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A STUDY OF MAINTENANCE PROCEDURES IN MEDICAL FACILITIES

By

Wasim S. Hashmi Syed
B.S., University of Engineering & Technology Lahore, 1986

A Thesis
Submitted to the Faculty of the
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for the Degree of

Master of Science

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A Thesis Approved on

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Finally, I dedicate this research to my beloved parents.

ABSTRACT

It is the intention of this thesis to outline a model of a maintenance program designed specifically for a hospital facility. The model for this maintenance program will be presented in its entirety by the author in a forthcoming Ph.D. dissertation. However, two aspects of this model are being presented in this thesis: 1) establishing due time of preventive maintenance or replacement for each type of equipment or system; 2) cost forecasting of each preventive maintenance action to be performed on equipment.

TABLE OF CONTENTS

Page

CHAPTER I - INTRODUCTION

CHAPTER II - SURVEY OF ENGINEERING DEPARTMENTS OF HOSPITAL FACILITY

CHAPTER III - REVIEW OF MAINTENANCE LITERATURE

CHAPTER IV - MODEL DERIVATION AND APPLICATION

CHAPTER V - NUMERICAL EXAMPLE

CHAPTER VI - CONCLUSIONS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

A. Overview

As hospitals progress and continue to rely more heavily upon technological equipment, there is a corresponding need for measures to improve maintenance strategies. Proper operation of equipment can mean the difference between life and death to a patient, and hospitals cannot afford to take risks when human life is involved. Therefore, good engineering and good maintenance are vital to the effective operation of any hospital.

Today's hospital engineering and maintenance departments must not only deal with the rapid improvements being made in engineering facilities, such as modular designs, computerized database systems, electronically controlled systems, etc., but also with the continued development of new technology in biomedical instrumentation for patient care. In order to assess the state of practice in this area, a study was conducted by the author at a system of hospital facilities. The overall objective of the study was to observe how maintenance of medical equipment is done and then determine what improvements could be made.

Numerous problems were found during this survey, most related to management and administrative policies regarding the treatment of equipment. Based upon the fact that the hospital system studied is one of the leaders in the field, one can argue that there is room for significant improvement in the current maintenance programs of most hospitals.

In particular, there is a need for maintenance programs which emphasize preventive maintenance(PM) using statistical and analytical methods to establish a schedule of planned maintenance on hospital equipment and facilities. Such systems have been shown to extend the life of the equipment, reduce costly failures, and ensure efficiency and effectiveness. The ultimate goal of such a program is to predict potential problems before they happen, and forecast when and what PM needs to be done, in as cost efficient a fashion as possible. Although an initial investment is required to implement any such program, it should be noted that a good hospital maintenance program can significantly affect profitability over the long run, since inefficient use and control of maintenance resources and labor is a costly and unnecessary waste. Thus, implementation of such a maintenance program can conceivably increase profit for the hospital while ensuring the reliability of the hospital equipment and improving patient care.

B. Scope of Thesis

It is the intention of this thesis to outline a model of a maintenance program designed specifically for a hospital facility. The model for this maintenance program will be presented in its entirety by the author in a forthcoming Ph.D. dissertation. However, two aspects of this model are being presented in this thesis: 1) establishing due time of preventive maintenance or replacement for each type of equipment or system; 2) cost forecasting of each preventive maintenance action to be performed on equipment.

This thesis is divided into six chapters. Chapter II provides a survey of a hospital facility to observe a currently implemented program for the maintainability of medical equipment that is representative of most hospitals. This survey examines the workings of the Biomedical Engineering Department and its currently implemented preventive maintenance program. The chapter outlines the numerous problems which were detected during this survey. Chapter III contains an overview of models and methodologies that have been developed for preventive maintenance programs which could, with suggested modifications, be applicable in hospital facilities. In Chapter IV a model by Jaybalan and Dipak [5] has been selected and its methodological approach is explained in detail. Following in Chapter V is a numerical example using their methodology. Chapter VI presents conclusions and recommended extensions to this research.

CHAPTER II

SURVEY OF ENGINEERING DEPARTMENTS OF A HOSPITAL FACILITY

A. Overview

Biomedical engineering and maintenance departments are vital to hospitals today. These departments influence every other department by ensuring that all medical and service equipment is operational. The aim of this survey was to detect the problems arising in the maintenance of medical equipment, and offer a systematic approach to improve the efficiency of each department. Note that departmental efficiency depends heavily upon the operation of equipment, since systematic operation is the keystone of modern maintenance systems.

There has been very little research done in the field of maintainability of hospital equipment during the last two decades. Perhaps the main reason has been that those at the managerial level are typically non-technical staff and thus are not skilled at dealing with engineering problems. In addition, current planned maintenance programs in hospitals are often not fully implemented because of a lack of commitment on the part of engineers and technical staff to the principles of planned maintenance.

The author recently conducted a survey of the Biomedical Engineering Department (BMED) of a large local hospital system. The survey was conducted over a 10-week period and involved working directly with administrative personnel, technical staff, and paramedics.

B. Preventive Maintenance Procedure of BMED

The BMED that was studied covers three facilities. Because it is a huge responsibility on the BMED staff to maintain the equipment, a well organized preventive maintenance program has been developed and implemented. Currently, however, they have a shortage of technical staff. There is one regular shift, which runs from 7:00 AM to 5:00 PM. From 5:00 PM to 7:00 AM, there are one or two technicians on call. In cases of emergency, their response is slow due to the low number of technicians in the facility.

Preventive maintenance of each equipment is dependent on the basic required maintenance and life cycle of the equipment. In most cases, the manufacturer's recommended maintenance procedures are adopted by the BMED. Technical groups, organized by skills, perform the preventive maintenance according to the equipment assigned to them. Table 1 shows the BMED preventive maintenance control program, which includes the equipment description, preventive maintenance due date, number of equipment, how many are done, percentage of completion, number of equipment not done, percentage of noncompletion, technical group title and quarter.

Data in this table shows that the reason for noncompletion of preventive maintenance is that the preventive maintenance group couldn't find the equipment in its original location. This indirectly affects the efficiency of the BMED, since it appears to them that equipment is missing or lost.

A database system has been developed which keeps all records of preventive maintenance as it is being performed on the equipment, and also any emergency work

DESCRIPTION	MONTH DUE	AMT EQP	PM COM	PRT CMP	TEC GP	QTR
AMP MISC	1-Jan	238	215	90%	AM	1
KCH LAB	1-Jan	113	113	100%	CO	1
NORTON ICU	2-Feb	110	110	100%	NO	1
NORTON CCU	2-Feb	56	55	98%	NO	1
CMU 5J	2-Feb	18	18	100%	WN	1
AMP ICU	3-Mar	39	38	97%	AM	1
AMP TCU	3-Mar	18	18	100%	AM	1
AMP VENTS	3-Mar	14	14	100%	AM	1
AMP CSS	4-Apr	134	102	76%	AM	2
NKC CSS	4-Apr	242	196	81%	CO	2
NKC EVENTS	4-Apr	140	140	100%	CO	2
AMP ANESTHE	5-May	15	15	100%	CO	2
KCH MONITORS	5-May	192	183	95%	WN	2
INCUBATORS	5-May	61	60	98%	KC	2
AMP DEFIBS	6-Jun	40	40	100%	AM	2
NKC PUMPS	6-Jun	42	42	100%	CO	2
IVAC PUMPS	7-Jul	375	356	95%	CO	3
KCH PICU	7-Jul	87	81	93%	KC	3
ECMO	8-Aug	32	24	75%	KC	3
AMP SURGERY	9-Sep	373	55	15%	AM	3

TABLE 1 EQUIPMENT DESCRIPTION WITH PM PERIOD & PM DONE FOR EACH EQUIPMENT DURING EACH QUATER

done and corrective action taken by Biomedical Engineering Technicians. The activities of the BMED during the preventive maintenance are shown in Figure 1. Table 2 shows the maintenance work order summary of each equipment separately for a certain time period. It also shows the time spent on each equipment to fix it, type of error, and corrective action taken by the technical staff.

It was observed from the previous records that some equipment have more frequent errors and need more corrective work. This causes more time and money to be spent on that specific equipment, which ultimately increases the cost of maintenance. The database system helps the BMED make changes in their preventive maintenance program, and also provides the condition of each equipment and its performance. It helps to schedule the preventive maintenance and calculate the workload of each technical group. The database gives a good idea of which equipment needs more maintenance and is causing an increase in the maintenance expenses.

Maintenance within the system of hospitals operates in a loop-like fashion. As operators use the system, a fault occurs; a work request is sent to the BMED; corrective action is taken; assurance of quality is given; and equipment returns to its parent department. Figure 2 illustrates this overall procedure.

