To the Graduate Council:

I am submitting herewith a thesis written by Ali Reza Mahmoudieh entitled "An Experimental Investigation of Shortest Repair Time Scheduling Procedure Using Computer Simulation." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Industrial Engineering.

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AN EXPERIMENTAL INVESTIGATION OF SHORTEST REPAIR TIME FOR MAINTENANCE SCHEDULING

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Ali Reza Mahmoudieh

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ABSTRACT

This study focused on that portion of downtime during which a failed equipment waits for service. The objective was to demonstrate the potential of the Shortest Repair Time scheduling procedure for reducing work order waiting time. In order to perform the analysis and test the feasibility of this scheduling procedure, several simulation models were developed. The simulation results showed that SRT can reduce downtime. A series of experiments with models using different operating conditions revealed that SRT's performance depends on work load, and at low levels of work load, SRT and FCFS are equivalent.

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CHAPTER I

INTRODUCTION

Just as the wheel totally changed the way of life for stone age man, new technology has brought to modern men changes that are equally revolutionary. Increasingly, we are becoming more and more of an automated society, totally dependent on our machines. Indeed, our senses of personal and professional productivity are linked to the availability of our machines. One way to insure this availability is by acquiring a maintenance program which is characterized, in part, by efficient scheduling.

In one way or another, everyone confronts situations that may require proper scheduling. One of the oldest, yet most common problem for industry is how to schedule work loads effectively and how to employ personnel advantageously. In a typical maintenance shop the responsibility of overseeing this process is delegated to the person known as the "dispatcher". Scheduling maintenance work can pose real challenges to the scheduler because he is faced with so many different scheduling alternatives. For instance, given a hypothetical situation in which there are five maintenance work orders, which are mutually exclusive and have the same priority, a scheduler is confronted with one hundred and twenty different scheduling alternatives. Choosing an effective means for processing these work orders is critical for any planner, both in terms of time and money. Very often, the scheduler uses some logical method for making his or her decision instead of just randomly selecting work orders. In many organizations, these methods and procedures are based on past practices which have been accepted over the years.

More often than not, the procedure employed by a scheduler is the First Come First Served (FCFS) method. According to Conway, Maxwell, and Miller (6) "an inherent sense of fair play has elevated the the 'first-come, first served' solution of sequencing problems to an eminence out of all proportion to its basic virtue." Indeed, given certain situations, the FCFS method may not be the most efficient procedure available to a scheduler. The aim of this research is to introduce a feasible alternative to the FCFS method of scheduling maintenance work. This alternative, the Shortest Repair Time (SRT) procedure, may be both practical and advisable given certain situations.

Preliminary Information

Maintenance work orders may be classified as being either corrective or preventive. Corrective maintenance consists of those activities which are carried out when the equipment fails or some measures of performance fall below an acceptable level. Preventive maintenance consists of those activities performed to keep a system in an operable condition. These activities may be performed at the site where the system is located or at some intermediate maintenance facility.

As stated previously, availability has a direct bearing on productivity. A system designer may improve availability by derating highly reliable components and by incorporating redundancy provisions in critical areas. A system user, on the other hand, can only achieve high availability by minimizing downtime. Blanchard (2) defines maintenance downtime as " the total elapsed time required (when the system is not operational) to repair and restore a system to full operating status, and/or to retain a system in that condition."

It is important to note that downtime can be broken down into the following categories: active repair time, logistic time, and administrative time. The duration of downtime is influenced by system design attributes and the maintenance policies of the system user. For example, if a fuse in a production machine blows, it is replaced rather than repaired, whereas if a motor fails, a repairman generally attempts to fix rather than discard the motor. The time it takes to replace a fuse is minimal in comparison to the time required to fix a motor.

Design Attributes

Maintainability, like reliability, is inherent in design. Maintenance can be costly when a system has design characteristics that make the repair task difficult. An apparent correlation exists between the system's serviceability and the time required to maintain it. The system designer's ultimate objective should be to develop and produce a system which can easily be maintained, thereby reducing and simplifying the maintenance task. This objective can only be achieved when maintainability is considered in various phases of system design and development. Benjamin Blanchard (2) emphasizes the importance of system design upon maintenance in Logistics Engineering and Management, pointing out that "a system should be designed such that it can be maintained without large investment of time, cost, or other resources (e.g., personnel, materials, facilities, test equipment) and without adversely affecting the mission of the system."

Maintenance Policies

The importance of a good maintenance policy cannot be overemphasized. It establishes the level, mix, and distribution of the maintenance resource. The problem of planning and implementing an effective policy can be fairly complex, because it involves consideration of many variables and alternatives, not to mention the uncertainties which every planner must face. Some of the most common sources of uncertainty are the demands for corrective maintenance and spare parts procurement lead time. The variables and alternatives that the planner must contemplate include the following factors:

1) Spare parts shortage cost
2) Spare parts inventory holding cost
3) Spare parts procurement time
4) Location of the maintenance department
5) Number, skill level, and cost of personnel
6) Time required to repair a system
7) Criticality of the failed system
8) Scheduling policy
9) Cost of test and repair equipment
10) Repair versus discard

A high degree of interaction exists among the above factors. Clearly, it is impossible to optimize every parameter and every cost benefit; however, the objective is to achieve an optimum balance between maintenance costs and availability. Accomplishment of this goal requires an effective line of communication between the planner and the rest of the organization so that all the necessary information can be easily obtained.

Objective Of The Study

The purpose of this study is to analyze the effect of maintenance scheduling policies on the availability of the equipment in a production facility. The analysis will be performed by simulating the operation of a intermediate maintenance department under two different scheduling scenarios: a first come first serve method and a shortest repair time rule. Simulation modeling has been recognized as an alternative approach for dealing with situations in which the analytical models are not practical. It is one of the most powerful techniques available to a decision maker for experimenting with an existing or proposed system. The language used to construct these models is the General Purpose Simulation Systems (GPSS). Because of its flexibility and simplicity, it is regarded as one of the best simulation languages available.

Summary

Although numerous situations exist in which the FCFS procedure is both a practical and logical scheduling method, one must not consider this procedure as the only option open to the scheduler. The weakness of FCFS is mainly attributable to the fact that this method processes jobs according to the sequence in which they arrive, ignoring all other consideration. This study attempts to introduce a viable alternative for scheduling maintenance work. If used skillfully, the shortest repair time technique can prove a useful tool for increasing the effectiveness of any maintenance department.

CHAPTER II

LITERATURE REVIEW

The frequency and the duration of downtime are highly dependent on a system's reliability and maintainability respectively. Although reliability and maintainability are closely related disciplines, they are, nonetheless, separate. Kuo (18) asserts that "reliability is not a measure of system effectiveness because it does not consider maintainability."

During the last three decades, the field of reliability has witnessed a phenomenal growth. Several books and technical papers pertaining to this subject have been published. Kapur and Lamberson (15) in Reliability in Engineering Design define reliability as "the probability that when operating under stated environmental conditions, the system will perform its intended function adequately for a specified interval of time."

In contrast to the maximum effort in reliability, maintainability has received very little attention until recently, possibly because of the simplistic nature of early equipment. In the last few years with increased system complexity, maintainability has been drawing considerable attention from researchers. Kapur and Lamberson (15) define maintainability as " the probability that a failed system can be made operable in a specified interval of down time". Lately, many papers on maintainability have been published, evidenced by such exhaustive surveys as Sherif's and Smith's (27), which contains 45 reference citations. Retter and Kowalski (26) trace the origins and chart the progress of maintainability, dividing it into three phases: The Beginnings Period (prior to 1966), the Adolescent Period (1966-1978), and The Maturation Period (1978 - present). Their findings identify much of the major research that has contributed to the development of the maintainability discipline.

A variety of technical papers dealing with different aspects of maintainability exists. Unfortunately, a good background in many disciplines is required to evaluate maintainability throughout the entire system's life cycle. The studies available, however, address only a particular phase of the life cycle. Thus, they are somewhat limited in scope. Kavanav, Ancker, and Schneidewind (16) in the Industrial Engineering Handbook state that "maintainability analysis consists of identifying maintainability requirements and selecting methods for meeting these requirements." They outline the following activities to be involved in this analysis:

- Describing maintainability tasks
- Selecting repair policy
- Establishing repair time for components, sub-systems, and systems;
- Developing equipment test procedures
- Developing repair procedures
- Developing calibration and adjustment procedures
- Developing methods for localizing malfunctions
- Establishing accessibility requirements
- Establishing test equipment and repair tool requirements
- Establishing technical manual requirements
- Establishing spare parts requirements
- Identifying number and types of maintenance personnel and their training requirements.

Several analytical techniques are used to analyze maintainability. These include queuing theory and Markov processes. In addition, simulation is emerging as a powerful tool for investigating maintainability. Many of the methods encountered in the literature incorporate the use of Markov processes for analyzing maintainability.

Markov Process

Miller and Braff (23) discuss the application of the 3-state Markov-chain model to study the relationship between the failure rate and technician visitation rate. Their major assumption is that "prior to failure a system will give an observable indication that it is about to fail." Gertsbakh's study (11) indicates that "the semi-Markov process can be used to give a satisfactory description of a broad circle of optimal preventive maintenance models." In "A Survey on Algorithmic Aspects in Preventive Maintenance," Lau (20) employs a logic similar to the aforementioned researchers indicating that "the dynamic behavior of a system can be described as a Markov process."

Queueing

A large number of papers in the field of operations research considers the use of analytical queueing models to describe the behavior of a maintained system. Locks (21) discusses the application of queueing theory for analyzing maintenance activities. His theory is as follows:

> Maintainability and availability analysis for a repairable system is related to queuing. It can be compared to the problem of determining the occupancy, arrival and service rates in a queue if the service performed is repair, the servers are maintenance crews or repairmen, and the customers or patrons are the machines, components, or systems which are repaired at random times, called failures.

Kelly and Harris (17) in <u>Management of Industrial Maintenance</u> advance a theory similar to Lock's; however, they warn of a serious shortcoming of queueing theory--that of not being sufficiently flexible to reflect the complexity of repair situations. Furthermore, Cook and

Russell (7) state that "the occasions for applying queueing theory are numerous, but there are also many practical situations where this approach is irrelevant."

Simulation

Simulation is a uniquely practical approach for analyzing maintainability. The literature contains diverse applications of simulation, one of which includes maintainability analyses. Unfortunately, few of the studies on maintainability utilize simulation.

Kelly and Harris (17) conclude that "simulation is a technique which is sufficiently flexible to model the complexity of maintenance situations." Widawsky (28) points out that simulation is an effective tool for analyzing reliability and maintainability parameters and has far-reaching applicability for efficient analyses. Particularly, he praises its ease of construction, its power, and its adaptability. He employs simulation to evaluate the effect of establishing repair priorities on the availability of the system. Kuo (19) utilizes an approach similar to Widawsky's in his article, "Maintainability for a Manufacturing Process," which investigates the effect of various maintenance policies on machine utilization in a complex manufacturing system.

Scheduling

In the literature on operations research, the term "scheduling" is associated with the job shop sequencing problem. The literature contains a variety of models, ranging from simple job shop scheduling problems, such as determining the sequence of n jobs to be processed by a single machine, to the most difficult scenarios in which n jobs are to be processed by m machines. Panwalkar and Iskander (25) in their article "A Survey of Scheduling Rules" list over one hundred scheduling rules and provide several cross-references for each procedure. Though the literature available reviews a number of scheduling techniques, this study centers on only one of these many methods, the shortest processing time (SPT).

Early work in job shop scheduling has been done by Conway, Baker and Dzielinski. In a series of studies, Conway et al. (4,5,6) evaluated various types of scheduling procedures for a job shop, concluding that when mean flow time is the criterion of performance, then SPT will minimize the average flow time. Baker and Dzielinski (1) reported findings similar to Conway's. Other researchers, notably, Johnson and Montgomery (14) insist that "sequencing the jobs according to the SPT rule results in a minimum mean flow time schedule." All of these researchers note, however, that the SPT method does have its drawbacks: namely, that low priority work orders requiring long repair times may wait an inordinate amount of time before servicing.

Although the activities of the job shop differ from those of the maintenance department, many similarities in the scheduling process exist. Johnson and Montgomery (14) assert that "while we traditionally think of the job shop as a machine shop, the job shop process is the underlying model for a considerable number of operational systems such as maintenance activities, construction operations, and so on." There is little in the literature supporting Johnson's and Montgomery's recommendation for applying SPT to maintenance scheduling. One study by Louis A. Martin-Vega (22), "SPT, Data Analysis, and a Bit of Common Sense in Bus Maintenance Operation: A Case Study," does utilize SPT as a scheduling criterion. Vega's findings conclude that SPT minimizes flow time.

