

# Maintenance planning and optimal replacement of sub-assemblies for Continuous Miners

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## *Abstract*

This project will focus on designing maintenance and optimal replacement schedules for the sub-assemblies (subs) of the Continuous Miners (CM). The current method of determining when sub failures will occur is done on averages breakdowns which have shown in the past is not always the case. The current maintenance and replacement schedule for the subs is set up with incorrect data and guides management in the wrong direction when they draw up the annual budget for the CM. In the past it was found that the budget used for CM's at Twistdraai mine was not accurate enough to cover all the expenditures the mine was forced to take.

The maintenance and optimal replacement schedule will be designed to represent real-life sub breakdowns as far as possible. This will help management at Twistdraai mine to improve on the annual budget for the Continuous Miners. The improved maintenance and optimal replacement schedule will be able to guide the managers at Twistdraai mine to take better informed decisions concerning replacement and overhauling of subs.

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# Chapter 1

## Introduction and Problem statement

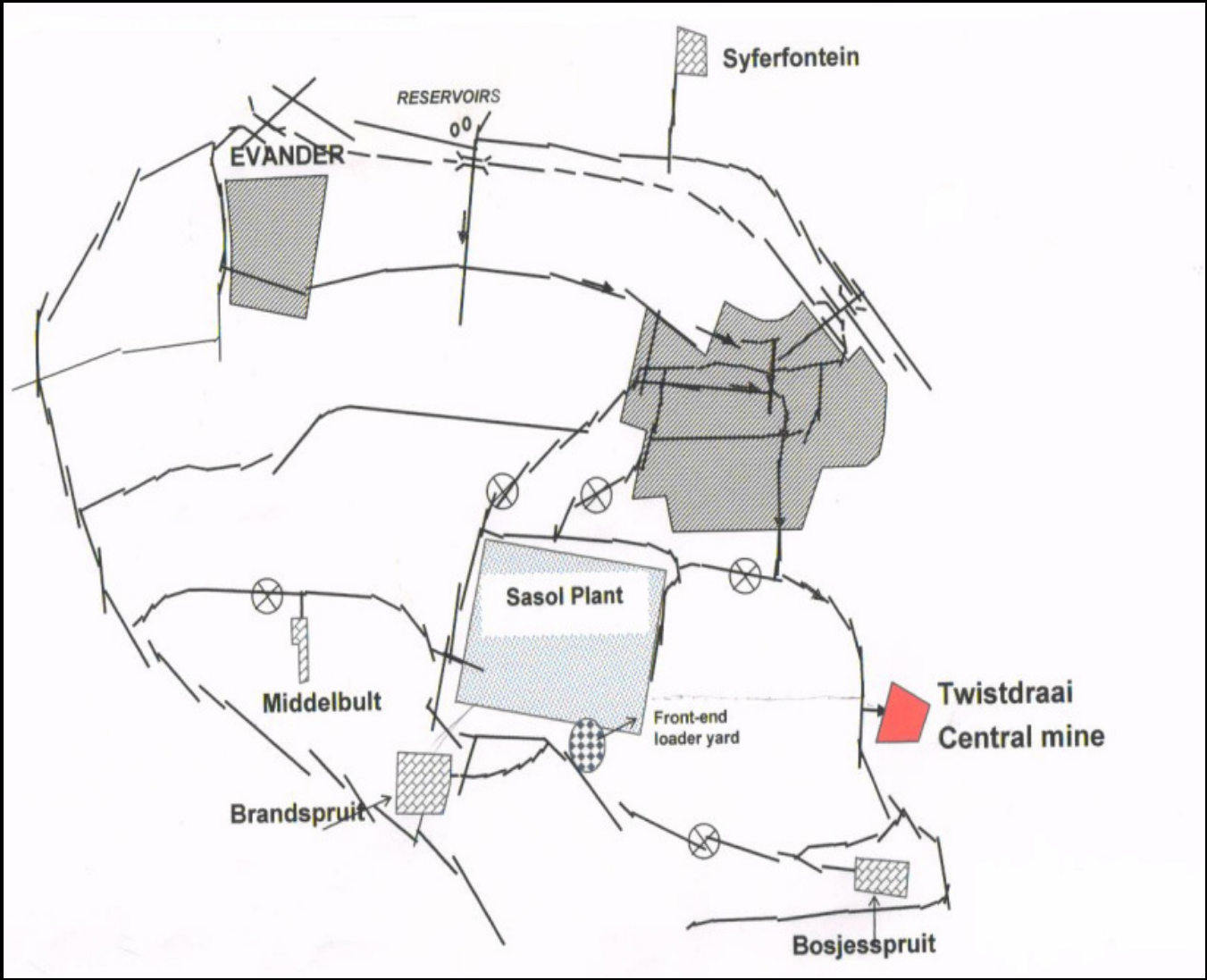
### *1.1 Introduction*

Sasol mining consist of five coal mines namely Twistdraai, Brandspruit, Bosjesspruit, Middelbult and Syferfontein. The annual budget for the five mines is a very high expenditure for the company. Any miss calculations can cause millions of Rand in losses. Accurate planning and preparation is necessary to insure that the budget for the next annum will be sufficient to cover all the expenditures of the mine.

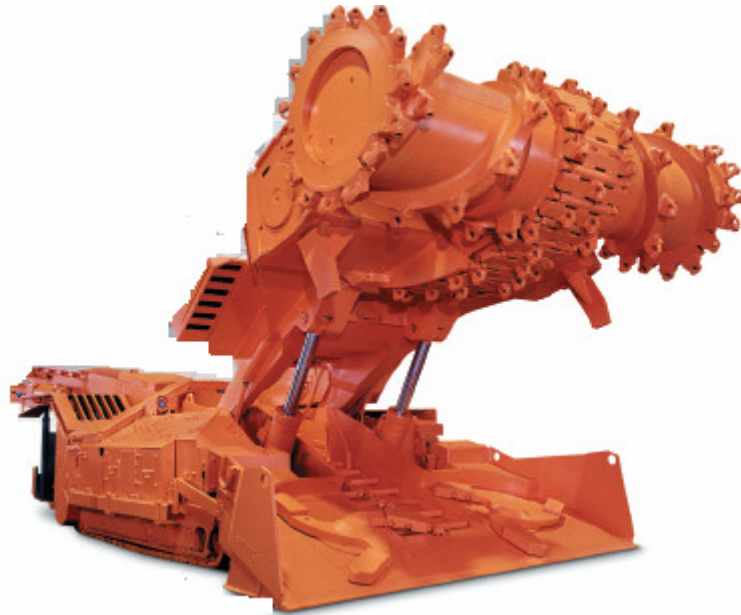
This project will be conducted at Twistdraai Central colliery. In figure one the map of where Twistdraai mine are located is illustrated. Twistdaai Central Colliery started to mine coal in the year 1979. After two decades of mining coal mine workers was forced to take long journeys to get to their workstations. Management decided to open two new shafts namely East and West shafts situated near Trichardt. These mines were opened in 1997.

These shafts mine coal on a board and pillar system in conjunction with the Nevid system for extraction of coal. In total ten million tons of coal are mined per annum. This coal is sent to the Beneficiary Plant, which in turn washes the coal in order to prepare it according to the specification required by export market. Different mines have different mining conditions (e.g. hard cutting, thin seams etc). At Twistdraai coal mine hard cutting CM's are used hence maintenance cost is very high.

Figure 1: Location map of Twistdraai central mine



The following picture is an illustration of how a Continuous Miner (CM) looks with all the sub-assemblies (subs). The CM has five critical subs that are expensive to maintain and replace. These subs are of high importance for the CM to function properly.



**Picture 1: Continuous Miner**

The reason for an optimal preventive replacement schedule is to give management some idea of when to expect a sub to fail and to replace that sub before it fails.

Currently management is struggling to determine a reliable preventive replacement schedule for the CM's subs.

The current maintenance and replacement schedule do not improve on the number of failing subs. For this reason management are reluctant to use the current schedule when planning the budget for sub replacements. They are forced to make decisions on experience and educated guesses. But this proved to be an unreliable approach.



Management is in need of a model that is able to advice them when to perform a preventive sub replacement. Maintaining a balance between the amounts spend on preventive replacements and their resulting benefits, that is reduced failure replacements is also a requirement the model should address.

In this project only the five critical subs was investigated. The reason for this was because these subs are very expensive to replace. Management regards these five critical subs as a high maintenance priority. Planning an optimal maintenance and replacement schedule for these five critical subs is of the utmost importance.

## 1.2 Background of a Continuous Miner

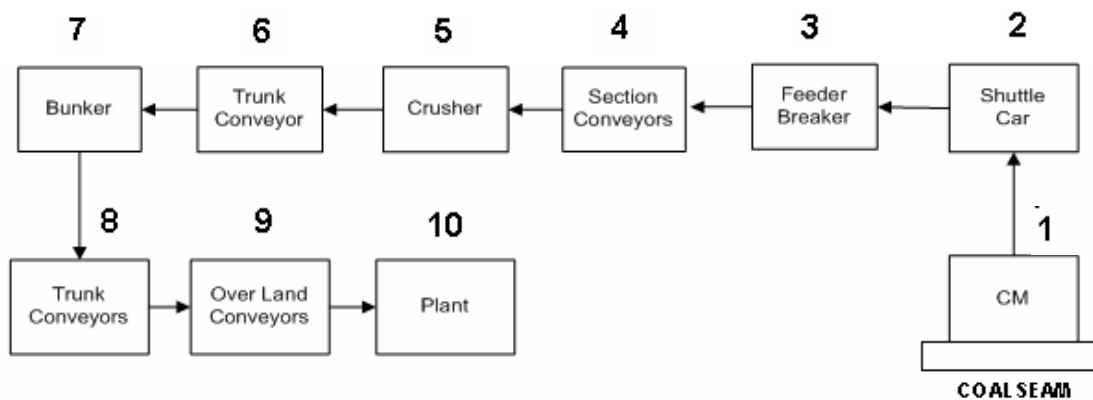
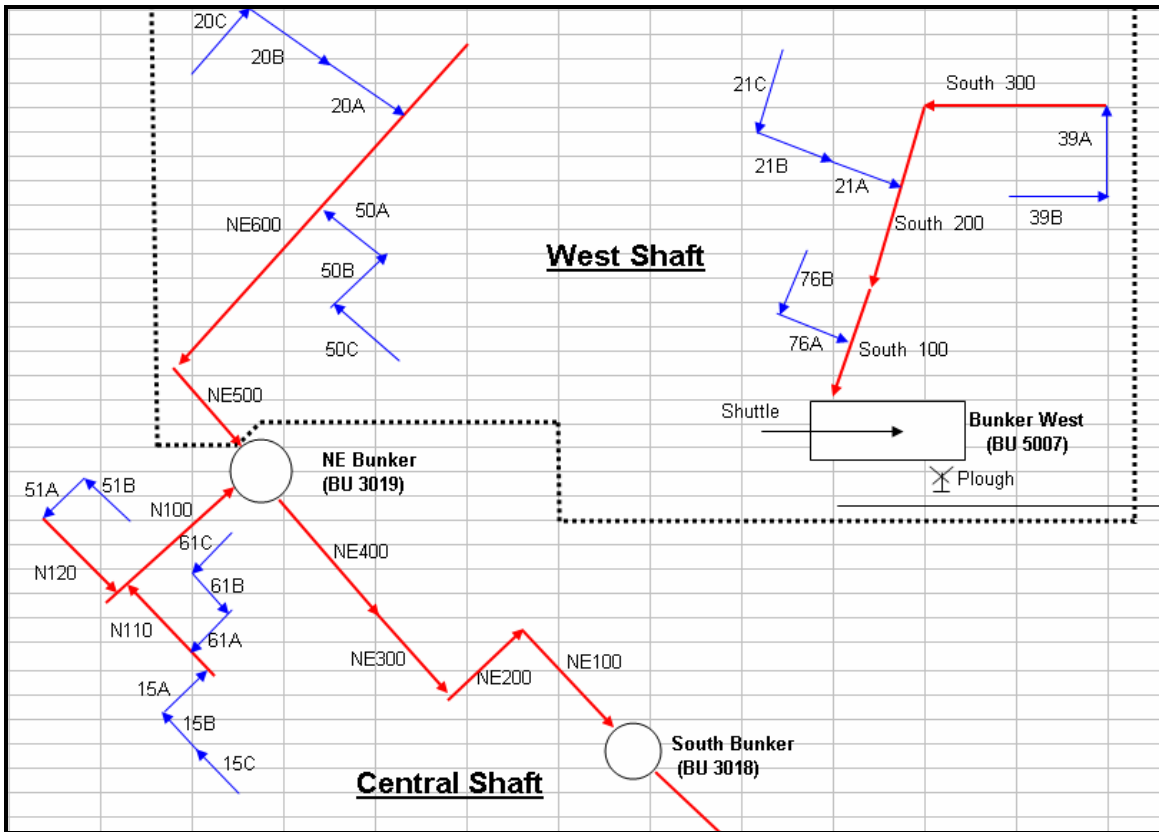


