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Rahman, Mohammad Shakil-ur, Ph.D.

Iowa State University, 1989

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Performance evaluation of generic
flexible manufacturing systems

by

Mohammad Shakil-ur Rahman

A Dissertation Submitted to the
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Iowa State University
Ames, Iowa

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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

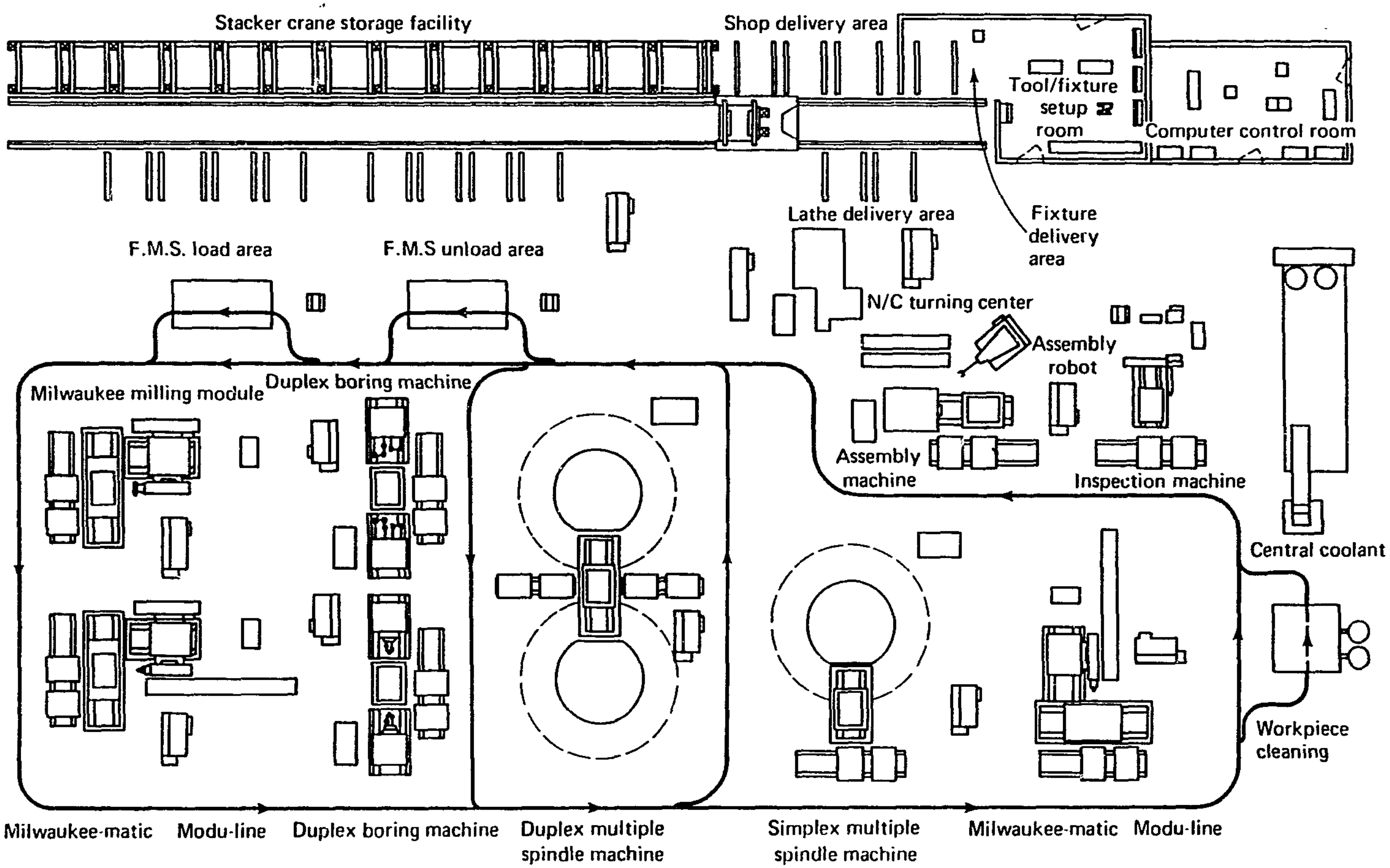


FIGURE 1. A sample FMS layout

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 carrousel 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:

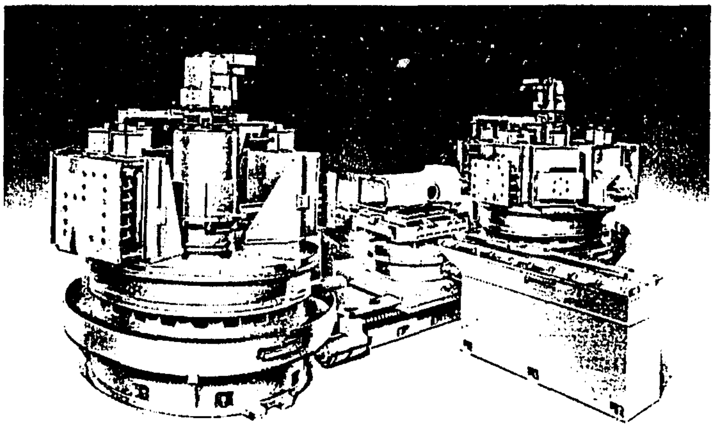
1. Dedicated FMS

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.

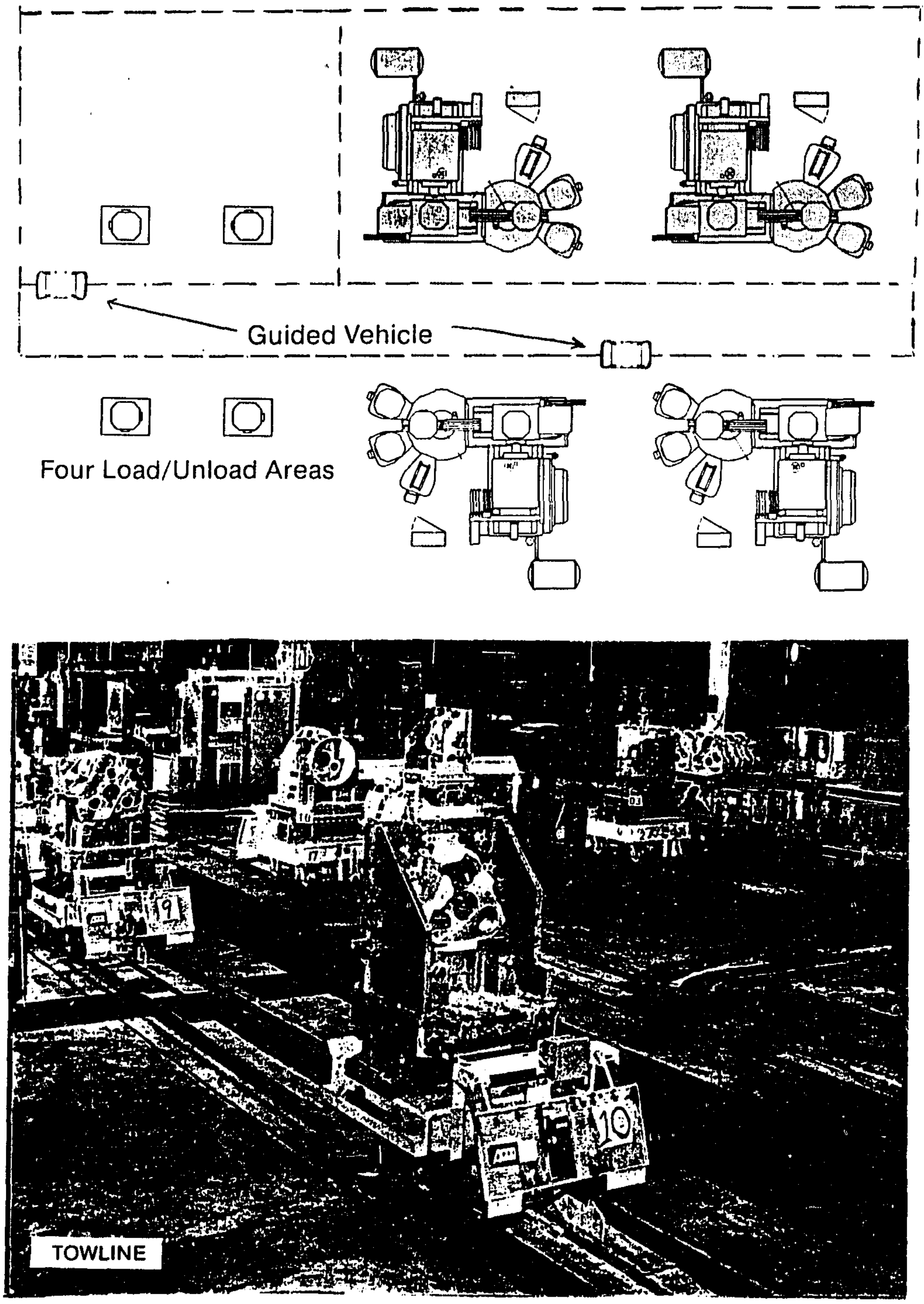


FIGURE 3.   AGVS versus tow-line

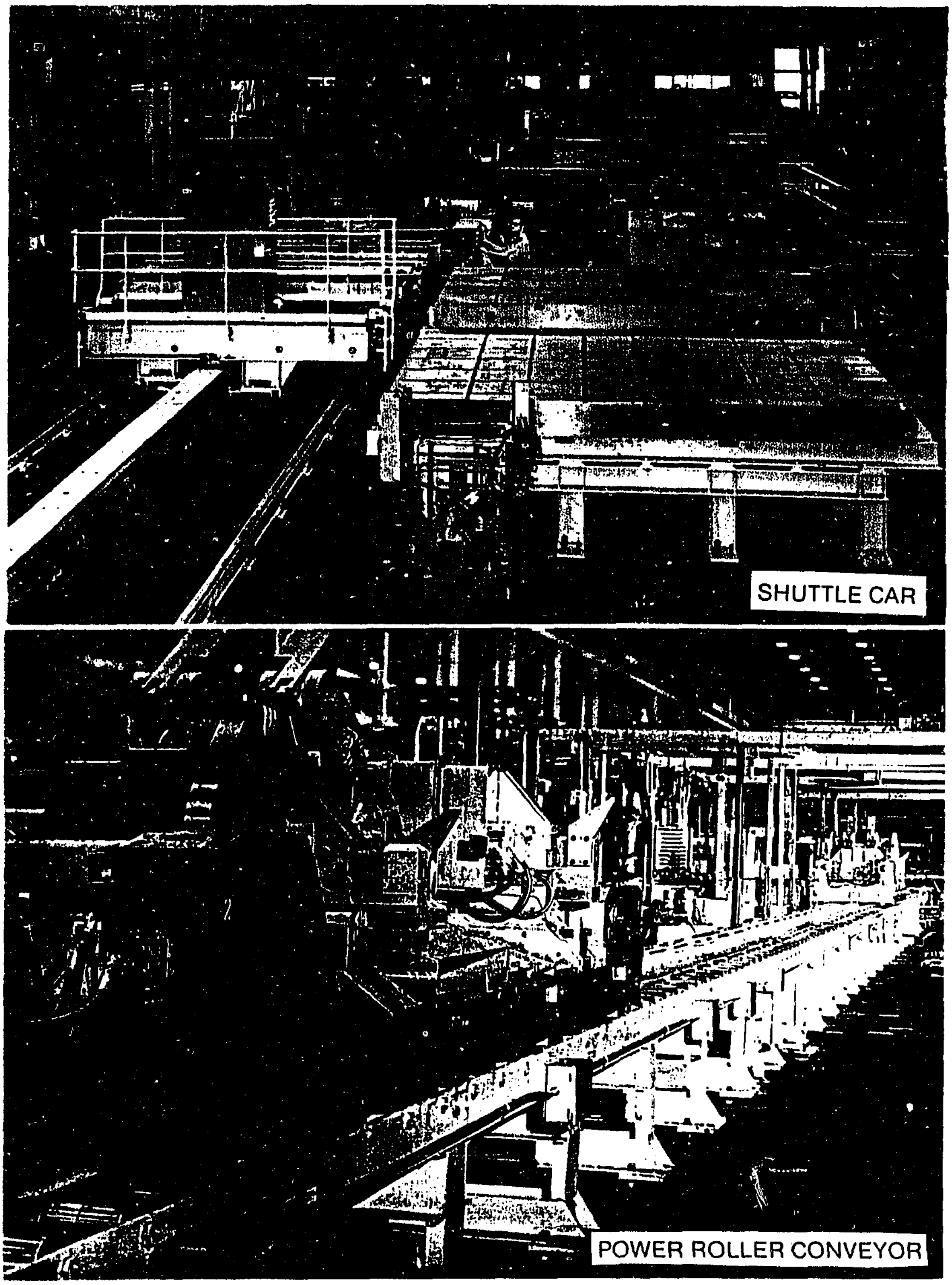


FIGURE 4. Power conveyor and shuttle car

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

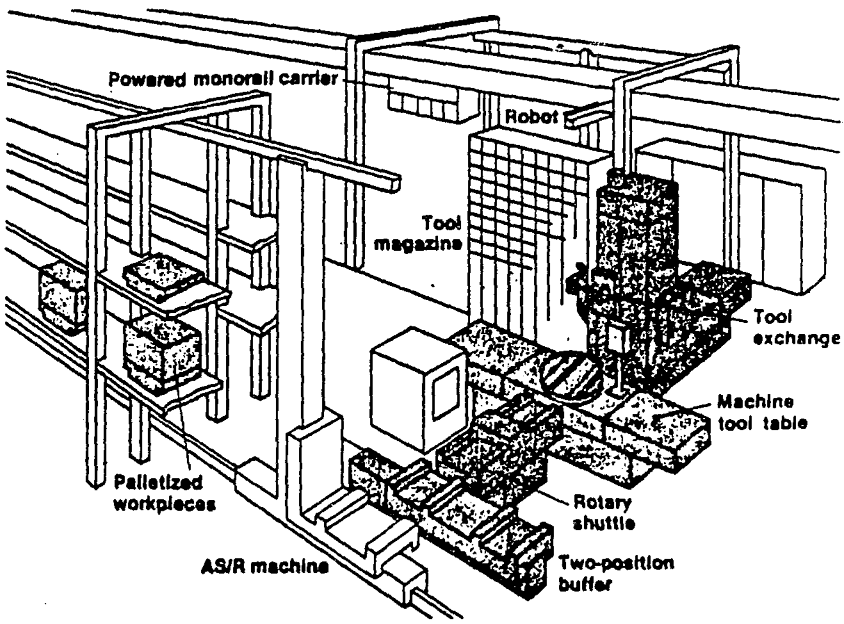


FIGURE 5. AS/RS storing and delivering parts to machines

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

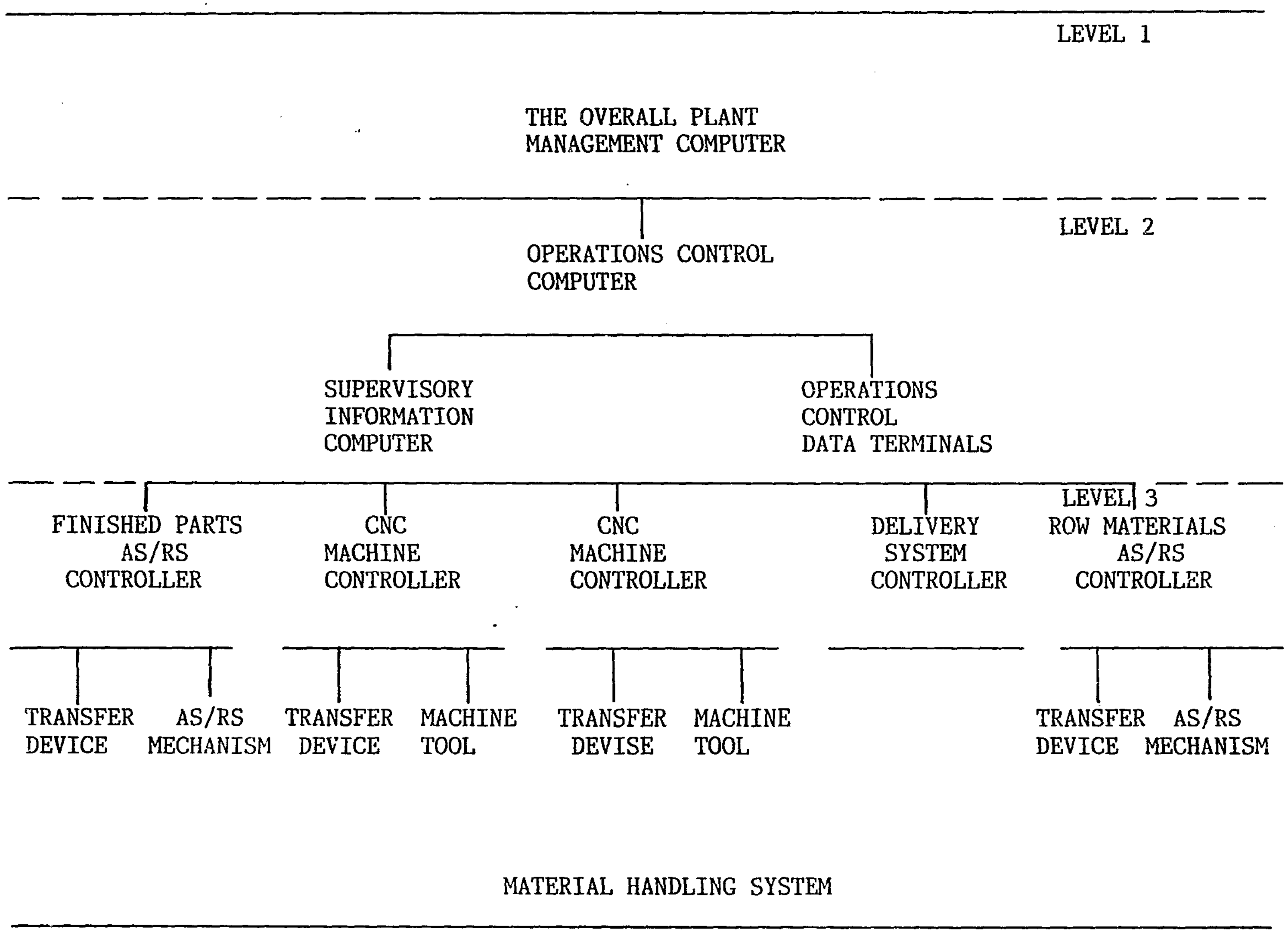


FIGURE 6. FMS computer hierarchy

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, discontinue 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 emperical 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 unforseen 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.

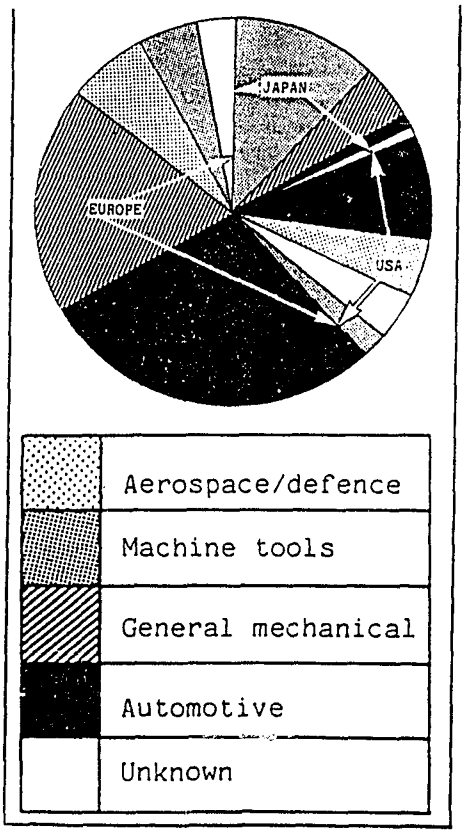
E. An Overview of Applications

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% Mechanicl 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.

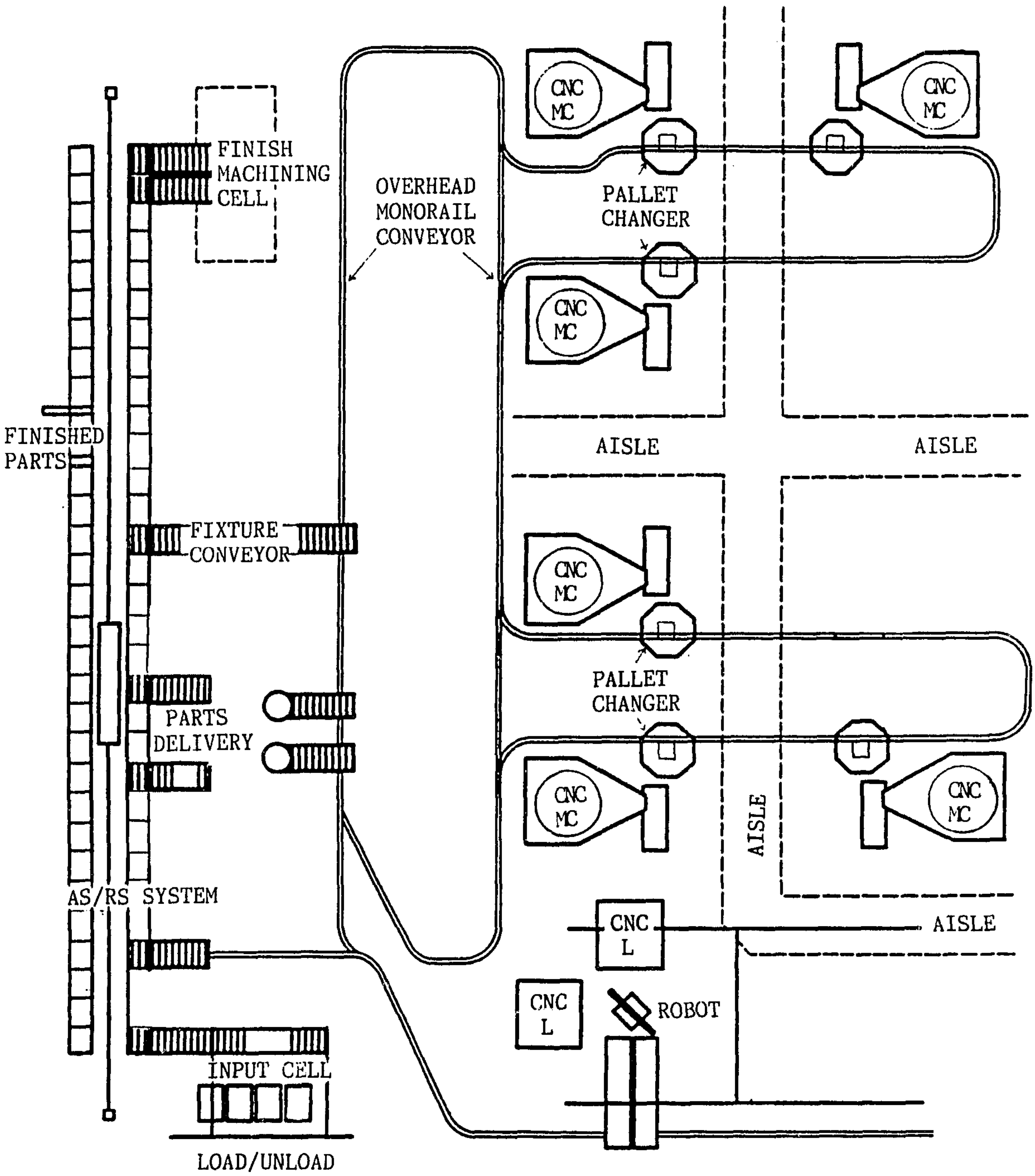


FIGURE 8. A conceptual FMS layout

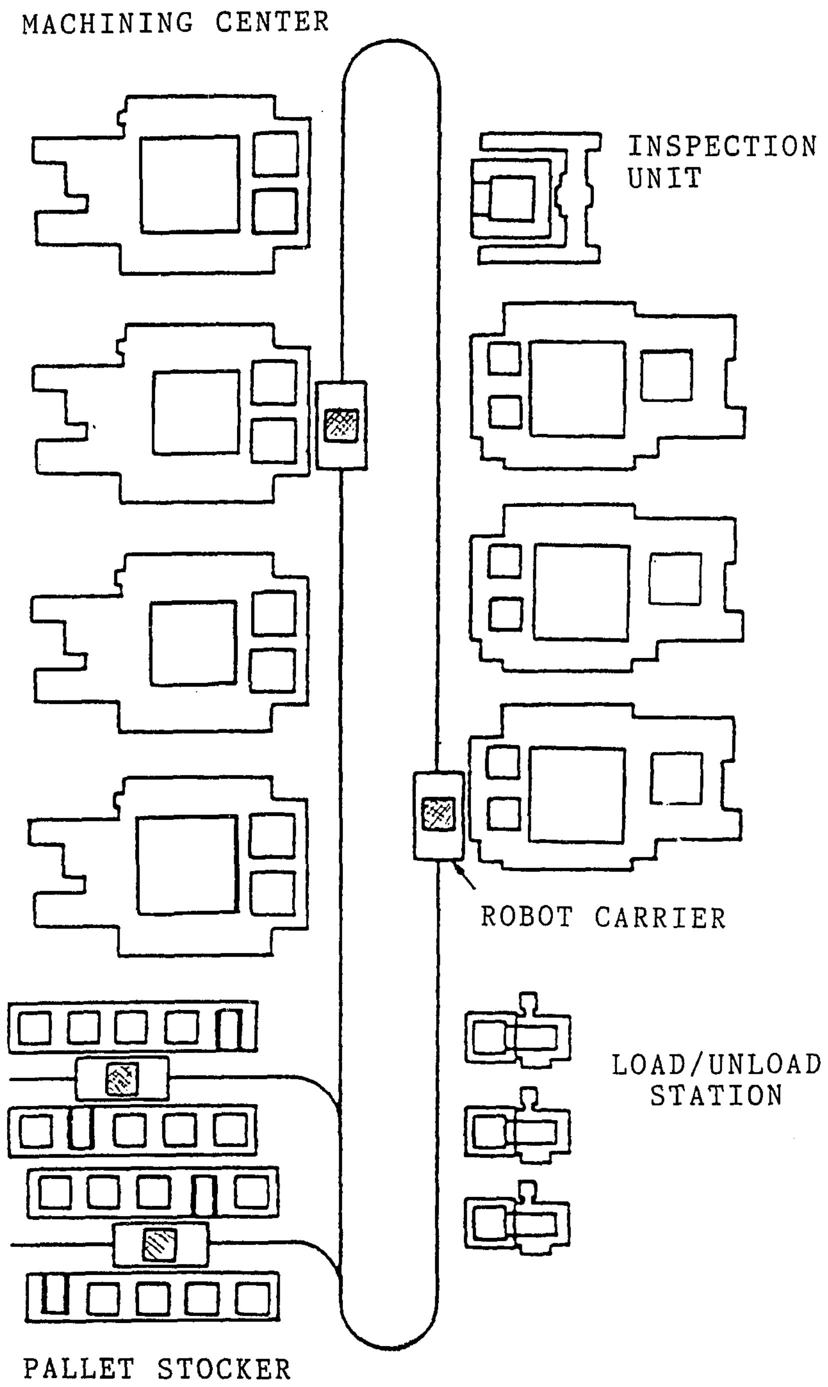


FIGURE 9. A generic FMS layout

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.

$$A(t) = \sum_{i \epsilon Q_O} P(t)$$

where Q = State space

Q_O = 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 $P = \min\,\{P_1, \ldots, P_n\}$

$P_o(t)$ = 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

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

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

$$E = f(\text{performance measures})$$
$$= f(\ A_O,\ U,\ Pr\ )$$

The A_O, 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.

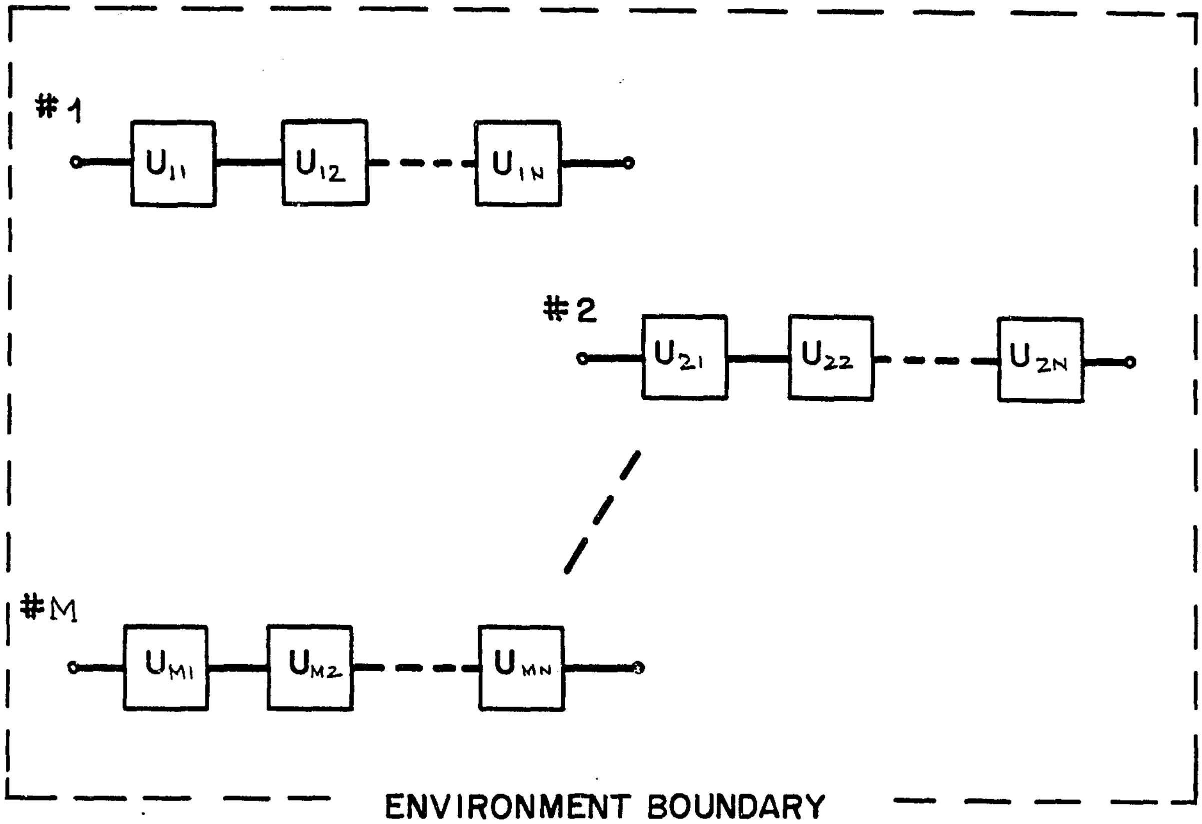


FIGURE 10. Diagram of a generic FMS containing M distinct systems

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.

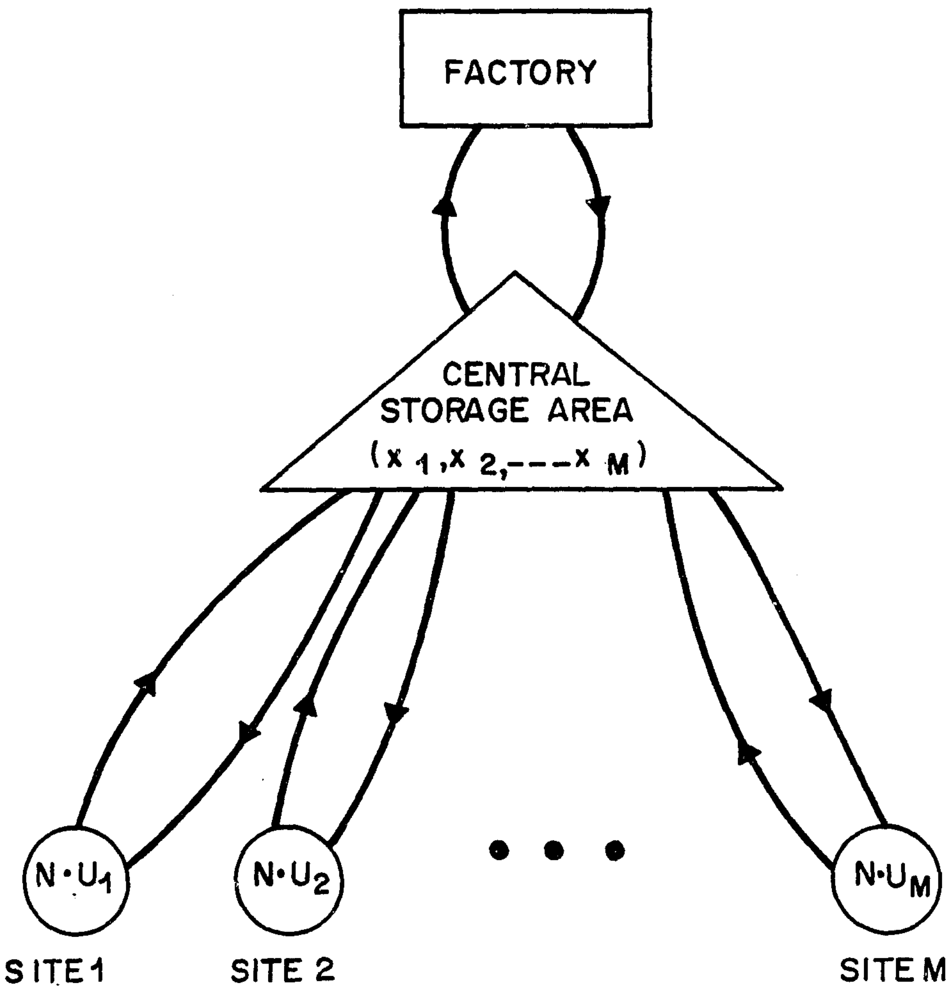


FIGURE 11. An environment of M distinct equipment types. Failures of any equipment types are sent to the central storage area, then routed to the factory for repair

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 $(i,j)^{th}$ 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, $k = 1,2,...,M$

x_k number of allocated spares for the k^{th} equipment type, $k = 1,2,...,M$

x number of allocated spares for one equipment type, a shorthand notation for x_k in later sections

$\overline{X}$ $(x_1, x_2,...,x_k,...,x_n)$

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)

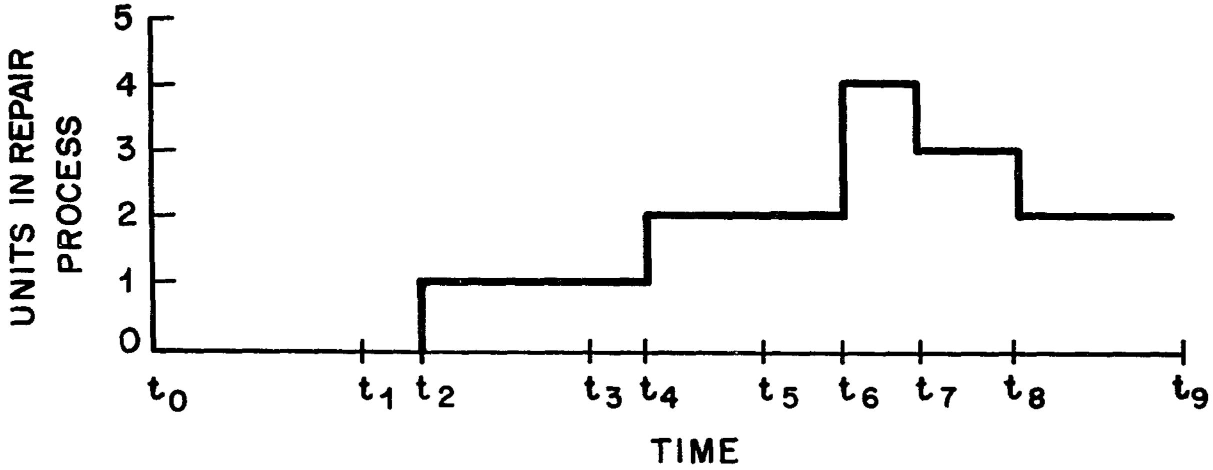


FIGURE 12. Units in the repair process during time interval (t_0, t_9)

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, ..., t_n, ...

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); $i = 0, 1, \ldots, n_{max}$, $j = 0, 1$. 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.

@A $$\lambda_0 P(0,0) = \mu_1 P(1,0) \qquad (1)$$

@B $$(\lambda_i+\mu_i) = p\beta_{i-1}P(i-1,1) + \mu_{i+1}P(i+1,0) \qquad (2)$$
$$\text{for } i = 1, 2, \ldots, x$$

@H $$(\lambda_i+\mu_i) = \beta_{i-1}P(i-1,1) + \mu_{i+1}P(i+1,0) \qquad (3)$$
$$\text{for } i = x+1, \ldots, n_{max}-1$$

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

@C $$p\beta_0 P(0,1) + \sum_{i'=1}^{x} \beta_{0i'}P(0,1) = \lambda_0 P(0,0) \qquad (5)$$

@D $$p\beta_i P(i,1) + \sum_{i'=i+1}^{x} \beta_{ii'}P(i,1) = \lambda_i P(i,0) + \sum_{i'=0}^{i-1} \beta_{i'i}P(i',1) \qquad (6)$$
$$\text{for } i = 1, 2, \ldots, x-1$$

@F $$\beta_x P(x,1) = \lambda_x P(x,0) + \sum_{i'=0}^{x-1} \beta_{i'x}P(i',1) \qquad (7)$$

@G $$\beta_i P(i,1) = \lambda_i P(i,0) \qquad (8)$$
$$\text{for } i = x+1, x+2, \ldots, n_{max}$$

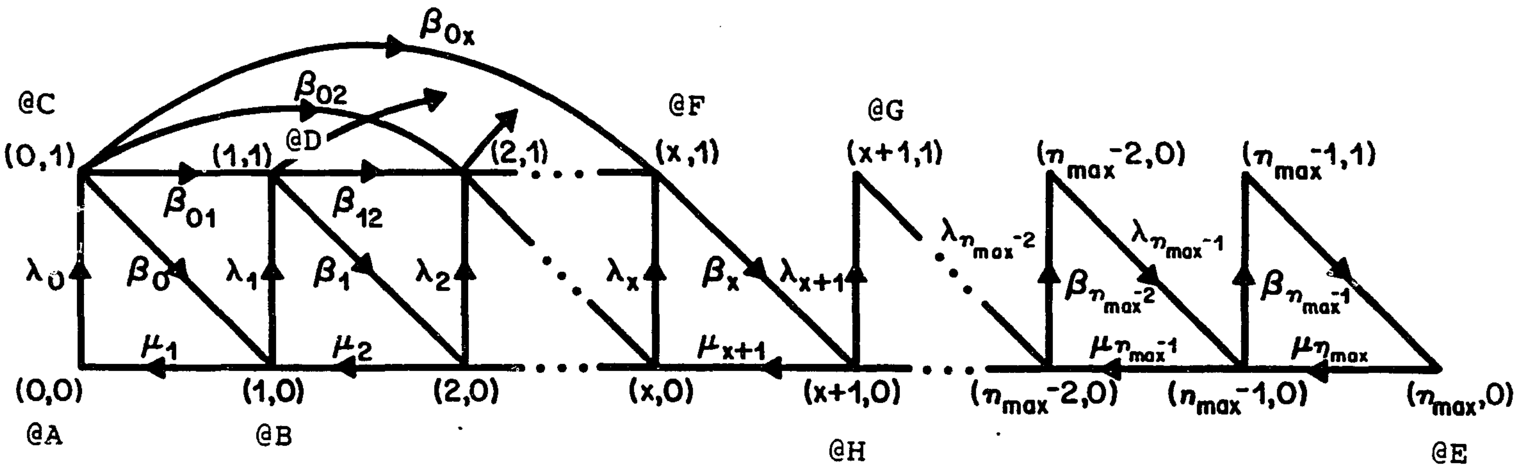


FIGURE 13. State space and transition rate

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

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

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, ... , n_{max}, j = 0, 1 can be obtained.

