THE UNIVERSITY OF QUEENSLAND

Bachelor of Engineering Thesis

Development of a Dynamic Budgeting Tool for Major Component Replacements in Mining Equipment

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ABSTRACT

The operational stage of a mining assets life cycle commonly requires maintenance periods for upkeep and monitoring of components. Assets, such as mining haul trucks, with numerous components face the dilemma of requiring maintenance actions on multiple components at different times. Irrespective of the maintenance procedures utilised, shutdowns cannot be avoided in their entirety, embracing the inevitability of shutdowns, the development of more sophisticated methods can lead to efficient utilisation of planned shutdowns known as turnarounds. Inevitable asset shutdowns should be approached with a systematic method of replacing multiple components simultaneously, reducing maintenance costs and both scheduled and unscheduled downtime.

The aim of this research project is to develop a dynamic budgeting tool for major component replacements, reducing cost, equipment downtime and maintenance of mining assets. Establishing the optimal time at which a planned shutdown should occur for the repair of components, requires an understanding of the relationship between the reliability, failure, cost and time. It is therefore integral to develop a model to accurately define the relationship between the cost of operation and the operating hours of the assets.

Using the cumulative failure distribution, it can be identified when block replacement in the form of a turnaround should optimally occur. By developing a function, an understanding of the maintenance cost pre operating hour is developed, which permits replacement operations to be scheduled accordingly. Successful implementation of the model within a functional dynamic budgeting tool permits optimisation for the replacement of multiple components, resulting in an increase of the assets reliability, reduction of the financial cost, and an increase in the assets availability. Utilising the data from a fleet of twelve Caterpillar 793 haul trucks, operating in a South American mine, the dynamic budgeting tool can be tested, and the results analysed.

The completion of the budgeting tool is used to further investigate the impacts variation of the input parameters including maintenance costs and failure characteristics. Limitations to the model are identified through the case study, and methods for ramification are advised. The investigation and development of the dynamic budgeting tool indicates that it can be used to assist in reducing the cost of maintenance and increasing the availability of mining assets currently utilised in the mining industry.

ACKNOWLEDGEMENTS

Foremost, I would like to express my sincere gratitude to my thesis supervisor Professor Peter Knights of the School of Mechanical and Mining Engineering at the University of Queensland. Without his guidance and immense knowledge this work would not have been possible. He has taught me more than I could credit him for and consistently opened his door for me whenever I experienced trouble or required clarification.

Finally, I express profound gratitude to my family and girlfriend for their unwavering support and ongoing encouragement, not only over the course of this work but throughout all my years of study. Without them my development as an engineer and person would not have been the same.

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1.0 INTRODUCTION

1.1 PROJECT OVERVIEW & MOTIVATION

The utilisation of effective asset management strategies is becoming a more widespread occurrence. Asset management is commonly applied to maximize the efficiency and productivity of assets. The Institute of Asset Management defines asset management as a process that takes into consideration and optimises conflicting priorities of:

- asset utilisation and asset care;
- short-term performance opportunities and long-term sustainability; and
- between capital investments and subsequent operating costs, risks and performance.

The mining industry has consciously adopted asset management as a widespread technique to improve returns and increase production.

The operational stage of a mining assets life cycle commonly requires maintenance periods for upkeep and monitoring of components. Maintenance can be considered a business expense that may not only have a significant capital cost but can also potentially decrease profits via downtime and reduced productivity. Unplanned asset downtime is often even more time consuming and expensive, causing major setbacks in a mines production. Evidently, the maintenance of mining equipment is a process that requires balancing the functional reliability of assets and reducing the maintenance downtime processes, all while minimising the financial impact.

Assets, such as mining haul trucks, with numerous components face the dilemma of requiring maintenance actions on multiple components at different times. Due to the multiple components and their inconsistent failure frequencies, it is likely that the mean time between failure (MTBF) of the overall system will be quite low. Organisations can be reluctant to initiate planned shutdowns in favour of other maintenance methods. However, irrespective of the maintenance procedures utilised, shutdowns cannot be avoided in their entirety. By embracing the inevitability of shutdowns in operation, the development of more sophisticated methods can lead to efficient utilisation of planned shutdowns known as turnarounds.

By analysing the failure distribution of components within an asset and generating equations regarding cost and operational time, a model may be developed to assist in planning turnarounds. The failure data for a fleet of twelve Caterpillar 793 (CAT793) mine haul trucks operating in a South American mining complex has been compiled for a period five years. Failure distribution parameters generated from this data can be implemented to produce results for the expected maintenance cost per unit of time. The development of a budgeting tool that employs an accurate expression can be utilised to assist asset management engineers in the industry to plan turnarounds that are not only cost effective but improve the overall MTBF. This improvement ultimately increases the asset availability while reducing the negative financial impacts of maintenance tasks.

1.2 AIMS & OBJECTIVES

The aim of this investigation is to develop a dynamic budgeting tool for major component replacements, reducing cost and equipment downtime in the operation and maintenance of mining equipment. Additional to the primary aim of the investigation, several project objectives have been identified. Project objectives of this study include:

- An accurate analysis of the maintenance of the primary components of a haul truck;
- Precise modelling and comparison of the maintenance costing per unit of time; and
- The development of an accurate budgeting tool with multiple dynamic variables.

1.3 SCOPE

The scope of this project considers five different components from a fleet of Caterpillar 793 haul trucks. Data analysis followed by reiterative model simulation is required for the development of the budgeting tool. Development of the tool should indicate the effect of the varying factors of maintenance cost and failure data.

It is not within the scope to initiate the collation of more failure data. Additionally, the Komatsu truck data listed with the Caterpillar 793 data is beyond the scope of this investigation. Despite various other maintenance approaches addressing the failure modes of each component, they will not be considered in the development of the budgeting tool.

2.0 BACKGROUND AND LITERATURE REVIEW

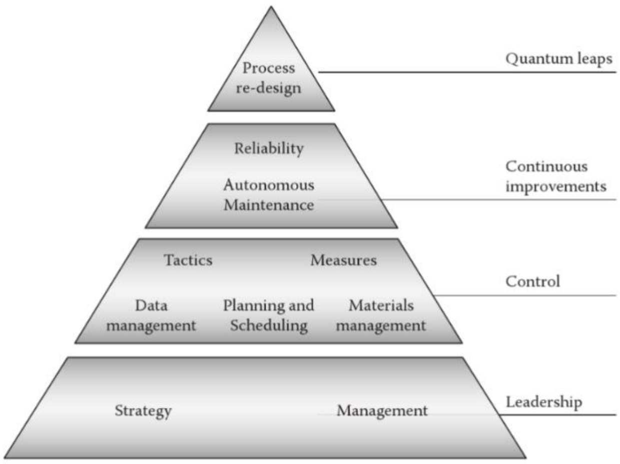
2.1 MAINTENANCE

Maintaining assets is an essential requirement of successful asset management. The operational stage of a mining assets life cycle commonly requires maintenance for upkeep and monitoring of components. The objective of maintenance processes is for safety assured, effective, as designed, operation of equipment leading to productive utilisation and minimal financial implications (Tomlingson, 1994). In instances where physical assets cannot continue operation due to breakdown or routine maintenance, a cost is incurred. The cost may present itself in the form of labour, components or potentially the disruption of production (Pintelon & Muchiri, 2009). In the mining industry maintenance costs commonly account for between 30% and 50% of the total operating costs (Krellis & Singleton, 1998). The availability of a physical asset can be represented as:

$$Availability = \frac{Available\ Hours}{Scheduled\ Calendar\ Hours}$$

The major factors typically reducing scheduled calendar hours to available hours are both scheduled and unscheduled losses. These losses are primarily a result of maintenance procedures, repairs and inspections (Knights, 2018). Optimising maintenance procedures can therefore increase the overall availability of an asset and ensure that production within a mine is maximised.

Figure 1:Maintenance Excellence Pyramid



As a result, achieving maintenance excellence is critical in the mining industry and can have various implications on the operations. Achieving maintenance excellence requires balancing performance, risks, and the resource inputs in pursuit of developing an optimal strategy (Jardine & Tsang, 2006). Maintenance excellence can be achieved by aligning the maintenance strategy with the structured approach outlined in Figure 1. The three types of objectives that must be met to achieve maintenance excellence are strategic, tactical and continuous improvement (Campbell et al., 2011).

