2

EVALUATION OF MODELS FOR DECISION MAKING IN INSPECTION AND REPAIR MAINTENANCE

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MARCH 1987

Submitted to the University of Cape Town in partial fulfillment of the requirements for the degree of Master of Science in Engineering

I, W.D. Coxon, submit this thesis for the degree of Master of Science in Engineering. I claim that this is my original work and that it has not been submitted in this or in a similar form for a degree at any University.

ABSTRACT

There has been growth in the costs of maintenance over the last 40 years. This can be linked directly to the changes in production technology over that period of time. However, there has also been growth in the field of management science and operations research. Many models have been developed to assist the maintenance function in its decisions. However, it would appear, from engineering journals and shop floor practice, that these models are not well used.

For this research the method of inspection and repair maintenance has been chosen. Mainly because it is one of the most widely used methods. The objectives of the research are as follows:

[1] To investigate the state of the art of plant and equipment maintenance paying particular attention to the inspection and repair policy.

[2] To establish what basic models are available for decision making in inspection and repair maintenance.

[3] To establish how feasible and useful each of these models is in the practical engineering environment.

[4] To consider factors in the implementation of a decision making model in the inspection and repair policy with particular reference to the most practical and feasible model investigated.

Three models were selected as being representative of work in the field. All three are used for determining the optimal inspection interval for plant and equipment. They are:

[1] The Reliability Function Model - This uses a direct relationship between the breakdown rate and inspection frequency for an economic decision.

[2] The Delay-Time Model - This uses the p.d.f of the delay-time as a basis for an economic decision. The delay-time being the duration of a fault from inception to catastrophic failure.

[3] The Markov Model - This uses a markov chain and defines the equipment as being in any one of a number of states. The cost of occupying or transferring states is used to make the economic decision.

The delay-time model was found to be the most practical and useful for implementation in an engineering context. The input data is easily available and it makes good use of the skill of the p.m. inspector.

Some of the practical aspects of implementing the delay-time model are also discussed. These include such aspects as the use of an information system and staffing.

In conclusion it was stated that decisions in the field of inspection and repair maintenance can be quantified. It was also recognised, however, that it is much more difficult to control and quantify many aspects of maintenance than production. However, this should be a challenge as the potential savings from any improvements are great.

A four point plan was recommended for the improvement of the maintenance function of any organization.

[1] Conduct a Maintenance Audit
[2] Employ the right staff
[3] Decide on scope and extent of changes
[4] Control and decision making must be linked.

It is hoped that this research has contributed to the bridging of the gap between the academic approach to maintenance and shop floor practice.

ACKNOWLEGEMENTS

Thanks are extended to the following:

Mr. W. Jervis of the University of Cape Town for his guidance as supervisor.

My employers, The South African Transport Services for their co-operation in this research.

CONTENTS

Page

1. INTRODUCTION 1

2. LITERATURE SURVEY 3

3. MAINTENANCE POLICIES 5
3.1 INTRODUCTION 5

3.2 DESCRIPTION OF MAINTENANCE POLICIES 6
3.2.1 Corrective Repair 6
3.2.2 Corrective - Opportunity Repair 6
3.2.3 Preventative - Inspection and Repair 6
3.2.4 Condition Monitoring 6
3.2.5 Preventative Replacement 7
3.2.6 Shut Down 7

3.3. SELECTION OF A POLICY 7
3.3.1 Factors to be Considered 7
3.3.2 The Decision Process 9

4. THE INSPECTION AND REPAIR POLICY 11
4.1 THE PURPOSE OF THE INSPECTION 11

4.2 INSPECTION AND REPAIR AND RELIABILITY 11

4.3 THE INSPECTION FREQUENCY 13
4.3.1 Cost and Reliability 13
4.3.2 Manufacturer's Manuals 14

5. MODELS IN THE INSPECTION AND REPAIR POLICY 15
5.1 INTRODUCTION 15

5.2 THE RELIABILITY FUNCTION MODEL 15
5.2.1 The Basic Model Concept 15
5.2.2 Data Required 16
5.2.3 Assumptions and Formulation 17

5.3 THE DELAY TIME MODEL 18
5.3.1 The Basic Model Concept 18
5.3.2 Data Required 19
5.3.3 Assumptions and Formulation 20

5.4 THE MARKOV MODEL 22
5.4.1 The Basic Model Concept 22
5.4.2 Data Required 22
5.4.3 Assumptions and Formulation 23

Page

6 EVALUATION OF THE MODELS IN THE INSPECTION AND REPAIR POLICY 25
6.1 INTRODUCTION 25

6.2 BASIC MODEL CONCEPT 25

6.3 DATA COLLECTION AND AVAILABILITY 27
6.3.1 Cost Related Data 27
6.3.2 Reliability Related Data 28

6.4 ACCURACY OF THE DECISION 30

6.5 DATA PROCESSING 31

6.6 THE P.M. INSPECTOR 33

6.7 CONCLUSION 34

7. IMPLEMENTING THE SYSTEM 35

7.1 INTRODUCTION 35

7.2 INFORMATION SYSTEM 35
7.2.1 The Paperwork 36
7.2.2 The Feedback System 36
7.2.3 The Data Used 37

7.3 MAINTENANCE STAFF 38
7.3.1 The Type of Staff 38
7.3.2 Training of Staff 40
7.3.3 Staff Control 40
7.3.3.1 Method Study 41
7.3.3.2 Time Study 41

7.4 MAINTENANCE RESOURCES 42
7.4.1 Tradeforce Location 42
7.4.2 Tradeforce Size 43
7.4.3 Work Scheduling 43

7.5 MAINTENANCE AND MANAGEMENT 44
7.5.1 Management Commitment 44
7.5.2 Organizational Structure 45

7.6 PRODUCTION AND MAINTENANCE 46

7.7 CONCLUSION 47

8. CONCLUSIONS 48

9 RECOMMENDATIONS 50

10. FUTURE STUDY 52

Page

REFERENCES 54

BIBLIOGRAPHY 57

APPENDIX A - Formulation for the Reliability Function Model

APPENDIX B - Numerical Example using the Reliability Function Model

APPENDIX C - Forumulation for the Delay-Time Model

APPENDIX D - Numerical Example using the Delay-Time Model

APPENDIX E - Notation used in Formulas

LIST OF ILLUSTRATIONS

Figures Page

3.1 Maintenance Structure 5
4.1 The "Bath-Tub" curve 12
4.2 Maintenance and Total Plant Cost 14
5.1 The Reliability Function 16
6.1 Obtaining The Reliability Function 29
A-1 The Affect of Inspection Frequency on Costs
C-1 The Incidence of a Breakdown

CHAPTER ONE

INTRODUCTION

The growth in the costs of maintenance over the last 40 years are directly related to the changes in production technology over that period. The second world war stimulated a phenomenal growth in the manufacturing industries. This was accompanied by a proportional increase in investment in machinery and equipment. The advent of the microchip and the computer lifted the ceiling on investment in plant again.

All these developments have placed increasing demands on the plant maintenance function. The physical quantity to be maintained has increased and the availability of this new generation plant is required to be much higher. In the United Kingdom estimates put the 1970 expenditure on maintenance by industry at £1100 million (Ref.1). Inflation alone would put that figure at well over £5000 million today. This is just raw expenditure on maintenance and does not take into account the effect of maintenance on the production account.

The political and economic developments in South Africa over the last few years have further increased the importance of the maintenance function. The difficulty of obtaining certain plant both in terms of the availability of suppliers willing to sell to South Africa, and the cost at prevailing exchange rates has forced organizations to make their plant last. The effect of these changes is still to be felt by maintenance organizations.

These developments in hardware have not been the only developments. Management science has had to grow as well. Managers now have more quantitative techniques available to them. However, a survey by Management Today (Ref.2) has shown that most managers make little use of these techniques. There is a mismatch between the academics' proposals and the managers' perceived needs. This reflects both the academics idealized view of life and the managers ignorance of what is available.

Nowhere is this contrast better to be seen than in the field of maintenance management. Much work has been done by academics in the fields of mathematical statistics and operations research as regards models for maintenance decision making. However, in the engineering journals and on the shop floor there seems to be little knowledge of these models or desire to use them. The current method of decision making relies on experience and the ability to translate that experience into a decision.

For this research the field of inspection and repair maintenance has been chosen. The objectives of the research are as follows:

[1] To investigate the state of the art of plant and equipment maintenance practice paying particular attention to the inspection and repair policy.

[2] To establish what basic models are available for decision making in inspection repair maintenance.

[3] To establish how feasible and useful each of these models is in the practical engineering environment.

[4] To consider factors in the implementation of a decision making model in the inspection and repair policy with particular reference to the most practical and feasible model investigated.

The research will be approached from an engineering point of view. While mathematics is involved this is essentially an engineering research project.

It is hoped that this work will make a contribution to bridging the gap between academics proposals and the engineering managers' needs.

CHAPTER TWO

LITERATURE SURVEY

A quantitative approach to maintenance management really began with the advent of operations research in the second world war. Much of the real growth in the field was precipitated by the advent of computer facilities. Some of the earliest work still of applicability today is by Barlow and Proschan (Ref.3) in their book "The Mathematical Theory of Reliability". They used reliability theory to help in the decision as to the frequency maintenance activities.

The concept of maintenance has been with us since the industrial revolution. As far back as 1931 there have been journals dedicated to the subject. These journals have dealt with the more practical aspects of maintenance and still do to this day. Often they review the basics of maintenance such as the steps to establishing a P.M. programme, as does Anderica in Plant Engineering (Ref.4). The more academic journals look at problems such as scheduling the workload of the maintenance department or setting time standards for this type of work (Refs.5&6).

The advent of the computer and particularly of the mini- and microcomputer has created a void in the knowledge of many in maintenance management. The engineering journals have moved in to fill this gap with articles such as that by Holden in Plant Engineering(Ref.7)

However, it is only the more academic journals that deal with decision making aspects of maintenance. Much of the work in the field of maintenance decision making involves decisions as to the optimal replacement intervals of components of equipment. (This and other maintenance policies are described in detail in section 3.2). Rueda and Miller review much of the work done in this field in Ref. 8. A more detailed review of one method of selecting an optimal part replacement policy is given by Knezevic in Ref. 9.

Most organizations, however, do not use an optimal part replacement policy, but an inspection and repair policy. It would appear, from the availability of literature in this field, that less work has been done here than in the optimal part replacement policy.

Jardine (Ref. 10 & 11) is one of the most widely published authors. In his book he deals with a spectrum of maintenance policies and methods of decision making for each of them. His method of decision making in inspection and repair (The reliability function model) is one of three examined in detail in this thesis. Christer and Waller have done much work in this field both in its application to building and industrial maintenance (Ref. 12 & 13). Their model is known as the Delay-Time model. One further model in the field is based on Markov processes. This is dealt with by Luss (Ref. 14) and Lapin (Ref. 15).

Much work has been done in the field of the philosophy of maintenance. As technologies have changed and maintenance costs increased, it has become necessary to set objectives for maintenance Labouchere (Ref. 16), in his set of articles entitled "What maintenance is worthwhile and When" sets about to define the objectives of maintenance. Kelly and Harris also deal with the subject in their book, "The Management of Industrial Maintenance".

CHAPTER THREE

MAINTENANCE POLICIES

3.1 INTRODUCTION

There are a number of different maintenance policies used by organization today. However, these fall into two broad categories: (1) Corrective maintenance and (2) Preventive maintenance. In the first maintenance is only done as a result of a breakdown. In the second maintenance is carried out in order to prevent breakdowns. A system is thus designed whereby money is invested in preventative maintenance in order that it may yield returns in the reduction of breakdowns and the costs associated with such breakdowns.