Repair Time

All of the methods discussed earlier have little value without proper input data. Many of the problems in the field of maintainability involve probabilistic variables (17). Dhillon and Reiche (10) argue that "probability theory is the backbone of reliability and maintainability engineering." A number of well-known probability distributions can be used to describe the frequency of occurrence of downtime and repair times. These include the normal, lognormal, exponential, weibull, and gamma distributions. One must carefully analyze the data in order to determine the distribution that is most appropriate. Kapur and Lamberson (15) propose, "the best way to select a distribution model would be to describe the physical phenomena producing the failure and then use these phenomena as a logical basis for derivation of a distribution model." The exponential distribution is used frequently for describing time-to-failure of systems where the failure rate is constant. Goldman and Slattery (12) suggest that "the distribution most commonly used to describe the actual frequencies of occurrence of downtime are negative exponential and log-normal."

Repair time is a function of failure type and maintenance policies. Goldman and Slattery (12) state that the various activities performed by maintenance technicians suggest "both a large number of relatively short-time repair periods and a smaller number of long periods." Locks (21) argues that the vast amount of empirical evidence supports the belief that "the time required to perform a variety of tasks of the same type but of different levels of difficulty is lognormally distributed." Blanchard's book on logistics engineering (2) has a section devoted to repair time distributions. He theorizes that the underlying distribution for repair times will usually be either normal or lognormal; nevertheless, some of the literature on this subject indicates otherwise. For example, Kuo (19) uses exponential distribution to describe the pattern of service time.

Today, more emphasis is being given to maintainability concepts. For example, the <u>IEEE Transactions on Reliability</u> (a journal) devotes one issue to USAF reliability and maintainability initiatives. Increased system complexities have resulted in a need for a rapid way of detecting and isolating failures. Currently, a major area of interest among maintainability researchers centers around testability philosophy (26). According to Dhilon and Reich (10), system users have recently demanded from the manufacturers better procedures to improve the process of identifying and isolating failures. Progress in maintenance activities is also related to technological progress in computer hardware and software development. It is anticipated that artificial intelligence techniques will have a direct impact on maintenance activities. In his article, "Smarter Maintenance with Expert Systems," Dallimonti (9) states:

> A relatively new class of computer software offers the potential for extending the capabilities of maintenance personnel. By drawing on the knowledge and thought processes of experienced people, these expert systems emulate their ability to diagnose problems and recommend corrective procedures. Although still in its infancy, the technology is being proved with practical applications.

The literature does not reveal any new theories or methods in maintainability. The methods and techniques appear to be quite well known. What is new in the literature are the applications of these old techniques to modern systems, possibly using powerful modern computer systems to solve the problems.

CHAPTER III

THE MODEL

Since downtime costs can be very expensive, greater emphasis has recently been placed on the importance of reducing the length of time that the system is unavailable. Studies of manufacturing processes indicate that scheduling affects the length of time that a job stays in the plant. Furthermore, many researchers have reported that the utilization of the shortest processing time procedure reduces average flow time. One hypothesis worth examining is whether or not this same concept which works for the manufacturing plant will also apply to maintenance. In order to ascertain whether this hypothesis is correct, models here are developed which represent the operation of a maintenance department under two scheduling disciplines. This makes it possible for one to draw inferences about the effectiveness of the SRT procedure without actually experimenting with a real system.

Blanchard and Fabrycky (3) have praised the usefulness of modeling when introducing a new system or for analyzing an already existing one. Obviously, if a model is to be useful, it must adequately represent the behavior of the real system. It is critical for the modeler to understand the logical relationship between the elements of the system and the interaction of specific variables. Almost always the success of a simulation analysis will depend on how accurately the modeler duplicates the entities, attributes, and activities of the real system.

Description of Maintenance Department

The hypothetical maintenance shop described here will be employed in each simulation model. This shop is responsible for maintaining all the production machines in a manufacturing company. Naturally, the availability of these machines is contingent upon the effectiveness of this department.

When a mechanical or electrical breakdown occurs, a work request is filed with the maintenance department. The work order contains various pieces of information, including the symptoms of failure and a notation concerning the urgency in which the order needs to be processed (See Figure 1). Once the scheduler receives the work request, he must make the following decisions. First, which priority should be assigned to the work request; second, what position should the job occupy in the queue. When the scheduler's task is completed, an available repairman does the needed repair work. There are six repairmen on duty at all times.

MAINTENANCE REQUEST No.

Mt'ce Code		Plant Number
2	3	7310

Plant Description 5 Ton Crane — Date 18/9/73

Plant Location Foundry — Time 10.15 a.m.

Cost Centre	A/C Number
108	274

Work Requested by J. Lead — When Required Urgent

Defect/Work Required

Crane will not operate

JOB PRIORITY			
Emergency	1	✓	Tick One Box
M/c Running	2		
Not Applicable	3		

Cause

Overload tripped
Hoist button jammed in with
gum. Top limit switch damaged

Cause			
Wear & Tear	4		Tick One Box
Accident, Misuse, Neglect	5	✓	
Component Failure	6		
Job Report	7		
Not Applicable	8		

Action Taken

Limit switch replaced.
Pendant control cleaned up,
overload reset and crane tested
O.K.

Repaired, Manufactured	9	✓	Tick Box
Replaced	10	✓	
Inspected, Adjusted	11		
Modified	12		
Relocated, Installed New	13		
Not Applicable	14		

Trade Code	Tradesman's Signature	Date	Time On	Time Off	Total Hours Hrs.	Total Hours Mins.	Clock Number
4 2 2	E Sparke	18/9	10.30	11.15	—	45	1 0 5 5
4 3 6	W. Smith	18/9	10.45	11.15	—	30	1 1 3 2

Maintenance Foreman's Signature J. Seward — Date Completed 18/9/73 — Week Number 42

For Office Use

Check history record on limit
switch maintenance. [initials]

	Hours	Mins.
Total Repair Time	1	15
Down Time	1	—

Figure 1. Maintenance-request form.

Source: A.S. Corder, Maintenance Management Technique, (New York: McGraw-Hill, 1976), p.57.

Model Assumptions

In most simulation models, it is usually not practical to consider every fine detail associated with the system under study. Certainly, the more that is known about the system in terms of its components, attributes, and relationships, the more exact the model will be; however, as the complexity of the model increases, so too does the cost. In order to simplify the modeling task somewhat and focus on the effect of scheduling, the following assumptions have been made:

1.) Preempting a job in progress causes no loss of time--that is, the repair can still be completed later within the time originally estimated for the job.

2.) The nature of repair is such that the job can be done by a single repair man.

3.) All the mechanics and electricians have equal capabilities in their respective shops.

4.) The work order arrival process is exponentially distributed.

5.) Each repairman has his own space and tools, thereby eliminating his waiting for equipment.

6.) Spare parts are always available upon demand.

7.) The number of repairmen remains constant.

8.) There exists some variation between estimated and actual repair time.

Features

Though the models contain many features, most of these are programming details and are not discussed here. The purpose of the models is to represent the activities of a real maintenance department. What is of interest to this research is the effectiveness of the shortest repair time scheduling procedure. In order to look at this, two models have been created whose basic structures are very similar. The only difference in the models is that one uses the first come first served method to schedule work orders and the other employs the shortest repair time rule. The following features provide the reader insight into the scheduling operation of these models.

Maintenance Scheduling

Work orders arrive in the maintenance department dynamically over a period of time. Maintenance scheduling is concerned with arranging the sequence in which work orders receive service. The scheduler should take into account a number of consideration in maintenance scheduling. First, when there is more than one work order he must consider the urgency of the request. Second, the scheduler must determine the sequence in which the work orders within each priority level are selected for service.

Priority Level

Each maintenance facility varies in the nature of service, the crew size, and its test equipment. Nonetheless, they all have a limited capacity for service. Naturally, it is impossible to provide immediate service whenever the demand for service exceeds the available capacity for that service. The question then becomes, "Which work order should be processed next?" The answer, of course, varies, depending on the priority policies of the firm and the scheduling method used.

Regardless of the scheduling method employed, the first and the foremost consideration with which the scheduler must deal is the priority of the work order. In many instances, the maintenance work orders are not equally important. Normally, a priority level is assigned to each work order, determining the expediency with which the repair must be accomplished. Preventive maintenance is usually designated as low priority work, whereas corrective maintenance is usually assigned a high priority level. Priority levels fall into one of the following categories:

1. Preemptive priorities
2. Nonpreemptive priorities

The main difference between these two categories is that a preemptive priority work order can displace a lower priority job already under repair.

Sequencing

When there is no waiting line or queue, it is unimportant which scheduling method is employed. When there are several work orders vying for attention, the scheduling method used becomes an important area of concern. Sequencing affects that portion of downtime during which work orders wait for service. Therefore, the goal of the scheduler is to minimize the average time that a work order waits for service.

A variety of methods may be employed in determining this order, two of which are the first come first serve method and the shortest repair time procedure.

FCFS

The first come first served method is, perhaps, the simplest and most common approach used for maintenance scheduling. Using this technique, the scheduler processes jobs in the order of their arrival. The only information the scheduler needs is the time when the work order arrives. Figure 2 illustrates this concept. When there is little variation in the duration of repair times of the work orders, this method can prove to be most effective; however, when the jobs require differing amounts of repair time, this procedure may not be the most efficient. For instance, jobs which require a long repair time block servicing of jobs which require only a short repair time, thereby increasing the average waiting time.

SRT

The shortest repair time approach is more complex than the first come first serve method. Jobs waiting to be processed are selected on the basis of the time required for servicing. The job having the shortest repair time receives service first. Figure 3 graphically illustrates this procedure. As previously stated, SRT has a major weakness, that of ignoring work orders with long repair times and low priorities. This problem can be easily rectified by imposing a limit on the length of time that a job in a given queue waits for service. once this limit is reached, the work order is reassigned a higher priority index and moved to the proper queue.

The steps the scheduler follows when estimating repair time vary, depending on whether the work request

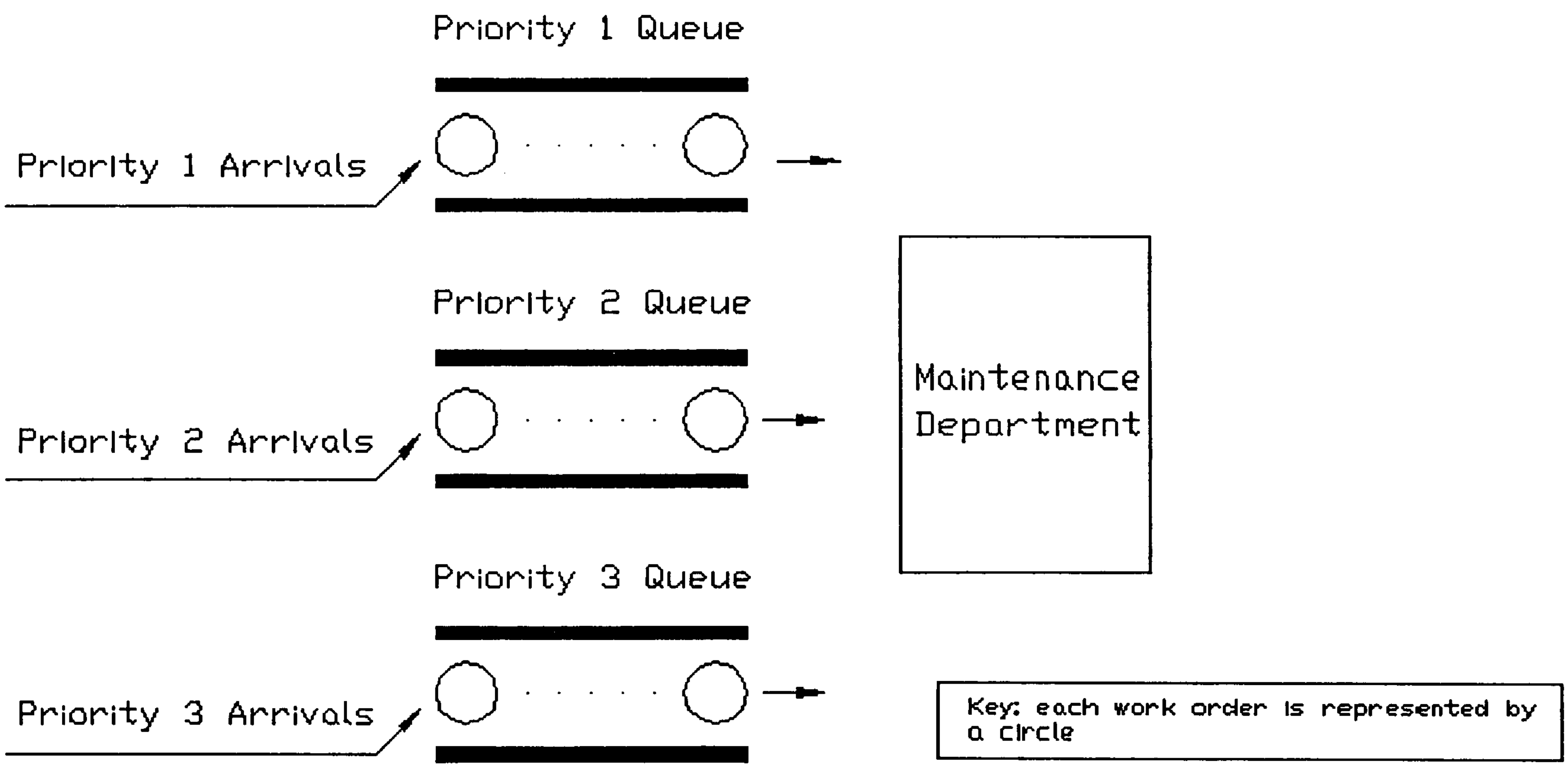

Figure 2. Graphical Representation of FCFS Scheduling for Maintenance Work in A Multiple Level Priority System.

