(10)
1583      PLK(10)=PLK10(1)+PLK10(2)+PLK10(3)+PLK10(4)+PLK10(5)+
1584      :      PLK10(6)+PLK10(7)+PLK10(8)+PLK10(9)
1585      IF ( AA1 .EQ. AA2 ) THEN
1586          PLKE=PLKE+1/2*(PLK(1)+PLK(2)+PLK(3)+PLK(4)+PLK(5)+
1587      :      PLK(6)+PLK(7)+PLK(8)+PLK(9)+PLK(10))
1588          PLKNE=0.0DO
1589      ELSE
1590          PLKNE=PLKNE+(PLK(1)+PLK(2)+PLK(3)+PLK(4)+PLK(5)+
1591      :      PLK(6)+PLK(7)+PLK(8)+PLK(9)+PLK(10))
1592          PLKE=0.0DO
1593      ENDIF
1594      PLKX = PLKX + PLKE + PLKNE
1595      ENDDO
1596      ENDDO
1597      END
```

XIII. APPENDIX E. PROGRAM LISTING FOR SENSITIVITY ANALYSIS
PROCEDURES

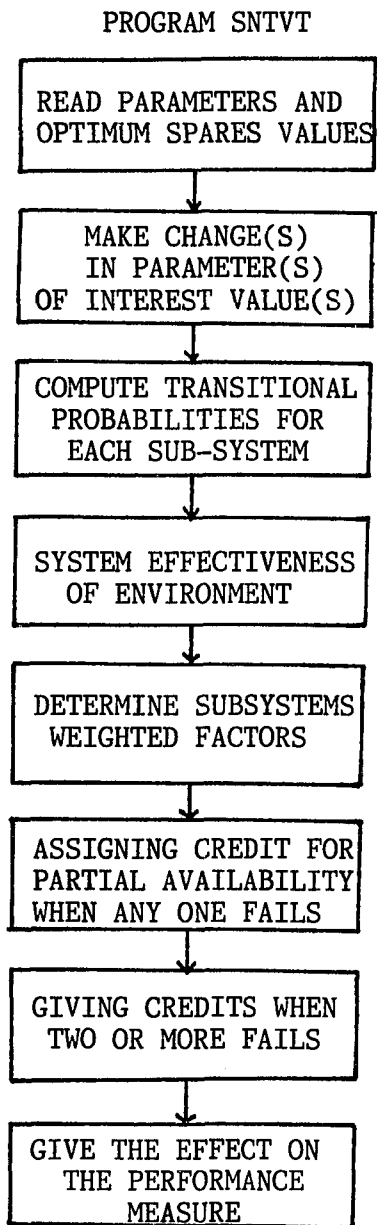


FIGURE 39. Flow chart of computer program SNTVT


```

1      PROGRAM SNTVT
2*****
2*
3*      PURPOSE: 1.COMPUTER CODE FOR SENSITIVITY ANALYSIS OF A
4*                GENERIC FLEXIBLE MANUFACTURING SYSTEM
5*                2.DETERMINES EFFECT ON THE SYSTEM PERFORMANCE
6*                MEASURE DUE TO CHANGE IN ONE OR ALL PARAMETERS
7*                OF INTEREST
8*
9*      PARAMETERS OF INTEREST:
10*             MTF: MEAN TIME TO FAILURE
11*             MTTR: MEAN TIME TO REPAIR
12*             MTR: MEAN TIME REPLACEMENT
13*
14*
15*      INPUT:   INTEGER,
16*             >M:   TYPES OF EQUIPMENT IN AN FMS
17*             >N:   NUMBER OF EACH TYPE IN FMS
18*             >IX:  OPTIMUM VALUES OF SPARE FOR ALL TYPES OF
19*                   EQUIPMENT
20*             INTERACTIVE REAL INPUT,
21*             >MTR: MEAN TIME REPLACEMENT
22*             >MTF: MEAN TIME TO FAILURE
23*             >MTTR: MEAN TIME TO REPAIR
24*
25*      LIMITATION:
26*             >M:   CANNOT BE ZERO OR MORE THAN 10
27*             >N:   CANNOT BE ZERO OR MORE THAN 10
28*
29*      OUTPUT: TABULATED FORM
30*             >PARAMETERS: MTF, MTTR, MTR
31*             >SYS-AVAIL:  SYSTEM PERFORMANCE MEASURE AT
32*                   GIVEN MTF, MTTR, MTR
33*
34*****
35      CHARACTER ANSWER*10
36      INTEGER N,M,X,IX(10),IN(10),NMX(10)
37      REAL MTTR(10),MTTF(10),MTR(10),BETAI(0:14),LAM(0:14),MEU(15)
38      DOUBLEPRECISION P1(0:15,0:1),P2(0:15,0:1),P3(0:15,0:1),
39      :P4(0:15,0:1),P5(0:15,0:1),P6(0:15,0:1),TP(0:15,0:1),
40      :P7(0:15,0:1),P8(0:15,0:1),P9(0:15,0:1),P10(0:15,0:1),PROB
41*
42*             INTERACTIVE DATA INPUT
43*
44      DATA IX/10*1.0/
45      WRITE(6,'(X,A)')'PLEASE SUPPLY THE VALUE OF "M"; WHERE M IS
46      WRITE(6,'(X,A)')'THE TYPES OF EQUIPMENT IN FMS ENVIRONMENT'
47      WRITE(6,*)
48      READ *, M
49      WRITE(6,*)
50      WRITE(6,'(X,A)')'PLEASE SUPPLY THE VALUE OF "N"; WHERE'

```

```

51     WRITE(6, '(X,A)') 'N IS THE # OF EACH TYPE OF EQUIPMENT'
52     DO I=1,M
53         WRITE(6, *)
54         WRITE(6, '(X,A,I2,A)') 'SUPPLY NOW THE VALUE OF N FOR TYPE #'
55     :   ,I, ' ONLY'
56         WRITE(6, *)
57         READ*, IN(I)
58     ENDDO
59     WRITE(6, '(X,A)') 'PLEASE SUPPLY THE OPTIMUM VALUE OF "X"; WHERE'
60     WRITE(6, '(X,A)') 'X IS THE # OF SPARE FOR EACH TYPE OF EQUIPMENT'
61     DO I=1,M
62         WRITE(6, *)
63         WRITE(6, '(X,A,I2,A)') 'SUPPLY NOW THE VALUE OF X FOR TYPE #'
64     :   ,I, ' ONLY'
65         WRITE(6, *)
66         READ*, IX(I)
67     ENDDO
68     DO I=1,M
69         NMX(I)=IN(I)+IX(I)
70     ENDDO
71     WRITE(6, '(X,A)') 'PLEASE SUPPLY THE VALUE OF "P"; WHERE P IS'
72     WRITE(6, '(X,A)') 'THE PROBABILITY THAT A SELECTED SPARE WORKS'
73     WRITE(6, *)
74     READ *, PROB
75     PRINT '(X,A)', '    SENSITIVITY ANALYSIS FOR A GENERIC FMS'
76     PRINT*
77     PRINT '(XM>(3(A,I2,2X)),2X,A)',
78 : ((' MTTF#',I, ' MTTR#',I, ' MTR# ',I),I=1,M), ' SYS-AVAIL'
79     DO WHILE ( ANSWER .NE. 'NO')
80*
81*         INPUT DISCRETE CHANGES IN PARAMETERS OF INTEREST
82*
83     DO I = 1,M
84         WRITE(6, '(X,A,I2,A)') 'SUPPLY VALUES OF "MTTF", "MTTR" & "MTR"
85     :   FOR THE EQUIPMENT TYPE #',I, ' ONLY'
86         WRITE(6, *)
87         WRITE(6, '(X,A,I2)') 'WHERE MTTF IS THE MEAN TIME TO FAILURE
88     :   FOR TYPE #',I
89         WRITE(6, '(X,A,I2)') 'WHERE MTTR IS THE MEAN TIME TO REPAIR
90     :   FOR TYPE #',I
91         WRITE(6, '(X,A,I2)') 'WHERE MTR IS THE MEAN TIME TO REPLACEMENT
92     :   FOR TYPE #',I
93         WRITE(6, *)
94         READ *, MTTF(I),MTTR(I),MTR(I)
95     ENDDO
96     DO JJ = 1,M
97         DO I = 0,NMX(JJ)-1
98             LAM(I) = 1/MTTF(JJ)
99             K = I + 1
100            MEU(K) = 1/(MTTR(JJ) * K)
101            BETA(I) = 1/MTR(JJ)

```