D. Evaluation of FMS Performance Measure

The final goal is to optimally allocate $\overline{X} = (x_1, x_2, \ldots, x_M)$ 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, $P_k[(i,0)|i \le x_k]$ 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 $i \le x_k$.

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

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

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

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

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 $i \le x_i$ for $i \ne k$, 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

$$A_1^k = P_k(x_k + 1,0) \prod_{\substack{k'=1 \\ k' \neq k}}^{M} \sum_{i=1}^{x_{k'}} P_{k'}[(i,0) | i \leq x_{k'}] \qquad (11)$$

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

$$A_{11}^{k1} = P_k(x_k + 1,0)P_\ell(x_\ell + 1,0) \prod_{\substack{k'=1 \\ k' \neq k \\ k' \neq \ell}}^{M} \sum_{i=0}^{x_{k'}} P_{k'}[(i,0) | i \leq x_{k'}] \qquad (12)$$

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 $i = 1, 2, \ldots, M$, 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 $i \le x_i$ for $i \ne k$, 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

$$A_2^k = P_k(x_k + 2,0) \prod_{\substack{k'=1 \\ k' \ne k}}^{M} \sum_{i=0}^{x_{k'}} P_{k'}[(i,0) \mid i \le x_{k'}] \qquad (13)$$

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 $i \le x_i$ for $i \ne k$ and $i \ne \ell$, 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

$$A_{22}^{kl} = P_k(x_k + 2,0)P_\ell(x_\ell + 2,0) \prod_{\substack{k'=1 \\ k' \ne k \\ k' \ne \ell}}^{M} \sum_{i=0}^{x_{k'}} P_{k'}[(i,0) \mid i \le x_{k'}] \qquad (14)$$

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

$$A^{k_1\ k_2\ \cdots\ k_m}_{a_1\ a_2\ \cdots\ a_m} =$$

$$\prod_{j=1}^{m} P_{k_j}(x_{k_j} + a_j) \prod_{\substack{k'=1 \\ k' \neq k_j \\ \forall\, j=1,\,2,\,\ldots,\,m}}^{M} \sum_{i=0}^{x_{k'}} P_{k'}[(i,0)\,|\,i \leq x_{k'}] \qquad (15)$$

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 $i \le x_i$ 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

$$W_1^k = (N - 1)/N \tag{16}$$

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 $i \le x_i$ for $i \neq k$ and $i \neq \ell$, the weighting factor of

$$W_{11}^{kl} = (N - 1)/N \cdot (N - 1)/N$$

$$= [\ (N - 1)/N\ ]^2 \tag{17}$$

should be assigned to A_{11}^{kl}.

For the k^{th} equipment type in the state $(x_k+2,0)$ while other equipment types in the state $(i,0)$ where $i \le x_i$ 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

$$W_2^k = (N - 2)/N \tag{18}$$

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 $i \le x_i$ for $i \ne k$ and $i \ne \ell$ implies that there are two local systems in down state. Hence, the weighting factor is

$$W_{12}^{kl} = (N - 1)/N \cdot (N - 2)/N$$

$$= (N - 1)(N - 2)/N^2 \qquad (19)$$

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 $i \le x_i$ for $i \ne k$ and $i \ne \ell$ implies that there are two local systems in down state.

$$W_{22}^{kl} = (N - 2)/N \cdot (N - 2)/N$$

$$= [\ (N - 2)/N\ ]^2 \qquad (20)$$

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 $i \le x_i$ for $i \ne k$, $i \ne \ell$, and $i \ne m$ implies that three local systems are in partially down or down state. We denote the weighting factor by

$$W_{123}^{klm} = (N - 1)/N \cdot (N - 2)/N \cdot (N - 3)/N$$

$$= (N - 1)(N - 2)(N - 3)/N^3 \qquad (21)$$

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

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

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. $W^{k_1\ k_2\ \ldots\ k_m}_{a_1\ a_2\ \ldots\ a_m}\ A^{k_1\ k_2\ \ldots\ k_m}_{a_1\ a_2\ \ldots\ a_m}$ where the k_{1th} 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.

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

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

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

$$+ \sum_{k_1=1}^{M} \sum_{k_2=1}^{M} \ldots \sum_{k_m=1}^{M} W^{k_1\ k_2\ \ldots\ k_m}_{N-1\ N-1\ \ldots\ N-1} A^{k_1\ k_2\ \ldots\ k_m}_{N-1\ N-1\ \ldots\ N-1}$$

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

$$W^{k_1\ k_2}_{a_1\ a_2} A^{k_1\ k_2}_{a_1\ a_2} + \ldots + \sum_{a_1=1}^{N-1} \sum_{a_2=1}^{N-1} \ldots \sum_{a_m=1}^{N-1} \sum_{k_1=1}^{M} \sum_{k_2=1}^{M} \ldots \sum_{k_m=1}^{M}$$

$$\cdot\, W^{k_1\, k_2\, \dots\, k_m}_{a_1\, a_2\, \dots\, a_m}\, A^{k_1\, k_2\, \dots\, k_m}_{a_1\, a_2\, \dots\, a_m}$$

$$P = A_0 + \sum_{a_1=1}^{N-1} [(N - a_1)/N] \sum_{k=1}^{M} A^{k}_{a_1}$$

$$+ \sum_{a_1=1}^{N-1} \sum_{a_2=1}^{N-1} [(N - a_1)/N][(N - a_2)/N] \sum_{k_1=1}^{M} \sum_{k_2=1}^{M} A^{k_1\, k_2}_{a_1\, a_2}$$

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

$$+ \sum_{a_1=1}^{N-1} \sum_{a_2=1}^{N-1} \dots \sum_{a_m=1}^{N-1} [(N - a_1)/N]\, [(N - a_2)/N] \dots$$

$$\dots [(N - a_m)/N] \sum_{k_1=1}^{M} \sum_{k_2=1}^{M} \dots \sum_{k_m=1}^{M} A^{k_1\, k_2\, \dots\, k_m}_{a_1\, a_2\, \dots\, a_m} \qquad (23)$$

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

$$Z = C(\overline{X})$$
$$= C(x_1, x_2, x_3, \ldots, x_m)$$

s.t.

$$g_1 = P(\overline{X}) \geq P_{min}$$
$$g_2 = A_o(\overline{X}) \geq A_{o,min}$$
$$\overline{X} \geq 0$$

where

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

P_{min} is the minimum performance requirement

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

$P(\overline{X})$ and $A_o(\overline{X})$ 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

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

where

$$\Delta_k g_i(\overline{X}) = P(x_1, x_2, \ldots, x_k+1, \ldots x_m) - P(x_1, x_2, \ldots, x_k, \ldots x_m)$$

$$\Delta_k Z(\overline{X}) = C(x_1, x_2, \ldots, x_k+1, \ldots x_m) - C(x_1, x_2, \ldots, x_k, \ldots x_m)$$

$F_k(X_k)$ 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 $\overline{X} = (x_1, x_2, x_3, \ldots, x_m) = (1, 1, 1, \ldots, 1)$

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

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

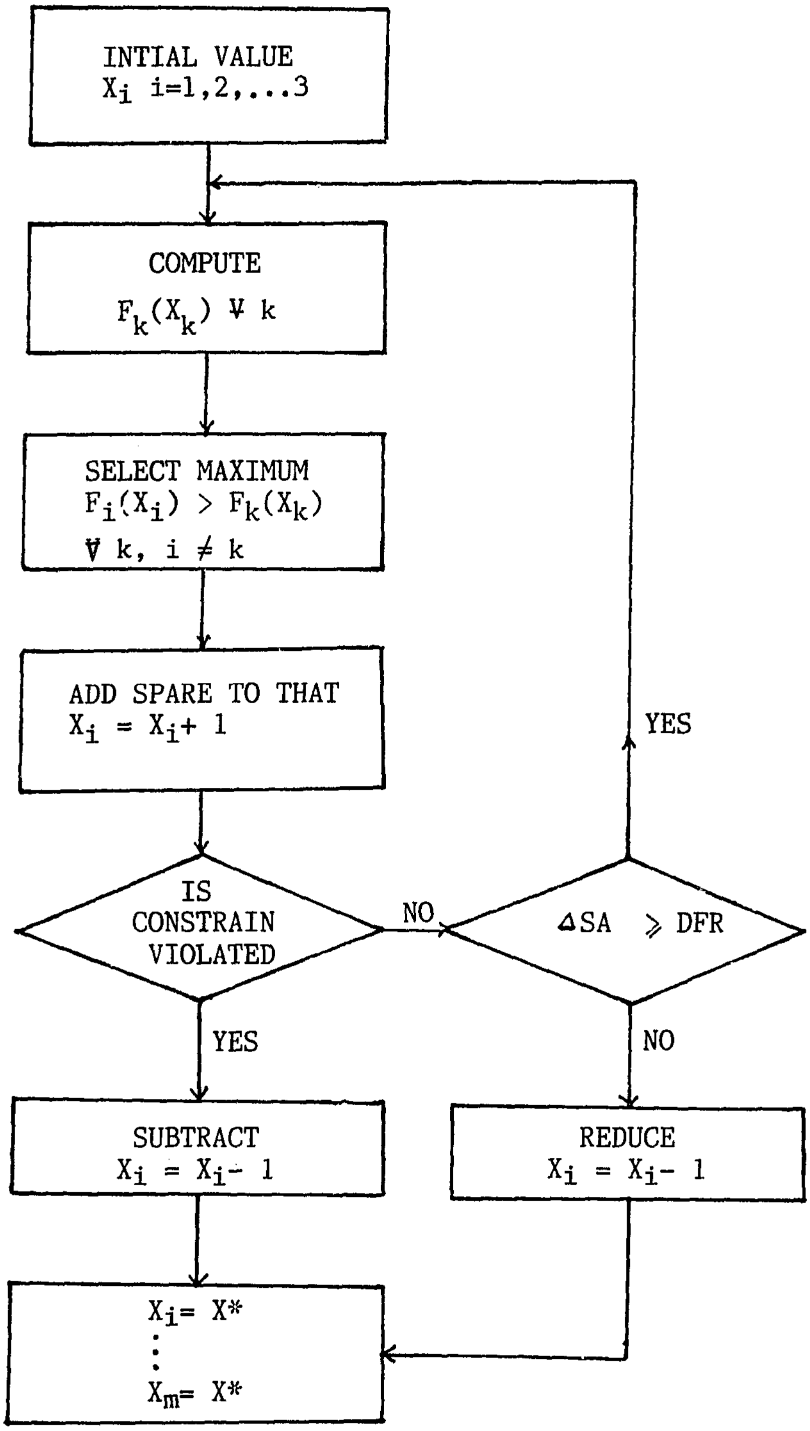


FIGURE 14. A flow diagram of heuristic approach

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 ≥ 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 $\overline{X}$ 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			
TYPE# 1	TYPE# 2	TYPE# 3	F(X)# 1	F(X)# 2	F(X)# 3	SYS AVAIL
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				
TYPE# 1	TYPE# 2	TYPE# 3	TYPE# 4	F(X)# 1	F(X)# 2	F(X)# 3	F(X)# 4	SYS AVAIL
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 $i = 1, 2, \ldots, 4$

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

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

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

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

Case-B

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

Case-C

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

Case-D

$$MTTF_1 + MTTF_2 + .. + MTTF_m \longrightarrow MTTF_1 + \Delta MTTF_1 + MTTF_2 + \Delta MTTF_2 + \ldots \ \ldots \ \ldots + MTTF_m + \Delta MTTF_m$$

$$MTTR_1 + MTTR_2 + .. + MTTR_m \longrightarrow MTTR_1 + \Delta MTTR_1 + MTTR_2 + \Delta MTTR_2 + \ldots \ \ldots \ \ldots + MTTR_m + \Delta MTTR_m$$

$$MTR_1 + MTR_2 + .. + MTR_m \longrightarrow MTR_1 + \Delta MTR_1 + MTR_2 + \Delta MTR_2 + \ldots \ \ldots \ \ldots + MTR_m + \Delta MTR_m$$

Case-E

$$MTTF_i + MTTR_i + MTR_i \longrightarrow MTTF_i + \Delta MTTF_i + MTTR_i + \Delta MTTR_i + MTR_i + \Delta MTR_i$$

$$i = 1, 2, .., m$$

Where $\Delta MTTF_i$, $\Delta MTTR_i$, 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.

<u>a. Change in $MTTF_i$</u> 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, .. 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

	Mean time to failure	System Availability
Type #1		
	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

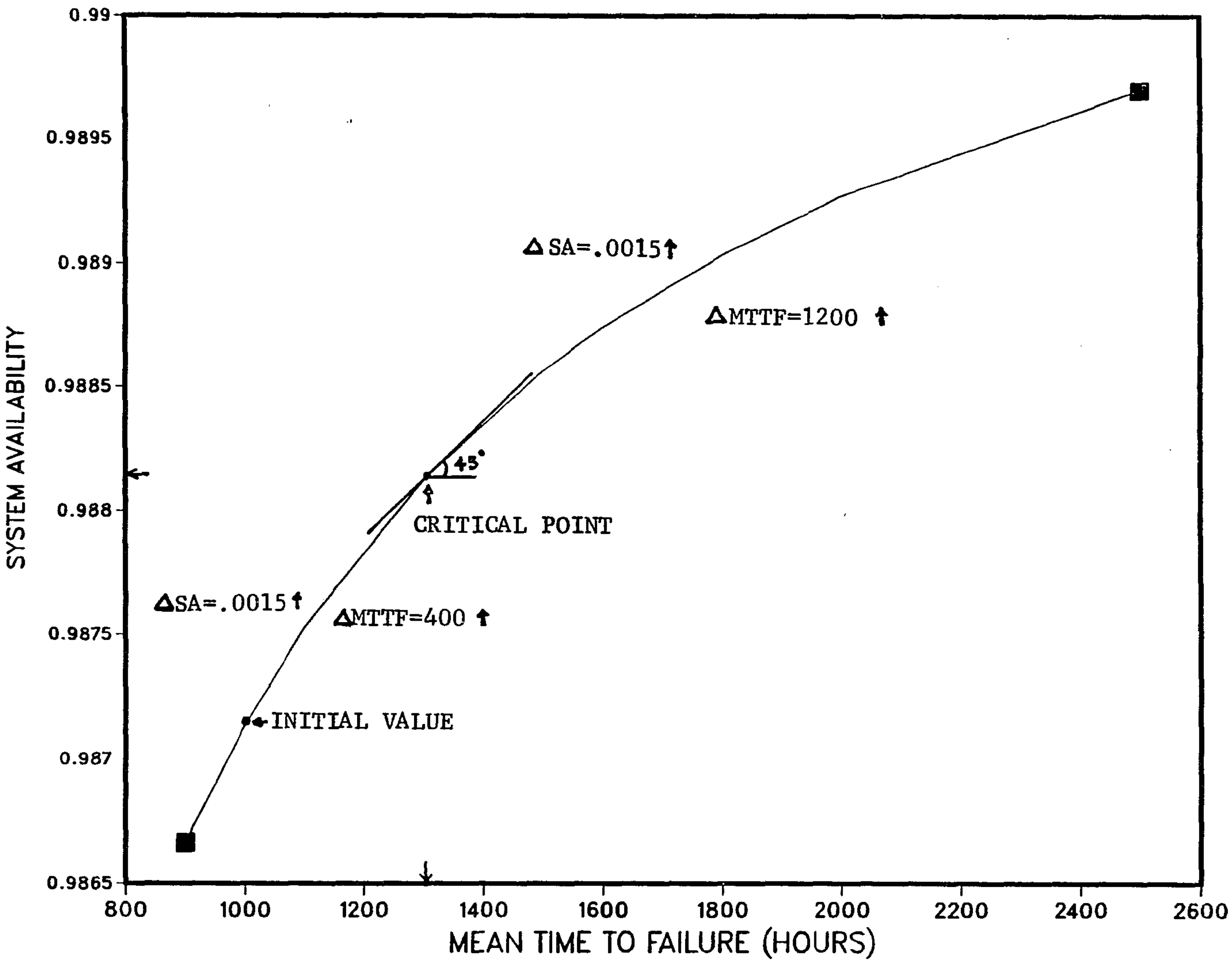


FIGURE 15. Sensitivity analysis: Change in MTTF for equipment type #1

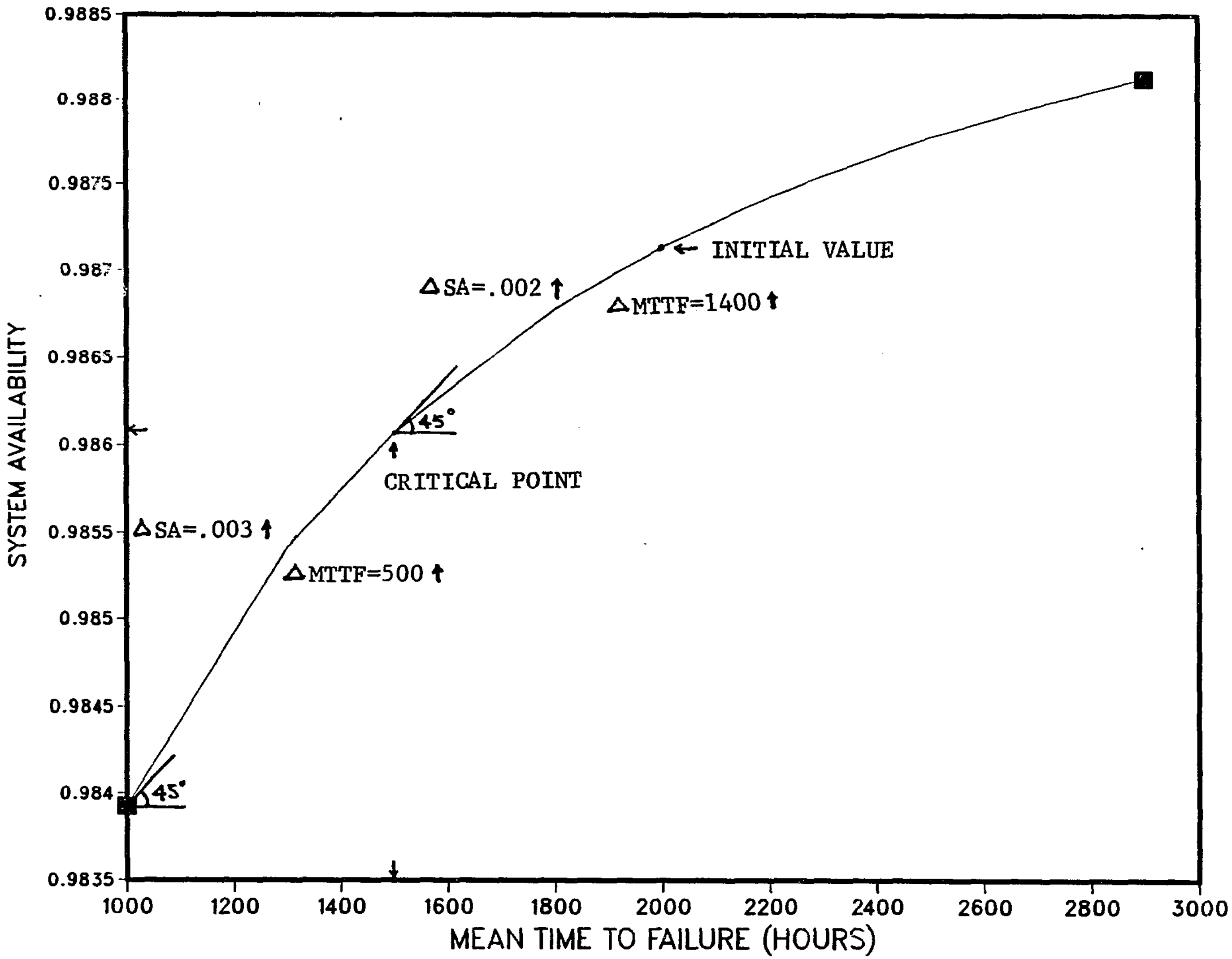


FIGURE 16. Sensitivity analysis: Change in MTTF for equipment type #2

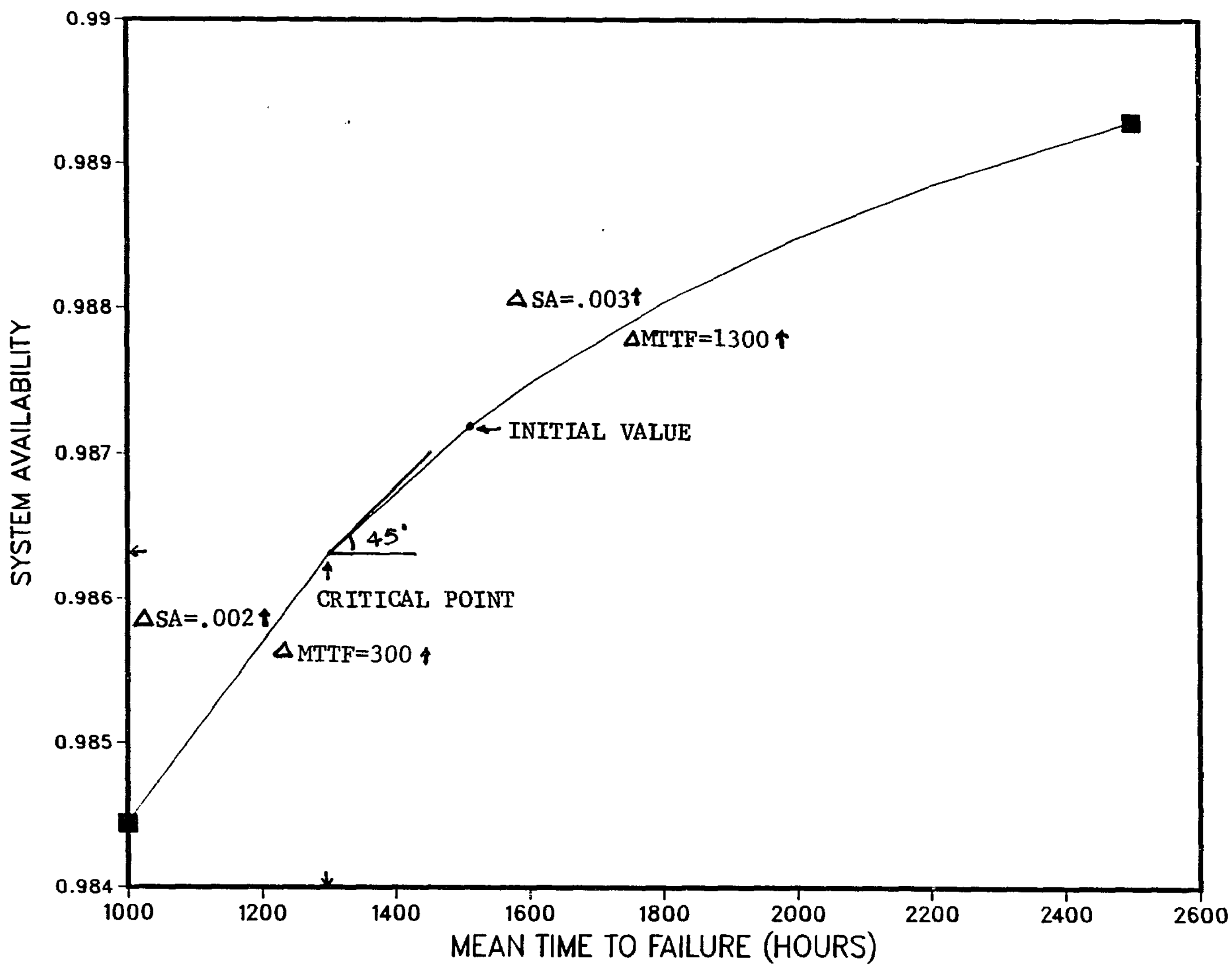


FIGURE 17. Sensitivity analysis: Change in MTTF for equipment type #3

<u>b. Change in $MTTR_i$</u> 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, .. 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.

<u>c. Change in MTR_i</u> 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, .. 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.

<u>d. Change in MTTF or MTTR or MTR of all Equipment Types</u>

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

	Mean time to repair	System Availability
Type #1		
	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

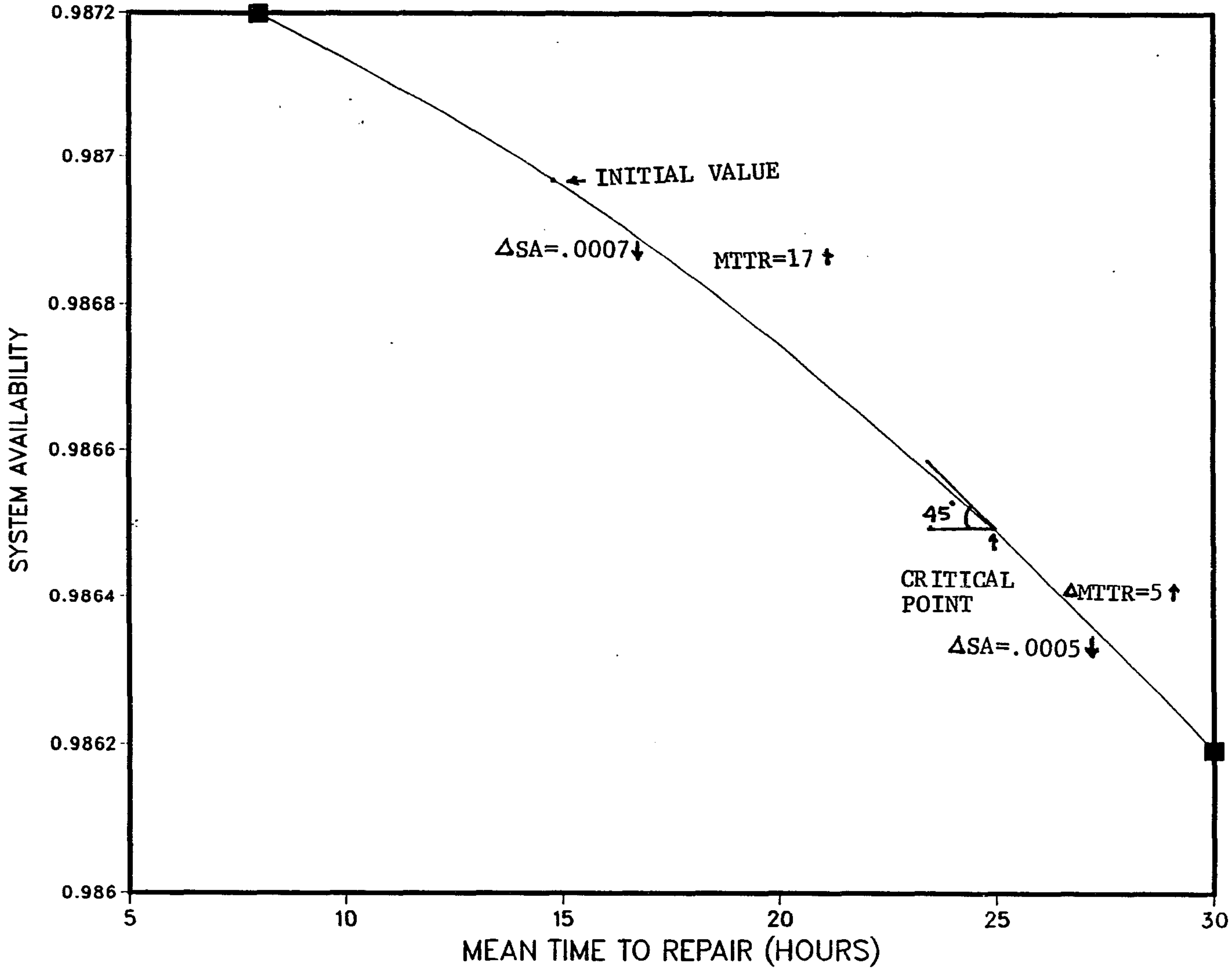


FIGURE 18. Sensitivity analysis: Change in MTTR for equipment type #1

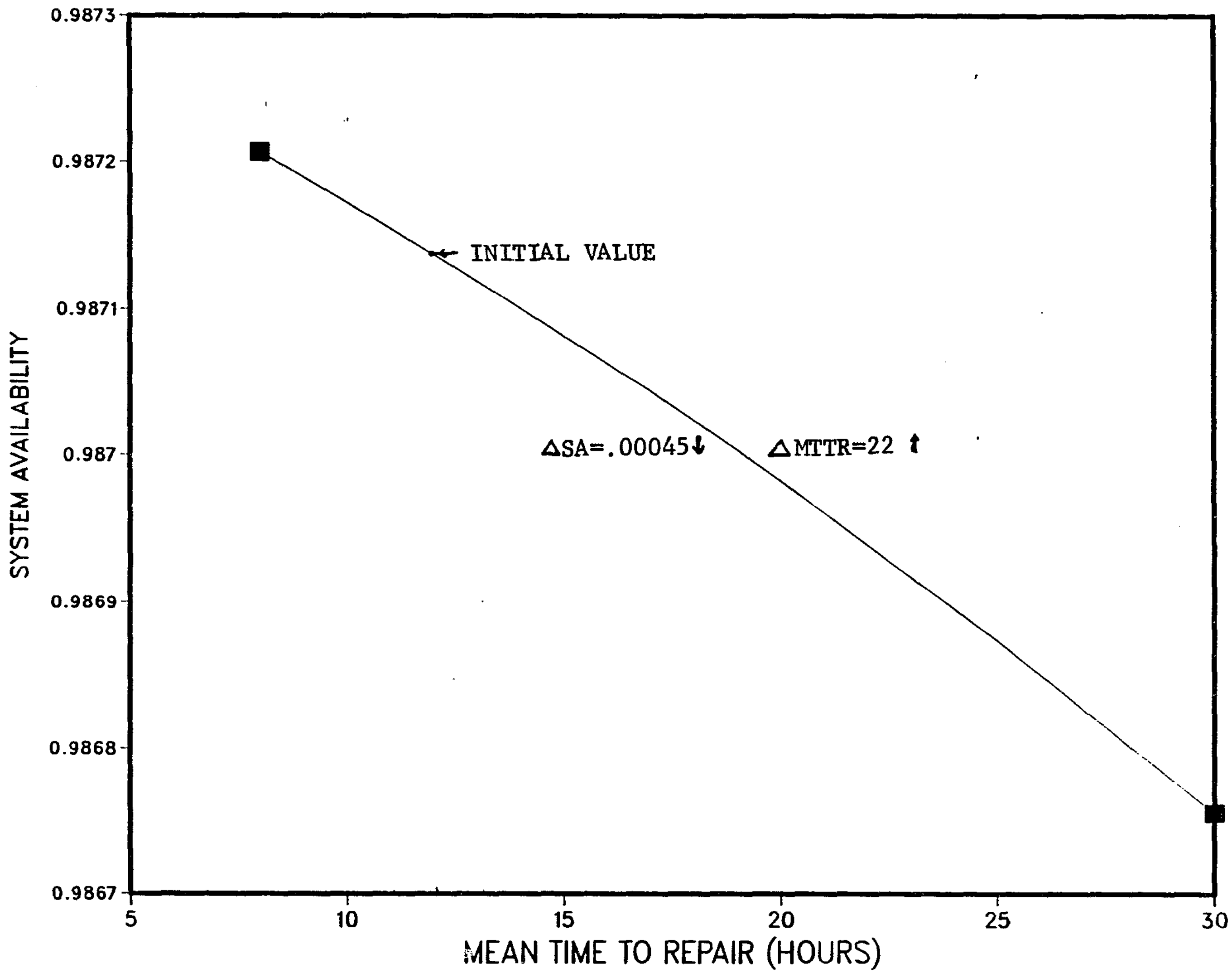


FIGURE 19. Sensitivity analysis: Change in MTTR for equipment type #2

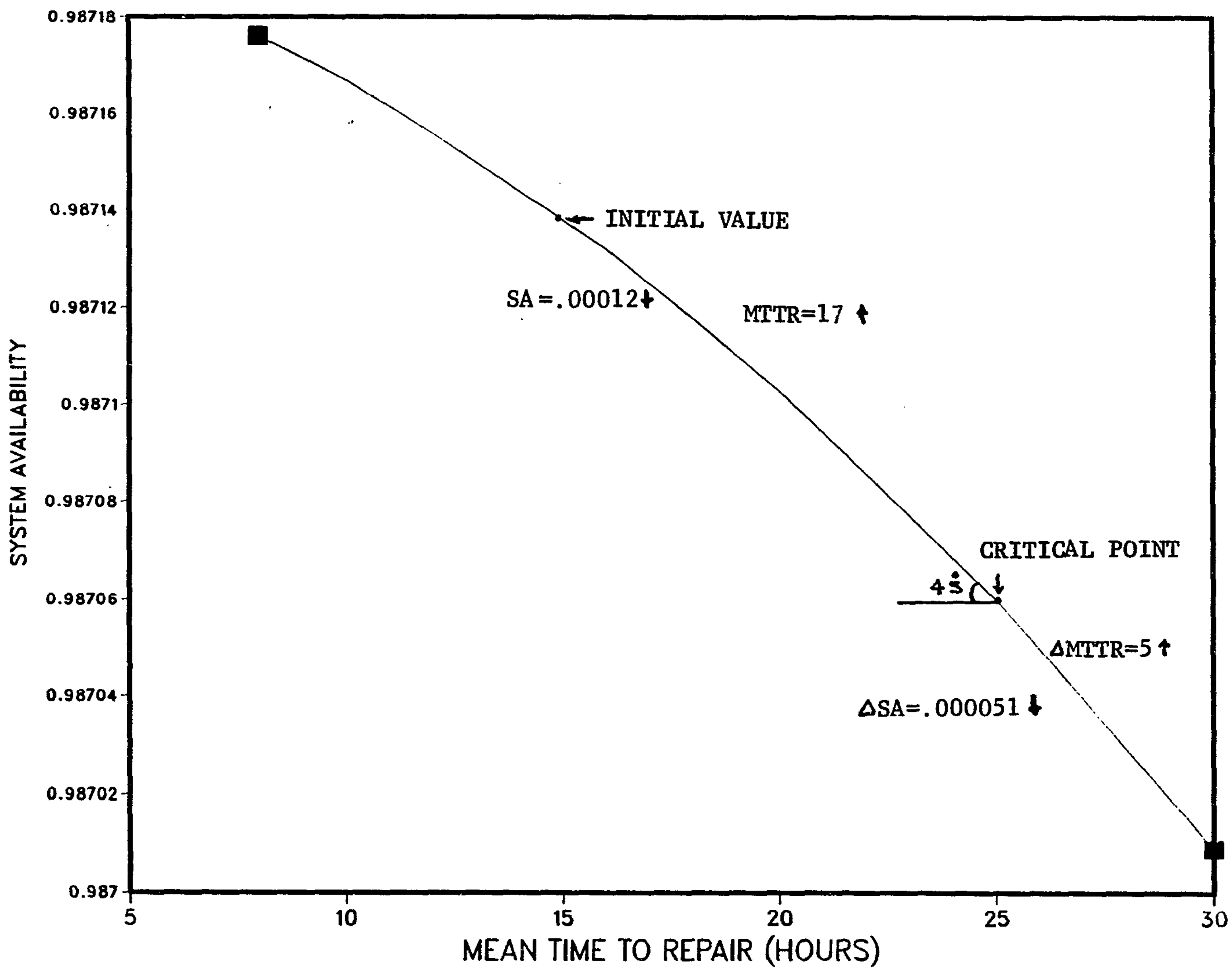


FIGURE 20. Sensitivity analysis: Change in MTTR for equipment type #3

TABLE 7. Variations in MTR for each equipment type

	Mean time to response	System Availability
Type #1		
	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