A structure of the basic maintenance policies is given in Fig. 3.1 A description of each is given in the next section.

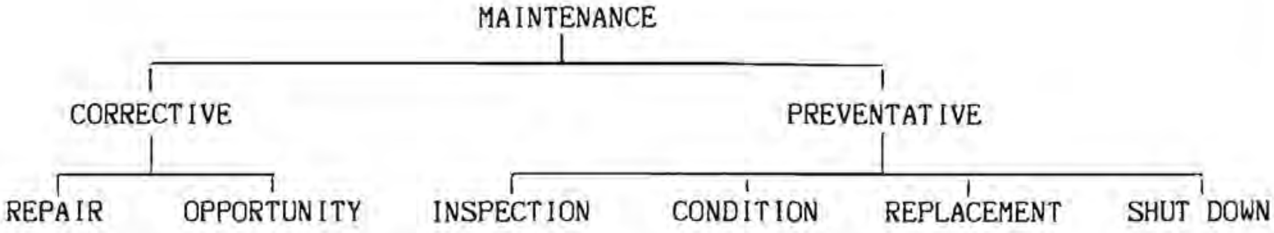


Fig. 3.1 MAINTENANCE STRUCTURE

3.2 DESCRIPTION OF MAINTENANCE POLICIES

3.2.1 Corrective Repair

Minimal action is taken to prevent failure. This is usually in the form of lubrication or belt tensioning. The emphasis is rather on efficient and effective repair after a breakdown. After a breakdown only those repairs necessary to restore the equipment to its prior condition are done.

3.2.2 Corrective - Opportunity Repair

This is similar to the corrective - repair policy in that little is done to prevent failure. However here, after a breakdown, the opportunity is taken to service items other than those that were the cause of the breakdown. For example: on a lathe, a burst oil seal may require the machine to be repaired. The artisan then takes the opportunity to replace a bearing in the gearbox that he notes is worn.

3.2.3 Preventative - Inspection and Repair

Equipment is inspected at regular intervals. Repairs or component replacements are recommended on the basis of inspections. The duration of the interval between inspections needs to be decided. Models that help in making this decision will be dealt with in detail in later sections.

3.2.4 Condition Monitoring

The condition of equipment is analysed continually or at frequent intervals. This is done using various types of transducers, circuitry and recording devices. The data provided by such monitoring can be used to predict imminent failure of components, or the need for service, very accurately.

3.2.5 Preventative Replacement

Equipment components are replaced before they fail. Normally, certain critical components are identified and, from failure data and reliability theory, their life is estimated. Taking into account the costs involved, their replacement is planned before their probability of failure is too high. (i.e. before the component is likely to fail).

3.2.6 Shut Down

An entire plant or section of a plant is shut down for a period. The plant is stripped down and components replaced where necessary. This is normally done with large and complex plant where it is difficult to isolate single machines without stopping production. A shut down is normally a few weeks long and done every 2 or 3 years. This type of maintenance must obviously be done in conjunction with one of the other maintenance policies, for the period between shut downs.

3.3. SELECTION OF A POLICY

In practice different maintenance policies are used for different types of equipment. A company that uses a preventative replacement policy for its production equipment would consider it ridiculous to use such a policy in maintaining the electric wall sockets in its drawing office.

3.3.1 Factors to be Considered

The decision on which maintenance policy to use is essentially one of investment and returns. Looking at Fig. 3.1 (page 5), it can be said that the policies increase in the extent of their resource investment from left to right. A corrective repair policy invests little resources in the future well being of the equipment. Money is only spent when it has to be, that is when the equipment breaks down. In the shut down maintenance policy vast amounts of money and time are invested in restoring the equipment to a good condition. This is invested in the hope that the equipment will continue to run for a long period with minimal attention.

The decision to use a shut down policy rather than a corrective repair policy (or a policy with a high investment rather than one with a low investment) is obviously made with the expectation of greater returns. These returns essentially come from three sources:

(1) A Reduction in the Cost of Breakdown Repairs:
Repairs after a breakdown are generally more expensive than those same repairs would have been if they had been done on a preventative basis. This is partly because damage has been caused to other components and partly because preventative repairs can be scheduled and thus use labour more efficiently.

(2) Reduction in Running Costs:
On some equipment, as components wear, the running cost of the plant increases. This increase is seen both in the increased energy consumption and/or in the poor performance of the equipment (i.e. reject items being produced or premature tool and die wear.)

(3) Reduction in Unproductive Downtime.
Equipment is generally bought because it can contribute to the profitability of the enterprise. Thus when such equipment is broken down profit is being lost because of the lost production. This problem becomes more acute when customer deadlines need to be met. If products are delivered late because of a breakdown, the downtime cost of the breakdown also includes the unquantified cost of goodwill. For machines linked in a production

line we need to consider the consequential downtime cost. If one machine breaks down all the machines are affected as a result. The consequential downtime cost is thus the downtime cost of all the machines in the production line affected.

The ratio of breakdown repair cost to preventative repair cost does not vary much from machine to machine. This cost is thus not a significant one in deciding which policy to use. The running cost is not a factor for many machines, but where it is, it could be fairly significant in the decision. The downtime cost of equipment varies greatly from thousands of rands per hour for some production lines, to almost negligible cost for items like bench grinders, where many are available in one workshop.

3.3.2 The Decision Process

It can thus be said that the decision as to what type of maintenance policy to use is based, to a large extent, on the downtime cost of the equipment in question. Thus in general items with low downtime costs such as extractor fans and bench grinders are repaired on a corrective basis.

Mechanical production lines, chemical process plants and other equipment with high downtime costs and consequential downtime costs are maintained on the shut-down, replacement or condition monitoring policies. Here other factors are considered such as the availability of statistical data for a replacement policy or the ease with which relevant parameters can be measured for condition monitoring.

Equipment in the average range of downtime costs is generally maintained on an inspection and repair basis. Thus motor cars and general machine shop equipment is maintained on this basis.

There are other non-quantifiable factors that organizations take into account. One of these is staff morale. The image of the company is another. These factors obviously bias any decision making process. In addition there are many instances in which it is necessary to use an overlap of policies. However, the decision to invest in some form of preventative maintenance should always be based, to a large extent, on expected return.

CHAPTER FOUR

THE INSPECTION AND REPAIR POLICY

4.1 THE PURPOSE OF THE INSPECTION

From the previous section it can be seen that any type of preventative maintenance policy involves an investment with the expectation of a return. In the inspection and repair policy the investment is the inspection and the repairs done as a result of the inspection. The return is the reduction in breakdown repairs.

According to Labouchere (Ref 16), there are four main reasons for carrying out maintenance.

1. To improve reliability
2. To reduce running cost
3. To improve performance
4. To extend the life of plant or equipment.

From section 3.3.1 we see that the cost of unreliability is high in terms of downtime costs. Thus improving reliability is usually the prime purpose of maintenance. It would seem logical to say, in terms of the investment and returns analogy, that the higher the investment the better the equipment reliability. This must obviously be within the limits of the equipments inherent reliability. Thus the more frequent the inspections (within a certain range) the better the equipment reliability.

4.2 INSPECTION AND REPAIR AND RELIABILITY

Most of the work done in the field of maintenance and reliability relates to preventative replacement policies (see section 3.2.5). Here the classical "bath-tub" curve, as shown in Fig. 4.1, is applicable.

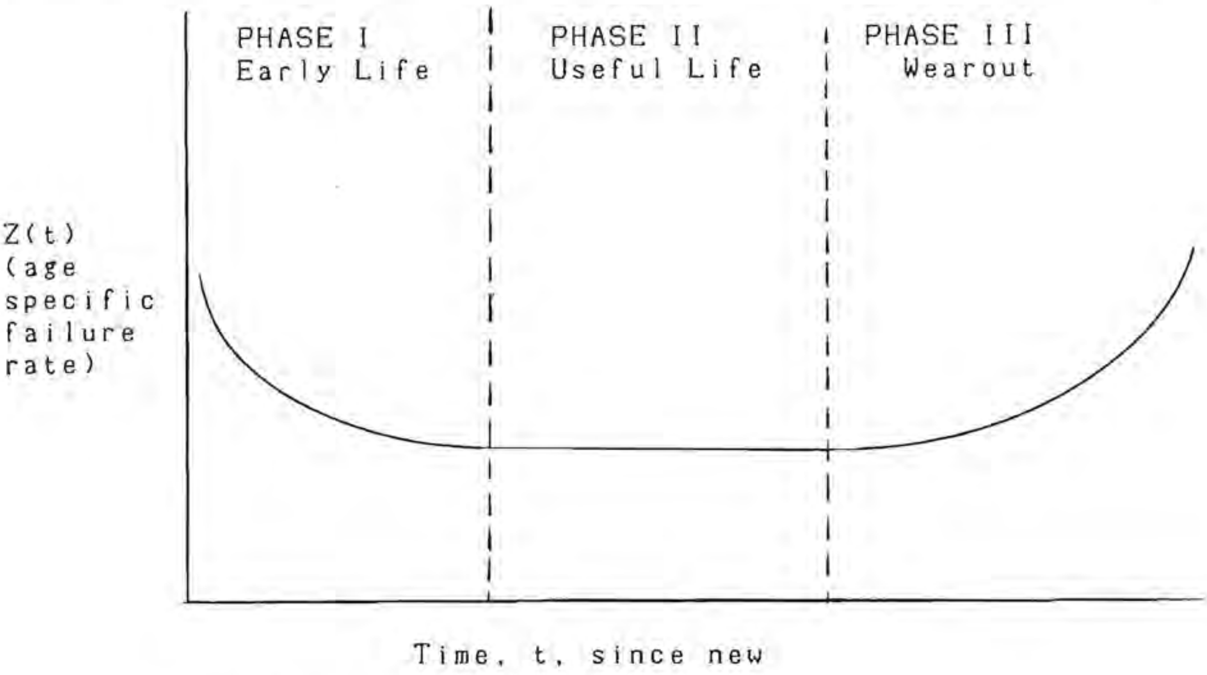


Fig. 4.1 THE BATH TUB CURVE

The age specific failure rate (i.e. the likelihood of failure at any particular age) is evaluated: A high likelihood of failure in the early life of the component, a low probability of failure for most of its useful life and then a decrease in reliability near the end of its life. It is important to note that this curve refers to the life of a single component.
Although intuition tells us that the probability of a breakdown between inspections follows a similar curve.

However, in the inspection and repair policy, components are not replaced because of an increased statistical likelihood of failure. The only reason they are replaced is because they are worn. But, it is important to note that equipment is inspected because of an increased statistical probability of failure.

From the above discussion it can be seen that they are two aspects of failure to be considered in the inspection and repair policy:

1. The probability of failure
2. Once the components has begun to fail (i.e. the component is worn) - how long it will take before the component will fail completely.

The first aspect is very important where components give little warning of complete failure. The second aspect is more useful where the components give a fair warning of catastrophic failure. This second aspect is more important in mechanical maintenance. General mechanical components, such as bearings, give a good warning of catastrophic failure. Thus it can be seen that the more frequent the inspections, the greater the probability will be that faults will be detected before they lead to catastrophic failure.