The movement of equipment from one department to another, as well as that to and from the BMED, is shown in Figure 3. Each activity in the loop mentioned above is based either on its procedure or depends upon its need. It was observed that each activity commonly blames the previous activity for problems in the system. For instance, the technical staff tends to blame the operators, suppliers, or purchasers. Similarly, the

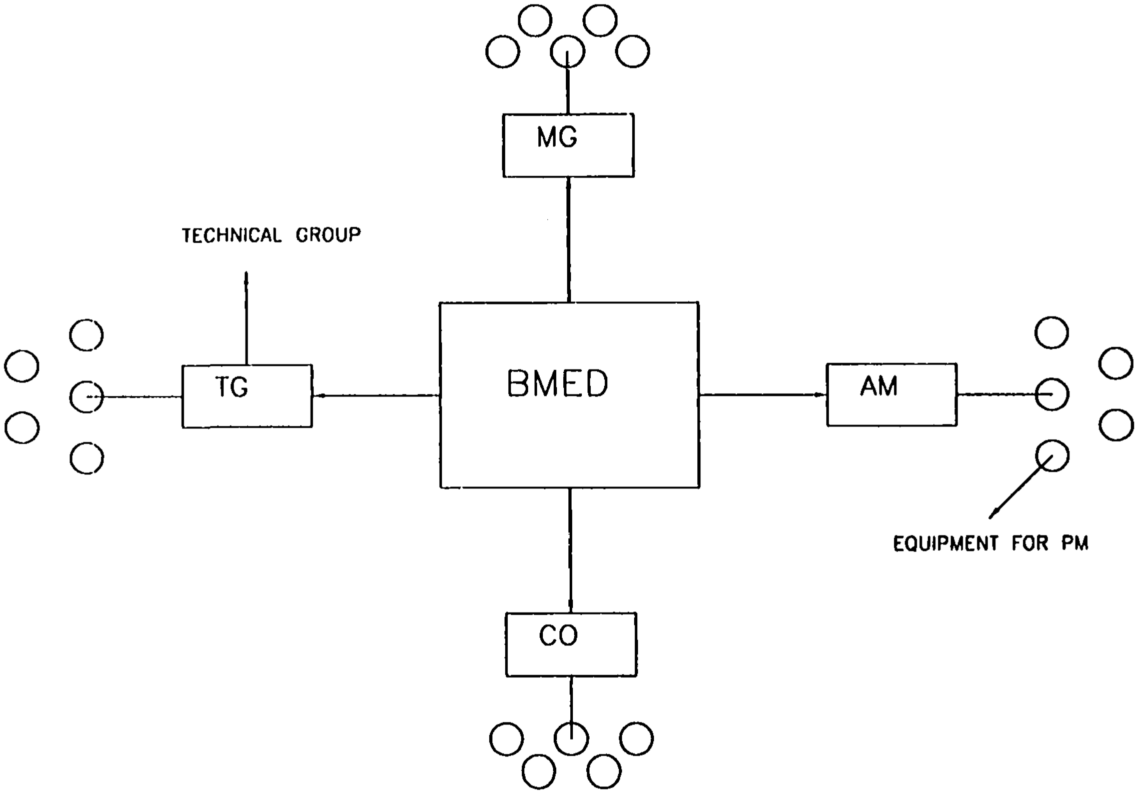

FIGURE 1. THE ACTIVITIES OF THE BMED DURING THE PM

EQUIPT DESCRIPTION	WORK REQUESTED	REQ DT	CMP DT	ACT HR
BIPOLAR COAGULAT	FOOT PEDAL REPAIR	10/10/94	10/10/94	1
VIDEO MONITOR	CONNECTOR LOOSE	10/10/94	10/10/94	1
INFANT WARMER	TEMP PROBE BROKEN	10/10/94	10/10/94	1.5
INFUSION PUMP	DOOR LATCH BROKEN	10/10/94	11/10/94	1.5
PULSE OXIMETER	CASE BROKEN	10/10/94	11/10/94	1.5
INFUSION PUMP	CHANNEL IN SER.MODE	10/11/94	10/11/94	1.5
INFANT WARMER	REP FAULTY ELEMENT	10/11/94	10/11/94	0.7
PROJECTOR	FILMS RUNS OUT	10/14/94	10/14/94	0.9
MONITOR	DISPLAY PROBLEM	10/14/94	10/14/94	1
PHOTOTHERAPY UNIT	FAULTY FAN	10/13/94	10/13/94	1
INFUSION PUMP	CHARGER MISSING	10/13/94	10/13/94	1
VENTILATOR	FAILS EST SENSOR	10/13/94	10/13/94	1
FETAL RECORDER	PROBLEM IN PRINTER	10/13/94	10/13/94	0.8
INFUSION PUMP	LOW BATTERY	10/11/94	10/11/94	0.8
INFUSION PUMP	REPAIR IN DB, LT, SM,	10/11/94	10/11/94	4
K-PAD PUMP	HEATING PROBLEM	10/11/94	10/11/94	0.5
ECT MACHINE	PULSE SWITCH FAULTY	10/12/94	10/12/94	2
ECT MACHINE	P.M. DUE	10/12/94	10/12/94	0.7
ELECTRONIC SCALE	SCALE REPAIR	10/12/94	10/12/94	0.4
VIDEO RECORDER	STUCK IN STANDBY	10/13/94	10/13/94	1

TABLE 2 TIME SPENT ON EQUIPMENT TO FIX & CORRECTIVE ACTION TAKEN BY BMED

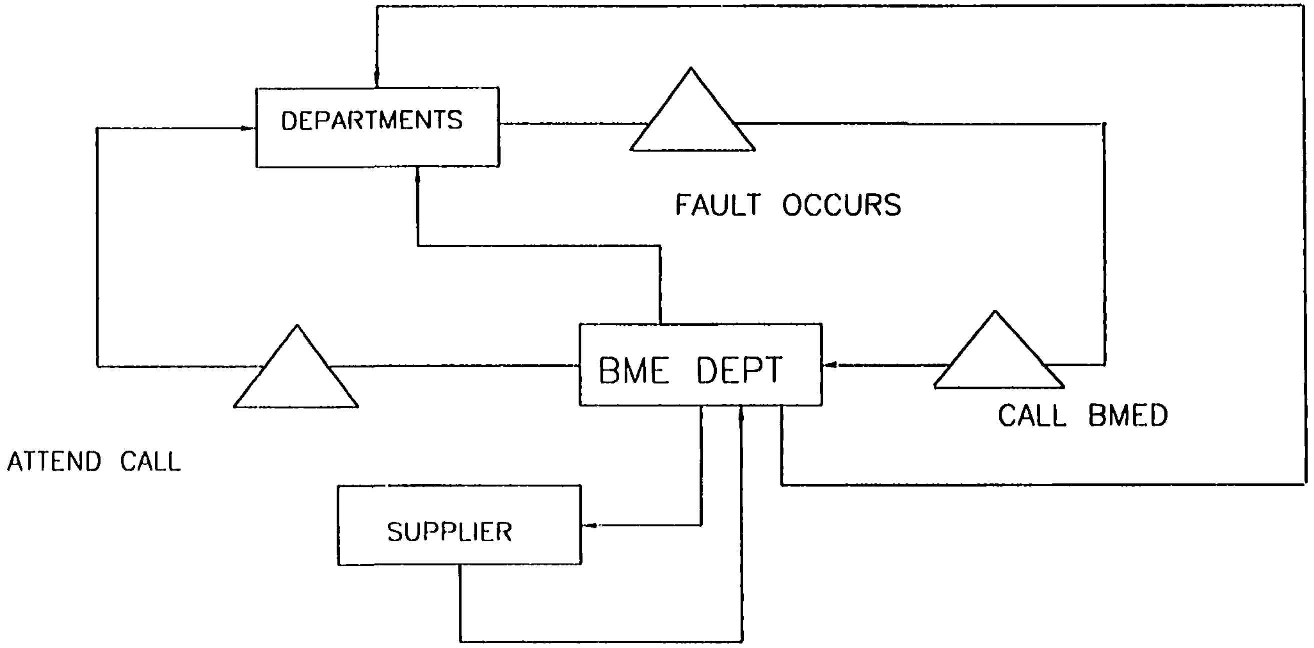

FIGURE 2. PROCEDURE TO FIX THE FAULTY EQUIPMENT

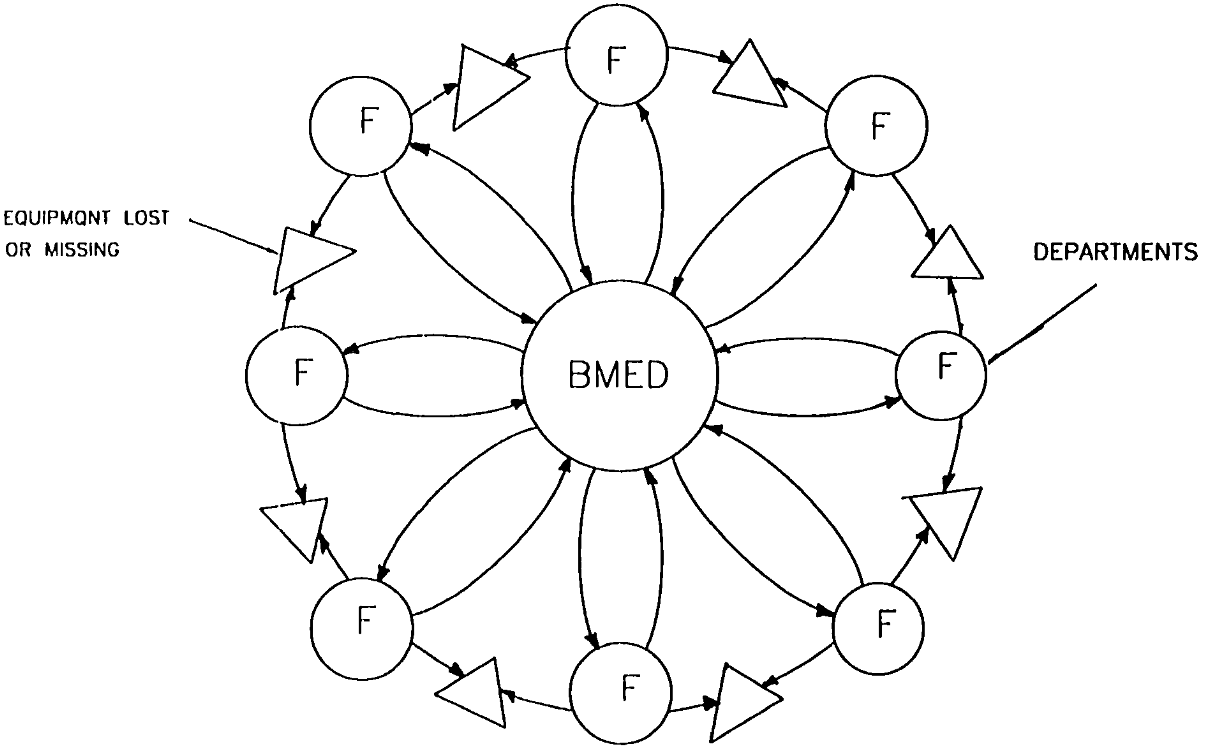

FIGURE 3. MOVEMENT OF EQUIPMENT FROM ONE DEPARTMENT TO OTHER & MOVEMENT OF EQUIPMENT FOR REPAIR TO BMED

operators blame management for buying poor equipment. In addition, complaints are often raised regarding inadequate demonstration of equipment operation and lack of training. Operators also blame the BMED, delay response of work requests, and show a lack of assurance of quality of equipment services. All these facts ultimately increase the cost of running the system efficiently.