- **Strategic:** This stage consists of the development of a comprehensive approach to asset management (Sivak & Schoettle, 2012). This consists of an assessment of the current position in comparison to the desired objectives of the organisation. Decision making criteria is developed in alignment to these objectives, with a focus on establishing a course of action to close the performance gap (Campbell et al., 2011)
- **Tactical:** Following on from the strategic objective, the tactical stage consists of developing maintenance processes with the utilisation of work management and materials management systems (Daley, 2008). These tactics need to be determined taking into account the organisational objectives and requirements. The most beneficial method of maintaining an asset may employ various maintenance strategies including reactive, predictive, preventive and reliability centred management (Sivak & Schoettle, 2012).
- **Continuous Improvement:** This strategy requires the organisation to look beyond day-to-day operations in order to identify methods that can improve the currently adopted practices. Optimal solutions can be formed by the investigation of data and fact-based arguments (Jardine & Tsang, 2006). The continuous improvement objective requires diligence to consistently achieve systematic maintenance excellence (Campbell et al., 2011).

2.2 PREVENTIVE MAINTENANCE

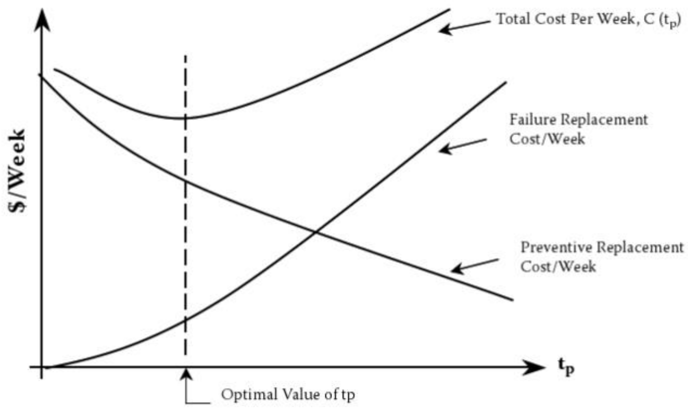
Preventive maintenance is executed at predetermined intervals or according to prescribed criteria with the intentions to reduce the probability of failure or the degradation of the equipment functionality with methods including repair or replacement (Koochaki, Bokhorst, Wortmann, & Klingenberg, 2011). Preventative maintenance is commonly employed if the cost of a replacement is greater after a failure occurrence than before, or if the downtime of failure replacement is greater than that of a preventive replacement (Campbell et al., 2011). The nature of preventive maintenance leads to the replacement of components that may be fully functional, leading to the unnecessary extra cost incurred for not utilising the full life-cycle of a component and additional labour costs (O’Connor & Kleyner, 2012). There is potential for these extra costs to be mitigated with continual optimisation.

2.3 MAINTENANCE OPTIMISATION

The maintenance of mining equipment is a process that requires optimising the functional reliability of the equipment, in order to ensure maximum operation and reduce the down time as a result of the maintenance processes. Achieving a balance between the maintenance requirements and resources is an intricate and expansive task (Khatab et al.,, 2013). As a component ages, deterioration is likely to occur, increasing the likelihood of failure. Using an age-based approach, the component should be replaced with a new component at a set time interval (Campbell et al., 2011). The replacement procedure incurs a fix setup cost, which includes the downtime cost and the cost of trained maintenance staff to carry out the procedure (Chuan-Wen Chiu, 2016)

Cost driven maintenance is largely a process of optimising the cost of failure replacement and preventive replacement, Figure 2 depicts the optimal time value for balancing both replacement costs (Jardine & Tsang, 2006).

Figure 2: Optimisation of Replacement Methods



The optimisation of maintenance can also be a factor of reducing the mean time to repair (MTTR) and increasing the mean time between failure (MTBF) (Campbell et al., 2011). Within the mining industry, the MTBF is frequently utilised as a measure of reliability. The MTTR or restore operational status to a physical asset is referred to as the maintainability, a measure of the ease of repair of an asset (Knights, 2018). The capability of the physical asset’s operation within a given period can be expressed as the availability and calculated using the following expression:

$$Availability = \frac{MTBF}{MTBF + MTTR}$$

(Jardine & Tsang, 2006). With this relationship established, two different types of actions can influence the availability of an asset; actions to increase the time between failures or actions to decrease the time to restore operation following a failure. Simply increasing maintainability will not be sufficient to increase availability. Replacing critical components at intervals before breakdown occurs can increase equipment reliability (Campbell et al., 2011). There is however a downside in the over utilisation of replacement maintenance. Not only is there a production loss via the MTTR but additionally a transitional loss is incurred. This transitional loss is comprised of wind-down and start-up losses. A wind-down loss refers to the decrease in production resulting from implications of maintenance on other operations within the organisation, this may include the negative effects of reassigning assets, transport obstruction and various other impacts on operational synergies (Knights, 2018). Start-up losses occur after a physical asset has completed the required maintenance tasks. Rather than the asset instantaneously returning to rated production, a gradual increase to steady state operating conditions exists, known as the start-up loss (Nakousib et al., 2018).

2.4 TURNAROUNDS

Turnarounds are planned shutdowns of a physical asset commonly utilised for maintenance (Istad et al., 2008). The method ensures that production is maximised and increases the assets reliability (Duffuaa et al., 2009). The primary advantages of successfully implemented turnarounds include:

- Increased safety of personnel with reduced environmental risks;
- Improvement in both overall asset availability and availability;
- Reduced risk of unplanned shutdown due to component failure;
- Increased efficiency and production of asset in operation; and
- Certify compliance with certification, insurance and regulatory requirements. (Lenahan, 2006) (Duffuaa et al., 2009)

Inevitable asset shutdowns should be approached with a systematic method in the form of turnaround management. Successful implementation of turnarounds performed at the optimal time interval for the replacement of multiple components will result in an increase of the assets reliability, reduction of the financial cost, and an increase in the assets availability (Campbell et al., 2011).

2.5 BLOCK REPLACEMENT POLICY

Since transitional losses only occur once for each maintenance period, this means that executing multiple maintenance tasks during each turnaround reduces the total losses over an asset’s lifecycle (Jardine & Tsang, 2006). One such method currently applied in the mining industry is block replacement. Block replacement policy entails replacing multiple components simultaneously, in set time blocks throughout an assets life cycle. The method is commonly utilised when there are multiple similar units within a system (Ke & Yao, 2016). Replacing multiple components simultaneously has the potential to reduce maintenance costs and both scheduled and unscheduled downtime. As such, this indicates the goal of developing more data supported sophistication in maintenance techniques to minimise the requirement for maintenance between shutdowns (Lenahan, 2006). The advantage of this policy, where replacements occur at fixed intervals, is the reduction of the likelihood of reactive maintenance resulting from component failure (Jardine & Tsang, 2006).

2.6 FAILURE DISTRIBUTION

Using the cumulative failure distribution, it can be identified when scheduled preventive maintenance should occur to ensure that the probability of failure does not exceed a particular percentage (Campbell et al., 2011). Mathematical maintenance optimisation is predominately based upon the statistical probability and failure mechanics (Jardine & Tsang, 2006). A common statistical distribution adopted among reliability engineers is the Weibull hazard function, which characterises a components failure rate against its age (O’Connor & Kleyner, 2012).

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} \exp\left(-\left(\frac{t-\gamma}{\eta}\right)^{\beta}\right) \qquad For\ t > \gamma \qquad (1)$$

$$f(t) = 0 \qquad For\ t \leq \gamma \qquad (2)$$

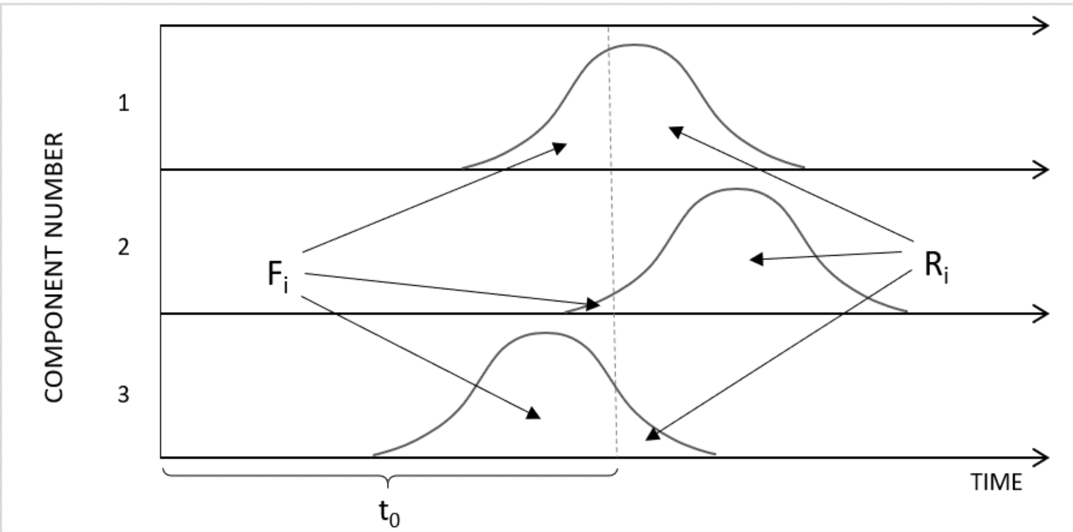
The Weibull function represented above has three parameters, the shape parameter, β, the location parameter, γ, and the scale parameter, η. Fitting a Weibull distribution model to data, the general distribution of component failure can be formulated (Verma et al., 2016). The use of the function provides an understanding of when components are likely to fail, permitting replacement operations to be scheduled accordingly (Campbell et al., 2011).