4.3 THE INSPECTION FREQUENCY

4.3.1 Cost and Reliability

We have established that there is a relationship between the expected reliability of a piece of equipment and the frequency of the inspections. However, the objective of any industrial maintenance is to maintain equipment at that level which minimises total plant cost. Maintenance is just one of the costs of production. There are many other costs that are affected by the maintenance function such as the machine running costs and capital costs. Whenever a machine is out of action, there is the opportunity cost of the profit that it could be producing (i.e. the downtime costs). Within a certain range, as the inspection frequency increases, so the overall production costs decrease. This is mostly because of an increase in reliability and thus a decrease in downtime costs. However, this leads to an increase in the maintenance departments expenditure.Fig. 4.2 shows that the sum of these costs is the total plant cost.

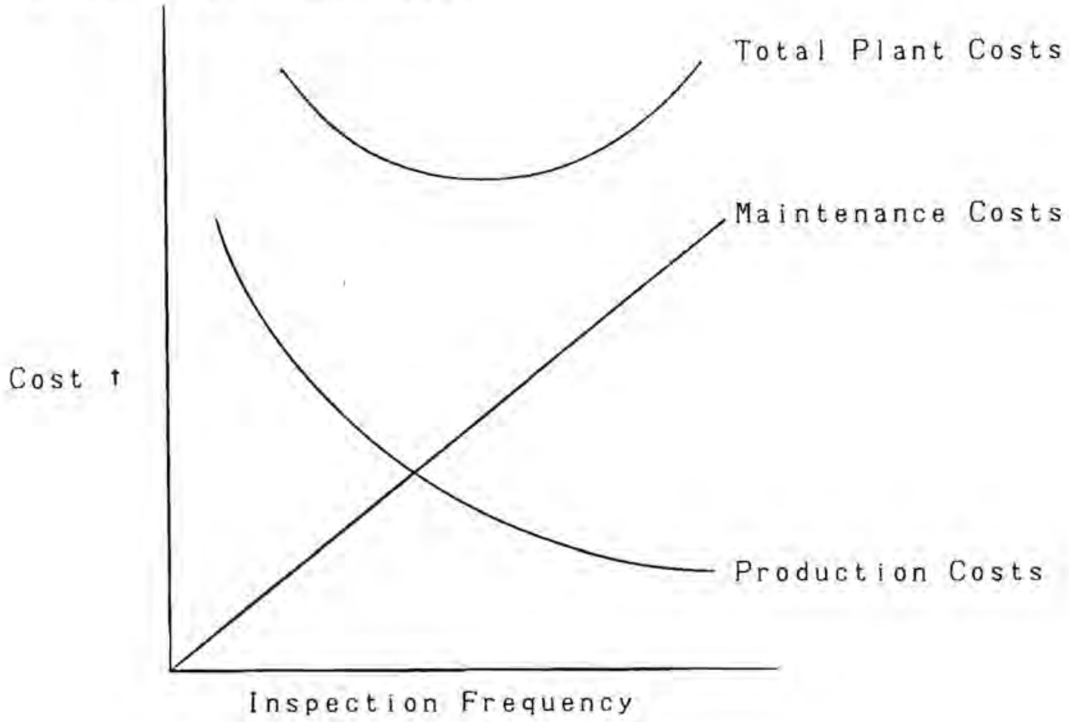


Fig. 4.2: MAINTENANCE AND TOTAL PLANT COSTS

This graph implies that there is an optimum inspection frequency for every piece of equipment. This optimum is found at the minimum total plant cost.

4.3.2 Manufacturer Manuals

This section would be incomplete without some mention of the manufacturers maintenance manuals. Unfortunately the usefulness of such manuals is often undermined by the lack of thought on the part of the equipment manufacturer. These manuals are obviously invaluable in diagnosis and repairs in that they give a technical description of the equipment. Often they also give some indication of the service (inspection) intervals. These intervals must be treated with suspicion.

In formulating them the operating conditions of the plant could not have been considered as these are unique to each work situation. However, they do form a good starting point for inspection in the early life of the equipment. Later the interval should be modified on the basis of operating information.

CHAPTER FIVE

MODELS IN THE INSPECTION AND REPAIR POLICY

5.1 INTRODUCTION

Having established the fact that there must be an optimum inspection frequency, it now remains to find a way of calculating such a frequency. In this chapter, three models are described that use different methods to calculate the optimum inspection frequency. The models all rely on input data as to the reliability of the equipment and maintenance and downtime costs. The models will be evaluated in Chapter Six. A standardised notation has been used for the formulas as given in Appendix E. For this reason some of the formulas given will look different from those in the source referenced.

5.2 THE RELIABILITY FUNCTION MODEL

5.2.1 The Basic Model Concept

The reliability function model is the simplest of the three models. This is both in terms of its concept and its mathematics. The description of the model as given here is based to a large extent on the work of Jardine (Ref. 10).

The model relies on the assumption that there is a direct relationship between the breakdown rate (i.e. the number of breakdowns per time unit), and the inspection frequency. This relationship is expressed in terms of a continuous curve or reliability function as shown in Fig. 5.1.

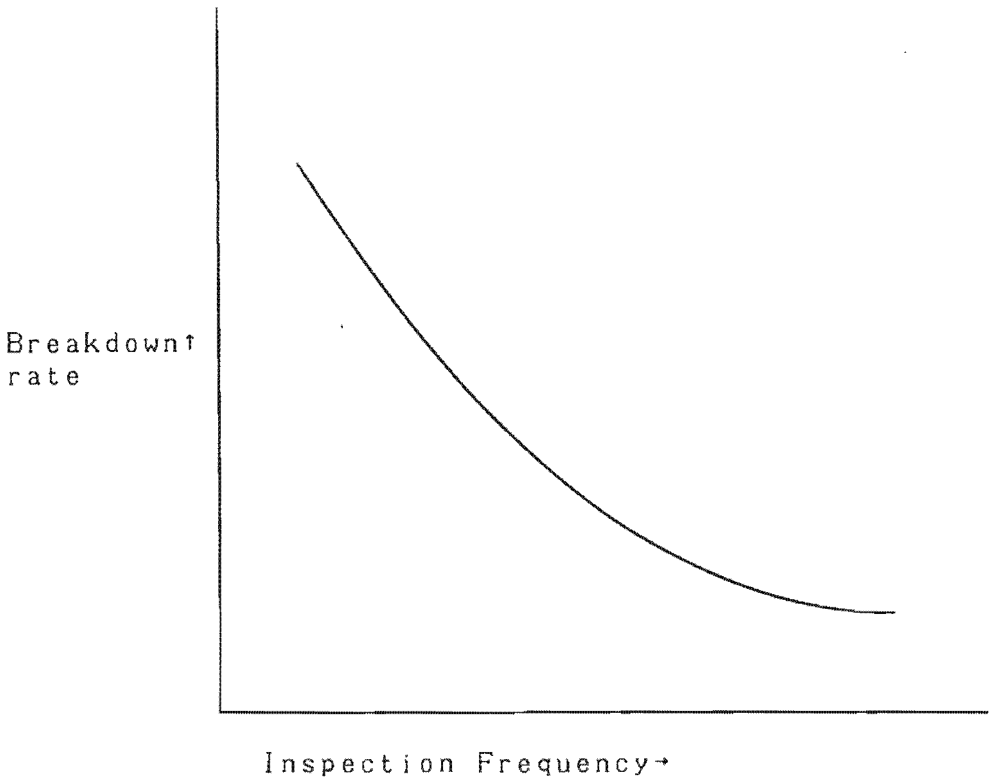


Fig. 5.1 THE RELIABILITY FUNCTION

This curve is used together with maintenance and production cost data to produce, in effect, a set of curves such as those given in Fig. 4.2. From this the optimal inspection frequency is found.

5.2.2 Data Required

From the preceding section it can be seen that two basic types of data are required:

1. Reliability data
2. Cost data (Maintenance and Production).

The reliability function provides the reliability data input. In order for the model to produce accurate decisions the curve must be based to some extent on historical data. This can only really be done by varying the inspection frequency and seeing its effect on the breakdown rate. Quite a number of points are required in order to plot a curve of any accuracy. However, if data is available from other similar machines approximation could help limit the number of points required. Even using this method it could take many years to establish such a curve.

The cost data must obviously include the costs of inspection and repair per time unit, the costs of breakdown repair per time unit (this is normally higher than that for inspection and repair) and the downtime costs per time unit. As the costs are all in rands per time unit, we obviously need the average length of time for the inspection and repair and a breakdown repair. It is important to note that an inspection and repair is considered one event as far as cost and time is concerned. This is in keeping with the investment and return analogy of section 4.1.

5.2.3 Assumptions and Formulation

Jardine (Ref. 10) considers a simple case of the inspection policy and thus makes the following assumptions.

1) That the mean time to perform a repair or inspection does not vary with the number of inspections.

2) That the relationship between breakdown repairs and the number of inspections is known.

3) That the profit per unit time is a continuous function of inspection frequency and can thus be differentiated.

Thus the following equation is derived (see Appendix A for derivation)

$$R' = \frac{t_i (G + C_i)}{t_b (G + C_b)}$$

where

R' - is the derivative of the breakdowns per time unit

t_s - is the mean time to complete breakdown repair

t_i - is the mean time to inspect (and do inspection repairs)

G - is the value of the output per uninterrupted time unit

C_i - is the cost of inspection per uninterrupted time unit

C_s - is the cost of repair per uninterrupted time unit

Equation 5.1 is solved for R'. However, R' is a function of N (the number of inspections per time unit). The derivative of the reliability function is thus substituted into the formula and the optimal inspection frequency is calculated. A complete numerical example is given in Appendix B.

5.3 THE DELAY TIME MODEL

5.3.1 The Basic Model Concept

This model in its basic concept has been widely used by many and as far back as 1965 by Barlow and Proschan (Ref.3), although not called by the same name. Much of the more recent work and practical application has been done by Christer (Ref.13). He has developed it both in the field of building (Ref.12) and industrial maintenance (Ref.13).

The basic concept is that of a delay time, h, which is a measure of the time from when a fault could first have been noticed, until such a fault would cause catastrophic failure. It can be shown that there is a relationship between the probability density function (p.d.f.) of the delay time, f(h) and the inspection interval (T). This relationship must include other variables such as the downtime and maintenance costs.

Thus from the p.d.f. of the delay time f(h) we can calculate the optimum inspection interval (T), by finding that interval with the lowest total cost.

5.3.2 Data Required

For the reliability function model two basic types of data were needed: Reliability and cost data. It is the same with the delay time model.

The p.d.f. of the delay time f(h), constitutes the data that gives an indication of an aspect of the reliability of a machine. It would be wrong to say this was a measure of the reliability of the equipment but it is a measure of an aspect of reliability that is important in this context.

The data can be collected from the subjective assessment of the equipment inspectors. Each time the inspector finds a fault during an inspection he must give estimations for the following:

1) How long ago the fault could first have been noticed by an inspector or operator (h_1).

2) How much longer the repair could be delayed before it leads to catastrophic failure (h_2).

It can be seen that by definition $h = h_1 + h_2$. After estimating h for a number of distinct faults, a distribution for h can be obtained and the probability density function f(h) can be found.

The model also requires the average fault arrival rate for the equipment concerned. This is easily obtained from historical data.

The cost and average time data required is the same as that for the reliability function model. Here, however, the costs and times for inspection are split from the cost and times for a subsequent repair.

5.3.3 Assumption and Formulation

Christer and Waller (Ref.13) consider the simplest possible case of an inspection policy. Thus they make the following assumptions:

1) The downtime for inspection (d) is much less than the inspection interval (T).
2) Inspections are perfect and thus any defect will be identified.
3) Defects identified at an inspection are repaired within that inspection period.
4) The time of origin of a fault is uniformly distributed over time since last inspection and independent of h.
5) The probability density function of the delay time f(h), is known.