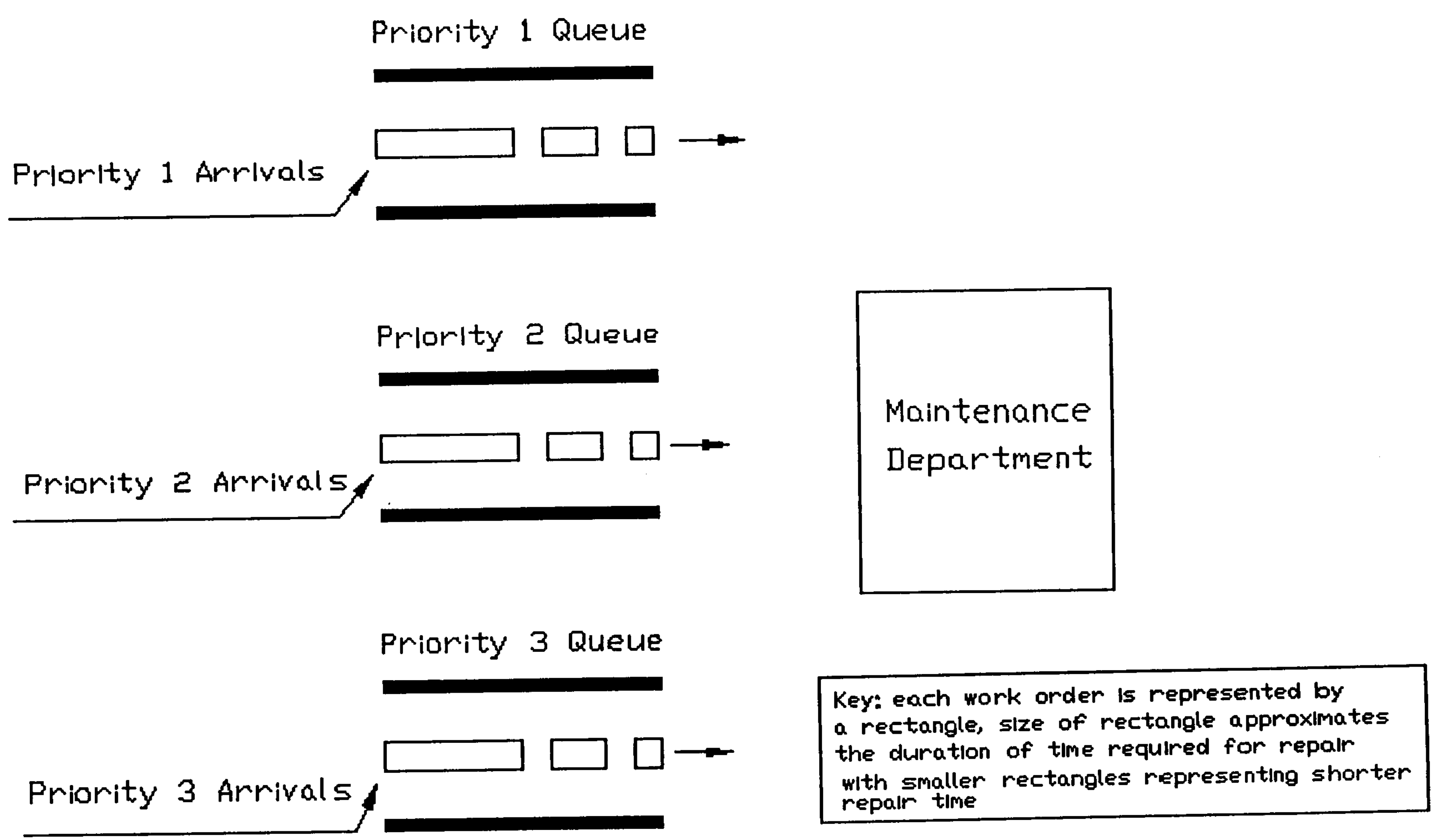

Figure 3. Graphical Representation of SRT Scheduling for Maintenance Work in A Multiple Level Priority System.

requires preventive or corrective maintenance. If the job requires preventive maintenance, this estimation may be determined readily by consulting the user manual and by taking into account the past history of the system or similar systems. Generally, the time needed for preventive maintenance can easily be determined, and little variation exists between time estimated for repair and the actual repair time.

Estimating repair time for corrective maintenance is a more difficult task than that needed for preventive maintenance. If corrective maintenance is required, then the scheduler must estimate the repair time by considering symptoms of failure. Based on these symptoms, the scheduler determines the type of repairs needed.

Although the nature of the repair needed varies from one work order to another, nonetheless, there is a series of steps which must be followed if the machine is to be restored to full operational status. Benjamin Blanchard outlines these necessary steps in his diagram of the corrective maintenance cycle (See Figure 4). It is the task of the scheduler to break the maintenance job into its basic steps and assign time values to each activity. Therefore the scheduler must have sufficient knowledge of the problems indicated by the symptoms of failure, as well as be able to estimate properly the amount of time

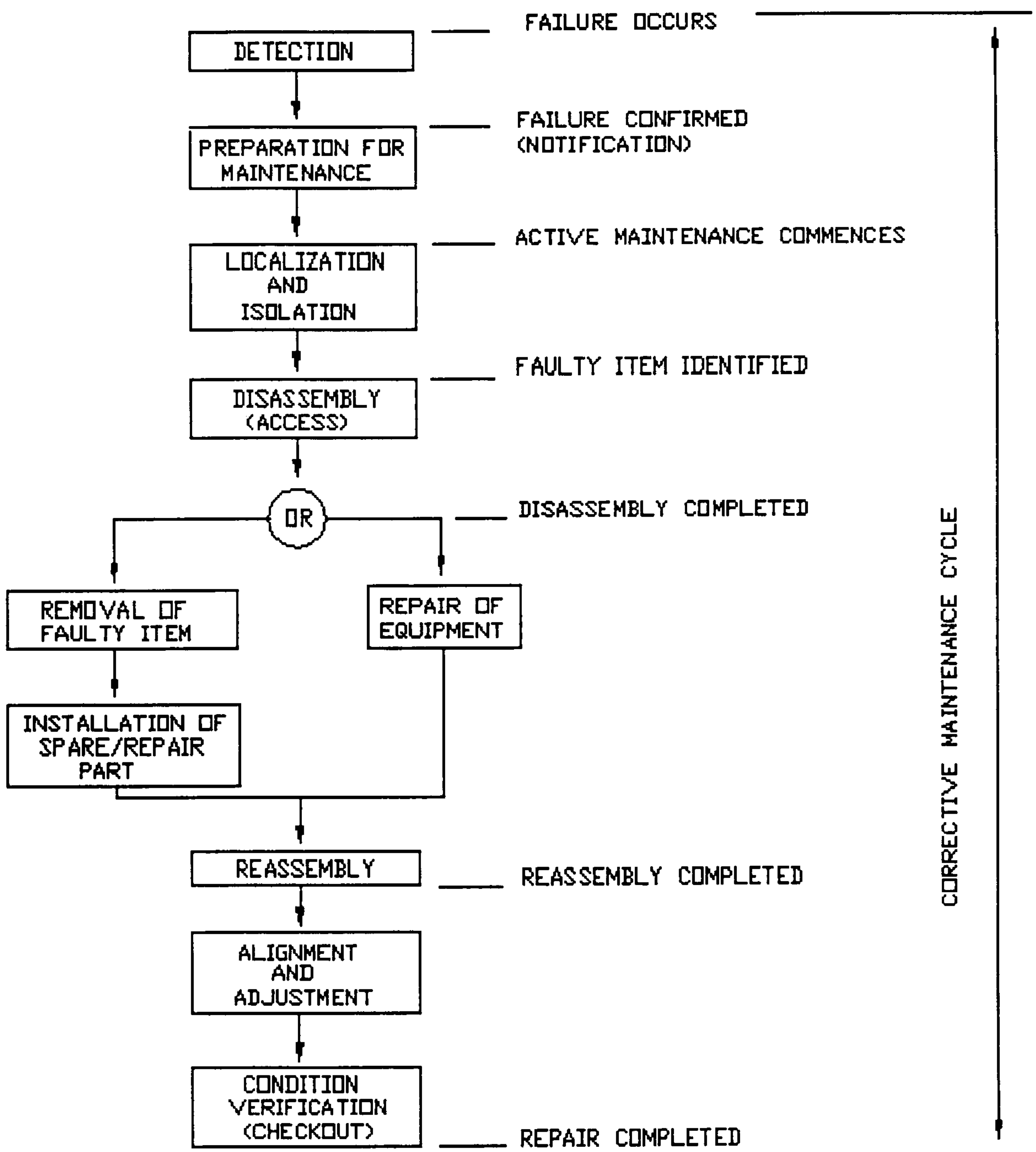

Figure 4. Corrective Maintenance Cycle.

Source: Benjamin S. Blanchard, Logistic Engineering and Management, (Englewood Clife: Prentice-Hall, 1986), P.35.

required for each step of the corrective maintenance procedure.

It is important to note that there is some variation between the actual time required for corrective maintenance and the time which the scheduler has estimated. The scheduler's estimation is based on the symptoms of failure, but symptoms of failure can sometimes be misleading; the actual repair work may take more time or less time than the scheduler first assumes.

Approach Taken in building a Model

In order to determine which method, the SRT or the FCFS, is superior the following models have been developed. These models are composed of two major sections. The first section simulates the arrival, scheduling, and repair of mechanical work orders. The second section simulates the arrival, scheduling, and repair of electrical work orders. Further, each major section is divided into four segments as shown in Table 1.

FCFS Model

The GPSS coding for this model is shown in Appendix A. Because both sections utilize the same logic, only the mechanical section needs to be explained in detail. The following discussion describes the processing of mechanical work orders.

Table 1. Summary: Segments of Simulation Models.

Segment	Block Number	Purpose
1	1-7	Represents the repairmen who then waits to be assigned jobs by the scheduler.
2	15-21	Represents work order arrival.
3	29-51	Represents the activities of the scheduler.
4	52-196	Represent the activities of the repairmen.

Segment 1

Block 1 generates only one transaction during the simulation run. This transaction moves to the next block where its parameter 1 is assigned a value of 1, designating this transaction as a mechanical repairman. The transaction proceeds to the next block where three copies of the transactions are made. Each copy represents a repairman. The transaction then continues to block 4, where it is removed from the system. Next, the copies move to block 7 where the parameter 7 of these transactions are assigned numbers 1-3 respectively. They then proceed to the LINK block where they wait until the scheduler gives them an assignment.

Segment 2

This segment creates arriving work orders. The first block generates transactions representing work orders at some specified rate. The transaction then proceeds to the next block which is used to gather statistics on the waiting experienced by the work order. Next, the transaction moves to three ASSIGN blocks where parameters 1-3 of the transaction are given values representing the type, priority, and nature of the failure. The transaction then proceeds to the LINK block, where it waits for the scheduler to process it.