3.0 METHODOLOGY

3.1 BUDGETTING TOOL DEVELOPMENT APPROACH

Establishing the optimal time at which a planned shutdown should occur for the repair of components, requires an understanding of the relationship between the reliability, failure, cost and time. It is, therefore, integral for further development of the budgeting tool that a model is derived with the purpose of defining the relationship between these factors. The graphic representation in Figure 3 displays an example of three components with different failure distribution functions and key variables associated with characteristics of the data.

Figure 3: Example of Components Failure Distribution



The development of the budgeting tool incorporates both the reliability of each component, R_i, and failure rate of each component, F_i, to analyse the time interval, t_0, at which replacement should occur.

3.2 FAILURE DATA ANALYSIS

Identification of time interval, t_0, at which replacement should occur, requires the development of a model that incorporates the failure data of the respective mining equipment. Analysis of the failure data permits the development of a Weibull hazard function which acts to interpret the data, producing parameters for model development. The process for data analysis entails filtering out irregularities and outlying data points from the raw data collated from the extensive operation of mining equipment. The filtered results undergo failure data analysis to resulting in the production of Weibull distribution function and diagram. The parameters generated by this diagram and function can be utilised to conduct statistical analysis of the respective component.

3.3 MODEL DEVELOPMENT

Using the Weibull function generated from failure data analysis, the shape parameter, β, location parameter, γ, and scale parameter, η, can be utilised to calculate the reliability of a component at any given time interval, t_0. The governing equation for the reliability of a component is given by:

$$R_i(t_0) = e^{-\left(\frac{t_0-\gamma}{\eta}\right)^{\beta}} \tag{3}$$

The probability that a component experiences failure is the complement of the components reliability and can therefore be represented as:

$$F_i(t_0) = 1 - R_i(t_0) \tag{4}$$

The expected cost of preventative maintenance at any time interval, t_0, can be calculated by summing the cost of preventative maintenance for every component of the system multiplied by the respective reliability at the given time interval.

$$\bar{C_p} = \sum C_{p_i} \times R_i(t_0) \tag{5}$$

Similarly, the expected cost of failure maintenance for a system, may be represented by the sum of the cost of failure maintenance for every component multiplied by the respective failure rate.

$$\bar{C_f} = \sum C_{f_i} \times F_i(t_0) \tag{6}$$

Both the failure rate and reliability of the entire system can be expressed as the products of the individual component failure rate and reliability respectively.

$$R_s(t_0) = \prod R_i(t_0) \tag{7}$$

$$F_s(t_0) = \prod F_i(t_0) \tag{8}$$

With these statistical parameters defined, an expression for the total expected cost of maintenance for the entire system can be derived.

$$C_S(t_0) = \bar{C_f} \times F_S(t_0) + \bar{C_p} \times R_S(t_0) \tag{9}$$

For a given time interval the average time at which failure will occur can be characterised by the following formula, where $f(t)$ is the probability density function of failure times.

$$M(t_0) = \frac{\int_{-\infty}^{t_0} t \times f(t)\, dt}{F_s(t_0)} \tag{10}$$

Utilising this expression for the mean time to failure and the various other derived expressions listed above, the expected maintenance cycle length of the entire system can be represented by the following equation:

$$T_s(t_0) = M(t_0) \times F_S(t_0) + t_0 \times R_S(t_0) \tag{11}$$

From the relationship between the expected cycle cost of maintenance and expected cycle length of the system, an expression can be derived for the expected maintenance cost per unit of time in the case of shutdown maintenance activities.

$$C_{per\ time}(t_0) = \frac{C_S(t_0)}{T_S(t_0)} = \frac{\bar{C}_f \times F_S(t_0) + \bar{C}_p \times R_S(t_0)}{M(t_0) \times F_S(t_0) + t_0 \times R_S(t_0)} \tag{12}$$

3.4 TOOL DEVELOPMENT

The model generated to express the relationship between the reliability and cost per unit time can be implemented in a dynamic budgeting tool. The dynamic budgeting tool was primarily developed using Microsoft Excel with an additional box and whisker plot tool developed using the statistical computing language, *R*. The dynamic budgeting tool iterates through different time intervals calculating the systems maintenance cost per operating hour. Using the Weibull parameters generated from failure analysis of data collected from an assets operation, the results are automatically generated with visual representation.

4.0 CASE STUDY

The development of the budgeting tool permits the analysis of industry data pertaining to mining haul trucks to be analysed. The data for analysis was collated over a period of approximately four years, from a fleet of twelve Caterpillar 793 haul trucks operating in a South American mine. Within the entirety of the operational haul truck system, five major components of the Caterpillar 793 have been identified, these include:

- Transmission;
- Differential;
- Diesel Motor;
- Torque Convertor; and
- Final Drive.

These components exhibit varying failure distribution data, with multiple instances over failure over their respective lifetimes. For a preventive maintenance technique to be feasible, the cost of a replacement should be greater after a failure occurrence than preventive replacement (Campbell et al., 2011).

Table 1: Maintenance Costs of Caterpillar 793 Haul Truck

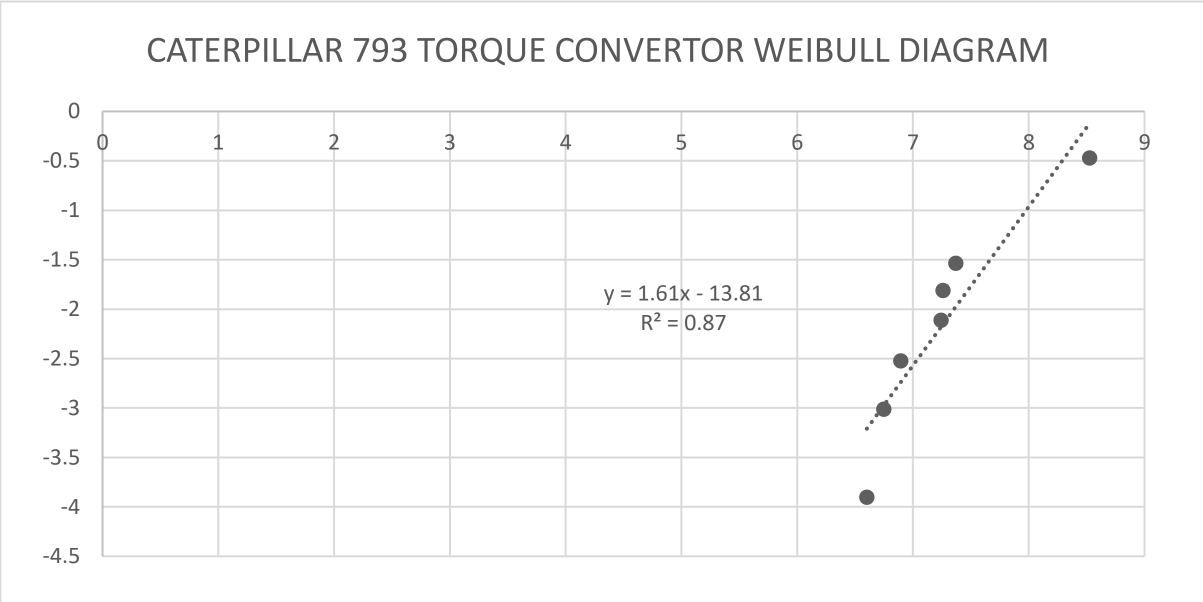
	Preventative Maintenance Cost C_p	**Failure Maintenance Cost C_f**
Differential	$71,720 US	$111,700 US
Torque Convertor	$23,700 US	$37,300 US
Final Drive	$71,720 US	$111,700 US
Diesel Motor	$184,252 US	$276,470 US
Transmission	$40,626 US	$56,479 US
Total Cost	$392,018 US	$593,649 US

Table 1 indicates that all five of the major CAT793 components incur a greater cost in the case of failure maintenance as opposed to preventative maintenance. These costs are susceptible to change, depending on economic conditions, political relations and certain government legislation.