The following equation is thus derived (See Appendix C for derivation).

$$C_m = \frac{1}{T+t_i} \{qT[C_s t_s b + C_s t_i (1-b)] + c_i (t_i - t_r))$$

where

C_m - is the cost of maintaining the plant per unit time

T - is the inspection internal

q - is the fault arrival rate

C_s - Cost of breakdown repair per time unit

C_i - Cost of inspection and consequential repair per time unit

t_s - Mean time for a breakdown repair

t_i - Mean time for an inspection (including consequential repair)

t_r - Mean time for an inspection repair and

and

$$b = \int_{h=0}^{T} \left[\frac{T - h}{T}\right] fh \; dh$$

The maintenance cost is obtained by finding the integral b first. Either a mathematical function is used to approximate the curve of f(h) or an approximate method such as Simpsons Rule is used to obtain the integral of the distribution. The cost of maintenance is thus easily found.

The downtime (d) is calculated using the following formula

$$d = \frac{T}{T + t_i} [qTt_r \; b + t_i]$$

thus the downtime cost is

$$d.Cd$$

where C_d - is the cost of downtime per time unit

Thus the total plant cost is

$$Cp = d.Cd + Cm$$

This cost can be minimised by calculating Cp for a number of inspection intervals, T, until the lowest cost is determined. A sample calculation can be found in Appendix D.

5.4 THE MARKOV MODEL

5.4.1 The Basic Model Concept

Markov was a Russian Mathematician who pioneered modern probability theory. His name has been given to this general statistical method that has been used to solve problems in a number of fields. A number of researchers have applied this method to the field of maintenance decision making including Barlow and Prochan (Ref.3), Luss (Ref.14) and Lapin (Ref.15).

The basic concept (when applied to the field of inspection and repair maintenance) is that of a machine that can be found in any one of a number of states. Where the number of states is finite, this is known as a Markov chain, as opposed to the more general case where a Markov process may have continuous states. Say a machine's operating condition is defined such that it may be in any one of four states. The Markov process deals with the probability of the machine staying in one of the states or transferring from one to another. The Markov process is, however, memoryless and the probability of moving from one state to another is independent of past history.

An inspection and repair, has the effect of transferring the machine to a "higher" state. Use of the machine transfers the machine over a period of time to a "lower" state. It is thus possible to consider the total cost of running a machine for a number of different inspection intervals. The minimum cost will identify the optimal inspection policy.

5.4.2 Data Required

As with the delay time and reliability function models both reliability and cost data inputs are required for the Markov model.

The definition of the states is the first step in forming the reliability data input. The next step is the allocation of transfer functions from one state to another. These are expressed in terms of the probability of a machine transferring from one state to another.

The costing data required is basically the same as that for the other two models. Here, however, the cost of occupancy of each of the states is required as well. This model thus takes into account variations in plant running costs.

5.4.3 Assumption and Formulation

Normally the model is in the form of a Markov chain (i.e. a finite number of states). This makes the analysts task easier, in that specific values can be assigned to each of the states. This assumption idealizes the situation to an extent. This is not serious and the other models (Delay Time and Reliability Function) in fact are more idealized in that they only consider two states (running or not running).

For the case of three states a matrix would be drawn up as follows:

$$\begin{array}{cccc} & X1 & X2 & X3 \\ X1 & P11 & P12 & P13 \\ X2 & 0 & P22 & P23 \\ X3 & 1 & 0 & 0 \end{array}$$

where X1, X2, X3 - are deteriorating states with X1 being as new and X3 being inoperable.

P - is the probability of transferring from one state to a lower one. i.e. P13 is the probability of moving from state 1 to state 3.

From the matrix it can be seen that the following assumptions are made.

1) The machine is returned to its 'as new' conditions after a breakdown.
2) The machine cannot otherwise move from a lower state to a higher one. This is in accordance with the law of increasing entropy.

One way of finding the optimum inspection interval (T) is by simulating the response of the matrix. The transformations are simulated for a number of periods, t (where t << T). At the end of each period t the cost of occupying the state simulated is calculated. This is done for a number of periods n (where nt > T - the more periods the better). A number of different inspection intervals are tested. The total cost of each option is calculated and the intervals that yields the lowest cost is selected.

Klein (Ref.18) has used linear programming methods for finding the optimal solution to the inspection problem. The basic Markov chain setup is however, the same. Both of these methods require the use of computer computational facilities in order to be viable.

CHAPTER 6

EVALUATION OF THE MODELS IN THE INSPECTION AND REPAIR POLICY

6.1 INTRODUCTION

Having looked at the factual details of the three models it now remains to evaluate them. In this section the models are evaluated in various categories. The categories explored are not all the ones important to the field of inspection and repair maintenance. Only those in which some models may have a relative advantage over others are considered. Other categories will be considered in the next section. From this section it is hoped that a useful model will emerge.

6.2 BASIC MODEL CONCEPT

The three models are similar in concept in that they all rely on the same basic assumptions. That is that there is a relationship between the reliability of an item of equipment and the frequency of preventative maintenance inspection.

In the reliability function model this relationship, expressed mathematically, is a direct input. Referring to section 5.2.1 it can be seen that the relationship between the breakdown rate (a measure of reliability), and the inspection frequency is one of the inputs. In the Markov model, this is an indirect input. The deterioration of the machine takes place in discrete states (a measure of its reliability), and the inspection and repair has an effect on these states. In the delay-time model this relationship is an even more indirect input. Here the relationship is seen as being related to the probability density function of the delay time. However, in the formulation in Section 5.3.3 this relationship can be seen. The reliability functions model is deterministic in concept while the other two are stochastic. Our experience of the world makes us suspicious of a deterministic model and leads us to believe that a stochastic model is a better reflection of reality. The Markov and delay time models are favoured as being more realistic although the reliability function model is mathematically more simple.

One of the unique aspects of the Markov model, in terms of its basic concept, is that it takes into account the running costs of a machine. This cost is included in the cost of occupying the state, as explained in section 5.3.3. This could be a very useful feature, particularly where a machine consumes more energy in a deteriorated state.

When looking at an inspection and repair model one of the variables to be considered is the level of inspection, (i.e. how detailed and thorough is the inspection?) It would seem, at first glance, that none of the models considered take this factor into account. However, they all do, in an indirect way.

In the reliability functions model the relationship between breakdowns and inspection frequency takes this into account. A certain level of inspection is assumed and the curve is generated on that basis. For the Markov model the level of inspection is incorporated in the effect of inspection and repair on transfer to a higher state. The p.d.f. of the delay time generated in the delay time model is also a function of the level of inspection.

6.3 DATA COLLECTION AND AVAILABILITY

6.3.1 Cost Related Data

All the models require basic cost data, such as the inspection and repair costs and the breakdown repair costs and the downtime costs. These costs are either per event or per unit time. Where cost data is required per unit time, the average duration of an event is also required. Although the accuracy of such data is very important for finding the optimal solution, it is not usually difficult to obtain from well kept historical records.

All companies keep records of maintenance and production costs. However, not all separate the costs of the inspection and repair programme and those of breakdowns. In terms of the earlier discussions as regards investment and returns (section 3.3) the importance of recording the cost of inspection and repair programme (the investment) and the breakdown repair costs (a reduction of which constitutes a return) separately can be seen. Thus the inspection and repair costs and times and breakdown repair costs and times must be kept on historical records for each item of equipment. This is essential for all the models.

As pointed out earlier, the Markov model is the only one that considers the state occupancy costs (i.e. running costs). These costs can be broken down into the energy consumption costs and increase in production costs due to equipment deterioration. Records of these sort of costs would not normally be kept in most production facilities. There would be little difficulty in obtaining such data, but that would entail extra cost.

The downtime cost of a machine is rather more difficult to estimate. The best person to estimate this is the production manager himself as he knows best the factors involved. The two main factors are the contribution to profit of the machine and the cost of operator idle time. It may well be, if there are many similar machines with a low utilization, that the downtime cost is zero.

6.3.2 Reliability Related Data

All the models require some input as to the reliability of the equipment. This input is normally based on historical data for that machine. In some cases, however, it may be necessary to estimate such a function.

The reliability function model requires the relationship between the breakdown rate and a particular inspection frequency (Fig. 5.1). It is clearly difficult to obtain a relationship from historical data. To do so would require the varying of the inspection frequency over time, whilst recording the incidence of breakdowns. Taking into account the response time involved in such an experiment it would take many years for useable data of any accuracy to emerge. Each one of the intercepts shown in Fig. 6.1 could take a few years to obtain.

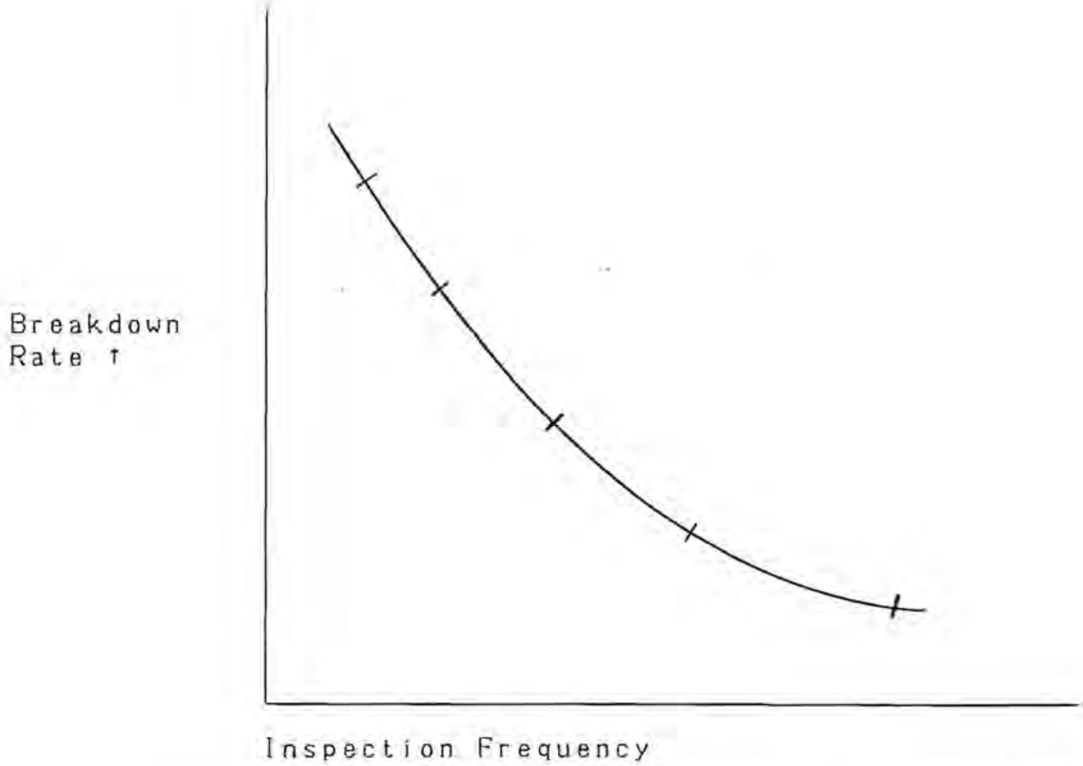


Fig. 6.1 OBTAINING THE RELIABILITY FUNCTION

One practical way of solving this problem is as follows:

1) Find the intercept on the curve for the current inspection frequency (ie the breakdown rate for the existing inspection frequency)
2) Estimate a function for the curve (from experience with similar equipment) and fit into the intercept found in 1.
3) Calculate the optimal inspection frequency and use it.
4) Once the new inspection frequency has been in use for a while the estimated curve can be checked and altered if necessary.