Segment 3

This segment represents the activities of the scheduler. Whenever a new work order arrives, LOGIC SWITCH 40 is set causing the transaction representing the scheduler to move through the segment which contains the scheduling logic. The program performs the following logical steps:

1.) places the transaction representing the work order in the proper queue (user chains 1-3) on the basis of FCFS

2.) informs an available repairman that there is work

3.) preempts jobs already under repair when a higher priority work order needs servicing and there is no available repairman

Segment 4

This segment simulates the activities of the repairmen. Both the repairmen and work order transactions move through this section. The first part of the segment is composed of a series of tests which determine which work order is to receive service first and which facility will be used. Once these decisions are made, the repairman transaction is directed to the proper block where it unlinks a work order. Next, it waits at the GATE block until the work order transaction sets the LOGIC SWITCH corresponding to that repairman (LOGIC SWITCHES 1-3 control the flow of transactions representing repairmen 1-3 respectively).

At this point the work order transaction starts moving through a series of blocks which first tabulate the amount of time a work order waits, and then transfers the estimated repair time from MATRIX SAVEVALUE 1 to the repairmen savevalue. SAVEVALUE 42-44 are associated with repairman 1-3 respectively. The MATRIX SAVEVALUE 1 contains the estimated repair time for each work order. It has two rows and six columns. The first row contains the repair time for different types of mechanical failures. Before its termination, the work order transaction sets the logic switch, allowing the repairman transaction to continue to the next block.

The repairman transaction next seizes a facility. There are three facilities in this segment, 1-3. A transaction can only use the facility that has a value which is the same as its parameter 7. For example, parameter 7 of the transaction representing repairman 1 has a value of 1, therefore it can only use facility 1. The time a transaction spends in a facility is decided by using the estimated repair time as the A operand of the Advance block and Fvariable 1 as the B operand. The B operand is used to show the variation between the estimated and actual repair times. As soon as the repairman is done with his job, he checks to see if there is any more work. If there is none, he goes to user chain 16 where he waits for another call.

SRT Model

The GPSS coding for this model is shown in Appendix B. Operation of this model is very similar to that of FCFS model; however, the following differences exist. First, the transaction representing the work order has four parameters instead of three. The first three parameters have the same information as contained in model 1. Parameter 4 represents the repair time. Second, work orders are merged into user chains 1-3 according to parameter 4. Thus, a transaction with the smallest repair time would occupy the first position in the user chain.

CHAPTER IV

RESULTS

Although the scenarios used in this study are scaled down versions of real world situations, they do exemplify valid concerns about the effects of differing scheduling procedures. A total of forty different simulation runs were made. Statistics were collected on repairmen utilization, waiting time, downtime, and maintenance shop congestion. Before the results of these simulations can be considered as indicators of the superiority of one scheduling procedure over another, the simulation models had to undergo specific tests.

Verification and Validation

Simulation results mean nothing if the model has not been verified and validated. Once a simulation program has been developed, the next logical step is to verify it. This verification process insures that the model performs as intended. After verification has been completed, the model then can be validated. Validation is the process of determining whether the simulation model is an accurate representation of the system under study.

Verification

One means of verifying a simulation program is to perform a manual simulation of the system under study and then to compare the results with those produced by the computer program. The presence of randomness in the models simulated made detection of errors difficult; therefore, the models were modified so that random elements were eliminated. This simplification is often necessary when one utilizes manual simulation as a means of checking a computer simulation program. The results of this verification process proved that the models were performing as intended: the average waiting times of the manual simulations were the same as those given by the computer. In addition to using the manual simulation, the model was further verified by extensive tracing of the GPSS code.

Validation

Generally, the validation of a simulation model is accomplished by checking the resemblance between the model's output and that of an actual system's data. A number of statistical tests exist that can aid the researcher in making such a comparison. Unfortunately, in this study no access to real maintenance system data was available. Therefore, the strategy chosen to check the validity of the models was to create scenarios in which, if the models were accurate representations of a real maintenance system, they would render the same output. In the first scenario, the demand for maintenance was deliberately set low, so that at any given time, no more than one work order awaited service. In the second scenario, it was assumed that all the work orders had the same repair time. Both models in each scenario produced the same results, thus enhancing the credibility of the simulation program.

Measures of Performance

In order to determine which method, SRT or FCFS, is superior, waiting time, downtime, and maintenance shop congestion for each model were simulated. Because waiting time is such an integral part of downtime, any change which reduces that portion of time will have a positive impact on the availability of production machines. This study also chose to employ shop congestion as an important measurement of performance. Since a congested maintenance shop implies that the service is poor, any scheduling procedure which can reduce congestion is preferable to one which cannot.

Length of Simulation Runs

One of the most important determinations a modeler or analyst must make when simulating a stochastic process is the length of the simulation run. Clearly, if the model is executed for a short period of time, the random nature of the process might render misleading results. Long simulation runs, however, can prove costly. The strategy employed in this study was to vary the lengths of the simulation runs. Increments of time were added and the average waiting time was then observed. Once the increments produced no significant change, then that time value, 180 days, was settled on as the time frame for simulation runs (See Figures 5,6). After establishing this period as the time frame, the next logical step was to determine to what extent the output varied when different sequences of random numbers were used. Therefore, a total of five simulation runs of each model were made in which different sequences of random numbers were applied. The means and the standard deviations for these runs were calculated and are summarized in Table 2. As can be seen in Table 2 some fluctuation occurs in the average waiting times for these runs; however, this is not surprising considering the extent to which the random variables were used throughout the models.

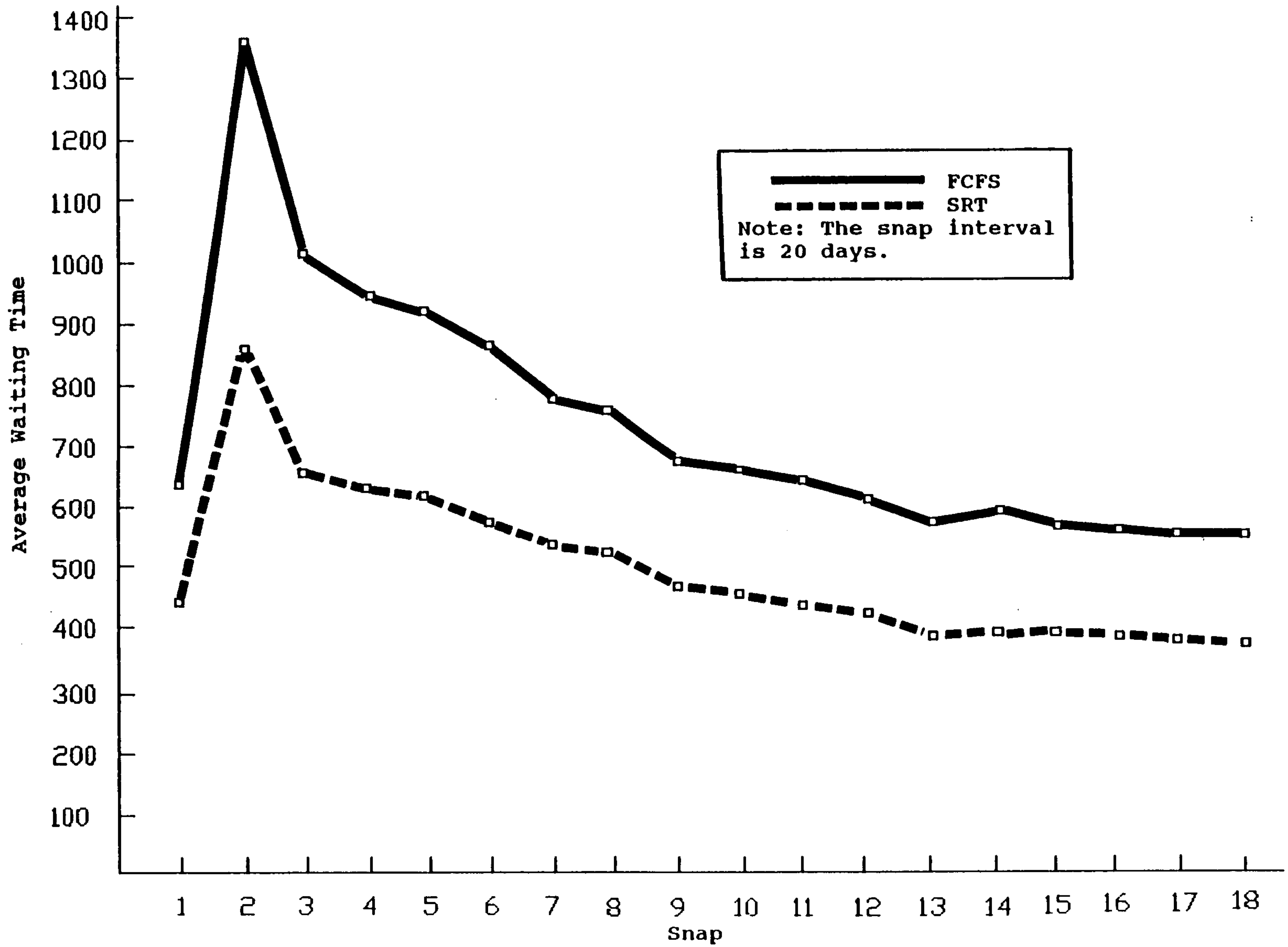

Figure 5. Average waiting Time of Mechanical Work Order as Time Increments Are Applied.

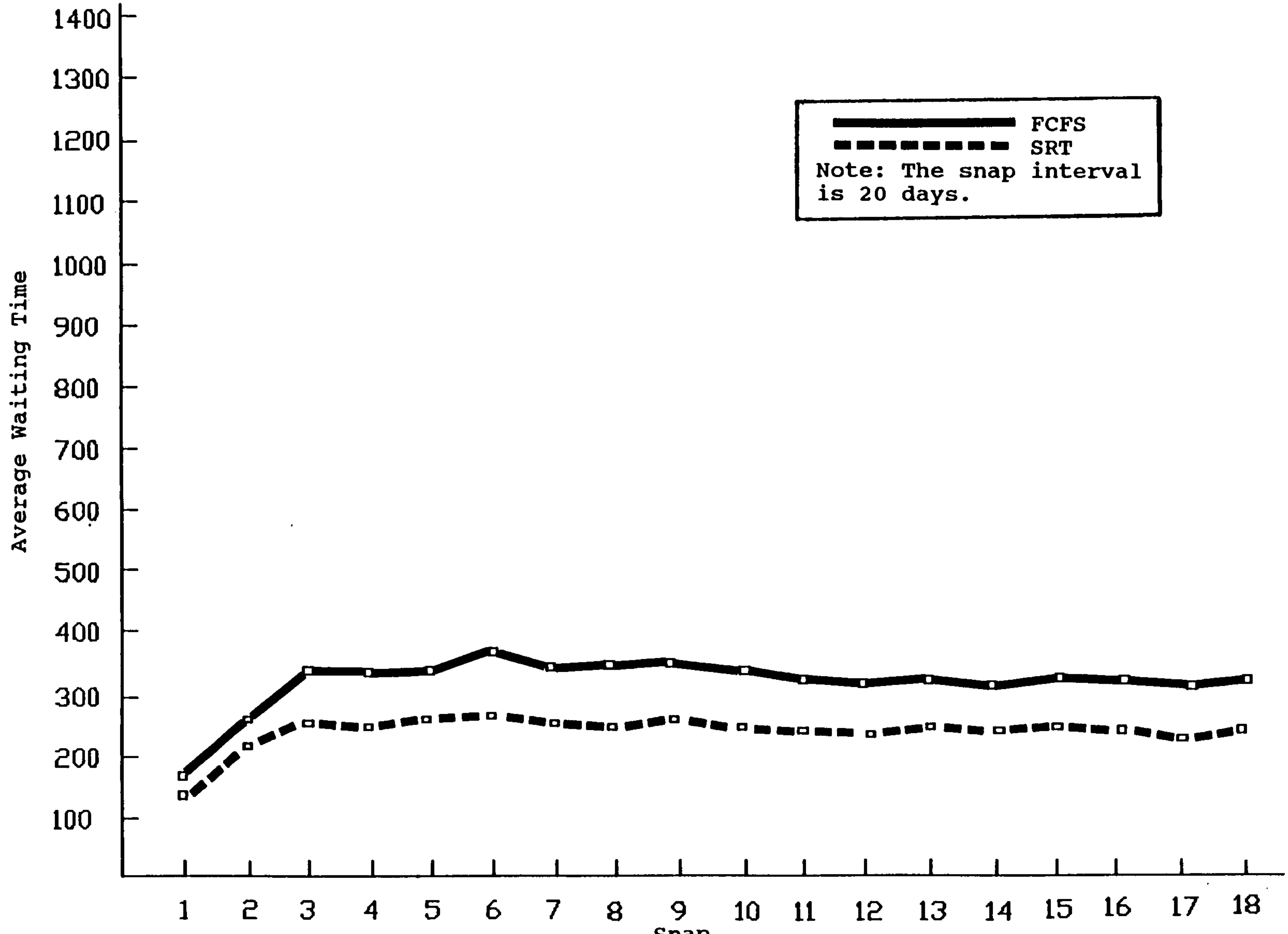

Figure 6. Average waiting Time of Electrical Work Order as Time Increments Are Applied.