```

102      ENDDO
103      IF ( JJ .EQ. 1 ) THEN
104          X=IX(JJ)
105          N=IN(JJ)
106          NMAX=N+X
107*
108*          TRANSITION PROBABILITY FOR EQUATION TYPE #1
109*
110          CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
111          DO I = 0,NMAX
112              IF ( I .LE. 7 ) THEN
113                  P1(I,0) = TP(2*I,0)
114                  P1(I,1) = TP(2*I+1,0)
115              ELSE
116                  P1(I,0) = TP(2*I-16,1)
117                  P1(I,1) = TP(2*I-15,1)
118              ENDIF
119          ENDDO
120      ELSEIF ( JJ .EQ. 2 ) THEN
121          X=IX(JJ)
122          N=IN(JJ)
123          NMAX=N+X
124*
125*          TRANSITION PROBABILITY FOR EQUATION TYPE #2
126*
127          CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
128          DO I = 0,NMAX
129              IF ( I .LE. 7 ) THEN
130                  P2(I,0) = TP(2*I,0)
131                  P2(I,1) = TP(2*I+1,0)
132              ELSE
133                  P2(I,0) = TP(2*I-16,1)
134                  P2(I,1) = TP(2*I-15,1)
135              ENDIF
136          ENDDO
137      ELSEIF ( JJ .EQ. 3 ) THEN
138          X=IX(JJ)
139          N=IN(JJ)
140          NMAX=N+X
141*
142*          TRANSITION PROBABILITY FOR EQUATION TYPE #3
143*
144          CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
145          DO I = 0,NMAX
146              IF ( I .LE. 7 ) THEN
147                  P3(I,0) = TP(2*I,0)
148                  P3(I,1) = TP(2*I+1,0)
149              ELSE
150                  P3(I,0) = TP(2*I-16,1)
151                  P3(I,1) = TP(2*I-15,1)
152              ENDIF

```

```

153      ENDDO
154      ELSEIF ( JJ .EQ. 4 ) THEN
155          X=IX(JJ)
156          N=IN(JJ)
157          NMAX=N+X
158*
159*      TRANSITION PROBABILITY FOR EQUATION TYPE #4
160*
161      CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
162      DO I = 0,NMAX
163          IF ( I .LE. 7 ) THEN
164              P4(I,0) = TP(2*I,0)
165              P4(I,1) = TP(2*I+1,0)
166          ELSE
167              P4(I,0) = TP(2*I-16,1)
168              P4(I,1) = TP(2*I-15,1)
169          ENDIF
170      ENDDO
171      ELSEIF ( JJ .EQ. 5 ) THEN
172          X=IX(JJ)
173          N=IN(JJ)
174          NMAX=N+X
175*
176*      TRANSITION PROBABILITY FOR EQUATION TYPE #5
177*
178      CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
179      DO I = 0,NMAX
180          IF ( I .LE. 7 ) THEN
181              P5(I,0) = TP(2*I,0)
182              P5(I,1) = TP(2*I+1,0)
183          ELSE
184              P5(I,0) = TP(2*I-16,1)
185              P5(I,1) = TP(2*I-15,1)
186          ENDIF
187      ENDDO
188      ELSEIF ( JJ .EQ. 6 ) THEN
189          X=IX(JJ)
190          N=IN(JJ)
191          NMAX=N+X
192*      TRANSITION PROBABILITY FOR EQUATION TYPE #6
193      CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
194      DO I = 0,NMAX
195          IF ( I .LE. 7 ) THEN
196              P6(I,0) = TP(2*I,0)
197              P6(I,1) = TP(2*I+1,0)
198          ELSE
199              P6(I,0) = TP(2*I-16,1)
200              P6(I,1) = TP(2*I-15,1)
201          ENDIF
202      ENDDO
203      ELSEIF ( JJ .EQ. 7 ) THEN

```

```

204      X=IX(JJ)
205      N=IN(JJ)
206      NMAX=N+X
207*     TRANSITION PROBABILITY FOR EQUATION TYPE #7
208     CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
209     DO I = 0,NMAX
210       IF ( I .LE. 7 ) THEN
211         P7(I,0) = TP(2*I,0)
212         P7(I,1) = TP(2*I+1,0)
213       ELSE
214         P7(I,0) = TP(2*I-16,1)
215         P7(I,1) = TP(2*I-15,1)
216       ENDIF
217     ENDDO
218     ELSEIF ( JJ .EQ. 8 ) THEN
219     X=IX(JJ)
220     N=IN(JJ)
221     NMAX=N+X
222*    TRANSITION PROBABILITY FOR EQUATION TYPE #8
223    CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
224    DO I = 0,NMAX
225      IF ( I .LE. 7 ) THEN
226        P8(I,0) = TP(2*I,0)
227        P8(I,1) = TP(2*I+1,0)
228      ELSE
229        P8(I,0) = TP(2*I-16,1)
230        P8(I,1) = TP(2*I-15,1)
231      ENDIF
232    ENDDO
233    ELSEIF ( JJ .EQ. 9 ) THEN
234    X=IX(JJ)
235    N=IN(JJ)
236    NMAX=N+X
237*   TRANSITION PROBABILITY FOR EQUATION TYPE #9
238   CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
239   DO I = 0,NMAX
240     IF ( I .LE. 7 ) THEN
241       P9(I,0) = TP(2*I,0)
242       P9(I,1) = TP(2*I+1,0)
243     ELSE
244       P9(I,0) = TP(2*I-16,1)
245       P9(I,1) = TP(2*I-15,1)
246     ENDIF
247   ENDDO
248   ELSEIF ( JJ .EQ. 10 ) THEN
249   X=IX(JJ)
250   N=IN(JJ)
251   NMAX=N+X
252*  TRANSITION PROBABILITY FOR EQUATION TYPE #10
253  CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
254  DO I = 0,NMAX

```

```

255         IF ( I .LE. 7 ) THEN
256             P10(I,0) = TP(2*I,0)
257             P10(I,1) = TP(2*I+1,0)
258         ELSE
259             P10(I,0) = TP(2*I-16,1)
260             P10(I,1) = TP(2*I-15,1)
261         ENDIF
262     ENDDO
263 ENDIF
264 ENDDO
265*
266*         COMPUTING AND FORMATTING THE OUTPUT
267*
268     CALL TAVAIL(M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,A0)
269     CALL SFAIL1(NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PAAX)
270     CALL SFAIL2(NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PLKX)
271     WRITE(6,*)
272     SYSAVAL=A0+PAAX+PLKX
273     WRITE(6,*)
274     PRINT'(3X>(3(F7.2,4X)),F9.6)',
275     : (MTTF(I),MTTR(I),MTR(I),I=1,M),SYSAVAL
276     WRITE(6,*)
277     WRITE(6,'(X,A)') 'DO YOU WANT TO PERFORM MORE DISCRETE CHANGES'
278     WRITE(6,'(X,A)') ' IN THE PARAMETER OR PARAMETERS OF INTEREST'
279     WRITE(6,'(X,A)') ' OR YOU ARE DONE; >> ANSWER "YES" OR "NO"'
280     READ'(A)',ANSWER
281     ENDDO
282     STOP
283     END
284*****
285*
286*     PURPOSE: SUBROUTINE FOR CALCULATING TRANSITION PROBABILITY :
287*             USING MARKOVIAN STEADY STATE EQUATIONS :
288*
289*     INPUT: :
290*     >      :N, M, X, P's, NMAX, PROB :
291*           ( EXPLAINED EARLIER ) :
292*
293*     OUTPUT: :
294*     >TP :TRANSITIONAL PROBABILITY :
295*
296*****
297     SUBROUTINE TPROB(N,M,X,NMAX,PROB,LAM,MEU,BI,TP)
298     INTEGER X
299     REAL LAM(0:NMAX-1),MEU(NMAX),BI(0:NMAX-1)
300     DOUBLEPRECISION TP(0:NMAX,0:1),A(31,31),RHS(31),
301     :B(0:4,1:5),BX,BIIP,PROB
302C     INITIALIZE THE MATRIX
303     DO I = 1,NMAX*2+1
304         DO J = 1,NMAX*2+1
305             A(I,J) = 0.0