Figure 2: Coal mining value chain

In figure 2 the coal mining value chain is shown. This chain show the link of resources involved to mine the coal and bring it to the surface. The numbers in figure 2 correspond to the numbered bullets that follow:

1. The CM is the starting stage of the production line. The CM cuts the coal from the coal seam. Then newly cut coal drops onto a conveyor belt that is in the centre of on the CM.
2. The Shuttle car moves underneath the conveyor belt and collects the coal that drops from the moving conveyor belt.
3. The Feeder breaker crushes the large pieces of coal to smaller pieces for ease of transport.
4. From the Feeder breaker the smaller pieces of coal are distributed on section conveyors that transport the coal to the Crusher.
5. The Crusher breaks the coal into smaller pieces.
6. The Trunk conveyor is used to transport the coal pieces to the underground Bunker.
7. The underground Bunker is a temporary storage place for the coal.
8. The function of the trunk conveyors is to transport the coal underground and to the surface. Trunk conveyors are moved around regularly wherever new sections of coal are being mined
9. The last link of the transportation is the overland conveyors that transport the coal to the plant.



**Figure 3: Underground section and Trunk 1**

Figure 3 is the map of the underground conveyors inside the mine that transport the coal. The red lines on the map represent the section conveyors. The section conveyors are fixed conveyors and do not get moved often. The blue lines represent the trunk conveyors. The trunk conveyors are moved around regularly wherever new sections of coal are being mined.

The following is a list of the five critical sub assemblies of the CM.

1. TRACTION DRIVE ASSEMBLY
2. TRACTION MOTOR
3. GATHERING MOTOR
4. GATHERING GEARBOX
5. SCR BRIDGE

### ***1.2.1 Maintenance at the mine***

The annual cost of maintenance (corrective and predictive) as a fraction of the total operating budget varies across industry sectors. In the mining industry it can be as high as 40-50 per cent which translates into (0.5 billion per year for a big mining firm). These maintenance operations can achieve significant savings in cost by making the right and opportune maintenance decisions. Most important of all, maintenance excellence is concerned with balancing performance, risk, and the resource inputs to achieve an optimal solution. This is not an easy task because much of what happens in an industrial environment is characterized by uncertainties.

For this reason maintenance management must insure that the correct maintenance and preventive replacements schedules are in place and regularly revised to stay globally competitive.

(D.N.P Murthy,A Atrens ,2002)

(A.K.S Jardine, A Tsang, 2006)

Management realized that maintenance can not be viewed in a narrow operational context dealing with equipment failures and their consequences. Rather maintenance must be viewed in the long term strategic context and must integrate the different technical and commercial issues in an effective manner.

## ***1.3 Problem statement***

Maintenance is the largest controllable cost in the mining industry. Significant cost reductions and improvement in equipment reliability and performance will be achieved through the implementation of rationalized proactive maintenance.

(M.W Lewis, 2001)

The problem maintenance management is facing, is when to perform preventative replacements for the subs of a CM. Management is currently making maintenance decision based on averages sub failures (breakdowns).

L Savage states that the flaw of average is: "plugging average values of uncertain inputs into a function of random variables does not result in the average value of the function." The output data tend to react in a certain way but does not always represent the real life situations.

The current sub replacement model being used by management is not able to determine when the optimal time is to perform preventative replacements for subs.

## ***1.4 Research objective***

The objective is to determine the optimal preventive replacements of the subs in order to minimize maintenance cost.

This model should advice management how to improve decision making in areas of uncertainty and provide them with tools to improve their skills when it come to making difficult choices .

Management wants to know what type of maintenance models are available that are able to predict optimal preventive replacement intervals and solve their maintenance problems.

## ***1.5 Contribution of the project***

The results of this project will contribute the following:

- Better prediction of optimal replacement
- Reduce maintenance cost
- Assist in annual maintenance budgets
- Good example of applying maintenance principles or strategies in practical situation

## ***1.6 Limitation of the research***

- The research will be based on history data and not on real time data.
- The research will use failure data not failure modes.

# Chapter 2

## Literature Review

### *2.1 Maintenance strategies*

“The squeaking wheel doesn’t always get the grease. Sometimes it gets replaced.”

*Vic gold*

The aim of developing a CM maintenance strategy is to reach a detailed maintenance strategy that is practical, cost effective and useful. The CM maintenance strategy consists of the maintenance activities, and the associated replacement intervals, that are required to ensure that the CM is available and its efficiency is maximized at an acceptable cost and risk.

(Tsang at el; 2006:1)

#### *2.1.1 What is maintenance?*

Equipment needs to be maintained from time to time. What does maintain mean? The dictionaries define maintain as "Cause to continue" or as "keep in existing state".

According to the classical view, the role of maintenance is to fix broken items. Taking such a narrow perspective, maintenance activities will be confined to reactive task or repair actions or item replacement triggered by failures.

(Tsang at el; 2006:1)

Maintenance of equipment is a significant fraction of the total operating cost in many industry sectors. Effective maintenance management requires a multi disciplinary approach where maintenance is viewed strategically from the overall business perspective.

The important features of this multi disciplinary are:

- The integration of technical and commercial issues
- A quantitative approach using mathematical models
- Continuous improvement of maintenance management.

(Murthy et al; 2002:1)

The interactive process for continuous improvement in maintenance management is shown in figure 4. Improvement leads to reduced maintenance cost, increased availability or both.

(Murthy et al; 2002:7)



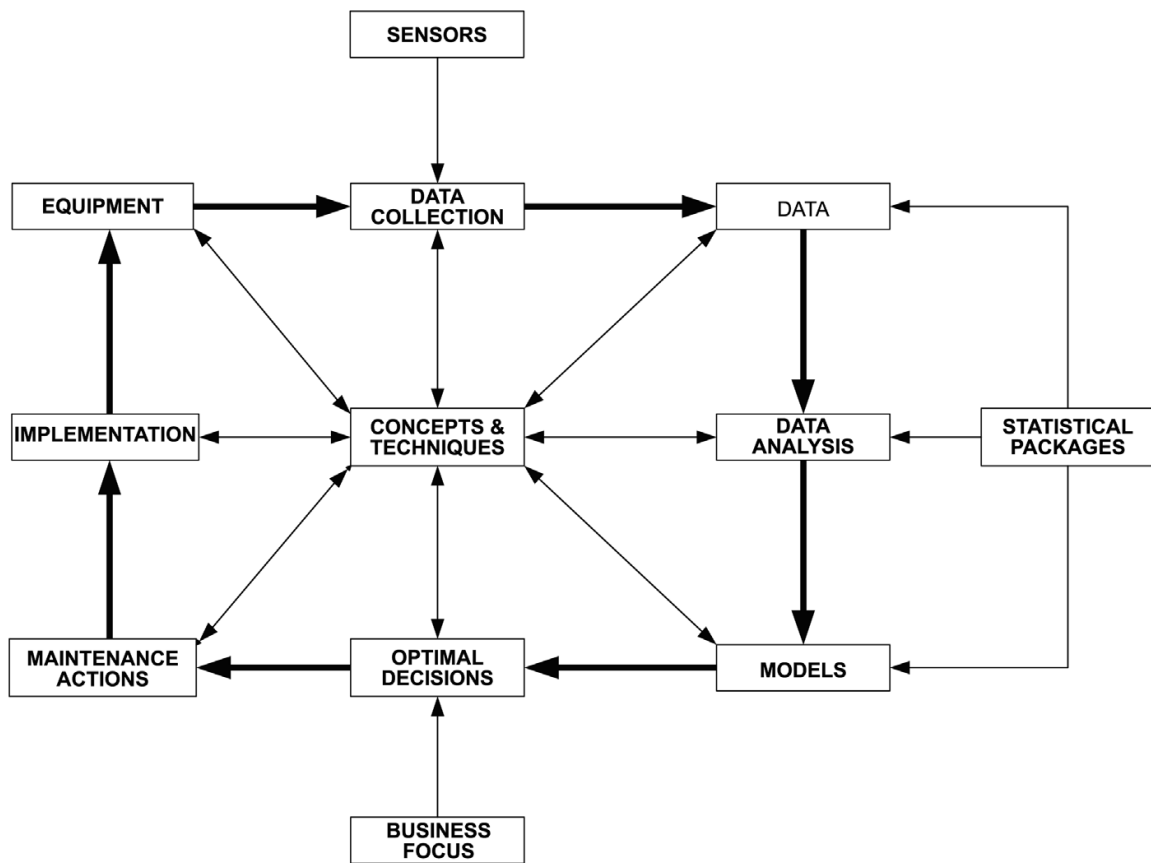


Figure 4: Continuous improvement in maintenance

## 2.1.2 What type of maintenance strategies are used in the mining environment?

Three types of maintenance strategies are used at the mine.

1. Scheduled replacement is done according to the tons and time in use.
2. The second strategy is to Condition based replacement. The sub will be replaced if not working properly.
3. The third strategy is called Run-to-failure meaning only replace the sub if the sub failed.

In the pursuit of continuous improvement three complementary methodologies that reflect different focuses are available to enhance reliability (uptime) of physical assets.

(Tsang et al; 2006:1)

The three methodologies to achieve continuous improvement and uptime of physical assets in the mining environment are:

- Total productive maintenance (TPM) – a people centered methodology
- Reliability-centered maintenance (RCM) – an asset- centered methodology
- Strategic maintenance management methodology

### **2.1.2.1 Total productive maintenance**

TPM is a people-centered methodology that has proven to be effective for optimizing equipment effectiveness and eliminating breakdowns. Routine servicing and minor repair of their machines creates a sense of ownership of the facility or machine they work on. To achieve zero breakdowns, hidden defects in the machine need to be exposed and corrected before they have deteriorated to the extent that they will cause the machine to break down. Its emphasis is on early detection of wear out to prevent in service failures.