Despite this maintenance program, they are still facing the following problems which are affecting the efficiency of the Biomedical Engineering Department.

- **Lack of a Purchasing Committee**

There is no official purchasing committee to buy new medical equipment. The managers of different departments purchase required equipment without consulting the BMED. This often results in the purchase of substandard equipment, which later causes problems for the BMED, generally when they perform preventive maintenance or attempt to fix faulty equipment. In many cases equipment is being installed directly by the supplier, and there is no record of the equipment in the Biomedical Department inventory.

- **Missing Equipment**

This problem occurs when BMED personnel attempt to perform preventive maintenance actions on small portable equipment. Because many departments borrow portable equipment and often fail to return it to its original location, the maintenance staff must locate the missing equipment, thereby losing valuable time.

- **Loss of Equipment**

Due to equipment being misplaced, it sometimes appears as if there is a shortage of that specific equipment. When the department needs that equipment and they cannot find it, they declare that the equipment has been lost and request that new equipment be purchased. Managers of different departments generally buy equipment according to the demands of the doctors and paramedics. Sometimes, when a department cannot find the required equipment, the equipment is bought in an emergency. In these cases, a department gets equipment which, in fact, they do not need. This results in an excess of equipment which, in turn, increases the work load of the staff of the Biomedical Engineering Department.

- **Lack of Responsibility**

This problem is directly related with the management and administration. Some of the above cited problems can be attributed to inadequate equipment inventory control. At the present time these problems appear to stem from a general lack of assigned responsibility to provide the control needed within this complex and diverse system.

- **Lack of Front-Line Management**

Paramedics have primary responsibility for operating medical equipment. Typically, they are not given responsibility for daily or routine checks on equipment before its use, even though such routine maintenance could help to improve the life of the equipment and also provide accurate results. Daily routine maintenance could decrease the errors and lessen the stress on operators to keep their equipment in working condition.

- **Lack of Training on Equipment**

Some maintenance problems are not the fault of the equipment, i.e., they can be traced to a lack of user experience and/or knowledge. Proper training programs and "hands-on" sessions should consistently be implemented to train the operators on the use of new equipment.

- **Communication Gap Between Paramedics and Maintenance Personnel**

This problem is related to employee behavior and attitudes within the workplace. The facts of this matter have been discussed with personnel of the BMED. It was determined that they have a serious problem of communication with paramedics of different departments. Major problems occur when Biomedical Technicians visit the departments for routine preventive maintenance and they do not find equipment in its proper place. This results in their having to spend a lot of time locating the equipment. If they ask the staff of the department about the missing equipment, they frequently get the reply that "we are too busy to help you people in locating the equipment."

- **Lack of Supervisors to Take Care of Equipment on Each Floor**

Nurses and staff feel that their duties are limited to patients. They don't believe that it is their responsibility to take care of equipment in their department, and thus a technical supervisor is needed to oversee the equipment.

- **Lack of Supplier Certification**

Sometimes managers of the departments purchase equipment from certain suppliers who are not reliable or have little previous experience supplying major equipment to any other medical facility. In many cases these suppliers are unable or unwilling to specify the expected life cycle of their equipment. This leads to planning problems within the hospital.

- **Lack of Central Supply Facility**

A central supply facility is an essential department for the supply of portable equipment. When equipment is needed in emergency situations, but is not available in the department, a central supply facility can provide required equipment. However, there is no such facility within the hospital system studied.

C. Research Needs

When one compares the hospital facility with manufacturing plants or service industries, many differences are uncovered. One can't take risks with human life, hence, reliability of equipment should be 100% in most circumstances, and availability of equipment should be 100% in all circumstances. To achieve such a goal, every node or station of the system should be coupled with the others. Every station should realize the needs and responsibilities of every other, and work together to ensure the constant availability of properly operating equipment.

Based upon the problems uncovered, the intent of this research is to develop a methodology to improve currently implemented maintenance programs for the maintainability of medical equipment. The ultimate approach will incorporate and expand on different research in the field of maintainability of equipment to:

1. Establish due time of preventive maintenance or replacement for each type of equipment or system
2. Cost forecast the optimal preventive maintenance activities for equipment type
3. Establish equipment needs based upon the importance of the department
4. Determine availability of vital equipment
5. Establish training requirements for technical staff for different types of equipment
6. Forecast quantity of standby equipment needed
7. Categorize the equipment into certain levels

This thesis will address, in depth, the first two areas of the above mentioned problems: establishing due time of preventive maintenance or replacement of equipment; and cost forecasting of preventive maintenance activities of equipment.

CHAPTER III

REVIEW OF MAINTENANCE LITERATURE

A. Overview of Preventive Maintenance

Maintenance can be expressed as actions taken to run a system or equipment in "as built" condition. It can be divided into different forms, but basic maintenance is either planned or unplanned. Unplanned has only one form, which is emergency maintenance. On the other hand, planned maintenance can be further classified into two categories, i.e, corrective maintenance and preventive maintenance. The relationship between the different types of maintenance is shown in Figure 4.

Emergency maintenance can be defined as taking immediate action to avoid serious consequences. Corrective maintenance can be described as action to be taken when a system is out of order, and preventive maintenance as when the system is in operation and maintenance is performed. Corrective maintenance can further be divided into two categories: a)minimal repair which is assumed to restore the system to the failure rate it had when it failed,i.e.,"bad as old", and b)corrective replacement which is assumed to restore the system failure rate to that of a new system, i.e., "good as new".

Planned Maintenance is categorized into two forms: simple preventive maintenance, (reduces the failure rate, but not to as "good as new") and preventive maintenance (replacement of the equipment restores the failure rate to as "good as new").

Preventive maintenance (PM) is the most important part of a proper maintenance

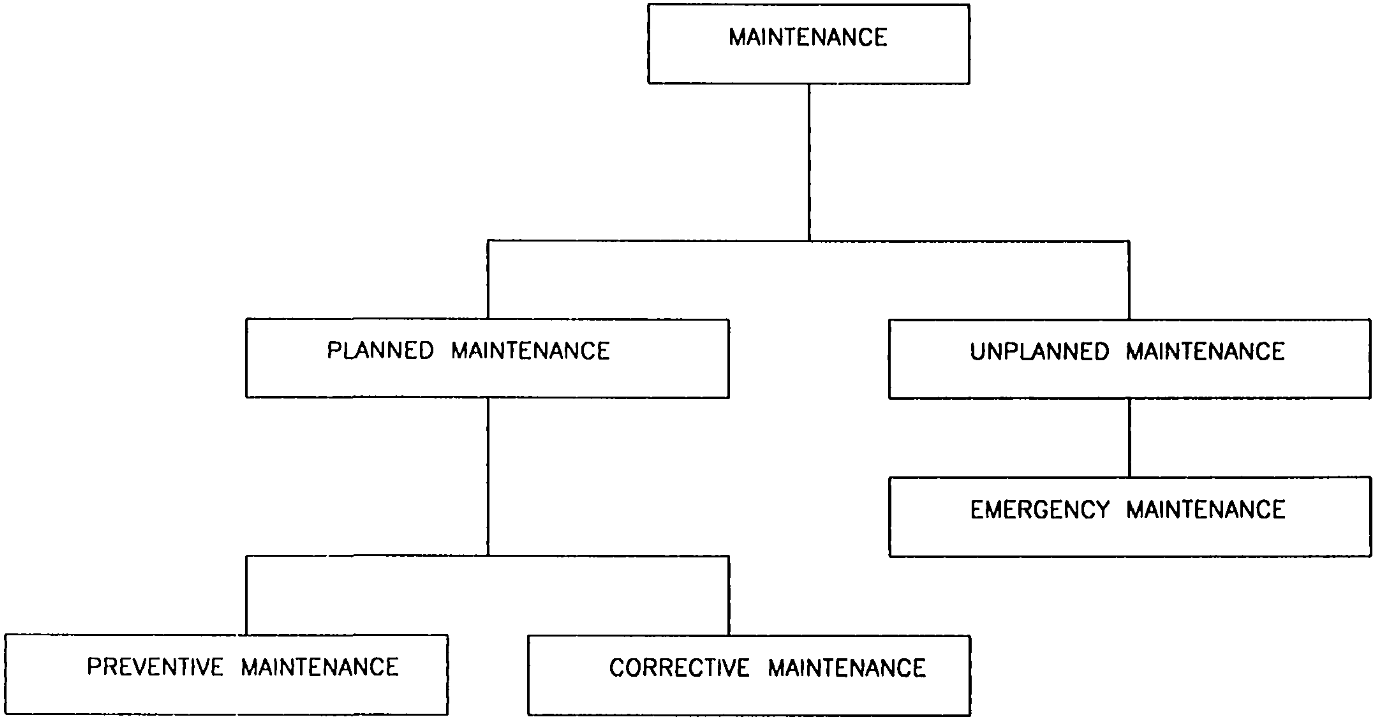

FIGURE 4 RELATIONSHIP BETWEEN VARIOUS FORMS OF MAINTENANCE

management system. It acts as a support between the production and maintenance management operations. Preventive maintenance is considered to be much more than simply periodic inspection of a system or equipment. For instance, Periodic inspections can be detrimental, if frequent checks cause the system or equipment to be in a nonoperating state at a needed moment. Ideally speaking, all maintenance should be preventive, being done before the system or equipment goes into failure mode.