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```

306      ENDDO
307      ENDDO
308      DO I = 0,NMAX
309          DO J = 0,1
310              TP(I,J)=0.0
311          ENDDO
312      ENDDO
313*
314*      CALCULATING TRANSITION PROBABILITY FROM (i,1) to (i',1)
315*      FOR ONE EQUIPMENT TYPE; WHERE i IS NOT EQUAL TO i'
316*
317      DO K = 0,X-1
318          IF ( K .EQ. 0 ) THEN
319              IF ( X .EQ. 1 ) THEN
320                  B(K,1)=(1-PROB)*PROB
321              ELSEIF ( X .EQ. 2 ) THEN
322                  B(K,1)=(1-PROB)*PROB
323                  B(K,2)=(1-PROB)**2*PROB
324              ELSEIF ( X .EQ. 3 ) THEN
325                  B(K,1)=(1-PROB)*PROB
326                  B(K,2)=(1-PROB)**2*PROB
327                  B(K,3)=(1-PROB)**3*PROB
328              ELSEIF ( X .EQ. 4 ) THEN
329                  B(K,1)=(1-PROB)*PROB
330                  B(K,2)=(1-PROB)**2*PROB
331                  B(K,3)=(1-PROB)**3*PROB
332                  B(K,4)=(1-PROB)**4*PROB
333              ELSEIF ( X .EQ. 5 ) THEN
334                  B(K,1)=(1-PROB)*PROB
335                  B(K,2)=(1-PROB)**2*PROB
336                  B(K,3)=(1-PROB)**3*PROB
337                  B(K,4)=(1-PROB)**4*PROB
338                  B(K,5)=(1-PROB)**5*PROB
339              ENDIF
340          ELSEIF ( K .EQ. 1 ) THEN
341              IF ( X .EQ. 2 ) THEN
342                  B(K,2)=(1-PROB)*PROB
343              ELSEIF ( X .EQ. 3 ) THEN
344                  B(K,2)=(1-PROB)*PROB
345                  B(K,3)=(1-PROB)**2*PROB
346              ELSEIF ( X .EQ. 4 ) THEN
347                  B(K,2)=(1-PROB)*PROB
348                  B(K,3)=(1-PROB)**2*PROB
349                  B(K,4)=(1-PROB)**3*PROB
350              ELSEIF ( X .EQ. 5 ) THEN
351                  B(K,2)=(1-PROB)*PROB
352                  B(K,3)=(1-PROB)**2*PROB
353                  B(K,4)=(1-PROB)**3*PROB
354                  B(K,5)=(1-PROB)**4*PROB
355              ENDIF
356          ELSEIF ( K .EQ. 2 ) THEN

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```

357         IF ( X .EQ. 3 ) THEN
358             B(K,3)=(1-PROB)*PROB
359         ELSEIF ( X .EQ. 4 ) THEN
360             B(K,3)=(1-PROB)*PROB
361             B(K,4)=(1-PROB)**2*PROB
362         ELSEIF ( X .EQ. 5 ) THEN
363             B(K,3)=(1-PROB)*PROB
364             B(K,4)=(1-PROB)**2*PROB
365             B(K,5)=(1-PROB)**3*PROB
366         ENDIF
367     ELSEIF ( K .EQ. 3 ) THEN
368         IF ( X .EQ. 4 ) THEN
369             B(K,4)=(1-PROB)*PROB
370         ELSEIF ( X .EQ. 5 ) THEN
371             B(K,4)=(1-PROB)*PROB
372             B(K,5)=(1-PROB)**2*PROB
373         ENDIF
374     ELSEIF ( K .EQ. 4 ) THEN
375         IF ( X .EQ. 5 ) THEN
376             B(K,5)=(1-PROB)*PROB
377         ENDIF
378     ENDIF
379 ENDDO
380*
381* EQUATION #1
382*
383* LAM(0)*TP(0,0) = MEU(1)*TP(1,0)
384 A(1,1) = -LAM(0)
385 A(1,3) = MEU(1)
386*
387* EQUATION #2A
388*
389* (LAM(I)+MEU(I))*TP(I,0) = PROB*BI(I-1)*TP(I-1,1)+MEU(I+1)*TP(I+1,0)
390 DO I = 1,X
391     A(I+1,2*I+1) = LAM(I)+MEU(I)
392     A(I+1,2*I) = -PROB*BI(I-1)
393     A(I+1,2*I+3) = -MEU(I+1)
394 ENDDO
395*
396* EQUATION #2B
397*
398* (LAM(I)+MEU(I))*TP(I,0) = BI(I-1)*TP(I-1,1)+MEU(I+1)*TP(I+1,0)
399 DO I = X+1,NMAX-2
400     A(I+1,2*I+1) = LAM(I)+MEU(I)
401     A(I+1,2*I) = -BI(I-1)
402     A(I+1,2*I+3) = -MEU(I+1)
403 ENDDO
404*
405* EQUATION #3
406*
407* MEU(NMAX)*TP(NMAX,0) = BI(NMAX-1)*TP(NMAX-1,1)

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408      A(NMAX,NMAX*2+1) = MEU(NMAX)
409      A(NMAX,NMAX*2) = -BI(NMAX-1)
410*
411*      EQUATION #4
412*
413      BX = 0.0DO
414      DO IP = 1,X
415          BX = BX + B(0,IP)
416      ENDDO
417*      PROB*BI(0)*TP(0,1)+BX*TP(0,1) = LAM(0)*TP(0,0)
418      A(NMAX+1,2) = PROB*BI(0)+BX
419      A(NMAX+1,1) = -LAM(0)
420*
421*      EQUATION #6
422*
423*      BIPX = 0.0
424*      DO IP = 0,X-1
425*          BIPX = BIPX + B(IP,X)*TP(IP,1)
426*      ENDDO
427*      BI(X)*TP(X,1) = LAM(X)*TP(X,0) + BIPX
428      IF ( X .EQ. 1 ) THEN
429          A(NMAX+2,2*X+2) = -BI(X)
430          A(NMAX+2,2*X+1) = LAM(X)
431          A(NMAX+2,2*X) = B(0,X)
432      ELSEIF ( X .EQ. 2 ) THEN
433          A(NMAX+2,2*X+2) = -BI(X)
434          A(NMAX+2,2*X+1) = LAM(X)
435          A(NMAX+2,2*X-2) = B(0,X)
436          A(NMAX+2,2*X) = B(1,X)
437      ELSEIF ( X .EQ. 3 ) THEN
438          A(NMAX+2,2*X+2) = -BI(X)
439          A(NMAX+2,2*X+1) = LAM(X)
440          A(NMAX+2,2*X-4) = B(0,X)
441          A(NMAX+2,2*X-2) = B(1,X)
442          A(NMAX+2,2*X) = B(2,X)
443      ELSEIF ( X .EQ. 4 ) THEN
444          A(NMAX+2,2*X+2) = -BI(X)
445          A(NMAX+2,2*X+1) = LAM(X)
446          A(NMAX+2,2*X-6) = B(0,X)
447          A(NMAX+2,2*X-4) = B(1,X)
448          A(NMAX+2,2*X-2) = B(2,X)
449          A(NMAX+2,2*X) = B(3,X)
450      ELSEIF ( X .EQ. 5 ) THEN
451          A(NMAX+2,2*X+2) = -BI(X)
452          A(NMAX+2,2*X+1) = LAM(X)
453          A(NMAX+2,2*X-8) = B(0,X)
454          A(NMAX+2,2*X-6) = B(1,X)
455          A(NMAX+2,2*X-4) = B(2,X)
456          A(NMAX+2,2*X-2) = B(3,X)
457          A(NMAX+2,2*X) = B(4,X)
458      ENDIF

```