(Tsang et al; 2006:6)

### **2.1.2.2 Reliability-centered maintenance**

The definition of RCM is based on the definition of maintenance. Reliability centered maintenance is a process used to determine what must be done to ensure that any physical asset continuous to do what its users want to do in its present operating context.

RCM uses a logic tree approach to determine the most appropriate maintenance task (predict or prevent each failure.)

The logic tree starts to determine whether:

- A condition based maintenance task is technical feasible and worthwhile doing.
- If not, it asks whether preventive maintenance task (e.g. Fixed Time Maintenance or inspections or routine overhaul) is technical feasible and worthwhile doing.
- If not, it suggest run-to-failure. Before applying run-to failure, one must check the financial, safety and environmental effects and consequences of this maintenance strategy. If run-to-failure is not suitable redesign or engineer-out maintenance should be done.

The three maintenance strategies approaches used by the RCM logic tree to determine the most appropriate maintenance task is explained in more detail in the following paragraphs

### **1. Predictive maintenance strategy ( Condition monitoring )**

Visual inspection, vibration analysis and oil analysis on the subs of the CM will be performed, where possible, to determine the physical conditions and assessing the risk of the subs. Recommendations from condition monitoring should be used in sub-assembly replacement decisions.

The optimal predictive replacement will help to replace a sub before it fails, but failures at random inside the preventive interval will still be present and failure replacement will still be necessary.

### **2. Preventive maintenance strategy**

Preventive maintenance tasks undertaken before a failure occurs, in order to prevent the subassembly or item from getting into a failed state. These tasks answers : "What can be done to predict or prevent each failure?" A preventive maintenance task on the CM is worth doing if it reduces the consequences of failure enough to justify the direct or indirect costs of doing the task.

Before considering whether a task is worth doing, we must of course determine whether it is technically feasible. A task is technically feasible if it is physically possible for the task to reduce, or enable action to be taken to reduce, the consequences of the associated failure mode to an extent that might be acceptable to the user of the asset.

a) Routine maintenance tasks

CM must undergo routine maintenance (two weekly) according to the RCM task lists.

b) Usage based sub-assembly replacement

The replacement of the critical subassemblies should be based on subassembly conditions and/or effective norms (economic life in tons).

### **3. Run-to-failure**

This is a reactive maintenance action where corrective maintenance is only taken after the failure has occurred. In this case it is not possible to predict a failure through inspection or testing or is not worthwhile to do preventive or predictive maintenance. If the risk of failure could significantly affect safety of the environment or production, the equipment or component must be redesign or modified.

Both RCM and TPM view maintenance in the broader business context and take into account the link between component failures and their impact on the business performance. However they assume a nominal operating condition and the optimal maintenance strategy is designed for this condition. As such they do not model the load on the equipment and its effects on the degradation process. In real life, the load (casing mechanical, electrical, heat stress on the components) depend on the production rate and this in turn depends on the demand pattern.

(Murthy et al; 2002:12)

### **2.1.2.3 Strategic maintenance management (SMM)**

Maintenance should be viewed in the long term strategic context and must integrate the different technical and commercial issues in an effective manner. This integration is captured in the SMM approach.

The two key elements of the SSM approach are:

- 1.** Maintenance management is a vital core business activity crucial for business survival and success, and as such it must be managed strategically.
- 2.** Effective maintenance management needs to be based on quantitative business models that integrate maintenance with other decisions such as production, etc.

In the SMM approach, maintenance is viewed as a multi-disciplinary activity. It involves

- Scientific understanding of degradation mechanisms and linking it with data collection and analysis to assess the state of the equipment.
- Building quantitative models to predict the impact of different actions (maintenance and operations) on equipment and degradation
- Managing maintenance from a strategic perspective.

Maintenance is also dependent on the inherent equipment reliability (less reliable equipment requiring greater maintenance effort) which is dependent on the decisions made during the design and manufacture of the equipment. As such operating and maintenance decisions need to be carried out jointly taking into account their impact on the equipment degradation and overall business objectives.

(Murthy et al; 2002:4)

Sasol mining uses Reliability Centered Maintenance (RCM) approach to determine the maintenance strategies for assets of the CM. In this project much attention was given to the preventive maintenance strategies.

## ***2.2 Optimal replacement models***

It is necessary to be able to identify which subs should be considered for preventative replacement, and which should be left to run until they fail. If the sub is a candidate for preventative replacement, then the subsequent question to be answered is: What is the best time?

Replacement problems (and maintenance problems in general) can be classed as either deterministic or probabilistic (stochastic). Failures of sub assemblies are according to a stochastic process.

Assuming the subs of the CM fails according to a probabilistic trend the timing and outcome of the replacement action depend on chance. In probabilistic problems it will be assumed that there are only two possible conditions of the equipment, good and failed, and that the condition is always known.

In determining when to perform a preventive replacement, we are interested in the sequence of times at which the replacement actions should take place. Andrew K.S Jardine and Albert H.C Tsang developed stochastic preventive replacement models that are able to determine optimal preventive replacement intervals of items subjected to breakdown.

(Tsang et al; 2006:27)

Before proceeding with the development of preventive replacement models, it is important to note that preventative replacement actions, that is, actions taken before equipment reaches failed state require a necessary condition. The total cost of replacement must be greater after a sub failure than before. This may be caused by a greater loss of production since replacement after failure is unplanned.

(Tsang et al; 2006:38)

In the literature study that follows replacement models from different authors were studied to try and find a suitable model/s that would be able to solve the difficult task of determining a reliable maintenance and replacement schedule for the subs of a CM.

### **2.2.1 Replacement Model One**

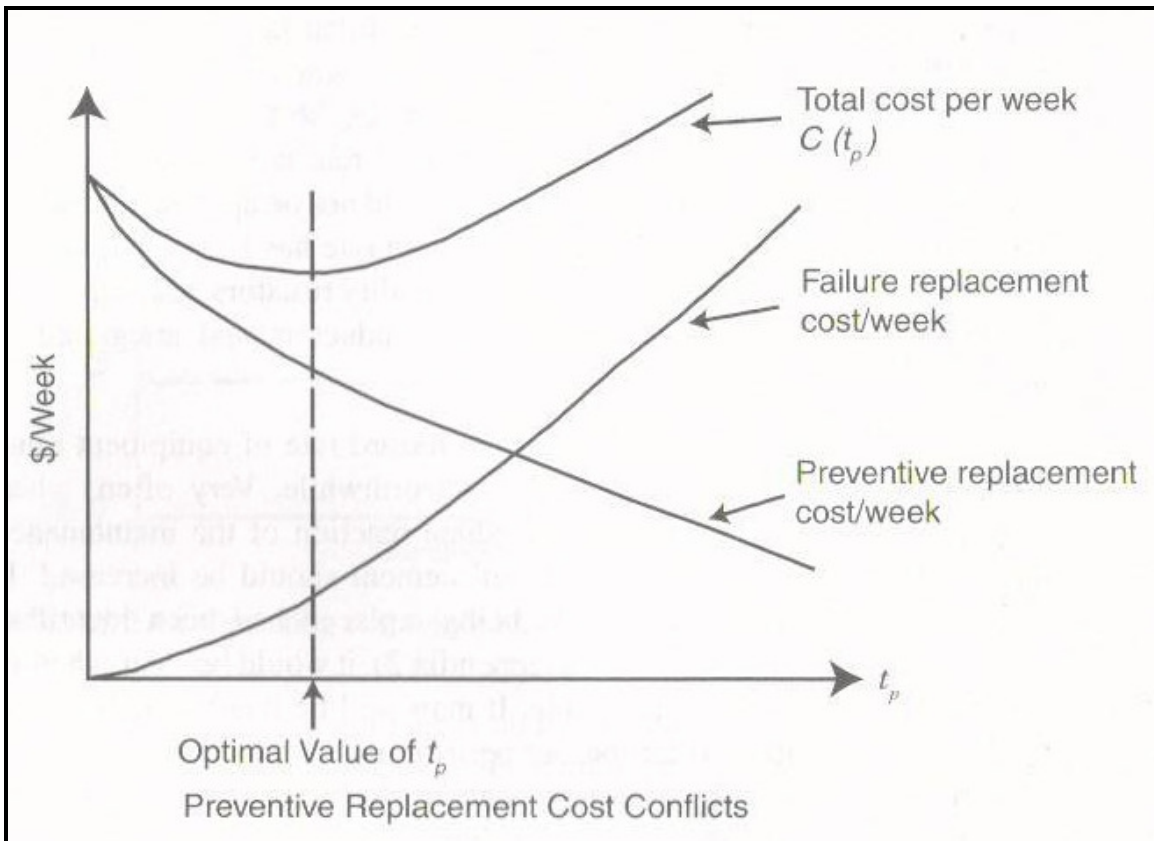
#### *Optimal preventive replacement interval of items subjected to breakdown*

*By Tsang A and Jardine A*

An item, sometimes termed a line replaceable unit (LRU) or part is subjected to sudden failure, and when it occurs the item has to be replaced. Since failure is unexpected, it is not unreasonable to assume that the failure replacement is more costly than preventive replacement.

In order to reduce the number of sub failures, preventive replacements can be scheduled to occur at specified intervals. The objective is to determine the optimal interval  $t_p$  between preventive replacements in order to minimize the total expected replacement cost per unit time this is shown in *figure 5*. However a balance is required between the amounts spent on the preventive replacements and their resulting benefits.

(Tsang et al; 2006:39)



**Figure 5: Optimal replacement time**

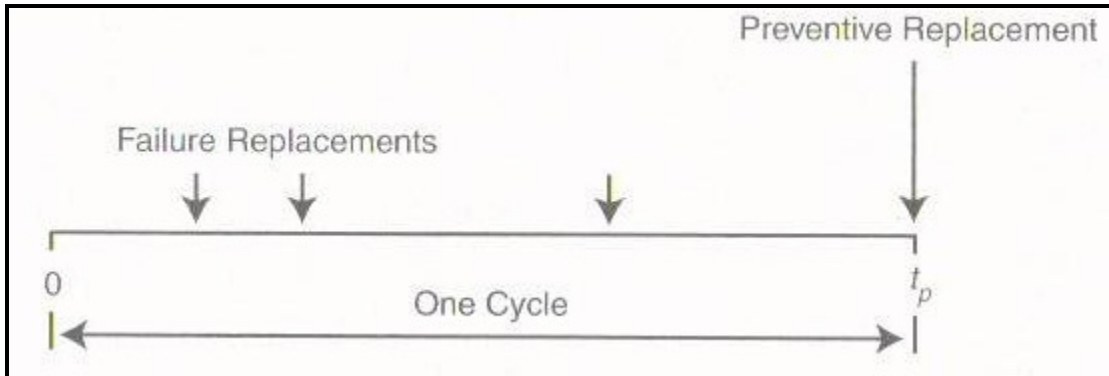
(Tsang et al; 2006:40)

### Assumptions for the model

- The replacement policy is one where preventive replacements occur at fixed intervals  $t_p$ , failure replacements occur wherever necessary.
- No account has been taken of the time required to make a failure replacement or a preventive replacement.
- Replacements scheduled on fixed intervals use calendar days. The time taken to do repairs, preventive maintenance and machine down time is excluded in the calculations.