However, this method is still very inaccurate and relies principally on data from breakdowns. Breakdowns are infrequent and thus the time taken to build up a reliable set of data could be long.

The Markov model requires a very comprehensive set of reliability data. To the extent that it is almost impossible to find this data from the past performance of the equipment. The probability of the equipment moving from one state of performance to another is required. This data could be gathered by continually monitoring the equipment, but this would be very expensive. It is thus necessary to estimate the variables here, from experience with other equipment.

The delay time model does not require comprehensive historical data on equipment reliability. This model relies on the educated estimates of the P.M. inspector himself. This estimate is made at the detection of a fault - a more frequent occurrence than a breakdown. A spread of data can thus be fairly quickly established, although an estimate may need to be made initially. It must be borne in mind, however, that this data is highly subjective. This would affect the optimality of the solution.

6.4 ACCURACY OF THE DECISION

In the two preceding sections the basic model concepts and data collection and availability were considered. These factors are both very important when considering the accuracy of any of the models for decision making.

In terms of its basic concept the delay time model must rely on raw data that is a result of a subjective assessment. Theoretically the reliability function model and the Markov model rely on more objective historical data for the decision. However, we have seen that for both the Markov and reliability function models, in practice, the reliability data is estimated. With the reliability function model the inputs can be to some extent based on historical data. This is more difficult to do with the Markov model.

Such estimates could easily induce more errors than those inherent in the delay time model for the following reasons:

1) The delay time model relies on a number of estimates for specific type of time period. These estimates are made by the inspectors, who have a good understanding of the factors involved. One cannot expect the same people to make estimates for the Markov and Reliability function models - where mathematical and statistical understanding is required.

2) There are a number of estimates made in the delay time model and the p.d.f. of these estimates is the input. The other models rely on single exact data inputs. Spurious estimates would soon be noticed in the delay time model. In the other models the decision may well be based on a spurious estimate.

Conceptually the Markov model seems to be the best reflection of reality. It is more correct to say that deterioration occurs in stages, than to assume that failure is the only symptom of deterioration.
However, this advantage of the Markov model is overshadowed by the difficulty of obtaining the accurate data required by the model.

6.5 DATA PROCESSING

As with any kind of decision making process the cost of optimizing the inspection interval must not be greater than the benefits derived from such an improvement. Thus it is important that the paperwork and data processing costs are kept to a minimum.

The data required for cost calculations is not normally a concern, as far as volumes of data processing is concerned. This data is required for accounting purposes as well and it is merely a question of ensuring that it is processed in the right form. This is so that it can be used by both accounting and maintenance. There may be a high initial cost in changing a system over to allow for this. Further discussion on data collection can be found in Section 7.2.

The reliability data, however, is only needed by the maintenance department and it is thus their responsibility to ensure that the correct volume of data is kept.

For the reliability function model records of the breakdowns as well as the inspection frequency need to be kept for each machine. This is not a significant amount of data to store and is probably the sort of data that is kept for the purpose of auditing items of equipment anyway.

The Markov model requires the storage of a large amount of data. Records would need to be kept of the time spent in each of the states and the state transfers. As mentioned in Section 6.3.2, however, it is unlikely that such data would be collected. The transfer functions would probably be estimated. In that event it would probably be acceptable to process the same sort of data as for the reliability function model.

The delay time model would require the recording of an extra item of data for each breakdown and some of the inspections (where repairs are carried out). This is over and above that data which would be collected for the reliability function model. This in itself would not create an excessive burden. The processing of such data would, however, need to be computerised. A database could easily be used to store the records and provide an updated p.d.f. of the delay times.

6.6 THE P.M. INSPECTOR

An important aspect that must be considered is the type of skills of the inspector that the model assumes and the way in which those skills are used by the model.

All the models assume a fairly high degree of technical ability. In any inspection and repair programme the inspector is expected to be able to diagnose faults identified by the operator and even to find faults that have not yet been noticed by the operator. He must also be able to effect repairs.

The inspector is sometimes called on to make decisions as regards inspection intervals. The current practice in many organizations is to ask the inspector his opinion of the optimum inspection frequency and to base the decision on that. The Markov model will more than likely require the inspectors opinion on the input data (the transfer functions). The reliability function model may also require his opinion to a lesser extent.

The delay-time model requires the opinion of the p.m. inspector directly, as one of its inputs. However, this input is within the field of his knowledge and experience - the reliability of equipment. The other models require his judgement on matters that involve statistics and economics. These subjects are outside his field of training and experience.

6.7 CONCLUSION

It would appear that for most of the sections outline above that the delay-time model is favoured. The exception is in the field of record keeping and processing. This, however, should not be a problem in this day of the micro-computer. Micro's are used by many maintenance organizations already in this area. It should also be noted, however, that this evaluation is from a practical and not a mathematical point of view.

The model certainly has advantages in terms of the easy availability of the input data. The involvement of the inspector in giving an estimate is good in that it draws on a source for decision making that is normally difficult to tap. The mathematical assumptions are sound and realistic. We would thus expect good decisions to be made using this model.

CHAPTER SEVEN

IMPLEMENTING THE SYSTEM

7.1 INTRODUCTION

In chapter 6 the delay-time model emerged as the most practical and useful in a situation where inspection and repair maintenance is practiced. There are many aspects to maintenance, other than the inspection frequency, that need to be considered. In this chapter we look at some of the aspects that need to be considered before implementing a maintenance system. some of these aspects will be particular to the case of the inspection and repair policy or the delay-time model while others will be applicable to maintenance systems in general. It will be appreciated that the discussion on most of the subjects is, of necessity, brief. References for further reading can be found in the reference and bibliography sections.

7.2 INFORMATION SYSTEM

In the past decade the computer has totally changed the rules as far as the flow of management information is concerned. The micro computer has become relatively cheap and able to process vast volumes of data. Sophisticated software has made the computer accessible to those with no formal computer training. These developments have potentially made the maintenance manager more effective and his task easier. He can now use the vast amount of machine reliability data available to him to measure the effectiveness of the maintenance programme. The keeping of maintenance histories for each machine is now much easier.

However, the computer will not cure all the ills of a maintenance department and may, in fact, create a few of its own. Some of the more important aspects of a maintenance information system are discussed below.

7.2.1 The Paperwork

Many plant managers make the mistake of trying to computerise the maintenance system without every having managed to make the manual system work (Ref.19).

The staff and management problems of an manual system are not going to be solved simply by the introduction of a computer system. In addition, unless the plant is one of the few with online computer terminals at each production section, much of the paperwork of the manual system will have to be retained to drive the computer system. Normally only the record keeping paperwork is discarded.

The computer can produce a vast variety of reports very simply and quickly. This has definite advantages in that different levels of management can be presented with the information most relevant to them. However, the manager must be careful not to generate too much paperwork. The system could end up creating more work than it saves.

7.2.2 The Feedback System

As mentioned earlier, the real advantage of the computer is its ability to process most amounts of data and provide feedback on the effectiveness of the maintenance programme. It is thus surprising that so few maintenance information systems utilize this ability. Many organizations use the computer's database merely to store records, but never use the information in the records for decision making.

These are two basic types of feedback:

1) Cost Feedback - This involves calculating various cost figures or ratios and comparing these with those found under similar circumstances. For example the ratio of maintenance cost to production costs should be common for similar types of operations. Examples of some useful indices can be found in Ref.20. It is not always necessary to have a dedicated maintenance software package to generate such information. A database or spreadsheet package makes the task easily attainable.

2) Inspection Frequency Feedback - This should be quite clear to the reader, as this has been the subject of much of the discussion up to now. The delay-time model has a particular advantage here, in that is uses the information gathered from each and every breakdown to generate feedback. The report sheet submitted by the repairman, after each job, is entered onto the computer and assists in the decision making process. Thus little extra work is generated in making the system generate very useful feedback for decision making.

7.2.3 The Data Used

It has been said that statistics lie. That is a good reason to be particularly cautious when dealing with any sort of data. It is thus important to look at the source of the maintenance history data. The question needs to be asked: Under what circumstances is this data generated?

Very often the data for the cost of maintaining machines is calculated from job cards filled out by the maintenance technician. The technician is unlikely to book fewer hours work than there are in a day. Thus if the maintenance staff are underloaded, machine maintenance costs could look inflated.

One solution to this problem is to ensure that the maintenance staff are over rather than under loaded (although this could bring problems in itself). The other solution is to make it the responsibility of the foreman of the section where they are doing repairs to sign the technicians in and out of each job. When the foreman realises that these costs affect the overheads of his section, he is bound to make sure that he is not paying for idle time. Under these circumstances staff must, of course, be allowed to book idle time when it occurs.

7.3 MAINTENANCE STAFF

7.3.1 The Type of Staff

The staff of any organization are recognised as being one of its most valuable assets. The labour costs of a maintenance department are normally much higher than the materials costs. It is thus very important that the right people are employed in the right jobs.

A number of different categories of staff are employed in a maintenance department.

1) Technicians - repair and service the equipment
2) Inspectors - carry out the p.m. inspections
3) Clerical Staff - process the paperwork
4) Accounting Staff - keep track of the costs
5) Management - plan, organize, lead and control the maintenance function
6) Labourers (semi-skilled and unskilled) - assist the technician

One very important difference between the staff employed in the maintenance department and those employed in production departments, is that all the staff in maintenance (except the labourers) are decision makers. The technician has to decide how thorough he must be and which parts he should replace. The clerk needs to decide how much detail of each job should be kept on permanent records. The decisions of the p.m.inspectors determine the costs of equipment maintenance. If the level of responsibility is measured by the financial effect of your decisions in rands (as is often the case) then the maintenance manager often has the greatest responsibility on the site.

Thus it is quite clear that more is required of an employee in maintenance, than would normally be the case in an equivalent job in production. The technician must not only be good technically but must also be able to think in terms of the cost consequences of his action. A perfectionist who produces very high quality work could easily set costs on an upward trend if he is not able to make the right decisions.

The p.m. inspector is normally promoted into that position after many years of experience as a technician. This experience should give him the ability to distinguish between those faults that need immediate attention and those that do not. For the delay-time analysis system he would also be required to estimate the duration of a fault from inception to catastrophic failure.

The type of labour employed by maintenance is also very important. The environment is very different to production, with its repetitive tasks. The man must have a relatively high intelligence and the ability to carry out instructions without too much explanation. for the labourer the rewards are a more interesting and varied job and for that reason such a person should not be too difficult to find.

More will be said about managerial and accounting staff in section 7.5. Clerical staff will often need some technical understanding, particularly if they are to keep records of the machine faults. However, finding people with an aptitude for this would be cheaper than using technicians for these tasks.

7.3.2 Training of Staff

The training of staff deserves some mention. The degree of specialisation of the technical staff is one of the biggest questions. Many smaller companies do not have the facilities to train specialist staff and in any event require their maintenance staff to be versatile. For larger companies, however, it may be worthwhile to have staff with specialist skills. This could disadvantage the company if it gets to the stage where many specialists are required to repair one machine. This inevitably wastes time and their money. Thus specialisation is more effective if it is geared towards a specific type of machine. Thus if a mechanical technician did a specialist course in electronic diagnostics, his training would gear him for C.N.C. machines. Normally both a mechanical and an electronic technician would be required for such a machine.

In the light of the discussion in section 7.3.1 it is obvious that technical staff require a grasp of the economic aspects of maintenance. Some training will probably be necessary here.