```

459*
460*   EQUATION #7
461*
462   DO I = X+1,NMAX-1
463*     BI(I)*TP(I,1) = LAM(I)*TP(I,0)
464     A(NMAX+2+I-X,2*I+2) = BI(I)
465     A(NMAX+2+I-X,2*I+1) = -LAM(I)
466   ENDDO
467*
468*   EQUATION #8
469*
470   PIO=0
471   PII=0
472   DO I =0,NMAX
473*     PIO = PIO + TP(I,0)
474     A(NMAX+2+N,2*I+1) = 1.
475     IF ( I .NE. NMAX ) THEN
476*       PII = PII + TP(I,1)
477       A(NMAX+2+N,2*I+2) = 1.
478     ENDIF
479   ENDDO
480*   PIO + PII = 1
481*
482*   EQUATION #5
483*
484   DO I = 1,X-1,1
485     BIIP = 0.0D0
486     DO IP = I+1,X
487       BIIP = BIIP + B(I,IP)
488     ENDDO
489*     BIPI = 0
490*     DO IP = 0,I-1
491*       BIPI = BIPI + B(IP,I)*TP(IP,1)
492*     ENDDO
493*     PROB*BI(I)*TP(I,1)+BIIP*TP(I,1)=LAM(I)*TP(I,0)+BIPI
494     IF ( I .EQ. 1 ) THEN
495       A(NMAX+N+2+I,2*I+2) =-PROB*BI(I)-BIIP
496       A(NMAX+N+2+I,2*I+1) = LAM(I)
497       A(NMAX+N+2+I,2*I)   = B(0,1)
498     ELSEIF ( I .EQ. 2 ) THEN
499       A(NMAX+N+2+I,2*I+2) =-PROB*BI(I)-BIIP
500       A(NMAX+N+2+I,2*I+1) = LAM(I)
501       A(NMAX+N+2+I,2*I)   = B(1,2)
502       A(NMAX+N+2+I,2*I-2) = B(0,2)
503     ELSEIF ( I .EQ. 3 ) THEN
504       A(NMAX+N+2+I,2*I+2) =-PROB*BI(I)-BIIP
505       A(NMAX+N+2+I,2*I+1) = LAM(I)
506       A(NMAX+N+2+I,2*I)   = B(2,3)
507       A(NMAX+N+2+I,2*I-2) = B(1,3)
508       A(NMAX+N+2+I,2*I-4) = B(0,3)
509     ELSEIF ( I .EQ. 4 ) THEN

```

```

510          A(NMAX+N+2+I,2*I+2) =-PROB*BI(I)-BIIP
511          A(NMAX+N+2+I,2*I+1) = LAM(I)
512          A(NMAX+N+2+I,2*I)   = B(3,4)
513          A(NMAX+N+2+I,2*I-2) = B(2,4)
514          A(NMAX+N+2+I,2*I-4) = B(1,4)
515          A(NMAX+N+2+I,2*I-6) = B(0,4)
516      ENDIF
517      ENDDO
518*
519*          COMPUTING TRANSITIONAL PROBABILITY
520*
521      DO I = 1,NMAX*2+1
522          RHS(I) = 0.0DO
523      ENDDO
524      RHS(NMAX+N+2) = 1.0DO
525      NB = 1
526      CALL DLSTSQ(31,31,NMAX*2+1,NMAX*2+1,A,RHS,NB,TP)
527      END
528*****
529*
530*      PURPOSE: CALCULATES THE TRADITIONAL AVAILABILITY WHEN
531*              NUMBER IN REPAIR PROCESS IS LESS OR EQUAL TO
531*              SPARE AVAILABLE
532*
533*      INPUT:
534*          >      :M, IX, P's, ( EXPLAINED EARLIER )
535*
536*      OUTPUT:
537*          >A0   : TRADITIONAL AVAILABILITY
538*
539*****
540      SUBROUTINE
541      :TAVAIL(M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,A0)
542      INTEGER S,X,IX(10)
543      DOUBLEPRECISION P1(0:IX(1),0:0),P2(0:IX(2),0:0),
544      :P3(0:IX(3),0:0),P4(0:IX(4),0:0),P5(0:IX(5),0:0),
545      :P6(0:IX(6),0:0),P7(0:IX(7),0:0),P8(0:IX(8),0:0),
546      :P9(0:IX(9),0:0),P10(0:IX(10),0:0),PP1,PP2,PP3,
547      :PP4,PP5,PP6,PP7,PP8,PP9,PP10
548*
549*              INITIALIZE
550*
551      DATA PP1,PP2,PP3,PP4,PP5,PP6,PP7,PP8,PP9,PP10
552      : /1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0/
553      DO I = 1,M
554          IF ( I .EQ. 1 ) THEN
555              PP1 = 0.0
556              DO S = 0,IX(1)
557                  PP1 = PP1 + P1(S,0)
558              ENDDO
559          ELSEIF ( I .EQ. 2 ) THEN

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```

560         PP2 = 0.0
561         DO S = 0, IX(2)
562             PP2 = PP2 + P2(S,0)
563         ENDDO
564     ELSEIF ( I .EQ. 3 ) THEN
565         PP3 = 0.0
566         DO S = 0, IX(3)
567             PP3 = PP3 + P3(S,0)
568         ENDDO
569     ELSEIF ( I .EQ. 4 ) THEN
570         PP4 = 0.0
571         DO S = 0, IX(4)
572             PP4 = PP4 + P4(S,0)
573         ENDDO
574     ELSEIF ( I .EQ. 5 ) THEN
575         PP5 = 0.0
576         DO S = 0, IX(5)
577             PP5 = PP5 + P5(S,0)
578         ENDDO
579     ELSEIF ( I .EQ. 6 ) THEN
580         PP6 = 0.0
581         DO S = 0, IX(6)
582             PP6 = PP6 + P6(S,0)
583         ENDDO
584     ELSEIF ( I .EQ. 7 ) THEN
585         PP7 = 0.0
586         DO S = 0, IX(7)
587             PP7 = PP7 + P7(S,0)
588         ENDDO
589     ELSEIF ( I .EQ. 8 ) THEN
590         PP8 = 0.0
591         DO S = 0, IX(8)
592             PP8 = PP8 + P8(S,0)
593         ENDDO
594     ELSEIF ( I .EQ. 9 ) THEN
595         PP9 = 0.0
596         DO S = 0, IX(9)
597             PP9 = PP9 + P9(S,0)
598         ENDDO
599     ELSEIF ( I .EQ. 10 ) THEN
600         PP10 = 0.0
601         DO S = 0, IX(10)
602             PP10 = PP10 + P10(S,0)
603         ENDDO
604     ENDIF
605     ENDDO
606     AO=PP1*PP2*PP3*PP4*PP5*PP6*PP7*PP8*PP9*PP10
607     END
608*****
609*
610*     PURPOSE: SUBROUTINE WHEN ONLY ONE EQUIPMENT TYPE IN THE

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611*           STATE (X+1,0)                               :
612*                                                    :
613*   INPUT:                                             :
614*       >       : M, IN, NMX, P's, (EXPLAINED EARLIER) :
615*   OUTPUT:                                           :
616*       >PAAX: PARTIAL CREDITS FOR PARTIAL AVAILABILITY :
617*                                                    :
618*****
619   SUBROUTINE
620   :SFALL1(NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PAAX)
621   INTEGER X,S,AA1,NMX(10),IX(10),IN(M)
622   DOUBLEPRECISION P1(0:NMX(1),0:1),P2(0:NMX(2),0:1),
623   :P3(0:NMX(3),0:1),P4(0:NMX(4),0:1),P5(0:NMX(5),0:1),
624   :P6(0:NMX(6),0:1),P7(0:NMX(7),0:1),P8(0:NMX(8),0:1),
625   :P9(0:NMX(9),0:1),P10(0:NMX(10),0:1),PP(10),PAA(10),PAAX
626   REAL Z(10)
627*
628*           INITIALIZE
629*
630   DATA PP/10*0.0D0/
631   DO I = 1,M
632     IF ( I .EQ. 1 ) THEN
633       DO S = 0,IX(1)
634         PP(1) = PP(1) + P1(S,0)
635       ENDDO
636     ELSEIF ( I .EQ. 2 ) THEN
637       DO S = 0,IX(2)
638         PP(2) = PP(2) + P2(S,0)
639       ENDDO
640     ELSEIF ( I .EQ. 3 ) THEN
641       DO S = 0,IX(3)
642         PP(3) = PP(3) + P3(S,0)
643       ENDDO
644     ELSEIF ( I .EQ. 4 ) THEN
645       DO S = 0,IX(4)
646         PP(4) = PP(4) + P4(S,0)
647       ENDDO
648     ELSEIF ( I .EQ. 5 ) THEN
649       DO S = 0,IX(5)
650         PP(5) = PP(5) + P5(S,0)
651       ENDDO
652     ELSEIF ( I .EQ. 6 ) THEN
653       DO S = 0,IX(6)
654         PP(6) = PP(6) + P6(S,0)
655       ENDDO
656     ELSEIF ( I .EQ. 7 ) THEN
657       DO S = 0,IX(7)
658         PP(7) = PP(7) + P7(S,0)
659       ENDDO
660     ELSEIF ( I .EQ. 8 ) THEN
661       DO S = 0,IX(8)