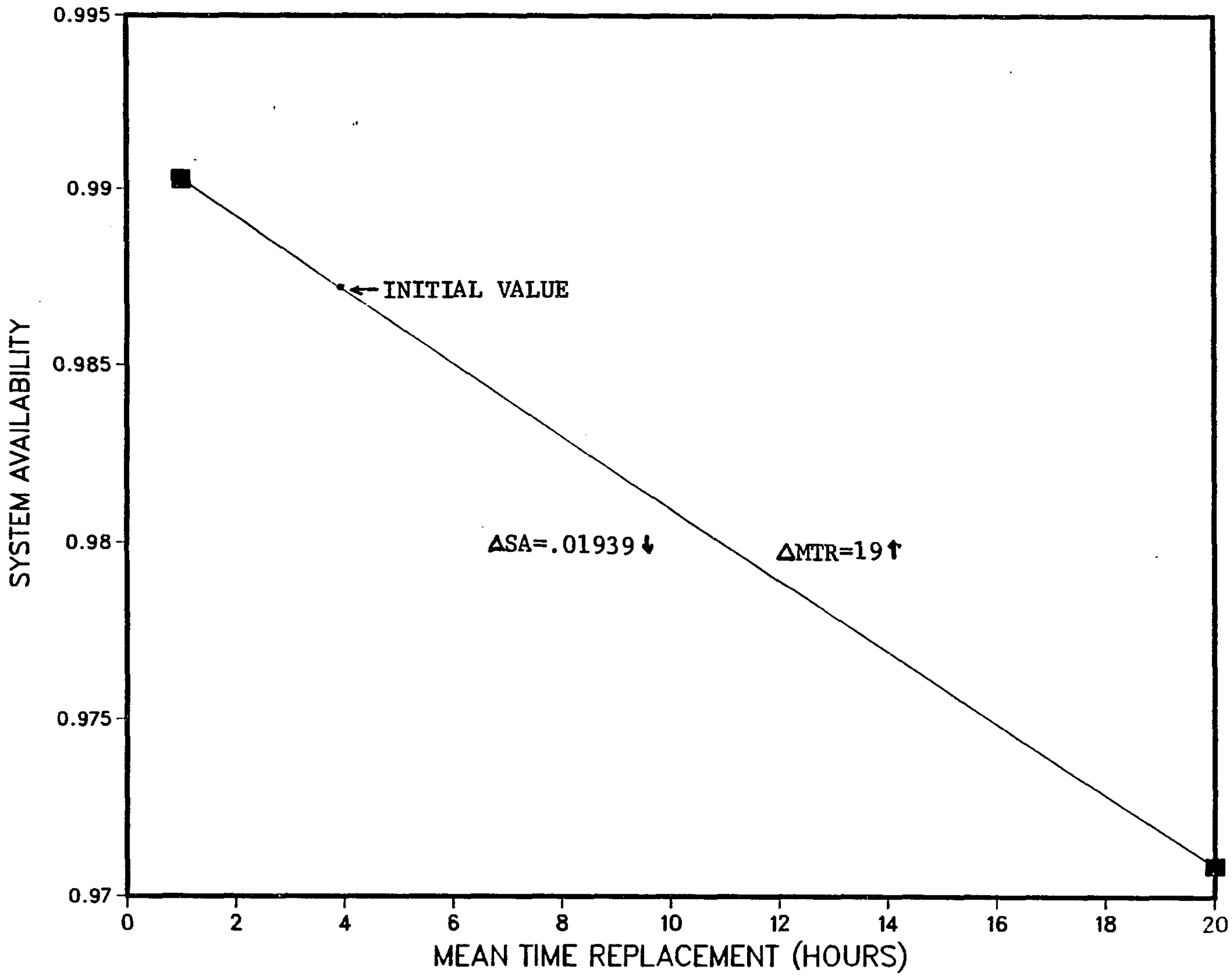


FIGURE 21. Sensitivity analysis: Change in MTR for equipment type #1

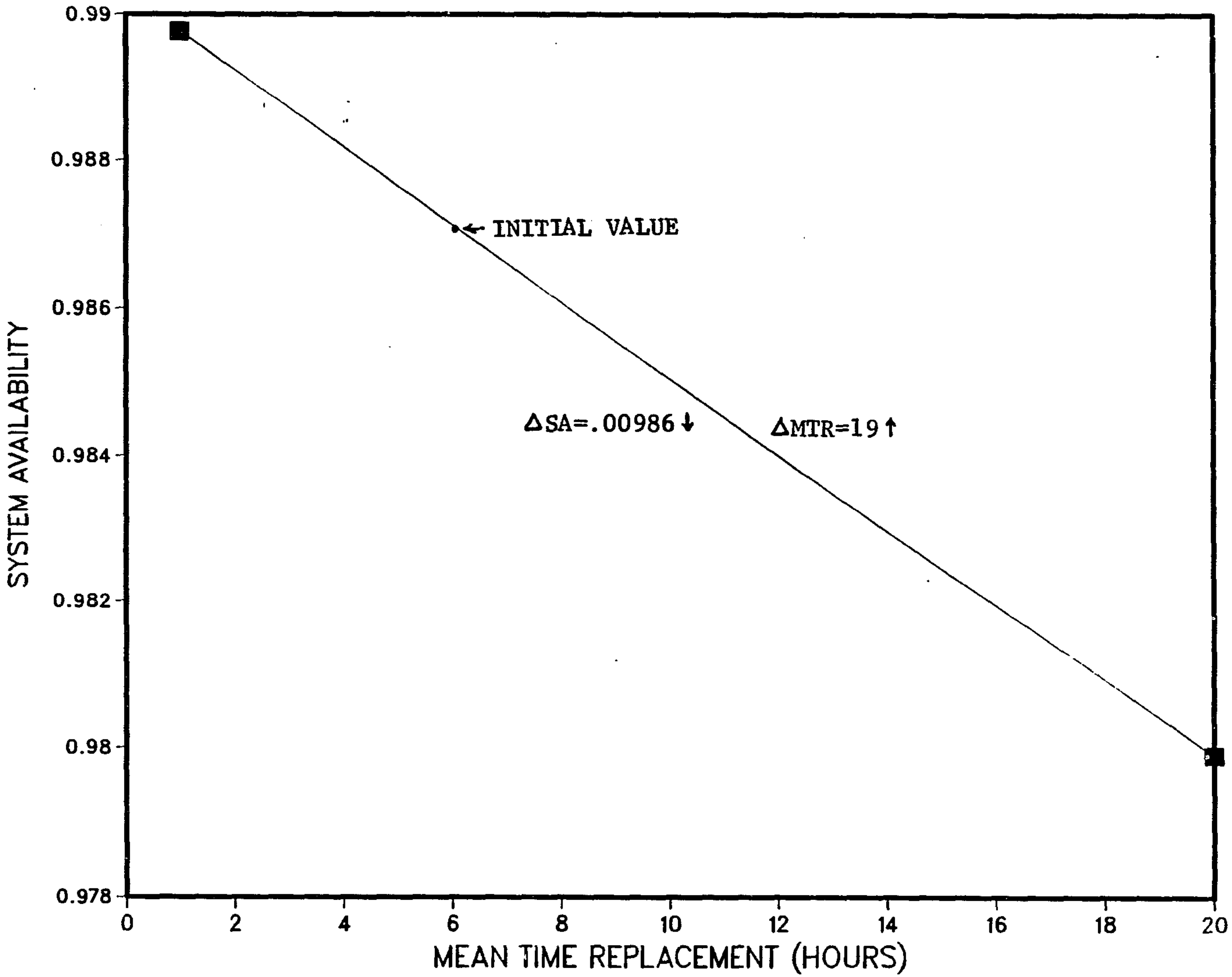


FIGURE 22. Sensitivity analysis: Change in MTR for equipment type #2

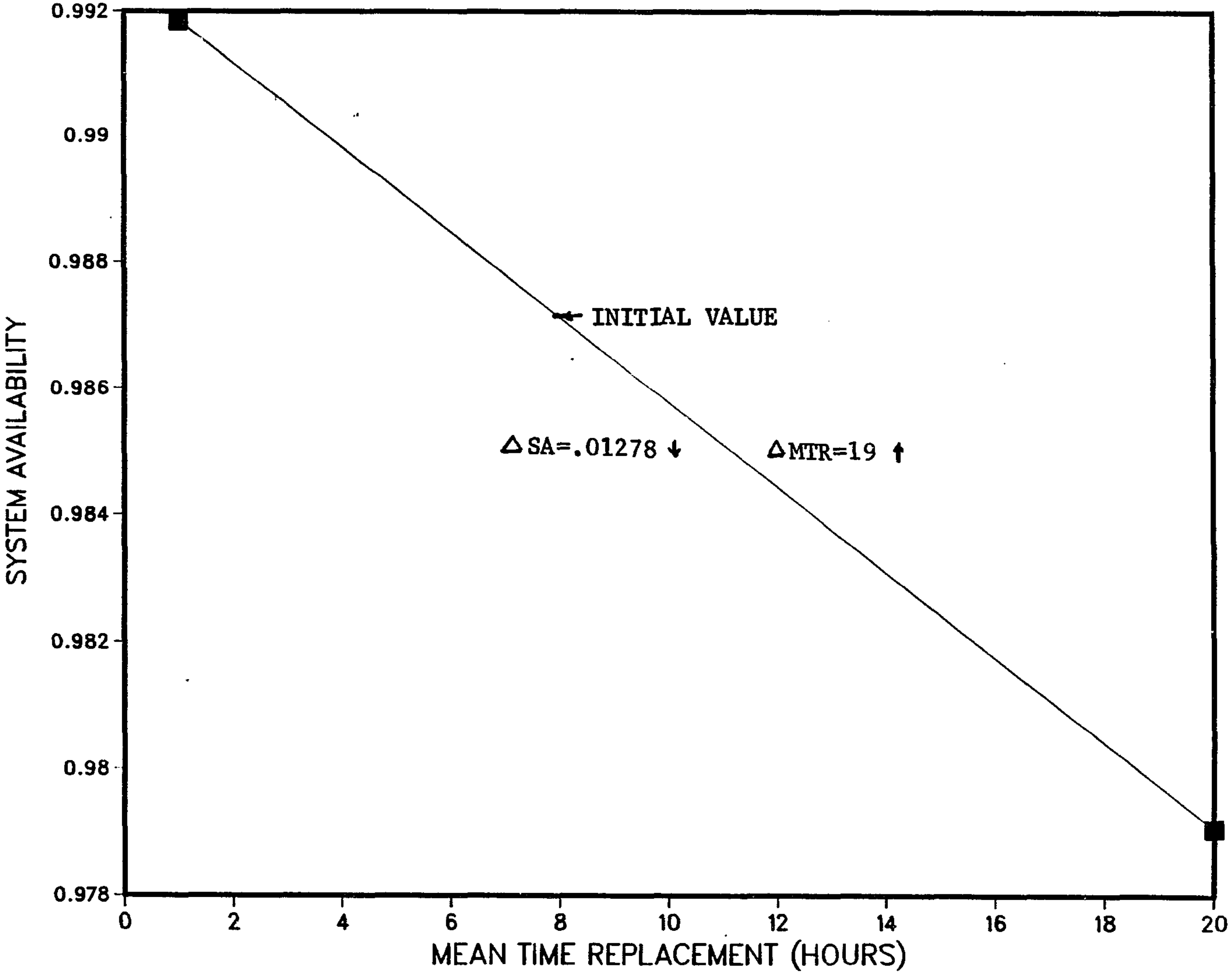


FIGURE 23. Sensitivity analysis: Change in MTR for equipment type #3

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, .. 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

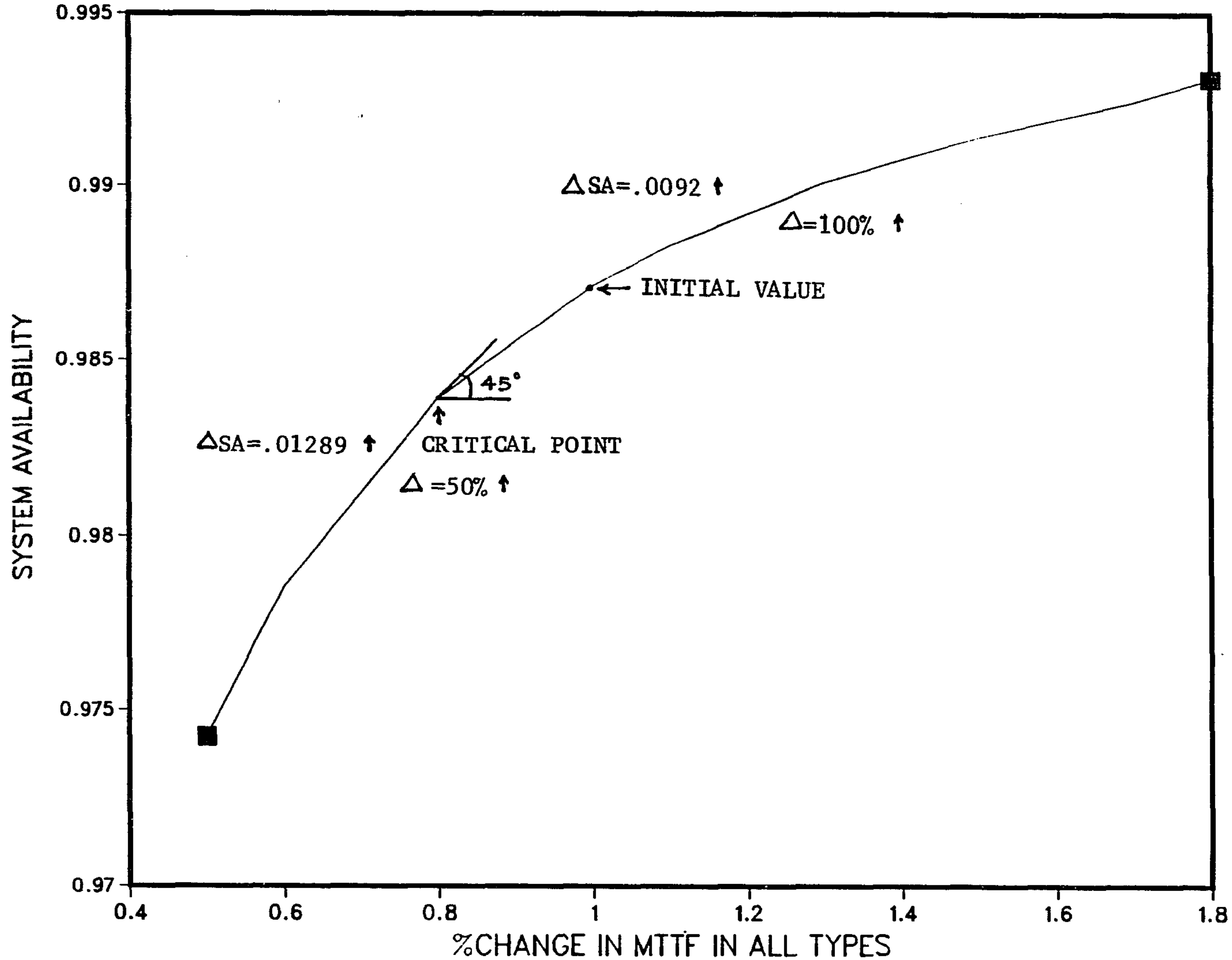


FIGURE 24. Sensitivity analysis: Change in MTTF for all equipment types

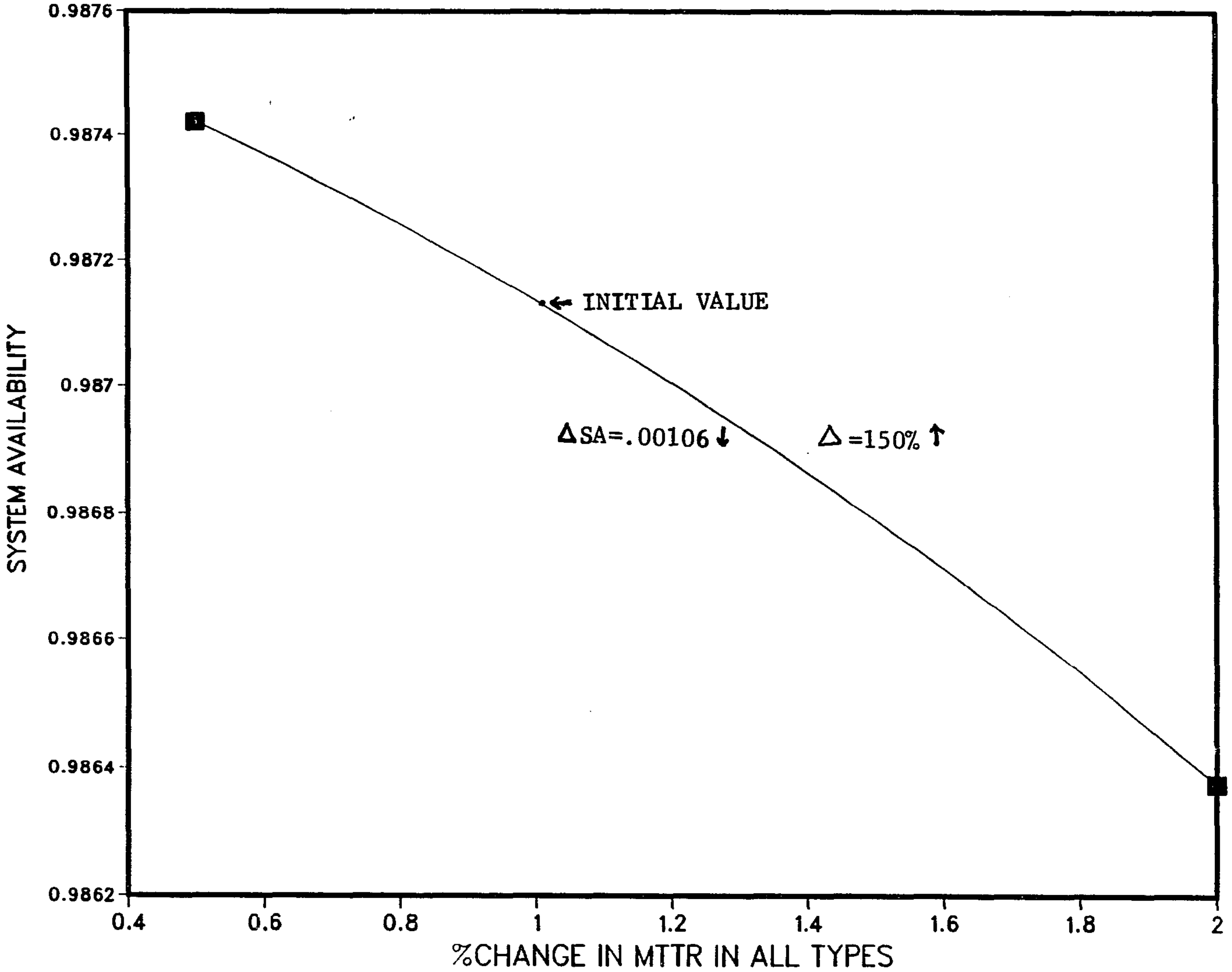


FIGURE 25. Sensitivity analysis: Change in MTTR for all equipment types

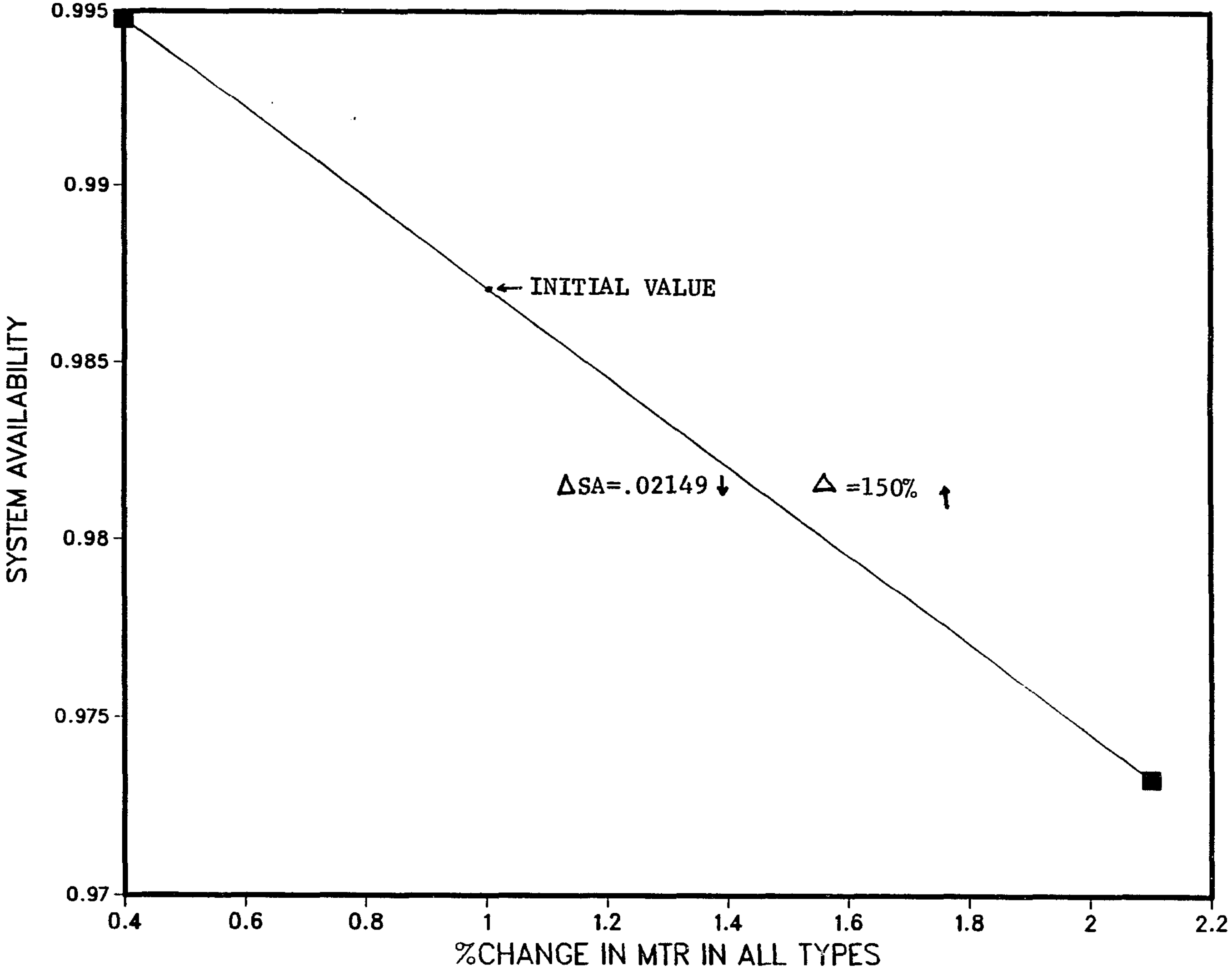


FIGURE 26. Sensitivity analysis: Change in MTR for all equipment types

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

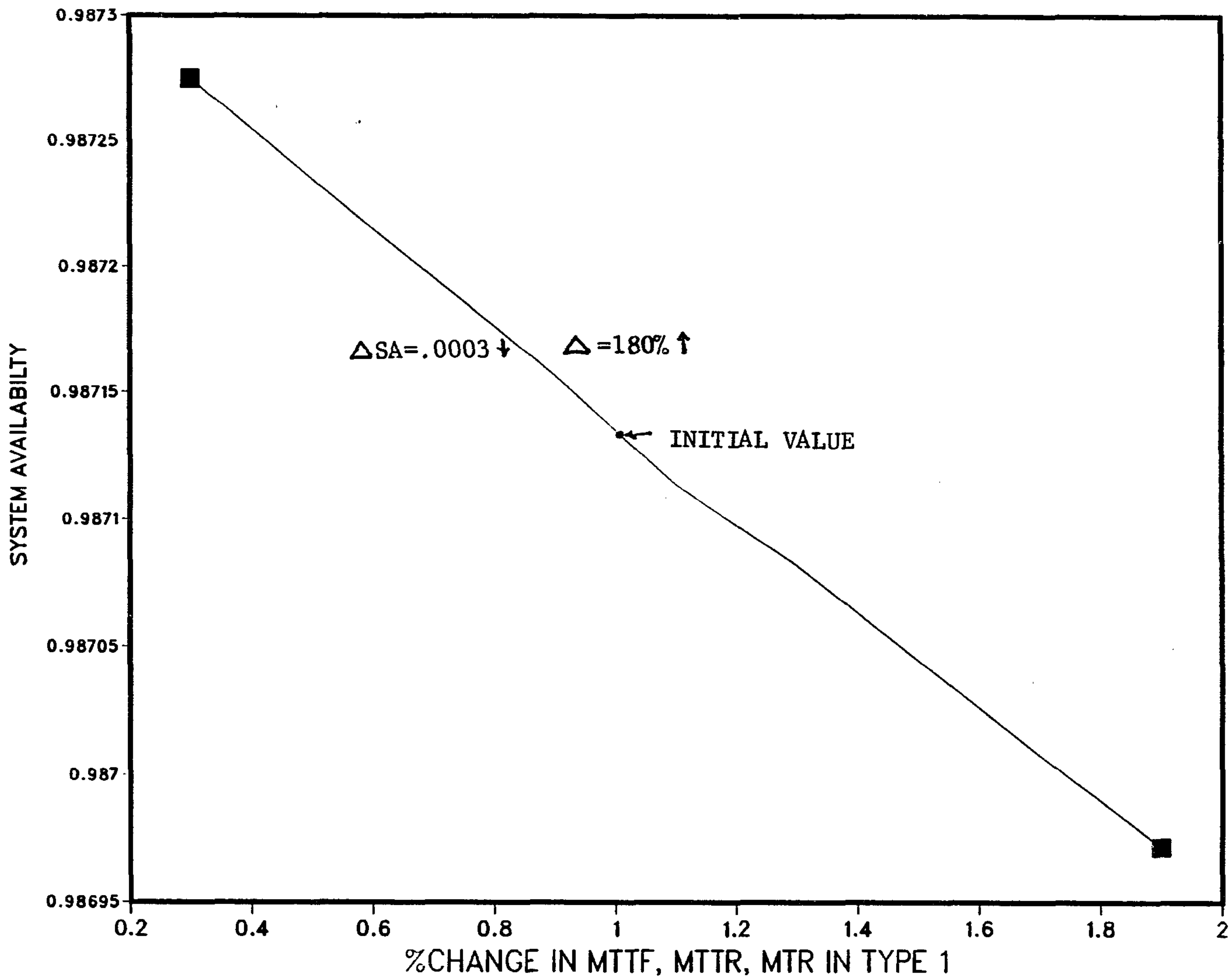


FIGURE 27. Sensitivity analysis: Changes in MTTF, MTTR, and MTR for type #1

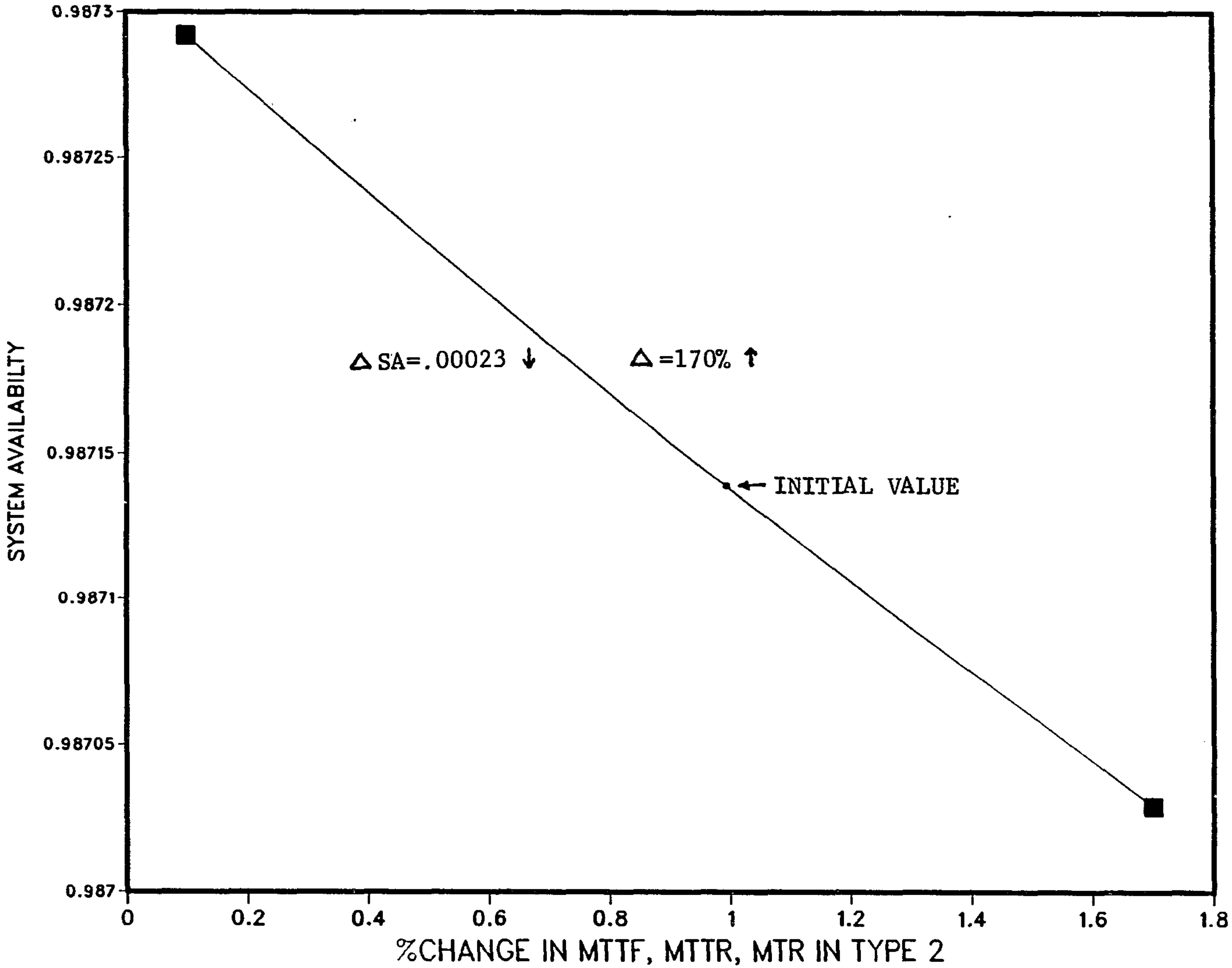


FIGURE 28. Sensitivity analysis: Changes in MTTF, MTTR, and MTR for type #2

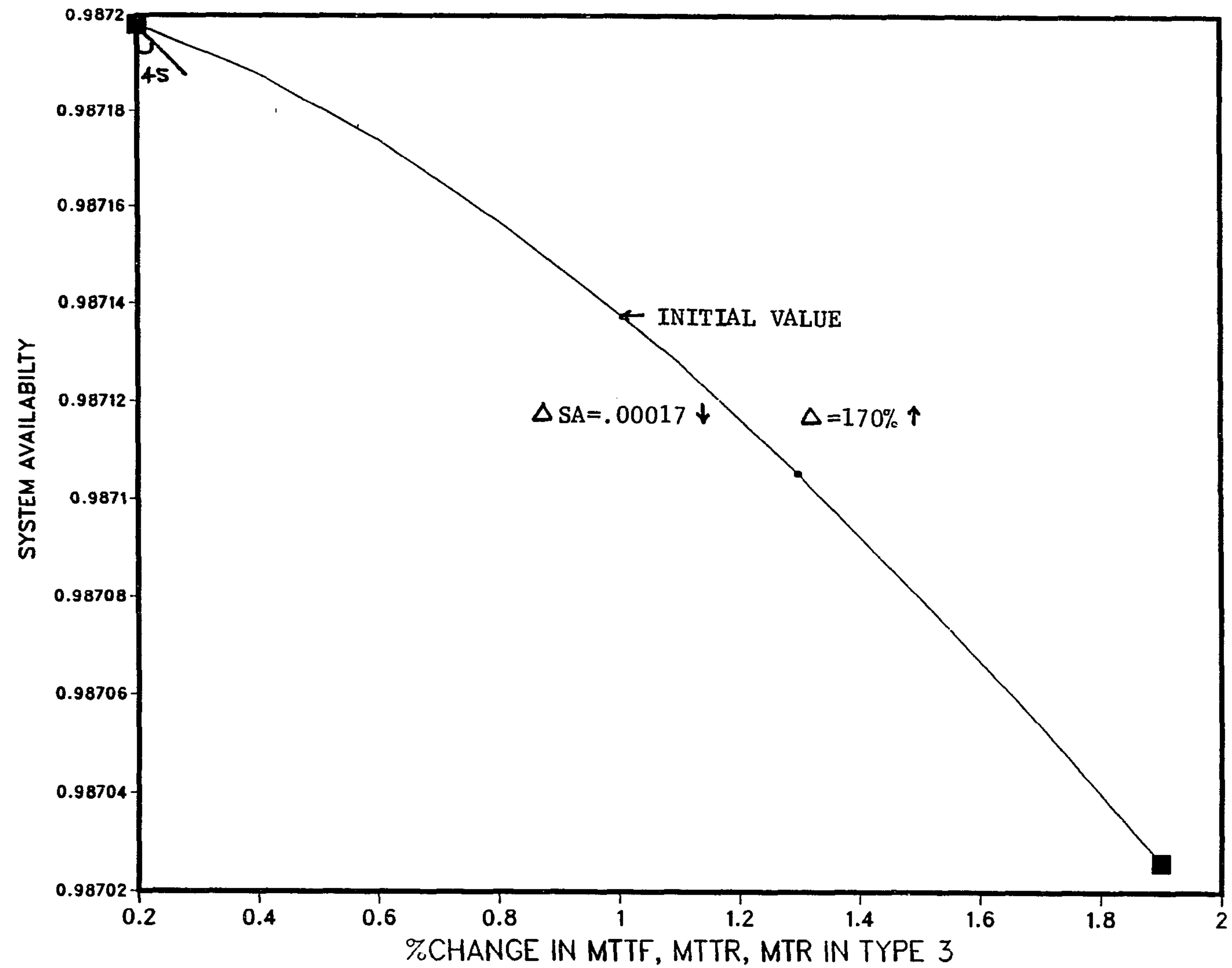


FIGURE 29. Sensitivity analysis: Changes in MTTF, MTTR, and MTR for type #3

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 forth equipment type has MTTF of 400 hours and MTTR of 20 hours. The steady-state availability of such system is

$$\prod_{i=1}^{M=4} \left(\frac{MTTF_i}{MTTF_i + MTTR_i} \right)$$

$$= \frac{300}{310} \cdot \frac{650}{662} \cdot \frac{500}{515} \cdot \frac{400}{420}$$

$$= 0.878594$$

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

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

$$= 0.504249$$

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)

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

In the state of (2,0)

$$+ [\ (3/5)P_1(2,0)\ P_2(0,0)\ P_3(0,0)\ P_4(0,0)\ ]$$
$$+ [\ P_1(0,0)\ (4/6)P_2(2,0)\ P_3(0,0)\ P_4(0,0)\ ]$$
$$+ [\ P_1(0,0)\ P_2(0,0)\ (2/4)P_3(2,0)\ P_4(0,0)\ ]$$
$$+ [\ P_1(0,0)\ P_2(0,0)\ P_3(0,0)\ (4/6)P_4(2,0)\ ]$$

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

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

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

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

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

In the state of (3,0)

+ [$(2/5)P_1(3,0)$ $P_2(0,0)$ $P_3(0,0)$ $P_4(0,0)$]

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

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

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

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

+ [$(4/5)P_1(1,0)$ $(4/6)P_2(2,0)$ $P_3(0,0)$ $P_4(0,0)$]

+ [$(4/5)P_1(1,0)$ $P_2(0,0)$ $(2/4)P_3(2,0)$ $P_4(0,0)$]

+ [$(4/5)P_1(1,0)$ $P_2(0,0)$ $P_3(0,0)$ $(4/6)P_4(2,0)$]

+ [$(3/5)P_1(2,0)$ $(5/6)P_2(1,0)$ $P_3(1,0)$ $P_4(0,0)$]

+ [$P_1(0,0)$ $(5/6)P_2(1,0)$ $(2/4)P_3(2,0)$ $P_4(0,0)$]

+ [$P_1(0,0)$ $(5/6)P_2(1,0)$ $P_3(0,0)$ $(4/6)P_4(2,0)$]

+ [$(3/5)P_1(2,0)$ $P_2(0,0)$ $(3/4)P_3(1,0)$ $P_4(0,0)$]

+ [$P_1(0,0)$ $(4/6)P_2(2,0)$ $(3/4)P_3(1,0)$ $P_4(0,0)$]

+ [$P_1(0,0)$ $P_2(0,0)$ $(3/4)P_3(1,0)$ $(4/6)P_4(2,0)$]

+ [$(2/5)P_1(2,0)$ $P_2(0,0)$ $P_3(0,0)$ $(5/6)P_4(1,0)$]

+ [$P_1(0,0)$ $(4/6)P_2(2,0)$ $P_3(0,0)$ $(5/6)P_4(1,0)$]

+ [$P_1(0,0)$ $P_2(0,0)$ $(2/4)P_3(2,0)$ $(5/6)P_4(1,0)$]

In the state of (4,0)

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

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

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

+ ... ... + ...