Table 2. Average Waiting Time Statistics for Five Different Sequence of Random Number.

Scheduling Procedure	Type of Failure	Mean	Standard Deviation
MSRT	Mechanical	296.2	25.7
MSRT	Electrical	225.2	42.5
FCFS	Mechanical	394.6	47.6
FCFS	Electrical	277.6	62.2

Model Input

The basic information needed to simulate a typical maintenance department includes input which describes the arrival rates, the service times, and the priorities of the work requests. When these input parameters were varied, a great number of possible combinations existed--more than this study could adequately investigate. Thus, it was decided only to vary the arrival rates.

Arrival Rate

Arrival rates, decreasing from heavy to light, were simulated in order to ascertain the effectiveness of SRT under differing work loads. The mean arrival rates of mechanical and electrical work orders were different in all the simulation models used in this study.

Service Time

The estimated repair times for both mechanical and electrical failures were divided into five categories, ranging from A to E. The relative frequencies and their corresponding service times are shown in Tables 3-4. The actual repair time for each type of failure was calculated by adding or subtracting a value from a random number stream to the estimated repair time. The random number stream was used to depict the variation between the actual and the estimated repair times. In

Table 3. Estimated Repair Times for Mechanical Failure

Category of Failure	Relative Frequency	Estimate Service Time (Minutes)
A	.22	30
B	.26	45
C	.30	100
D	.12	200
E	.10	500

Table 4. Estimated Repair Time for Electrical Failure.

Category of Failure	Relative Frequency	Estimated Service Time (Minutes)
A	.20	20
B	.30	35
C	.30	90
D	.14	250
E	.06	550

the case of electrical failures, it was assumed a variation existed which was within 30% of the estimated repair time, whereas for mechanical failures, this variation was assumed to be only 15%.

Work Order Priority

Each time a machine fails, a priority level was assigned to it which was relative to its importance to production. High priority work orders comprised 5% of the total arrivals; middle priority work orders made up 52% of arrivals; and low priority orders were 43% of arrivals. These values remained the same throughout the study.

Model Output

At the end of each simulation run, the GPSS processor furnished extensive data about the model's performance, including statistics on facilities and queues. Facility statistics provided information about the average utilization of each facility and the total number of entries to it. Queue statistics, given for each queue in the system, included the total number of entries, the average waiting time, and the maximum content within the queue. The following tables contain the results of sixteen simulation runs of SRT and FCFS models:

Table 5 -- Mechanical Work Order Queue Statistics

Table 6 -- Electrical Work Order Queue Statistics

Table 7 -- Average Downtime for Mechanical Equipment

Table 8 -- Average Downtime for Electrical Equipment

In the first run of each model, as seen in Tables 3-6, the time between arrivals was deliberately set so that repairmen were busy at least 97% of the time. Increments of time were gradually applied until repairmen were busy no more than 44% of the time. The results indicated that SRT reduced downtime and queue content. Note, however, that as the time between arrivals was increased, the effectiveness of the SRT procedure was decreased.

In chapter III a deficiency of the SRT procedure was discussed. This deficiency was a major area of concern to this study. In order to determine if individual jobs that had long repair times and low priorities were experiencing any lengthy delays, the waiting times were tabulated. Indeed, the results indicated that some individual jobs were experiencing long delays, confirming what many researchers have previously cited as an SRT weakness. Furthermore, the extent of delays was dependent on the arrival rates of the maintenance orders. For example, in the first

Table 5. Mechanical Work Order Queue Statistics.

Procedure	Time Between Arrivals (Minutes)	Average Waiting Time (Minutes)	Average Content	Repairmen Utilization
FCFS	43	1291.06	30.58	.97
SRT	43	441.09	10.45	.97
FCFS	46	442.72	9.83	.92
SRT	46	213.81	4.72	.92
FCFS	48	303.61	6.42	.89
SRT	48	169.81	3.59	.88
FCFS	50	151.96	3.07	.85
SRT	50	106.74	2.16	.85
FCFS	53	112.97	2.15	.80
SRT	53	81.94	1.56	.80
FCFS	68	42.81	.63	.63
SRT	68	34.66	.51	.62
FCFS	83	29.65	.36	.51
SRT	83	25.83	.31	.51
FCFS	98	12.54	.13	.44
SRT	98	11.58	.12	.44

Table 6. Electrical Work Order Queue Statistics.

Procedure	Time Between Arrivals (Minutes)	Average Waiting Time (Minutes)	Average content	Repairmen Utilization
FCFS	39	898.51	23.05	.96
SRT	39	346.12	8.88	.96
FCFS	42	349.15	8.29	.90
SRT	42	203.64	4.83	.89
FCFS	44	189.35	4.28	.84
SRT	44	142.30	3.22	.85
FCFS	46	204.70	4.47	.82
SRT	46	146.07	3.19	.82
FCFS	49	93.11	1.88	.76
SRT	49	68.28	1.38	.76
FCFS	64	35.28	.54	.59
SRT	64	29.34	.45	.59
FCFS	79	16.32	.20	.47
SRT	79	14.93	.19	.47
FCFS	94	12.81	.13	.41
SRT	94	11.26	.12	.41

Table 7. Average Downtime Statistics for Mechanical Equipment.

Procedure	Time Between Arrivals (Minutes)	Average Time Spent in the system (Minutes)	Standard Deviation
FCFS	43	1356.51	2142
SRT	43	530.63	1384
FCFS	46	569.63	896
SRT	46	339.12	653
FCFS	48	429.90	532
SRT	48	295.21	415
FCFS	50	277.85	322
SRT	50	232.80	309
FCFS	53	239.61	275
SRT	53	208.28	263
FCFS	68	170.25	194.31
SRT	68	160.92	189.81
FCFS	83	157.79	180.94
SRT	83	153.65	180.75
FCFS	98	140.31	163.31
SRT	98	138.77	159.38

Table 8. Average Downtime Statistics for Electrical Equipment.

Procedure	Time Between Arrivals (Minutes)	Average time Spent in the system (Minutes)	Standard Deviation
FCFS	39	1012.22	1527
SRT	39	459.32	1295
FCFS	42	463.01	588
SRT	42	316.62	476
FCFS	44	301.68	383
SRT	44	255.23	398
FCFS	46	313.74	388
SRT	46	257.70	348
FCFS	49	206.72	253.25
SRT	49	182.24	229.19
FCFS	64	150.16	182.19
SRT	64	143.95	181.94
FCFS	79	130.46	164.31
SRT	79	129.14	164.25
FCFS	94	132.05	169.31
SRT	94	129.66	167.13

scenario in which the time between arrivals was such that the repairmen were busy 97% of time (See Table 5), 47 work orders had to wait 200 hours or more before receiving service. In order to rectify this problem of individual work orders experiencing lengthy delays, the SRT model was modified: a limit was imposed on the amount of time a work order could wait for service. For work orders designated as priority 3, this limit was 960 minutes, whereas for work orders designated as as priority 2, the limit was 480 minutes. This new model the Modified Shortest Repair Time (MSRT), assigned the work order a higher priority once it had reached its time limit.

The results of the simulation runs using MSRT scheduling procedure are summarized in the the following tables:

Table 9 -- Mechanical Work Order Queue Statistics

Table 10 -- Electrical Work Order Queue Statistics

Table 11 -- Average Downtime for Mechanical Equipment

Table 12 -- Average Downtime for Electrical Equipment

The simulation results indicated that when MSRT was employed instead of SRT, the average waiting time was increased; however, no individual job experienced a long delay. As was the case with SRT, the performance of MSRT was dependent on whether or not the system was busy.

Table 9. Queue Statistics for Mechanical Work Orders.

Procedure	Time Between Arrivals (Minutes)	Average Waiting Time (Minutes)	Average Content	Repairmen Utilization
FCFS	43	1291.06	30.56	.97
MSRT	43	803.66	19.03	.97
FCFS	46	444.72	9.83	.92
MSRT	46	297.49	6.57	.92
FCFS	48	303.61	6.42	.89
MSRT	48	228.25	4.82	.88
FCFS	50	151.96	3.07	.85
MSRT	50	144.99	2.93	.85
FCFS	53	112.97	2.15	.80
MSRT	53	90.96	1.73	.80
FCFS	68	42.81	.63	.63
MSRT	68	34.90	.51	.62
FCFS	83	29.65	.36	.51
MSRT	83	25.86	.31	.51
FCFS	98	12.54	.13	.44
MSRT	98	11.58	.12	.44

Table 10. Queue Statistics for Electrical Work Orders.

Procedure	Time Between Arrivals (Minutes)	Average Waiting time (Minutes)	Average Content	Repairmen Utilization
FCFS	39	898.51	23.05	.96
MSRT	39	615.96	15.80	.96
FCFS	42	349.15	8.29	.90
MSRT	42	264.36	6.27	.89
FCFS	44	189.35	4.28	.84
MSRT	44	188.02	4.25	.85
FCFS	46	204.70	4.47	.82
MSRT	46	141.20	3.08	.83
FCFS	49	93.11	1.88	.76
MSRT	49	68.81	1.39	.75
FCFS	64	35.28	.54	.59
MSRT	64	27.77	.43	.59
FCFS	79	16.32	.20	.47
MSRT	79	14.86	.18	.47
FCFS	94	12.81	.13	.41
MSRT	94	11.26	.12	.40

Table 11. Mechanical Equipment Downtime Statistics.

Procedure	Time Between Arrivals (Minutes)	Average Time Spent in the system (Minutes)	Standard Deviation
FCFS	43	1356.51	2142
MSRT	43	913.62	1016
FCFS	46	569.63	896
MSRT	46	422.61	505
FCFS	48	429.90	532
MSRT	48	353.92	410
FCFS	50	277.85	322
MSRT	50	271.29	310
FCFS	53	239.61	275
MSRT	53	271.58	264
FCFS	68	170.25	194.31
MSRT	68	161.69	191.25
FCFS	83	157.79	180.94
MSRT	83	153.67	180.68
FCFS	98	140.31	163.31
MSRT	98	138.77	159.38

Table 12. Electrical Equipment Downtime Statistics.

Procedure	Time Between Arrivals (Minutes)	Average Time Spent in the system (Minutes)	Standard Deviation
FCFS	39	1012.22	1527
MSRT	39	729.27	776
FCFS	42	463.01	588
MSRT	42	337.60	441
FCFS	44	301.68	383
MSRT	44	300.65	410
FCFS	46	313.74	388
MSRT	46	253.24	346
FCFS	49	206.72	253.25
MSRT	49	182.70	230.81
FCFS	64	150.16	182.19
MSRT	64	142.07	177.75
FCFS	79	130.46	164.31
MSRT	79	128.94	164.38
FCFS	94	132.05	169.31
MSRT	94	129.66	167.13

In the scenarios here, "busy" meant that the repairmen were utilized 82% of time or more. Clearly, if the input parameters (e.g. repair times, work order priorities, and time between arrivals) were varied, then a value other than 82% would be required before MSRT could produce significant reduction in the waiting time. Because of the added expense when one uses MSRT or SRT, such application is only practical when a maintenance system is extremely active.

CHAPTER V

CONCLUSIONS

The ultimate objective of a maintenance dispatcher is to be able to efficiently utilize the limited resources available to him. Proper scheduling plays an important role in this process. Using repair time as the criterion for developing the sequence in which work orders receive service, this study explored a new possibility for scheduling maintenance work.

An evaluation of the SRT scheduling method required a base against which to compare results. In this study, FCFS, the oldest and most common method for scheduling, provided this necessary base. Computer simulations were used as a means of carrying out the investigation, making it possible to consider differing work loads and varying scheduling alternatives. Because the behavior and the characteristics of the maintenance system were difficult to analyze using mathematical techniques, simulation modeling proved an appropriate technique for assessing the effectiveness of SRT. The models took into account many of the operations occurring in a typical maintenance shop (e.g. the dynamic arrival of work orders, assignment of priority levels, and the interruption of on going maintenance work). In addition, the models contained provisions for discrepancies between estimated and actual repair times.