4.1 PRELIMINARY DATA ANALYSIS

Each component of the haul trucks can be individually analysed using Weibull analysis to determine the failure distribution parameters. Failure data analysis through the application of spreadsheets produce the Weibull diagrams for each similarly to Figure 4. The diagrams for the remaining four components are collated in appendix A

Figure 4: Torque Convertor Weibull Diagram



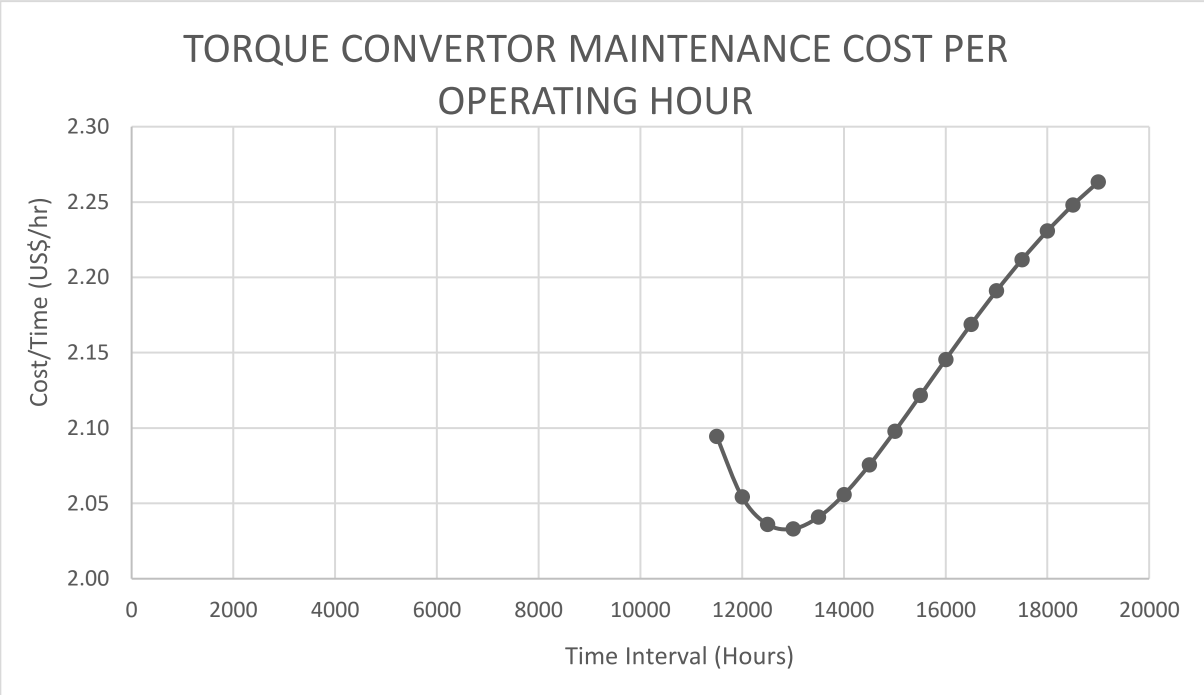
By completing the Weibull analysis for the failure data of each individual component, the failure distribution parameters required for the utilisation of the model are achieved. The following table is a collation of the required parameters for each component.

Table 2: Failure Distribution Parameters

	Location Parameter (γ)	Shape Parameter (β)	Scale Parameter (η)
Final Drive	3,000	2.36	11,174
Diesel Motor	2,900	1.42	14,930
Transmission	0	1.53	12,158
Differential	0	1.85	16,242
Torque Convertor	11,100	1.61	5,436

Using the values represented in table 2, generated from the failure data of the CAT793 haul trucks, the reliability and cost of maintenance for each component can be modelled. Before investigating the overall system, each components maintenance cost per operating hour can be analysed and modelled. Figure 5 is a representation of the maintenance cost per hour of operation for a Caterpillar 793 torque convertor. Similar graphs were generated for the other four components which are presented in appendix A.

Figure 5: Torque Convertor Maintenance Cost

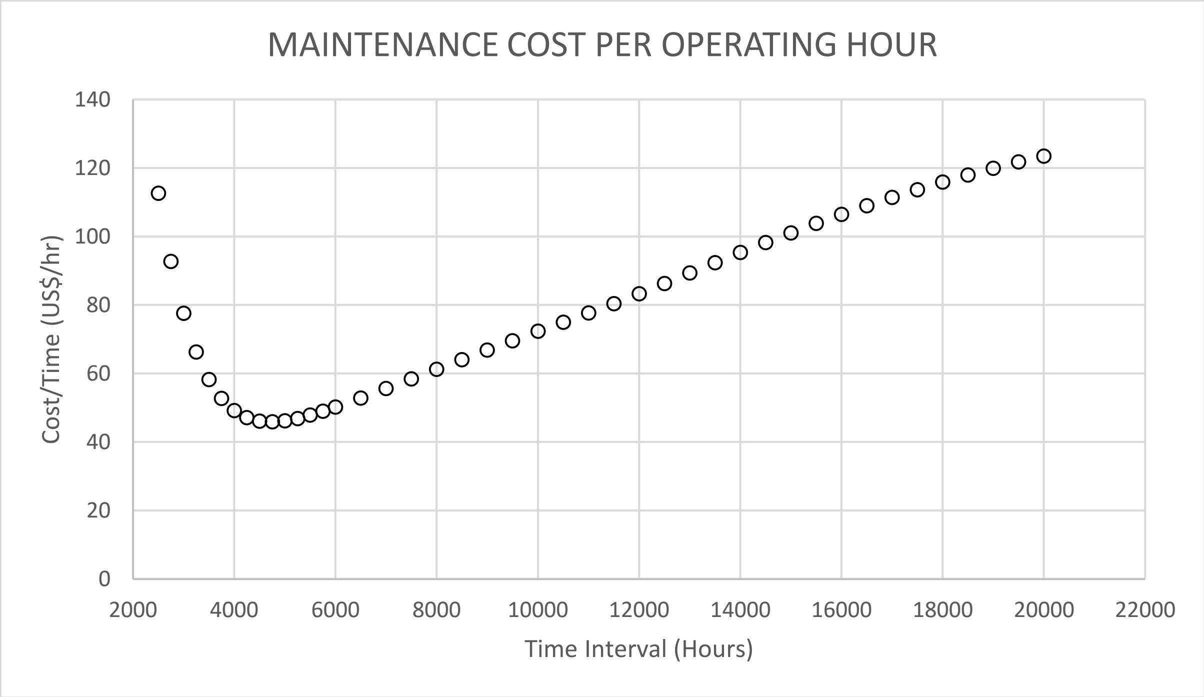


4.2 CASE STUDY RESULTS & ANALYSIS

With the completion of primary data analysis and identification of Weibull parameters for each component, the dynamic budgeting tool can be utilised to identify the optimum time at which maintenance should occur. Analysis of the failure data with the budgeting tool can facilitate both a decrease in the operational cost and an increase in the productivity over an asset's lifecycle. The budgeting tool can also be utilised to identify the effects of variation in the Weibull shape parameter, as well as the costs of both preventive and failure maintenance

The following graph is automatically generated by the budgeting tool to visually represent the maintenance cost per operating hour of the CAT793 haul truck.

Figure 6: Maintenance Cost per Operating Hour



The result indicates that at the 4750-hour time interval, the cost per operating hour of maintenance reaches a minimum. The maintenance cost at this time interval for the CAT793 haul truck is US$45.90 per hour. One of the most notable characteristics of the result generated by the budgeting tool is when critical failure if estimated to occur. At the time interval of 7000 hours, the systems predicted reliability is approximately 0.