The involvement of PM can be categorized into different levels. A review of the previous data or work done on the system can aid in determining what to include in a PM program. Following are the basic factors which can determine the level to which PM should be involved:

- the breakdown of equipment can put the whole facility or portion of it out of service
- availability of standby equipment
- replacement of equipment is less expensive than performing the PM
- redesigned the equipment to extends its life cycle
- distinguish whether the equipment operates on an intermittent or continuous basis

A frequency of inspection for the equipment or system should be developed, which can be specified on following considerations:

- if equipment is critical, then it needs more attention
- similar equipment can help to determine the frequency of PM operations

- on older equipment it's easier to know its frequent failures
- operating characteristics can be used to determine the frequency i.e., whether equipment operates on a continuous or intermittent basis.

PM is usually scheduled over periodic time intervals for each equipment or system. There is a trend in manufacturing or service facilities to delay the PM work and attend to all the emergency or breakdown work orders. When this happens frequently, all PM scheduled work changes into a form of emergency work.

Preventive maintenance, which by its very nature is planned, is more readily scheduled than emergency maintenance. Thus, PM workorders are generally completed in the time allocated for them. However, there will be times when the work must be continued the next day or done on an overtime basis. Such is sometimes the case with one specialized category of PM, the major overhaul or "turnaround". When the PM work to be done is extensive, and the chance of overrun is great, the scheduler must plan for this and adjust the schedule so that adequate time to complete the work is available.

The overall advantages of well implemented PM are:

- reduced overall maintenance cost
- reduced downtime
- reduced spare parts inventory
- reduced emergency maintenance

- reduced requirement of standby equipment
- lower direct labor cost
- improved safety factors
- reduction of delays
- maintenance scheduling
- improved long range planning
- decreased maintenance program budget
- timelier maintenance actions

B. Literature Review of PM models

Although very little research has been done on the topic of maintainability of medical equipment, enormous research has been done in the field of maintainability in other areas, including: manufacturing plants, military bases, and service industries.

Preventive maintenance is essentially all actions taken to maintain a system and improve its reliability performance characteristics. It is possible that PM staff can make errors during the preventive actions or replacement of equipment, so there is a need for an optimal PM policy. Many circumstances can play a role in determining this policy.

There are a few PM models that can be used to determine optimal PM policy. Most of the models require reliable statistical data related to lifetime distributions.

One such model is known as "the age replacement" model.[7] According to this model, equipment should be replaced by new at the time of failure or if its age reaches some prescribed value. The system can be categorized into only two states, good and failure.

Another type of model allows for a system to be categorized as being in states other than good and failure[7]. These varying intermediate states make it possible to estimate when a system will be approaching failure. In such a model, a randomly changing time-depending parameter is used. This parameter can be used for both continuous and discrete conditions, and can be helpful in acquiring information about the internal condition of the system and the chances of failure.

Another model [7] uses the equipment's failure distribution function to project its eminent failure, thereby eliminating the need for emergency repair (ER). In knowing the distribution function, it is possible that preventive repair (PR) can be performed before the failure. PR should be performed at such time that the total time of failure-free operation becomes equal to a multiple of a certain constant time period (T). This process is illustrated in Figure 5.

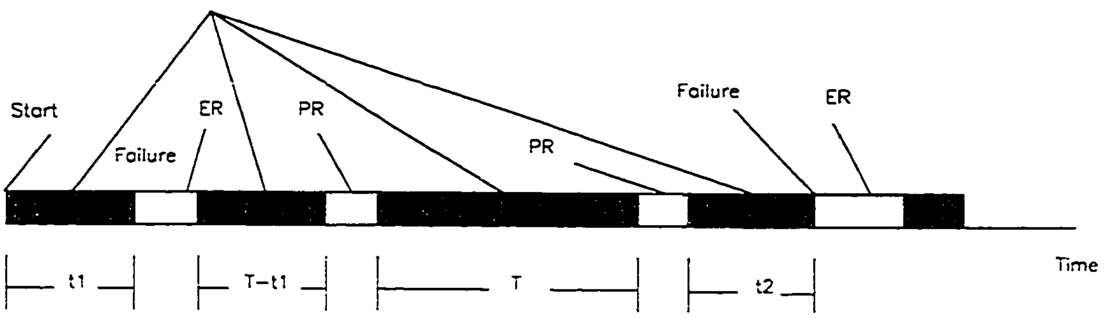

FIGURE 6 PR & ER EVENTS ARE SHOWN DURING THE OPERATION

In another model,[7] randomly changing parameter [n(t)] of the equipment is measured and its failure is defined as an event "n(t)>M", where M represents the inoperable condition of equipment. Inspection of the equipment is done periodically, at times T, 2T,... as shown in Figure 6. Using this model, the maintenance rule is as follows: if testing discovers that $n(t)<M_c$ (M_c denoting the critical level), nothing need be done. If the condition is such that $M_c<=n(t)<=M$, preventive repair should be done.

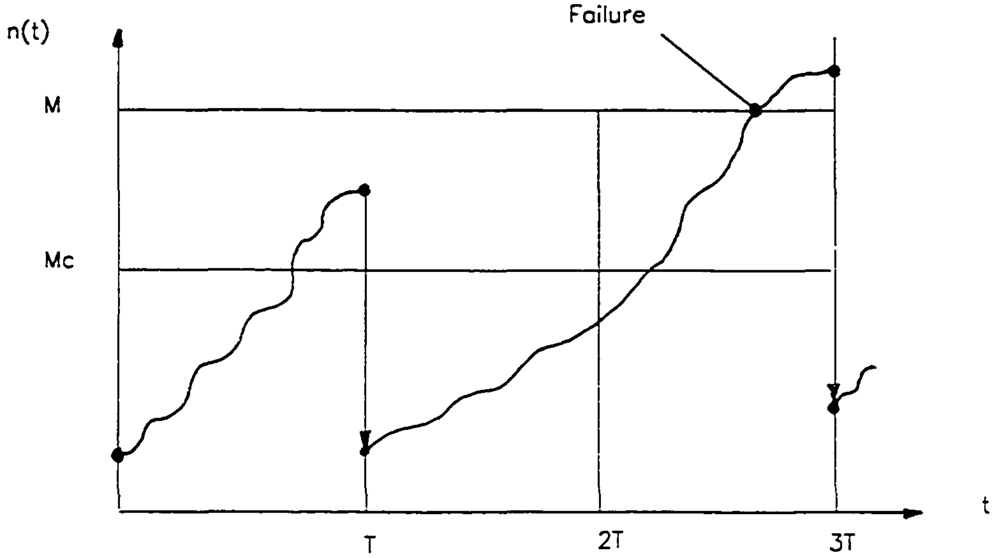

FIGURE 5 PM BASED ON OBERVATIONS OF THE SYSTEM'S OUTPUT PARAMETER

As a result, the value of the parameter n(t) returns to, or near to, its initial level. Each repair has an associated cost (C_0) and failures occurring between checkups are considered as breakdowns, causing a payment (C_1), where C_1)>C_0. The value of C_1

depends on the amount of time the equipment spends in the inoperable state.

Most of the models developed for PM assume that the hazard function of the equipment after PM is restored to like new. While it is true that PM reduces stress and the rate of degradation, one must consider that during the PM no major repair has been done so the hazard rate should be uniform and the level of degradation should be unchanged.

Canfield [1] presents a model for cost optimization of periodic preventive maintenance. The methodology enables the user to calculate an optimum time interval between each PM, i.e. one that minimizes the average cost-rate(cost/time) of a system. The model depends upon two assumptions: (1) operation produces stress, which causes degradation and (2) performance of PM lessens the stress and level of degradation. It is necessary to distinguish between the level of hazard and the shape of the hazard function as they relate to system degradation over time. The shape of the hazard function at a given time reflects the rate at which hazard is changing and the hazard level reflects the extent of system degradation.

Chang and Young [2] present an algorithm which determines the appropriate type and timing of PM needed. This algorithm determines how the cost rate for equipment is obtained by taking the ratio of the average cost for a cycle (time between replacement) to an average cycle length. The number of simple preventive maintenance procedures can be obtained before the preventive replacement is done by minimizing the cost rate when the failure times are Weibull distributed. This model is feasible only when simple PM and PR (preventive repair) are performed on the system.

Malik [3] also presents a model for reliable preventive maintenance scheduling. He proposes that preventive maintenance programs for service-producing systems and equipment should be designed with system reliability in mind. Maintenance of goods-producing systems is undertaken on the principle of minimizing the total cost (with total cost including both repair costs and projected production losses). However, in the case of service systems, since failures can result in the loss of human life, systems should be maintained at predetermined and acceptable levels of reliability, irrespective of cost.

Malik describes four types of assumptions that can be made in regard to repair or replacement of equipment:

(1) Replacement is the only maintenance; even if other maintenance has been performed it cannot improve the survival probability.

(2) Repaired equipment can be made to be "good as new".

(3) After performing maintenance, the equipment reliability is "bad as old".

(4) After performing the maintenance, equipment behaves as "good as new".

At first glance, assumptions (2) and (4) may seem to be the same. However, assumption (2) (whether a system can be good as new) depends upon how much money is spent on the repair of the equipment. On the other hand, assumption (4) depends upon the maintenance action, which improves the reliability of the equipment or system to as "good as new". Therefore, in the case of assumption (2), part or all of the equipment is replaced and actually is new, whereas in assumption (4) the equipment is only behaving as new.