The replacement policy is illustrated in figure 6. The goal is to perform preventive replacement at constant optimal intervals of length  $t_p$ , irrespective of the age of the item, and failure replacement occur as many times as requires in interval  $(0, t_p)$



**Figure 6: Replacement cycle: constant-interval policy**

(Tsang et al; 2006:41)

Acronyms used in model

1.  $C_p$  is the total cost of a preventive replacement
2.  $C_f$  is the total cost of a failure replacement
3.  $f(t)$  is the probability density function of an items failure times
4.  $t_p$  is the constant intervals length of the preventive replacements, irrespective of the age of the item, and the failure replacements occur as many times as requires in interval  $(0, t_p)$
5.  $C(t_p)$  is the total expected cost per unit time for preventive replacement at intervals of length  $t_p$

## Model formulation

$$C(t_p) = \frac{C_f + C_f H(t_p)}{t_p} \quad (1)$$

## Discussion of model

Equation (1) is used to determine the total expected cost per unit time for preventive replacement at intervals of length  $t_p$ . For every length  $t_p$  a different expected cost will be calculated.

When the literature study was done on this model it seemed to be a candidate model for solving the maintenance decisions that management was struggling with. The reason this model was considered was because the model was able to specify for a component a fixed Preventive replacement interval.

After further experimenting and studying of Tsang and Jardine's model a serious flaw was discovered. When a component failure occurs a repair is done to fix the failure but, there exist a possibility that preventive maintenance could be scheduled for that component shortly after the replacement was done. If that was the case preventive maintenance will loose its advantage and actually increase maintenance cost due to over-maintenance.

(Tsang et al; 2006:39)

The other key issues with the component preventive replacements in this model was that only one variable was being used to estimate the health of an item as described by its probability of failure.

(Tsang et al; 2006:40)

Even a novice that don't know anything about maintenance of mining equipment will tell you that many factors contribute to the health of a component and that the probability of sub failure is not adequate information to describe a real life failure occurrence.

The model should be solved and on the results of this model an analysis should be done to determine where the model does represent the current failure and replacement patterns.

### ***2.2.2 Replacement Model Two***

#### *Optimal preventive replacement age of an item subject to breakdown*

*By A Tsang and A Jardine*

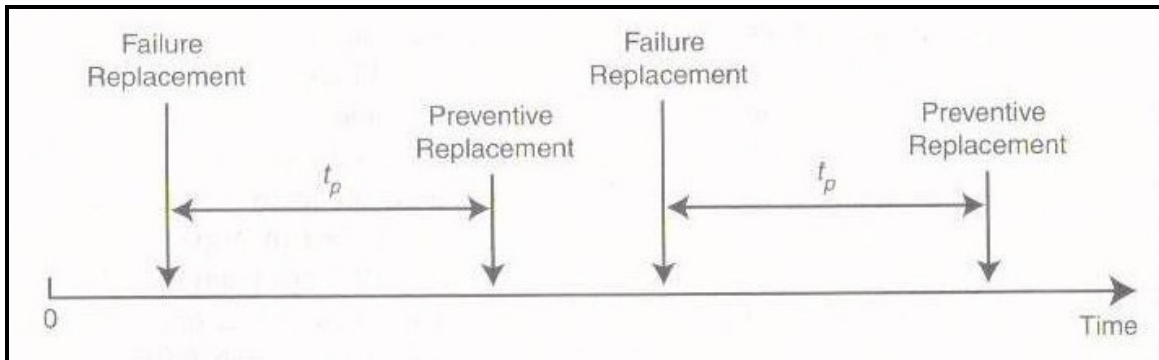
The difference in this model to that of the previous model is that instead of making preventive replacements at fixed intervals, with the possibility of performing a preventive replacement shortly after a failure replacement, the time at which the preventive replacement occurs in this model depends on the age of the item. When failures occur, failure replacements are made.

(Tsang et al; 2006:49)

When a preventive replacement takes place the replacement actions returns the equipment to the "as new" condition, thus continuing to produce exactly the same service as the equipment that has just been replaced when it was new.

Again the problem is to balance the cost of the preventive replacement against their benefits, and this is done by determining the optimal preventive replacement age for the item to minimize the expected cost of replacement per unit time.

The preventive replacement for a component is done only if the component has reached a specific age  $t_p$ . Failure replacements are done when necessary. This is shown in figure 7.



**Figure 7: Replacement cycle: age base policy**

(Tsang et al; 2006:50)

There are two possible cycles of operation:

- Cycle one being determined by the item reaching its planned replacement age  $t_p$ ,
- The other cycle being determined by the equipment ceasing to operate due to a failure occurring before the planned preventive replacement time.

## Assumptions for the model

- No account has been taken of the time required to make a failure replacement or a preventive replacement.
- Only two possible conditions of the equipment used, good and failed, and that the condition is always known.
- When a preventive replacement takes place the replacement actions returns the equipment to the “as new” condition, thus continuing to produce exactly the same service as the equipment that has just been replaced when it was new.
- Age of the CM is determined by using only working days. A working day consists of two shifts of 12 hours each. The time taken to do repairs, preventive maintenance and machine down time is excluded in the calculations.

(Tsang et al; 2006:50)

## Acronyms used in the model

1.  $C_p$  is the total cost of a preventive replacement
2.  $C_f$  is the total cost of a failure replacement
3.  $f(t)$  is the probability density function of an item's failure times
4.  $t_p$  is the specified age of the component at which a preventive replacement takes place
5.  $R(t_p)$  is the probability of a preventive cycle
6.  $M(t_p)$  is the expected length of failure cycle
7.  $C(t_p)$  is the total expected cost per unit time for preventive replacement when the component is at age  $t_p$

## Model formulation

$$C(t_p) = \frac{C_p \times R(t_p) + C_f \times [1 - R(t_p)]}{t_p \times R(t_p) + M(t_p) \times [1 - R(t_p)]} \quad (2)$$

## Discussion of model

Equation (2) is used to determine the total expected cost per unit time for preventive replacement at intervals of length  $t_p$

During literature study of this model it became clear that this model could be a candidate model for solving the problems maintenance management was facing. The reason for this was that this model was able to specify for each component the time at which the preventive replacement should occur depending on the ages of the component.

This model will be solved and the solutions will be compared with the replacement model in section **2.2.1** to verify if the solutions are consistent and reliable.

### **2.2.3 Replacement Model Three**

#### *Optimal maintenance service contracts negotiation with aging equipment*

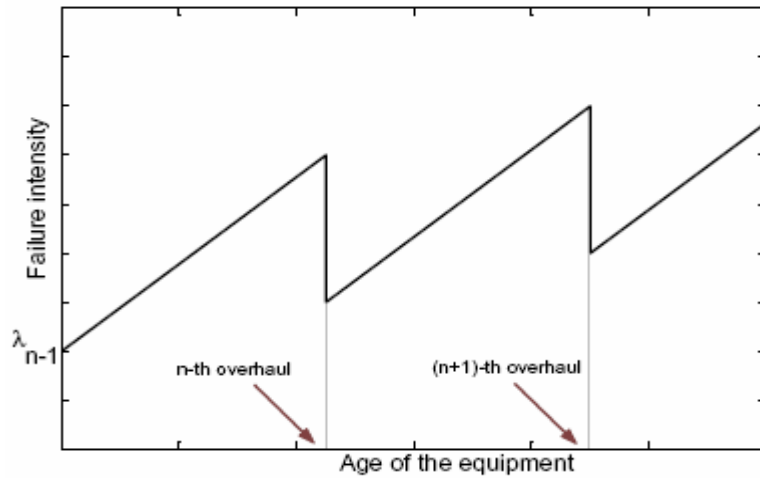
*By C Jackson, R Pascual*

C Jackson states that: "The client owning equipment has to know the time periods between maintenance and also the time between the replacements of sub assemblies in order to improve on preventive maintenance. Performing the maintenance on the right time has a significant impact on the performance of equipment". Management needs to know when to replace a certain

unit or component. Knowing when to replace or overhaul a machine is a difficult task the maintenance engineer has to deal with.

(C Jackson, R Pascual: 2007)

Maintenance actions have significant impacts on the equipment performance. Maintenance actions control the failure intensity of equipment. Equipment has increasing failure intensity due to imperfect maintenance and the aging of equipment. This is illustrated in figure 8.



**Figure 8: Failure intensity vs. age of equipment**

(Jackson et al 2007: 390)

### Assumptions for the model

- Equipment has the same level of reliability and will decrease due to mechanical aging
- The arrival rate and service rate and maintenance improvement level is known
- Aging rate of the equipment is in terms of its deterioration suffered due to usage.
- Life expectancy of any equipment is assumed to be fairly long period
- Equipment is subjected to corrective and preventive maintenance
- No account has been taken of the time required to make a failure replacement or a preventive replacement.

### Acronyms used in model

1.  $\lambda(t)$  is the failure hazard
2.  $\lambda_n(t)$  is the failure intensity after nth overhaul
3. P is the improvement factor that describes the level of maintenance of an overhaul, for  $(0 < p < 1)$ .
4. T = the interval between preventive maintenance is constant.
5.  $\hat{H}(t)$  is the expected value for number of failures of the sub assemblies
6.  $f(N,T)$  is the objective function

### Model formulation

$$\hat{H}(NT) = \lambda_0 NT + rT^2 \frac{N^2(1-p) + Np}{2} \quad (3)$$

$$f(N, T) = \frac{\pi(N, T)}{NT} = \frac{R}{2} \left(1 - \frac{\bar{\lambda}}{\mu}\right) - \frac{C_m}{2} \bar{\lambda} - \frac{C_o}{2} \left(\frac{1}{T} - \frac{1}{NT}\right) - \frac{C_r}{2NT} \quad (4)$$



## Discussion of model

Equation (3) determines the expected number of sub failures. The results of equation (3) are used by the client owning the equipment to get an idea of the expected number of failure replacements that will be necessary during the total life cycle of the component.

When the arrival rate and service rate as well as the improvement factor become known, the expected number of sub failure times can be calculated given there are  $n$  number of overhauls that were carried out over the period  $[0, t]$ .

Equation (4) is the objective function. The main goal of the objective function is to maximize the expected profit per unit time by using the optimal preventive replacement intervals and optimal life cycles duration.

This model was designed with the purpose to advice owners of equipment when preventive maintenance will be necessary and what the number of overhauls for each component (during the component life cycle) necessary in order to maximize expected profit per unit time.

At the starting phase of the literature study of the model by *C Jackson, R Pascual* it seemed to be a candidate model that could provide feasible solutions for the problems maintenance management is facing. The numerical example in the appendix of their journal showed good results and was the driving force to continue with further studies of their model.

After studying the model more in depth, many challenges occurred. The difficult part was to find relevant data required by the model to find results. This proved to be a very difficult hurdle to overcome. The other problem was to understand the mathematical approach that *C Jackson, R Pascual* used in their models. They used highly complex algorithms and difficult formulations to solve their models.

The decision not to further study the model was based on the fact of not enough data was available to solve their model and also not being able to find appropriate solving software to solve their model.

## Findings

During the student's literature study, three replacement models were studied. Enough data was available to solve model one and model two. Model three will not be solved due to insufficient data. Model one and model two will be solved in Microsoft Excel and their results will be discussed in chapter three and analyzed in chapter four.

# Chapter 3

## Results

### ***3.1 Results***

As mentioned in chapter one only the five most critical subs were investigated. The reason was that the critical subs are very expensive to replace and that is why it is essential to find the right time to do the preventive replacement.