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662         PP(8) = PP(8) + P8(S,0)
663         ENDDO
664     ELSEIF ( I .EQ. 9 ) THEN
665         DO S = 0,IX(9)
666             PP(9) = PP(9) + P9(S,0)
667         ENDDO
668     ELSEIF ( I .EQ. 10 ) THEN
669         DO S = 0,IX(10)
670             PP(10) = PP(10) + P10(S,0)
671         ENDDO
672     ENDIF
673     ENDDO
674     DO I=M+1,10
675         PP(I)=1.0
676     ENDDO
677     DO I=1,M
678         Z(I)=IN(I)
679     ENDDO
680     PAAX = 0.0
681     X=MIN(IX(1),IX(2),IX(3),IX(4),IX(5),
682 :       IX(6),IX(7),IX(8),IX(9),IX(10))
683     NMAX=MAX(NMX(1),NMX(2),NMX(3),NMX(4),NMX(5),
684 :       NMX(6),NMX(7),NMX(8),NMX(9),NMX(10))
685     DO K=1,10
686         PAA(K)=0.000
687     ENDDO
688*
689*         COMPUTING PARTIAL CREDITS
690*
691     DO AAL = X+1,NMAX-1
692         DO K = 1,M
693             IF (K .EQ. 1
694 :             .AND. IX(1) .LT. AAL .AND. NMX(1) .GT. AAL)THEN
695                 WAA1 = ((NMX(1)-AAL)/Z(1))
696                 PAA(1)=P1(AAL,0)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*
697 :                 PP(8)*PP(9)*PP(10)*WAA1
698             ELSEIF ( K .EQ. 2 .AND.
699 :                 IX(2) .LT. AAL .AND. NMX(2) .GT. AAL ) THEN
700                 WAA2 = ((NMX(2)-AAL)/Z(2))
701                 PAA(2)=P2(AAL,0)*PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*
702 :                 PP(8)*PP(9)*PP(10)*WAA2
703             ELSEIF ( K .EQ. 3 .AND.
704 :                 IX(3) .LT. AAL .AND. NMX(3) .GT. AAL ) THEN
705                 WAA3 = ((NMX(3)-AAL)/Z(3))
706                 PAA(3)=P3(AAL,0)*PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*
707 :                 PP(8)*PP(9)*PP(10)*WAA3
708             ELSEIF ( K .EQ. 4 .AND.
709 :                 IX(4) .LT. AAL .AND. NMX(4) .GT. AAL ) THEN
710                 WAA4 = ((NMX(4)-AAL)/Z(4))
711                 PAA(4)=P4(AAL,0)*PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*
712 :                 PP(8)*PP(9)*PP(10)*WAA4

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713      ELSEIF ( K .EQ. 5 .AND.
714 :          IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
715      WAA5 = ((NMX(5)-AA1)/Z(5))
716      PAA(5)=P5(AA1,0)*PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*
717 :          PP(8)*PP(9)*PP(10)*WAA5
718      ELSEIF ( K .EQ. 6 .AND.
719 :          IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
720      WAA6 = ((NMX(6)-AA1)/Z(6))
721      PAA(6)=P6(AA1,0)*PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*
722 :          PP(8)*PP(9)*PP(10)*WAA6
723      ELSEIF ( K .EQ. 7 .AND.
724 :          IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
725      WAA7 = ((NMX(7)-AA1)/Z(7))
726      PAA(7)=P7(AA1,0)*PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*
727 :          PP(8)*PP(9)*PP(10)*WAA7
728      ELSEIF ( K .EQ. 8 .AND.
729 :          IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
730      WAA8 = ((NMX(8)-AA1)/Z(8))
731      PAA(8)=P8(AA1,0)*PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*
732 :          PP(7)*PP(9)*PP(10)*WAA8
733      ELSEIF ( K .EQ. 9 .AND.
734 :          IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
735      WAA9 = ((NMX(9)-AA1)/Z(9))
736      PAA(9)=P9(AA1,0)*PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*
737 :          PP(7)*PP(8)*PP(10)*WAA9
738      ELSEIF ( K .EQ. 10 .AND.
739 :          IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
740      WAA10 = ((NMX(10)-AA1)/Z(10))
741      PAA(10)=P10(AA1,0)*PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)
742 :          *PP(7)*PP(8)*PP(9)*WAA10
743      ENDIF
744      ENDDO
745      PAAX = PAAX+(PAA(1)+PAA(2)+PAA3+PAA(4)+PAA(5)+PAA(6)+
746 :          PAA(7)+PAA(8)+PAA(9)+PAA(10))
747      ENDDO
748      END
749*****
750*
751*      PURPOSE: SUBROUTINE WHEN ANY TWO EQUIPMENT TYPES IN
752*              THE STATE (X+1,0)
753*
754*      INPUT:
755*          >      : M, IN, IX, NMX, P's
756*                  (EXPLAINED EARLIER)
757*      OUTPUT:
758*          >PLKX: PARTIAL CREDITS FOR PARTIAL
759*                  AVAILABILITY
760*
761*****
762      SUBROUTINE
763      :SFAL2(NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PLKX)

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764     INTEGER X,S,AA1,AA2,A1,A2,A3,A4,A5,A6,A7,A8,A9,A10
765     INTEGER IX(10),IN(M),NMX(10)
766     DOUBLEPRECISION P1(0:NMX(1),0:1),P2(0:NMX(2),0:1),
767     :P3(0:NMX(3),0:1),P4(0:NMX(4),0:1),P5(0:NMX(5),0:1),
768     :P6(0:NMX(6),0:1),P7(0:NMX(7),0:1),P8(0:NMX(8),0:1),
769     :P9(0:NMX(9),0:1),P10(0:NMX(10),0:1),PP(10),PLKE,PLKNE,
770     :PLK1,PLK2,PLK3,PLK4,PLK5,PLK6,PLK7,PLK8,PLK9,PLK10,PLKX
771     REAL Z(10)
772*
773*           INITIALIZE
774*
775     DATA PP(1),PP(2),PP(3),PP(4),PP(5),PP(6),PP(7),PP(8),PP(9),
776     :      PP(10)/0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/,
777     :      PLK1,PLK2,PLK3,PLK4,PLK5,PLK6,PLK7,PLK8,PLK9,PLK10
778     :      /0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/,
779     :      PLK12,PLK13,PLK14,PLK15,PLK16,PLK17,PLK18,PLK19,PLK110
780     :      /0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/,
781     :      PLK21,PLK23,PLK24,PLK25,PLK26,PLK27,PLK28,PLK29,PLK210
782     :      /0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/,
783     :      PLK31,PLK32,PLK34,PLK35,PLK36,PLK37,PLK38,PLK39,PLK310
784     :      /0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/,
785     :      PLK41,PLK42,PLK43,PLK45,PLK46,PLK47,PLK48,PLK49,PLK410
786     :      /0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/,
787     :      PLK51,PLK52,PLK53,PLK54,PLK56,PLK57,PLK58,PLK59,PLK510
788     :      /0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/,
789     :      PLK61,PLK62,PLK63,PLK64,PLK65,PLK67,PLK68,PLK69,PLK610
790     :      /0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/,
791     :      PLK71,PLK72,PLK73,PLK74,PLK75,PLK76,PLK78,PLK79,PLK710
792     :      /0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/,
793     :      PLK81,PLK82,PLK83,PLK84,PLK85,PLK86,PLK87,PLK89,PLK810
794     :      /0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/,
795     :      PLK91,PLK92,PLK93,PLK94,PLK95,PLK96,PLK97,PLK98,PLK910
796     :      /0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/,
797     :      PLK101,PLK102,PLK103,PLK104,PLK105,PLK106,PLK107,PLK108,
798     :      PLK109/0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/
799     DO I = 1,M
800         IF ( I .EQ. 1 ) THEN
801             DO S = 0,IX(1)
802                 PP(1) = PP(1) + P1(S,0)
803             ENDDO
804         ELSEIF ( I .EQ. 2 ) THEN
805             DO S = 0,IX(2)
806                 PP(2) = PP(2) + P2(S,0)
807             ENDDO
808         ELSEIF ( I .EQ. 3 ) THEN
809             DO S = 0,IX(3)
810                 PP(3) = PP(3) + P3(S,0)
811             ENDDO
812         ELSEIF ( I .EQ. 4 ) THEN
813             DO S = 0,IX(4)
814                 PP(4) = PP(4) + P4(S,0)