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

$$+ \frac{4}{5}\frac{4}{6}\left(\frac{10}{310}\right)^{1}\left(\frac{300}{310}\right)^{4}\left(\frac{12}{662}\right)^{2}\left(\frac{650}{662}\right)^{4}\left(\frac{500}{515}\right)^{4}\left(\frac{400}{420}\right)^{6}$$

$$+ \frac{4}{5}\frac{2}{4}\left(\frac{10}{310}\right)^{1}\left(\frac{300}{310}\right)^{4}\left(\frac{15}{515}\right)^{2}\left(\frac{500}{515}\right)^{2}\left(\frac{650}{662}\right)^{6}\left(\frac{400}{420}\right)^{6}$$

$$+ \frac{4}{5}\frac{4}{6}\left(\frac{10}{310}\right)^{1}\left(\frac{300}{310}\right)^{4}\left(\frac{20}{420}\right)^{2}\left(\frac{400}{420}\right)^{4}\left(\frac{650}{662}\right)^{6}\left(\frac{500}{515}\right)^{4}$$

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

$$+ \frac{5}{6}\frac{2}{4}\left(\frac{12}{662}\right)^{1}\left(\frac{650}{662}\right)^{5}\left(\frac{15}{515}\right)^{2}\left(\frac{500}{515}\right)^{2}\left(\frac{300}{310}\right)^{5}\left(\frac{400}{420}\right)^{6}$$

$$+ \frac{5}{6}\frac{4}{6}\left(\frac{12}{662}\right)^{1}\left(\frac{650}{662}\right)^{5}\left(\frac{20}{420}\right)^{2}\left(\frac{400}{420}\right)^{4}\left(\frac{300}{310}\right)^{5}\left(\frac{500}{515}\right)^{4}$$

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

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

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

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

$$+ \frac{4}{6}\frac{5}{6}\left(\frac{12}{662}\right)^{2}\left(\frac{650}{662}\right)^{4}\left(\frac{20}{420}\right)^{1}\left(\frac{400}{420}\right)^{5}\left(\frac{300}{310}\right)^{5}\left(\frac{500}{515}\right)^{4}$$

$$+ \frac{2}{4}\frac{5}{6}\left(\frac{15}{515}\right)^{2}\left(\frac{500}{515}\right)^{2}\left(\frac{20}{420}\right)^{1}\left(\frac{400}{420}\right)^{5}\left(\frac{300}{310}\right)^{5}\left(\frac{650}{662}\right)^{6}$$

Any one equipment type in (4,0) state

$$+ \frac{1}{5}\left(\frac{10}{310}\right)^4\left(\frac{300}{310}\right)^1\left(\frac{650}{662}\right)^6\left(\frac{500}{515}\right)^4\left(\frac{400}{420}\right)^6$$

$$+ \frac{2}{6}\left(\frac{12}{662}\right)^4\left(\frac{650}{662}\right)^2\left(\frac{300}{310}\right)^5\left(\frac{500}{515}\right)^4\left(\frac{600}{420}\right)^6$$

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

$$+ \ldots \quad \ldots \quad \ldots \quad \ldots + \ldots \quad \ldots \quad \ldots \quad \ldots + \ldots$$

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

	Transition Rate			
Parameters	Equipment Type 1	Equipment Type 2	Equipment Type 3	Equipment Type 4
λ_i i = 0, 1, .. N_i	1/300	1/650	1/500	1/400
μ_i i = 1, 2, .. n_{max_i}	1/10i	1/12i	1/15i	1/20
β_i i = 0, 1, .. 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:

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

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

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

for i = 1, 2, ..., 4

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

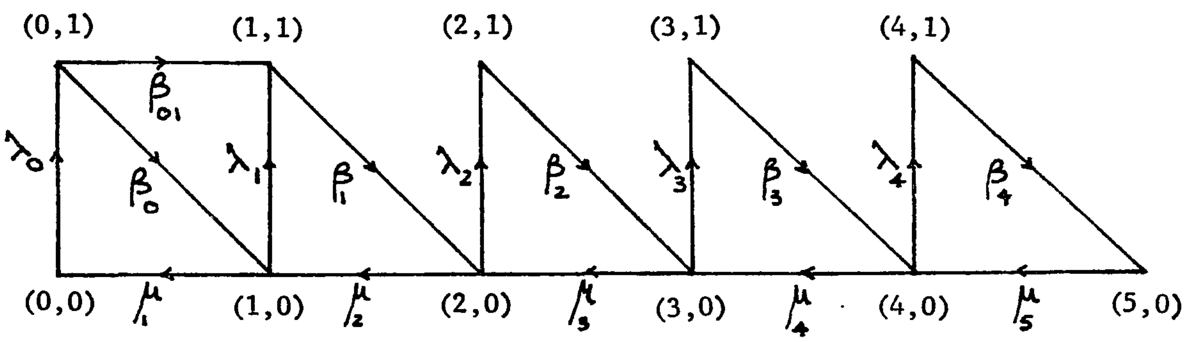
$$P(i,1) = \frac{\lambda_i}{\mu_i} P(i,0)$$

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

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

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

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

$$= (0.949980 + 0.031666)\cdot(0.970012 + 0.017908)$$

$$\cdot(0.949106 + 0.028473)\cdot(0.930222 + 0.046511)$$

$$= 0.981646 \times 0.987920 \times 0.977579 \times 0.976733$$

$$= 0.925986$$

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	State Probabilities: 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}

$= 4/5 \{P_1(2,0)\ [P_2(0,0)+P_2(1,0)]$

$[P_3(0,0)+P_3(1,0)]\ [P_4(0,0)+P_4(1,0)]\}$

$+ 5/6 \{P_2(2,0)\ [P_1(0,0)+P_1(1,0)]$

$[P_3(0,0)+P_3(1,0)]\ [P_4(0,0)+P_4(1,0)]\}$

$+ 3/4 \{P_3(2,0)\ [P_1(0,0)+P_1(1,0)]$

$[P_2(0,0)+P_2(1,0)]\ [P_4(0,0)+P_4(1,0)]\}$

$+ 5/6 \{P_4(2,0)\ [P_1(0,0)+P_1(1,0)]$

$[P_2(0,0)+P_2(1,0)]\ [P_3(0,0)+P_3(1,0)]\}$

$= 0.003431 + 0.002100 + 0.004210 + 0.007174$

$= 0.0169158$

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

$$\sum_{k=1}^{4} W_2^k A_2^k = 3/5\ A_2^1 + 4/6\ A_2^2 + 2/4\ A_2^3 + 4/6\ A_2^4$$

$= 3/5 \{P_1(3,0)\ [P_2(0,0)+P_2(1,0)]$

$[P_3(0,0)+P_3(1,0)]\ [P_4(0,0)+P_4(1,0)]\}$

$+ 4/6 \{P_2(3,0)\ [P_1(0,0)+P_1(1,0)]$

$[P_3(0,0)+P_3(1,0)]\ [P_4(0,0)+P_4(1,0)]\}$

$+ 2/4 \{P_3(3,0)\ [P_1(0,0)+P_1(1,0)]$

$[P_2(0,0)+P_2(1,0)]\ [P_4(0,0)+P_4(1,0)]\}$

$+ 4/6 \{P_4(3,0)\ [P_1(0,0)+P_1(1,0)]$

$[P_2(0,0)+P_2(1,0)]\ [P_3(0,0)+P_3(1,0)]\}$

= 1.4639E-3 or 0.001464

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

$$\sum_{k=1}^{4} W_3^k A_3^k = 2/5\ A_3^1 + 3/6\ A_3^2 + 1/4\ A_3^3 + 3/6\ A_3^4$$

$$= 2/5\ \{P_1(4,0)\ [P_2(0,0)+P_2(1,0)]\ [P_3(0,0)+P_3(1,0)]\ [P_4(0,0)+P_4(1,0)]\}$$

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

$$+ 1/4\ \{P_3(4,0)\ [P_1(0,0)+P_1(1,0)]\ [P_2(0,0)+P_2(1,0)]\ [P_4(0,0)+P_4(1,0)]\}$$

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

$$= 1.723E-4 \quad \text{or} \quad 0.000172$$

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

$$\sum_{k=1}^{4} W_4^k A_4^k = 1/5\ A_4^1 + 2/6\ A_4^2 + 2/6\ A_4^4$$

$$= 1/5\ \{P_1(5,0)\ [P_2(0,0)+P_2(1,0)]\ [P_3(0,0)+P_3(1,0)]\ [P_4(0,0)+P_4(1,0)]\}$$

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

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

$$= 2.37E-5 \quad \text{or} \quad 0.000024$$

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

$$\sum_{k=1}^{4} W_5^k A_5^k = 1/6\ A_5^2 + 1/6\ A_5^4$$

$$+ 1/6\ \{P_2(6,0)\ [P_1(0,0)+P_1(1,0)]\ [P_3(0,0)+P_3(1,0)]\ [P_4(0,0)+P_4(1,0)]\}$$

$$+ 1/6\ \{P_4(6,0)\ [P_1(0,0)+P_1(1,0)]\ [P_2(0,0)+P_2(1,0)]\ [P_3(0,0)+P_3(1,0)]\}$$

$$= 3.30E-6 \quad \text{or} \quad 0.000003$$

2) Two or more equipment types in failure states

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

$$\sum_{\substack{l=1 \\ l \neq k}}^{4} \sum_{k=1}^{4} W_{11}^{kl} A_{11}^{kl} = 4/5\ (\ 5/6\ A_{11}^{12} + 3/4\ A_{11}^{13} + 5/6\ A_{11}^{14}\ )$$

$$+ 5/6\ (\ 3/4\ A_{11}^{23} + 5/6\ A_{11}^{24}\ ) + 3/4 \cdot 5/6\ A_{11}^{34}$$

$$= 2/3\ \{P_1(2,0)\ P_2(2,0)\ [P_3(0,0)+P_3(1,0)]\ [P_4(0,0)+P_4(1,0)]\}$$

$$+ 3/5\ \{P_1(2,0)\ P_3(2,0)\ [P_2(0,0)+P_2(1,0)]\ [P_4(0,0)+P_4(1,0)]\}$$

$$+ 2/3\ \{P_1(2,0)\ P_4(2,0)\ [P_2(0,0)+P_2(1,0)]\ [P_3(0,0)+P_3(1,0)]\}$$

$$+ 5/8\ \{P_2(2,0)\ P_3(2,0)\ [P_1(0,0)+P_1(1,0)]\ [P_4(0,0)+P_4(1,0)]\}$$

$$+ 25/36\ \{P_2(2,0)\ P_4(2,0)\ [P_1(0,0)+P_1(1,0)]\ [P_3(0,0)+P_3(1,0)]\}$$

$$+ 5/8\ \{P_3(2,0)\ P_4(2,0)\ [P_2(0,0)+P_2(1,0)]\ [P_3(0,0)+P_3(1,0)]\}$$

$$= 0.000008 + 0.000016 + 0.000026$$

$$+ 0.000009 + 0.000016 + 0.000032$$

$$= 0.000107$$

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

$$= 0.925986 + 0.018578 + 0.000107 + o(10^{-7})$$

$$= 0.944672$$

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.

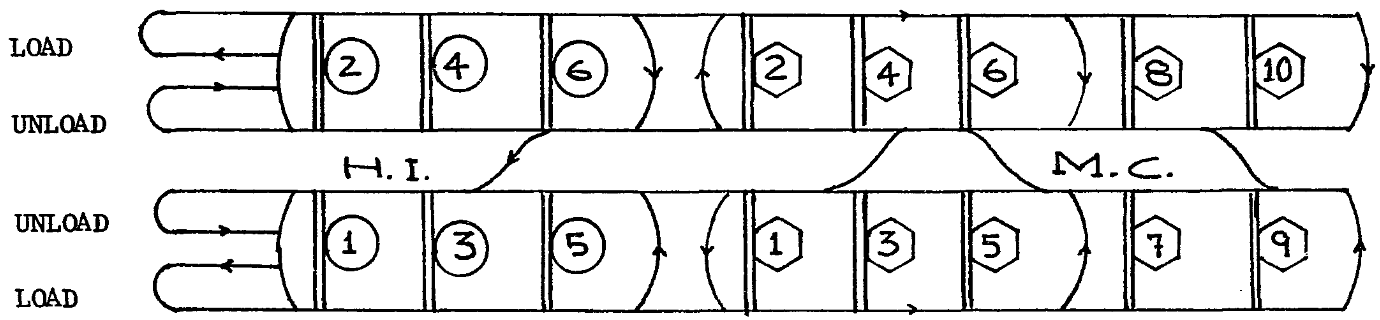


FIGURE 31. Case study: State-of-the-art FMS layout

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

	Transition Rate	
Parameters	Sub-system Type #1	Sub-system Type #2
λ_i i = 0, 1, .. N_i	1/69.20	1/95.38
μ_i i = 1, 2, .. n_{max_i}	1/5.36i	1/13.25i
β_i i = 0, 1, .. 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		

[a]These 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	State Probabilities 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	State Probabilities	
	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		
TYPE# 1	TYPE# 2	F(X)# 1	F(X)# 2	SYS AVAIL
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.

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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

	Mean time to failure	System Availability
Type #1		
	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

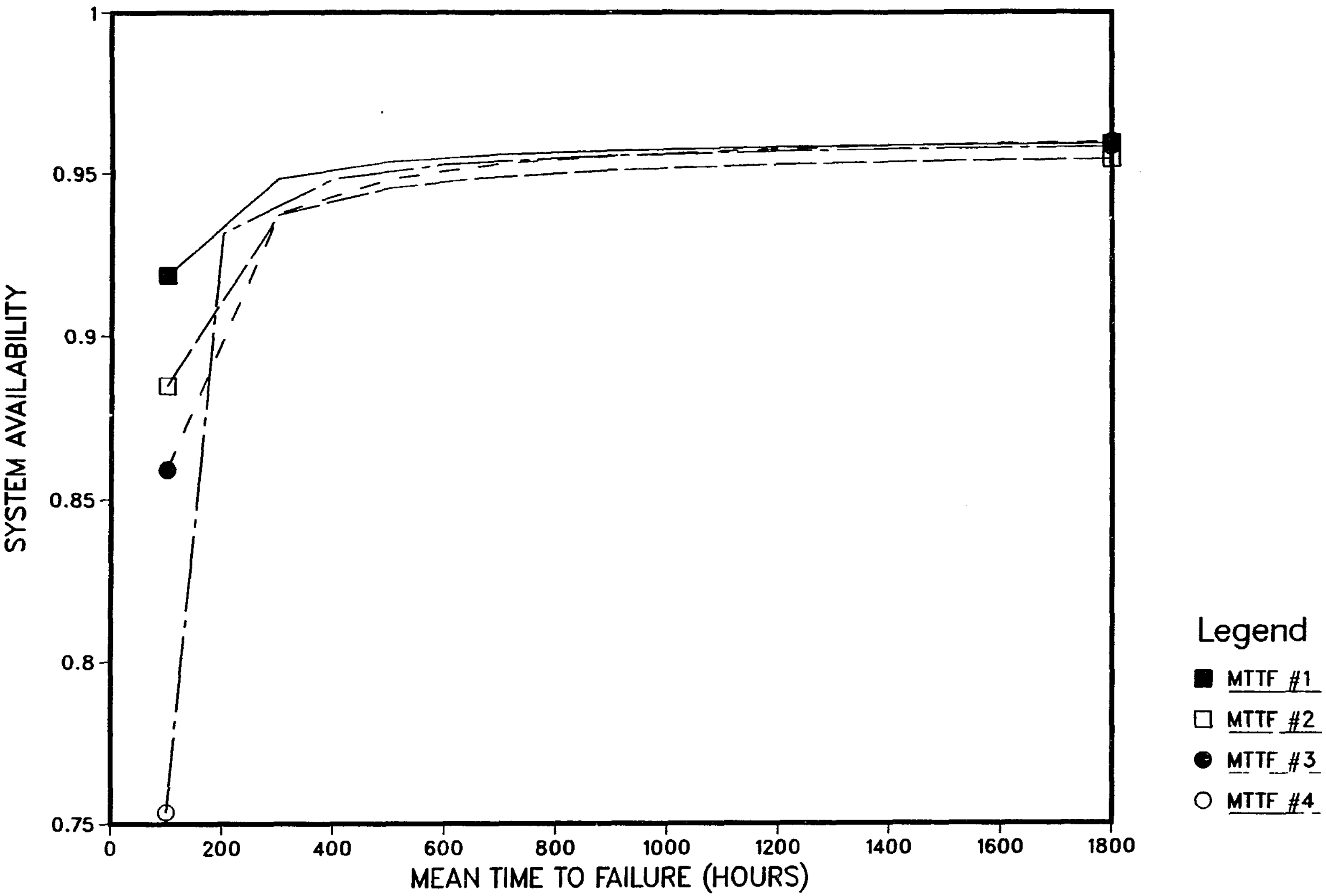

FIGURE 32. Sensitivity analysis: Change in MTTF for equipment type #1/#2/#3/#4

TABLE 20. Variations in MTTR for each equipment

	Mean time to repair	System Availability
Type #1		
	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

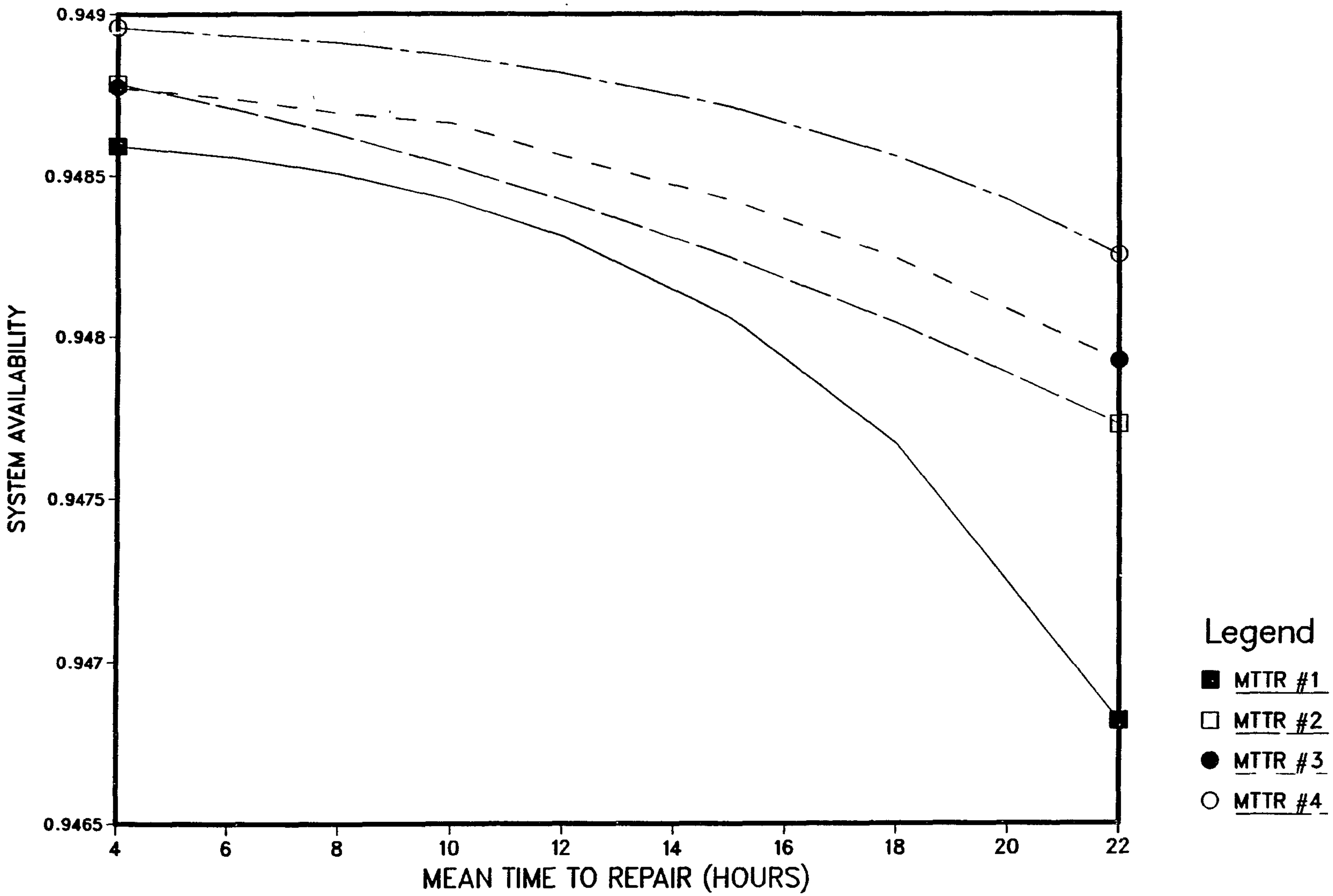

FIGURE 33. Sensitivity analysis: Change in MTTR for equipment type #1/#2/#3/#4

TABLE 21. Variations in MTR for each equipment

	Mean time to response	System Availability
Type #1		
	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

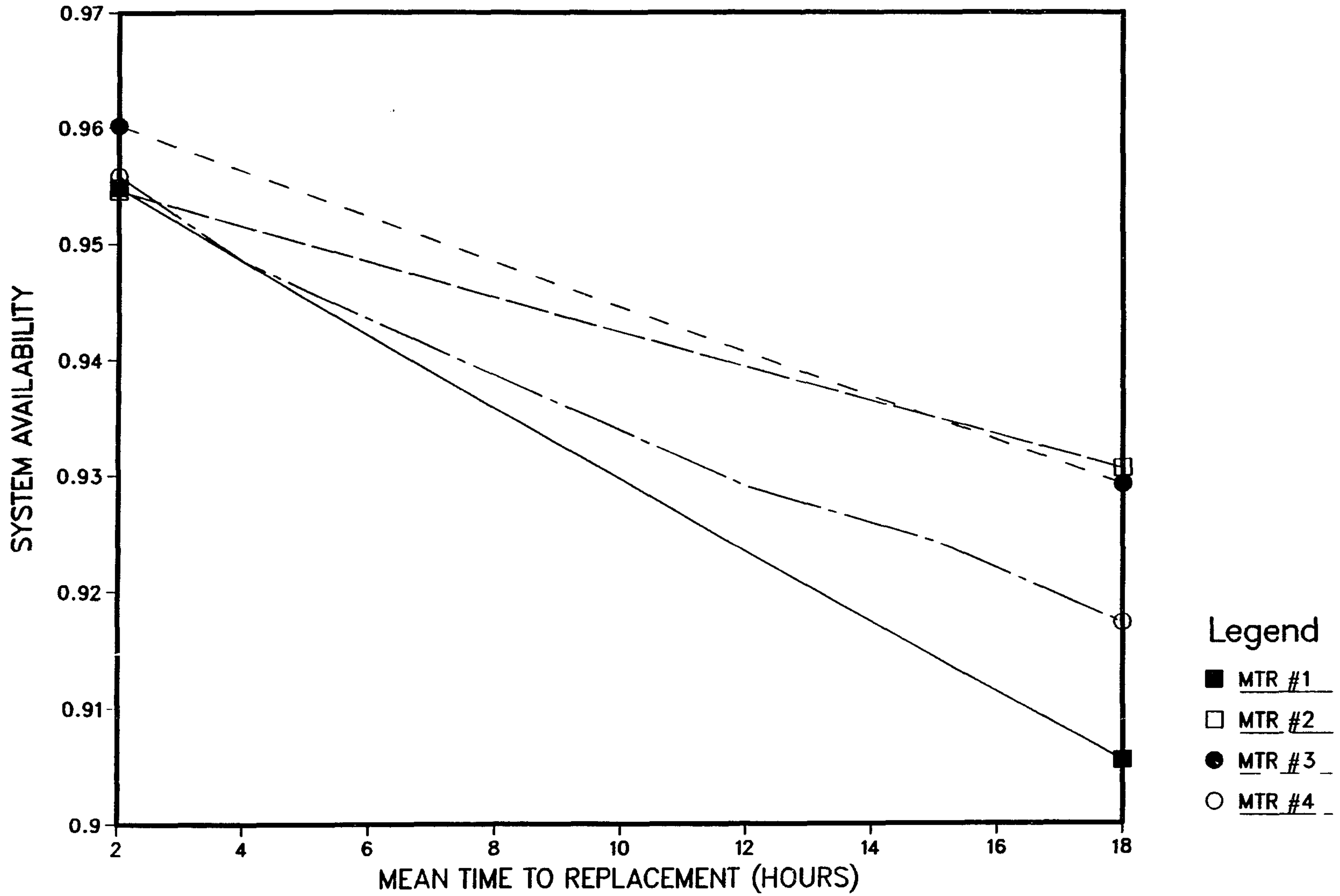

FIGURE 34. Sensitivity analysis: Change in MTR for equipment type #1/#2/#3/#4

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

Percent Increase	Type #1	Type #2	Type #3	Type #4	System Availability
		MEAN TIME TO FAILURE			
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	Type #1	Type #2	Type #3	Type #4	System Availability
		MEAN TIME TO REPAIR			
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	Type #1	Type #2	Type #3	Type #4	System Availability
		MEAN TIME TO RESPONSE			
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