Three years of sub failure data was available. The failure distributions for the critical subs were determined with the add-in Microsoft Excel program @Risk. The failure distribution graphs are shown in appendix A.

The two replacement models that A Tsang and A Jardine designed were solved and the following results were obtained.

#### ***3.1.1 Results for replacement Model One***

The preventive replacement model one was the first model studied in the Literature study. The objective of this model is to determine the optimal time interval between sub replacements in order to minimize the total expected replacement cost per unit time given that the sub is subjected to a breakdown.

A preventive and failure replacement cost were determined for the critical subs. The preventive replacement cost is always 60% of the standard repair price and the failure replacement cost is 40% of the standard repair price. These are accepted percentages used in the mining environment when determining preventive and failure replacement costs of a CM. The standard

repair price is the price mines pay to the OEM (original equipment manufacturer) to repair the sub to the OEM standard in order to receive six months of warranty.

**All five critical subs were individually investigated and the following results were obtained.**

### 3.1.1.1 Traction drive assembly

In table 1 the results obtained from model one for the Traction drive assembly is illustrated. The preventive replacement and failure replacement was determined. The minimum expected replacement cost was found to be R210,000 at the replacement interval of two years.

<b>Sub Number</b>	<b>Preventive Replacement Cost (mean)</b>	<b>Failure Replacement Cost (mean)</b>	<b>Mean Failure Times (Years)</b>	<b>Minimum expected replacement cost</b>	<b>Optimal Replacement Interval (years)</b>
<u>1</u>	R 232,250	R 544,650	1.5	R210,000	2

Table 1: Results for Traction drive assembly

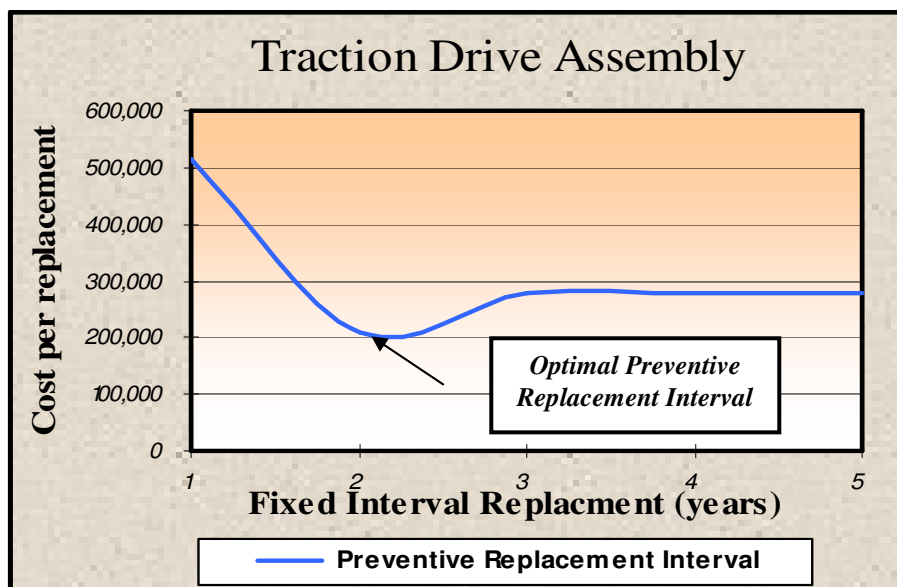


Figure 9: Preventive replacement graph for the Traction drive Assembly

Figure 9 is a graph of the total cost as a function of the different replacement intervals. To minimize the total expected replacement cost per unit time the model suggests that the preventive replacement should be performed at a fixed interval of two years. The arrow on the graph indicates the optimal preventive replacement interval.

### 3.1.1.2 Traction motor

In table 2 the results obtained from model one for the Traction motor is illustrated. The preventive replacement and failure replacement was determined. The minimum expected replacement cost was found to be R 78 180 at the replacement interval of between two and three years.

<b>Sub Number</b>	<b>Preventive Replacement Cost (mean)</b>	<b>Failure Replacement Cost (mean)</b>	<b>Mean Failure Times (Years)</b>	<b>Minimum expected replacement cost</b>	<b>Optimal Replacement Interval (years)</b>
2	R 41,500	R 111,550	1.7	R 78 180	Between 2-3

Table 2: Results for the Traction motor

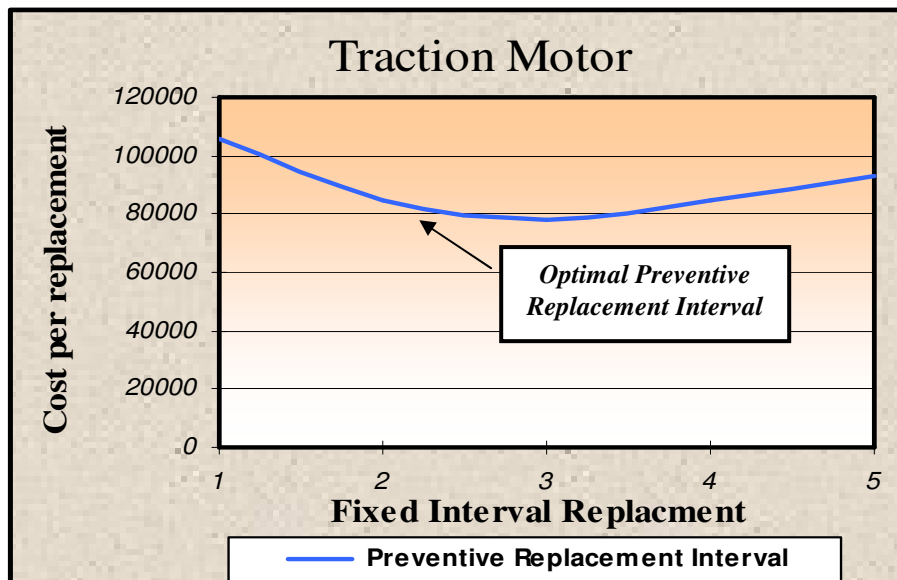


Figure 10: Preventive replacement graph for the Traction Motor

In figure 10 the graph has the shape of a flat parabola. The cost as a function of the different replacement intervals was plotted. The arrow indicates the optimal preventive replacement time is between two years and three years.

### 3.1.1.3 Gathering motor

In table 3 the results of the gathering motor is illustrated. The preventive replacement and failure replacement was determined. The minimum expected replacement cost was found to be R 59 830 at the replacement interval of two years.

<i>Sub Number</i>	<i>Preventive Replacement Cost (mean)</i>	<i>Failure Replacement Cost (mean)</i>	<i>Mean Failure Times (Years)</i>	<i>Minimum expected replacement cost</i>	<i>Optimal Replacement Interval (years)</i>
3	R 25,490	R 64,990	1.6	R 59 830	2

Table 3: Results for the Gathering motor

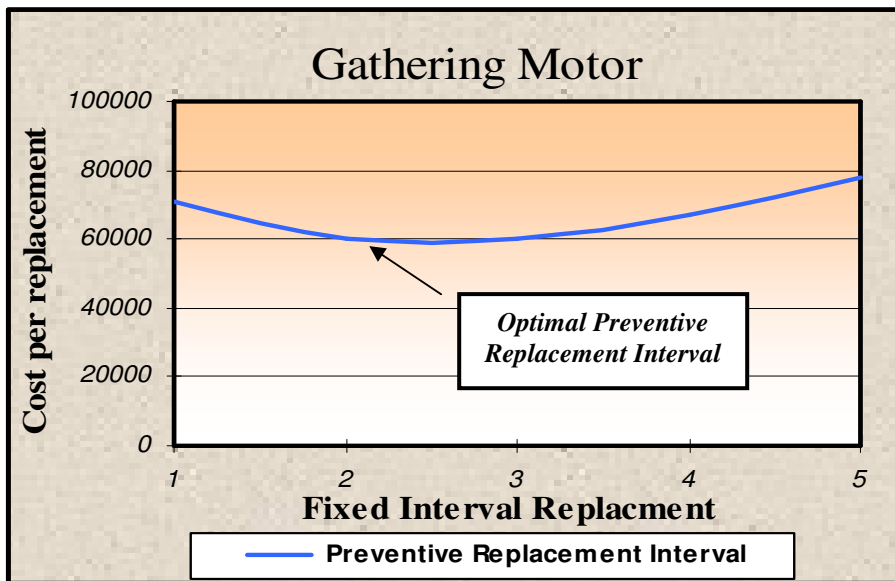


Figure 11: Preventive replacement graph for the Gathering motor

In figure 11 the graph of the total cost as a function of different replacement intervals was plotted. The lowest point on the graph (shape of a flat parabola) between year two and three is the optimal replacement interval. The graph show that the expected replacement cost is likely to increase as time passes by. This is because the probability of a failure occurring after two years is very likely to occur.

### 3.1.1.4 Gathering Gearbox

Table 4 illustrates the result for the Gathering gearbox. The minimum expected replacement cost was found to be R 59 240. The optimal replacement interval at that cost is between year two and three.

<b>Sub Number</b>	<b>Preventive Replacement Cost (mean)</b>	<b>Failure Replacement Cost (mean)</b>	<b>Mean Failure Times (Years)</b>	<b>Minimum expected replacement cost</b>	<b>Optimal Replacement Interval (years)</b>
<u>4</u>	R 23 950	R 83 950	1.48	R 59 240	Between 2-3

Table 4: Results for the Gathering Gearbox

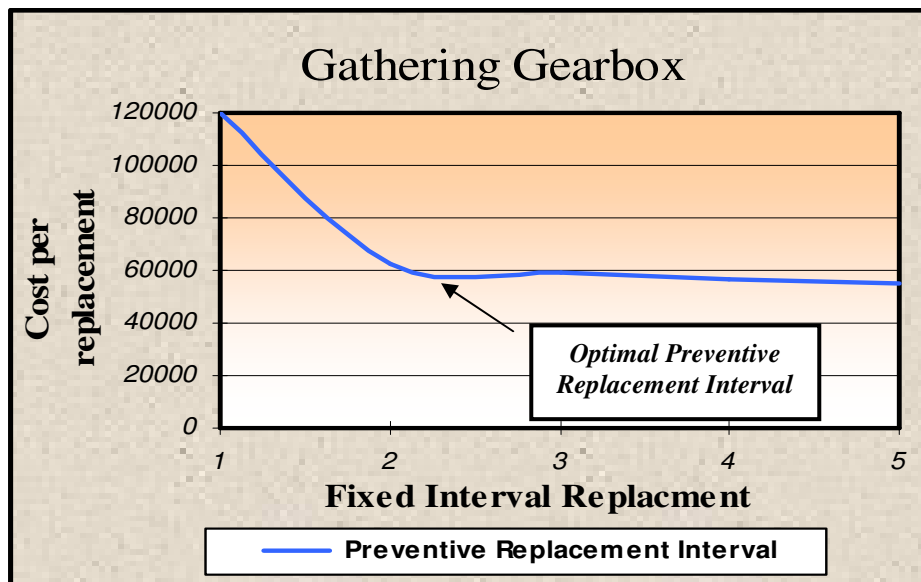


Figure 12: Preventive replacement graph for the Gathering Gearbox

Figure 12 is the graph of the cost as functions of the different replacement intervals. The optimal replacement interval is indicated with the arrow. Between two and three years the preventive replacement should be considered. The although the expected replacement cost in the graph show a flat curve over the third and fourth year of operation the probability of a failure occurring during those years is very high.