In the view of Ascher [4], in regard to assumptions (3) and (4) and their corresponding states "bad as old" and "good as new", good as new is the better state of the two. He further contends that replacement of the equipment is an improvement over all the other states.

The best assumption may lie somewhere in between the above mentioned assumptions. If maintenance has been done, it should improve equipment reliability, otherwise, performing maintenance wastes resources. So, to say that assumption (1) is an improvement over assumption (3) is not right. Also, to achieve complete renewal, replacement is the only solution. Thus, assumption (2), while used for tractability purposes, is rarely true. Assumption (4) can be reasonably used when a system is subject to memoryless failures such as under the exponential distribution when any unfailed system is as "good as new". This implies that under wear-out failures, maintenance cannot restore the system or equipment to its original condition. A system can go faulty during operation, but it can also fail by chance. This shows that the system's overall failure is a result of the compound action of chance and wear out.

Malik also introduces an improvement factor to account for the case when maintenance is performed on a system or equipment and its rate of survival improves. The improvement of the system or equipment after maintenance is not equal to its original condition. If equipment is t years old, its post-maintenance age is reduced to t/β, where β is an improvement factor which varies between one and infinity. When β

equals one, there is no improvement in the equipment failure rate after performing the maintenance, (assumption 1). Similarly, when β reaches infinity, the situation is similar to assumptions (2) and (4). By using this approach, it is possible to achieve generality in maintenance improvement, from none to full "renewal".

Jayabalan and Dipak [5] present a two-phase algorithm for cost optimization of maintenance scheduling for a system with assured reliability. The first phase of this methodology yields "optimal" time intervals between preventive maintenance events on equipment.

The first phase yields an estimate of the time to schedule preventive maintenance (referred to as 1P-maintenance) by using the improvement factor approach previously discussed.

The second phase involves the calculation of the total cost of both maintenance and replacement to determine the optimal time of replace (referred to as 2P-maintenance).

The total cost of the system or equipment can be estimated by using the initial cost of the system and the maintenance cost factor. The maintenance cost can be calculated by using acquisition cost and maintenance cost factor. If the cumulative maintenance cost exceeds the replacement cost of the system, replacement is needed (2P-maintenance).

Their research describes how service systems subject to compound failure are to be maintained at predetermined points to assure that the system has a failure rate at or below a fixed value.

Jayabalan and Dipak's model has been selected to serve as the foundation for the research being presented in this thesis. It was chosen because it is a compilation of all the above mentioned researchers work in the field of maintainability of equipment or systems.

CHAPTER IV

Model Derivation and Application

A. Due Time of Preventive Maintenance

There are two types of maintenance proposed in Jayabalan and Dipak's model, (1P) preventive maintenance, and (2P) replacement of equipment or system.

The first phase presents the time to estimate the 1P-maintenance schedule by using the improvement factor. The second phase proposes a methodology to calculate the total cost of PM for a given time period, in order to determine the optimal replacement time.

Assumptions

- the planning period is fixed, β is constant
- acquisition cost and preventive maintenance cost factors remain constant during the planning period
- failure rate should be low, to have less probability of failure
- 1P or 2P types of maintenance are performed only when system reaches its maximum failure rate
- preventive maintenance and replacement times and cost of failure are negligible

Notation

t_0	time the system starts working; $t_0 = 0$
t_1	time when system goes to maximum failure rate
n_j-1	number of 1P-Maintenance for system j
n	number of 1P-Maintenance
D_i	reduction in effective age
R_i	reduction in failure rate
λ_{max}	maximum acceptable failure rate
C_j	acquisition cost of system j
T_{max}	planning period
T_j	time of 2P-maintenance for system j
r_1	annual rate of increase in acquisition cost
r_2	maintenance-cost factor
$t_{i(j)}$	time of 1P-maintenance i intervention for system j
$t_{n(j)}$	period of operation of system j
Tc_j	total cost
M_i	maintenance cost
A_i	cumulative maintenance cost

Preventive maintenance done at t_1 reduces the effective age of the system to t_1/β. The age of the system after maintenance is reduced by $R_1 = t_1(1-1/\beta)$; i.e, the failure rate of the system after 1P-maintenance at t_1 is the same as when the system is at $t_1(1-1/\beta)$.

The second 1P-maintenance is performed at:

$$t_2 = t_1 + t_1(1-1/\beta) \qquad (1)$$

Similarly, the next 1P-maintenance is performed at:

$$t_3 = t_2 + t_1(1-1/\beta)^2$$

In general the nth 1P-maintenance is performed at:

$$t_n = t_{(n-1)} + t_1(1-1/\beta)^{n-1} \qquad (2)$$

$$= \sum_{i=1}^{n} (1-1/\beta)^{i-1} t_1$$

Reduction in failure rate:

$$R_i = t_1(1-1/\beta)^{n-1} \qquad (3)$$

Reduction in effective system age:

$$D_i = t_1 - t_1(1-1/\beta)^{n-1} \qquad (4)$$

Figure 7 illustrates that the first 1P-maintenance is due at time t_1 as the system reaches its maximum failure rate. Note that, after the first maintenance, the failure rate does not drop back to zero. Rather, it only drops to a level that is governed by the improvement factor. Thus, the model allows for equipment that cannot be considered "good-as-new", after maintenance occurs.

This methodology can be applied to calculate the due time of preventive maintenance for each piece of medical equipment.

B. Cost Forecasting

As was shown back in Figure 7, it may, at some point,become more cost effective to simply replace equipment instead of continually performing 1P-maintenance. If the planning period is to be considered, then 2P-maintenance (replacement of equipment) should be performed to keep the overall cost low. The cost is estimated by including the

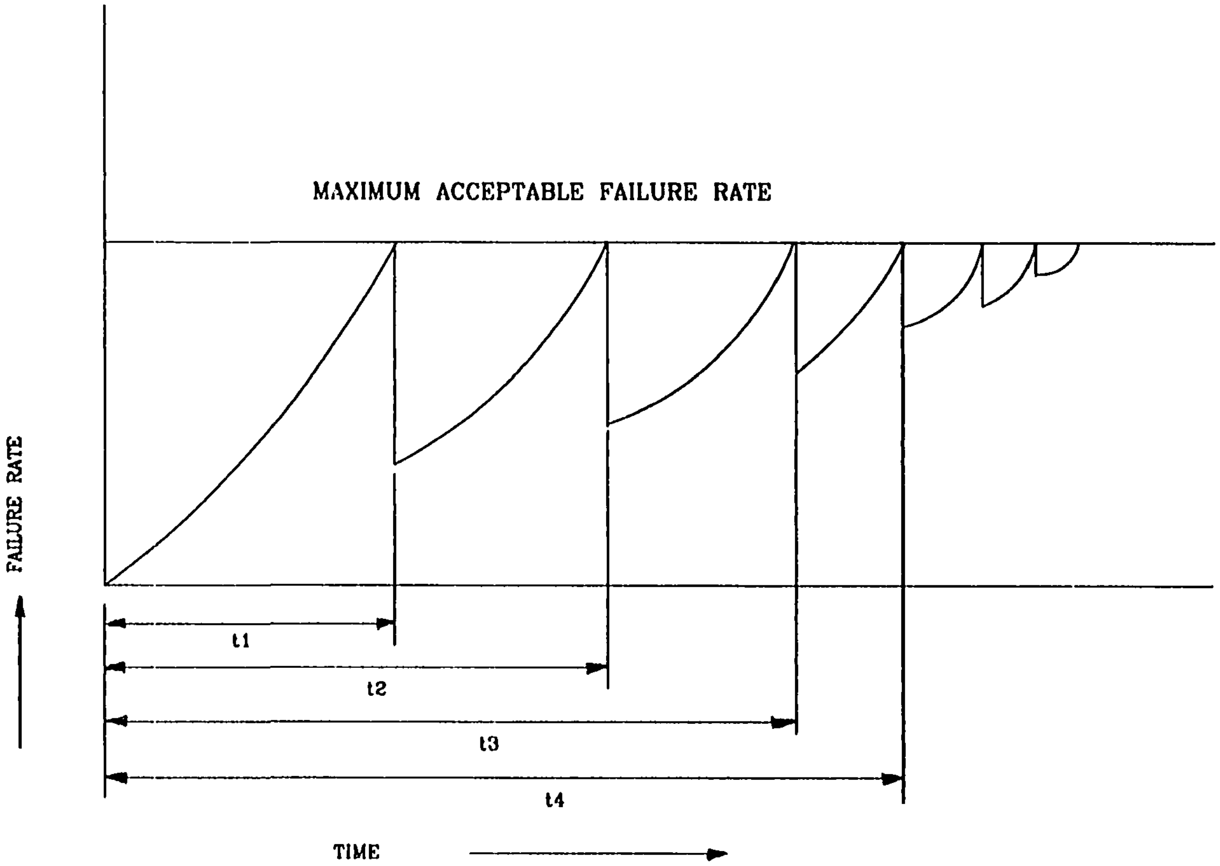

FIGURE 7 SCHEDULED 1P–MAINTENANCE TIMES

acquisition cost and the annual rate of increase in the acquisition cost of the system. The total cost of the system or equipment can be calculated by using the initial cost of the system and the maintenance cost factor. The maintenance cost can by estimated by using the acquisition cost and maintenance cost factor, as follows.

Assume that the equipment or system has been installed at time T_1 at a cost of C_1. The cost to perform one 1P-maintenance is r_2 (maintenance-cost factor) times the acquisition cost of the system. The acquisition cost of the system at T_2 time period is:

$$C_2 = C_1 + C_1 r_2 T_2$$

where $T_2 = t_{n(1)}$

In general the acquisition cost of jth replacement is:

$$C_j = C_1 + C_1 r_1 T_j;$$

where,

$$T_j = \sum_{i=1}^{j-1} t_{n(i)}, \; j > 1$$

As shown in Figure 8, the 1P-maintenance can be discontinued when failure rate is maximum, and replacement of the system can be considered at this point to minimize the total cost.