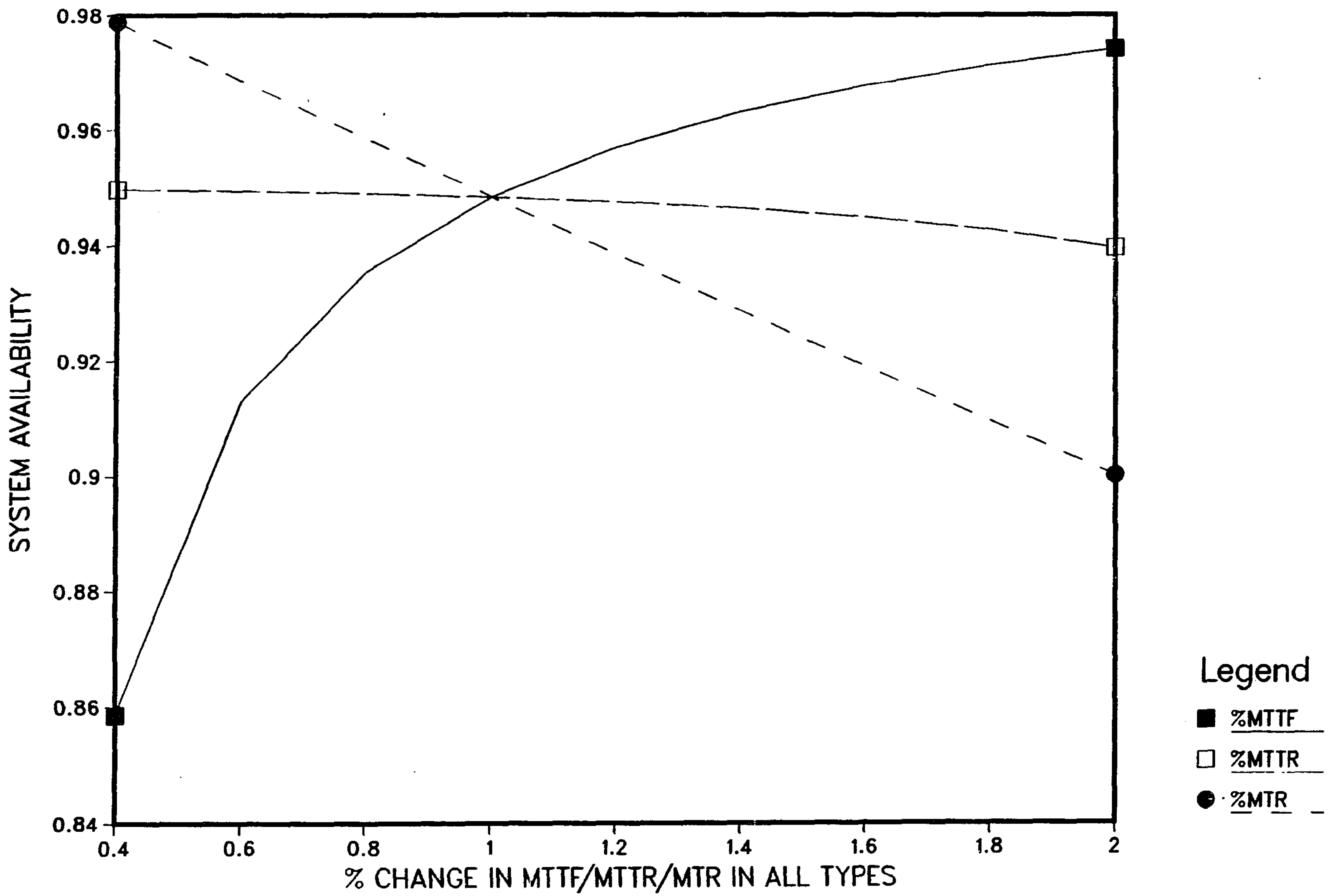

FIGURE 35. Sensitivity analysis: Change in MTTF/MTTR/MTR for all equipment types

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

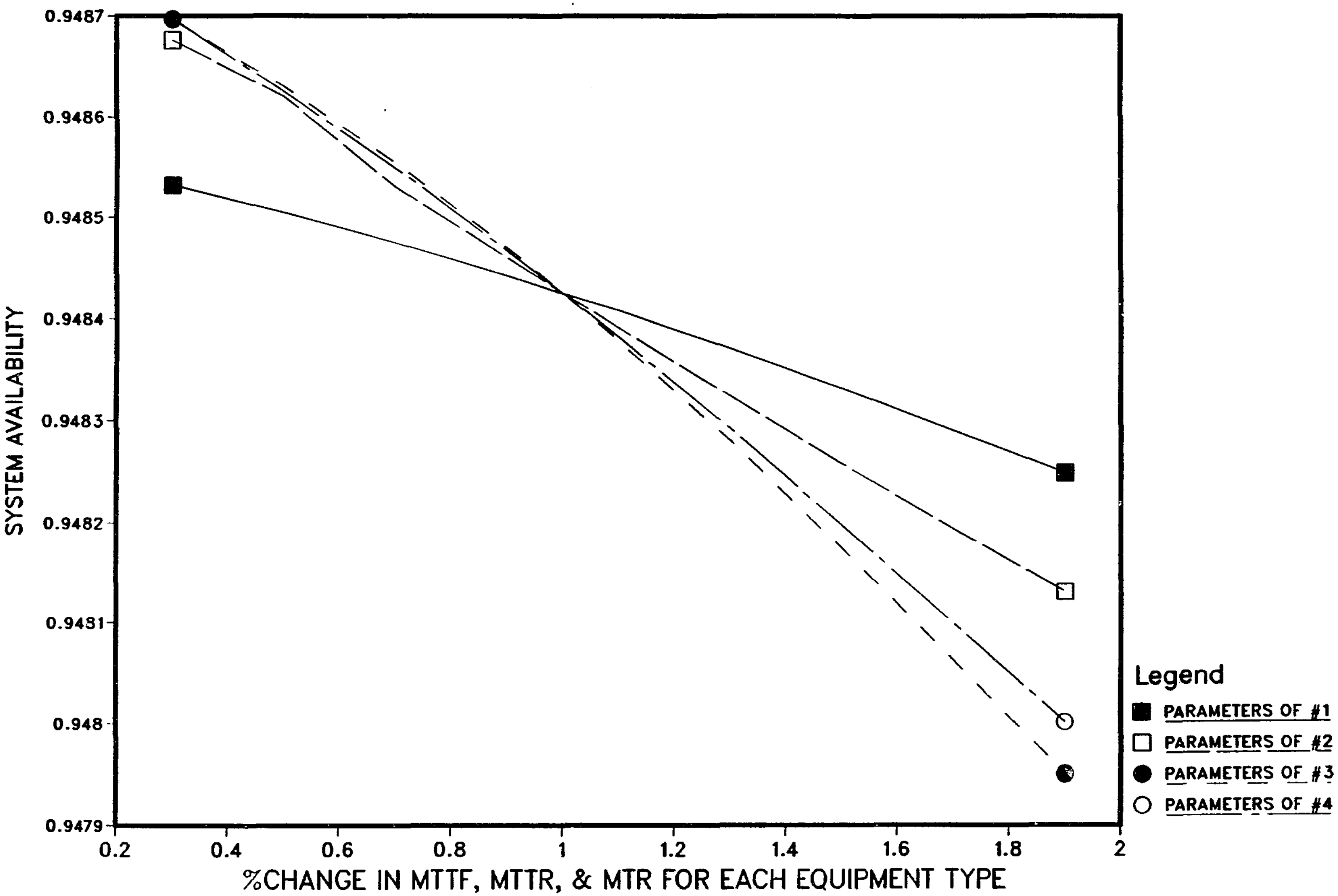

FIGURE 36. Sensitivity analysis: Changes in MTTF, MTTR, & MTR for each equipment

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

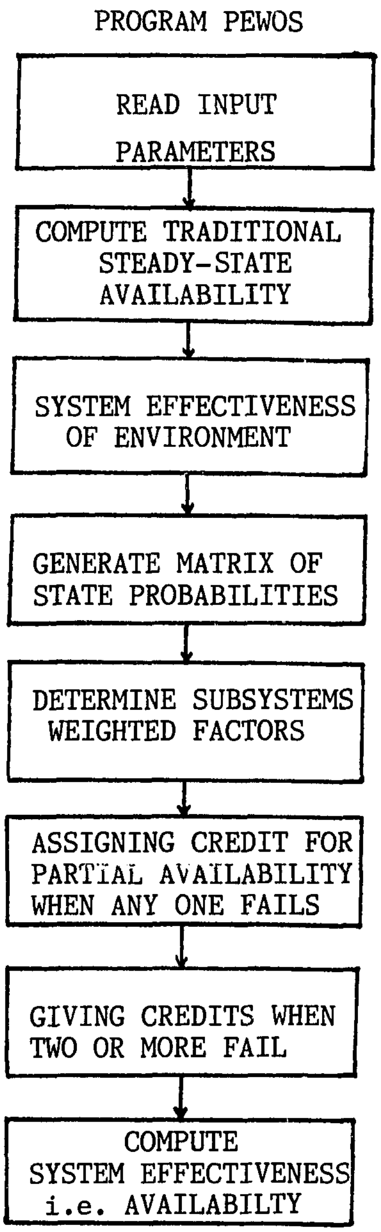

FIGURE 37. Flow chart of computer program PEWOS

```
 PROGRAM PEWOS
***********************************************************************
*                                                                     :
*     PURPOSE: 1.THIS PROGRAM EVALUATES THE PERFORMANCE USING         :
*                WEIGHTED FACTORS FOR A  GENERIC FLEXIBLE             :
*                MANUFACTURING SYSTEM WITHOUT HAVING SPARES           :
*                FOR FAILING EQUIPMENT                                :
*              2.TAKES INTO ACCOUNT PARTIAL CREDIT FOR                :
*                PARTIAL AVAILABILITY                                 :
*                                                                     :
*     INPUT:   INTEGER,                                               :
*            >M:      M IS THE TYPES OF EQUIPMENT IN AN FMS           :
*            >N:      N IS THE NUMBER OF EACH TYPE OF                 :
*                     EQUIPMENT IN FMS ENVIRONMENT                    :
*              REAL,                                                  :
*            >MTTF:  MTTF IS THE MEAN TIME TO FAILURE                 :
*            >MTTR:  MTTR IS THE MEAN TIME TO REPAIR                  :
*                                                                     :
*     LIMITATION:                                                     :
*            >M:      M CANNOT BE GREATER THEN 10                     :
*            >N:      N CANNOT BE GREATER THEN 10                     :
*                                                                     :
*     OUTPUT:                                                         :
*          >S.S-A   STEADY-STATE AVAILABILITY                         :
*          >SYS-A   SYSTEM'S OVERALL AVAILABILITY                     :
*                                                                     :
***********************************************************************
*
      REAL MTTR(10),MTTF(10)
      INTEGER M,A1,A2,A3,A4,A5,A6,A7,A8,A9,A10,N(10)
      DOUBLEPRECISION P1(0:9,0:0),P2(0:9,0:0),P3(0:9,0:0),
     :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),
     :P9(0:9,0:0),P10(0:9,0:0),ATRAD,SSAVAL,P0,PA1,PA1A2
*
*                      INITIALIZE DATA
*
      DATA N/10*1/
      DATA P1(0,0),P2(0,0),P3(0,0),P4(0,0),P5(0,0),P6(0,0),P7(0,0),
     :P8(0,0),P9(0,0),P10(0,0)/1.,1.,1.,1.,1.,1.,1.,1.,1.,1./
*
*                   INTERACTIVE DATA INPUT
*
      WRITE(6,'(X,A)')'PLEASE SUPPLY THE VALUE OF "M"; WHERE'
      WRITE(6,'(X,A)')'M IS THE TYPES OF EQUIPMENT IN FMS'
      WRITE(6,*)
      READ *, M
      WRITE(6,*)
      WRITE(6,'(X,A)')'PLEASE SUPPLY THE VALUE OF "N"; WHERE'
      WRITE(6,'(X,A)')'N IS THE # OF EACH TYPE OF EQUIPMENT IN FMS'
      WRITE(6,*)
      DO I=1,M
```

```
        WRITE(6,'(X,A,I2,A)')'SUPPLY NOW THE VALUE OF "N" FOR
     :  TYPE#',I,' ONLY'
        WRITE(6,*)
        READ*,N(I)
      ENDDO
      DO I=1,M
       WRITE(6,'(X,A,I2,A)')'SUPPLY VALUES OF "MTTF" AND "MTTR"
     : FOR THE EQUIPMENT TYPE #',I,' ONLY'
       WRITE(6,'(X,A,I2)')'WHERE MTTF IS THE MEAN TIME TO FAILURE
     : FOR TYPE #',I,' ONLY'
       WRITE(6,'(X,A,I2)')'WHERE MTTR IS THE MEAN TIME TO REPAIR
     : FOR TYPE #',I,' ONLY'
       WRITE(6,*)
       READ*,MTTF(I),MTTR(I)
       WRITE(6,*)
      ENDDO
      ATRAD = 1.0D0
*
*               DETERMINING STEADY-STATE AVAILABILITY
*
      DO J = 1,M
        SSAVAL= (MTTF(J)/( MTTF(J) + MTTR(J) ))
        ATRAD=ATRAD*SSAVAL**N(J)
      ENDDO
      PRINT*
      PRINT'(X,A,F9.6)','STEADY-STATE AVAILABILITY =',ATRAD
      PRINT*
*
*                PROBABILITY OF FAILURE FOR TYPE #1
*
      DO A1 = 0,N(1)-1
        D1 = MTTR(1) + MTTF(1)
        P1(A1,0) = (MTTR(1)/D1)**A1 * (MTTF(1)/D1)**(N(1)-A1)
      ENDDO
*
*                PROBABILITY OF FAILURE FOR TYPE #2
*
      IF ( M .GE. 2 ) THEN
        DO A2 = 0,N(2)-1
          D2 = MTTR(2) + MTTF(2)
          P2(A2,0) = (MTTR(2)/D2)**A2 * (MTTF(2)/D2)**(N(2)-A2)
        ENDDO
      ENDIF
*
*                PROBABILITY OF FAILURE FOR TYPE #3
*
      IF ( M .GE. 3 ) THEN
        DO A3 = 0,N(3)-1
          D3 = MTTR(3) + MTTF(3)
          P3(A3,0) = (MTTR(3)/D3)**A3 * (MTTF(3)/D3)**(N(3)-A3)
        ENDDO
```

```
      ENDIF
*
*                PROBABILITY OF FAILURE FOR TYPE #4
*
      IF ( M .GE. 4 ) THEN
        DO A4 = 0,N(4)-1
          D4 = MTTR(4) + MTTF(4)
          P4(A4,0) = (MTTR(4)/D4)**A4 * (MTTF(4)/D4)**(N(4)-A4)
        ENDDO
      ENDIF
*
*                PROBABILITY OF FAILURE FOR TYPE #5
*
      IF ( M .GE. 5 ) THEN
        DO A5 = 0,N(5)-1
          D5 = MTTR(5) + MTTF(5)
          P5(A5,0) = (MTTR(5)/D5)**A5 * (MTTF(5)/D5)**(N(5)-A5)
        ENDDO
      ENDIF
*                PROBABILITY OF FAILURE FOR TYPE #6
      IF ( M .GE. 6 ) THEN
        DO A6 = 0,N(6)-1
          D6 = MTTR(6) + MTTF(6)
          P6(A6,0) = (MTTR(6)/D6)**A6 * (MTTF(6)/D6)**(N(6)-A6)
        ENDDO
      ENDIF
*                PROBABILITY OF FAILURE FOR TYPE #7
      IF ( M .GE. 7 ) THEN
        DO A7 = 0,N(7)-1
          D7 = MTTR(7) + MTTF(7)
          P7(A7,0) = (MTTR(7)/D7)**A7 * (MTTF(7)/D7)**(N(7)-A7)
        ENDDO
      ENDIF
*                PROBABILITY OF FAILURE FOR TYPE #8
      IF ( M .GE. 8 ) THEN
        DO A8 = 0,N(8)-1
          D8 = MTTR(8) + MTTF(8)
          P8(A8,0) = (MTTR(8)/D8)**A8 * (MTTF(8)/D8)**(N(8)-A8)
        ENDDO
      ENDIF
*                PROBABILITY OF FAILURE FOR TYPE #9
      IF ( M .GE. 9 ) THEN
        DO A9 = 0,N(9)-1
          D9 = MTTR(9) + MTTF(9)
          P9(A9,0) = (MTTR(9)/D9)**A9 * (MTTF(9)/D9)**(N(9)-A9)
        ENDDO
      ENDIF
*                PROBABILITY OF FAILURE FOR TYPE #10
      IF ( M .GE. 10 ) THEN
        DO A10 = 0,N(10)-1
          D10 = MTTR(10) + MTTF(10)
```

```
        P10(A10,0)=(MTTR(10)/D10)**A10*(MTTF(10)/D10)**(N(10)-A10)
      ENDDO
    ENDIF
*
*                       NO FAILURE
*
    P0 = P1(0,0)*P2(0,0)*P3(0,0)*P4(0,0)*P5(0,0)*P6(0,0)*P7(0,0)*
   :     P8(0,0)*P9(0,0)*P10(0,0)
*
*                    ONE OR MORE FAILURES
*
    CALL FAIL1 (N,M,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PA1)
    CALL FAIL2 (N,M,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PA1A2)
    PRINT*
    PRINT '(X,A,F9.6)','SYSTEM AVAILABILITY=',P0+PA1+PA1A2
    PRINT*
    STOP
    END
*****************************************************************
*                                                               :
*   PURPOSE: 1.ACCOUNTING FOR PARTIAL CREDITS FOR PARTIAL       :
*              AVAILABILITY                                     :
*            2.WHEN ANY ONE TYPE OF EQUIPMENT IN THE FAILURE    :
*              STATE                                            :
*                                                               :
*   INPUT:                                                      :
*           >M   :TYPES OF EQUIPMENT IN FMS                     :
*           >N   :NUMBER OF EACH TYPE IN FMS                    :
*           >P's :STATE PROBABILITIES                           :
*                                                               :
*   OUTPUT:                                                     :
*           >PA1 :PARTIAL CREDITS FROM ENVIRONMENT VIEWPOINT    :
*                 IF ONLY SOME LOCAL SYSTEMS ARE AVAILABLE      :
*                                                               :
*****************************************************************
*
    SUBROUTINE FAIL1 (N,M,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PA1)
    INTEGER N(10),A1,A2,A3,A4,A5,A6,A7,A8,A9,A10
    DOUBLEPRECISION P1(0:N(1)-1,0:0),P2(0:N(2)-1,0:0),
   :P3(0:N(3)-1,0:0),P4(0:N(4)-1,0:0),P5(0:N(5)-1,0:0),
   :P6(0:N(6)-1,0:0),P7(0:N(7)-1,0:0),P8(0:N(8)-1,0:0),
   :P9(0:N(9)-1,0:0),P10(0:N(10)-1,0:0),PA1,PK(10)
    REAL Z(10)
*
*                    INITIALIZATION
*
    DATA PK/10*0.0D0/
    PA1 = 0.0D0
    DO I=1,M
      Z(I)=N(I)
    ENDDO
```

```
      NMAX=MAX(N(1),N(2),N(3),N(4),N(5),N(6),N(7),N(8),N(9),N(10))

*
*                  ACCOUNTING FOR PARTIAL CREDITS
*
      DO A1 = 1,NMAX-1
        DO I = 1,M
           PK(I) = 0.0
        ENDDO
        DO K = 1,M
         IF ( K .EQ. 1 .AND. A1 .LT. N(1) ) THEN
          WA1=((N(1)-A1)/Z(1))
          PK(1)=P1(A1,0)*P2(0,0)*P3(0,0)*P4(0,0)*P5(0,0)*P6(0,0)*
     :         P7(0,0)*P8(0,0)*P9(0,0)*P10(0,0)*WA1
          ELSEIF ( K .EQ. 2 .AND. A1 .LT. N(2) ) THEN
          A2 = A1
          WA2=((N(2)-A1)/Z(2))
          PK(2)=P1(0,0)*P2(A2,0)*P3(0,0)*P4(0,0)*P5(0,0)*P6(0,0)*
     :         P7(0,0)*P8(0,0)*P9(0,0)*P10(0,0)*WA2
          ELSEIF ( K .EQ. 3 .AND. A1 .LT. N(3) ) THEN
          A3 = A1
          WA3=((N(3)-A1)/Z(3))
          PK(3)=P1(0,0)*P2(0,0)*P3(A3,0)*P4(0,0)*P5(0,0)*P6(0,0)*
     :         P7(0,0)*P8(0,0)*P9(0,0)*P10(0,0)*WA3
          ELSEIF ( K .EQ. 4 .AND. A1 .LT. N(4)  ) THEN
          A4 = A1
          WA4=((N(4)-A1)/Z(4))
          PK(4)=P1(0,0)*P2(0,0)*P3(0,0)*P4(A4,0)*P5(0,0)*P6(0,0)*
     :         P7(0,0)*P8(0,0)*P9(0,0)*P10(0,0)*WA4
          ELSEIF ( K .EQ. 5 .AND. A1 .LT. N(5) ) THEN
          A5 = A1
          WA5=((N(5)-A1)/Z(5))
          PK(5)=P1(0,0)*P2(0,0)*P3(0,0)*P4(0,0)*P5(A5,0)*P6(0,0)*
     :         P7(0,0)*P8(0,0)*P9(0,0)*P10(0,0)*WA5
          ELSEIF ( K .EQ. 6 .AND. A1 .LT. N(6) ) THEN
          A6 = A1
          WA6=((N(6)-A1)/Z(6))
          PK(6)=P1(0,0)*P2(0,0)*P3(0,0)*P4(0,0)*P5(0,0)*P6(A6,0)*
     :         P7(0,0)*P8(0,0)*P9(0,0)*P10(0,0)*WA6
          ELSEIF ( K .EQ. 7 .AND. A1 .LT. N(7) ) THEN
          A7 = A1
          WA7=((N(7)-A1)/Z(7))
          PK(7)=P1(0,0)*P2(0,0)*P3(0,0)*P4(0,0)*P5(0,0)*P6(0,0)*
     :         P7(A7,0)*P8(0,0)*P9(0,0)*P10(0,0)*WA7
          ELSEIF ( K .EQ. 8 .AND. A1 .LT. N(8) ) THEN
          A8 = A1
          WA8=((N(8)-A1)/Z(8))
          PK(8)=P1(0,0)*P2(0,0)*P3(0,0)*P4(0,0)*P5(0,0)*P6(0,0)*
     :         P7(0,0)*P8(A8,0)*P9(0,0)*P10(0,0)*WA8
          ELSEIF ( K .EQ. 9 .AND. A1 .LT. N(9) ) THEN
          A9 = A1
```

```
          WA9=((N(9)-A1)/Z(9))
          PK(9)=P1(0,0)*P2(0,0)*P3(0,0)*P4(0,0)*P5(0,0)*P6(0,0)*
     :        P7(0,0)*P8(0,0)*P9(A9,0)*P10(0,0)*WA9
          ELSEIF ( K .EQ. 10 .AND. A1 .LT. N(10) ) THEN
          A10 = A1
          WA10=((N(10)-A1)/Z(10))
          PK(10)=P1(0,0)*P2(0,0)*P3(0,0)*P4(0,0)*P5(0,0)*P6(0,0)*
     :        P7(0,0)*P8(0,0)*P9(0,0)*P10(10,0)*WA10
         ENDIF
        ENDDO
        PA1=PA1+(PK(1)+PK(2)+
     :           PK(3)+PK(4)+PK(5)+PK(6)+PK(7)+PK(8)+PK(9)+PK(10))
      ENDDO
      END
*******************************************************************
*                                                                 :
*     PURPOSE: 1.ACCOUNTING FOR PARTIAL CREDITS FOR PARTIAL       :
*                AVAILABILITY                                     :
*              2.WHEN ANY TWO TYPES OF EQUIPMENT IN THE FAILURE   :
*                STATE                                            :
*                                                                 :
*     INPUT:                                                      :
*             >M     :TYPES OF EQUIPMENT IN FMS                   :
*             >N     :NUMBER OF EACH TYPE IN FMS                  :
*             >P's   :STATE PROBABILITIES                         :
*                                                                 :
*     OUTPUT:                                                     :
*             >PA1A2:PARTIAL CREDITS FROM ENVIRONMENT VIEWPOINT   :
*                    IF ONLY SOME LOCAL SYSTEMS ARE AVAILABLE     :
*                                                                 :
*******************************************************************
*
      SUBROUTINE FAIL2 (N,M,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PA1A2)
      INTEGER N(10),M,K1,K2,A(10),AA1,AA2
      DOUBLEPRECISION P1(0:N(1)-1,0:0),P2(0:N(2)-1,0:0),
     :P3(0:N(3)-1,0:0),P4(0:N(4)-1,0:0),P5(0:N(5)-1,0:0),
     :P6(0:N(6)-1,0:0),P7(0:N(7)-1,0:0),P8(0:N(8)-1,0:0),A1EA2,
     :P9(0:N(9)-1,0:0),P10(0:N(10)-1,0:0),A1NEA2,PA1A2,PK1K2(10)
      REAL Z(10),WA1(10)
*
*                      INITIALIZATION
*
      DATA PK1K2/10*0.0D0/
      PA1A2 = 0.0D0
      A1EA2 = 0.0D0
      A1NEA2 = 0.0D0
      DO I=1,M
        Z(I)=N(I)
      ENDDO
      NMAX=MAX(N(1),N(2),N(3),N(4),N(5),N(6),N(7),N(8),N(9),N(10))
*
```

```
*                     ACCOUNTING FOR PARTIAL CREDITS
*
      DO AA1 = 1,NMAX-1
        DO I = 1,M
          WA1(I) = 0.0
        ENDDO
        DO AA2 = AA1,NMAX-1
          DO K1 = 1,M
            DO I =1,M
              PK1K2(I) = 0.0D0
            ENDDO
            DO K2 = 1,M
              DO I=1,10
                 A(I)=0.0
              ENDDO
              IF ( K1 .EQ. 1 .AND. AA1 .LT. N(1) ) THEN
                A(1)=AA1
                WA1(1)=((N(1)-AA1)/Z(1))
               ELSEIF ( K1 .EQ. 2 .AND. AA1 .LT. N(2) ) THEN
                A(2)=AA1
                WA1(2)=((N(2)-AA1)/Z(2))
               ELSEIF ( K1 .EQ. 3 .AND. AA1 .LT. N(3) ) THEN
                A(3)=AA1
                WA1(3)=((N(3)-AA1)/Z(3))
               ELSEIF ( K1 .EQ. 4 .AND. AA1 .LT. N(4) ) THEN
                A(4)=AA1
                WA1(4)=((N(4)-AA1)/Z(4))
               ELSEIF ( K1 .EQ. 5 .AND. AA1 .LT. N(5) ) THEN
                A(5)=AA1
                WA1(5)=((N(5)-AA1)/Z(5))
               ELSEIF ( K1 .EQ. 6 .AND. AA1 .LT. N(6) ) THEN
                A(6)=AA1
                WA1(6)=((N(6)-AA1)/Z(6))
               ELSEIF ( K1 .EQ. 7 .AND. AA1 .LT. N(7) ) THEN
                A(7)=AA1
                WA1(7)=((N(7)-AA1)/Z(7))
               ELSEIF ( K1 .EQ. 8 .AND. AA1 .LT. N(8) ) THEN
                A(8)=AA1
                WA1(8)=((N(8)-AA1)/Z(8))
               ELSEIF ( K1 .EQ. 9 .AND. AA1 .LT. N(9) ) THEN
                A(9)=AA1
                WA1(9)=((N(9)-AA1)/Z(9))
               ELSEIF ( K1 .EQ. 10 .AND. AA1 .LT. N(10) ) THEN
                A(10)=AA1
                WA1(10)=((N(10)-AA1)/Z(10))
              ENDIF
             IF ( K2 .NE. K1 ) THEN
              IF ( K2 .EQ. 1 .AND. AA2 .LT. N(1) ) THEN
                A(1)=AA2
                WA21=((N(1)-AA2)/Z(1))
                PK1K2(1)=P1(A(1),0)*P2(A(2),0)*P3(A(3),0)*P4(A(4),0)*
```

```
:                    P5(A(5),0)*P6(A(6),0)*P7(A(7),0)*P8(A(8),0)*
:                    P9(A(9),0)*P10(A(10),0)*WA1(K1)*WA21
         ELSEIF ( K2 .EQ. 2 .AND. AA2 .LT. N(2) ) THEN
          A(2)=AA2
          WA22=((N(2)-AA2)/Z(2))
          PK1K2(2)=P1(A(1),0)*P2(A(2),0)*P3(A(3),0)*P4(A(4),0)*
:                    P5(A(5),0)*P6(A(6),0)*P7(A(7),0)*P8(A(8),0)*
:                    P9(A(9),0)*P10(A(10),0)*WA1(K1)*WA22
         ELSEIF ( K2 .EQ. 3 .AND. AA2 .LT. N(3) ) THEN
          A(3)=AA2
          WA23=((N(3)-AA2)/Z(3))
          PK1K2(3)=P1(A(1),0)*P2(A(2),0)*P3(A(3),0)*P4(A(4),0)*
:                    P5(A(5),0)*P6(A(6),0)*P7(A(7),0)*P8(A(8),0)*
:                    P9(A(9),0)*P10(A(10),0)*WA1(K1)*WA23
         ELSEIF ( K2 .EQ. 4 .AND. AA2 .LT. N(4) ) THEN
          A(4)=AA2
          WA24=((N(4)-AA2)/Z(4))
          PK1K2(4)=P1(A(1),0)*P2(A(2),0)*P3(A(3),0)*P4(A(4),0)*
:                    P5(A(5),0)*P6(A(6),0)*P7(A(7),0)*P8(A(8),0)*
:                    P9(A(9),0)*P10(A(10),0)*WA1(K1)*WA24
         ELSEIF ( K2 .EQ. 5 .AND. AA2 .LT. N(5) ) THEN
          A(5)=AA2
          WA25=((N(5)-AA2)/Z(5))
          PK1K2(5)=P1(A(1),0)*P2(A(2),0)*P3(A(3),0)*P4(A(4),0)*
:                    P5(A(5),0)*P6(A(6),0)*P7(A(7),0)*P8(A(8),0)*
:                    P9(A(9),0)*P10(A(10),0)*WA1(K1)*WA25
         ELSEIF ( K2 .EQ. 6 .AND. AA2 .LT. N(6) ) THEN
          A(6)=AA2
          WA26=((N(6)-AA2)/Z(6))
          PK1K2(6)=P1(A(1),0)*P2(A(2),0)*P3(A(3),0)*P4(A(4),0)*
:                    P5(A(5),0)*P6(A(6),0)*P7(A(7),0)*P8(A(8),0)*
:                    P9(A(9),0)*P10(A(10),0)*WA1(K1)*WA26
         ELSEIF ( K2 .EQ. 7 .AND. AA2 .LT. N(7) ) THEN
          A(7)=AA2
          WA27=((N(7)-AA2)/Z(7))
          PK1K2(7)=P1(A(1),0)*P2(A(2),0)*P3(A(3),0)*P4(A(4),0)*
:                    P5(A(5),0)*P6(A(6),0)*P7(A(7),0)*P8(A(8),0)*
:                    P9(A(9),0)*P10(A(10),0)*WA1(K1)*WA27
         ELSEIF ( K2 .EQ. 8 .AND. AA2 .LT. N(8) ) THEN
          A(8)=AA2
          WA28=((N(8)-AA2)/Z(8))
          PK1K2(8)=P1(A(1),0)*P2(A(2),0)*P3(A(3),0)*P4(A(4),0)*
:                    P5(A(5),0)*P6(A(6),0)*P7(A(7),0)*P8(A(8),0)*
:                    P9(A(9),0)*P10(A(10),0)*WA1(K1)*WA28
         ELSEIF ( K2 .EQ. 9 .AND. AA2 .LT. N(9) ) THEN
          A(9)=AA2
          WA29=((N(9)-AA2)/Z(9))
          PK1K2(9)=P1(A(1),0)*P2(A(2),0)*P3(A(3),0)*P4(A(4),0)*
:                    P5(A(5),0)*P6(A(6),0)*P7(A(7),0)*P8(A(8),0)*
:                    P9(A(9),0)*P10(A(10),0)*WA1(K1)*WA29
         ELSEIF ( K2 .EQ. 10 .AND. AA2 .LT. N(10) ) THEN
```

```
                A(10)=AA2
                WA210=((N(10)-AA2)/Z(10))
                PK1K2(10)=P1(A(1),0)*P2(A(2),0)*P3(A(3),0)*P4(A(4),0)
     :                  *P5(A(5),0)*P6(A(6),0)*P7(A(7),0)*P8(A(8),0)*
     :                  P9(A(9),0)*P10(A(10),0)*WA1(K1)*WA210
              ENDIF
             ENDIF
           ENDDO
             IF ( AA1 .EQ. AA2 ) THEN
               A1EA2=0.5*(PK1K2(1)+PK1K2(2)+PK1K2(3)+PK1K2(4)+
     :         PK1K2(5)+PK1K2(6)+PK1K2(7)+PK1K2(8)+PK1K2(9)+PK1K2(10))
               A1NEA2=0.0D0
             ELSE
               A1NEA2=(PK1K2(1)+PK1K2(2)+PK1K2(3)+PK1K2(4)+
     :         PK1K2(5)+PK1K2(6)+PK1K2(7)+PK1K2(8)+PK1K2(9)+PK1K2(10))
               A1EA2=0.0D0
             ENDIF
             PA1A2 = PA1A2 + A1EA2 + A1NEA2
          ENDDO
        ENDDO
      ENDDO
      END
```