### 3.1.1.5 SCR Bridge

In table 5 the results for the SCR Bride is illustrated. The preventive and replacement cost was determined. The minimum expected replacement cost is R 6100 at an optimal replacement interval of two years.

<i>Sub Number</i>	<i>Preventive Replacement Cost (mean)</i>	<i>Failure Replacement Cost (mean)</i>	<i>Mean Failure Times (Years)</i>	<i>Minimum expected replacement cost</i>	<i>Optimal Replacement Interval (years)</i>
<u>5</u>	R 4,520	R 13,420	1.65	R 6 100	2

Table 5: Results for the SCR Bridge

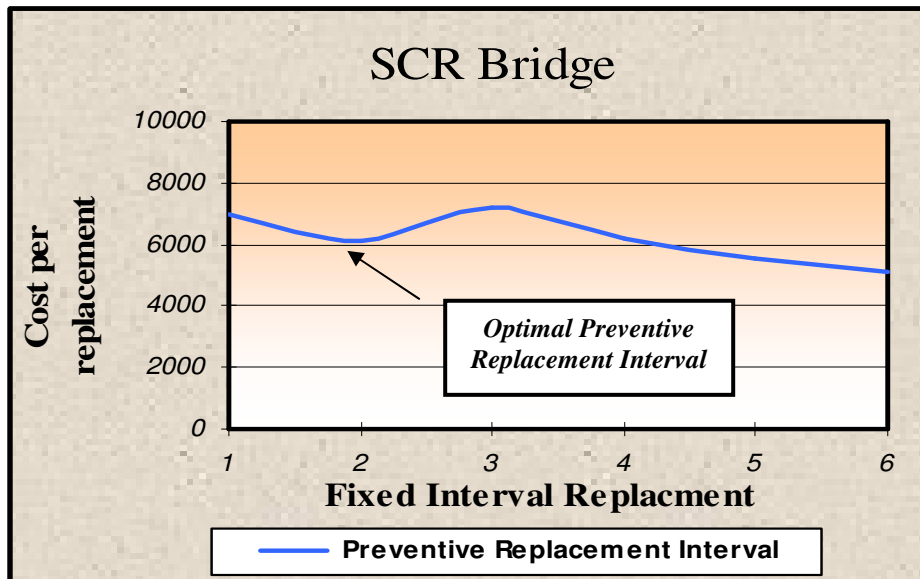


Figure 13: Preventive replacement graph for the SCR Bridge



The graph in figure 13 is the cost as functions of different replacement intervals. Although a decrease in expected replacement cost is evidence from year three till year six. At year three the replacement cost is above  $R7200$ . The advisable time to perform a preventive replacement according to the model is at year two.

### ***3.1.2 Results for replacement Model Two***

The optimal preventive replacement model by Tsang A and Jardine A was the second replacement model studied in the Literature study. This model takes age into account. Machine age was explained in chapter two in section 2.2.2.

Again the problem is to balance the cost of the preventive replacement against their benefits, and we do this by determining the optimal preventive replacement age for the item to minimize the expected cost of replacement per unit given that the sub is still subjected to a breakdown.

(Tsang et al; 2006:49)

When failures or breakdown occur, failure replacements are made. When this occurs, the time clock is reset to zero, and the preventive replacement occurs only when the item has been in use for the specified period. This was illustrated in figure 6

(Tsang et al; 2006:49)

The following results were obtained from solving the model in Microsoft Excel. Insight was gained on when the optimal replacement age  $t_p$  is reached in relation to the total expected replacement cost per unit time.

Again each of the critical subs was individually investigated and the following results were obtained.

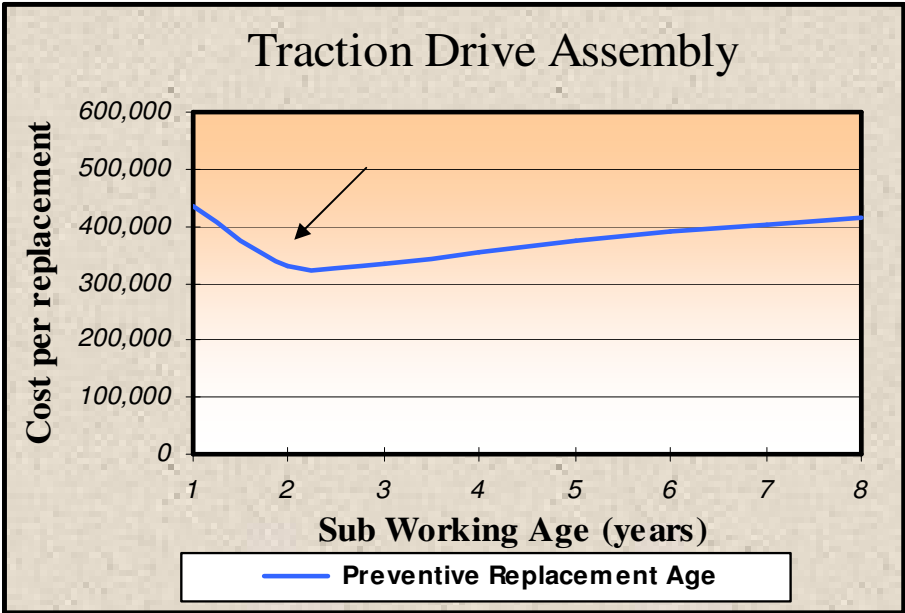
**3.1.2.1 Traction drive assembly**

The results from the model showed that the optimal replacement age is at two years. The expected cost at that age is R 331,185. This is illustrated in table 6.

<i>Preventive replacement age</i>	<i>Expected cost to replace</i>
1	R 434,101
2	<b>R 331,185</b>
3	R 335,806
4	R 355,186
5	R 374,612
6	R 391,258
7	R 404,279
8	R 413,919

*Optimal replacement age is at two years*

**Table 6: Replacement age for Sub assembly one - Traction drive assembly**



**Figure 14: Optimal replacement age for Traction Drive assembly**

In figure 14 the graph clearly shows that when the specified age of the sub increases the expected cost per replacement will increase. The optimal age to replace this sub is at the lowest point on the graph this will occur when the sub reach two years. If the sub is replaced after two years the expected replacement cost will increase. If this sub is replaced in operation year one the expected cost to replace the sub will be very high when weighing it up against the benefits it could still offer to the company.

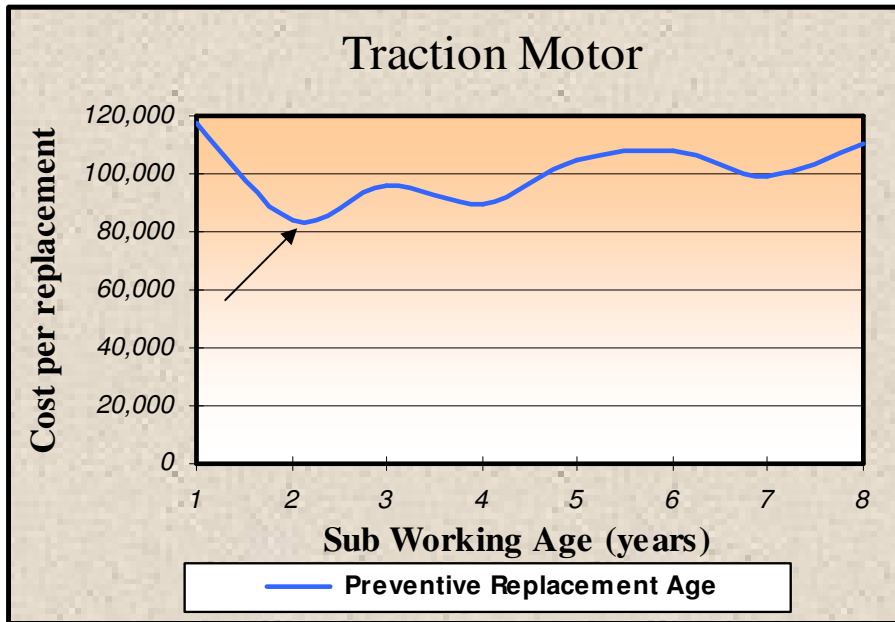
### 3.1.2.2 Traction motor

In table 7 the results from the model showed that the optimal replacement age is at two years. The expected cost to perform a preventive replacement at that age is R 83,789.

<i>Preventive replacement age</i>	<i>Expected cost to replace</i>
1	R 117,204
<b>2</b>	<b>R 83,789</b>
3	R 96,293
4	R 89,227
5	R 105,199
6	R 107,757
7	R 99,222
8	R 110,005

*Optimal replacement age is at two years*

**Table 7: Replacement age for Sub assembly two – Traction Motor**



**Figure 15: Optimal replacement age for the Traction motor**

In figure 15 the result for the Traction drive assembly is plotted. The arrow indicated the optimal age to perform a preventive replacement. The optimal age to replace this sub is at the lowest point on the graph this will occur when the sub reach two years.

If maintenance management decides to perform the preventive replacement after two years the expected replacement cost will be lower in at some ages due to different conditions and failure probabilities.

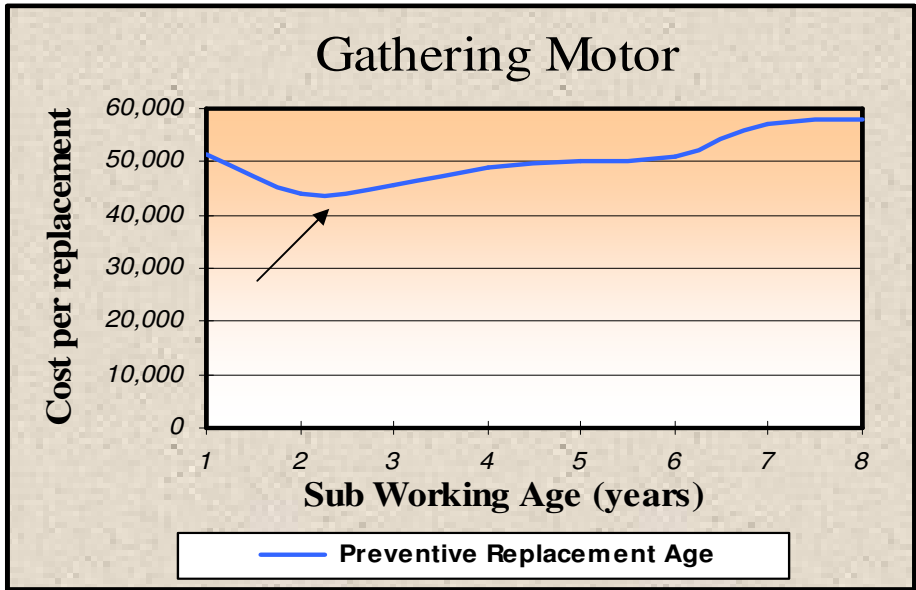
### **3.1.2.3 Gathering motor**

For the Gathering motor the model found the optimal age to perform a preventive maintenance is at year two. The expected cost to do a replacement at that age was calculated to be R 44,019.