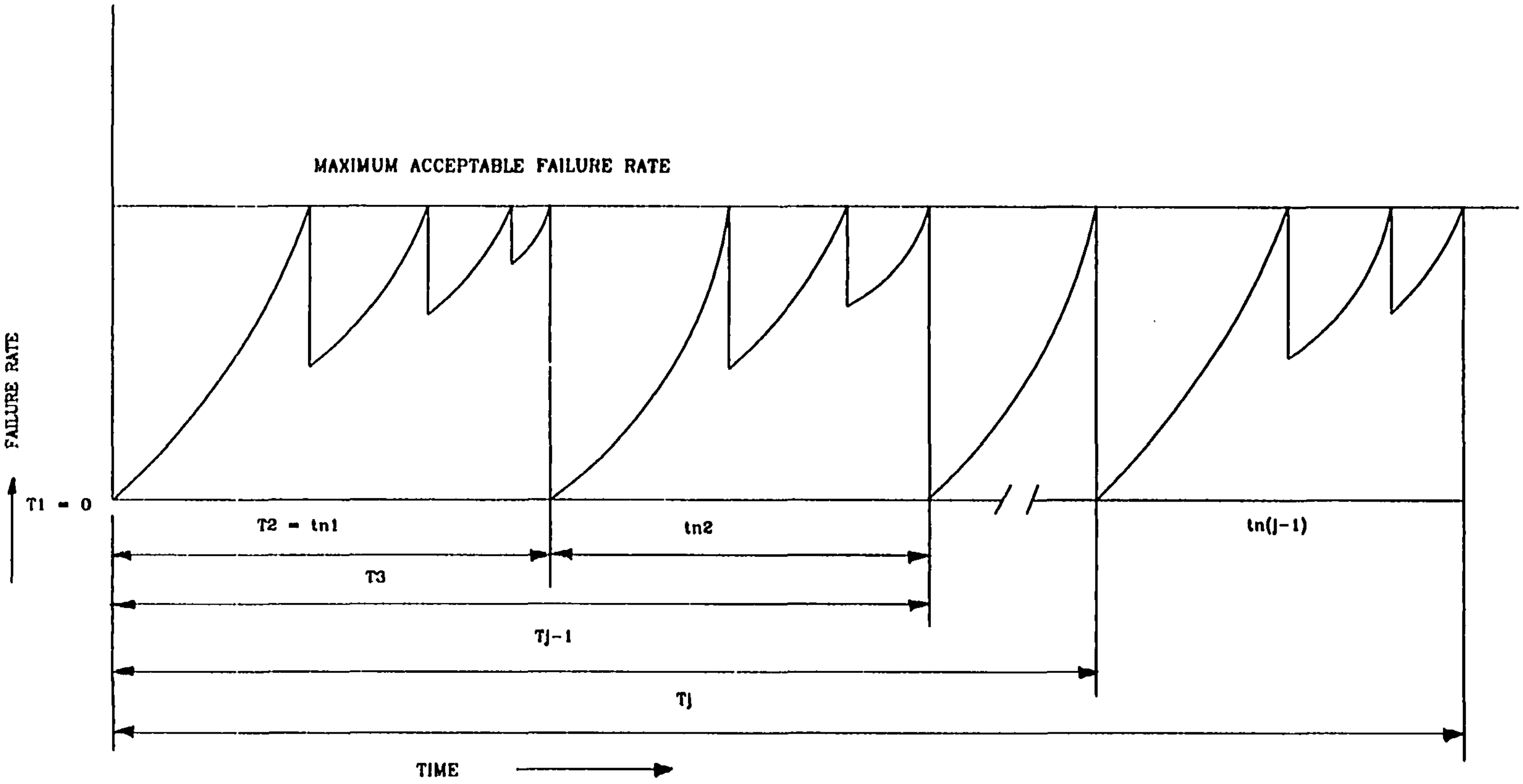

FIGURE 8 NUMBER OF 1P-MAINTENANCES BETWEEN EACH 2P-MAINTENANCE

Total cost can be calculated, when $t_{(n)1} >= T_{max}$

$$TC_1 = C_1 + C_1 r_2 (n_1 - 1)$$

When the system is replaced by a new one at time T_2 at cost C_2, the total cost for the replacement of the system will be:

$$TC_2 = TC_1 + C_2 + C_2 r_2 n_2 - C_2 r_2$$

where $T_2 + t_{n(2)} >= T_{max}$

Similarly, in general the total cost for the jth replacement is:

$$TC_j = TC_{j-1} + C_j[1 + r_2(n_j - 1)]$$

where $T_j + t_{n(j)} >= T_{max}$.

This method minimizes the average total cost, the number of replacements, and the number of 1P-maintenance events between each replacement for the given planning period.

Chapter V

Numerical Example

A. Determining the 1P-Maintenance Scheduled Times

To determine the scheduled 1P-maintenance times, one needs to know the improvement factor and the period the system first reaches its maximum failure rate (λ_{max}). The improvement factor depends upon the type of equipment. For example, electro-mechanical equipment is subject to more wear and tear, as compared to equipment whose functions are mostly electronic. In such a case the improvement factor would be higher than that of an electronically operated system. The improvement factor can play a vital role in the scheduling of preventive maintenance. The concept of maximum failure in this model is dependent upon the recommendation of the manufacturer or service department. It's obvious that there are some rules for each equipment, for example when the first preventive maintenance is required for that specific equipment after its installation and operation.

As a numerical example, consider the case where (γ) = 6 and (t_1) = 1.5. Using (1), the second 1P-maintenance time will be found as:

$$t_2 = 1.5 + (1-1/6)1.5 = 2.7500$$

Table 3 shows the first fifteen scheduled 1P-maintenance times as calculated using (2).

The scheduled 1P-maintenance times are also plotted in Figure 9. The reduction in failure rates (R_i) after each maintenance, and reduction in effetive age(D_i) after each scheduled maintenance as calculated using (3) and (4), are computed in Table 4 and plotted in Figure 10.

This model clearly indicates the need to replace the equipment, when the time difference between the last and the next due maintenance becomes minimal. As shown on the graph, the equipment or system becomes increasingly faulty over time, i.e., the time difference between t_5 and t_6 maintenance is considerably less than that between t_1 and t_2. Note that after every 1P-maintenance the reduction in failure rate decreases as shown in Figure 10. The first 1P-maintenance is due when the maximum failure rate (λ_{max}) reaches to its maximum for the first time.

B. Determining the Time of 2P-Maintenance

Deciding on the best time to replace the equipment depends upon two factors. One is the cost comparison between the maintenance cost and the total replacement cost. The other factor is the estimated life of the equipment.

To calculate the acquisition cost of the system, r_1 is introduced (annual rate of increase in acquisition cost of the system or equipment). In this numerical example,

Period of Years (t_n)	**Maintenance Time** $t_i = t_1 + t_1(1-1/\gamma)^{n-1}$
t_1	1.5000
t_2	2.7500
t_3	3.7916
t_4	4.6597
t_5	5.3831
t_6	5.9859
t_7	6.4882
t_8	6.9068
t_9	7.2557
t_{10}	7.5464
t_{11}	7.7887
t_{12}	7.9905
t_{13}	8.1588
t_{14}	8.2990

TABLE 3 Scheuled 1P-Maintenance Times

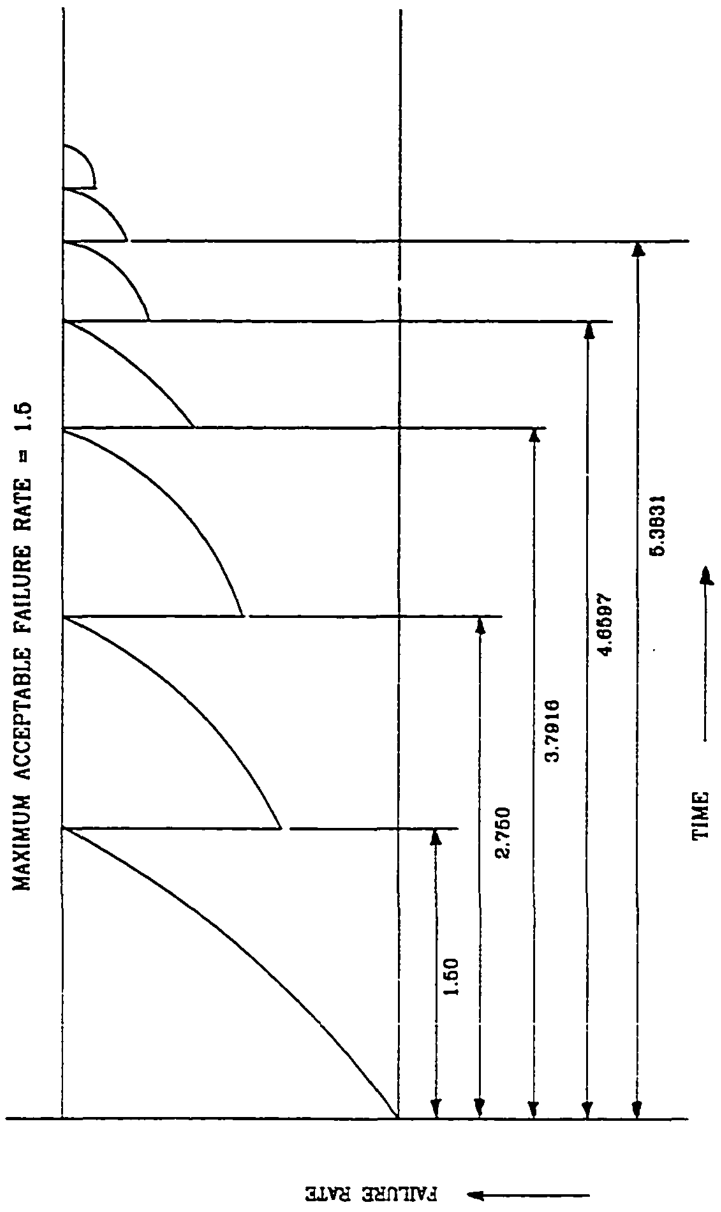

FIGURE 9 SCHEDULED 1P--MAINTENANCE TIMES

Period	**Reduction in Failure Rate** $R_i = t_1(1-1/\gamma)^{n-1}$	**Reduction in Effective Age** $D_i = t_1 - t_1(1-1/\gamma)^{n-1}$
1	1.5000	0.00
2	1.2500	0.2500
3	1.0416	0.4583
4	0.8680	0.6319
5	0.7233	0.7766
6	0.6028	0.8971
7	0.5023	0.9976
8	0.4186	1.0813
9	0.3488	1.1511
10	0.2907	1.2092
11	0.2422	1.2577
12	0.2018	1.2981
13	0.1682	1.3317
14	0.1401	1.3598