7.3.3 Staff Control

Work measurement techniques are often used in assisting in planning and controlling in a production. In this section we look at the applicability of method study and time study to the maintenance environment.

7.3.3.1 Method Study

"Method study is the systematic recording and critical examination of existing and proposed ways of doing work, as a means of developing and applying easier and more effective methods and reducing costs" (Ref.21). The method of doing many of the more repetitive tasks in the maintenance function can be studied and changed with improvement in both effect and cost. The costs of such a study must always be weighed up against any potential saving.

The actual inspection schedule for each machine is a good place to start with method study. These schedules are used repeatedly and thus any cost saving or improvement in effectiveness will provide a long term saving. Method study probably has limited applications for the actual repair tasks in the inspection and repair policy, because of the varied nature of such tasks. Its application is more suited to the shut down maintenance policy where the same repair tasks are done for each shut down.

7.3.3.2 Time Study

"Time study is the procedure used to measure the time required by a qualified operator working at the normal performance level to perform a given task in accordance with a specified method" (Ref.22). Time study is closely related to method study. They can, however, be carried out independently of one another. One of the most common reasons for doing a time study is to use the time as a basis for productivity incentive schemes. Because of the non-repetitive nature of most of the tasks within the inspection and repair policy, the cost of setting up time standards would be prohibitively high. Here again, as with method study, the most obvious applications is the inspection schedule of each machine.

There has been work done on the setting of time standards for low repetitive tasks such as maintenance repair tasks. The methods used are known as U.M.S. (Universal Maintenance Standards) or Comparative Estimating. The subject is really beyond the scope of this thesis but Knott and Pena (Ref.6) deal with it in detail.

The above discussion shows that it is difficult to implement a productivity incentive scheme based on time. This reinforces the necessity of having self-motivated staff employed in the maintenance department.

7.4 MAINTENANCE RESOURCES

7.4.1 Tradeforce Location

The problem of where to locate the maintenance staff only becomes an issue in large plants. Here the work is distributed over a large area. A decentralized tradeforce normally entails greater supervisory costs and a certain loss in organizational unity. Resources can be more effectively utilized in a centralized set up. This is because the idle time of a large group is statistically less than that of a number of small groups serving the same function.

The costs of travelling time, both in terms of the cost to maintenance and to production (downtime in the event of a breakdown) are much higher for a centralized taskforce. A further advantage of a decentralized taskforce revolves around the specialisation of maintenance staff. This was mentioned in section 7.3. The technicians know the machines in their sections and are more competent at maintaining these machines. This is particularly the case where different types of machines are in different sections.

7.4.2 <u>Tradeforce Size</u>

According to Kelly and Harris (Ref.17), the maintenance workload falls into two categories:

1) <u>The Deterministic Load</u> - That maintenance that can be planned in the long term (i.e. P.M. inspection and repairs and modifications).

2) <u>The Probabilistic Load</u> - That maintenance that can be planned only for the short term (i.e. breakdown repairs). It is difficult to estimate even the average of this load.

No matter how thorough a p.m. programme is there are still going to be some breakdowns. The number of breakdowns being dependent on the level of p.m. So with any p.m. programme there is going to be a proportion of the load that is probabilistic.

Determining the size of the tradeforce needed to service the deterministic load is relatively straight forward. It is merely a function of the p.m.programme. The probabilistic load needs to be worked out either by simulation (using historical breakdown records) or using queueing theory. Szendrovitz (Ref.23) has a detailed section on the subject of determining the maintenance load from queueing theory.

7.4.3 <u>Work Scheduling</u>

Not much needs to be said about work scheduling if most of the work is of a preventative nature. Here the p.m. work is done to a programme with some slack to allow for breakdowns. When a breakdown occurs, it must take precedence over any p.m. maintenance.

A problem occurs when much of the work is breakdown repair work. Here a decision needs to be taken as to the scheduling of one breakdown before another. A first come, first served basis is probably the easiest way of doing it, but not necessarily the best. The maintenance manager takes into account other factors, such as the machines involved and the probable duration of the repair task. If this sort of information is available it is possible to schedule on a minimum cost basis. This is often done by the manager in more simple cases just by thinking on his feet. However, in more complex cases it will be necessary to use more accurate cost figures and computer facilities.

7.5 MAINTENANCE AND MANAGEMENT

7.5.1 Management Commitment

It has often been said that if an organization fails to reach its objectives it is the fault of the management. This is certainly true of the maintenance manager. Yet very often the commitment to maintenance by top management is so low, that the maintenance manager is not properly equipped for the job. Management often suffer from the same misconceptions as regards maintenance as do maintenance technicians. Maintenance costs one often regarded as a necessary evil. The maintenance function, it is often claimed cannot be controlled. With attitudes like these, there is little wonder that there is a lack of commitment to maintenance.

It is true that maintenance is different to production work and is probably more difficult to control.
However, this is no reason not to control it at all. Management needs to understand the basic concept of investment and returns as regards maintenance (as outlined in Chapter 3). Once this is grasped, the need to control will become obvious.

The importance management attaches to a particular section, can be measured by the management staff and investment capital it allocates to that section. Implementing a system like the delay-time system will involve some investment and management needs to be convinced of the worth such investment.

The difficulty of controlling the maintenance function is in itself, a strong motivation for the allocation of a strong management for the section. Much can be said of the advantages of employing a specialist maintenance accountant. Such a person would be able to implement a system to keep close control of maintenance costs.

7.5.2 Organizational Structure

As can well be imagined, the number of different organizational structures is virtually infinite. It is not possible to discuss these in detail here. Only a few comments will be made as regards the most suitable structure for a delay-time model programme.

For the delay-time model it is best for the chain of command be as short as possible. It is also best if the p.m. inspector liase directly with the maintenance technician who is going to do the work. It often happens that such communication goes via a foreman, but this limits the flow of information. For control purposes it makes sense for the maintenance technician only to take order from his foreman. This will ensure that the maintenance foreman is in full control of the work loading on his staff.

7.6 PRODUCTION AND MAINTENANCE

The maintenance department is there to serve the production department. This must be at a minimum cost to the entire department. Chapters 3 and 4 explain this principle in detail. For the most part this thesis has looked at ways in which maintenance can minimise costs, however, some practices of the production department need to be looked at.

Productivity incentives boost production and yield a far lower cost per item than would normally be the case. However, these incentives often have the effect of raising maintenance costs. The man who is trying to get maximum production will not normally take time to clean his machine. The speeds at which he operates his equipment may also be to the detriment of the maintenance account. To a certain extent these higher maintenance costs may be acceptable. However, it is up to production to set economically acceptable limits for machine speeds and to schedule in time for cleaning the machines. Production foremen need to be more responsible for the maintenance cost of the machines under their control.

Production and maintenance need to liase continually, both as regards the regular maintenance scheduling and the major overhaul work. It has happened that maintenance has carried out a major overhaul on a machine, only to find that the production contract using that machine has come to an end and the machine is being put out of commission.

7.7 CONCLUSION

Many of the aspects considered are of a systems nature. These require more management commitment and staff education than actual raw cash expenditure. However, the cost of education and training can often be far in excess of any expenditure on hardware. The experience of companies with successful maintenance departments, however, will show that it is well worthwhile.

CHAPTER EIGHT

CONCLUSIONS

This research project has clearly shown that maintenance decisions in inspection and repair maintenance can be quantified. The extra effort required to do so is minimal as much of the data is required for auditing purposes anyway.

Some caution, however, is needed when applying quantitative techniques to the field of maintenance management. Many of the inputs in a decision are based on factors that can be affected by subjectivity. For example, the lengths to which an inspector goes in his p.m. inspection is beyond the control of quantitative methods. Most organizations have an inspection sheet detailing the item to be inspected on each machine, but it is difficult to control how thoroughly each item is checked. Much is left to his personal judgement.

This should not cause us to abandon quantitative techniques. They are definitely better than guessing. It should be obvious by now that there is no short cut around employing good staff well trained in the principals of maintenance.

There are cases when the cost of implementing quantitative techniques would be greater than the returns. For instance some very small companies may be better off guessing maintenance intervals, than working them out using a computer. However, the extra cost involved in implementing the delay-time model for decision making would not be that large for most companies.

A large number of computer maintenance management systems available as software do not use any form of decision making. This is a waste of much of the information stored by the computer. To a large extent many of these systems are a waste of money, unless they use the information to make maintenance decisions.

Their is much room for improvement in many aspects of the maintenance function. It is much more difficult to quantify and control many aspects of maintenance than, for instance, production. This should be a challenge, rather than a cause for despair. Because of this difficulty, the potential saving from any successful programme could be very significant.

CHAPTER NINE

RECOMMENDATIONS

This research project is not aimed at a particular problem in a particular organization. For this reason the recommendations are of a general nature. These recommendations are aimed at the management of any organization with a significant maintenance account.

1) CONDUCT MAINTENANCE AUDIT

It is quite easy if maintenance has a low priority, for management to be unaware of how it functions. This will be a learning exercise to find the starting point of any proposed changes, but could highlight some significant problems.

2) EMPLOY THE RIGHT STAFF -

Much has been said about the importance of employing well trained staff, with an aptitude for the sort of work found in a maintenance department. Maintenance should have priority in choosing technicians trained up in the organizations. Good staff are essential whether or not any changes are going to take place.

3) DECIDE ON SCOPE AND EXTENT OF CHANGES -

Fault will be found with the maintenance department, of some sort or another. A decision needs to be made as to what changes, if any need to be made. This decision must be made considering the whole concept of investment and returns of maintenance, as outlined in Chapters Three and Four.

4) CONTROL AND DECISION MAKING MUST BE LINKED -

In any maintenance management information system, the control information system must be linked with the decision making information system. This goes for a paper or computer system. The amount of unnecessary paper work created by separating the two, costs the organization significantly. This is clearly spelt out in Chapter Seven.

CHAPTER TEN

FUTURE STUDY

Future developments in the field of maintenance will, to a large extent, be determined by developments in production technology. The trend is still towards greater automation. Generally the greater the automation the higher the downtime cost of the equipment. In Chapter Three we saw that a higher down-time normally leads to greater investment in preventative maintenance. The trend would thus be organizations moving from, for example, using an inspection and repair policy to using a shut-down policy.

The trend in the South African situation is more difficult to predict. In most fields our production technology lags behind that of the first world. The current political and economic situation could increase the extent of that lag. Equipment is probably required to last longer here and that would cause the investment in maintenance to increase. It can thus be seen that maintenance in a South African context does have a number of distinctives. To what extent we can validly transfer the industrialised worlds maintenance technology to our context could be the subject of further research.

Much work has been done in the field of maintenance decisions of an economic nature. This thesis is a contribution to that field. However, the growth in the field of information technology, makes it possible for computers to be used in helping make technical decisions. The development of expert systems is an exciting development in information technology. It has been applied to the field of medical diagnostics and there is no reason to believe it cannot be applied to mechanical diagnostics. The costs of developing such a system will probably be high, but it could still be worthwhile to develop such a system for mass produced equipment. The motor industry, for example, could benefit by applying such a system to motor vehicle maintenance.

This research has clearly shown that the delay-time model is a practical and usable method for decision making in maintenance. Although it is hoped that this has bridged the gap between engineering and management to an extent, this is clearly not enough. More work needs to be done in developing an actual usable system. The development of a software package for use by maintenance departments, that links the decision making and control aspects, is clearly a priority.