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

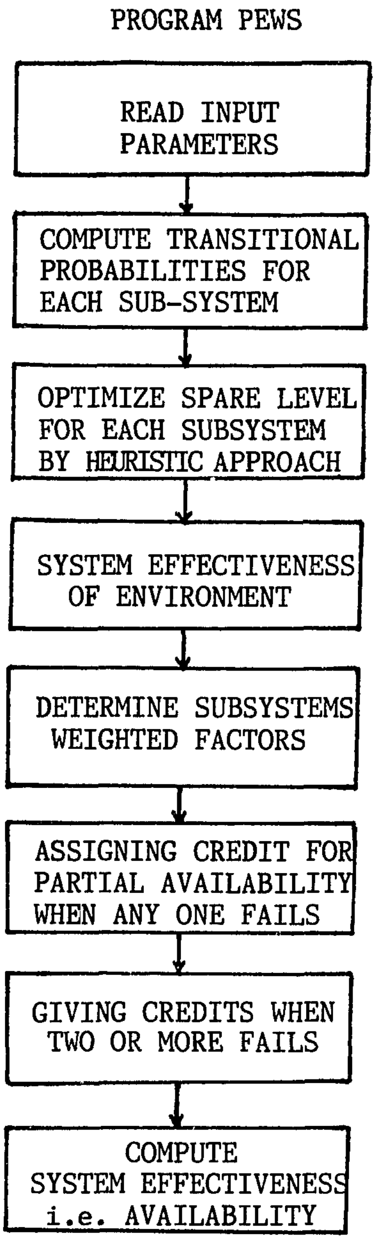

FIGURE 38. Flow chart of computer program PEWS

```
      PROGRAM PEWS
**********************************************************************
*                                                                    :
*     PURPOSE: 1.HEURISTIC PROGRAMMING FOR OPTIMIZING THE           :
*                SPARES-STORAGE LEVEL OF GENERIC FLEXIBLE           :
*                MANUFACTURING SYSTEMS                              :
*              2.EVALUATES THE PERFORMANCE USING WEIGHTED           :
*                FACTORS FOR AN FMS HAVING A CENTRALIZED            :
*                STORAGE FOR SPARES                                 :
*              3.TAKES INTO ACCOUNT PARTIAL CREDITS ONLY            :
*                IF SOME SYSTEMS FUNCTION                           :
*                                                                    :
*     INPUT:  INTEGER,                                               :
*             >M:    WHERE M IS THE TYPES OF EQUIPMENT IN FMS        :
*             >N:    WHERE N IS THE NUMBER OF EACH TYPE OF           :
*                    EQUIPMENT IN FMS ENVIRONMENT                    :
*             REAL,                                                  :
*             >P:    WHERE IS THE PROBABILITY THAT A SELECTED        :
*                    SPARE WORKS                                     :
*             >DFR:  WHERE DFR IS A DESIRABILITY FACTOR RATIO        :
*             >MTR   WHERE MTR IS THE MEAN TIME REPLACEMENT          :
*             >MTTF: WHERE MTTF IS THE MEAN TIME TO FAILURE          :
*             >MTTR: WHERE MTTR IS THE MEAN TIME TO REPAIR           :
*                                                                    :
*     LIMITATION:                                                    :
*             >M:    M CANNOT BE GREATER THEN 10                     :
*             >N:    N CANNOT BE GREATER THEN 10                     :
*                                                                    :
*     OUTPUT: TABULATED FORM                                         :
*             >TYPE# SPARE COMPONENTS REQUIRED FOR EACH TYPE         :
*             >F(X)# SUB-SYSTEM SELECTION FACTOR                     :
*             >SYS-A SYSTEM AVAILABILITY AT GIVEN NUMBER OF          :
*                    OF SPARE FOR EACH TYPE OF EQUIPMENT             :
*             >OPTIMUM NUMBER OF SPARES                              :
*                                                                    :
**********************************************************************
      INTEGER N,M,X,IX(10),IN(10),NMX(10),IXP(10)
      REAL MTTR(10),MTTF(10),MTR(10),BETAI(0:14),LAM(0:14),MEU(15)
      DOUBLEPRECISION P1(0:15,0:1),P2(0:15,0:1),P3(0:15,0:1),
     :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),
     :P9(0:15,0:1),P10(0:15,0:1),TP(0:15,0:1),AVL(10),TRDA(10),ASTOR(2),
     :CHECK(10),AVLMIN,DFR,PROB
:
:                     INTERACTIVE DATA INPUT
:
      DATA IX/10*1./
      DATA IXP/10*1/
      WRITE(6,'(X,A)')'PLEASE SUPPLY THE VALUE OF "M"; WHERE'
      WRITE(6,'(X,A)')'M IS THE TYPES OF EQUIPMENT IN FMS ENVIRONMENT'
      WRITE(6,*)
      READ *, M
```

```
      WRITE(6,*)
      WRITE(6,'(X,A)')'PLEASE SUPPLY THE VALUE OF "N"; WHERE'
      WRITE(6,'(X,A)')'N IS THE # OF EACH TYPE OF EQUIPMENT'
      DO I=1,M
        WRITE(6,*)
        WRITE(6,'(X,A,I2,A)')'SUPPLY NOW THE VALUE OF N FOR TYPE #',I,
     :' ONLY'
        WRITE(6,*)
        READ*,IN(I)
      ENDDO
      DO I=1,M
        NMX(I)=IN(I)+IX(I)
      ENDDO
      WRITE(6,'(X,A)')'PLEASE SUPPLY THE VALUE OF "P"; WHERE'
      WRITE(6,'(X,A)')'P IS THE PROBABILITY THAT A SELECTED SPARE WORKS'
      WRITE(6,*)
      READ *, PROB
      DO I = 1,M
        WRITE(6,'(X,A,I2,A)')'SUPPLY  VALUES OF "MTTF", "MTTR" & "MTR"
     : FOR THE EQUIPMENT TYPE #',I,' ONLY'
       WRITE(6,*)
        WRITE(6,'(X,A,I2)')'WHERE MTTF IS THE MEAN TIME TO FAILURE FOR
     : TYPE #',I
        WRITE(6,'(X,A,I2)')'WHERE MTTR IS THE MEAN TIME TO REPAIR FOR
     : TYPE #',I
        WRITE(6,'(X,A,I2)')'WHERE MTR IS THE MEAN TIME TO REPLACEMENT FOR
     : TYPE #',I
       WRITE(6,*)
        READ *, MTTF(I),MTTR(I),MTR(I)
      ENDDO
      DO I=1,10
        AVL(I)=1.0D5
        CHECK(I)=0.0D0
      ENDDO
      WRITE(6,'(X,A)')'PLEASE SUPPLY THE VALUE OF "DFR"; WHERE'
      WRITE(6,'(X,A)')'DFR IS THE DESIRABILITY FACTOR RATIO'
      WRITE(6,*)
      READ*, DFR
      INDEX = 0.0
:
:           DETERMINE SUB-SYSTEM SELECTION FUNCTION VALUE
:
      DO WHILE ( INDEX .LT. M )
         INDEX = INDEX+1
         IF ( INDEX .NE. 1 )THEN
 111         CONTINUE
             DO I = 1,M
                IX(I)=IXP(I)
             ENDDO
              DO I = 1,10
                 NMX(I) = IX(I) + IN(I)
```

```
            ENDDO
          ENDIF
       DO JJ = 1,M
         DO I = 0,NMX(JJ)-1
            LAM(I) = 1/MTTF(JJ)
            K = I + 1
            MEU(K) = 1/(MTTR(JJ) * K)
            BETAI(I) = 1/MTR(JJ)
         ENDDO
         IF ( JJ .EQ. 1 ) THEN
            X=IX(JJ)
            N=IN(JJ)
            NMAX=N+X

            TRANSITION PROBABILITY FOR EQUIPMENT TYPE #1

            CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
            DO I = 0,NMAX
               IF ( I .LE. 7 ) THEN
                 P1(I,0) = TP(2*I,0)
                 P1(I,1) = TP(2*I+1,0)
                ELSE
                 P1(I,0) = TP(2*I-16,1)
                 P1(I,1) = TP(2*I-15,1)
               ENDIF
            ENDDO

            DETERMINATION OF SUB-SYSTEM #1 SELECTION FACTOR

       CALL TAVAIL(JJ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TAVAL)
       CALL SFAIL1(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL1)
       CALL SFAIL2(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL2)
       TRDA(1) = TAVAL
       PERF(1) = TAVAL+FAIL1+FAIL2
       AVL(1)  = TRDA(1)*PERF(1)
          ELSEIF ( JJ .EQ. 2 ) THEN
            X=IX(JJ)
            N=IN(JJ)
            NMAX=N+X

            TRANSITION PROBABILITY FOR EQUIPMENT TYPE #2

            CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
            DO I = 0,NMAX
               IF ( I .LE. 7 ) THEN
                 P2(I,0) = TP(2*I,0)
                 P2(I,1) = TP(2*I+1,0)
                ELSE
                 P2(I,0) = TP(2*I-16,1)
                 P2(I,1) = TP(2*I-15,1)
               ENDIF
```

```
           ENDDO

           DETERMINATION OF SUB-SYSTEM #2 SELECTION FACTOR

       CALL TAVAIL(JJ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TAVAL)
       CALL SFAIL1(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL1)
       CALL SFAIL2(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL2)
       TRDA(2) = TAVAL
       PERF(2) = TAVAL+FAIL1+FAIL2
       AVL(2)  = TRDA(2)*PERF(2)
          ELSEIF ( JJ .EQ. 3 ) THEN
           X=IX(JJ)
           N=IN(JJ)
           NMAX=N+X

           TRANSITION PROBABILITY FOR EQUIPMENT TYPE #3

           CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
           DO I = 0,NMAX
              IF ( I .LE. 7 ) THEN
                P3(I,0) = TP(2*I,0)
                P3(I,1) = TP(2*I+1,0)
               ELSE
                P3(I,0) = TP(2*I-16,1)
                P3(I,1) = TP(2*I-15,1)
              ENDIF
           ENDDO

           DETERMINATION OF SUB-SYSTEM #3 SELECTION FACTOR

       CALL TAVAIL(JJ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TAVAL)
       CALL SFAIL1(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL1)
       CALL SFAIL2(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL2)
       TRDA(3) = TAVAL
       PERF(3) = TAVAL+FAIL1+FAIL2
       AVL(3)  = TRDA(3)*PERF(3)
          ELSEIF ( JJ .EQ. 4 ) THEN
           X=IX(JJ)
           N=IN(JJ)
           NMAX=N+X

           TRANSITION PROBABILITY FOR EQUIPMENT TYPE #4

           CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
           DO I = 0,NMAX
              IF ( I .LE. 7 ) THEN
                P4(I,0) = TP(2*I,0)
                P4(I,1) = TP(2*I+1,0)
               ELSE
                P4(I,0) = TP(2*I-16,1)
                P4(I,1) = TP(2*I-15,1)
```

```
              ENDIF
            ENDDO

            DETERMINATION OF SUB-SYSTEM #4 SELECTION FACTOR

        CALL TAVAIL(JJ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TAVAL)
        CALL SFAIL1(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL1)
        CALL SFAIL2(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL2)
        TRDA(4) = TAVAL
        PERF(4) = TAVAL+FAIL1+FAIL2
        AVL(4)  = TRDA(4)*PERF(4)
           ELSEIF ( JJ .EQ. 5 ) THEN
            X=IX(JJ)
            N=IN(JJ)
            NMAX=N+X

            TRANSITION PROBABILITY FOR EQUIPMENT TYPE #5

            CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
            DO I = 0,NMAX
               IF ( I .LE. 7 ) THEN
                 P5(I,0) = TP(2*I,0)
                 P5(I,1) = TP(2*I+1,0)
                ELSE
                 P5(I,0) = TP(2*I-16,1)
                 P5(I,1) = TP(2*I-15,1)
               ENDIF
            ENDDO

            DETERMINATION OF SUB-SYSTEM #5 SELECTION FACTOR

        CALL TAVAIL(JJ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TAVAL)
        CALL SFAIL1(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL1)
        CALL SFAIL2(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL2)
        TRDA(5) = TAVAL
        PERF(5) = TAVAL+FAIL1+FAIL2
        AVL(5)  = TRDA(5)*PERF(5)
           ELSEIF ( JJ .EQ. 6 ) THEN
            X=IX(JJ)
            N=IN(JJ)
            NMAX=N+X
            TRANSITION PROBABILITY FOR EQUIPMENT TYPE #6
            CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
            DO I = 0,NMAX
               IF ( I .LE. 7 ) THEN
                 P6(I,0) = TP(2*I,0)
                 P6(I,1) = TP(2*I+1,0)
                ELSE
                 P6(I,0) = TP(2*I-16,1)
                 P6(I,1) = TP(2*I-15,1)
               ENDIF
```

```
           ENDDO
           DETERMINATION OF SUB-SYSTEM #6 SELECTION FACTOR
       CALL TAVAIL(JJ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TAVAL)
       CALL SFAIL1(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL1)
       CALL SFAIL2(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL2)
       TRDA(6) = TAVAL
       PERF(6) = TAVAL+FAIL1+FAIL2
       AVL(6)  = TRDA(6)*PERF(6)
          ELSEIF ( JJ .EQ. 7 ) THEN
           X=IX(JJ)
           N=IN(JJ)
           NMAX=N+X
           TRANSITION PROBABILITY FOR EQUIPMENT TYPE #7
           CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
           DO I = 0,NMAX
              IF ( I .LE. 7 ) THEN
                P7(I,0) = TP(2*I,0)
                P7(I,1) = TP(2*I+1,0)
               ELSE
                P7(I,0) = TP(2*I-16,1)
                P7(I,1) = TP(2*I-15,1)
              ENDIF
           ENDDO
           DETERMINATION OF SUB-SYSTEM #7 SELECTION FACTOR
       CALL TAVAIL(JJ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TAVAL)
       CALL SFAIL1(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL1)
       CALL SFAIL2(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL2)
       TRDA(7) = TAVAL
       PERF(7) = TAVAL+FAIL1+FAIL2
       AVL(7)  = TRDA(7)*PERF(7)
          ELSEIF ( JJ .EQ. 8 ) THEN
           X=IX(JJ)
           N=IN(JJ)
           NMAX=N+X
           TRANSITION PROBABILITY FOR EQUIPMENT TYPE #8
           CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
           DO I = 0,NMAX
              IF ( I .LE. 7 ) THEN
                P8(I,0) = TP(2*I,0)
                P8(I,1) = TP(2*I+1,0)
               ELSE
                P8(I,0) = TP(2*I-16,1)
                P8(I,1) = TP(2*I-15,1)
              ENDIF
           ENDDO
           DETERMINATION OF SUB-SYSTEM #8 SELECTION FACTOR
       CALL TAVAIL(JJ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TAVAL)
       CALL SFAIL1(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL1)
       CALL SFAIL2(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL2)
       TRDA(8) = TAVAL
       PERF(8) = TAVAL+FAIL1+FAIL2
```

```
       AVL(8)   = TRDA(8)*PERF(8)
          ELSEIF ( JJ .EQ. 9 ) THEN
           X=IX(JJ)
           N=IN(JJ)
           NMAX=N+X
           TRANSITION PROBABILITY FOR EQUIPMENT TYPE #9
           CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
           DO I = 0,NMAX
              IF ( I .LE. 7 ) THEN
                P9(I,0) = TP(2*I,0)
                P9(I,1) = TP(2*I+1,0)
               ELSE
                P9(I,0) = TP(2*I-16,1)
                P9(I,1) = TP(2*I-15,1)
              ENDIF
           ENDDO
           DETERMINATION OF SUB-SYSTEM #9 SELECTION FACTOR
       CALL TAVAIL(JJ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TAVAL)
       CALL SFAIL1(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL1)
       CALL SFAIL2(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL2)
       TRDA(9) = TAVAL
       PERF(9) = TAVAL+FAIL1+FAIL2
       AVL(9)   = TRDA(9)*PERF(9)
          ELSEIF ( JJ .EQ. 10 ) THEN
           X=IX(JJ)
           N=IN(JJ)
           NMAX=N+X
           TRANSITION PROBABILITY FOR EQUIPMENT TYPE #10
           CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
           DO I = 0,NMAX
              IF ( I .LE. 7 ) THEN
                P10(I,0) = TP(2*I,0)
                P10(I,1) = TP(2*I+1,0)
               ELSE
                P10(I,0) = TP(2*I-16,1)
                P10(I,1) = TP(2*I-15,1)
              ENDIF
           ENDDO
           DETERMINATION OF SUB-SYSTEM #10 SELECTION FACTOR
       CALL TAVAIL(JJ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TAVAL)
       CALL SFAIL1(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL1)
       CALL SFAIL2(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL2)
           TRDA(10) = TAVAL
           PERF(10) = TAVAL+FAIL1+FAIL2
           AVL(10)   = TRDA(10)*PERF(10)
        ENDIF
      ENDDO
      MAXX = MAX(IX(1),IX(2),IX(3),IX(4),
     :            IX(5),IX(6),IX(7),IX(8),IX(9),IX(10))

           DELIVERING SOLUTION
```

```
       IF ( MAXX .EQ. 1 .AND. INDEX .EQ. 1 ) THEN
        JJZ=0
        CALL TAVAIL(JJZ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TAVAL)
        CALL SFAIL1(JJZ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL1)
        CALL SFAIL2(JJZ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL2)
        ASTOR(1)=TAVAL+FAIL1+FAIL2
        PRINT'(<M>(I4,4X),<M>(F7.6,2X),2X,F9.6)',
     : ((IX(I),I=1,M),(AVL(I),I=1,M),ASTOR(1))
       ENDIF
       IF ( MAXX .NE. 1 .AND. IFLAG .EQ. 1 ) THEN
        PRINT'(<M>(I4,4X),<M>(F7.6,2X),2X,F9.6)',
     : ((IX(I),I=1,M),(AVL(I),I=1,M),ASTOR(1))
       ENDIF

          CHECK MAXIMUM/MINIMUM VALUE OF SELECTION FACTOR F(X)'S

       AVLMIN=MIN((AVL(1)+CHECK(1)),(AVL(2)+CHECK(2)),(AVL(3)+CHECK(3)),
     :              (AVL(4)+CHECK(4)),(AVL(5)+CHECK(5)),(AVL(6)+CHECK(6)),
     :              (AVL(7)+CHECK(7)),(AVL(8)+CHECK(8)),(AVL(9)+CHECK(9)),
     :              (AVL(10)+CHECK(10)))

       ADDING ONE SPARE TO SUB-SYSTEM HAVING REQUIRED BEST F(X)

       IF ( ((AVL(1)+CHECK(1)) .EQ. AVLMIN ) THEN
           IX(1)=IX(1)+1
         ELSEIF ( ((AVL(2)+CHECK(2)) .EQ. AVLMIN ) THEN
           IX(2)=IX(2)+1
         ELSEIF ( ((AVL(3)+CHECK(3)) .EQ. AVLMIN ) THEN
           IX(3)=IX(3)+1
         ELSEIF ( ((AVL(4)+CHECK(4)) .EQ. AVLMIN ) THEN
           IX(4)=IX(4)+1
         ELSEIF ( ((AVL(5)+CHECK(5)) .EQ. AVLMIN ) THEN
           IX(5)=IX(5)+1
         ELSEIF ( ((AVL(6)+CHECK(6)) .EQ. AVLMIN ) THEN
           IX(6)=IX(6)+1
         ELSEIF ( ((AVL(7)+CHECK(7)) .EQ. AVLMIN ) THEN
           IX(7)=IX(7)+1
         ELSEIF ( ((AVL(8)+CHECK(8)) .EQ. AVLMIN ) THEN
           IX(8)=IX(8)+1
         ELSEIF ( ((AVL(9)+CHECK(9)) .EQ. AVLMIN ) THEN
           IX(9)=IX(9)+1
         ELSEIF ( ((AVL(10)+CHECK(10)) .EQ. AVLMIN ) THEN
           IX(10)=IX(10)+1
       ENDIF
       DO I = 1,M
         IXP(I) = IX(I)
       ENDDO
       DO I = 1,10
         NMX(I) = IX(I) + IN(I)
       ENDDO
```

```
      JJZ=0
      CALL TAVAIL(JJZ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TAVAL)
      CALL SFAIL1(JJZ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL1)
      CALL SFAIL2(JJZ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,FAIL2)
      ASTOR(2)=TAVAL+FAIL1+FAIL2

         COMPARING FEASIBILITY OF ONE SPARE ADDITION

      IF ( (ASTOR(2)-ASTOR(1)) .GE. DFR ) THEN
         IFLAG = 1.0
         ASTOR(1)=ASTOR(2)
         GO TO 111
       ELSE
         IFLAG = 0.0
         IF ( ((AVL(1)+CHECK(1)) .EQ. AVLMIN ) THEN
            IX(1)=IX(1)-1
          ELSEIF ( ((AVL(2)+CHECK(2)) .EQ. AVLMIN ) THEN
            IX(2)=IX(2)-1
          ELSEIF ( ((AVL(3)+CHECK(3)) .EQ. AVLMIN ) THEN
            IX(3)=IX(3)-1
          ELSEIF ( ((AVL(4)+CHECK(4)) .EQ. AVLMIN ) THEN
            IX(4)=IX(4)-1
          ELSEIF ( ((AVL(5)+CHECK(5)) .EQ. AVLMIN ) THEN
            IX(5)=IX(5)-1
          ELSEIF ( ((AVL(6)+CHECK(6)) .EQ. AVLMIN ) THEN
            IX(6)=IX(6)-1
          ELSEIF ( ((AVL(7)+CHECK(7)) .EQ. AVLMIN ) THEN
            IX(7)=IX(7)-1
          ELSEIF ( ((AVL(8)+CHECK(8)) .EQ. AVLMIN ) THEN
            IX(8)=IX(8)-1
          ELSEIF ( ((AVL(9)+CHECK(9)) .EQ. AVLMIN ) THEN
            IX(9)=IX(9)-1
          ELSEIF ( ((AVL(10)+CHECK(10)) .EQ. AVLMIN ) THEN
            IX(10)=IX(10)-1
        ENDIF
        DO I = 1,M
           IXP(I) = IX(I)
        ENDDO
        DO I = 1,10
           NMX(I) = IX(I) + IN(I)
        ENDDO

          ASSIGNING HIGH VALUE TO DISCARD SUB-SYSTEM FROM
                     FURTHER CONSIDERATION

        DO I = 1,M
           IF ( ((AVL(I)+CHECK(I)) .EQ. AVLMIN ) THEN
              CHECK(I)=1.0D5
              GO TO 222
           ENDIF
        ENDDO
```

```
      ENDIF
  222 CONTINUE
      ENDDO
      STOP
      END
*********************************************************************
                                                                    :
      PURPOSE:SUBROUTINE FOR CALCULATING TRANSITIONAL PROBABILITY   :
              USING THE MARKOVIAN STEADY-STATE EQUATIONS            :
                                                                    :
      INPUT:                                                        :
             >M      :TYPES OF EQUIPMENT                            :
             >N      :NUMBER OF EACH TYPE                           :
             >X      :NUMBER OF EACH TYPE OF SPARE                  :
             >P      :PROBABILITY A SPARE WORKS                     :
             >BI     :RECIPROCAL OF MTR                             :
             >MEU    :RECIPROCAL OF MTTR                            :
             >NMAX   :SUM OF N AND X FOR EACH TYPE                  :
             >LAMBDA:RECIPROCAL OF MTTF                             :
      OUTPUT:                                                       :
             >TP   TRANSITIONAL PROBABILITY VECTOR                  :
                                                                    :
*********************************************************************
      SUBROUTINE TPROB(N,M,X,NMAX,PROB,LAM,MEU,BI,TP)
      INTEGER X
      REAL LAM(0:NMAX-1),MEU(NMAX),BI(0:NMAX-1)
      DOUBLEPRECISION TP(0:NMAX,0:1),A(31,31),RHS(31),
     :B(0:4,1:5),BX,BIIP,PROB

                   INITIALIZE MATRICES

      DO I = 1,NMAX*2+1
        DO J = 1,NMAX*2+1
          A(I,J) = 0.0
        ENDDO
      ENDDO
      DO I = 0,NMAX
         DO J = 0,1
            TP(I,J)=0.0
         ENDDO
      ENDDO

        CALCULATING TRANSITION PROBABILITY FROM (i,1) to (i',1)
        FOR ONE EQUIPMENT TYPE; WHERE i IS NOT EQUAL TO i'

      DO K = 0,X-1
        IF ( K .EQ. 0 ) THEN
           IF ( X .EQ. 1 ) THEN
              B(K,1)=(1-PROB)*PROB
             ELSEIF ( X .EQ. 2 )THEN
              B(K,1)=(1-PROB)*PROB
```

```
           B(K,2)=(1-PROB)**2*PROB
          ELSEIF ( X .EQ. 3 ) THEN
           B(K,1)=(1-PROB)*PROB
           B(K,2)=(1-PROB)**2*PROB
           B(K,3)=(1-PROB)**3*PROB
          ELSEIF ( X .EQ. 4 ) THEN
           B(K,1)=(1-PROB)*PROB
           B(K,2)=(1-PROB)**2*PROB
           B(K,3)=(1-PROB)**3*PROB
           B(K,4)=(1-PROB)**4*PROB
          ELSEIF ( X .EQ. 5 ) THEN
           B(K,1)=(1-PROB)*PROB
           B(K,2)=(1-PROB)**2*PROB
           B(K,3)=(1-PROB)**3*PROB
           B(K,4)=(1-PROB)**4*PROB
           B(K,5)=(1-PROB)**5*PROB
        ENDIF
       ELSEIF ( K .EQ. 1 ) THEN
        IF ( X .EQ. 2 )THEN
           B(K,2)=(1-PROB)*PROB
          ELSEIF ( X .EQ. 3 ) THEN
           B(K,2)=(1-PROB)*PROB
           B(K,3)=(1-PROB)**2*PROB
          ELSEIF ( X .EQ. 4 ) THEN
           B(K,2)=(1-PROB)*PROB
           B(K,3)=(1-PROB)**2*PROB
           B(K,4)=(1-PROB)**3*PROB
          ELSEIF ( X .EQ. 5 ) THEN
           B(K,2)=(1-PROB)*PROB
           B(K,3)=(1-PROB)**2*PROB
           B(K,4)=(1-PROB)**3*PROB
           B(K,5)=(1-PROB)**4*PROB
        ENDIF
       ELSEIF ( K .EQ. 2 ) THEN
        IF ( X .EQ. 3 )THEN
           B(K,3)=(1-PROB)*PROB
          ELSEIF ( X .EQ. 4 ) THEN
           B(K,3)=(1-PROB)*PROB
           B(K,4)=(1-PROB)**2*PROB
          ELSEIF ( X .EQ. 5 ) THEN
           B(K,3)=(1-PROB)*PROB
           B(K,4)=(1-PROB)**2*PROB
           B(K,5)=(1-PROB)**3*PROB
        ENDIF
       ELSEIF ( K .EQ. 3 ) THEN
        IF ( X .EQ. 4 )THEN
           B(K,4)=(1-PROB)*PROB
          ELSEIF ( X .EQ. 5 ) THEN
           B(K,4)=(1-PROB)*PROB
           B(K,5)=(1-PROB)**2*PROB
        ENDIF
```

```
          ELSEIF ( K .EQ. 4 ) THEN
           IF ( X .EQ. 5 ) THEN
              B(K,5)=(1-PROB)*PROB
           ENDIF
        ENDIF
      ENDDO
C
C     EQUATION #1
C
      LAM(0)*TP(0,0) = MEU(1)*TP(1,0)
      A(1,1) =-LAM(0)
      A(1,3) = MEU(1)
C
C     EQUATION #2A
C
      (LAM(I)+MEU(I))*TP(I,0) =PROB*BI(I-1)*TP(I-1,1)+MEU(I+1)*TP(I+1,0)
      DO I = 1,X
        A(I+1,2*I+1) = LAM(I)+MEU(I)
        A(I+1,2*I)   =-PROB*BI(I-1)
        A(I+1,2*I+3) =-MEU(I+1)
      ENDDO
C
C     EQUATION #2B
C
      (LAM(I)+MEU(I))*TP(I,0) = BI(I-1)*TP(I-1,1)+MEU(I+1)*TP(I+1,0)
      DO I = X+1,NMAX-2
        A(I+1,2*I+1) = LAM(I)+MEU(I)
        A(I+1,2*I)   =-BI(I-1)
        A(I+1,2*I+3) =-MEU(I+1)
      ENDDO
C
C     EQUATION #3
C
      MEU(NMAX)*TP(NMAX,0) = BI(NMAX-1)*TP(NMAX-1,1)
      A(NMAX,NMAX*2+1) = MEU(NMAX)
      A(NMAX,NMAX*2) =-BI(NMAX-1)
C
C     EQUATION #4
C
      BX = 0.0D0
      DO IP = 1,X
        BX = BX + B(0,IP)
      ENDDO
      PROB*BI(0)*TP(0,1)+BX*TP(0,1) = LAM(0)*TP(0,0)
      A(NMAX+1,2) = PROB*BI(0)+BX
      A(NMAX+1,1) =-LAM(0)
C
C     EQUATION #6
C
      BIPX = 0.0
      DO IP = 0,X-1
```

```
          BIPX = BIPX + B(IP,X)*TP(IP,1)
      ENDDO
      BI(X)*TP(X,1) = LAM(X)*TP(X,0) + BIPX
      IF ( X .EQ. 1 ) THEN
          A(NMAX+2,2*X+2) =-BI(X)
          A(NMAX+2,2*X+1) = LAM(X)
          A(NMAX+2,2*X)   = B(0,X)
        ELSEIF ( X .EQ. 2 ) THEN
          A(NMAX+2,2*X+2) =-BI(X)
          A(NMAX+2,2*X+1) = LAM(X)
          A(NMAX+2,2*X-2) = B(0,X)
          A(NMAX+2,2*X) = B(1,X)
        ELSEIF ( X .EQ. 3 ) THEN
          A(NMAX+2,2*X+2) =-BI(X)
          A(NMAX+2,2*X+1) = LAM(X)
          A(NMAX+2,2*X-4) = B(0,X)
          A(NMAX+2,2*X-2) = B(1,X)
          A(NMAX+2,2*X) = B(2,X)
        ELSEIF ( X .EQ. 4 ) THEN
          A(NMAX+2,2*X+2) =-BI(X)
          A(NMAX+2,2*X+1) = LAM(X)
          A(NMAX+2,2*X-6) = B(0,X)
          A(NMAX+2,2*X-4) = B(1,X)
          A(NMAX+2,2*X-2) = B(2,X)
          A(NMAX+2,2*X) = B(3,X)
        ELSEIF ( X .EQ. 5 ) THEN
          A(NMAX+2,2*X+2) =-BI(X)
          A(NMAX+2,2*X+1) = LAM(X)
          A(NMAX+2,2*X-8) = B(0,X)
          A(NMAX+2,2*X-6) = B(1,X)
          A(NMAX+2,2*X-4) = B(2,X)
          A(NMAX+2,2*X-2) = B(3,X)
          A(NMAX+2,2*X) = B(4,X)
      ENDIF
C
C     EQUATION #7
C
      DO I = X+1,NMAX-1
        BI(I)*TP(I,1) = LAM(I)*TP(I,0)
        A(NMAX+2+I-X,2*I+2) = BI(I)
        A(NMAX+2+I-X,2*I+1) =-LAM(I)
      ENDDO
C
C     EQUATION #8
C
      PI0=0
      PI1=0
      DO I =0,NMAX
        PI0 = PI0 + TP(I,0)
        A(NMAX+2+N,2*I+1) = 1.
        IF ( I .NE. NMAX ) THEN
```

```
:          PI1 = PI1 + TP(I,1)
           A(NMAX+2+N,2*I+2) = 1.
         ENDIF
       ENDDO
:      PIO + PI1 = 1
C
C      EQUATION #5
C
       DO I = 1,X-1,1
          BIIP = 0.0D0
          DO IP = I+1,X
            BIIP = BIIP + B(I,IP)
          ENDDO
:         BIPI = 0
:         DO IP = 0,I-1
:           BIPI = BIPI + B(IP,I)*TP(IP,1)
:         ENDDO
:         PROB*BI(I)*TP(I,1)+BIIP*TP(I,1)=LAM(I)*TP(I,0)+BIPI
          IF ( I .EQ. 1 ) THEN
             A(NMAX+N+2+I,2*I+2) =-PROB*BI(I)-BIIP
             A(NMAX+N+2+I,2*I+1) = LAM(I)
             A(NMAX+N+2+I,2*I)   = B(0,1)
            ELSEIF ( I .EQ. 2 ) THEN
             A(NMAX+N+2+I,2*I+2) =-PROB*BI(I)-BIIP
             A(NMAX+N+2+I,2*I+1) = LAM(I)
             A(NMAX+N+2+I,2*I)   = B(1,2)
             A(NMAX+N+2+I,2*I-2) = B(0,2)
            ELSEIF ( I .EQ. 3 ) THEN
             A(NMAX+N+2+I,2*I+2) =-PROB*BI(I)-BIIP
             A(NMAX+N+2+I,2*I+1) = LAM(I)
             A(NMAX+N+2+I,2*I)   = B(2,3)
             A(NMAX+N+2+I,2*I-2) = B(1,3)
             A(NMAX+N+2+I,2*I-4) = B(0,3)
            ELSEIF ( I .EQ. 4 ) THEN
             A(NMAX+N+2+I,2*I+2) =-PROB*BI(I)-BIIP
             A(NMAX+N+2+I,2*I+1) = LAM(I)
             A(NMAX+N+2+I,2*I)   = B(3,4)
             A(NMAX+N+2+I,2*I-2) = B(2,4)
             A(NMAX+N+2+I,2*I-4) = B(1,4)
             A(NMAX+N+2+I,2*I-6) = B(0,4)
          ENDIF
       ENDDO
:
:          SOLUTION OF MATRIX "A" USING PORTLIB
:              GIVES TRANSITION PROBABILITY
:
       DO I = 1,NMAX*2+1
          RHS(I) = 0.0D0
       ENDDO
       RHS(NMAX+N+2) = 1.0D0
       NB = 1.0D0
```

```
      CALL DLSTSQ(31,31,NMAX*2+1,NMAX*2+1,A,RHS,NB,TP)
      END
*********************************************************************
:                                                                   :
      PURPOSE: CALCULATES TRADITIONAL AVAILABILITY WHEN NUMBER IN   :
               REPAIR PROCESS IS LESS OR EQUAL TO SPARE AVAILABLE   :
:                                                                   :
      INPUT:                                                        :
              >M   :TYPES OF EQUIPMENT IN FMS                       :
              >IX  :SPARE FOR EACH TYPE                             :
              >JJ  :COMPUTATION CONTROLLING INDEX                   :
              >P's :TRANSITIONAL PROBABILITIES                      :
      OUTPUT:                                                       :
              >AO  :TRADITIONAL AVAILABILITY OF                     :
                    A SYSTEM                                        :
:                                                                   :
*********************************************************************
      SUBROUTINE TAVAIL(JJ,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,AO)
      INTEGER S,IX(10)
      DOUBLEPRECISION P1(0:IX(1),0:0),P2(0:IX(2),0:0),P3(0:IX(3),0:0),
     :P4(0:IX(4),0:0),P5(0:IX(5),0:0),P6(0:IX(6),0:0),P7(0:IX(7),0:0),
     :P8(0:IX(8),0:0),P9(0:IX(9),0:0),P10(0:IX(10),0:0),PP(10),AO
:
                  INITIALIZATION
:
      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
        PP(5)=0.0D0
        DO S = 0,IX(5)
          PP(5) = PP(5) + P5(S,0)
        ENDDO
       ELSEIF ( (I .EQ. 6 .AND. JJ .EQ. 6) .OR.
              (I .EQ. 6 .AND. JJ .EQ. 0) ) THEN
        PP(6)=0.0D0
        DO S = 0,IX(6)
          PP(6) = PP(6) + P6(S,0)
        ENDDO
       ELSEIF ( (I .EQ. 7 .AND. JJ .EQ. 7) .OR.
              (I .EQ. 7 .AND. JJ .EQ. 0) ) THEN
        PP(7)=0.0D0
        DO S = 0,IX(7)
          PP(7) = PP(7) + P7(S,0)
        ENDDO
       ELSEIF ( (I .EQ. 8 .AND. JJ .EQ. 8) .OR.
              (I .EQ. 8 .AND. JJ .EQ. 0) ) THEN
        PP(8)=0.0D0
        DO S = 0,IX(8)
          PP(8) = PP(8) + P8(S,0)
        ENDDO
       ELSEIF ( (I .EQ. 9 .AND. JJ .EQ. 9) .OR.
              (I .EQ. 9 .AND. JJ .EQ. 0) ) THEN
        PP(9)=0.0D0
        DO S = 0,IX(9)
          PP(9) = PP(9) + P9(S,0)
        ENDDO
       ELSEIF ( (I .EQ. 10 .AND. JJ .EQ. 10) .OR.
              (I .EQ. 10 .AND. JJ .EQ. 0) ) THEN
        PP(10)=0.0D0
        DO S = 0,IX(10)
          PP(10) = PP(10) + P10(S,0)
        ENDDO
     ENDIF
   ENDDO
:
:  COMPUTING OVER ALL SYSTEM TRADITIONAL AVAILABILITY
:
   A0=PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
   END
*************************************************************************
:                                                                       :
:  PURPOSE: 1.WHEN ONLY ANY ONE EQUIPMENT TYPE IN THE STATE             :
:              OF (X+1,0)                                               :
:           2.TAKES INTO ACCOUNT PARTIAL CREDITS FOR THE                :
:              PARTIAL AVAILABILITY OF SUBSYSTEMS                       :
```

```
:                                                                      :
:     INPUT:                                                           :
:               >    : M, IN, JJ, NMX, P's, (EXPLAINED EAPLIER)        :
:                                                                      :
:     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,AA1,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
```

```
            PP(5)=0.0D0
            DO S = 0,IX(5)
              PP(5) = PP(5) + P5(S,0)
            ENDDO
          ELSEIF ( (I .EQ. 6 .AND. JJ .EQ. 6) .OR.
                 (I .EQ. 6 .AND. JJ .EQ. 0) ) THEN
            PP(6)=0.0D0
            DO S = 0,IX(6)
              PP(6) = PP(6) + P6(S,0)
            ENDDO
          ELSEIF ( (I .EQ. 7 .AND. JJ .EQ. 7) .OR.
                 (I .EQ. 7 .AND. JJ .EQ. 0) ) THEN
            PP(7)=0.0D0
            DO S = 0,IX(7)
              PP(7) = PP(7) + P7(S,0)
            ENDDO
          ELSEIF ( (I .EQ. 8 .AND. JJ .EQ. 8) .OR.
                 (I .EQ. 8 .AND. JJ .EQ. 0) ) THEN
            PP(8)=0.0D0
            DO S = 0,IX(8)
              PP(8) = PP(8) + P8(S,0)
            ENDDO
          ELSEIF ( (I .EQ. 9 .AND. JJ .EQ. 9) .OR.
                 (I .EQ. 9 .AND. JJ .EQ. 0) ) THEN
            PP(9)=0.0D0
            DO S = 0,IX(9)
              PP(9) = PP(9) + P9(S,0)
            ENDDO
          ELSEIF ( (I .EQ. 10 .AND. JJ .EQ. 10) .OR.
                 (I .EQ. 10 .AND. JJ .EQ. 0) ) THEN
            PP(10)=0.0D0
            DO S = 0,IX(10)
              PP(10) = PP(10) + P10(S,0)
            ENDDO
        ENDIF
      ENDDO
      DO I=1,M
        Z(I)=IN(I)
      ENDDO
      PAAX = 0.0
      X=MIN(IX(1),IX(2),IX(3),IX(4),IX(5),
     :      IX(6),IX(7),IX(8),IX(9),IX(10))
      NMAX=MAX(NMX(1),NMX(2),NMX(3),NMX(4),NMX(5),
     :         NMX(6),NMX(7),NMX(8),NMX(9),NMX(10))
:
:                    ACCOUNTING FOR PARTIAL CREDITS
:
      DO AA1 = X+1,NMAX-1
       DO I = 1,10
         PAA(I)=0.0D0
         WAA(I)=0.0D0
```

```
      ENDDO
      DO K = 1,M
       IF ( (K .EQ. 1 .AND. IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1
     :     .AND. JJ .EQ. 1) .OR. (K .EQ. 1 .AND. IX(1) .LT. AA1
     :     .AND. NMX(1) .GT. AA1 .AND. JJ .EQ. 0) )THEN
          WAA1 = ((NMX(1)-AA1)/Z(1))
          PAA(1)=P1(AA1,0)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*
     :               PP(8)*PP(9)*PP(10)*WAA1
        ELSEIF ( (K .EQ. 2 .AND. IX(2) .LT. AA1 .AND. NMX(2) .GT.
     :          AA1 .AND. JJ .EQ. 2) .OR. (K .EQ. 2 .AND. IX(2) .LT.
     :          AA1 .AND. NMX(2) .GT. AA1 .AND. JJ .EQ. 0) )THEN
                WAA2 = ((NMX(2)-AA1)/Z(2))
                PAA(2)=P2(AA1,0)*PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*
     :                PP(8)*PP(9)*PP(10)*WAA2
        ELSEIF ( (K .EQ. 3 .AND. IX(3) .LT. AA1 .AND. NMX(3) .GT.
     :          AA1 .AND. JJ .EQ. 3) .OR. (K .EQ. 3 .AND. IX(3) .LT.
     :          AA1 .AND. NMX(3) .GT. AA1 .AND. JJ .EQ. 0) )THEN
                WAA3 = ((NMX(3)-AA1)/Z(3))
                PAA(3)=P3(AA1,0)*PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*
     :                PP(8)*PP(9)*PP(10)*WAA3
        ELSEIF ( (K .EQ. 4 .AND. IX(4) .LT. AA1 .AND. NMX(4) .GT.
     :          AA1 .AND. JJ .EQ. 4) .OR. (K .EQ. 4 .AND. IX(4) .LT.
     :          AA1 .AND. NMX(4) .GT. AA1 .AND. JJ .EQ. 0) )THEN
                WAA4 = ((NMX(4)-AA1)/Z(4))
                PAA(4)=P4(AA1,0)*PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*
     :                PP(8)*PP(9)*PP(10)*WAA4
        ELSEIF ( (K .EQ. 5 .AND. IX(5) .LT. AA1 .AND. NMX(5) .GT.
     :          AA1 .AND. JJ .EQ. 5) .OR. (K .EQ. 5 .AND. IX(5) .LT.
     :          AA1 .AND. NMX(5) .GT. AA1 .AND. JJ .EQ. 0) )THEN
                WAA5 = ((NMX(5)-AA1)/Z(5))
                PAA(5)=P5(AA1,0)*PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*
     :                PP(8)*PP(9)*PP(10)*WAA5
        ELSEIF ( (K .EQ. 6 .AND. IX(6) .LT. AA1 .AND. NMX(6) .GT.
     :          AA1 .AND. JJ .EQ. 6) .OR. (K .EQ. 6 .AND. IX(6) .LT.
     :          AA1 .AND. NMX(6) .GT. AA1 .AND. JJ .EQ. 0) )THEN
                WAA6 = ((NMX(6)-AA1)/Z(6))
                PAA(6)=P6(AA1,0)*PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*
     :                PP(8)*PP(9)*PP(10)*WAA6
        ELSEIF ( (K .EQ. 7 .AND. IX(7) .LT. AA1 .AND. NMX(7) .GT.
     :          AA1 .AND. JJ .EQ. 7) .OR. (K .EQ. 7 .AND. IX(7) .LT.
     :          AA1 .AND. NMX(7) .GT. AA1 .AND. JJ .EQ. 0) )THEN
                WAA7 = ((NMX(7)-AA1)/Z(7))
                PAA(7)=P7(AA1,0)*PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*
     :                PP(8)*PP(9)*PP(10)*WAA7
        ELSEIF ( (K .EQ. 8 .AND. IX(8) .LT. AA1 .AND. NMX(8) .GT.
     :          AA1 .AND. JJ .EQ. 8) .OR. (K .EQ. 8 .AND. IX(8) .LT.
     :          AA1 .AND. NMX(8) .GT. AA1 .AND. JJ .EQ. 0) )THEN
                WAA8 = ((NMX(8)-AA1)/Z(8))
                PAA(8)=P8(AA1,0)*PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*
     :                PP(7)*PP(9)*PP(10)*WAA8
        ELSEIF ( (K .EQ. 9 .AND. IX(9) .LT. AA1 .AND. NMX(9) .GT.
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     :        AA1 .AND. JJ .EQ. 9) .OR. (K .EQ. 9 .AND. IX(9) .LT.
     :        AA1 .AND. NMX(9) .GT. AA1 .AND. JJ .EQ. 0) )THEN
              WAA9 = ((NMX(9)-AA1)/Z(9))
              PAA(9)=P9(AA1,0)*PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*
     :                PP(7)*PP(8)*PP(10)*WAA9
          ELSEIF ((K .EQ. 10 .AND. IX(10) .LT. AA1 .AND. NMX(10) .GT.
     :        AA1 .AND. JJ .EQ. 10) .OR. (K .EQ. 10 .AND. IX(10) .LT.
     :        AA1 .AND. NMX(10) .GT. AA1 .AND. JJ .EQ. 0) )THEN
              WAA10 = ((NMX(10)-AA1)/Z(10))
              PAA(10)=P10(AA1,0)*PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*
     :                PP(7)*PP(8)*PP(9)*WAA10
         ENDIF
        ENDDO
        PAAX = PAAX+(PAA(1)+PAA(2)+PAA3+PAA(4)+PAA(5)+PAA(6)+
     :                PAA(7)+PAA(8)+PAA(9)+PAA(10))
       ENDDO
       END
:*******************************************************************
:                                                                  :
:      PURPOSE: 1.WHEN ANY TWO EQUIPMENT TYPES IN THE STATE        :
:                 OF (X+1,0)                                       :
:               2.TAKES INTO ACCOUNT PARTIAL CREDITS FOR           :
:                 PARTIAL AVAILABILITY                             :
:                                                                  :
:      INPUT:                                                      :
:              >    : M, IN, IX, JJ, P's, NMX,                     :
:                      (  EXPLAINED  EARLIER  )                    :
:      OUTPUT:                                                     :
:              >PLKX: PARTIAL CREDITS FOR PARTIAL                  :
:                     AVAILABILITY                                 :
:                                                                  :
********************************************************************
        SUBROUTINE
       :SFAIL2(JJ,NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PLKX)
        INTEGER X,S,AA1,AA2,A1,A2,A3,A4,A5,A6,A7,A8,A9,A10
        INTEGER IX(10),IN(M),NMX(10)
        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),PLKE,PLKNE,
       :PLKX,PLK(10),PLK1(10),PLK2(10),PLK3(10),PLK4(10),PLK5(10),
       :PLK6(10),PLK7(10),PLK8(10),PLK9(10),PLK10(10)
        REAL Z(10)
:
:                      INITIALIZE
:
        DO I=1,10
           PP(I)   =1.0D0
           PLK(I)  =0.0D0
           PLK1(I) =0.0D0
           PLK2(I) =0.0D0
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      PLK3(I) =0.0D0
      PLK4(I) =0.0D0
      PLK5(I) =0.0D0
      PLK6(I) =0.0D0
      PLK7(I) =0.0D0
      PLK8(I) =0.0D0
      PLK9(I) =0.0D0
      PLK10(I)=0.0D0
   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
           PP(5)=0.0D0
           DO S = 0,IX(5)
              PP(5) = PP(5) + P5(S,0)
           ENDDO
       ELSEIF ( (I .EQ. 6 .AND. JJ .EQ. 6) .OR.
              (I .EQ. 6 .AND. JJ .EQ. 0) ) THEN
           PP(6)=0.0D0
           DO S = 0,IX(6)
              PP(6) = PP(6) + P6(S,0)
           ENDDO
       ELSEIF ( (I .EQ. 7 .AND. JJ .EQ. 7) .OR.
              (I .EQ. 7 .AND. JJ .EQ. 0) ) THEN
           PP(7)=0.0D0
           DO S = 0,IX(7)
              PP(7) = PP(7) + P7(S,0)
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              ENDDO
          ELSEIF ( (I .EQ. 8 .AND. JJ .EQ. 8) .OR.
                 (I .EQ. 8 .AND. JJ .EQ. 0) ) THEN
              PP(8)=0.0D0
              DO S = 0,IX(8)
                 PP(8) = PP(8) + P8(S,0)
              ENDDO
          ELSEIF ( (I .EQ. 9 .AND. JJ .EQ. 9) .OR.
                 (I .EQ. 9 .AND. JJ .EQ. 0) ) THEN
              PP(9)=0.0D0
              DO S = 0,IX(9)
                 PP(9) = PP(9) + P9(S,0)
              ENDDO
          ELSEIF ( (I .EQ. 10 .AND. JJ .EQ. 10) .OR.
                 (I .EQ. 10 .AND. JJ .EQ. 0) ) THEN
              PP(10)=0.0D0
              DO S = 0,IX(10)
                 PP(10) = PP(10) + P10(S,0)
              ENDDO
         ENDIF
       ENDDO
       DO I=1,M
         Z(I)=IN(I)
       ENDDO
       X=MIN(IX(1),IX(2),IX(3),IX(4),IX(5),
     :         IX(6),IX(7),IX(8),IX(9),IX(10))
       NMAX=MAX(NMX(1),NMX(2),NMX(3),NMX(4),NMX(5),
     :            NMX(6),NMX(7),NMX(8),NMX(9),NMX(10))
       PLKE  = 0.0D0
       PLKNE = 0.0D0
       PLKX  = 0.0D0
:
:             ACCOUNTING FOR PARTIAL CREDITS
:
       DO AA1 = X+1,NMAX-1
        DO AA2 = X+1,NMAX-1
         DO L = 1,M
          IF ( L .EQ. 1 ) THEN
             A1 = AA1
             WA11 = ((NMX(1)-AA1)/Z(1))
            ELSEIF ( L .EQ. 2 ) THEN
             A2 = AA1
             WA12 = ((NMX(2)-AA1)/Z(2))
            ELSEIF ( L .EQ. 3 ) THEN
             A3 = AA1
             WA13 = ((NMX(3)-AA1)/Z(3))
            ELSEIF ( L .EQ. 4 ) THEN
             A4 = AA1
             WA14 = ((NMX(4)-AA1)/Z(4))
            ELSEIF ( L .EQ. 5 ) THEN
             A5 = AA1
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              WA15 = ((NMX(5)-AA1)/Z(5))
             ELSEIF ( L .EQ. 6 ) THEN
              A6 = AA1
              WA16 = ((NMX(6)-AA1)/Z(6))
             ELSEIF ( L .EQ. 7 ) THEN
              A7 = AA1
              WA17 = ((NMX(7)-AA1)/Z(7))
             ELSEIF ( L .EQ. 8 ) THEN
              A8 = AA1
              WA18 = ((NMX(8)-AA1)/Z(8))
             ELSEIF ( L .EQ. 9 ) THEN
              A9 = AA1
              WA19 = ((NMX(9)-AA1)/Z(9))
             ELSEIF ( L .EQ. 10 ) THEN
              A10 = AA1
              WA110 = ((NMX(10)-AA1)/Z(10))
           ENDIF
           DO K = 1,M
            IF ( K .NE. L ) THEN
             IF ((K .EQ. 1 .AND. IX(1) .LT. AA2 .AND. NMX(1) .GT.
     :          AA2 .AND. JJ .EQ. 1) .OR. (K .EQ. 1 .AND. IX(1)
     :          .LT. AA2 .AND. NMX(1) .GT. AA2 .AND. JJ .EQ. 0))THEN
                WA21 = ((NMX(1)-AA2)/Z(1))
                A1=AA2
                IF ( L .EQ. 2 .AND.
     :             IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
                   PLK1(2)=P1(A1,0)*P2(A2,0)*WA12*WA21*
     :             PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
                  ELSEIF ( L .EQ. 3 .AND.
     :             IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
                   PLK1(3)=P1(A1,0)*P3(A3,0)*WA13*WA21*
     :             PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
                  ELSEIF ( L .EQ. 4 .AND.
     :             IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
                   PLK1(4)=P1(A1,0)*P4(A4,0)*WA14*WA21*
     :             PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
                  ELSEIF ( L .EQ. 5 .AND.
     :             IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
                   PLK1(5)=P1(A1,0)*P5(A5,0)*WA15*WA21*
     :             PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
                  ELSEIF ( L .EQ. 6 .AND.
     :             IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
                   PLK1(6)=P1(A1,0)*P6(A6,0)*WA16*WA21*
     :             PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
                  ELSEIF ( L .EQ. 7 .AND.
     :             IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
                   PLK1(7)=P1(A1,0)*P7(A7,0)*WA17*WA21*
     :             PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
                  ELSEIF ( L .EQ. 8 .AND.
     :             IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
                   PLK1(8)=P1(A1,0)*P8(A8,0)*WA18*WA21*
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     :          PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 9 .AND.
     :          IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
                PLK1(9)=P1(A1,0)*P9(A9,0)*WA19*WA21*
     :          PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
               ELSEIF ( L .EQ. 10 .AND.
     :          IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
                PLK1(10)=P1(A1,0)*P10(A10,0)*WA110*WA21*
     :          PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
             ENDIF
            ELSEIF ((K .EQ. 2 .AND. IX(2) .LT. AA2 .AND. NMX(2)
     :       .GT. AA2 .AND. JJ .EQ. 2) .OR. (K .EQ. 2 .AND. IX(2)
     :       .LT. AA2 .AND. NMX(2) .GT. AA2 .AND. JJ .EQ. 0))THEN
             WA22 = ((NMX(2)-AA2)/Z(2))
             A2=AA2
             IF ( L .EQ. 1 .AND.
     :          IX(1) .LT. AA1 .AND. NMXN1) .GT. AA1) THEN
                PLK2(1)=P1(A1,0)*P2(A2,0)*WA11*WA22*
     :          PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 3 .AND.
     :          IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
                PLK2(3)=P2(A2,0)*P3(A3,0)*WA13*WA22*
     :          PP(1)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 4 .AND.
     :          IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
                PLK2(4)=P2(A2,0)*P4(A4,0)*WA14*WA22*
     :          PP(1)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 5 .AND.
     :          IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
                PLK2(5)=P2(A2,0)*P5(A5,0)*WA15*WA22*
     :          PP(1)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 6 .AND.
     :          IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
                PLK2(6)=P2(A2,0)*P6(A6,0)*WA16*WA22*
     :          PP(1)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 7 .AND.
     :          IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
                PLK2(7)=P2(A2,0)*P7(A7,0)*WA17*WA22*
     :          PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 8 .AND.
     :          IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
                PLK2(8)=P2(A2,0)*P8(A8,0)*WA18*WA22*
     :          PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 9 .AND.
     :          IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
                PLK2(9)=P2(A2,0)*P9(A9,0)*WA19*WA22*
     :          PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
               ELSEIF ( L .EQ. 10 .AND.
     :          IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
                PLK2(10)=P2(A2,0)*P10(A10,0)*WA110*WA22*
     :          PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
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               ENDIF
             ELSEIF ((K .EQ. 3 .AND. IX(3) .LT. AA2 .AND. NMX(3)
     :        .GT. AA2 .AND. JJ .EQ. 3) .OR. (K .EQ. 3 .AND. IX(3)
     :        .LT. AA2 .AND. NMX(3) .GT. AA2 .AND. JJ .EQ. 0))THEN
              WA23 = ((NMX(3)-AA2)/Z(3))
              A3=AA2
              IF ( L .EQ. 1 .AND.
     :          IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
                PLK3(1)=P1(A1,0)*P3(A3,0)*WA11*WA23*
     :          PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 2 .AND.
     :          IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
                PLK3(2)=P2(A2,0)*P3(A3,0)*WA12*WA23*
     :          PP(1)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 4 .AND.
     :          IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
                PLK3(4)=P3(A3,0)*P4(A4,0)*WA14*WA23*
     :          PP(1)*PP(2)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 5 .AND.
     :          IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
                PLK3(5)=P3(A3,0)*P5(A5,0)*WA15*WA23*
     :          PP(1)*PP(2)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 6 .AND.
     :          IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
                PLK3(6)=P3(A3,0)*P6(A6,0)*WA16*WA23*
     :          PP(1)*PP(2)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 7 .AND.
     :          IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
                PLK3(7)=P3(A3,0)*P7(A7,0)*WA17*WA23*
     :          PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 8 .AND.
     :          IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
                PLK3(8)=P3(A3,0)*P8(A8,0)*WA18*WA23*
     :          PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 9 .AND.
     :          IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
                PLK3(9)=P3(A3,0)*P9(A9,0)*WA19*WA23*
     :          PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
               ELSEIF ( L .EQ. 10 .AND.
     :          IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
                PLK3(10)=P3(A3,0)*P10(A10,0)*WA110*WA23*
     :          PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
              ENDIF
             ELSEIF ((K .EQ. 4 .AND. IX(4) .LT. AA2 .AND. NMX(4)
     :        .GT. AA2 .AND. JJ .EQ. 4) .OR. (K .EQ. 4 .AND. IX(4)
     :        .LT. AA2 .AND. NMX(4) .GT. AA2 .AND. JJ .EQ. 0))THEN
              WA24 = ((NMX(4)-AA2)/Z(4))
              A4=AA2
              IF ( L .EQ. 1 .AND.
     :          IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
                PLK4(1)=P1(A1,0)*P4(A4,0)*WA11*WA24*
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     :        PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
             ELSEIF ( L .EQ. 2 .AND.
     :        IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
              PLK4(2)=P2(A2,0)*P4(A4,0)*WA12*WA24*
     :        PP(1)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
             ELSEIF ( L .EQ. 3 .AND.
     :        IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
              PLK4(3)=P3(A3,0)*P4(A4,0)*WA13*WA24*
     :        PP(1)*PP(2)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
             ELSEIF ( L .EQ. 5 .AND.
     :        IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
              PLK4(5)=P4(A4,0)*P5(A5,0)*WA15*WA24*
     :        PP(1)*PP(2)*PP(3)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
             ELSEIF ( L .EQ. 6 .AND.
     :        IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
              PLK4(6)=P4(A4,0)*P6(A6,0)*WA16*WA24*
     :        PP(1)*PP(2)*PP(3)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
             ELSEIF ( L .EQ. 7 .AND.
     :        IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
              PLK4(7)=P4(A4,0)*P7(A7,0)*WA17*WA24*
     :        PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
             ELSEIF ( L .EQ. 8 .AND.
     :        IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
              PLK4(8)=P4(A4,0)*P8(A8,0)*WA18*WA24*
     :       PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
             ELSEIF ( L .EQ. 9 .AND.
     :        IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
              PLK4(9)=P4(A4,0)*P9(A9,0)*WA19*WA24*
     :        PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
             ELSEIF ( L .EQ. 10 .AND.
     :        IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
              PLK4(10)=P4(A4,0)*P10(A10,0)*WA110*WA24*
     :        PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
           ENDIF
          ELSEIF ((K .EQ. 5 .AND. IX(5) .LT. AA2 .AND. NMX(5)
     :     .GT. AA2 .AND. JJ .EQ. 5) .OR. (K .EQ. 5 .AND. IX(5)
     :     .LT. AA2 .AND. NMX(5) .GT. AA2 .AND. JJ .EQ. 0))THEN
           WA25 = ((NMX(5)-AA2)/Z(5))
           A5=AA2
           IF ( L .EQ. 1 .AND.
     :        IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
              PLK5(1)=P1(A1,0)*P5(A5,0)*WA11*WA25*
     :        PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
             ELSEIF ( L .EQ. 2 .AND.
     :        IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
              PLK5(2)=P2(A2,0)*P5(A5,0)*WA12*WA25*
     :        PP(1)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
             ELSEIF ( L .EQ. 3 .AND.
     :        IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
              PLK5(3)=P3(A3,0)*P5(A5,0)*WA13*WA25*
     :        PP(1)*PP(2)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
```

```
              ELSEIF ( L .EQ. 4 .AND.
     :         IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
               PLK5(4)=P4(A4,0)*P5(A5,0)*WA14*WA25*
     :         PP(1)*PP(2)*PP(3)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
              ELSEIF ( L .EQ. 6 .AND.
     :         IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
               PLK5(6)=P5(A5,0)*P6(A6,0)*WA16*WA25*
     :         PP(1)*PP(2)*PP(3)*PP(4)*PP(7)*PP(8)*PP(9)*PP(10)
              ELSEIF ( L .EQ. 7 .AND.
     :         IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
               PLK5(7)=P5(A5,0)*P7(A7,0)*WA17*WA25*
     :         PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(8)*PP(9)*PP(10)
              ELSEIF ( L .EQ. 8 .AND.
     :         IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
               PLK5(8)=P5(A5,0)*P8(A8,0)*WA18*WA25*
     :         PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(9)*PP(10)
              ELSEIF ( L .EQ. 9 .AND.
     :         IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
               PLK5(9)=P5(A5,0)*P9(A9,0)*WA19*WA25*
     :         PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(10)
              ELSEIF ( L .EQ. 10 .AND.
     :         IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
               PLK5(10)=P5(A5,0)*P10(A10,0)*WA110*WA25*
     :         PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)
            ENDIF
           ELSEIF ((K .EQ. 6 .AND. IX(6) .LT. AA2 .AND. NMX(6)
     :      .GT. AA2 .AND. JJ .EQ. 6) .OR. (K .EQ. 6 .AND. IX(6)
     :      .LT. AA2 .AND. NMX(6) .GT. AA2 .AND. JJ .EQ. 0))THEN
            WA26 = ((NMX(6)-AA2)/Z(6))
            A6=AA2
            IF ( L .EQ. 1 .AND.
     :         IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
               PLK6(1)=P1(A1,0)*P6(A6,0)*WA11*WA26*
     :         PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
              ELSEIF ( L .EQ. 2 .AND.
     :         IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
               PLK6(2)=P2(A2,0)*P6(A6,0)*WA12*WA26*
     :         PP(1)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
              ELSEIF ( L .EQ. 3 .AND.
     :         IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
               PLK6(3)=P3(A3,0)*P6(A6,0)*WA13*WA26*
     :         PP(1)*PP(2)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
              ELSEIF ( L .EQ. 4 .AND.
     :         IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
               PLK6(4)=P4(A4,0)*P6(A6,0)*WA14*WA26*
     :         PP(1)*PP(2)*PP(3)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
              ELSEIF ( L .EQ. 5 .AND.
     :         IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
               PLK6(5)=P5(A5,0)*P6(A6,0)*WA15*WA26*
     :         PP(1)*PP(2)*PP(3)*PP(4)*PP(7)*PP(8)*PP(9)*PP(10)
              ELSEIF ( L .EQ. 7 .AND.
```

```
:           IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
            PLK6(7)=P6(A6,0)*P7(A7,0)*WA17*WA26*
:           PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(8)*PP(9)*PP(10)
          ELSEIF ( L .EQ. 8 .AND.
:           IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
            PLK6(8)=P6(A6,0)*P8(A8,0)*WA18*WA26*
:           PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(9)*PP(10)
          ELSEIF ( L .EQ. 9 .AND.
:           IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
            PLK6(9)=P6(A6,0)*P9(A9,0)*WA19*WA26*
:           PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(10)
          ELSEIF ( L .EQ. 10 .AND.
:           IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
            PLK6(10)=P6(A6,0)*P10(A10,0)*WA110*WA26*
:           PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)
        ENDIF
      ELSEIF ((K .EQ. 7 .AND. IX(7) .LT. AA2 .AND. NMX(7)
:       .GT. AA2 .AND. JJ .EQ. 7) .OR. (K .EQ. 7 .AND. IX(7)
:       .LT. AA2 .AND. NMX(7) .GT. AA2 .AND. JJ .EQ. 0))THEN
        WA27 = ((NMX(7)-AA2)/Z(7))
        A7=AA2
        IF ( L .EQ. 1 .AND.
:           IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
            PLK7(1)=P1(A1,0)*P7(A7,0)*WA11*WA27*
:           PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
          ELSEIF ( L .EQ. 2 .AND.
:           IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
            PLK7(2)=P2(A2,0)*P7(A7,0)*WA12*WA27*
:           PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
          ELSEIF ( L .EQ. 3 .AND.
:           IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
            PLK7(3)=P3(A3,0)*P7(A7,0)*WA13*WA27*
:           PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
          ELSEIF ( L .EQ. 4 .AND.
:           IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
            PLK7(4)=P4(A4,0)*P7(A7,0)*WA14*WA27*
:           PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
          ELSEIF ( L .EQ. 5 .AND.
:           IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
            PLK7(5)=P5(A5,0)*P7(A7,0)*WA15*WA27*
:           PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(8)*PP(9)*PP(10)
          ELSEIF ( L .EQ. 6 .AND.
:           IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
            PLK7(6)=P6(A6,0)*P7(A7,0)*WA16*WA27*
:           PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(8)*PP(9)*PP(10)
          ELSEIF ( L .EQ. 8 .AND.
:           IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
            PLK7(8)=P7(A7,0)*P8(A8,0)*WA18*WA27*
:           PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(9)*PP(10)
          ELSEIF ( L .EQ. 9 .AND.
:           IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
```

```
                PLK7(9)=P7(A7,0)*P9(A9,0)*WA19*WA27*
     :          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(10)
               ELSEIF ( L .EQ. 10 .AND.
     :          IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
                PLK7(10)=P7(A7,0)*P10(A10,0)*WA110*WA27*
     :          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)
             ENDIF
            ELSEIF ((K .EQ. 8 .AND. IX(8) .LT. AA2 .AND. NMX(8)
     :       .GT. AA2 .AND. JJ .EQ. 8) .OR. (K .EQ. 8 .AND. IX(8)
     :       .LT. AA2 .AND. NMX(8) .GT. AA2 .AND. JJ .EQ. 0))THEN
             WA28 = ((NMX(8)-AA2)/Z(8))
             A8=AA2
             IF ( L .EQ. 1 .AND.
     :          IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
                PLK8(1)=P1(A1,0)*P8(A8,0)*WA11*WA28*
     :          PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 2 .AND.
     :          IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
                PLK8(2)=P2(A2,0)*P8(A8,0)*WA12*WA28*
     :          PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 3 .AND.
     :          IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
                PLK8(3)=P3(A3,0)*P8(A8,0)*WA13*WA28*
     :          PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 4 .AND.
     :          IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
                PLK8(4)=P4(A4,0)*P8(A8,0)*WA14*WA28*
     :          PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 5 .AND.
     :          IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
                PLK8(5)=P5(A5,0)*P8(A8,0)*WA15*WA28*
     :          PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 6 .AND.
     :          IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
                PLK8(6)=P6(A6,0)*P8(A8,0)*WA16*WA28*
     :          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 7 .AND.
     :          IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
                PLK8(7)=P7(A7,0)*P8(A8,0)*WA17*WA28*
     :          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 9 .AND.
     :          IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
                PLK8(9)=P8(A8,0)*P9(A9,0)*WA19*WA28*
     :          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(10)
               ELSEIF ( L .EQ. 10 .AND.
     :          IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
                PLK8(10)=P8(A8,0)*P10(A10,0)*WA110*WA28*
     :          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)
             ENDIF
            ELSEIF ((K .EQ. 9 .AND. IX(9) .LT. AA2 .AND. NMX(9)
     :       .GT. AA2 .AND. JJ .EQ. 9) .OR. (K .EQ. 9 .AND. IX(9)
```

```
:         .LT. AA2 .AND. NMX(9) .GT. AA2 .AND. JJ .EQ. 0))THEN
          WA29 = ((NMX(9)-AA2)/Z(9))
          A9=AA2
          IF ( L .EQ. 1 .AND.
:            IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
             PLK9(1)=P1(A1,0)*P9(A9,0)*WA11*WA29*
:            PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
            ELSEIF ( L .EQ. 2 .AND.
:            IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
             PLK9(2)=P2(A2,0)*P9(A9,0)*WA12*WA29*
:            PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
            ELSEIF ( L .EQ. 3 .AND.
:            IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
             PLK9(3)=P3(A3,0)*P9(A9,0)*WA13*WA29*
:            PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
            ELSEIF ( L .EQ. 4 .AND.
:            IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
             PLK9(4)=P4(A4,0)*P9(A9,0)*WA14*WA29*
:            PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
            ELSEIF ( L .EQ. 5 .AND.
:            IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
             PLK9(5)=P5(A5,0)*P9(A9,0)*WA15*WA29*
:            PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(10)
            ELSEIF ( L .EQ. 6 .AND.
:            IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
             PLK9(6)=P6(A6,0)*P9(A9,0)*WA16*WA29*
:            PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(10)
            ELSEIF ( L .EQ. 7 .AND.
:            IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
             PLK9(7)=P7(A7,0)*P9(A9,0)*WA17*WA29*
:            PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(10)
            ELSEIF ( L .EQ. 8 .AND.
:            IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
             PLK9(8)=P8(A8,0)*P9(A9,0)*WA18*WA29*
:            PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(10)
            ELSEIF ( L .EQ. 10 .AND.
:            IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
             PLK9(10)=P9(A9,0)*P10(A10,0)*WA110*WA29*
:            PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)
          ENDIF
        ELSEIF ((K .EQ. 10 .AND. IX(10) .LT. AA2 .AND. NMX(10)
:         .GT. AA2 .AND. JJ .EQ. 10).OR.(K .EQ. 10 .AND. IX(10)
:         .LT. AA2 .AND. NMX(10) .GT. AA2 .AND. JJ .EQ. 0))THEN
          WA210 = ((NMX(10)-AA2)/Z(10))
          A10=AA2
          IF ( L .EQ. 1 .AND.
:            IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
             PLK10(1)=P1(A1,0)*P10(A10,0)*WA11*WA210*
:            PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
            ELSEIF ( L .EQ. 2 .AND.
:            IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
```