A truly detailed analysis of inaccuracies in the scheduler's estimates of repair time as they affect the performance of SRT was outside the scope of this research. Obviously, this study addressed this problem of discrepancies between estimates and actual repair times but only to a limited extent. In order to examine these discrepancies, a series of simulation runs were conducted in which the error of estimate were gradually increased. The results of these simulations indicated that the estimates of repair times did not have to be perfect in order for SRT to perform well; however, as the difference between the actual and estimated repair times increased, SRT's performance deteriorated.

The simulation results showed considerable variations in the performance of the SRT procedure. For the particular maintenance system and environment posed here, the SRT procedure rendered significant improvement in the average waiting times as the backlog of work orders awaiting service increased; that is, as time between arrivals decreased, the SRT proved superior to FCFS.

Although SRT reduced average waiting time, an analysis of waiting time experienced by individual work orders revealed that work orders with low priority levels and long repair times experienced lengthy delays. This problem was overcome by modifying the SRT models; the new model, MSRT, contained provisions which imposed limits on the amount of time an individual work order was allowed to wait. Once this limit was reached, the work order was assigned the next higher priority level and was moved to that priority queue. This modification resulted in an increase in waiting times. However, the MSRT's waiting times were still less than those waiting times when the FCFS scheduling procedure was used. Also, like SRT, MSRT's performance was influenced by the amount of the work load: the busier the system, the better results in the reduction of average waiting time.

A scheduler who employs the FCFS procedure does not have to possess any special qualifications beyond a knowledge of the basic rudiments of scheduling. In contrast, the scheduler who utilizes MSRT should be adept at estimating repair time based on the symptoms of failure. Consequently experience with the maintenance tasks is very important. Because hiring an experience scheduler is more costly than employing a typical scheduler, the application of MSRT is justified only when the reduction in downtime costs compensate for the added expense incurred when this technique is utilized. This study concludes that the MSRT procedure is both practical and feasible for scheduling maintenance work.

REFERENCES

REFERENCES

(1) C. T. Baker, B. P. Dzielinski, "Simulation of a Simplified Job Shop," Management Science, Vol. 6, No. 3, 1960, PP 311-323.

(2) Benjamin S. Blanchard, Logistics Engineering and Management, Prentice-Hall, 1986.

(3) Benjamin S. Blanchard, Wolter J. Fabrycky, Systems Engineering and Analysis, Prentice-Hall, 1981.

(4) W. R. Conway, "Priority Dispatching and Work-in-Process Inventory in a Job Shop," Journal of Industrial Engineering, vol. 16, NO. 2, March-April 1965a, PP 123-130.

(5) W. R. Conway, B. M. Johnson, W. L. Maxwell, "An Experimental Investigation of Priority Dispatching", Journal of Industrial Engineering, vol. 11, NO. 3, May-June 1960, PP 221-230.

(6) W. R. Conway, W. L. Maxwell, L. W. Miller, Theory of Scheduling, Addison-Wesley, Reading, Mass.,1967.

(7) Thomas M. Cook, Robert A. Russell, Introduction to Management Science, Prentice-Hall, 1985.

(8) Anthony F. Czajkowsli, "Managerial Decision-Making in Establishing R&M Design Goals," IEEE Transactions on Reliability, Vol. R-32, 1983 Aug, pp 253-258.

(9) Renzo Dallimonti, "Smarter Maintenance with Expert System,"Plant Engineering, Vol. 41, 1987 June, PP 51-55.

(10) Balbir S. Dhillon, Hans Reiche, Reliability and Maintainability Management, Van Nostrand Reinhold, 1985.

(11) I. B. Gertsbakh, Models of Preventive Maintenance, North-Holland Publishing Company, 1977.

(12) A. S. Goldman, T. B. Slattery, Maintainability: A Major Element of System Effectiveness, John Wiley & Sons, 1964.

(13) Donald Gross, Douglas R. Miller, Richard M. Soland. "On Some Common Interests Among Reliability, Inven-ntory, and Queuing,"IEEE Transactions on Reliability, Vol. R-34, 1985 Aug, PP 204-208.

(14) Lynwood A. Johnson, Douglas C. Montgomery, Operations Research in Production Planning, Scheduling, and Inventory Control, John Wiley & Sons, 1974.

(15) K. C. Kapur, L. R. Lamberson, Reliability in Engineering Design, John Wiley & Sons, 1977.

(16) Lawrence L. Kavanau, Clinton J. Ancker, Jr., Norman F. Schneidewind, Industrial Engineering Handbook, McGraw-Hill, 1971.

(17) A. Kelly, M. J. Harris, Management of Industrial Maintenance, Butterworth, 1978.

(18) Way Kuo, "Simulation Properties of the Bayesian and Maximuml Likelihood Estimators of Availability, "Microelectronics and Reliability, Vol. 24, 1984, PP 1057-61.

(19) Way Kuo, "Maintainability for a Manufacturing Process. "Proceedings Annual Reliability and Maintainability Symposium, 1987, PP 57-63.

(20) H. T. Lau, "A Survey on Algorithmic Aspects in Preventive Maintenance," Microelectronics and Reliability, Vol. 25, 1985, 299-311.

(21) Mitchell O. Locks, Reliability, Maintainability, and Availability Assessment, Hayden Book, 1973.

(22) Louis A. Martin-Vega, "SPT, Data Analysis, and a Bit of Common Sense in Bus Maintenance Operations: A Case Study," AIIE Transactions, Vol. 13, 1981 Dec, PP 349-356.

(23) Gilbert H. Miller, Ronald Braff, "Impact of the Frequency of Technician Visits on Facility Failure Rate," IEEE Transactions on Reliability, Vol. R-26, 1977 Oct, PP 245-47.

(24) Marvin A. Moss, Designing for Minimal Maintenance Expense, Marcel Dekker, 1985.

(25) S. S. Panwalkar, W. Iskander, "A Survey of Scheduling Rules," Operations Research, Vol. 25, No. 1, January-February 1977, PP 45-61.

(26) Bernard L. Retter, Richard A. Kowalski, "Maintainability: A Historical Perspective," IEEE Transactions on Reliability, Vol. R-33, 1984 Apr, PP 56-58.

(27) Y.S. Sherif, M.L. Smith, "Optimal Maintenance Models for Systems Subject to Failure - A Review," Naval Research Logistics Quarterly, Vol. 28, 1981, PP 47-52.

(28) William H. Widawsky, " Reliability and Maintainability Parameters Evaluated with Simulation, "IEEE Transactions on Reliability, Vol. 20, 1971 Oct, PP 158-63.