TABLE 4 Reduction in Failure Rate and Effeective System age after Each 1P-Maintenance

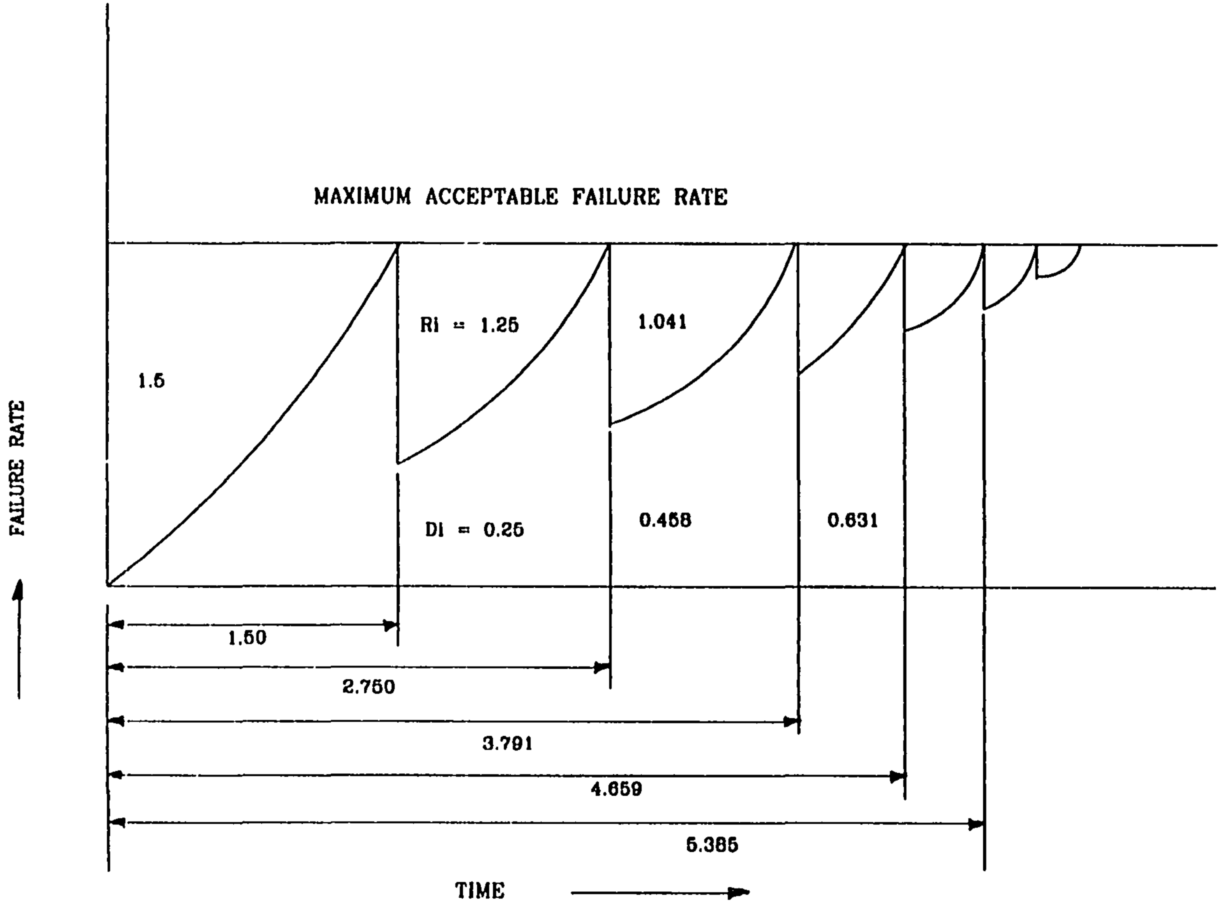

FIGURE 10 REDUCTION IN FAILURE RATE & REDUCTION IN EFFECTIVE AGE

assumed $r_1 = 0.1$, and $C_1 = 1000$. The acquisition cost is calculated as:

$$C_j = C_1(1 + r_1(t_n))$$

$$C_2 = 1000(1 + 0.1(1.5)) = \$1150.00$$

Table 5 shows the acquisition cost of the equipment or system. The maintenance cost of the system at each preventive maintenance period has been calculated by using the maintenance cost factor (r_2), here assumed to be 0.2, and acquisition cost of the system. Table 6 shows the maintenance cost of the first fifteen 1P-maintenances, as calculated using:

$$M_i = C_j{*}r_2$$

For example:

$$M_1 = 1150{*}0.2 = \$230.00$$

As shown in Table 7, the total cost of the system has been calculated as:

$$TC = C_1{*}(1+r_2)$$

For example:

$$TC_1 = 1000{*}(1+0.2) = \$1200.00$$

A comparison of cumulative cost and maintenance cost is shown in Table 8. This comparison shows that if the cumulative cost for the maintenance exceeds the replacement cost of the system, then replacement is needed.

Period of Years (t_n)	**Maintenance Time** $t_i = t_1 + t_1(1-1/\gamma)^{n-1}$	**Acquisition Cost of the System** $C_j = C_1(1 + r_1(t_n))$
t_1	1.5000	$1150.000
t_2	2.7500	$1275.000
t_3	3.7916	$1379.166
t_4	4.6597	$1465.972
t_5	5.3831	$1538.310
t_6	5.9859	$1598.591
t_7	6.4882	$1648.826
t_8	6.9068	$1690.688
t_9	7.2557	$1725.573
t_{10}	7.5464	$1754.645
t_{11}	7.7887	$1778.870
t_{12}	7.9905	$1799.059
t_{13}	8.1588	$1815.882
t_{14}	8.2990	$1829.902

TABLE 5 Acquisition Cost of the System

Period of Years (t_n)	**Acquisition Cost of the System** $C_j = C_1(1 + r_1(t_n))$	**Maintenance Cost** $M_i = C_j * r_2$
t_1	\$1150.000	\$230.000
t_2	\$1275.000	\$255.000
t_3	\$1379.166	\$275.833
t_4	\$1465.972	\$293.194
t_5	\$1538.310	\$307.662
t_6	\$1598.591	\$319.718
t_7	\$1648.826	\$329.765
t_8	\$1690.688	\$338.137
t_9	\$1725.573	\$345.114
t_{10}	\$1754.645	\$350.929
t_{11}	\$1778.870	\$355.774
t_{12}	\$1799.059	\$359.811
t_{13}	\$1815.882	\$363.176
t_{14}	\$1829.902	\$365.980

TABLE 6 Acquisition Cost & Maintenance Cost of the System

Maintenace Cost $M_i = C_j * r_2$	**Cumulative Maintenance Cost** $A_i = A_{i-1} + M_i$	**Total Cost** $TC = C_1 * (1 + r_2)$	**Replacement**
$230.000	$230.000	$1200.00	0.00
$255.000	$485.000	$1200.00	0.00
$275.833	$760.833	$1200.00	0.00
$293.194	$1054.027	$1200.00	0.00
$307.662	$1361.689	$1200.00	1
$319.718	$1681.408	$1200.00	1
$329.765	$2011.173	$1200.00	1
$338.137	$2349.311	$1200.00	1
$345.114	$2694.426	$1200.00	1
$350.929	$3045.354	$1200.00	1
$355.774	$3401.129	$1200.00	1
$359.811	$3760.940	$1200.00	1
$363.176	$4124.117	$1200.00	1
$365.980	$4490.097	$1200.00	1

TABLE 7 Cumulative Maintenance Cost, Total Cost & Replacement Unit

Cumulative Maintenance Cost $A_i = A_{i-1} + M_i$	**Maintenance Time** $t_i = t_1 + t_1(1-1/\gamma)^{n-1}$	**Total Cost** $TC = C_1 * (1 + r_2)$
$230.000	1.5	$1200.00
$485.000	2.75	$1200.00
$760.833	3.7916	$1200.00
$1054.027	4.6597	$1200.00
$1361.689	5.3831	$1200.00
$1681.408	5.9859	$1200.00
$2011.173	6.4882	$1200.00
$2349.311	6.9068	$1200.00
$2694.426	7.2557	$1200.00
$3045.354	7.5464	$1200.00
$3401.129	7.7887	$1200.00
$3760.940	7.9905	$1200.00
$4124.117	8.1588	$1200.00
$4490.097	8.299	$1200.00

TABLE 8 Cumulative Maintenance Cost, Maintenance Time & Total Cost

While 1P-maintenance does improve the life of the equipment it does not return it to good as new. Instead of doing further 1P-maintenance, it is better to replace the equipment at the time when maintenance costs exceed the replacement cost. Table 8 shows that at time 5.383 years, i.e., the fifth maintenance event, the cumulative maintenance cost ($1361.68) exceeds the replacement cost ($1200). As a result, 2P-maintenance should be performed at this time.