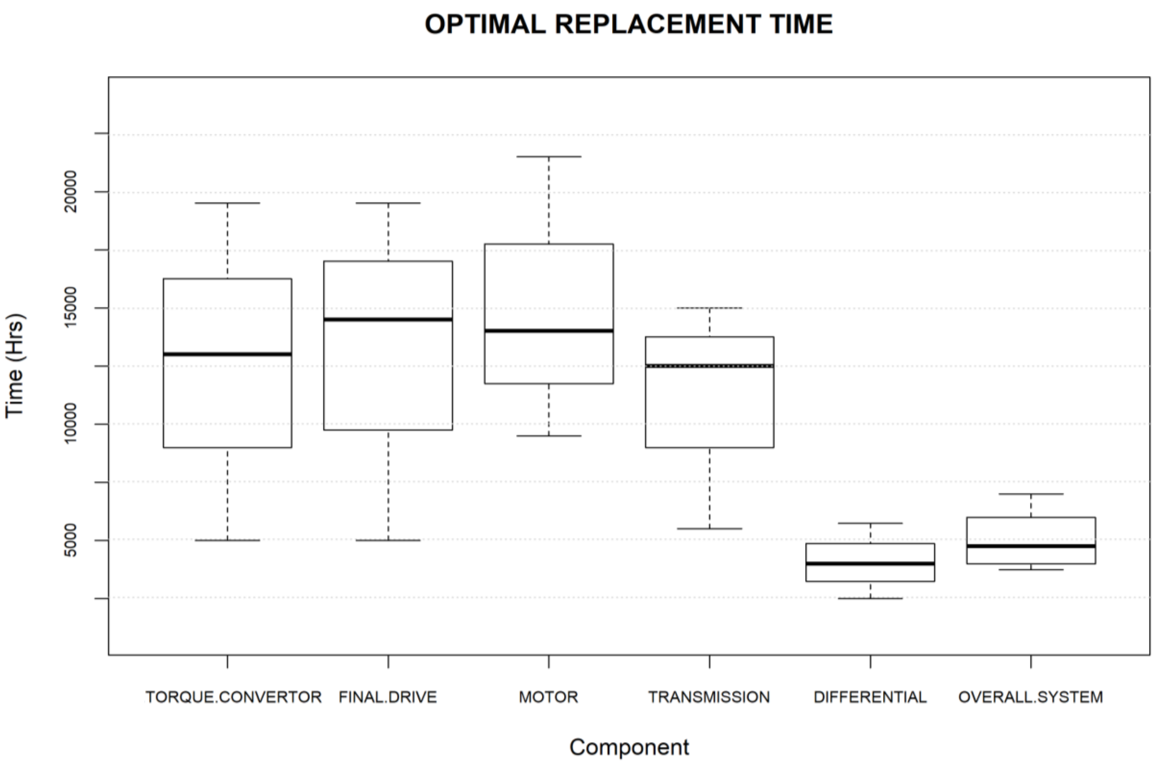


Figure 7: Optimal Replacement Time

Figure 7 represents the optimal replacement time of the five individual components and the optimal replacement time for the overall system. This figure indicates that the failure data of the CAT793 differential, significantly reduces the optimal time for the turnaround procedure. Replacing all the components at 4750 hours would lead to significant underutilisation of all components excluding the differential. At the time interval of 4750 hours the torque convertor still has a predicted reliability of greater than 99%. Utilising the budgeting tool to process the failure data while disregarding the differential further emphasises the significant negative effect on the overall optimal replacement time and maintenance cost per hour.

Figure 8: Comparison of Maintenance Cost per Operating Hour

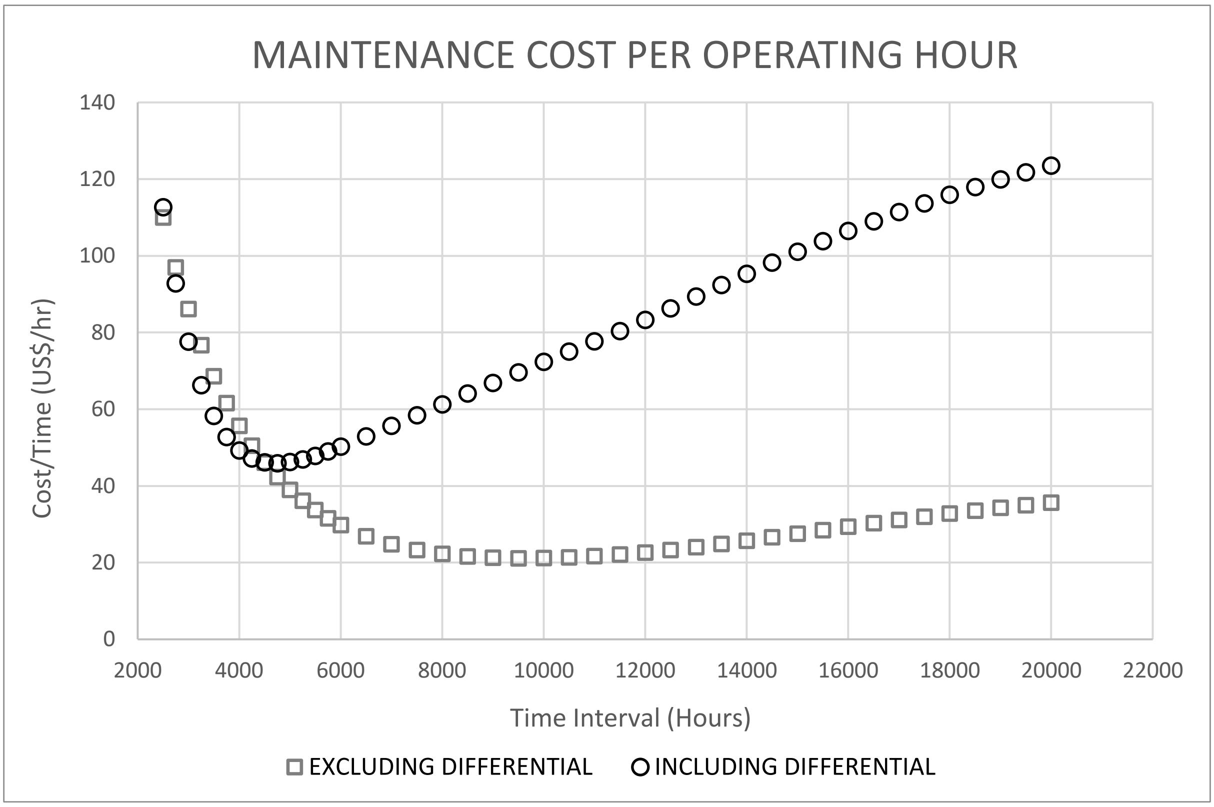


Figure 8 indicates that maintenance cost per operating hour of the system improves with the exclusion of the differential system. The optimal time for a turnaround procedure to occur for this particular set of data becomes 9500 hours; almost double the period achieved with the all five components. Presenting the optimal solution graphically, also aids in displaying the rate at which the cost per operating hour exceeds. This rate of change provides an understanding and flexibility to management, as the effects of deviation from the mathematical optimum are visible represented. The shallower curve of the system excluding the differential, is more forgiving in cases where the optimal turnaround period is not utilised.

In a similar fashion to before, the individual components and systems optimal replacement time are represented in Figure 9, this time excluding the differential component. With the existence of multiple similar units within the system, the figure indicates that block replacement is more feasible for the four-component system. Conducting maintenance at the mathematical optimal time of 9500 hours reduces the significant underutilisation of the torque convertor, final drive, motor and transmission, caused by block replacement occurring at 4750 hours.