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815         ENDDO
816     ELSEIF ( I .EQ. 5 ) THEN
817         DO S = 0,IX(5)
818             PP(5) = PP(5) + P5(S,0)
819         ENDDO
820     ELSEIF ( I .EQ. 6 ) THEN
821         DO S = 0,IX(6)
822             PP(6) = PP(6) + P6(S,0)
823         ENDDO
824     ELSEIF ( I .EQ. 7 ) THEN
825         DO S = 0,IX(7)
826             PP(7) = PP(7) + P7(S,0)
827         ENDDO
828     ELSEIF ( I .EQ. 8 ) THEN
829         DO S = 0,IX(8)
830             PP(8) = PP(8) + P8(S,0)
831         ENDDO
832     ELSEIF ( I .EQ. 9 ) THEN
833         DO S = 0,IX(9)
834             PP(9) = PP(9) + P9(S,0)
835         ENDDO
836     ELSEIF ( I .EQ. 10 ) THEN
837         DO S = 0,IX(10)
838             PP(10) = PP(10) + P10(S,0)
839         ENDDO
840     ENDIF
841     ENDDO
842     DO I=M+1,10
843         PP(I)=1.0
844     ENDDO
845     DO I=1,M
846         Z(I)=IN(I)
847     ENDDO
848     X=MIN(IX(1),IX(2),IX(3),IX(4),IX(5),
849 :       IX(6),IX(7),IX(8),IX(9),IX(10))
850     NMAX=MAX(NMX(1),NMX(2),NMX(3),NMX(4),NMX(5),
851 :       NMX(6),NMX(7),NMX(8),NMX(9),NMX(10))
852     PLKE = 0.0D0
853     PLKNE = 0.0D0
854     PLKX = 0.0D0
855*
856*         PARTIAL CREDITS DETERMINATION
857*
858     DO AA1 = X+1,NMAX-1
859     DO AA2 = X+1,NMAX-1
860     DO L = 1,M
861     IF ( L .EQ. 1 ) THEN
862         A1 = AA1
863         WA11 = ((NMX(1)-AA1)/Z(1))
864     ELSEIF ( L .EQ. 2 ) THEN
865         A2 = AA1

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917 :      PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
918 :      ELSEIF ( L .EQ. 7 .AND.
919 :      IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
920 :      PLK17=P1(A1,0)*P7(A7,0)*WA17*WA21*
921 :      PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
922 :      ELSEIF ( L .EQ. 8 .AND.
923 :      IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
924 :      PLK18=P1(A1,0)*P8(A8,0)*WA18*WA21*
925 :      PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
926 :      ELSEIF ( L .EQ. 9 .AND.
927 :      IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
928 :      PLK19=P1(A1,0)*P9(A9,0)*WA19*WA21*
929 :      PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
930 :      ELSEIF ( L .EQ. 10 .AND.
931 :      IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
932 :      PLK110=P1(A1,0)*P10(A10,0)*WA110*WA21*
933 :      PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
934 :      ENDIF
935 :      ELSEIF ( K .EQ. 2 .AND.
936 :      IX(2) .LT. AA2 .AND. NMX(2) .GT. AA2) THEN
937 :      WA22 = ((NMX(2)-AA2)/Z(2))
938 :      A2=AA2
939 :      IF ( L .EQ. 1 .AND.
940 :      IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
941 :      PLK21=P1(A1,0)*P2(A2,0)*WA11*WA22*
942 :      PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
943 :      ELSEIF ( L .EQ. 3 .AND.
944 :      IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
945 :      PLK23=P2(A2,0)*P3(A3,0)*WA13*WA22*
946 :      PP(1)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
947 :      ELSEIF ( L .EQ. 4 .AND.
948 :      IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
949 :      PLK24=P2(A2,0)*P4(A4,0)*WA14*WA22*
950 :      PP(1)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
951 :      ELSEIF ( L .EQ. 5 .AND.
952 :      IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
953 :      PLK25=P2(A2,0)*P5(A5,0)*WA15*WA22*
954 :      PP(1)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
955 :      ELSEIF ( L .EQ. 6 .AND.
956 :      IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
957 :      PLK26=P2(A2,0)*P6(A6,0)*WA16*WA22*
958 :      PP(1)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
959 :      ELSEIF ( L .EQ. 7 .AND.
960 :      IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
961 :      PLK27=P2(A2,0)*P7(A7,0)*WA17*WA22*
962 :      PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
963 :      ELSEIF ( L .EQ. 8 .AND.
964 :      IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
965 :      PLK28=P2(A2,0)*P8(A8,0)*WA18*WA22*
966 :      PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
967 :      ELSEIF ( L .EQ. 9 .AND.

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968      :      IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
969      :      PLK29=P2(A2,0)*P9(A9,0)*WA19*WA22*
970      :      PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
971      :      ELSEIF ( L .EQ. 10 .AND.
972      :      IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
973      :      PLK210=P2(A2,0)*P10(A10,0)*WA110*WA22*
974      :      PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
975      :      ENDIF
976      :      ELSEIF ( K .EQ. 3 .AND.
977      :      IX(3) .LT. AA2 .AND. NMX(3) .GT. AA2) THEN
978      :      WA23 = ((NMX(3)-AA2)/Z(3))
979      :      A3=AA2
980      :      IF ( L .EQ. 1 .AND.
981      :      IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
982      :      PLK31=P1(A1,0)*P3(A3,0)*WA11*WA23*
983      :      PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
984      :      ELSEIF ( L .EQ. 2 .AND.
985      :      IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
986      :      PLK32=P2(A2,0)*P3(A3,0)*WA12*WA23*
987      :      PP(1)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
988      :      ELSEIF ( L .EQ. 4 .AND.
989      :      IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
990      :      PLK34=P3(A3,0)*P4(A4,0)*WA14*WA23*
991      :      PP(1)*PP(2)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
992      :      ELSEIF ( L .EQ. 5 .AND.
993      :      IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
994      :      PLK35=P3(A3,0)*P5(A5,0)*WA15*WA23*
995      :      PP(1)*PP(2)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
996      :      ELSEIF ( L .EQ. 6 .AND.
997      :      IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
998      :      PLK36=P3(A3,0)*P6(A6,0)*WA16*WA23*
999      :      PP(1)*PP(2)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
1000     :      ELSEIF ( L .EQ. 7 .AND.
1001     :      IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
1002     :      PLK37=P3(A3,0)*P7(A7,0)*WA17*WA23*
1003     :      PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
1004     :      ELSEIF ( L .EQ. 8 .AND.
1005     :      IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
1006     :      PLK38=P3(A3,0)*P8(A8,0)*WA18*WA23*
1007     :      PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
1008     :      ELSEIF ( L .EQ. 9 .AND.
1009     :      IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
1010     :      PLK39=P3(A3,0)*P9(A9,0)*WA19*WA23*
1011     :      PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
1012     :      ELSEIF ( L .EQ. 10 .AND.
1013     :      IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
1014     :      PLK310=P3(A3,0)*P10(A10,0)*WA110*WA23*
1015     :      PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
1016     :      ENDIF
1017     :      ELSEIF ( K .EQ. 4 .AND.
1018     :      IX(4) .LT. AA2 .AND. NMX(4) .GT. AA2) THEN