As in this model, the time of the replacement depends upon two factors, the cost comparison between the cumulative maintenance cost and total cost; and upon the life cycle of the equipment or system. However, the second factor may be eliminated, due to the requirement of upgrading the equipment. Although the equipment life given by suppliers may be five years, due to quickly changing technology, equipment could require replacement before reaching its maximum life. So, especially for hospital equipment, the life cycle is not as important, since the equipment will probably be replaced earlier because of technology improvements.

C. Computational Experience

A computer program has been developed in C language to calculate the following factors: the scheduled 1P-maintenance time, acquisition cost of the system, maintenance cost of the system, replacement cost of the system, reduction in effective age, reduction in failure rate, cumulative maintenance cost, and time of replacement of the system. A listing of the source code is given in Appendix .

This program starts with the requirement of certain input data. First, the user must enter the number of 1P-maintenances, the maximum failure rate, the improvement factor, the maintenance cost factor, the annual increase in acquisition cost factor, and the initial cost of the system. Upon entering the above mentioned parameters, the program calculates the scheduled 1P-maintenance times, acquisition cost of the system, maintenance cost of the system, replacement cost of the system, drop of failure rate, reduction in failure rate, cumulative maintenance cost, and time of replacement of the system for the stated number of 1P-maintenances.

Chapter VI

CONCLUSIONS

A. Overview

Implementing planned maintenance programs in hospitals is no longer optional. Rather, it is essential as hospitals become increasingly dependent upon emerging technologies in the field of Biomedical Engineering. To execute a planned maintenance program, skill and unity are required. However, the success of the program depends upon the way management deals with the system, and the committment of the staff to the policy of planned maintenance.

There are numerous preventive maintenance programs currently in use in many hospitals. However, when one evaluates them in detail, it becomes apparent that there is a need for a more cost efficient and systematic approach to maintaining availability of hospital equipment.

The engineering department of a hospital can play a vital role in minimizing the overall cost of equipment in a hospital. With regard to improving the performance and life cycles of the equipment, it is important to apply a methodology which gives a fair idea of how much money will be required to maintain the system, facility, or equipment.

There is also a need to develop a model for maintaining medical equipment that will ensure its constant availability. The model should cover all vital problems, such as: due time of preventive maintenance of each equipment; cost estimation of each PM (preventive maintenance); technical staff required to maintain the facility; availability of equipment; and the requirement of equipment according to the facility. This model can be applicable to each and every department of a hospital, depending upon the equipment they have in their department.

This thesis has examined the first two aspects of such a model: establishing the due time of each preventive maintenance of equipment, and cost estimation of each preventive maintenance. The remaining areas of this model will be presented in the author's upcoming dissertation.

B. Recommendations for Further Study

The methodology developed by Jayabalan and Dipak can be improved by introducing two factors: the interest rate and cost of failure. In their assumptions, the interest rate has been neglected and also the cost of failure is zero (repair time is negligible). These two factors, if considered, can greatly affect the total cost and maintenance cost.

The methodology to calculate the time for 1P-maintenances is dependent upon the failure rate (λ_{max}), and is taken as constant. But Figure 7 shows that when the first replacement is being done, the maximum failure rate is still the same. As technology changes rapidly, one cannot treat the system or equipment the same as it was previously treated. So, the failure rate will be different after each replacement, as was shown in Figure 11. Also, after each replacement, the failure rate cannot be assumed to be constant. Rather, it will be changing according to the upgrading of the technology.

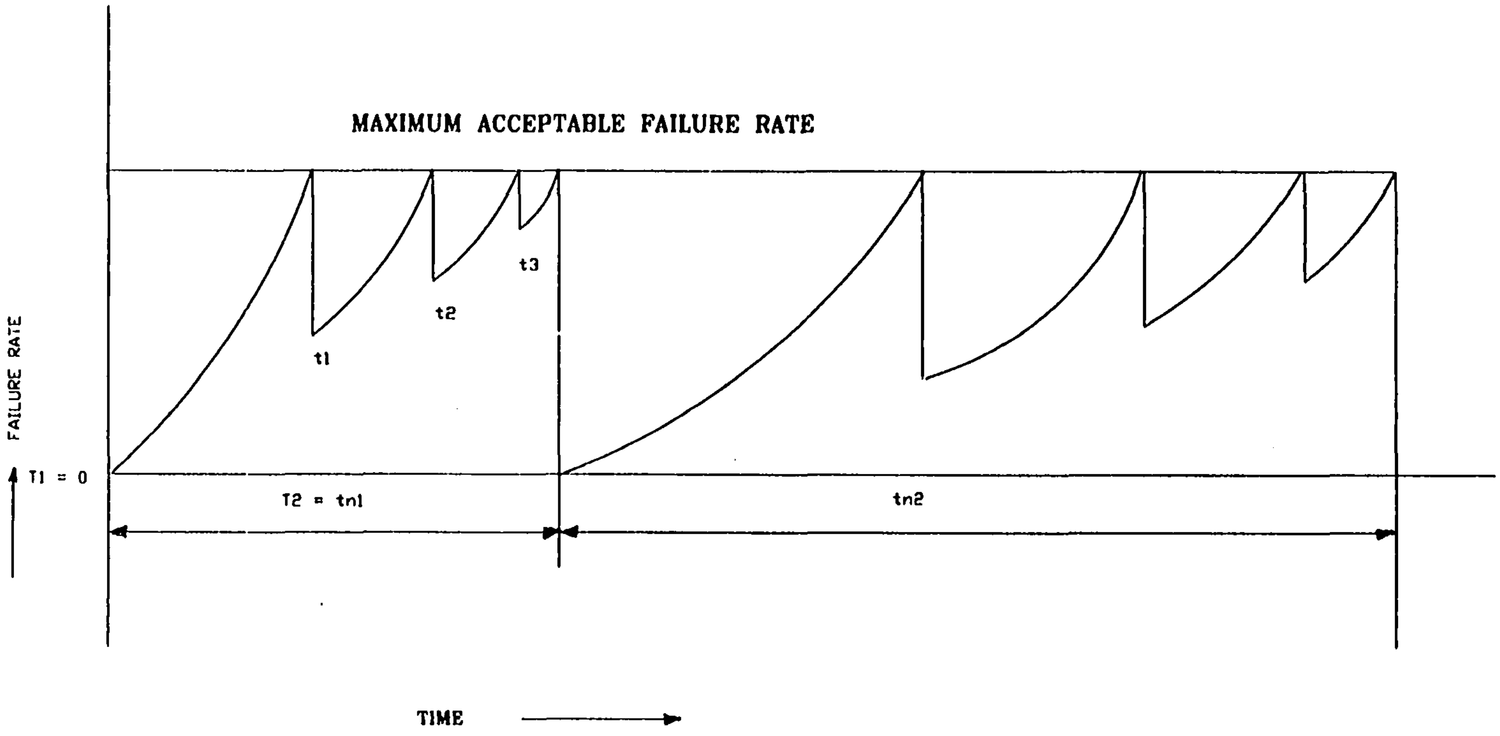

FIGURE 11. NUMBER OF 1P-MAINTENANCES BETWEEN EACH 2P-MAINTENANCE

Thus, the area of preventive maintenance modeling is in great need of further research efforts. Only by such efforts can the medical field hope to improve operations, increase system effectiveness, and at the same time reduce overall cost.

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APPENDIX

```
# include <stdio.h>

# include <stdlib.h>

# include <math.h>


main()


    {

        float *R, *D, r, *t, *C, *T, *TC, *G, r1, r2, C1;

        int i, n, x;

        G = (float*) malloc(sizeof (float) * n);

        R = (float*) malloc(sizeof (float) * n);

        t = (float*) malloc(sizeof (float) * n);

        D = (float*) malloc(sizeof (float) * n);

        C = (float*) malloc(sizeof (float) * n);

        T = (float*) malloc(sizeof (float) * n);

        TC = (float*) malloc(sizeof (float) * n);


        printf("Enter the value of n :");

        scanf("%f", &n);

        printf(" Enter the value of maximum failure rate:");
```

```
scanf("%f", &t[1]);

printf(" Enter the value of improvement factor:");

scanf("%f", &r);

printf(" Enter the value of maintenance factor:");

scanf("%f", &r2);

printf( "Enter the value of annual increase in cost of the system:");

scanf("%f", &r1);

printf( "Enter the value of initial cost of the system:");

scanf("%f", &r1);

printf( "Maintenance Time    Reduction in Failure Rate Reduction in

        Effective Age\n");


for (i=1; i<n; ++i

{

        t[i] = t[i-1] + R[i];

        R[i] = t[1]*pow( (double)(1-1/r), (double)(i-1));

        D[i] = t[1] - R[i];

printf("%5f %15f %25f\n", t[i], R[i], D[i]);

}

printf(" Acquisition Cost of the System    Maintenance Cost\n");

for (i=1; i<n; ++i);
```

```
        {
            C[i] = C1*(1+r1*t[i]):
            G[i] = C[i]*r2;
        printf("%5f %15f\n", C[i], G[i] );
        }

        printf(" Maintenance Cost    Cumulative Maintenance Cost
            Total Cost   Replacement Time");
        for (i=1; i<n; ++i);
        }
            G[i] = C[i]*r2;
            T[i] = T[i-1] + G[i];
            TC[i] = C1*(1+r2);
        if ( TC[i] >= T[i])
            x = 0
            else
            x = 1
        printf("%5f %15f %25f %20f\n", G[i], T[i], TC[i], x);
        }
    }
```

VITA

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