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                 PLK10(2)=P2(A2,0)*P10(A10,0)*WA12*WA210*
     :           PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
                ELSEIF ( L .EQ. 3 .AND.
     :           IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
                 PLK10(3)=P3(A3,0)*P10(A10,0)*WA13*WA210*
     :           PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
                ELSEIF ( L .EQ. 4 .AND.
     :           IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
                 PLK10(4)=P4(A4,0)*P10(A10,0)*WA14*WA210*
     :           PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
                ELSEIF ( L .EQ. 5 .AND.
     :           IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
                 PLK10(5)=P5(A5,0)*P10(A10,0)*WA15*WA210*
     :           PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)
                ELSEIF ( L .EQ. 6 .AND.
     :           IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
                 PLK10(6)=P6(A6,0)*P10(A10,0)*WA16*WA210*
     :           PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)
                ELSEIF ( L .EQ. 7 .AND.
     :           IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
                 PLK10(7)=P7(A7,0)*P10(A10,0)*WA17*WA210*
     :           PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)
                ELSEIF ( L .EQ. 8 .AND.
     :           IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
                 PLK10(8)=P8(A8,0)*P10(A10,0)*WA17*WA210*
     :           PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)
                ELSEIF ( L .EQ. 9 .AND.
     :           IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
                 PLK10(9)=P9(A9,0)*P10(A10,0)*WA19*WA210*
     :           PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)
              ENDIF
           ENDIF
          ENDIF
         ENDDO
        ENDDO
        PLK(1)=PLK1(2)+PLK1(3)+PLK1(4)+PLK1(5)+PLK1(6)+PLK1(7)
     :         +PLK1(8)+PLK1(9)+PLK1(10)
        PLK(2)=PLK2(1)+PLK2(3)+PLK2(4)+PLK2(5)+PLK2(6)+PLK2(7)
     :         +PLK2(8)+PLK2(9)+PLK2(10)
        PLK(3)=PLK3(1)+PLK3(2)+PLK3(4)+PLK3(5)+PLK3(6)+PLK3(7)
     :         +PLK3(8)+PLK3(9)+PLK3(10)
        PLK(4)=PLK4(1)+PLK4(2)+PLK4(3)+PLK4(5)+PLK4(6)+PLK4(7)
     :         +PLK4(8)+PLK4(9)+PLK4(10)
        PLK(5)=PLK5(1)+PLK5(2)+PLK5(3)+PLK5(4)+PLK5(6)+PLK5(7)
     :         +PLK5(8)+PLK5(9)+PLK5(10)
        PLK(6)=PLK6(1)+PLK6(2)+PLK6(3)+PLK6(4)+PLK6(5)+PLK6(7)
     :         +PLK6(8)+PLK6(9)+PLK6(10)
        PLK(7)=PLK7(1)+PLK7(2)+PLK7(3)+PLK7(4)+PLK7(5)+PLK7(6)
     :         +PLK7(8)+PLK7(9)+PLK7(10)
        PLK(8)=PLK8(1)+PLK8(2)+PLK8(3)+PLK8(4)+PLK8(5)+PLK8(6)
     :         +PLK8(7)+PLK8(9)+PLK8(10)
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      PLK(9)=PLK9(1)+PLK9(2)+PLK9(3)+PLK9(4)+PLK9(5)+PLK9(6)
     :       +PLK9(7)+PLK9(8)+PLK9(10)
      PLK(10)=PLK10(1)+PLK10(2)+PLK10(3)+PLK10(4)+PLK10(5)+
     :       PLK10(6)+PLK10(7)+PLK10(8)+PLK10(9)
      IF ( AA1 .EQ. AA2 ) THEN
          PLKE=PLKE+1/2*(PLK(1)+PLK(2)+PLK(3)+PLK(4)+PLK(5)+
     :         PLK(6)+PLK(7)+PLK(8)+PLK(9)+PLK(10))
          PLKNE=0.0D0
         ELSE
          PLKNE=PLKNE+(PLK(1)+PLK(2)+PLK(3)+PLK(4)+PLK(5)+
     :          PLK(6)+PLK(7)+PLK(8)+PLK(9)+PLK(10))
          PLKE=0.0D0
      ENDIF
      PLKX = PLKX + PLKE + PLKNE
     ENDDO
    ENDDO
    END
```

XIII. APPENDIX E. PROGRAM LISTING FOR SENSITIVITY ANALYSIS PROCEDURES

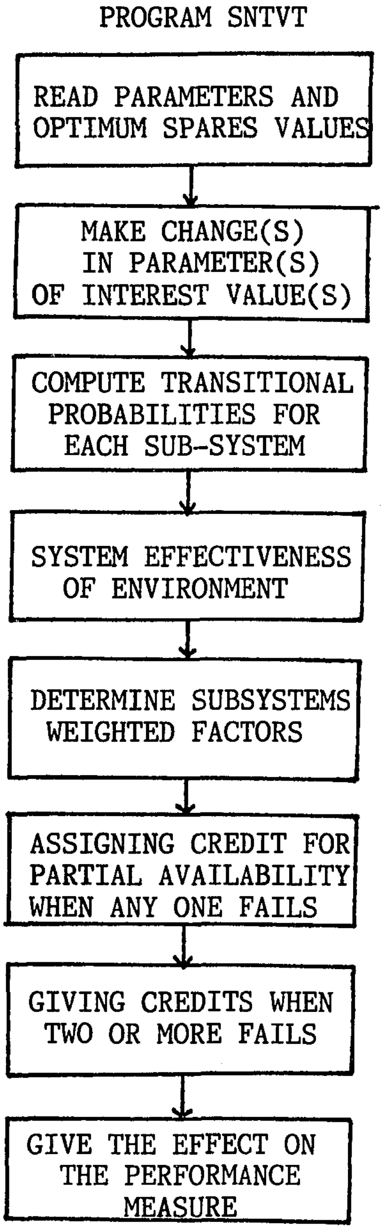

FIGURE 39. Flow chart of computer program SNTVT

```
      PROGRAM SNTVT
*****************************************************************
*                                                               :
*     PURPOSE: 1.COMPUTER CODE FOR SENSITIVITY ANALYSIS OF A    :
*                GENERIC FLEXIBLE MANUFACTURING SYSTEM          :
*              2.DETERMINES EFFECT ON THE SYSTEM PERFORMANCE    :
*                MEASURE DUE TO CHANGE IN ONE OR ALL PARAMETERS :
*                OF INTEREST                                    :
*                                                               :
*     PARAMETERS OF INTEREST:                                   :
*              MTTF: MEAN TIME TO FAILURE                       :
*              MTTR: MEAN TIME TO REPAIR                        :
*              MTR:  MEAN TIME REPLACEMENT                      :
*                                                               :
*                                                               :
*     INPUT:   INTEGER,                                         :
*             >M:    TYPES OF EQUIPMENT IN AN FMS               :
*             >N:    NUMBER OF EACH TYPE IN FMS                 :
*             >IX:   OPTIMUM VALUES OF SPARE FOR ALL TYPES OF   :
*                    EQUIPMENT                                  :
*              INTERACTIVE REAL INPUT,                          :
*             >MTR:  MEAN TIME REPLACEMENT                      :
*             >MTTF: MEAN TIME TO FAILURE                       :
*             >MTTR: MEAN TIME TO REPAIR                        :
*                                                               :
*     LIMITATION:                                               :
*             >M:    CANNOT BE ZERO OR MORE THAN 10             :
*             >N:    CANNOT BE ZERO OR MORE THAN 10             :
*                                                               :
*     OUTPUT:TABULATED FORM                                     :
*           >PARAMETERS: MTTF, MTTR, MTR                        :
*           >SYS-AVAIL:  SYSTEM PERFORMANCE MEASURE AT          :
*                        GIVEN MTTF, MTTR, MTR                  :
*                                                               :
*****************************************************************
      CHARACTER ANSWER*10
      INTEGER N,M,X,IX(10),IN(10),NMX(10)
      REAL MTTR(10),MTTF(10),MTR(10),BETAI(0:14),LAM(0:14),MEU(15)
      DOUBLEPRECISION P1(0:15,0:1),P2(0:15,0:1),P3(0:15,0:1),
     :P4(0:15,0:1),P5(0:15,0:1),P6(0:15,0:1),TP(0:15,0:1),
     :P7(0:15,0:1),P8(0:15,0:1),P9(0:15,0:1),P10(0:15,0:1),PROB
*
*                  INTERACTIVE DATA INPUT
*
      DATA IX/10*1.0/
      WRITE(6,'(X,A)')'PLEASE SUPPLY THE VALUE OF "M"; WHERE M IS
      WRITE(6,'(X,A)')'THE TYPES OF EQUIPMENT IN FMS ENVIRONMENT'
      WRITE(6,*)
      READ *, M
      WRITE(6,*)
      WRITE(6,'(X,A)')'PLEASE SUPPLY THE VALUE OF "N"; WHERE'
```

```
      WRITE(6,'(X,A)')'N IS THE # OF EACH TYPE OF EQUIPMENT'
      DO I=1,M
        WRITE(6,*)
        WRITE(6,'(X,A,I2,A)')'SUPPLY NOW THE VALUE OF N FOR TYPE #'
     :  ,I,' ONLY'
        WRITE(6,*)
        READ*,IN(I)
      ENDDO
      WRITE(6,'(X,A)')'PLEASE SUPPLY THE OPTIMUM VALUE OF "X"; WHERE'
      WRITE(6,'(X,A)')'X IS THE # OF SPARE FOR EACH TYPE OF EQUIPMENT'
      DO I=1,M
        WRITE(6,*)
        WRITE(6,'(X,A,I2,A)')'SUPPLY NOW THE VALUE OF X FOR TYPE #'
     :  ,I,' ONLY'
        WRITE(6,*)
        READ*,IX(I)
      ENDDO
      DO I=1,M
        NMX(I)=IN(I)+IX(I)
      ENDDO
      WRITE(6,'(X,A)')'PLEASE SUPPLY THE VALUE OF "P"; WHERE P IS'
      WRITE(6,'(X,A)')'THE PROBABILITY THAT A SELECTED SPARE WORKS'
      WRITE(6,*)
      READ *, PROB
      PRINT'(X,A)','   SENSITIVITY ANALYSIS FOR A GENERIC FMS'
      PRINT*
      PRINT'(X<M>(3(A,I2,2X)),2X,A)',
     :((' MTTF#',I,' MTTR#',I,' MTR# ',I),I=1,M),' SYS-AVAIL'
      DO WHILE ( ANSWER .NE. 'NO')
*
*           INPUT DISCRETE CHANGES IN PARAMETERS OF INTEREST
*
      DO I = 1,M
        WRITE(6,'(X,A,I2,A)')'SUPPLY  VALUES OF "MTTF", "MTTR" & "MTR"
     :  FOR THE EQUIPMENT TYPE #',I,' ONLY'
        WRITE(6,*)
        WRITE(6,'(X,A,I2)')'WHERE MTTF IS THE MEAN TIME TO FAILURE
     :  FOR TYPE #',I
        WRITE(6,'(X,A,I2)')'WHERE MTTR IS THE MEAN TIME TO REPAIR
     :  FOR TYPE #',I
        WRITE(6,'(X,A,I2)')'WHERE MTR IS THE MEAN TIME TO REPLACEMENT
     :  FOR TYPE #',I
        WRITE(6,*)
        READ *, MTTF(I),MTTR(I),MTR(I)
      ENDDO
      DO JJ = 1,M
        DO I = 0,NMX(JJ)-1
           LAM(I) = 1/MTTF(JJ)
           K = I + 1
           MEU(K) = 1/(MTTR(JJ) * K)
           BETAI(I) = 1/MTR(JJ)
```

```
      ENDDO
      IF ( JJ .EQ. 1 ) THEN
         X=IX(JJ)
         N=IN(JJ)
         NMAX=N+X

         TRANSITION PROBABILITY FOR EQUATION TYPE #1

         CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
         DO I = 0,NMAX
            IF ( I .LE. 7 ) THEN
              P1(I,0) = TP(2*I,0)
              P1(I,1) = TP(2*I+1,0)
             ELSE
              P1(I,0) = TP(2*I-16,1)
              P1(I,1) = TP(2*I-15,1)
            ENDIF
         ENDDO
        ELSEIF ( JJ .EQ. 2 ) THEN
         X=IX(JJ)
         N=IN(JJ)
         NMAX=N+X

         TRANSITION PROBABILITY FOR EQUATION TYPE #2

         CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
         DO I = 0,NMAX
            IF ( I .LE. 7 ) THEN
              P2(I,0) = TP(2*I,0)
              P2(I,1) = TP(2*I+1,0)
             ELSE
              P2(I,0) = TP(2*I-16,1)
              P2(I,1) = TP(2*I-15,1)
            ENDIF
         ENDDO
        ELSEIF ( JJ .EQ. 3 ) THEN
         X=IX(JJ)
         N=IN(JJ)
         NMAX=N+X

         TRANSITION PROBABILITY FOR EQUATION TYPE #3

         CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
         DO I = 0,NMAX
            IF ( I .LE. 7 ) THEN
              P3(I,0) = TP(2*I,0)
              P3(I,1) = TP(2*I+1,0)
             ELSE
              P3(I,0) = TP(2*I-16,1)
              P3(I,1) = TP(2*I-15,1)
            ENDIF
```

```
           ENDDO
          ELSEIF ( JJ .EQ. 4 ) THEN
           X=IX(JJ)
           N=IN(JJ)
           NMAX=N+X

           TRANSITION PROBABILITY FOR EQUATION TYPE #4

           CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
           DO I = 0,NMAX
              IF ( I .LE. 7 ) THEN
                P4(I,0) = TP(2*I,0)
                P4(I,1) = TP(2*I+1,0)
               ELSE
                P4(I,0) = TP(2*I-16,1)
                P4(I,1) = TP(2*I-15,1)
              ENDIF
           ENDDO
          ELSEIF ( JJ .EQ. 5 ) THEN
           X=IX(JJ)
           N=IN(JJ)
           NMAX=N+X

           TRANSITION PROBABILITY FOR EQUATION TYPE #5

           CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
           DO I = 0,NMAX
              IF ( I .LE. 7 ) THEN
                P5(I,0) = TP(2*I,0)
                P5(I,1) = TP(2*I+1,0)
               ELSE
                P5(I,0) = TP(2*I-16,1)
                P5(I,1) = TP(2*I-15,1)
              ENDIF
           ENDDO
          ELSEIF ( JJ .EQ. 6 ) THEN
           X=IX(JJ)
           N=IN(JJ)
           NMAX=N+X
           TRANSITION PROBABILITY FOR EQUATION TYPE #6
           CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
           DO I = 0,NMAX
              IF ( I .LE. 7 ) THEN
                P6(I,0) = TP(2*I,0)
                P6(I,1) = TP(2*I+1,0)
               ELSE
                P6(I,0) = TP(2*I-16,1)
                P6(I,1) = TP(2*I-15,1)
              ENDIF
           ENDDO
          ELSEIF ( JJ .EQ. 7 ) THEN
```

```
             X=IX(JJ)
             N=IN(JJ)
             NMAX=N+X
             TRANSITION PROBABILITY FOR EQUATION TYPE #7
             CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
             DO I = 0,NMAX
                IF ( I .LE. 7 ) THEN
                  P7(I,0) = TP(2*I,0)
                  P7(I,1) = TP(2*I+1,0)
                 ELSE
                  P7(I,0) = TP(2*I-16,1)
                  P7(I,1) = TP(2*I-15,1)
                ENDIF
             ENDDO
            ELSEIF ( JJ .EQ. 8 ) THEN
             X=IX(JJ)
             N=IN(JJ)
             NMAX=N+X
             TRANSITION PROBABILITY FOR EQUATION TYPE #8
             CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
             DO I = 0,NMAX
                IF ( I .LE. 7 ) THEN
                  P8(I,0) = TP(2*I,0)
                  P8(I,1) = TP(2*I+1,0)
                 ELSE
                  P8(I,0) = TP(2*I-16,1)
                  P8(I,1) = TP(2*I-15,1)
                ENDIF
             ENDDO
            ELSEIF ( JJ .EQ. 9 ) THEN
             X=IX(JJ)
             N=IN(JJ)
             NMAX=N+X
             TRANSITION PROBABILITY FOR EQUATION TYPE #9
             CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
             DO I = 0,NMAX
                IF ( I .LE. 7 ) THEN
                  P9(I,0) = TP(2*I,0)
                  P9(I,1) = TP(2*I+1,0)
                 ELSE
                  P9(I,0) = TP(2*I-16,1)
                  P9(I,1) = TP(2*I-15,1)
                ENDIF
             ENDDO
            ELSEIF ( JJ .EQ. 10 ) THEN
             X=IX(JJ)
             N=IN(JJ)
             NMAX=N+X
             TRANSITION PROBABILITY FOR EQUATION TYPE #10
             CALL TPROB(N,M,X,NMAX,PROB,LAM,MEU,BETAI,TP)
             DO I = 0,NMAX
```

```
                IF ( I .LE. 7 ) THEN
                  P10(I,0) = TP(2*I,0)
                  P10(I,1) = TP(2*I+1,0)
                 ELSE
                  P10(I,0) = TP(2*I-16,1)
                  P10(I,1) = TP(2*I-15,1)
                ENDIF
             ENDDO
          ENDIF
        ENDDO
*
*                 COMPUTING AND FORMATTING THE OUTPUT
*
        CALL TAVAIL(M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,A0)
        CALL SFAIL1(NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PAAX)
        CALL SFAIL2(NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PLKX)
        WRITE(6,*)
        SYSAVAL=A0+PAAX+PLKX
        WRITE(6,*)
        PRINT'(3XM>(3(F7.2,4X)),F9.6)',
       :(MTTF(I),MTTR(I),MTR(I),I=1,M),SYSAVAL
        WRITE(6,*)
        WRITE(6,'(X,A)')'DO YOU WANT TO PERFORM MORE DISCRETE CHANGES'
        WRITE(6,'(X,A)')' IN THE PARAMETER OR PARAMETERS OF INTEREST'
        WRITE(6,'(X,A)')'  OR YOU ARE DONE; >> ANSWER "YES" OR "NO"'
        READ'(A)',ANSWER
        ENDDO
        STOP
        END
**********************************************************************
*                                                                    :
*       PURPOSE: SUBROUTINE FOR CALCULATING TRANSITION PROBABILITY   :
*                USING MARKOVIAN STEADY STATE EQUATIONS              :
*                                                                    :
*       INPUT:                                                       :
*               >    :N, M, X, P's, NMAX, PROB                       :
*                  (  EXPLAINED  EARLIER  )                          :
*                                                                    :
*       OUTPUT:                                                      :
*               >TP  :TRANSITIONAL PROBABILITY                       :
*                                                                    :
**********************************************************************
        SUBROUTINE TPROB(N,M,X,NMAX,PROB,LAM,MEU,BI,TP)
        INTEGER X
        REAL LAM(0:NMAX-1),MEU(NMAX),BI(0:NMAX-1)
        DOUBLEPRECISION TP(0:NMAX,0:1),A(31,31),RHS(31),
       :B(0:4,1:5),BX,BIIP,PROB
C       INITIALIZE THE MATRIX
        DO I = 1,NMAX*2+1
          DO J = 1,NMAX*2+1
             A(I,J) = 0.0
```

```
        ENDDO
      ENDDO
      DO I = 0,NMAX
         DO J = 0,1
            TP(I,J)=0.0
         ENDDO
      ENDDO
*
*       CALCULATING TRANSITION PROBABILITY FROM (i,1) to (i',1)
*         FOR ONE EQUIPMENT TYPE; WHERE i IS NOT EQUAL TO i'
*
      DO K = 0,X-1
        IF ( K .EQ. 0 ) THEN
           IF ( X .EQ. 1 ) THEN
              B(K,1)=(1-PROB)*PROB
             ELSEIF ( X .EQ. 2 )THEN
              B(K,1)=(1-PROB)*PROB
              B(K,2)=(1-PROB)**2*PROB
             ELSEIF ( X .EQ. 3 ) THEN
              B(K,1)=(1-PROB)*PROB
              B(K,2)=(1-PROB)**2*PROB
              B(K,3)=(1-PROB)**3*PROB
             ELSEIF ( X .EQ. 4 ) THEN
              B(K,1)=(1-PROB)*PROB
              B(K,2)=(1-PROB)**2*PROB
              B(K,3)=(1-PROB)**3*PROB
              B(K,4)=(1-PROB)**4*PROB
             ELSEIF ( X .EQ. 5 ) THEN
              B(K,1)=(1-PROB)*PROB
              B(K,2)=(1-PROB)**2*PROB
              B(K,3)=(1-PROB)**3*PROB
              B(K,4)=(1-PROB)**4*PROB
              B(K,5)=(1-PROB)**5*PROB
           ENDIF
          ELSEIF ( K .EQ. 1 ) THEN
           IF ( X .EQ. 2 )THEN
              B(K,2)=(1-PROB)*PROB
             ELSEIF ( X .EQ. 3 ) THEN
              B(K,2)=(1-PROB)*PROB
              B(K,3)=(1-PROB)**2*PROB
             ELSEIF ( X .EQ. 4 ) THEN
              B(K,2)=(1-PROB)*PROB
              B(K,3)=(1-PROB)**2*PROB
              B(K,4)=(1-PROB)**3*PROB
             ELSEIF ( X .EQ. 5 ) THEN
              B(K,2)=(1-PROB)*PROB
              B(K,3)=(1-PROB)**2*PROB
              B(K,4)=(1-PROB)**3*PROB
              B(K,5)=(1-PROB)**4*PROB
           ENDIF
          ELSEIF ( K .EQ. 2 ) THEN
```

```
          IF ( X .EQ. 3 )THEN
             B(K,3)=(1-PROB)*PROB
            ELSEIF ( X .EQ. 4 ) THEN
             B(K,3)=(1-PROB)*PROB
             B(K,4)=(1-PROB)**2*PROB
            ELSEIF ( X .EQ. 5 ) THEN
             B(K,3)=(1-PROB)*PROB
             B(K,4)=(1-PROB)**2*PROB
             B(K,5)=(1-PROB)**3*PROB
          ENDIF
         ELSEIF ( K .EQ. 3 ) THEN
          IF ( X .EQ. 4 )THEN
             B(K,4)=(1-PROB)*PROB
            ELSEIF ( X .EQ. 5 ) THEN
             B(K,4)=(1-PROB)*PROB
             B(K,5)=(1-PROB)**2*PROB
          ENDIF
         ELSEIF ( K .EQ. 4 ) THEN
          IF ( X .EQ. 5 ) THEN
             B(K,5)=(1-PROB)*PROB
          ENDIF
       ENDIF
     ENDDO
*
*    EQUATION #1
*
*    LAM(0)*TP(0,0) = MEU(1)*TP(1,0)
     A(1,1) =-LAM(0)
     A(1,3) = MEU(1)
*
*    EQUATION #2A
*
*    (LAM(I)+MEU(I))*TP(I,0) =PROB*BI(I-1)*TP(I-1,1)+MEU(I+1)*TP(I+1,0)
     DO I = 1,X
        A(I+1,2*I+1) = LAM(I)+MEU(I)
        A(I+1,2*I)   =-PROB*BI(I-1)
        A(I+1,2*I+3) =-MEU(I+1)
     ENDDO
*
*    EQUATION #2B
*
*    (LAM(I)+MEU(I))*TP(I,0) = BI(I-1)*TP(I-1,1)+MEU(I+1)*TP(I+1,0)
     DO I = X+1,NMAX-2
        A(I+1,2*I+1) = LAM(I)+MEU(I)
        A(I+1,2*I)   =-BI(I-1)
        A(I+1,2*I+3) =-MEU(I+1)
     ENDDO
*
*    EQUATION #3
*
*    MEU(NMAX)*TP(NMAX,0) = BI(NMAX-1)*TP(NMAX-1,1)
```

```
      A(NMAX,NMAX*2+1) = MEU(NMAX)
      A(NMAX,NMAX*2) =-BI(NMAX-1)
*
*     EQUATION #4
*
      BX = 0.0D0
      DO IP = 1,X
         BX = BX + B(0,IP)
      ENDDO
*     PROB*BI(0)*TP(0,1)+BX*TP(0,1) = LAM(0)*TP(0,0)
      A(NMAX+1,2) = PROB*BI(0)+BX
      A(NMAX+1,1) =-LAM(0)
*
*     EQUATION #6
*
*     BIPX = 0.0
*     DO IP = 0,X-1
*        BIPX = BIPX + B(IP,X)*TP(IP,1)
*     ENDDO
*     BI(X)*TP(X,1) = LAM(X)*TP(X,0) + BIPX
      IF ( X .EQ. 1 ) THEN
          A(NMAX+2,2*X+2) =-BI(X)
          A(NMAX+2,2*X+1) = LAM(X)
          A(NMAX+2,2*X)   = B(0,X)
        ELSEIF ( X .EQ. 2 ) THEN
          A(NMAX+2,2*X+2) =-BI(X)
          A(NMAX+2,2*X+1) = LAM(X)
          A(NMAX+2,2*X-2) = B(0,X)
          A(NMAX+2,2*X) = B(1,X)
        ELSEIF ( X .EQ. 3 ) THEN
          A(NMAX+2,2*X+2) =-BI(X)
          A(NMAX+2,2*X+1) = LAM(X)
          A(NMAX+2,2*X-4) = B(0,X)
          A(NMAX+2,2*X-2) = B(1,X)
          A(NMAX+2,2*X) = B(2,X)
        ELSEIF ( X .EQ. 4 ) THEN
          A(NMAX+2,2*X+2) =-BI(X)
          A(NMAX+2,2*X+1) = LAM(X)
          A(NMAX+2,2*X-6) = B(0,X)
          A(NMAX+2,2*X-4) = B(1,X)
          A(NMAX+2,2*X-2) = B(2,X)
          A(NMAX+2,2*X) = B(3,X)
        ELSEIF ( X .EQ. 5 ) THEN
          A(NMAX+2,2*X+2) =-BI(X)
          A(NMAX+2,2*X+1) = LAM(X)
          A(NMAX+2,2*X-8) = B(0,X)
          A(NMAX+2,2*X-6) = B(1,X)
          A(NMAX+2,2*X-4) = B(2,X)
          A(NMAX+2,2*X-2) = B(3,X)
          A(NMAX+2,2*X) = B(4,X)
      ENDIF
```

```
      EQUATION #7

      DO I = X+1,NMAX-1
         BI(I)*TP(I,1) = LAM(I)*TP(I,0)
         A(NMAX+2+I-X,2*I+2) = BI(I)
         A(NMAX+2+I-X,2*I+1) =-LAM(I)
      ENDDO

      EQUATION #8

      PIO=0
      PI1=0
      DO I =0,NMAX
         PIO = PIO + TP(I,0)
         A(NMAX+2+N,2*I+1) = 1.
         IF ( I .NE. NMAX ) THEN
            PI1 = PI1 + TP(I,1)
            A(NMAX+2+N,2*I+2) = 1.
         ENDIF
      ENDDO
      PIO + PI1 = 1