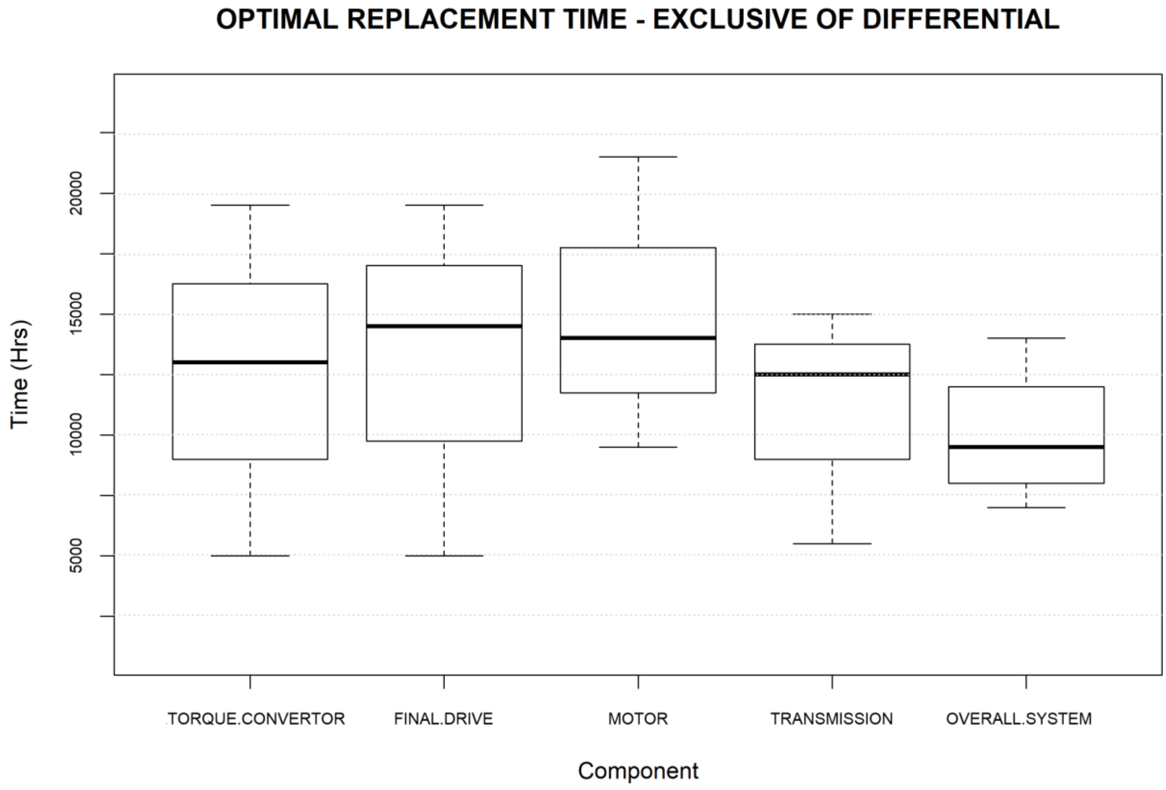
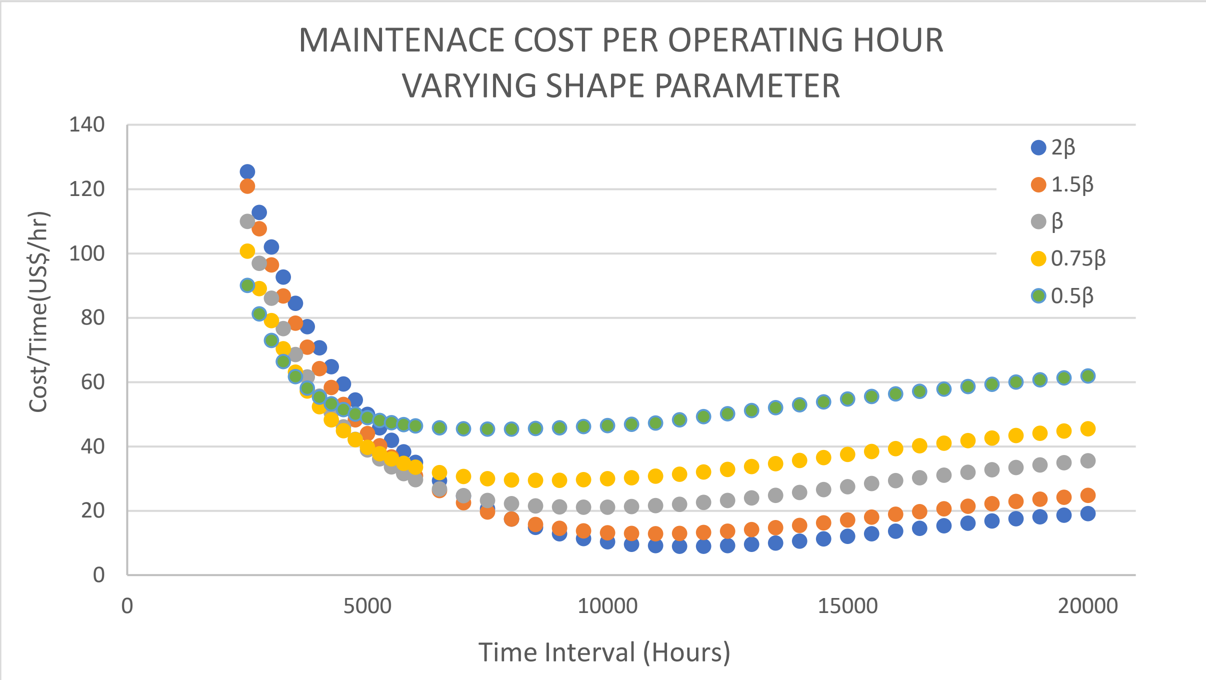


Figure 9: Optimal Replacement Time with the Differential Component Excluded

Operational or management constrictions, may not permit a turnaround to be conducted at the identified optimal point. In this case, a time interval in the upper or lower quartile of the overall system boxplot should be considered. Exceeding the optimal time may increase the availability of the asset over its entire lifecycle, but the risk of failure increases which would require the more expensive failure maintenance procedure and increase downtime. Replacing the component before the optimal time increase the overall reliability but comes at the cost of underutilising components before replacement. The decision for which replacement policy to pursue should be made in compliance with the operations policy on managing risk.

In the operation of an asset there are multiple variables that can affect the maintenance cost per operating hour. The failure distribution of components is a major influencing factor in the optimisation of maintenance procedures. Variation in the shape parameter β, may be brought about by a change in the distribution of each component's failure data. Figure 10 is generated by the budgeting tool to represent the effects that the shape factor has on the overall systems maintenance cost per operating hour.

Figure 10: Effects of Varying Shape Parameter on the Maintenance Cost per Operating Hour



The Weibull shape parameter is analysed with the budgeting tool by varying the scaling of β and solving the maintenance cost per operating hour. The variation of the shape parameter produces the results in Table 3 regarding the optimal time for maintenance, identified by the utilisation of the budgeting tool.

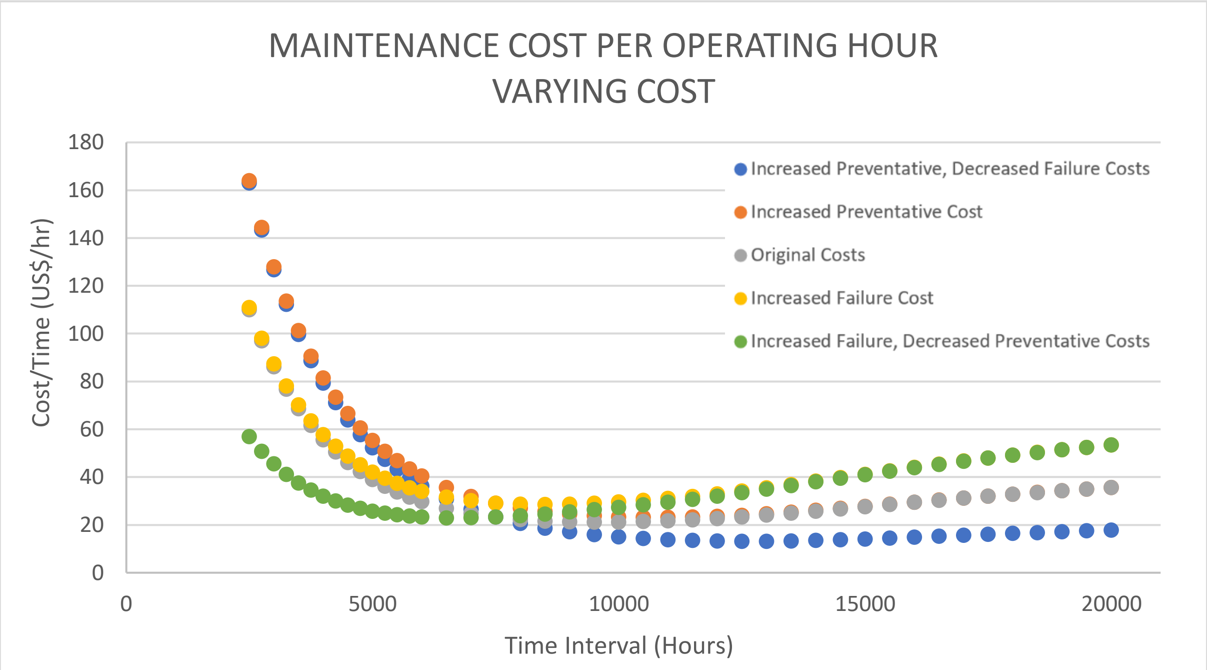
Table 3: Optimal Time for Maintenance – Varying Shape Parameter

Shape Parameter	Optimal Time for Maintenance (hrs)
2 β	11500
1.5 β	11000
β	9500
0.75 β	8500
0.5 β	7500

Table 3 indicates that an increase in the value of the shape parameter, leads the optimal time for maintenance to occur later, with a decrease in β leading to an earlier occurrence of the optimal time for maintenance. The analysis indicates that the system incurs a relatively smaller maintenance cost per operating hour in the early stages of the maintenance cycle when the component shape parameters are reduced. By the time interval of optimum maintenance, the system with reduced shape parameters achieves a higher maintenance cost per hour than their larger β counterparts. The results produced by the budgeting tool indicate that as the shape parameter increases for a system the maintenance cost per operating hour in the later stages of the maintenance cycle decreases.

Another variable that has a significant effect on the cost per operating hour is the cost of maintenance. The cost of preventative maintenance and failure maintenance as listed in Table 1 are different from one another. Both forms of maintenance cost can change due to numerous influencing factors. These cost changes are accounted for by the budgeting tool through the implementation of a cost scaling factor. Figure 11, generated by the dynamic budgeting tool, visual represents the affect that varying the cost of different maintenance techniques has on the overall maintenance cost per operating hour.

Figure 11: Effects of a Cost Variation on the Maintenance Cost per Operating Hour



From the cost analysis, the budgeting tool identified the optimal time interval for maintenance under each cost varying situation. The minimum cost per hour is represented in the following table.