APPENDIXES

APPENDIX A

```
        SIMULATE
 1      MATRIX     X,3,5
        INITIAL    MX1(1,1),30
        INITIAL    MX1(1,2),45
        INITIAL    MX1(1,3),100
        INITIAL    MX1(1,4),200
        INITIAL    MX1(1,5),500
        INITIAL    MX1(2,1),20
        INITIAL    MX1(2,2),35
        INITIAL    MX1(2,3),90
        INITIAL    MX1(2,4),250
        INITIAL    MX1(2,5),550
        INITIAL    X44,1
        INITIAL    X45,1
        INITIAL    X46,1
        INITIAL    X54,1
        INITIAL    X55,1
        INITIAL    X56,1
 1      FVARIABLE  P8*15/100
 2      FVARIABLE  P8*30/100
 1      FUNCTION   RN2,D3
.05,1/.57,2/1,3
 2      FUNCTION   RN2,D5
.22,1/.48,2/.78,3/.9,4/1,5
 5      FUNCTION   RN3,D3
.05,1/.57,2/1,3
 6      FUNCTION   RN3,D5
.2,1/.5,2/.80,3/.94,4/1,5
 3      FUNCTION   RN3,C24
0,0/.1,.104/.2,.222/.3,.355/.4,.509/.5,.69
.6,.915/.7,1.2/.75,1.38/.8,1.6/.84,1.83/.88,2.12
.9,2.3/.92,2.52/.94,2.81/.95,2.99/.96,3.2/.97,3.5
.98,3.9/.99,4.6/.995,5.3/.998,6.2/.999,7/.9997,8
 1      TABLE      M1,0,1000,34
 2      TABLE      M1,0,1000,34
 3      TABLE      M1,0,1000,24
 4      TABLE      M1,0,1000,24
*************************SECTION 1*****************************
***
*
*************SEGMENT 1*************
        GENERATE   1,,,1
        ASSIGN     6,1
        SPLIT      3,MECH
        TERMINATE
```

```
MECH    SAVEVALUE  1+,1
        ASSIGN     7,X1
        LINK       16,FIFO
*************SEGMENT 2***********
        GENERATE   43,FN3
        QUEUE      1
        ASSIGN     1,1
        ASSIGN     2,FN1
        ASSIGN     3,FN2
        LOGIC S    40
        LINK       10,P2
*************SEGMENT 3************
        GENERATE   1,,,1
BBB     GATE LS    40
        LOGIC R    40
        UNLINK     10,MMM,1,1,1
        GATE LS    42
        LOGIC R    42
        TEST NE    CH16,0,PMA
        SPLIT      1,MUU
        GATE LS    43
        LOGIC R    43
        TRANSFER   ,BBB
MMM     LOGIC S    42
        TEST E     P2,1,MDD
        PRIORITY   10
        LOGIC S    45
        LINK       1,FIFO
MDD     TEST E     P2,2,MAA
        LINK       2,FIFO
MAA     LINK       3,FIFO
MUU     UNLINK     16,MCC,1,6,1,MSP
        TERMINATE
MSP     LOGIC S    43
        TERMINATE
PMA     GATE LS    45,BBB
        LOGIC R    45
        SPLIT      1,PMO
        GATE LS    43
        LOGIC R    43
        TRANSFER   ,BBB
PMO     LOGIC S    43
PME     TEST E     X44,1,PMG
        SAVEVALUE  44,2
        UNLINK     1,PMB,1
        ADVANCE    2
        PREEMPT    1
        ASSIGN     8,X40
        ADVANCE    X40,V1
        LOGIC S    181
        RETURN     1
```

```
        SAVEVALUE  44,1
        TERMINATE
PMB     DEPART     1
        TABULATE   1
        SAVEVALUE  40,MX1(P1,P3)
        GATE LS    181
        LOGIC R    181
        TABULATE   3
        TERMINATE
PMG     TEST E     X45,1,PMY
        SAVEVALUE  45,2
        UNLINK     1,PMC,1
        ADVANCE    2
        PREEMPT    2
        ASSIGN     8,X41
        ADVANCE    X41,V1
        LOGIC S    182
        RETURN     2
        SAVEVALUE  45,1
        TERMINATE
PMC     DEPART     1
        TABULATE   1
        SAVEVALUE  41,MX1(P1,P3)
        GATE LS    182
        LOGIC R    182
        TABULATE   3
        TERMINATE
PMY     TEST E     X46,1,PMK
        SAVEVALUE  46,2
        UNLINK     1,PMF,1
        ADVANCE    2
        PREEMPT    3
        ASSIGN     8,X42
        ADVANCE    X42,V1
        LOGIC S    183
        RETURN     3
        SAVEVALUE  46,1
        TERMINATE
PMF     DEPART     1
        TABULATE   1
        SAVEVALUE  42,MX1(P1,P3)
        GATE LS    183
        LOGIC R    183
        TABULATE   3
        TERMINATE
PMK     ADVANCE    5
        TRANSFER   ,PME
*************SEGMENT 4****************
MCC     LOGIC S    43
MPP     TEST E     P7,1,MNN
        TEST NE    CH1,0,MBB
```

```
        ASSIGN      9,1
        TRANSFER    ,MKK
MBB     TEST NE     CH2,0,MFF
        ASSIGN      9,2
        TRANSFER    ,MKK
MFF     TEST NE     CH3,0,MOF
        ASSIGN      9,3
MKK     UNLINK      P9,MQQ,1
        GATE LS     1
        LOGIC R     1
        SEIZE       1
        ASSIGN      8,X40
        ADVANCE     X40,V1
        LOGIC S     191
        RELEASE     1
        GATE LS     46,MPS
        SAVEVALUE   44,1
        LOGIC R     46
MPS     SPLIT       1,MTT
        LINK        16,FIFO
MQQ     DEPART      1
        TABULATE    1
        TEST E      P2,1,MPH
        SAVEVALUE   44,2
        LOGIC S     46
MPH     SAVEVALUE   40,MX1(P1,P3)
        LOGIC S     1
        GATE LS     191
        LOGIC R     191
        TABULATE    3
        TERMINATE
MNN     TEST E      P7,2,MOO
        TEST NE     CH1,0,MYY
        ASSIGN      9,1
        TRANSFER    ,MJJ
MYY     TEST NE     CH2,0,MZZ
        ASSIGN      9,2
        TRANSFER    ,MJJ
MZZ     TEST NE     CH3,0,MOF
        ASSIGN      9,3
MJJ     UNLINK      P9,MSS,1
        GATE LS     2
        LOGIC R     2
        SEIZE       2
        ASSIGN      8,X41
        ADVANCE     X41,V1
        LOGIC S     192
        RELEASE     2
        GATE LS     47,MPW
        SAVEVALUE   45,1
        LOGIC R     47
```

```
MPW    SPLIT        1,MTT
       LINK         16,FIFO
MSS    DEPART       1
       TABULATE     1
       TEST E       P2,1,MPV
       SAVEVALUE    45,2
       LOGIC S      47
MPV    SAVEVALUE    41,MX1(P1,P3)
       LOGIC S      2
       GATE LS      192
       LOGIC R      192
       TABULATE     3
       TERMINATE
MOO    TEST NE      CH1,0,MII
       ASSIGN       9,1
       TRANSFER     ,MHH
MII    TEST NE      CH2,0,MWW
       ASSIGN       9,2
       TRANSFER     ,MHH
MWW    TEST NE      CH3,0,MOF
       ASSIGN       9,3
MHH    UNLINK       P9,MLL,1
       GATE LS      3
       LOGIC R      3
       SEIZE        3
       ASSIGN       8,X42
       ADVANCE      X42,V1
       LOGIC S      193
       RELEASE      3
       GATE LS      48,MPZ
       SAVEVALUE    46,1
       LOGIC R      48
MPZ    SPLIT        1,MTT
       LINK         16,FIFO
MLL    DEPART       1
       TABULATE     1
       TEST E       P2,1,MPT
       SAVEVALUE    46,2
       LOGIC S      48
MPT    SAVEVALUE    42,MX1(P1,P3)
       LOGIC S      3
       GATE LS      193
       LOGIC R      193
       TABULATE     3
       TERMINATE
MTT    TEST E       CH1,0,MVV
       TEST E       CH2,0,MVV
       TEST E       CH3,0,MVV
       TERMINATE
MVV    UNLINK       16,MPP,1,6,1
       TERMINATE
```

```
 MOF   LINK        16,FIFO
*************************SECTION 2*************************
*
*************SEGMENT 1****************
       GENERATE    1,,,1
       ASSIGN      6,2
       SPLIT       3,ELEC
       TERMINATE
 ELEC  SAVEVALUE   1+,1
       ASSIGN      7,X1
       LINK        18,FIFO
*************SEGMENT 2****************
       GENERATE    39,FN3
       QUEUE       2
       ASSIGN      1,2
       ASSIGN      2,FN5
       ASSIGN      3,FN6
       LOGIC S     50
       LINK        14,P2
*************SEGMENT 3****************
       GENERATE    1,,,1
 CCC   GATE LS     50
       LOGIC R     50
       UNLINK      14,EEE,1,1,2
       GATE LS     52
       LOGIC R     52
       TEST NE     CH18,0,PEA
       SPLIT       1,EUU
       GATE LS     53
       LOGIC R     53
       TRANSFER    ,CCC
 EEE   LOGIC S     52
       TEST E      P2,1,EDD
       PRIORITY    10
       LOGIC S     55
       LINK        4,FIFO
 EDD   TEST E      P2,2,EAA
       LINK        5,FIFO
 EAA   LINK        6,FIFO
 EUU   UNLINK      18,ECC,1,6,2,ESP
       TERMINATE
 ESP   LOGIC S     53
       TERMINATE
 PEA   GATE LS     55,CCC
       LOGIC R     55
       SPLIT       1,PEO
       GATE LS     53
       LOGIC R     53
       TRANSFER    ,CCC
 PEO   LOGIC S     53
 PEE   TEST E      X54,1,PEG
```

```
        SAVEVALUE  54,2
        UNLINK     4,PEP,1
        ADVANCE    2
        PREEMPT    4
        ASSIGN     8,X50
        ADVANCE    X50,V2
        LOGIC S    184
        RETURN     4
        SAVEVALUE  54,1
        TERMINATE
PEP     DEPART     2
        TABULATE   2
        SAVEVALUE  50,MX1(P1,P3)
        GATE LS    184
        LOGIC R    184
        TABULATE   4
        TERMINATE
PEG     TEST E     X55,1,PEY
        SAVEVALUE  55,2
        UNLINK     4,PEC,1
        ADVANCE    2
        PREEMPT    5
        ASSIGN     8,X51
        ADVANCE    X51,V2
        LOGIC S    185
        RETURN     5
        SAVEVALUE  55,1
        TERMINATE
PEC     DEPART     2
        TABULATE   2
        SAVEVALUE  51,MX1(P1,P3)
        GATE LS    185
        LOGIC R    185
        TABULATE   4
        TERMINATE
PEY     TEST E     X56,1,PEK
        SAVEVALUE  56,2
        UNLINK     4,PEF,1
        ADVANCE    2
        PREEMPT    6
        ASSIGN     8,X52
        ADVANCE    X52,V2
        LOGIC S    186
        RETURN     6
        SAVEVALUE  56,1
        TERMINATE
PEF     DEPART     2
        TABULATE   2
        SAVEVALUE  52,MX1(P1,P3)
        GATE LS    186
        LOGIC R    186
```

```
        TABULATE    4
        TERMINATE
PEK     ADVANCE     5
        TRANSFER    ,PEE
*****************SEGMENT 4*******************
ECC     LOGIC S     53
EPP     TEST E      P7,4,ENN
        TEST NE     CH4,0,EBB
        ASSIGN      9,4
        TRANSFER    ,EKK
EBB     TEST NE     CH5,0,EFF
        ASSIGN      9,5
        TRANSFER    ,EKK
EFF     TEST NE     CH6,0,EOF
        ASSIGN      9,6
EKK     UNLINK      P9,EQQ,1
        GATE LS     4
        LOGIC R     4
        SEIZE       4
        ASSIGN      8,X50
        ADVANCE     X50,V2
        LOGIC S     194
        RELEASE     4
        GATE LS     56,EPS
        SAVEVALUE   54,1
        LOGIC R     56
EPS     SPLIT       1,ETT
        LINK        18,FIFO
EQQ     DEPART      2
        TABULATE    2
        TEST E      P2,1,EPH
        SAVEVALUE   54,2
        LOGIC S     56
EPH     SAVEVALUE   50,MX1(P1,P3)
        LOGIC S     4
        GATE LS     194
        LOGIC R     194
        TABULATE    4
        TERMINATE
ENN     TEST E      P7,5,EOO
        TEST NE     CH4,0,EYY
        ASSIGN      9,4
        TRANSFER    ,EJJ
EYY     TEST NE     CH5,0,EZZ
        ASSIGN      9,5
        TRANSFER    ,EJJ
EZZ     TEST NE     CH6,0,EOF
        ASSIGN      9,6
EJJ     UNLINK      P9,ESS,1
        GATE LS     5
        LOGIC R     5
```

```
        SEIZE      5
        ASSIGN     8,X51
        ADVANCE    X51,V2
        LOGIC S    195
        RELEASE    5
        GATE LS    57,EPW
        SAVEVALUE  55,1
        LOGIC R    57
EPW     SPLIT      1,ETT
        LINK       18,FIFO
ESS     DEPART     2
        TABULATE   2
        TEST E     P2,1,EPV
        SAVEVALUE  55,2
        LOGIC S    57
EPV     SAVEVALUE  51,MX1(P1,P3)
        LOGIC S    5
        GATE LS    195
        LOGIC R    195
        TABULATE   4
        TERMINATE
EOO     TEST NE    CH4,0,EII
        ASSIGN     9,4
        TRANSFER   ,EHH
EII     TEST NE    CH5,0,EWW
        ASSIGN     9,5
        TRANSFER   ,EHH
EWW     TEST NE    CH6,0,EOF
        ASSIGN     9,6
EHH     UNLINK     P9,ELL,1
        GATE LS    6
        LOGIC R    6
        SEIZE      6
        ASSIGN     8,X52
        ADVANCE    X52,V2
        LOGIC S    196
        RELEASE    6
        GATE LS    58,EPZ
        SAVEVALUE  56,1
        LOGIC R    58
EPZ     SPLIT      1,ETT
        LINK       18,FIFO
ELL     DEPART     2
        TABULATE   2
        TEST E     P2,1,EPT
        SAVEVALUE  56,2
        LOGIC S    58
EPT     SAVEVALUE  52,MX1(P1,P3)
        LOGIC S    6
        GATE LS    196
        LOGIC R    196
```

```
       TABULATE   4
       TERMINATE
ETT    TEST E     CH4,0,EVV
       TEST E     CH5,0,EVV
       TEST E     CH6,0,EVV
       TERMINATE
EVV    UNLINK     18,EPP,1,6,2
       TERMINATE
EOF    LINK       18,FIFO
       TERMINATE
*******************************************************
       GENERATE   259200
       TERMINATE  1
       START      1
       END
```