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1019      WA24 = ((NMX(4)-AA2)/Z(4))
1020      A4=AA2
1021      IF ( L .EQ. 1 .AND.
1022 :      IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
1023      PLK41=P1(A1,0)*P4(A4,0)*WA11*WA24*
1024 :      PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
1025      ELSEIF ( L .EQ. 2 .AND.
1026 :      IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
1027      PLK42=P2(A2,0)*P4(A4,0)*WA12*WA24*
1028 :      PP(1)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
1029      ELSEIF ( L .EQ. 3 .AND.
1030 :      IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
1031      PLK43=P3(A3,0)*P4(A4,0)*WA13*WA24*
1032 :      PP(1)*PP(2)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
1033      ELSEIF ( L .EQ. 5 .AND.
1034 :      IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
1035      PLK45=P4(A4,0)*P5(A5,0)*WA15*WA24*
1036 :      PP(1)*PP(2)*PP(3)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
1037      ELSEIF ( L .EQ. 6 .AND.
1038 :      IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
1039      PLK46=P4(A4,0)*P6(A6,0)*WA16*WA24*
1040 :      PP(1)*PP(2)*PP(3)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
1041      ELSEIF ( L .EQ. 7 .AND.
1042 :      IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
1043      PLK47=P4(A4,0)*P7(A7,0)*WA17*WA24*
1044 :      PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
1045      ELSEIF ( L .EQ. 8 .AND.
1046 :      IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
1047      PLK48=P4(A4,0)*P8(A8,0)*WA18*WA24*
1048 :      PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
1049      ELSEIF ( L .EQ. 9 .AND.
1050 :      IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
1051      PLK49=P4(A4,0)*P9(A9,0)*WA19*WA24*
1052 :      PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
1053      ELSEIF ( L .EQ. 10 .AND.
1054 :      IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
1055      PLK410=P4(A4,0)*P10(A10,0)*WA110*WA24*
1056 :      PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
1057      ENDIF
1058      ELSEIF ( K .EQ. 5 .AND.
1059 :      IX(5) .LT. AA2 .AND. NMX(5) .GT. AA2) THEN
1060      WA25 = ((NMX(5)-AA2)/Z(5))
1061      A5=AA2
1062      IF ( L .EQ. 1 .AND.
1063 :      IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
1064      PLK51=P1(A1,0)*P5(A5,0)*WA11*WA25*
1065 :      PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
1066      ELSEIF ( L .EQ. 2 .AND.
1067 :      IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
1068      PLK52=P2(A2,0)*P5(A5,0)*WA12*WA25*
1069 :      PP(1)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)

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1070      ELSEIF ( L .EQ. 3 .AND.
1071 :      IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
1072      PLK53=P3(A3,0)*P5(A5,0)*WA13*WA25*
1073 :      PP(1)*PP(2)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
1074      ELSEIF ( L .EQ. 4 .AND.
1075 :      IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
1076      PLK54=P4(A4,0)*P5(A5,0)*WA14*WA25*
1077 :      PP(1)*PP(2)*PP(3)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
1078      ELSEIF ( L .EQ. 6 .AND.
1079 :      IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
1080      PLK56=P5(A5,0)*P6(A6,0)*WA16*WA25*
1081 :      PP(1)*PP(2)*PP(3)*PP(4)*PP(7)*PP(8)*PP(9)*PP(10)
1082      ELSEIF ( L .EQ. 7 .AND.
1083 :      IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
1084      PLK57=P5(A5,0)*P7(A7,0)*WA17*WA25*
1085 :      PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(8)*PP(9)*PP(10)
1086      ELSEIF ( L .EQ. 8 .AND.
1087 :      IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
1088      PLK58=P5(A5,0)*P8(A8,0)*WA18*WA25*
1089 :      PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(9)*PP(10)
1090      ELSEIF ( L .EQ. 9 .AND.
1091 :      IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
1092      PLK59=P5(A5,0)*P9(A9,0)*WA19*WA25*
1093 :      PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(10)
1094      ELSEIF ( L .EQ. 10 .AND.
1095 :      IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
1096      PLK510=P5(A5,0)*P10(A10,0)*WA110*WA25*
1097 :      PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)
1098      ENDIF
1099      ELSEIF ( K .EQ. 6 .AND.
1100 :      IX(6) .LT. AA2 .AND. NMX(6) .GT. AA2) THEN
1101      WA26 = ((NMX(6)-AA2)/Z(6))
1102      A6=AA2
1103      IF ( L .EQ. 1 .AND.
1104 :      IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
1105      PLK61=P1(A1,0)*P6(A6,0)*WA11*WA26*
1106 :      PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
1107      ELSEIF ( L .EQ. 2 .AND.
1108 :      IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
1109      PLK62=P2(A2,0)*P6(A6,0)*WA12*WA26*
1110 :      PP(1)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
1111      ELSEIF ( L .EQ. 3 .AND.
1112 :      IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
1113      PLK63=P3(A3,0)*P6(A6,0)*WA13*WA26*
1114 :      PP(1)*PP(2)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
1115      ELSEIF ( L .EQ. 4 .AND.
1116 :      IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
1117      PLK64=P4(A4,0)*P6(A6,0)*WA14*WA26*
1118 :      PP(1)*PP(2)*PP(3)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
1119      ELSEIF ( L .EQ. 5 .AND.
1120 :      IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN

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1121          PLK65=P5(A5,0)*P6(A6,0)*WA15*WA26*
1122 :          PP(1)*PP(2)*PP(3)*PP(4)*PP(7)*PP(8)*PP(9)*PP(10)
1123 ELSEIF ( L .EQ. 7 .AND.
1124 :          IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1 ) THEN
1125          PLK67=P6(A6,0)*P7(A7,0)*WA17*WA26*
1126 :          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(8)*PP(9)*PP(10)
1127 ELSEIF ( L .EQ. 8 .AND.
1128 :          IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1 ) THEN
1129          PLK68=P6(A6,0)*P8(A8,0)*WA18*WA26*
1130 :          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(9)*PP(10)
1131 ELSEIF ( L .EQ. 9 .AND.
1132 :          IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1 ) THEN
1133          PLK69=P6(A6,0)*P9(A9,0)*WA19*WA26*
1134 :          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(10)
1135 ELSEIF ( L .EQ. 10 .AND.
1136 :          IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1 ) THEN
1137          PLK610=P6(A6,0)*P10(A10,0)*WA110*WA26*
1138 :          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)
1139 ENDIF
1140 ELSEIF ( K .EQ. 7 .AND.
1141 :          IX(7) .LT. AA2 .AND. NMX(7) .GT. AA2 ) THEN
1142          WA27 = ((NMX(7)-AA2)/Z(7))
1143          A7=AA2
1144          IF ( L .EQ. 1 .AND.
1145 :              IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1 ) THEN
1146              PLK71=P1(A1,0)*P7(A7,0)*WA11*WA27*
1147 :              PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
1148          ELSEIF ( L .EQ. 2 .AND.
1149 :              IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1 ) THEN
1150              PLK72=P2(A2,0)*P7(A7,0)*WA12*WA27*
1151 :              PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
1152          ELSEIF ( L .EQ. 3 .AND.
1153 :              IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1 ) THEN
1154              PLK73=P3(A3,0)*P7(A7,0)*WA13*WA27*
1155 :              PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
1156          ELSEIF ( L .EQ. 4 .AND.
1157 :              IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1 ) THEN
1158              PLK74=P4(A4,0)*P7(A7,0)*WA14*WA27*
1159 :              PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
1160          ELSEIF ( L .EQ. 5 .AND.
1161 :              IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1 ) THEN
1162              PLK75=P5(A5,0)*P7(A7,0)*WA15*WA27*
1163 :              PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(8)*PP(9)*PP(10)
1164          ELSEIF ( L .EQ. 6 .AND.
1165 :              IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1 ) THEN
1166              PLK76=P6(A6,0)*P7(A7,0)*WA16*WA27*
1167 :              PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(8)*PP(9)*PP(10)
1168          ELSEIF ( L .EQ. 8 .AND.
1169 :              IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1 ) THEN
1170              PLK78=P7(A7,0)*P8(A8,0)*WA18*WA27*
1171 :              PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(9)*PP(10)