REFERENCES

1. STUBBS, P.C. "An Economist's View of Maintenance Engineering", Maintenance Management International, No. 4 1984, p.269-272

2. GALLAGHER, C., METCALF, A. "How Managers Use Numerate Techniques", Management Today, December 1982, p.35-38.

3. BARLOW, R.E., PROSCHAN, F. "Mathematical Theory of Reliability". John Wiley and Sons, New York (1965).

4. ANDRICA, J.D. "Establishing a P.M. Inspection Programme", Plant Engineering, 9 August 1979 p.109-112.

5 POULSEN, L. "Simulating Maintenance Work in a Fully Loaded Machine Shop : A Model". Maintenance Management International, No. 4 1984, p.89-101.

6. KNOTT, K., PENA, M.F. "An Improved Method for Setting Time Standards for Maintenance Work". IIE Transactions, March 1985, p.17-24.

7. HOLDEN, L. "Maintenance and the Computer : Ensuring a Winning Combination", Plant Engineering, 22 August 1985.

8 RUEDA, A.G., MILLER, F.G. "A Comparative Analysis of Techniques for Determining Component Maintenance Intervals in Fleets". Maintenance Management International No.5, 1985, p.279-295.

9. KNEZEVIC, J. "Methodology "Exeter" for Selecting an Optimal Part-Replacement Policy". Maintenance Management International No. 5, 1985, p.209-218.

10. JARDINE, A.K.S. "Maintenance, Replacement and Reliability," Pitman and Sons, London (1973).

11. JARDINE, A.K.S., BUZACOTT, J.A. "Equipment Reliability and Maintenance". European Journal of Operational Research, No. 19, 1985. p.285-296.

12. CHRISTER, A.H. "Modelling Inspection Policies for Building Maintenance". Journal of the Operational Research Society, Vol. 33 (1982) p.723-732.

13. CHRISTER, A.H., WALLER, W.M. "Delay Time Models of Industrial Inspection Maintenance Problems", Journal of the Operational Research Society, Vol. 35, No. 5 (1984) p.401-406.

14. LUSS, H. "Maintenance Policies when deterioration can be observed by Inspection". Operations Research, Vol.24, No.2 (1976).

15. LAPIN, L. "Quantitative Methods for Business Decisions" Harcourt, Brace, Jovanovich, New York (1976).

16. LABOUCHERE, C. "What Maintenance is Worthwhile and When?" Power and Plant in Southern Africa, May (1981) p.3-5, June (1981) p.45-49, July (1981) p.20-23, August (1981) p.28-31, September (1981) p.58-64.

17. KELLY, A., HARRIS, J.J. "The Management of Industrial Maintenance". Butterworth and Co, London (1979).

18. KLEIN, M. "Inspection - Maintenance - Replacement Schedules under Markovian Determinations". Management Science, Vol.9, No.1 October (1962).

19 HICKMAN, W.E., MOORE, W.D. "Managing the Maintenance Dollar", Chemical Engineering 14 April, (1986).

20. COOLING, W.C. "Controlling Maintenance in a Small Plant", Plant Engineering, 26 November (1971).

21. BRITISH STANDARD 3138:1979 "Glossary of Terms Used in

Workstudy and Organization and Method (O&M)" British Standards Institution, London (1979).

22. MAYNARD, H.B. (Editor) "<u>Industrial Engineering Handbook</u>" 3rd Ed., McGraw-Hill, New York (1971), p.3-12.

23. SZENDROVITZ, A.Z. "<u>An Introduction to Production Management</u>", McMaster University, Hamilton, Ontario (1973).

BIBLIOGRAPHY

1. BRITISH STANDARD 3811 : 1984. "Glossary of Maintenance Management Terms in Terotechnology". British Standards Institution, London (1984).

2. WESTERKAMP, T.A. "How to Test Maintenance Productivity", Plant Engineering, Sept. 12 (1985).

3. CLAIRE, F.V. "Evaluating Maintenance Operations" Plant Engineering, 9 June (1977) p.181-184, 23 June (1977), p.125-128.

4. KOOP, J.E. "Measuring Maintenance Department Performance" Plant Engineering, 22 August (1974), p.97-98.

5. WILKINSON, J.J. "How to Manage Maintenance". Harvard Business Review, March-April (1968), p.36-47.

6. JARDINE, A.K.S. (Editor) "Operational Research in Maintenance" Manchester University Press, Manchester (1970).

7. TURCO, F., PAROLINI, P. "A Nearly Optimal Policy for Productive Equipment" International Journal for Production Research. Vol.22 No.3 (1984), p.515-528.

8. MALIK, M.A.K. "Reliable Preventative Maintenance Scheduling" American Institute of Industrial Engineers Transactions, September (1979) p.221-228.

9 CZAJKIEWICZ, Z.J. "Optimization of the Maintenance Process" Simulation, March (1985) p.137-141.

10. CHRISTER, A.H., WALLER, W.M. "An Operational Research Approach to Planned Maintenance Modelling P.M. for a Vehicle Fleet." Journal of the Operational Research Soc., Vol.35, No.11 (1984), p.967-984.

11. MALIN, J.L., BUNJON, I. "H.P. Maintenance Management : A New Approach to Software Customer Solutions", Hewlett-Packard Journal, March 1985, p.4-10.

12. BOS, M., DAVIS, T.B., REDDING, J.M. "Key Steps to Establishing Sound Productive Maintenance" Plant Engineering, 12 December (1985), p.38-40.

13. HUGGETT, P.J. "The Optimal Management of Maintenance" Power and Plant in Southern Africa, October (1981), p.37-39, November (1981) p.43, December (1981) p.24.

14. JONES, T. "Predictive Maintenance and Cost Control" The Certificated Engineer, August 1983, p.112-118.

APPENDIX A

FORMULATION FOR THE RELIABILITY FUNCTION MODEL

The derivation given below is from Jardine (Ref.10) p.105 and 106.

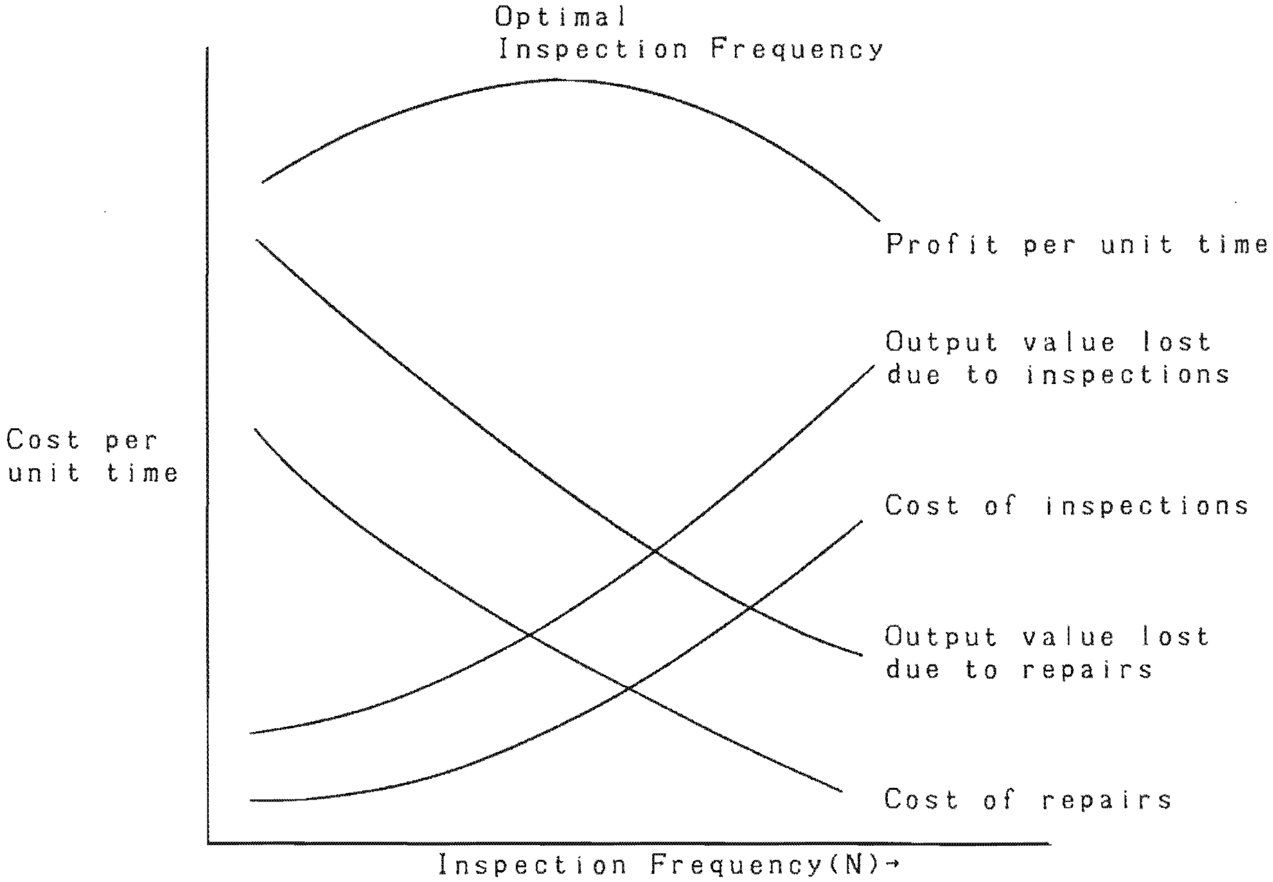


Figure A-1 THE AFFECT OF INSPECTION FREQUENCY ON COSTS

Fig. A-1 shows the relationship between profit per unit time and the inspection frequency. Profit per unit time (P) can be calculated using the following formula.

P = Value of output per uninterrupted unit time
- Output value lost due to repairs per unit time
- Output value lost due to inspections per unit time
- Cost of repairs per unit time
- Cost of inspections per unit time

where:

Output value lost due to repairs per unit time
= Value of output per uninterrupted unit of time (G)
x No. of repairs per unit time (R)
x Mean time to repair (t_s)

$= G.R.t_s$

Output value lost due to inspections per unit time
= Value of output per uninterrupted unit time (G)
x No. of inspections per unit time (N)
x Mean time to inspect (t_i)

$= G.N.t_i$

Cost of repairs per unit time
= Cost of repairs per uninterrupted unit of time (C_s)
x No. of repairs per unit time (R)
x Mean time to repair (t_s)

$= C_s R\ t_s$

Cost of inspections per unit time
= cost of inspection per unit time (C_i)
x No. of inspection per unit time (N)
x Mean time to inspect (t_i)

$= C_i.N.t_i$

thus

$$P = G - GRt_s - GNt_i - C_sRt_s - C_iNt_i$$

R is a function of N and for the sake of this model P is assumed to be a continuous function of N. We need to maximise P to find optimum N

thus

$$\frac{dP}{dN} = G\ t_s\ R' - Gt_i - C_s\ t_s\ R' - C_i\ t_i$$

where $R' = \frac{dR}{dN}$

therefore for maximum $\frac{dP}{dn} = 0$

$$0 = R't_s(G + C_s) + t_i\ (G + C_i)$$

thus max $R' = -\frac{t_i\ (G + C_i)}{t_s\ (G + C_s)}$ -------- (eqn A-1)

When the derivative of the repair frequency function (R') is equal to the right hand side of the equation then optimal inspection frequency has been found.

APPENDIX B

NUMERICAL EXAMPLE USING THE RELIABILITY FUNCTION MODEL.