<i>Preventive replacement age</i>	<i>Expected cost to replace</i>
1	R 51,373
<b>2</b>	<b>R 44,019</b>
3	R 45,693
4	R 49,000
5	R 50,000
6	R 51,000
7	R 57,000
8	R 58,000

*Optimal replacement age is at two years*

**Table 8: Replacement age for Sub assembly three – Gathering Motor**



**Figure 16: Optimal replacement age for Gathering motor**

The results were plotted in figure 16 and showed that when the specified age increases the cost per replacement also increases. The arrow on the graph indicates the optimal age to perform a preventive replacement is at two years.

### 3.1.2.4 Gathering Gearbox

For the Gathering gearbox the model found the optimal age to perform a preventive maintenance is also at year two. The expected cost to do a preventive replacement at that age was calculated to be **R141,039**. This is illustrated in table 9.

<i>Preventive replacement age</i>	<i>Expected cost to replace</i>
1	R 169,304
<b>2</b>	<b>R 141,039</b>
3	R 166,759
4	R 175,278
5	R 175,699
6	R 175,706
7	R 175,706
8	R 175,706

*Optimal replacement age is at two years*

Table 9: Replacement age for Sub assembly four – Gathering Gearbox

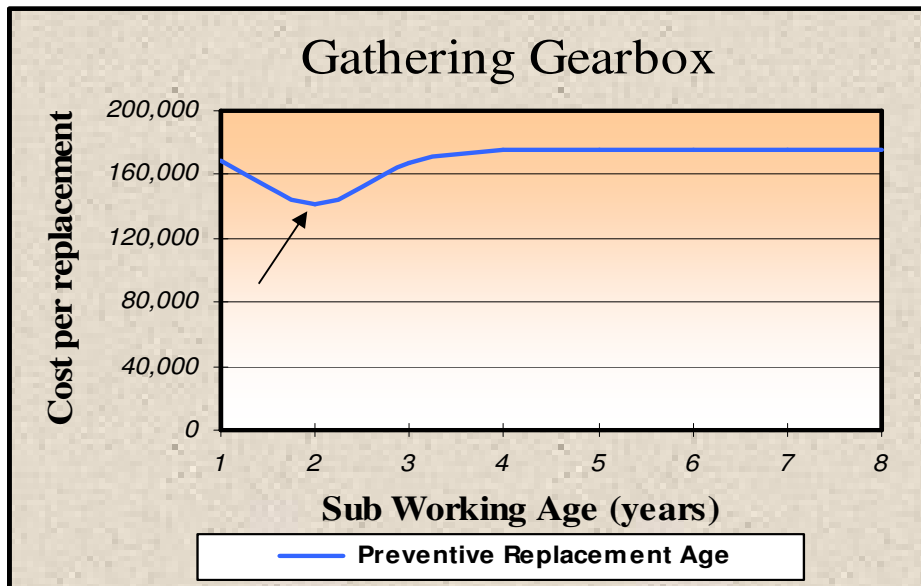


Figure 17: Optimal replacement age for the Gathering gearbox

The results were plotted in figure 17 and the result showed that when the specified age increases the cost per replacement also increases. The arrow on the graph indicates the optimal age to perform a preventive replacement is at two years.

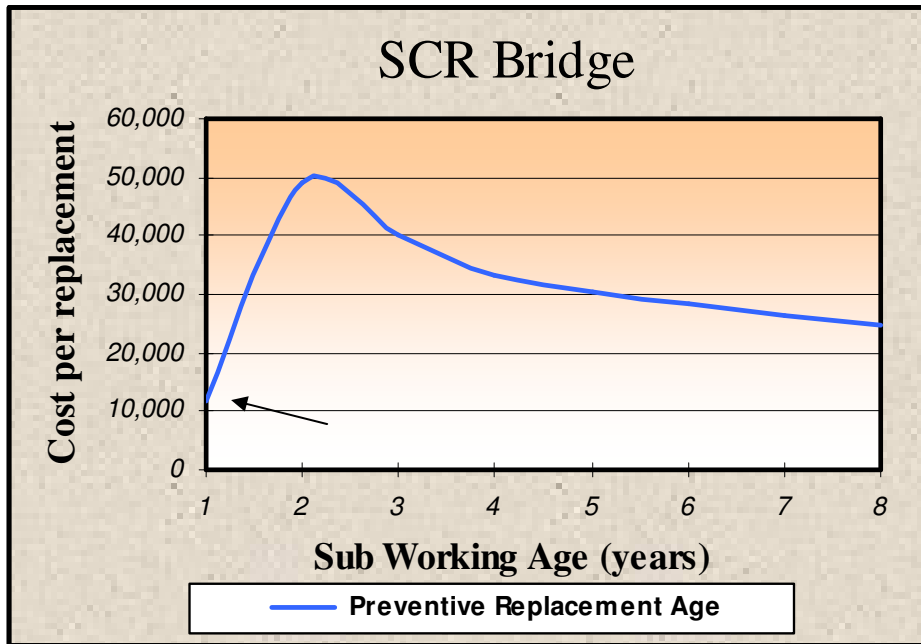
### 3.1.2.5 SCR Bridge

The results from the model are illustrated in table 10 that the optimal replacement age is at one year. The expected cost at that age is *R11, 699*.

<i>Preventive replacement age</i>	<i>Expected cost to replace</i>
<i>1</i>	<i>R 11,699</i>
<i>2</i>	<i>R 48,868</i>
<i>3</i>	<i>R 39,964</i>
<i>4</i>	<i>R 33,191</i>
<i>5</i>	<i>R 30,452</i>
<i>6</i>	<i>R 28,225</i>
<i>7</i>	<i>R 26,307</i>
<i>8</i>	<i>R 24,611</i>

*Optimal replacement age is at one year*

**Table 10: Replacement age for Sub assembly five – SCR Bridge**



**Figure 18: Optimal replacement age for the SCR Bridge**

The Graph in figure 18 clearly shows that when the specified age of the sub increases the expected cost per replacement will decrease. When the SCR Bridge reaches two years the expected replacement cost will be at the highest point and cost the company R 48,868 to replace.

The optimal age to replace this sub is at the lowest point on the graph (indicated by the arrow) this will occur when the sub reach one year.



# Chapter 4

## Analysis and Evaluation of results

### *4.1 Analysis and evaluation of results*

Tsang A and Jardine A designed two replacement models that were able to calculate the optimal time intervals to perform preventive replacements. Model one used a fixed interval approach. The model derived fixed intervals that specify when to perform preventive replacements. Their second model used a unit age base approach to determine the optimal time to perform preventive replacements.

#### *4.1.1 Analysis of replacement model one*

The goal of the replacement model is to decrease the number of sub failures. This can be achieved by scheduling preventive replacements at fixed intervals. A balance is required between the amount spend on preventive replacements and their resulting benefits, that is reduced failure replacements.

(Tsang at el; 2006:39)

Each sub was investigated individually. The model found the optimal time interval between replacements to occur when the expected cost to perform that replacement reach the lowest rand value.

<b>Sub Assembly</b>	<b>Optimal Replacement Interval</b>	<b>Cost Per Unit Replacement</b>
TRACTION DRIVE ASSEMBLY	<i>2 years</i>	<i>R 210 000</i>
TRACTION MOTOR	<i>2-3 years</i>	<i>R 78 180</i>
GATHERING MOTOR	<i>2 years</i>	<i>R 59 830</i>
GATHERING GEARBOX	<i>2-3 years</i>	<i>R 59 240</i>
SCR BRIDGE	<i>2 years</i>	<i>R 6 100</i>

**Table 11: Results of model one**

For all five the subs the optimal fixed replacement interval has an associate optimal cost connected to it this is tabularized in table 11.

### **Problems limiting the accuracy of the model's results**

- When a preventive replacement is scheduled on a fixed time basis (years) there exists a possibility of performing a preventive replacement shortly after a failure replacement was done.
- The mathematical model did not take into account the time it requires to perform failure and preventive replacement because the model assumed that time to be very short compared to the mean time between replacements.
- Assumed that the subs utilization is constant and this will not always be the case.
- Only one variable is being use to determine the optimal replacement interval of a sub as described by its probability of failure. Many factors contribute to the failure of a component.

Although the model found results the above mentioned limitations could cause the data to move away from realistic failure patterns. Model one's results will first have to be compared to the results of model two to verify the consistency in the results found.

### 4.1.2 Analysis of Replacement Model Two

The goal of the second replacement model is similar to that of the first replacement model, to decrease the number of sub failures. The main difference between the model one and model two was that model two specifies the time interval at which the preventive replacement should occur depend on the age of the sub.

Age of the CM is determined by using only working days. A working day consists of two shifts of 12 hours each. The time taken to do repairs, preventive maintenance and machine down time was not included in the calculations.

The optimal age to perform a preventive replacement was determined by the lowest expected replacement cost over a period (years). Table 12 gives a summary of the optimal machine age and the expected cost per unit replacement.

<b>Sub assembly</b>	<b>Optimal replace age</b>	<b>Cost per unit replacement</b>
TRACTION DRIVE ASSEMBLY	<i>2 years</i>	<i>R 331 185</i>
TRACTION MOTOR	<i>2 years</i>	<i>R 83 789</i>
GATHERING MOTOR	<i>2 years</i>	<i>R 44 019</i>
GATHERING GEARBOX	<i>2 years</i>	<i>R 141 039</i>
SCR BRIDGE	<i>2 years</i>	<i>R 11 699</i>

**Table 12: Results of model two**

## Problems limiting the accuracy of the model two's results

- The mathematical formulations did not take into account the time it requires to perform failure and preventive replacements because the model assumed that time to be very short, compared to the mean time between replacements.
- The down time of the CM was not included in the calculations. This is a varying factor that depends on the availability of spare subs. The repair on subs should be as fast as possible to minimize CM downtime.
- The mathematical formulations assumed that preventive maintenance is regularly preformed.

Model two found the replacement ages with their associated expected replacement cost. This result should be compared to the results of model one to verify consistency in results.

## Comparison between the results of model one and model two

Both models were able to determine optimal times to replace the five critical sub assemblies. When the results were compared both models' optimal times to replace a sub was very similar this is shown in table 13. Model one used calendar dates to specify fixed intervals between preventive replacements. Model two used the operating machine age of the subs to determine when a preventive replacement should occur.

<b>Sub assembly</b>	<b>Model one Optimal Replacement Interval</b>	<b>Model two Optimal replace age</b>
TRACTION DRIVE ASSEMBLY	<i>2 years</i>	<i>2 years</i>
TRACTION MOTOR	<i>2-3 years</i>	<i>2 years</i>
GATHERING MOTOR	<i>2 years</i>	<i>2 years</i>
GATHERING GEARBOX	<i>2-3 years</i>	<i>2 years</i>
SCR BRIDGE	<i>2 years</i>	<i>2 years</i>

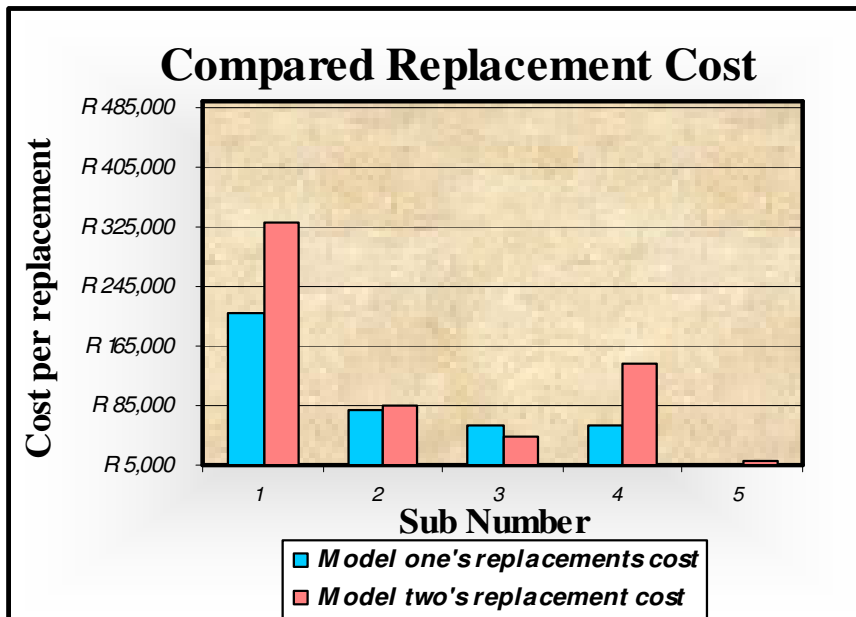
**Table 13: The comparison between replacements periods**

Although the replacement intervals and replacement ages show similar results, the results of model two should represent replacements more realistic. This is explained by looking at sub two the Traction motor.