APPENDIX B

```
        SIMULATE
 1      MATRIX       X,3,5
        INITIAL      MX1(1,1),30
        INITIAL      MX1(1,2),45
        INITIAL      MX1(1,3),100
        INITIAL      MX1(1,4),200
        INITIAL      MX1(1,5),500
        INITIAL      MX1(2,1),20
        INITIAL      MX1(2,2),35
        INITIAL      MX1(2,3),90
        INITIAL      MX1(2,4),250
        INITIAL      MX1(2,5),550
        INITIAL      X44,1
        INITIAL      X45,1
        INITIAL      X46,1
        INITIAL      X54,1
        INITIAL      X55,1
        INITIAL      X56,1
 1      FVARIABLE    P8*15/100
 2      FVARIABLE    P8*30/100
 1      FUNCTION     RN2,D3
.05,1/.57,2/1,3
 2      FUNCTION     RN2,D5
.22,1/.48,2/.78,3/.9,4/1,5
 5      FUNCTION     RN3,D3
.05,1/.57,2/1,3
 6      FUNCTION     RN3,D5
.2,1/.5,2/.80,3/.94,4/1,5
 3      FUNCTION     RN3,C24
0,0/.1,.104/.2,.222/.3,.355/.4,.509/.5,.69
.6,.915/.7,1.2/.75,1.38/.8,1.6/.84,1.83/.88,2.12
.9,2.3/.92,2.52/.94,2.81/.95,2.99/.96,3.2/.97,3.5
.98,3.9/.99,4.6/.995,5.3/.998,6.2/.999,7/.9997,8
 1      TABLE        M1,0,1000,34
 2      TABLE        M1,0,1000,34
 3      TABLE        M1,0,1000,24
 4      TABLE        M1,0,1000,24
**********************SECTION 1*************************
*
**************SEGMENT 1****************
        GENERATE     1,,,1
        ASSIGN       6,1
        SPLIT        3,MECH
        TERMINATE
 MECH   SAVEVALUE    1+,1
```

```
          ASSIGN      7,X1
          LINK        16,FIFO
*************SEGMENT 2*****************
          GENERATE    43,FN3
          QUEUE       1
          ASSIGN      1,1
          ASSIGN      2,FN1
          ASSIGN      3,FN2
          ASSIGN      4,MX1(P1,P3)
          LOGIC S     40
          LINK        10,P2
*************SEGMENT 3*****************
          GENERATE    1,,,1
 BBB      GATE LS     40
          LOGIC R     40
          UNLINK      10,MMM,1,1,1
          GATE LS     42
          LOGIC R     42
          TEST NE     CH16,0,PMA
          SPLIT       1,MUU
          GATE LS     43
          LOGIC R     43
          TRANSFER    ,BBB
 MMM      LOGIC S     42
          TEST E      P2,1,MDD
          PRIORITY    10
          LOGIC S     45
          LINK        1,P4
 MDD      TEST E      P2,2,MAA
          LINK        2,P4
 MAA      LINK        3,P4
 MUU      UNLINK      16,MCC,1,6,1,MSP
          TERMINATE
 MSP      LOGIC S     43
          TERMINATE
 PMA      GATE LS     45,BBB
          LOGIC R     45
          SPLIT       1,PMO
          GATE LS     43
          LOGIC R     43
          TRANSFER    ,BBB
 PMO      LOGIC S     43
 PME      TEST E      X44,1,PMG
          SAVEVALUE   44,2
          UNLINK      1,PMB,1
          ADVANCE     2
          PREEMPT     1
          ASSIGN      8,X40
          ADVANCE     X40,V1
          LOGIC S     181
          RETURN      1
```

```
        SAVEVALUE  44,1
        TERMINATE
PMB     DEPART     1
        TABULATE   1
        SAVEVALUE  40,MX1(P1,P3)
        GATE LS    181
        LOGIC R    181
        TABULATE   3
        TERMINATE
PMG     TEST E     X45,1,PMY
        SAVEVALUE  45,2
        UNLINK     1,PMC,1
        ADVANCE    2
        PREEMPT    2
        ASSIGN     8,X41
        ADVANCE    X41,V1
        LOGIC S    182
        RETURN     2
        SAVEVALUE  45,1
        TERMINATE
PMC     DEPART     1
        TABULATE   1
        SAVEVALUE  41,MX1(P1,P3)
        GATE LS    182
        LOGIC R    182
        TABULATE   3
        TERMINATE
PMY     TEST E     X46,1,PMK
        SAVEVALUE  46,2
        UNLINK     1,PMF,1
        ADVANCE    2
        PREEMPT    3
        ASSIGN     8,X42
        ADVANCE    X42,V1
        LOGIC S    183
        RETURN     3
        SAVEVALUE  46,1
        TERMINATE
PMF     DEPART     1
        TABULATE   1
        SAVEVALUE  42,MX1(P1,P3)
        GATE LS    183
        LOGIC R    183
        TABULATE   3
        TERMINATE
PMK     ADVANCE    5
        TRANSFER   ,PME
**************SEGMENT 4**************
MCC     LOGIC S    43
MPP     TEST E     P7,1,MNN
        TEST NE    CH1,0,MBB
```

```
        ASSIGN      9,1
        TRANSFER    ,MKK
MBB     TEST NE     CH2,0,MFF
        ASSIGN      9,2
        TRANSFER    ,MKK
MFF     TEST NE     CH3,0,MOF
        ASSIGN      9,3
MKK     UNLINK      P9,MQQ,1
        GATE LS     1
        LOGIC R     1
        SEIZE       1
        ASSIGN      8,X40
        ADVANCE     X40,V1
        LOGIC S     191
        RELEASE     1
        GATE LS     46,MPS
        SAVEVALUE   44,1
        LOGIC R     46
MPS     SPLIT       1,MTT
        LINK        16,FIFO
MQQ     DEPART      1
        TABULATE    1
        TEST E      P2,1,MPH
        SAVEVALUE   44,2
        LOGIC S     46
MPH     SAVEVALUE   40,MX1(P1,P3)
        LOGIC S     1
        GATE LS     191
        LOGIC R     191
        TABULATE    3
        TERMINATE
MNN     TEST E      P7,2,MOO
        TEST NE     CH1,0,MYY
        ASSIGN      9,1
        TRANSFER    ,MJJ
MYY     TEST NE     CH2,0,MZZ
        ASSIGN      9,2
        TRANSFER    ,MJJ
MZZ     TEST NE     CH3,0,MOF
        ASSIGN      9,3
MJJ     UNLINK      P9,MSS,1
        GATE LS     2
        LOGIC R     2
        SEIZE       2
        ASSIGN      8,X41
        ADVANCE     X41,V1
        LOGIC S     192
        RELEASE     2
        GATE LS     47,MPW
        SAVEVALUE   45,1
        LOGIC R     47
```

```
MPW     SPLIT        1,MTT
        LINK         16,FIFO
MSS     DEPART       1
        TABULATE     1
        TEST E       P2,1,MPV
        SAVEVALUE    45,2
        LOGIC S      47
MPV     SAVEVALUE    41,MX1(P1,P3)
        LOGIC S      2
        GATE LS      192
        LOGIC R      192
        TABULATE     3
        TERMINATE
MOO     TEST NE      CH1,0,MII
        ASSIGN       9,1
        TRANSFER     ,MHH
MII     TEST NE      CH2,0,MWW
        ASSIGN       9,2
        TRANSFER     ,MHH
MWW     TEST NE      CH3,0,MOF
        ASSIGN       9,3
MHH     UNLINK       P9,MLL,1
        GATE LS      3
        LOGIC R      3
        SEIZE        3
        ASSIGN       8,X42
        ADVANCE      X42,V1
        LOGIC S      193
        RELEASE      3
        GATE LS      48,MPZ
        SAVEVALUE    46,1
        LOGIC R      48
MPZ     SPLIT        1,MTT
        LINK         16,FIFO
MLL     DEPART       1
        TABULATE     1
        TEST E       P2,1,MPT
        SAVEVALUE    46,2
        LOGIC S      48
MPT     SAVEVALUE    42,MX1(P1,P3)
        LOGIC S      3
        GATE LS      193
        LOGIC R      193
        TABULATE     3
        TERMINATE
MTT     TEST E       CH1,0,MVV
        TEST E       CH2,0,MVV
        TEST E       CH3,0,MVV
        TERMINATE
MVV     UNLINK       16,MPP,1,6,1
        TERMINATE
```

```
 MOF   LINK       16,FIFO
*************************SECTION 2**********************
*
**************SEGMENT 1**********
      GENERATE   1,,,1
      ASSIGN     6,2
      SPLIT      3,ELEC
      TERMINATE
 ELEC SAVEVALUE  1+,1
      ASSIGN     7,X1
      LINK       18,FIFO
**************SEGMENT 2**********
      GENERATE   39,FN3
      QUEUE      2
      ASSIGN     1,2
      ASSIGN     2,FN5
      ASSIGN     3,FN6
      ASSIGN     4,MX1(P1,P3)
      LOGIC S    50
      LINK       14,P2
**************SEGMENT 3**********
      GENERATE   1,,,1
 CCC  GATE LS    50
      LOGIC R    50
      UNLINK     14,EEE,1,1,2
      GATE LS    52
      LOGIC R    52
      TEST NE    CH18,0,PEA
      SPLIT      1,EUU
      GATE LS    53
      LOGIC R    53
      TRANSFER   ,CCC
 EEE  LOGIC S    52
      TEST E     P2,1,EDD
      PRIORITY   10
      LOGIC S    55
      LINK       4,P4
 EDD  TEST E     P2,2,EAA
      LINK       5,P4
 EAA  LINK       6,P4
 EUU  UNLINK     18,ECC,1,6,2,ESP
      TERMINATE
 ESP  LOGIC S    53
      TERMINATE
 PEA  GATE LS    55,CCC
      LOGIC R    55
      SPLIT      1,PEO
      GATE LS    53
      LOGIC R    53
      TRANSFER   ,CCC
 PEO  LOGIC S    53
```

```
PEE     TEST E      X54,1,PEG
        SAVEVALUE   54,2
        UNLINK      4,PEP,1
        ADVANCE     2
        PREEMPT     4
        ASSIGN      8,X50
        ADVANCE     X50,V2
        LOGIC S     184
        RETURN      4
        SAVEVALUE   54,1
        TERMINATE
PEP     DEPART      2
        TABULATE    2
        SAVEVALUE   50,MX1(P1,P3)
        GATE LS     184
        LOGIC R     184
        TABULATE    4
        TERMINATE
PEG     TEST E      X55,1,PEY
        SAVEVALUE   55,2
        UNLINK      4,PEC,1
        ADVANCE     2
        PREEMPT     5
        ASSIGN      8,X51
        ADVANCE     X51,V2
        LOGIC S     185
        RETURN      5
        SAVEVALUE   55,1
        TERMINATE
PEC     DEPART      2
        TABULATE    2
        SAVEVALUE   51,MX1(P1,P3)
        GATE LS     185
        LOGIC R     185
        TABULATE    4
        TERMINATE
PEY     TEST E      X56,1,PEK
        SAVEVALUE   56,2
        UNLINK      4,PEF,1
        ADVANCE     2
        PREEMPT     6
        ASSIGN      8,X52
        ADVANCE     X52,V2
        LOGIC S     186
        RETURN      6
        SAVEVALUE   56,1
        TERMINATE
PEF     DEPART      2
        TABULATE    2
        SAVEVALUE   52,MX1(P1,P3)
        GATE LS     186
```

```
        LOGIC R     186
        TABULATE    4
        TERMINATE
PEK     ADVANCE     5
        TRANSFER    ,PEE
*************SEGMENT 4**************
ECC     LOGIC S     53
EPP     TEST E      P7,4,ENN
        TEST NE     CH4,0,EBB
        ASSIGN      9,4
        TRANSFER    ,EKK
EBB     TEST NE     CH5,0,EFF
        ASSIGN      9,5
        TRANSFER    ,EKK
EFF     TEST NE     CH6,0,EOF
        ASSIGN      9,6
EKK     UNLINK      P9,EQQ,1
        GATE LS     4
        LOGIC R     4
        SEIZE       4
        ASSIGN      8,X50
        ADVANCE     X50,V2
        LOGIC S     194
        RELEASE     4
        GATE LS     56,EPS
        SAVEVALUE   54,1
        LOGIC R     56
EPS     SPLIT       1,ETT
        LINK        18,FIFO
EQQ     DEPART      2
        TABULATE    2
        TEST E      P2,1,EPH
        SAVEVALUE   54,2
        LOGIC S     56
EPH     SAVEVALUE   50,MX1(P1,P3)
        LOGIC S     4
        GATE LS     194
        LOGIC R     194
        TABULATE    4
        TERMINATE
ENN     TEST E      P7,5,EOO
        TEST NE     CH4,0,EYY
        ASSIGN      9,4
        TRANSFER    ,EJJ
EYY     TEST NE     CH5,0,EZZ
        ASSIGN      9,5
        TRANSFER    ,EJJ
EZZ     TEST NE     CH6,0,EOF
        ASSIGN      9,6
EJJ     UNLINK      P9,ESS,1
        GATE LS     5
```

```
        LOGIC R     5
        SEIZE       5
        ASSIGN      8,X51
        ADVANCE     X51,V2
        LOGIC S     195
        RELEASE     5
        GATE LS     57,EPW
        SAVEVALUE   55,1
        LOGIC R     57
EPW     SPLIT       1,ETT
        LINK        18,FIFO
ESS     DEPART      2
        TABULATE    2
        TEST E      P2,1,EPV
        SAVEVALUE   55,2
        LOGIC S     57
EPV     SAVEVALUE   51,MX1(P1,P3)
        LOGIC S     5
        GATE LS     195
        LOGIC R     195
        TABULATE    4
        TERMINATE
EOO     TEST NE     CH4,0,EII
        ASSIGN      9,4
        TRANSFER    ,EHH
EII     TEST NE     CH5,0,EWW
        ASSIGN      9,5
        TRANSFER    ,EHH
EWW     TEST NE     CH6,0,EOF
        ASSIGN      9,6
EHH     UNLINK      P9,ELL,1
        GATE LS     6
        LOGIC R     6
        SEIZE       6
        ASSIGN      8,X52
        ADVANCE     X52,V2
        LOGIC S     196
        RELEASE     6
        GATE LS     58,EPZ
        SAVEVALUE   56,1
        LOGIC R     58
EPZ     SPLIT       1,ETT
        LINK        18,FIFO
ELL     DEPART      2
        TABULATE    2
        TEST E      P2,1,EPT
        SAVEVALUE   56,2
        LOGIC S     58
EPT     SAVEVALUE   52,MX1(P1,P3)
        LOGIC S     6
        GATE LS     196
```

```
        LOGIC R     196
        TABULATE    4
        TERMINATE
ETT     TEST E      CH4,0,EVV
        TEST E      CH5,0,EVV
        TEST E      CH6,0,EVV
        TERMINATE
EVV     UNLINK      18,EPP,1,6,2
        TERMINATE
EOF     LINK        18,FIFO
        TERMINATE
*******************************************************
        GENERATE    259200
        TERMINATE   1
        START       1
        END
```

VITA

Ali Reza Mahmoudieh was born in Isfahan, Iran on January 2, 1961. He was graduated from Darlington School, Rome, Georgia in 1979. Upon graduation he enrolled at Middle Georgia College, Cochran, Georgia where he completed his freshman year. In the summer 1980 he transferred to The University Of Tennessee where he received a Bachelor of Science degree in Industrial Engineering, March 1984. In the summer of 1985, he was awarded an assistantship in the Industrial Engineering department and served as a teaching assistant until his graduation. He received a Master of Science degree in Industrial Engineering, December 1988.

The author is a member of the American Institute of Industrial Engineers and Alpha Pi Mu.