      EQUATION #5

      DO I = 1,X-1,1
         BIIP = 0.0D0
         DO IP = I+1,X
           BIIP = BIIP + B(I,IP)
         ENDDO
         BIPI = 0
         DO IP = 0,I-1
            BIPI = BIPI + B(IP,I)*TP(IP,1)
         ENDDO
         PROB*BI(I)*TP(I,1)+BIIP*TP(I,1)=LAM(I)*TP(I,0)+BIPI
         IF ( I .EQ. 1 ) THEN
            A(NMAX+N+2+I,2*I+2) =-PROB*BI(I)-BIIP
            A(NMAX+N+2+I,2*I+1) = LAM(I)
            A(NMAX+N+2+I,2*I)   = B(0,1)
           ELSEIF ( I .EQ. 2 ) THEN
            A(NMAX+N+2+I,2*I+2) =-PROB*BI(I)-BIIP
            A(NMAX+N+2+I,2*I+1) = LAM(I)
            A(NMAX+N+2+I,2*I)   = B(1,2)
            A(NMAX+N+2+I,2*I-2) = B(0,2)
           ELSEIF ( I .EQ. 3 ) THEN
            A(NMAX+N+2+I,2*I+2) =-PROB*BI(I)-BIIP
            A(NMAX+N+2+I,2*I+1) = LAM(I)
            A(NMAX+N+2+I,2*I)   = B(2,3)
            A(NMAX+N+2+I,2*I-2) = B(1,3)
            A(NMAX+N+2+I,2*I-4) = B(0,3)
           ELSEIF ( I .EQ. 4 ) THEN
```

```
          A(NMAX+N+2+I,2*I+2) =-PROB*BI(I)-BIIP
          A(NMAX+N+2+I,2*I+1) = LAM(I)
          A(NMAX+N+2+I,2*I)   = B(3,4)
          A(NMAX+N+2+I,2*I-2) = B(2,4)
          A(NMAX+N+2+I,2*I-4) = B(1,4)
          A(NMAX+N+2+I,2*I-6) = B(0,4)
        ENDIF
      ENDDO
*
*           COMPUTING TRANSITIONAL PROBABILITY
*
      DO I = 1,NMAX*2+1
         RHS(I) = 0.0D0
      ENDDO
      RHS(NMAX+N+2) = 1.0D0
      NB = 1
      CALL DLSTSQ(31,31,NMAX*2+1,NMAX*2+1,A,RHS,NB,TP)
      END
*****************************************************************
*                                                               :
*     PURPOSE: CALCULATES THE TRADITIONAL AVAILABILITY WHEN     :
*              NUMBER IN REPAIR PROCESS IS LESS OR EQUAL TO     :
*              SPARE AVAILABLE                                  :
*                                                               :
*     INPUT:                                                    :
*            >     :M, IX, P's, ( EXPLAINED EARLIER )           :
*                                                               :
*     OUTPUT:                                                   :
*            >A0   : TRADITIONAL AVAILABILITY                   :
*                                                               :
*****************************************************************
      SUBROUTINE
     :TAVAIL(M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,A0)
      INTEGER S,X,IX(10)
      DOUBLEPRECISION P1(0:IX(1),0:0),P2(0:IX(2),0:0),
     :P3(0:IX(3),0:0),P4(0:IX(4),0:0),P5(0:IX(5),0:0),
     :P6(0:IX(6),0:0),P7(0:IX(7),0:0),P8(0:IX(8),0:0),
     :P9(0:IX(9),0:0),P10(0:IX(10),0:0),PP1,PP2,PP3,
     :PP4,PP5,PP6,PP7,PP8,PP9,PP10
*
*                      INITIALIZE
*
      DATA PP1,PP2,PP3,PP4,PP5,PP6,PP7,PP8,PP9,PP10
     :     /1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0/
      DO I = 1,M
        IF ( I .EQ. 1 ) THEN
           PP1 = 0.0
           DO S = 0,IX(1)
             PP1 = PP1 + P1(S,0)
           ENDDO
          ELSEIF ( I .EQ. 2 ) THEN
```

```
              PP2 = 0.0
              DO S = 0,IX(2)
                PP2 = PP2 + P2(S,0)
              ENDDO
            ELSEIF ( I .EQ. 3 ) THEN
              PP3 = 0.0
              DO S = 0,IX(3)
                PP3 = PP3 + P3(S,0)
              ENDDO
            ELSEIF ( I .EQ. 4 ) THEN
              PP4 = 0.0
              DO S = 0,IX(4)
                PP4 = PP4 + P4(S,0)
              ENDDO
            ELSEIF ( I .EQ. 5 ) THEN
              PP5 = 0.0
              DO S = 0,IX(5)
                PP5 = PP5 + P5(S,0)
              ENDDO
            ELSEIF ( I .EQ. 6 ) THEN
              PP6 = 0.0
              DO S = 0,IX(6)
                PP6 = PP6 + P6(S,0)
              ENDDO
            ELSEIF ( I .EQ. 7 ) THEN
              PP7 = 0.0
              DO S = 0,IX(7)
                PP7 = PP7 + P7(S,0)
              ENDDO
            ELSEIF ( I .EQ. 8 ) THEN
              PP8 = 0.0
              DO S = 0,IX(8)
                PP8 = PP8 + P8(S,0)
              ENDDO
            ELSEIF ( I .EQ. 9 ) THEN
              PP9 = 0.0
              DO S = 0,IX(9)
                PP9 = PP9 + P9(S,0)
              ENDDO
            ELSEIF ( I .EQ. 10 ) THEN
              PP10 = 0.0
              DO S = 0,IX(10)
                PP10 = PP10 + P10(S,0)
              ENDDO
          ENDIF
        ENDDO
        A0=PP1*PP2*PP3*PP4*PP5*PP6*PP7*PP8*PP9*PP10
        END
***********************************************************************
*                                                                     :
*       PURPOSE: SUBROUTINE WHEN ONLY ONE EQUIPMENT TYPE IN THE       :
```

```
*              STATE (X+1,0)                                        :
*                                                                   :
*    INPUT:                                                         :
*              >    : M, IN, NMX, P's, (EXPLAINED EARLIER)          :
*    OUTPUT:                                                        :
*              >PAAX: PARTIAL CREDITS FOR PARTIAL AVAILABILITY      :
*                                                                   :
********************************************************************
      SUBROUTINE
     :SFAIL1(NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PAAX)
      INTEGER X,S,AA1,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),PAAX
      REAL Z(10)
*
*                    INITIALIZE
*
      DATA PP/10*0.0D0/
      DO I = 1,M
        IF ( I .EQ. 1 ) THEN
           DO S = 0,IX(1)
             PP(1) = PP(1) + P1(S,0)
           ENDDO
          ELSEIF ( I .EQ. 2 ) THEN
           DO S = 0,IX(2)
             PP(2) = PP(2) + P2(S,0)
           ENDDO
          ELSEIF ( I .EQ. 3 ) THEN
           DO S = 0,IX(3)
             PP(3) = PP(3) + P3(S,0)
           ENDDO
          ELSEIF ( I .EQ. 4 ) THEN
           DO S = 0,IX(4)
             PP(4) = PP(4) + P4(S,0)
           ENDDO
          ELSEIF ( I .EQ. 5 ) THEN
           DO S = 0,IX(5)
             PP(5) = PP(5) + P5(S,0)
           ENDDO
          ELSEIF ( I .EQ. 6 ) THEN
           DO S = 0,IX(6)
             PP(6) = PP(6) + P6(S,0)
           ENDDO
          ELSEIF ( I .EQ. 7 ) THEN
           DO S = 0,IX(7)
             PP(7) = PP(7) + P7(S,0)
           ENDDO
          ELSEIF ( I .EQ. 8 ) THEN
           DO S = 0,IX(8)
```

```
            PP(8) = PP(8) + P8(S,0)
          ENDDO
         ELSEIF ( I .EQ. 9 ) THEN
          DO S = 0,IX(9)
            PP(9) = PP(9) + P9(S,0)
          ENDDO
         ELSEIF ( I .EQ. 10 ) THEN
          DO S = 0,IX(10)
            PP(10) = PP(10) + P10(S,0)
          ENDDO
       ENDIF
     ENDDO
     DO I=M+1,10
        PP(I)=1.0
     ENDDO
     DO I=1,M
       Z(I)=IN(I)
     ENDDO
     PAAX = 0.0
     X=MIN(IX(1),IX(2),IX(3),IX(4),IX(5),
    :       IX(6),IX(7),IX(8),IX(9),IX(10))
     NMAX=MAX(NMX(1),NMX(2),NMX(3),NMX(4),NMX(5),
    :          NMX(6),NMX(7),NMX(8),NMX(9),NMX(10))
     DO K=1,10
        PAA(K)=0.0D0
     ENDDO
*
*             COMPUTING PARTIAL CREDITS
*
     DO AA1 = X+1,NMAX-1
        DO K = 1,M
          IF (K .EQ. 1
    :            .AND. IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1)THEN
             WAA1 = ((NMX(1)-AA1)/Z(1))
             PAA(1)=P1(AA1,0)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*
    :               PP(8)*PP(9)*PP(10)*WAA1
            ELSEIF ( K .EQ. 2 .AND.
    :                IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
             WAA2 = ((NMX(2)-AA1)/Z(2))
             PAA(2)=P2(AA1,0)*PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*
    :               PP(8)*PP(9)*PP(10)*WAA2
            ELSEIF ( K .EQ. 3 .AND.
    :                IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
             WAA3 = ((NMX(3)-AA1)/Z(3))
             PAA(3)=P3(AA1,0)*PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*
    :               PP(8)*PP(9)*PP(10)*WAA3
            ELSEIF ( K .EQ. 4 .AND.
    :                IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
             WAA4 = ((NMX(4)-AA1)/Z(4))
             PAA(4)=P4(AA1,0)*PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*
    :               PP(8)*PP(9)*PP(10)*WAA4
```

```
            ELSEIF ( K .EQ. 5 .AND.
     :               IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
             WAA5 = ((NMX(5)-AA1)/Z(5))
             PAA(5)=P5(AA1,0)*PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*
     :              PP(8)*PP(9)*PP(10)*WAA5
            ELSEIF ( K .EQ. 6 .AND.
     :               IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
             WAA6 = ((NMX(6)-AA1)/Z(6))
             PAA(6)=P6(AA1,0)*PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*
     :              PP(8)*PP(9)*PP(10)*WAA6
            ELSEIF ( K .EQ. 7 .AND.
     :               IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
             WAA7 = ((NMX(7)-AA1)/Z(7))
             PAA(7)=P7(AA1,0)*PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*
     :              PP(8)*PP(9)*PP(10)*WAA7
            ELSEIF ( K .EQ. 8 .AND.
     :               IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
             WAA8 = ((NMX(8)-AA1)/Z(8))
             PAA(8)=P8(AA1,0)*PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*
     :              PP(7)*PP(9)*PP(10)*WAA8
            ELSEIF ( K .EQ. 9 .AND.
     :               IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
             WAA9 = ((NMX(9)-AA1)/Z(9))
             PAA(9)=P9(AA1,0)*PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*
     :              PP(7)*PP(8)*PP(10)*WAA9
            ELSEIF ( K .EQ. 10 .AND.
     :       IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
             WAA10 = ((NMX(10)-AA1)/Z(10))
             PAA(10)=P10(AA1,0)*PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)
     :               *PP(7)*PP(8)*PP(9)*WAA10
          ENDIF
        ENDDO
        PAAX = PAAX+(PAA(1)+PAA(2)+PAA3+PAA(4)+PAA(5)+PAA(6)+
     :               PAA(7)+PAA(8)+PAA(9)+PAA(10))
      ENDDO
      END
*******************************************************************
*                                                                 :
*     PURPOSE: SUBROUTINE WHEN ANY TWO EQUIPMENT TYPES IN         :
*              THE STATE (X+1,0)                                  :
*                                                                 :
*     INPUT:                                                      :
*             >    : M, IN, IX, NMX, P's                          :
*                    (EXPLAINED EARLIER)                          :
*     OUTPUT:                                                     :
*             >PLKX: PARTIAL CREDITS FOR PARTIAL                  :
*                    AVAILABILITY                                 :
*                                                                 :
*******************************************************************
      SUBROUTINE
     :SFAIL2(NMX,IN,M,IX,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PLKX)
```

```
      INTEGER X,S,AA1,AA2,A1,A2,A3,A4,A5,A6,A7,A8,A9,A10
      INTEGER IX(10),IN(M),NMX(10)
      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),PLKE,PLKNE,
     :PLK1,PLK2,PLK3,PLK4,PLK5,PLK6,PLK7,PLK8,PLK9,PLK10,PLKX
      REAL Z(10)
*
*                  INITIALIZE
*
      DATA PP(1),PP(2),PP(3),PP(4),PP(5),PP(6),PP(7),PP(8),PP(9),
     :     PP(10)/0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/,
     :     PLK1,PLK2,PLK3,PLK4,PLK5,PLK6,PLK7,PLK8,PLK9,PLK10
     :     /0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/,
     :     PLK12,PLK13,PLK14,PLK15,PLK16,PLK17,PLK18,PLK19,PLK110
     :     /0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/,
     :     PLK21,PLK23,PLK24,PLK25,PLK26,PLK27,PLK28,PLK29,PLK210
     :      /0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/,
     :     PLK31,PLK32,PLK34,PLK35,PLK36,PLK37,PLK38,PLK39,PLK310
     :     /0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/,
     :     PLK41,PLK42,PLK43,PLK45,PLK46,PLK47,PLK48,PLK49,PLK410
     :     /0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/,
     :     PLK51,PLK52,PLK53,PLK54,PLK56,PLK57,PLK58,PLK59,PLK510
     :     /0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/,
     :     PLK61,PLK62,PLK63,PLK64,PLK65,PLK67,PLK68,PLK69,PLK610
     :     /0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/,
     :     PLK71,PLK72,PLK73,PLK74,PLK75,PLK76,PLK78,PLK79,PLK710
     :     /0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/,
     :     PLK81,PLK82,PLK83,PLK84,PLK85,PLK86,PLK87,PLK89,PLK810
     :     /0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/,
     :     PLK91,PLK92,PLK93,PLK94,PLK95,PLK96,PLK97,PLK98,PLK910
     :     /0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/,
     :     PLK101,PLK102,PLK103,PLK104,PLK105,PLK106,PLK107,PLK108,
     :     PLK109/0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0/
      DO I = 1,M
        IF ( I .EQ. 1 ) THEN
           DO S = 0,IX(1)
             PP(1) = PP(1) + P1(S,0)
           ENDDO
          ELSEIF ( I .EQ. 2 ) THEN
           DO S = 0,IX(2)
             PP(2) = PP(2) + P2(S,0)
           ENDDO
          ELSEIF ( I .EQ. 3 ) THEN
           DO S = 0,IX(3)
             PP(3) = PP(3) + P3(S,0)
           ENDDO
          ELSEIF ( I .EQ. 4 ) THEN
           DO S = 0,IX(4)
             PP(4) = PP(4) + P4(S,0)
```

```
          ENDDO
        ELSEIF ( I .EQ. 5 ) THEN
         DO S = 0,IX(5)
           PP(5) = PP(5) + P5(S,0)
         ENDDO
        ELSEIF ( I .EQ. 6 ) THEN
         DO S = 0,IX(6)
           PP(6) = PP(6) + P6(S,0)
         ENDDO
        ELSEIF ( I .EQ. 7 ) THEN
         DO S = 0,IX(7)
           PP(7) = PP(7) + P7(S,0)
         ENDDO
        ELSEIF ( I .EQ. 8 ) THEN
         DO S = 0,IX(8)
           PP(8) = PP(8) + P8(S,0)
         ENDDO
        ELSEIF ( I .EQ. 9 ) THEN
         DO S = 0,IX(9)
           PP(9) = PP(9) + P9(S,0)
         ENDDO
        ELSEIF ( I .EQ. 10 ) THEN
         DO S = 0,IX(10)
           PP(10) = PP(10) + P10(S,0)
         ENDDO
      ENDIF
    ENDDO
    DO I=M+1,10
       PP(I)=1.0
    ENDDO
    DO I=1,M
      Z(I)=IN(I)
    ENDDO
    X=MIN(IX(1),IX(2),IX(3),IX(4),IX(5),
   :      IX(6),IX(7),IX(8),IX(9),IX(10))
    NMAX=MAX(NMX(1),NMX(2),NMX(3),NMX(4),NMX(5),
   :         NMX(6),NMX(7),NMX(8),NMX(9),NMX(10))
    PLKE = 0.0D0
    PLKNE = 0.0D0
    PLKX = 0.0D0
*
*            PARTIAL CREDITS DETERMINATION
*
    DO AA1 = X+1,NMAX-1
     DO AA2 = X+1,NMAX-1
      DO L = 1,M
       IF ( L .EQ. 1 ) THEN
          A1 = AA1
          WA11 = ((NMX(1)-AA1)/Z(1))
         ELSEIF ( L .EQ. 2 ) THEN
          A2 = AA1
```

```
          WA12 = ((NMX(2)-AA1)/Z(2))
         ELSEIF ( L .EQ. 3 ) THEN
          A3 = AA1
          WA13 = ((NMX(3)-AA1)/Z(3))
         ELSEIF ( L .EQ. 4 ) THEN
          A4 = AA1
          WA14 = ((NMX(4)-AA1)/Z(4))
         ELSEIF ( L .EQ. 5 ) THEN
          A5 = AA1
          WA15 = ((NMX(5)-AA1)/Z(5))
         ELSEIF ( L .EQ. 6 ) THEN
          A6 = AA1
          WA16 = ((NMX(6)-AA1)/Z(6))
         ELSEIF ( L .EQ. 7 ) THEN
          A7 = AA1
          WA17 = ((NMX(7)-AA1)/Z(7))
         ELSEIF ( L .EQ. 8 ) THEN
          A8 = AA1
          WA18 = ((NMX(8)-AA1)/Z(8))
         ELSEIF ( L .EQ. 9 ) THEN
          A9 = AA1
          WA19 = ((NMX(9)-AA1)/Z(9))
         ELSEIF ( L .EQ. 10 ) THEN
          A10 = AA1
          WA110 = ((NMX(10)-AA1)/Z(10))
      ENDIF
      DO K = 1,M
       IF ( K .NE. L ) THEN
        IF ( K .EQ. 1 .AND.
     :    IX(1) .LT. AA2 .AND. NMX(1) .GT. AA2 ) THEN
          WA21 = ((NMX(1)-AA2)/Z(1))
          A1=AA2
          IF ( L .EQ. 2 .AND.
     :      IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
            PLK12=P1(A1,0)*P2(A2,0)*WA12*WA21*
     :      PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
           ELSEIF ( L .EQ. 3 .AND.
     :      IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
            PLK13=P1(A1,0)*P3(A3,0)*WA13*WA21*
     :      PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
           ELSEIF ( L .EQ. 4 .AND.
     :      IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
            PLK14=P1(A1,0)*P4(A4,0)*WA14*WA21*
     :      PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
           ELSEIF ( L .EQ. 5 .AND.
     :      IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
            PLK15=P1(A1,0)*P5(A5,0)*WA15*WA21*
     :      PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
           ELSEIF ( L .EQ. 6 .AND.
     :      IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
            PLK16=P1(A1,0)*P6(A6,0)*WA16*WA21*
```

```
:             PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
             ELSEIF ( L .EQ. 7 .AND.
:             IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
              PLK17=P1(A1,0)*P7(A7,0)*WA17*WA21*
:             PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
             ELSEIF ( L .EQ. 8 .AND.
:             IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
              PLK18=P1(A1,0)*P8(A8,0)*WA18*WA21*
:             PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
             ELSEIF ( L .EQ. 9 .AND.
:             IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
              PLK19=P1(A1,0)*P9(A9,0)*WA19*WA21*
:             PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
             ELSEIF ( L .EQ. 10 .AND.
:             IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
              PLK110=P1(A1,0)*P10(A10,0)*WA110*WA21*
:             PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
            ENDIF
           ELSEIF ( K .EQ. 2 .AND.
:           IX(2) .LT. AA2 .AND. NMX(2) .GT. AA2) THEN
            WA22 = ((NMX(2)-AA2)/Z(2))
            A2=AA2
            IF ( L .EQ. 1 .AND.
:             IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
              PLK21=P1(A1,0)*P2(A2,0)*WA11*WA22*
:             PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
             ELSEIF ( L .EQ. 3 .AND.
:             IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
              PLK23=P2(A2,0)*P3(A3,0)*WA13*WA22*
:             PP(1)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
             ELSEIF ( L .EQ. 4 .AND.
:             IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
              PLK24=P2(A2,0)*P4(A4,0)*WA14*WA22*
:             PP(1)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
             ELSEIF ( L .EQ. 5 .AND.
:             IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
              PLK25=P2(A2,0)*P5(A5,0)*WA15*WA22*
:             PP(1)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
             ELSEIF ( L .EQ. 6 .AND.
:             IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
              PLK26=P2(A2,0)*P6(A6,0)*WA16*WA22*
:             PP(1)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
             ELSEIF ( L .EQ. 7 .AND.
:             IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
              PLK27=P2(A2,0)*P7(A7,0)*WA17*WA22*
:             PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
             ELSEIF ( L .EQ. 8 .AND.
:             IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
              PLK28=P2(A2,0)*P8(A8,0)*WA18*WA22*
:             PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
             ELSEIF ( L .EQ. 9 .AND.
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```
:          IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
           PLK29=P2(A2,0)*P9(A9,0)*WA19*WA22*
:          PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
          ELSEIF ( L .EQ. 10 .AND.
:          IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
           PLK210=P2(A2,0)*P10(A10,0)*WA110*WA22*
:          PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
         ENDIF
        ELSEIF ( K .EQ. 3 .AND.
:        IX(3) .LT. AA2 .AND. NMX(3) .GT. AA2) THEN
         WA23 = ((NMX(3)-AA2)/Z(3))
         A3=AA2
         IF ( L .EQ. 1 .AND.
:          IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
           PLK31=P1(A1,0)*P3(A3,0)*WA11*WA23*
:          PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
          ELSEIF ( L .EQ. 2 .AND.
:          IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
           PLK32=P2(A2,0)*P3(A3,0)*WA12*WA23*
:          PP(1)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
          ELSEIF ( L .EQ. 4 .AND.
:          IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
           PLK34=P3(A3,0)*P4(A4,0)*WA14*WA23*
:          PP(1)*PP(2)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
          ELSEIF ( L .EQ. 5 .AND.
:          IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
           PLK35=P3(A3,0)*P5(A5,0)*WA15*WA23*
:          PP(1)*PP(2)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
          ELSEIF ( L .EQ. 6 .AND.
:          IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
           PLK36=P3(A3,0)*P6(A6,0)*WA16*WA23*
:          PP(1)*PP(2)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
          ELSEIF ( L .EQ. 7 .AND.
:          IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
           PLK37=P3(A3,0)*P7(A7,0)*WA17*WA23*
:          PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
          ELSEIF ( L .EQ. 8 .AND.
:          IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
           PLK38=P3(A3,0)*P8(A8,0)*WA18*WA23*
:          PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
          ELSEIF ( L .EQ. 9 .AND.
:          IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
           PLK39=P3(A3,0)*P9(A9,0)*WA19*WA23*
:          PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
          ELSEIF ( L .EQ. 10 .AND.
:          IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
           PLK310=P3(A3,0)*P10(A10,0)*WA110*WA23*
:          PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
         ENDIF
        ELSEIF ( K .EQ. 4 .AND.
:        IX(4) .LT. AA2 .AND. NMX(4) .GT. AA2) THEN
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              WA24 = ((NMX(4)-AA2)/Z(4))
              A4=AA2
              IF ( L .EQ. 1 .AND.
     :          IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
                PLK41=P1(A1,0)*P4(A4,0)*WA11*WA24*
     :          PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 2 .AND.
     :          IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
                PLK42=P2(A2,0)*P4(A4,0)*WA12*WA24*
     :          PP(1)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 3 .AND.
     :          IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
                PLK43=P3(A3,0)*P4(A4,0)*WA13*WA24*
     :          PP(1)*PP(2)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 5 .AND.
     :          IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
                PLK45=P4(A4,0)*P5(A5,0)*WA15*WA24*
     :          PP(1)*PP(2)*PP(3)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 6 .AND.
     :          IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
                PLK46=P4(A4,0)*P6(A6,0)*WA16*WA24*
     :          PP(1)*PP(2)*PP(3)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 7 .AND.
     :          IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
                PLK47=P4(A4,0)*P7(A7,0)*WA17*WA24*
     :          PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 8 .AND.
     :          IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
                PLK48=P4(A4,0)*P8(A8,0)*WA18*WA24*
     :        PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 9 .AND.
     :          IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
                PLK49=P4(A4,0)*P9(A9,0)*WA19*WA24*
     :          PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
               ELSEIF ( L .EQ. 10 .AND.
     :          IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
                PLK410=P4(A4,0)*P10(A10,0)*WA110*WA24*
     :          PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
              ENDIF
            ELSEIF ( K .EQ. 5 .AND.
     :        IX(5) .LT. AA2 .AND. NMX(5) .GT. AA2) THEN
              WA25 = ((NMX(5)-AA2)/Z(5))
              A5=AA2
              IF ( L .EQ. 1 .AND.
     :          IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
                PLK51=P1(A1,0)*P5(A5,0)*WA11*WA25*
     :          PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 2 .AND.
     :          IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
                PLK52=P2(A2,0)*P5(A5,0)*WA12*WA25*
     :          PP(1)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
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            ELSEIF ( L .EQ. 3 .AND.
     :       IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
             PLK53=P3(A3,0)*P5(A5,0)*WA13*WA25*
     :       PP(1)*PP(2)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
            ELSEIF ( L .EQ. 4 .AND.
     :       IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
             PLK54=P4(A4,0)*P5(A5,0)*WA14*WA25*
     :       PP(1)*PP(2)*PP(3)*PP(6)*PP(7)*PP(8)*PP(9)*PP(10)
            ELSEIF ( L .EQ. 6 .AND.
     :       IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
             PLK56=P5(A5,0)*P6(A6,0)*WA16*WA25*
     :       PP(1)*PP(2)*PP(3)*PP(4)*PP(7)*PP(8)*PP(9)*PP(10)
            ELSEIF ( L .EQ. 7 .AND.
     :       IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
             PLK57=P5(A5,0)*P7(A7,0)*WA17*WA25*
     :       PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(8)*PP(9)*PP(10)
            ELSEIF ( L .EQ. 8 .AND.
     :       IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
             PLK58=P5(A5,0)*P8(A8,0)*WA18*WA25*
     :       PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(9)*PP(10)
            ELSEIF ( L .EQ. 9 .AND.
     :       IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
             PLK59=P5(A5,0)*P9(A9,0)*WA19*WA25*
     :       PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(10)
            ELSEIF ( L .EQ. 10 .AND.
     :       IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
             PLK510=P5(A5,0)*P10(A10,0)*WA110*WA25*
     :       PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)
           ENDIF
          ELSEIF ( K .EQ. 6 .AND.
     :     IX(6) .LT. AA2 .AND. NMX(6) .GT. AA2) THEN
           WA26 = ((NMX(6)-AA2)/Z(6))
           A6=AA2
           IF ( L .EQ. 1 .AND.
     :       IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
             PLK61=P1(A1,0)*P6(A6,0)*WA11*WA26*
     :       PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
            ELSEIF ( L .EQ. 2 .AND.
     :       IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
             PLK62=P2(A2,0)*P6(A6,0)*WA12*WA26*
     :       PP(1)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
            ELSEIF ( L .EQ. 3 .AND.
     :       IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
             PLK63=P3(A3,0)*P6(A6,0)*WA13*WA26*
     :       PP(1)*PP(2)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
            ELSEIF ( L .EQ. 4 .AND.
     :       IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
             PLK64=P4(A4,0)*P6(A6,0)*WA14*WA26*
     :       PP(1)*PP(2)*PP(3)*PP(5)*PP(7)*PP(8)*PP(9)*PP(10)
            ELSEIF ( L .EQ. 5 .AND.
     :       IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
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                PLK65=P5(A5,0)*P6(A6,0)*WA15*WA26*
     :          PP(1)*PP(2)*PP(3)*PP(4)*PP(7)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 7 .AND.
     :          IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
                PLK67=P6(A6,0)*P7(A7,0)*WA17*WA26*
     :          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 8 .AND.
     :          IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
                PLK68=P6(A6,0)*P8(A8,0)*WA18*WA26*
     :          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 9 .AND.
     :          IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
                PLK69=P6(A6,0)*P9(A9,0)*WA19*WA26*
     :          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(10)
               ELSEIF ( L .EQ. 10 .AND.
     :          IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
                PLK610=P6(A6,0)*P10(A10,0)*WA110*WA26*
     :          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)
              ENDIF
             ELSEIF ( K .EQ. 7 .AND.
     :        IX(7) .LT. AA2 .AND. NMX(7) .GT. AA2 ) THEN
              WA27 = ((NMX(7)-AA2)/Z(7))
              A7=AA2
              IF ( L .EQ. 1 .AND.
     :          IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
                PLK71=P1(A1,0)*P7(A7,0)*WA11*WA27*
     :          PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 2 .AND.
     :          IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
                PLK72=P2(A2,0)*P7(A7,0)*WA12*WA27*
     :          PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 3 .AND.
     :          IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
                PLK73=P3(A3,0)*P7(A7,0)*WA13*WA27*
     :          PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 4 .AND.
     :          IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
                PLK74=P4(A4,0)*P7(A7,0)*WA14*WA27*
     :          PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 5 .AND.
     :          IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
                PLK75=P5(A5,0)*P7(A7,0)*WA15*WA27*
     :          PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 6 .AND.
     :          IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
                PLK76=P6(A6,0)*P7(A7,0)*WA16*WA27*
     :          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(8)*PP(9)*PP(10)
               ELSEIF ( L .EQ. 8 .AND.
     :          IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
                PLK78=P7(A7,0)*P8(A8,0)*WA18*WA27*
     :          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(9)*PP(10)
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          ELSEIF ( L .EQ. 9 .AND.
:          IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
           PLK79=P7(A7,0)*P9(A9,0)*WA19*WA27*
:          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(10)
          ELSEIF ( L .EQ. 10 .AND.
:          IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
           PLK710=P7(A7,0)*P10(A10,0)*WA110*WA27*
:          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)
         ENDIF
        ELSEIF ( K .EQ. 8 .AND.
:        IX(8) .LT. AA2 .AND. NMX(8) .GT. AA2) THEN
         WA28 = ((NMX(8)-AA2)/Z(8))
         A8=AA2
         IF ( L .EQ. 1 .AND.
:          IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
           PLK81=P1(A1,0)*P8(A8,0)*WA11*WA28*
:          PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
          ELSEIF ( L .EQ. 2 .AND.
:          IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
           PLK82=P2(A2,0)*P8(A8,0)*WA12*WA28*
:          PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
          ELSEIF ( L .EQ. 3 .AND.
:          IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
           PLK83=P3(A3,0)*P8(A8,0)*WA13*WA28*
:          PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
          ELSEIF ( L .EQ. 4 .AND.
:          IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
           PLK84=P4(A4,0)*P8(A8,0)*WA14*WA28*
:          PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(9)*PP(10)
          ELSEIF ( L .EQ. 5 .AND.
:          IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
           PLK85=P5(A5,0)*P8(A8,0)*WA15*WA28*
:          PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(9)*PP(10)
          ELSEIF ( L .EQ. 6 .AND.
:          IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
           PLK86=P6(A6,0)*P8(A8,0)*WA16*WA28*
:          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(9)*PP(10)
          ELSEIF ( L .EQ. 7 .AND.
:          IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
           PLK87=P7(A7,0)*P8(A8,0)*WA17*WA28*
:          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(9)*PP(10)
          ELSEIF ( L .EQ. 9 .AND.
:          IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
           PLK89=P8(A8,0)*P9(A9,0)*WA19*WA28*
:          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(10)
          ELSEIF ( L .EQ. 10 .AND.
:          IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
           PLK810=P8(A8,0)*P10(A10,0)*WA110*WA28*
:          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)
         ENDIF
        ELSEIF ( K .EQ. 9 .AND.
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:         IX(9) .LT. AA2 .AND. NMX(9) .GT. AA2) THEN
          WA29 = ((NMX(9)-AA2)/Z(9))
          A9=AA2
          IF ( L .EQ. 1 .AND.
:           IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
            PLK91=P1(A1,0)*P9(A9,0)*WA11*WA29*
:           PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
           ELSEIF ( L .EQ. 2 .AND.
:           IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
            PLK92=P2(A2,0)*P9(A9,0)*WA12*WA29*
:           PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
           ELSEIF ( L .EQ. 3 .AND.
:           IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
            PLK93=P3(A3,0)*P9(A9,0)*WA13*WA29*
:           PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
           ELSEIF ( L .EQ. 4 .AND.
:           IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
            PLK94=P4(A4,0)*P9(A9,0)*WA14*WA29*
:           PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(10)
           ELSEIF ( L .EQ. 5 .AND.
:           IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
            PLK95=P5(A5,0)*P9(A9,0)*WA15*WA29*
:           PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(10)
           ELSEIF ( L .EQ. 6 .AND.
:           IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
            PLK96=P6(A6,0)*P9(A9,0)*WA16*WA29*
:           PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(10)
           ELSEIF ( L .EQ. 7 .AND.
:           IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
            PLK97=P7(A7,0)*P9(A9,0)*WA17*WA29*
:           PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(10)
           ELSEIF ( L .EQ. 8 .AND.
:           IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
            PLK98=P8(A8,0)*P9(A9,0)*WA18*WA29*
:           PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(10)
           ELSEIF ( L .EQ. 10 .AND.
:           IX(10) .LT. AA1 .AND. NMX(10) .GT. AA1) THEN
            PLK910=P9(A9,0)*P10(A10,0)*WA110*WA29*
:           PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)
          ENDIF
        ELSEIF ( K .EQ. 10 .AND.
:         IX(10) .LT. AA2 .AND. NMX(10) .GT. AA2) THEN
          WA210 = ((NMX(10)-AA2)/Z(10))
          A10=AA2
          IF ( L .EQ. 1 .AND.
:           IX(1) .LT. AA1 .AND. NMX(1) .GT. AA1) THEN
            PLK101=P1(A1,0)*P10(A10,0)*WA11*WA210*
:           PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
           ELSEIF ( L .EQ. 2 .AND.
:           IX(2) .LT. AA1 .AND. NMX(2) .GT. AA1) THEN
            PLK102=P2(A2,0)*P10(A10,0)*WA12*WA210*
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     :          PP(1)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
               ELSEIF ( L .EQ. 3 .AND.
     :          IX(3) .LT. AA1 .AND. NMX(3) .GT. AA1) THEN
                PLK103=P3(A3,0)*P10(A10,0)*WA13*WA210*
     :          PP(1)*PP(2)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
               ELSEIF ( L .EQ. 4 .AND.
     :          IX(4) .LT. AA1 .AND. NMX(4) .GT. AA1) THEN
                PLK104=P4(A4,0)*P10(A10,0)*WA14*WA210*
     :          PP(1)*PP(2)*PP(3)*PP(5)*PP(6)*PP(7)*PP(8)*PP(9)
               ELSEIF ( L .EQ. 5 .AND.
     :          IX(5) .LT. AA1 .AND. NMX(5) .GT. AA1) THEN
                PLK105=P5(A5,0)*P10(A10,0)*WA15*WA210*
     :          PP(1)*PP(2)*PP(3)*PP(4)*PP(6)*PP(7)*PP(8)*PP(9)
               ELSEIF ( L .EQ. 6 .AND.
     :          IX(6) .LT. AA1 .AND. NMX(6) .GT. AA1) THEN
                PLK106=P6(A6,0)*P10(A10,0)*WA16*WA210*
     :          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(7)*PP(8)*PP(9)
               ELSEIF ( L .EQ. 7 .AND.
     :          IX(7) .LT. AA1 .AND. NMX(7) .GT. AA1) THEN
                PLK107=P7(A7,0)*P10(A10,0)*WA17*WA210*
     :          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(8)*PP(9)
               ELSEIF ( L .EQ. 8 .AND.
     :          IX(8) .LT. AA1 .AND. NMX(8) .GT. AA1) THEN
                PLK108=P8(A8,0)*P10(A10,0)*WA17*WA210*
     :          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(9)
               ELSEIF ( L .EQ. 9 .AND.
     :          IX(9) .LT. AA1 .AND. NMX(9) .GT. AA1) THEN
                PLK109=P9(A9,0)*P10(A10,0)*WA19*WA210*
     :          PP(1)*PP(2)*PP(3)*PP(4)*PP(5)*PP(6)*PP(7)*PP(8)
              ENDIF
            ENDIF
          ENDIF
        ENDDO
      ENDDO
      PLK1=PLK12+PLK13+PLK14+PLK15+PLK16+PLK17+PLK18+PLK19
     :     +PLK110
      PLK2=PLK21+PLK23+PLK24+PLK25+PLK26+PLK27+PLK28+PLK29
     :     +PLK210
      PLK3=PLK31+PLK32+PLK34+PLK35+PLK36+PLK37+PLK38+PLK39
     :     +PLK310
      PLK4=PLK41+PLK42+PLK43+PLK45+PLK46+PLK47+PLK48+PLK49
     :     +PLK410
      PLK5=PLK51+PLK52+PLK53+PLK54+PLK56+PLK57+PLK58+PLK59
     :     +PLK510
      PLK6=PLK61+PLK62+PLK63+PLK64+PLK65+PLK67+PLK68+PLK69
     :     +PLK610
      PLK7=PLK71+PLK72+PLK73+PLK74+PLK75+PLK76+PLK78+PLK79
     :     +PLK710
      PLK8=PLK81+PLK82+PLK83+PLK84+PLK85+PLK86+PLK87+PLK89
     :     +PLK810
      PLK9=PLK91+PLK92+PLK93+PLK94+PLK95+PLK96+PLK97+PLK98
```

```
     :       +PLK910
        PLK10=PLK101+PLK102+PLK103+PLK104+PLK105+PLK106+PLK107
     :       +PLK108+PLK109
        IF ( AA1 .EQ. AA2 ) THEN
            PLKE=PLKE+1/2*(PLK1+PLK2+PLK3+PLK4+PLK5+PLK6
     :           +PLK7+PLK8+PLK9+PLK10)
            PLKNE=0.0
           ELSE
            PLKNE=PLKNE+(PLK1+PLK2+PLK3+PLK4+PLK5+PLK6
     :            +PLK7+PLK8+PLK9+PLK10)
            PLKE=0.0
        ENDIF
        PLKX = PLKX + PLKE + PLKNE
       ENDDO
      ENDDO
      END
```