Model one advises that the optimal replacement interval for the Traction motor should be every 2-3 years. But if a failure occurs before the scheduled replacement a failure replacement will be necessary. If management stays true to the preventive replacement schedule there exists a possibility of performing a preventive replacement shortly after a failure replacement. This will result in over-maintenance.

To avoid such an occurrence the replacement schedule of model two should rather be used. Model two advise that when the Traction motor reach an operational age of two years and no failures occurred during that time, the Traction motor should get replaced. But if the Traction motor failed during that period the sub should be replaced.

The advantage of model two above that of model one results is that when a preventive replacement takes place the replacement actions returns the equipment to the “as new” condition, thus continuing to produce exactly the same service as the equipment that has just been replaced when it was new. The next scheduled preventive replacement will occur after an operational age of two years.



**Figure 19: Model one’s replacements cost vs. model two’s replacement cost**

In figure 19 the replacement cost of the two models was compared to verify consistency in expected replacement cost. The overall replacement costs for model one (blue bars on graph) were slightly lower than the replacement costs for model two (pink bars). The reason for this could be that in the mathematical formulations of model one, only a single variable (probabilities of failures) was used to calculate the cost per replacement where model two uses two variables in the formulations to calculate the cost of replacement. Both models show almost the same result for sub two, three and five. Although the two models uses different approaches in calculating cost per replacement both models show similar patterns in results.

This is convincing evidence that the models do give realistic preventive replacement time periods. As mentioned in the paragraphs above management is advised to rather use model two’s results when planning and scheduling maintenance and replacements for the critical subs. Both models use basic mathematical formulations to find results. Clear assumptions were made when not enough information could be obtained.

These assumptions sometimes tend to change what really happens underground in the mine.

Although both models show good consistency in results, maintenance management should conduct further studies to increase confidence levels in the results that were found by the two models.

# Chapter 5

## *Conclusion*

This project focused on designing optimal maintenance and replacement schedules for the sub-assemblies for the Continuous miners. Three models were studied in the literature study but only two replacement models were eventually chosen.

Two models were studied and both models yielded sub replacement schedules. The second model by Tsang and Jardine was found to be the better suitable model for the maintenance problems at Twistdraai mine.

Optimal preventive replacements for subs of the CM can now be planned according to the new replacement schedule. This sub replacement schedule was determined by model two and uses history failure patterns rather than average sub breakdowns.

The student is convinced that if management stay true to the suggested preventive replacement schedule that a significant improvement in sub failures will be achieved.

The new optimal maintenance and replacement schedule will be able to guide the managers at Twistdraai mine to take better informed replacement and overhauling decisions concerning sub assemblies of the Continuous Miners.



# Appendix one

Failure distributions of the five critical subs

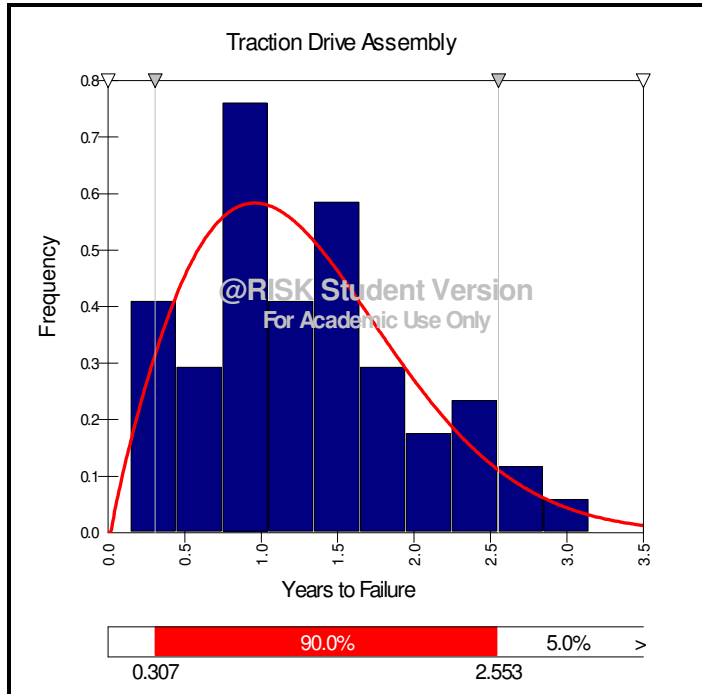


Figure 20 : Failure distribution of the Traction drive assembly

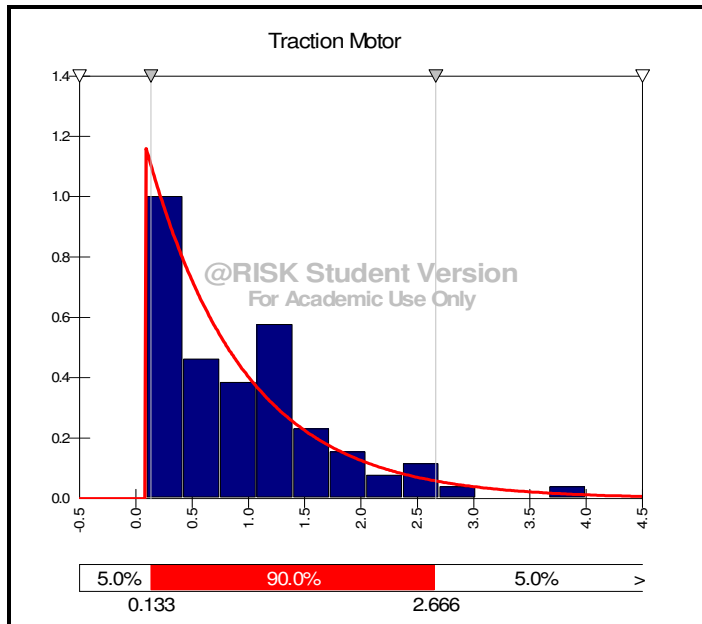
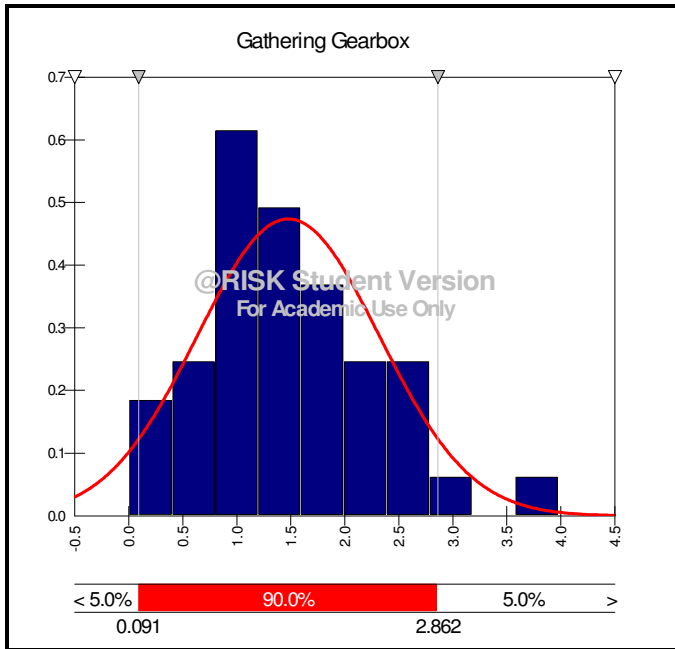
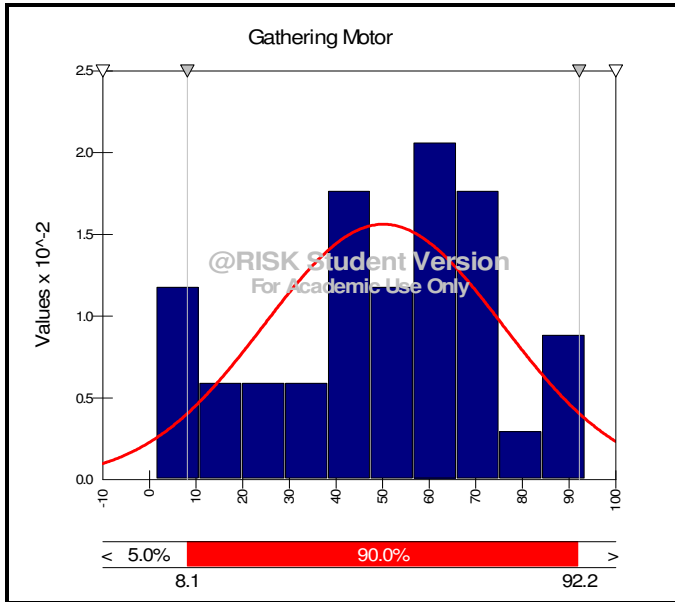


Figure 21 : Failure distribution of the Traction motor



**Figure 22 : Failure distribution of the Gathering Gearbox**



**Figure 23 : Failure distribution of the Gathering motor**

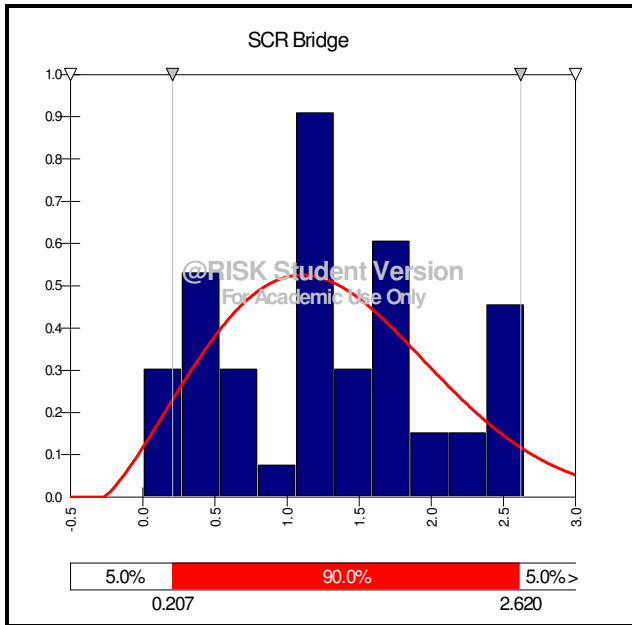


Figure 25 : Failure distribution of the SCR Bridge

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