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1172      ELSEIF ( L .EQ. 9 .AND.
1173 :      IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
1174      PLK79=P7(A7,0)*P9(A9,0)*WA19*WA27*
1175 :      PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(10)
1176      ELSEIF ( L .EQ. 10 .AND.
1177 :      IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
1178      PLK710=P7(A7,0)*P10(A10,0)*WA110*WA27*
1179 :      PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)
1180      ENDIF
1181      ELSEIF ( K .EQ. 8 .AND.
1182 :      IX(8) .LT. AA2 .AND. NMX(8) .GT. AA2) THEN
1183      WA28 = ((NMX(8)-AA2)/Z(8))
1184      A8=AA2
1185      IF ( L .EQ. 1 .AND.
1186 :      IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
1187      PLK81=P1(A1,0)*P8(A8,0)*WA11*WA28*
1188 :      PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
1189      ELSEIF ( L .EQ. 2 .AND.
1190 :      IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
1191      PLK82=P2(A2,0)*P8(A8,0)*WA12*WA28*
1192 :      PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
1193      ELSEIF ( L .EQ. 3 .AND.
1194 :      IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
1195      PLK83=P3(A3,0)*P8(A8,0)*WA13*WA28*
1196 :      PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
1197      ELSEIF ( L .EQ. 4 .AND.
1198 :      IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
1199      PLK84=P4(A4,0)*P8(A8,0)*WA14*WA28*
1200 :      PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
1201      ELSEIF ( L .EQ. 5 .AND.
1202 :      IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
1203      PLK85=P5(A5,0)*P8(A8,0)*WA15*WA28*
1204 :      PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(9)*PP(10)
1205      ELSEIF ( L .EQ. 6 .AND.
1206 :      IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
1207      PLK86=P6(A6,0)*P8(A8,0)*WA16*WA28*
1208 :      PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(9)*PP(10)
1209      ELSEIF ( L .EQ. 7 .AND.
1210 :      IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
1211      PLK87=P7(A7,0)*P8(A8,0)*WA17*WA28*
1212 :      PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(9)*PP(10)
1213      ELSEIF ( L .EQ. 9 .AND.
1214 :      IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
1215      PLK89=P8(A8,0)*P9(A9,0)*WA19*WA28*
1216 :      PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(10)
1217      ELSEIF ( L .EQ. 10 .AND.
1218 :      IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
1219      PLK810=P8(A8,0)*P10(A10,0)*WA110*WA28*
1220 :      PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)
1221      ENDIF
1222      ELSEIF ( K .EQ. 9 .AND.

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1223 : IX(9) .LT. AA2 .AND. NMX(9) .GT. AA2) THEN
1224 : WA29 = ((NMX(9)-AA2)/Z(9))
1225 : A9=AA2
1226 : IF ( L .EQ. 1 .AND.
1227 : IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
1228 : PLK91=P1(A1,0)*P9(A9,0)*WA11*WA29*
1229 : PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
1230 : ELSEIF ( L .EQ. 2 .AND.
1231 : IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
1232 : PLK92=P2(A2,0)*P9(A9,0)*WA12*WA29*
1233 : PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
1234 : ELSEIF ( L .EQ. 3 .AND.
1235 : IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
1236 : PLK93=P3(A3,0)*P9(A9,0)*WA13*WA29*
1237 : PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
1238 : ELSEIF ( L .EQ. 4 .AND.
1239 : IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
1240 : PLK94=P4(A4,0)*P9(A9,0)*WA14*WA29*
1241 : PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
1242 : ELSEIF ( L .EQ. 5 .AND.
1243 : IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
1244 : PLK95=P5(A5,0)*P9(A9,0)*WA15*WA29*
1245 : PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(10)
1246 : ELSEIF ( L .EQ. 6 .AND.
1247 : IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
1248 : PLK96=P6(A6,0)*P9(A9,0)*WA16*WA29*
1249 : PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(10)
1250 : ELSEIF ( L .EQ. 7 .AND.
1251 : IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
1252 : PLK97=P7(A7,0)*P9(A9,0)*WA17*WA29*
1253 : PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(10)
1254 : ELSEIF ( L .EQ. 8 .AND.
1255 : IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
1256 : PLK98=P8(A8,0)*P9(A9,0)*WA18*WA29*
1257 : PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(10)
1258 : ELSEIF ( L .EQ. 10 .AND.
1259 : IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
1260 : PLK910=P9(A9,0)*P10(A10,0)*WA110*WA29*
1261 : PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)
1262 : ENDIF
1263 : ELSEIF ( K .EQ. 10 .AND.
1264 : IX(10) .LT. AA2 .AND. NMX(10) .GT. AA2) THEN
1265 : WA210 = ((NMX(10)-AA2)/Z(10))
1266 : A10=AA2
1267 : IF ( L .EQ. 1 .AND.
1268 : IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
1269 : PLK101=P1(A1,0)*P10(A10,0)*WA11*WA210*
1270 : PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
1271 : ELSEIF ( L .EQ. 2 .AND.
1272 : IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
1273 : PLK102=P2(A2,0)*P10(A10,0)*WA12*WA210*

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1274 :      PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
1275 :      ELSEIF ( L .EQ. 3 .AND.
1276 :      IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
1277 :      PLK103=P3(A3,0)*P10(A10,0)*WA13*WA210*
1278 :      PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
1279 :      ELSEIF ( L .EQ. 4 .AND.
1280 :      IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
1281 :      PLK104=P4(A4,0)*P10(A10,0)*WA14*WA210*
1282 :      PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
1283 :      ELSEIF ( L .EQ. 5 .AND.
1284 :      IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
1285 :      PLK105=P5(A5,0)*P10(A10,0)*WA15*WA210*
1286 :      PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)
1287 :      ELSEIF ( L .EQ. 6 .AND.
1288 :      IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
1289 :      PLK106=P6(A6,0)*P10(A10,0)*WA16*WA210*
1290 :      PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)
1291 :      ELSEIF ( L .EQ. 7 .AND.
1292 :      IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
1293 :      PLK107=P7(A7,0)*P10(A10,0)*WA17*WA210*
1294 :      PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)
1295 :      ELSEIF ( L .EQ. 8 .AND.
1296 :      IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
1297 :      PLK108=P8(A8,0)*P10(A10,0)*WA17*WA210*
1298 :      PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)
1299 :      ELSEIF ( L .EQ. 9 .AND.
1300 :      IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
1301 :      PLK109=P9(A9,0)*P10(A10,0)*WA19*WA210*
1302 :      PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)
1303 :      ENDIF
1304 :      ENDIF
1305 :      ENDIF
1306 :      ENDDO
1307 :      ENDDO
1308 :      PLK1=PLK12+PLK13+PLK14+PLK15+PLK16+PLK17+PLK18+PLK19
1309 :      +PLK110
1310 :      PLK2=PLK21+PLK23+PLK24+PLK25+PLK26+PLK27+PLK28+PLK29
1311 :      +PLK210
1312 :      PLK3=PLK31+PLK32+PLK34+PLK35+PLK36+PLK37+PLK38+PLK39
1313 :      +PLK310
1314 :      PLK4=PLK41+PLK42+PLK43+PLK45+PLK46+PLK47+PLK48+PLK49
1315 :      +PLK410
1316 :      PLK5=PLK51+PLK52+PLK53+PLK54+PLK56+PLK57+PLK58+PLK59
1317 :      +PLK510
1318 :      PLK6=PLK61+PLK62+PLK63+PLK64+PLK65+PLK67+PLK68+PLK69
1319 :      +PLK610
1320 :      PLK7=PLK71+PLK72+PLK73+PLK74+PLK75+PLK76+PLK78+PLK79
1321 :      +PLK710
1322 :      PLK8=PLK81+PLK82+PLK83+PLK84+PLK85+PLK86+PLK87+PLK89
1323 :      +PLK810
1324 :      PLK9=PLK91+PLK92+PLK93+PLK94+PLK95+PLK96+PLK97+PLK98

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1325      :      +PLK910
1326      PLK10=PLK101+PLK102+PLK103+PLK104+PLK105+PLK106+PLK107
1327      :      +PLK108+PLK109
1328      IF ( AA1 .EQ. AA2 ) THEN
1329          PLKE=PLKE+1/2*(PLK1+PLK2+PLK3+PLK4+PLK5+PLK6
1330          :      +PLK7+PLK8+PLK9+PLK10)
1331          PLKNE=0.0
1332      ELSE
1333          PLKNE=PLKNE+(PLK1+PLK2+PLK3+PLK4+PLK5+PLK6
1334          :      +PLK7+PLK8+PLK9+PLK10)
1335          PLKE=0.0
1336      ENDIF
1337      PLKX = PLKX + PLKE + PLKNE
1338      ENDDO
1339      ENDDO
1340      END
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