Table 4: Optimal Time for Maintenance – Varying Maintenance Cost

Cost Variance	Optimal Time for Maintenance (hrs)
Increased Preventative, Decreased Failure Costs	12500
Increased Preventative Cost	11000
Original Costs	9500
Increased Failure Cost	8500
Increased Failure, Decreased Preventative Costs	6500

The results generated by the budgeting tool in regard to a variation in maintenance cost, assist to develop an understanding of optimisation of the systems maintenance. Figure 11 indicates as the preventative maintenance increases relative to the failure maintenance, the cost per operating hour increases significantly in the early stages of the systems operation cycle. Conversely, when the cost of failure maintenance increases relative to preventative maintenance, an increase in cost per hour is experience in the later stages of the block cycle. The cost analysis also indicates through Table 4 that the optimal time for maintenance to occur is affected by the varying costs of both maintenance modes. With the original cost values, supplied by the mining operation, the optimal time for maintenance occurs at 9500 hours. When preventative maintenance cost increases in respect to the failure replacement cost, the optimal time for replacement occurs later in the systems operational cycle. On the contrary, an increase in the failure maintenance cost, would lead the minimum cost per operating hour to occur earlier in an asset's lifecycle.

The results achieved in the case study indicate that the utilisation of the dynamic budgeting tool permits the optimisation of turnarounds in the form of block replacement. For the case of the fleet of Caterpillar 793 haul trucks, an optimal time for maintenance to occur has been identified at 9500 hours. The results visually represent the effects of deviating from the optimal time, as well as the effects of the input parameter varying. Using the results, informed decisions can be made dependent on the prioritisation of cost or availability. The application of the tool works to assist in reducing the cost of maintenance and increasing the availability of major assets currently utilised in industrial applications.

5.0 RECOMMENDATIONS

The analysis of the case study indicates that although the budgeting tool can successfully be implemented to produces valuable insight into the optimisation of the maintenance cost per operating hour, there are certain limitations that negatively affect the feasibility of the results.

Simply removing the differential failure data from the analysis doesn't mean that it can be ignored. Failure still occurs and maintenance is still required. The differential maintenance for the CAT793 should be grouped with other maintenance tasks that share similar failure distributions. Further investigation could lead to the development of sequential replacement models in which not every component is replaced at each turnaround. Although the CAT793 data analysed only identified one component that had a significantly varying lifecycle from the other components, there is evidence to suggest that the diesel motor and torque convertor can be operated for longer periods than the data sampled. This evidence is presented in the individual component's maintenance cost per operating hour graphs in appendix a, which indicate that the cost continues to trend downwards even after the sample time Sequential preventative maintenance would also become more feasible as more complex systems are analysed. Systems with more components would exhibit further variance in failure distribution and lifecycles

Further development of the budgeting tool, for future iterations, could automate the failure data analysis. Raw data, collated from field operation, would essential be saved in a spreadsheet with the parameters; condition at replacement and component lifetime. The first stage would incorporate calling the values from the raw failure data spreadsheet for filtration, requiring manual removal of outliers. Developing an automatic Weibull calculator would permit the filtered data to automatically generate the shape parameter, β, the location parameter, γ, and the scale parameter, η. The automation of this process would lead directly into the analysis of the individual component's maintenance cost and reliability. With all the required parameters calculated, the overall system analysis via the budgeting tool would initialise, essential automating the entire process, less data filtration.

Implementing these major recommendations in future iterations of the dynamic budgeting tool could increase the extent at which utilisation of the tool could be deemed feasible.

6.0 CONCLUSION

Managing the maintenance of an asset is critical to the ongoing operation of many industry projects. With the consistently growing market competition and demand for efficiency, maintenance procedures should be approached with systematic methods, derived from mathematical optimisation. The aim of this work was to develop a dynamic budgeting tool for major component replacements, reducing cost and equipment downtime in the operation and maintenance of mining equipment. Several outcomes were achieved throughout the investigation, including:

- **The derivation of an accurate model of the relationship between the cost of maintenance and the operational time**. The core model derived for the development of the maintenance budgeting tool utilises failure data analysis to calculate the reliability and failure rate of various components within a system. Utilising these statistical expressions alongside both the cost of preventative and failure maintenance, the expected cost of maintenance at a time interval can be expressed. Dividing the maintenance cost by the expected maintenance cycle length provides the model for the expected maintenance cost per unit of time (12) in the case of shutdown maintenance activities,

$$C_{per\ time}(t_0) = \frac{C_S(t_0)}{T_S(t_0)} = \frac{\bar{C_f} \times F_S(t_0) + \bar{C_p} \times R_S(t_0)}{M(t_0) \times F_S(t_0) + t_0 \times R_S(t_0)} \quad (12)$$

- **The development of a fully functioning dynamic budgeting tool with parameter controls.** The budgeting tool utilises the model derived for expected maintenance cost per unit of time (12), to produce a visual representation of the maintenance cost per hour over a systems component lifecycle. The tool operates with the required inputs of each components Weibull failure parameters and the cost of each components preventative and failure maintenance. Additional figures are produced to visually represent the effects of variation in the cost and failure parameters.
- **A case study was conducted utilising failure data collated from a fleet of twelve Caterpillar 793 haul trucks operating in a South American mine.** From the preliminary failure data, a failure analysis provided the Weibull parameters describing the failure distribution of the components. Alongside the provided costs of each components preventative and failure maintenance, the Weibull parameters were input to the budgeting tool. The results were negatively affected by a single component with a significant difference in failure

distribution, the results were generated with this component excluded. Visual results were produced which were supported by the literature, and an optimum maintenance interval suggested by the budgeting tool. The budgeting tool produced results to convey the effects of the variation of the input parameters.

The major limitation to the tool is the inclusion of components that experience significantly different failure distributions. Sequential maintenance scheduling should be investigated to address systems with substantially different failure distribution. The utilisation of the dynamic budgeting tool produces valuable insight into the optimisation of the maintenance cost per operating hour of a mining asset. Successful implementation of the model within a functional dynamic budgeting tool permits the optimisation of turnarounds in the form of block replacement. The application of the tool works to assist in reducing the cost of maintenance and increasing the availability of major assets currently utilised in industrial applications. The culmination of this study has resulted in a practical budgeting tool that has been developed for the utilisation of asset management engineers in the industry.

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APPENDIX A: COMPONENT ANALYSIS