We first need to find the repair frequency function. As explained in Section 5.2.2, this is not easy. However, for the sake of this example we will assume that the breakdown rate varies inversely with the number of inspections.

thus

$$R = \frac{K}{N} \qquad \text{(eqn B-1)}$$

where K is a constant

$$R' = -\frac{K}{N^2} \qquad \text{(eqn B-2)}$$

thus substituting eqn B-1 into eqn A-1 we get

$$N = \sqrt{K \, \frac{t_s}{t_i} \, \left[\frac{G + C_s}{G + C_i}\right]} \qquad \text{(eqn B-3)}$$

From the asset record cards and expenditure statements the following data is extracted for a particular machine.

Average no of breakdowns per month (K) = 1
Mean time to perform a repair (t_s) = 4 hours
Mean time to perform an inspection (t_i) = 0,8 hours
Value of output per uninterrupted month (G) = R10 000
Cost of repair per hour (C_s) = R35
Cost of inspection per hour (C_i) = R45

All the figures using hours must be reduced to a month basis. Assume a 220 hour month

t_s = 0,0182 months
t_i = 0,0036 months
C_s = R7700
C_i = R9900

thus from eqn B-3

$$N = 1 \times \frac{0,0182}{0,0036} \left[\frac{10000 + 7700}{10000 + 9900}\right]$$

$$= 4,49$$

Thus to maximise profit we should have between 4 and 5 inspection per month.

APPENDIX C

FORMULATION FOR THE DELAY TIME MODEL

The derivation as given below is based on that by Christer and Waller (Ref.13).

The following assumptions are made

(i) The inspection interval is T, the inspection costing C_i and taking t_i where $t_i << T$.

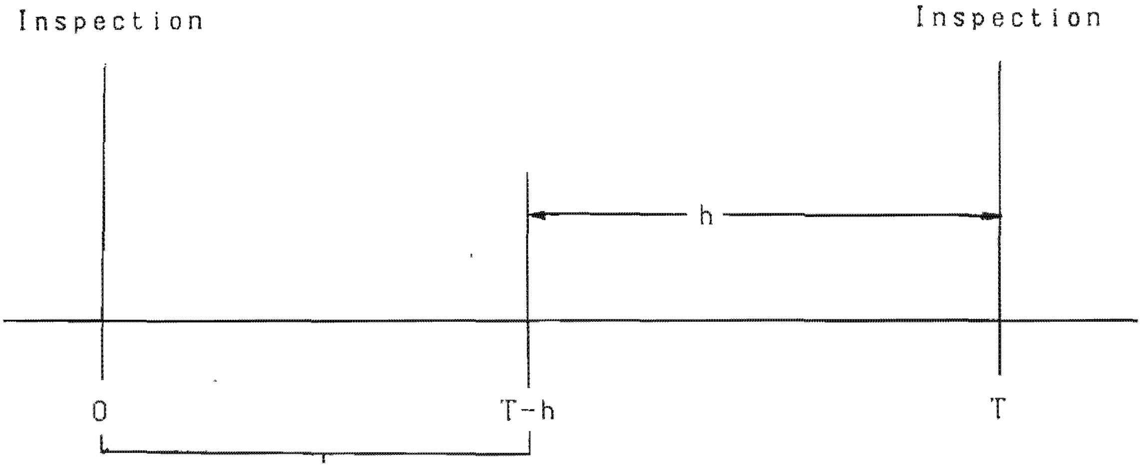
(ii) Inspections are perfect and any defect in the plant will be identified.

(iii) Defects identified at inspection will be repaired within the inspection period (t_i).

(iv) The initial instant at which the defect first arises (the time of origin of the fault) is uniformly distributed over time since last fault and independent of h. Fault arrival rate is q.

(v) The probability density function (p.d.f.) of the delay time is known and is f(h).

The probability of a fault arising between 0 and T with a delay time in the internal h and h + dh is f(h) dh. From Fig. C-1 it can be seen that the fault will be repaired as a breakdown repair if it arises in the period 0 to T-h. Otherwise it will be repaired at inspection.



Faults arising in this region will need repair before the next inspection (i.e. breakdown repair)

Figure C-1 THE INCIDENCE OF A BREAKDOWN

If a fault is to arise the probability that it will arise before T-h is (t-h)/T. Thus the probability that a fault with delay time in the region h and h+dh will be repaired as a breakdown is

$$\frac{(T - h)}{T} f(h)\ dh$$

Thus for all h the probability of a breakdown repair (b)

$$b = \int_{h=0}^{T} \left[\frac{T - h}{T}\right] fh\ dh \qquad \text{(eqn C-1)}$$

The average downtime for a breakdown repair is t_s. Thus the downtime per unit time (d) is given by

$$d = \frac{1}{T + t_i} [q\ Tt_s\ b + t_i] \qquad \text{(eqn C-2)}$$

The average breakdown repair costs C_s per unit time while an inspection repair cost C_r per unit time. Thus the cost of maintaining the plant per unit time (C_m).

$$C_m = \frac{1}{T + t_i} [q\, T\, (C_e t_e b + C_s t_i (1-b)) + C_i (t_i - t_r)] \qquad \text{(eqn C-3)}$$

and the downtime costs are

$d\, C_d$ per unit time

Where Cd is the cost of downtime per unit time of downtime

Thus total plant cost (C_p) is

$$C_p = C_m + dC_d \qquad \text{(eqn C-4)}$$

APPENDIX D

NUMERICAL EXAMPLE USING THE DELAY-TIME MODEL

From Appendix C it can be seen that there are four formula required for the calculation of the optimal inspection interval.

$$b = \int_{h=0}^{T} \left[\frac{T-h}{T}\right] fh \, dh \qquad \text{(eqn C-1)}$$

$$d = \frac{1}{T + t_i} [q \ Tt_s \ b + t_i] \qquad \text{(eqn C-2)}$$

$$C_m = \frac{1}{T + t_i} [q \ T \ \{C_s t_s b + C_s t_i (1-b)\} + C_i (t_i - t_r)] \qquad \text{(eqn C-3)}$$

$$C_p = C_m + dC_d \qquad \text{(eqn C-4)}$$

The aim is to find that inspection interval (T) at which the total plant cost (c_p) is at a minimum.

First Calculate b

An estimate is made for the p.d.f. of the delay-time ((f(h)). This would normally be calculated from raw data.

Thus let $f(h) = 0{,}05e^{-0.05h}$

$$b = \int_{h=0}^{T} \left[\frac{T-h}{T}\right] 0{,}05e^{-0.05h}$$

$$\int_{h=0}^{T} \left[1 - \frac{h}{t}\right] 0{,}05e^{-0.05h}$$

$$= \left[\frac{0{,}05e^{-0.05h}}{-0{,}05} - \frac{0{,}05}{T} \cdot \left[\frac{e^{-0.05h}}{-0{,}05}\right] \left[h - \frac{1}{-0{,}05}\right]\right]_{0}^{T}$$

$$= \left[-e^{-0.05h} + \frac{1}{T}\, e^{-0.05h}\,(h + 20)\right]_{0}^{T}$$

$$= \left[-e^{-0.05h} + \frac{1}{T}\, e^{-0.05T}\,(T + 20)\right] - \left[-1 + \frac{1}{T} \times 20 \times 1\right]$$

$$= \frac{20e^{-0.05T} + T-20}{T}$$

A spread sheet is then set up using this value of b in equations C-2 and C-3 for various values of T. (see D-3). The value of C_p is thus calculated for a range of inspection intervals.

Minimum C_p = R136,21 at an inspection interval of 1,6 months. It can be seen that the cost, in this case is not highly sensitive to inspection interval and any interval between 1,1 and 2.4 months would yield a cost of less than R140 for that machine in a month.

DELAY TIME MODEL CALCULATIONS SPREADSHEET

T	b	q	ts	ti	d	Cs	Ci	tr	Cd	Cm	Cp
0.1	0.002495	2	0.0182	0.0036	0.034836	7700	9900	0.0018	10000	88.45672	436.8239
0.5	0.012396	2	0.0182	0.0036	0.007596	7700	9900	0.0018	10000	93.19621	169.1615
1	0.024588	2	0.0182	0.0036	0.004478	7700	9900	0.0018	10000	96.26193	141.0509
1.1	0.027002	2	0.0182	0.0036	0.004241	7700	9900	0.0018	10000	96.83437	139.2518
1.2	0.029408	2	0.0182	0.0036	0.004058	7700	9900	0.0018	10000	97.40008	137.9831
1.3	0.031807	2	0.0182	0.0036	0.003916	7700	9900	0.0018	10000	97.96024	137.1218
1.4	0.034197	2	0.0182	0.0036	0.003806	7700	9900	0.0018	10000	98.51562	136.5798
1.5	0.036579	2	0.0182	0.0036	0.003722	7700	9900	0.0018	10000	99.06684	136.2925
1.6	0.038954	2	0.0182	0.0036	0.003659	7700	9900	0.0018	10000	99.61435	136.2113
1.7	0.041320	2	0.0182	0.0036	0.003614	7700	9900	0.0018	10000	100.1585	136.2992
1.8	0.043679	2	0.0182	0.0036	0.003582	7700	9900	0.0018	10000	100.6995	136.5273
1.9	0.046030	2	0.0182	0.0036	0.003563	7700	9900	0.0018	10000	101.2377	136.8728
2	0.048374	2	0.0182	0.0036	0.003554	7700	9900	0.0018	10000	101.7732	137.3174
2.1	0.050709	2	0.0182	0.0036	0.003554	7700	9900	0.0018	10000	102.3061	137.8464
2.2	0.053037	2	0.0182	0.0036	0.003561	7700	9900	0.0018	10000	102.8366	138.4477
2.3	0.055357	2	0.0182	0.0036	0.003574	7700	9900	0.0018	10000	103.3648	139.1113
2.4	0.057670	2	0.0182	0.0036	0.003593	7700	9900	0.0018	10000	103.8907	139.8288
2.5	0.059975	2	0.0182	0.0036	0.003617	7700	9900	0.0018	10000	104.4144	140.5933
3	0.071386	2	0.0182	0.0036	0.003793	7700	9900	0.0018	10000	107.0021	144.9413
3.5	0.082611	2	0.0182	0.0036	0.004031	7700	9900	0.0018	10000	109.5417	149.8565
4	0.093653	2	0.0182	0.0036	0.004305	7700	9900	0.0018	10000	112.0362	155.0875
4.5	0.104516	2	0.0182	0.0036	0.004600	7700	9900	0.0018	10000	114.4879	160.4951
5	0.115203	2	0.0182	0.0036	0.004909	7700	9900	0.0018	10000	116.8981	165.9966
5.5	0.125716	2	0.0182	0.0036	0.005227	7700	9900	0.0018	10000	119.2681	171.5402
6	0.136060	2	0.0182	0.0036	0.005549	7700	9900	0.0018	10000	121.5989	177.0917
6.5	146238	2	0.0182	0.0036	0.005873	7700	9900	0.0018	10000	123.8915	182.6281

APPENDIX E

NOTATION USED IN FORMULAS

P - Profit per unit time
G - Value of output per uninterrupted unit time
R - No. of repairs per unit time
N - No. of inspections per unit time
K - Constant
T - Interval between inspection in unit time
h - Delay time in unit time
q - Arrival of faults per unit time
b - Probability of a breakdown
d - Downtime per uninterrupted unit time
t_s - Mean time for a breakdown repair
t_i - Mean time for an inspection (including repair)
t_r - Mean time for an inspection repair
C_s - Cost of a repair per uninterrupted unit time
C_i - Cost of inspection per uninterrupted unit time
C_d - Cost of downtime per uninterrupted unit time
C_m - Cost of Maintenance per uninterrupted unit time
C_p - total plant cost per uninterrupted unit time.