WEIBULL DIAGRAMS

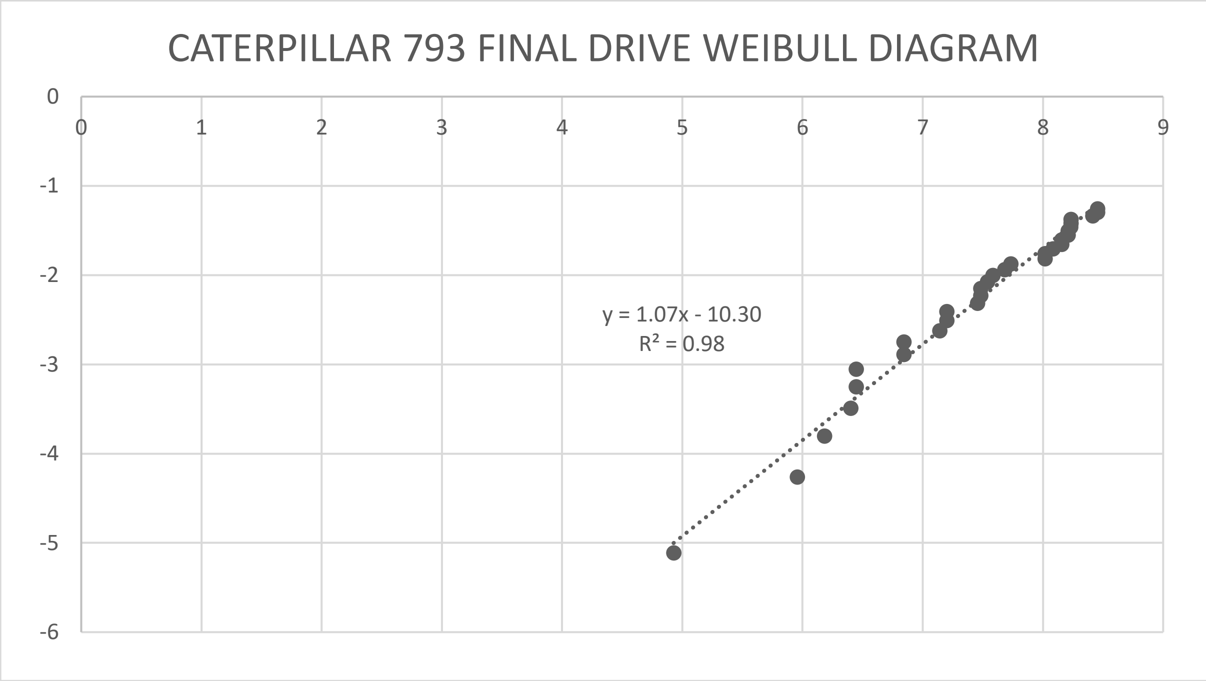


Figure 13: Final Drive Weibull Diagram

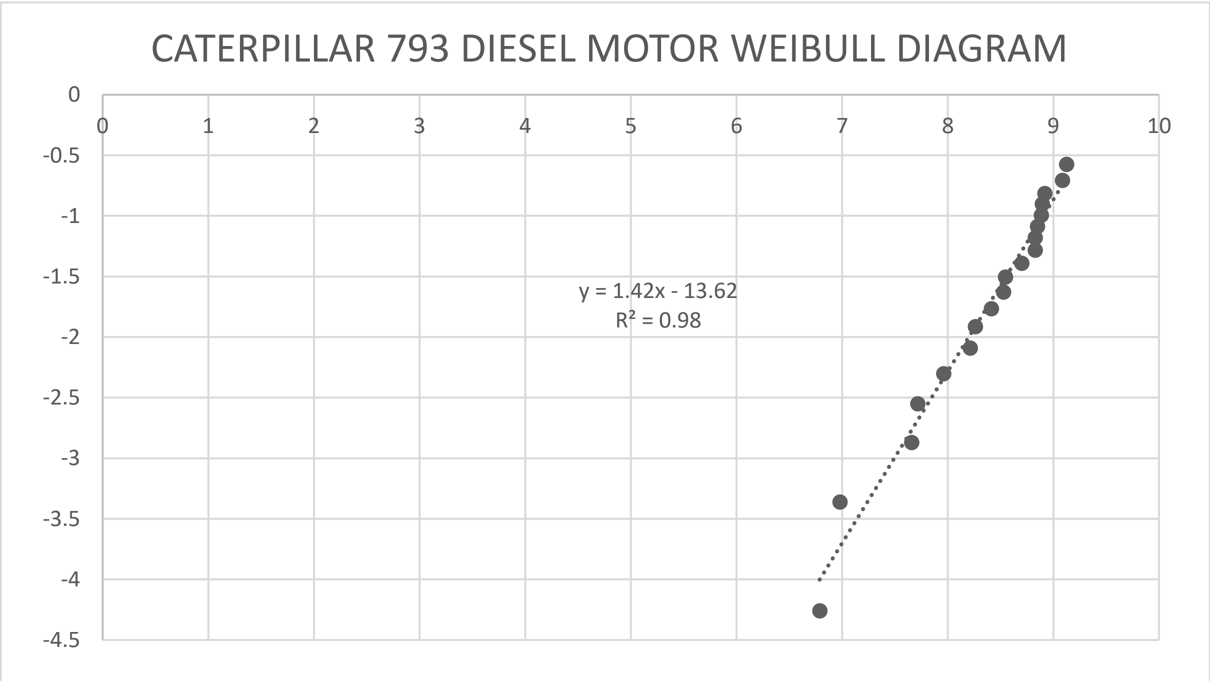


Figure 12: Diesel Motor Weibull Diagram

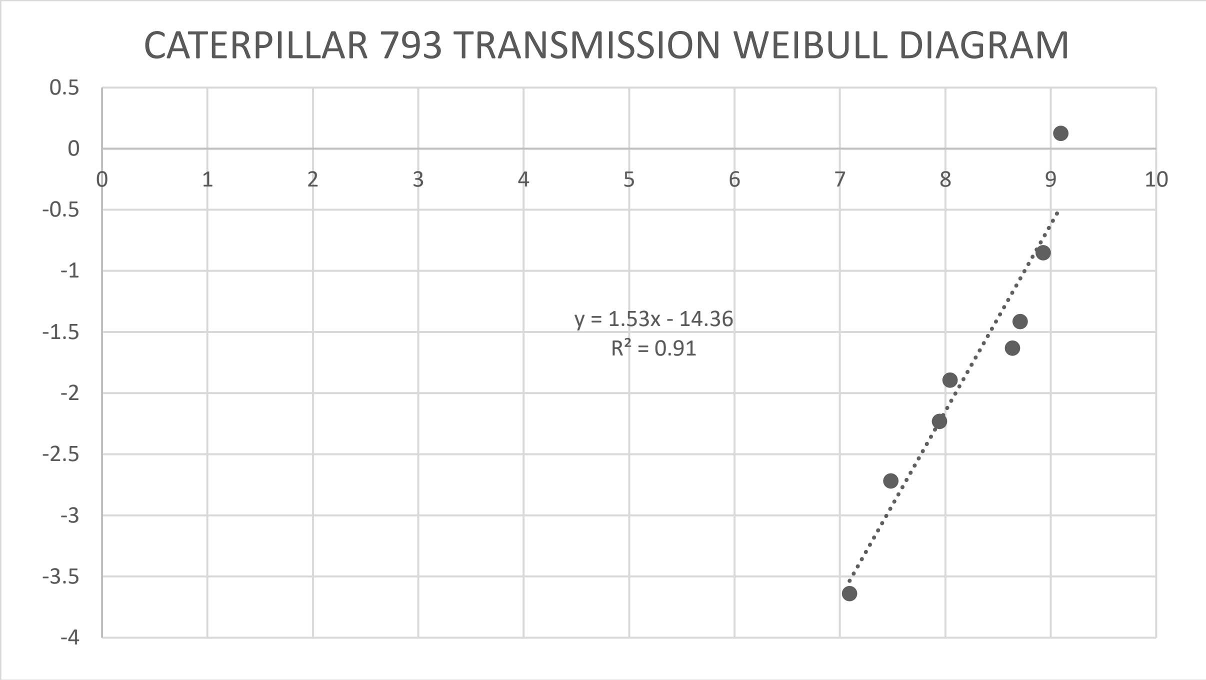


Figure 15: Transmission Weibull Diagram

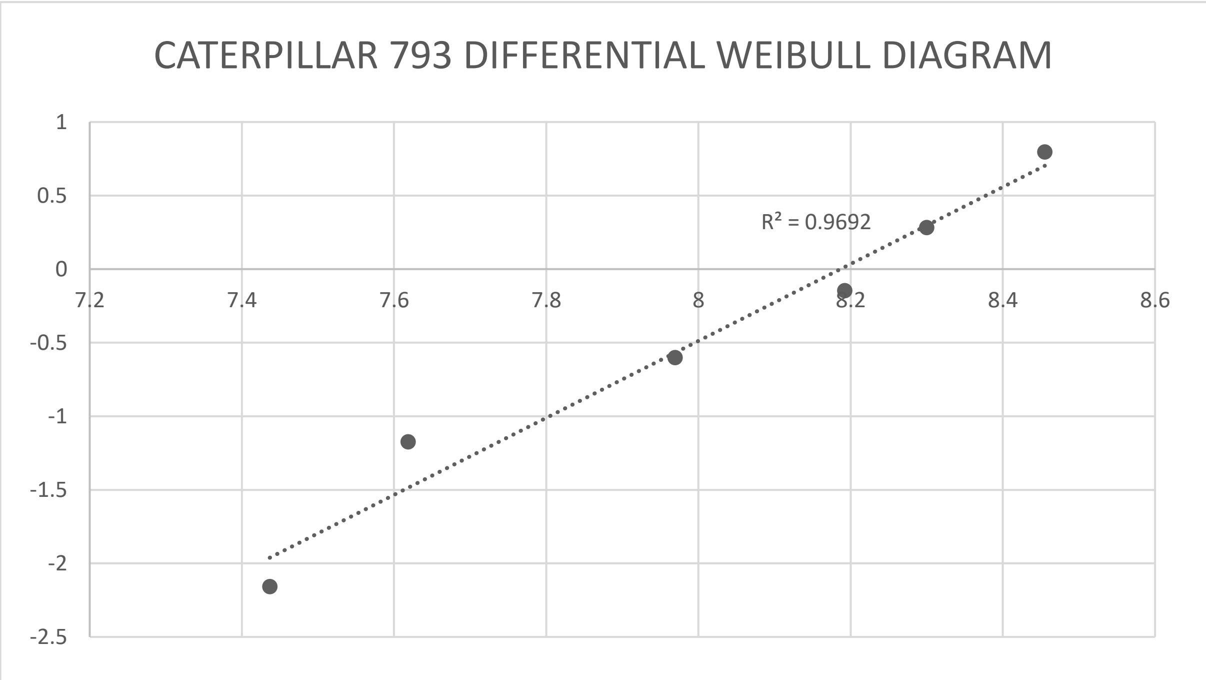


Figure 14: Differential Weibull Diagram

COMPONENT MAINTENANCE COST PER OPERATING HOUR

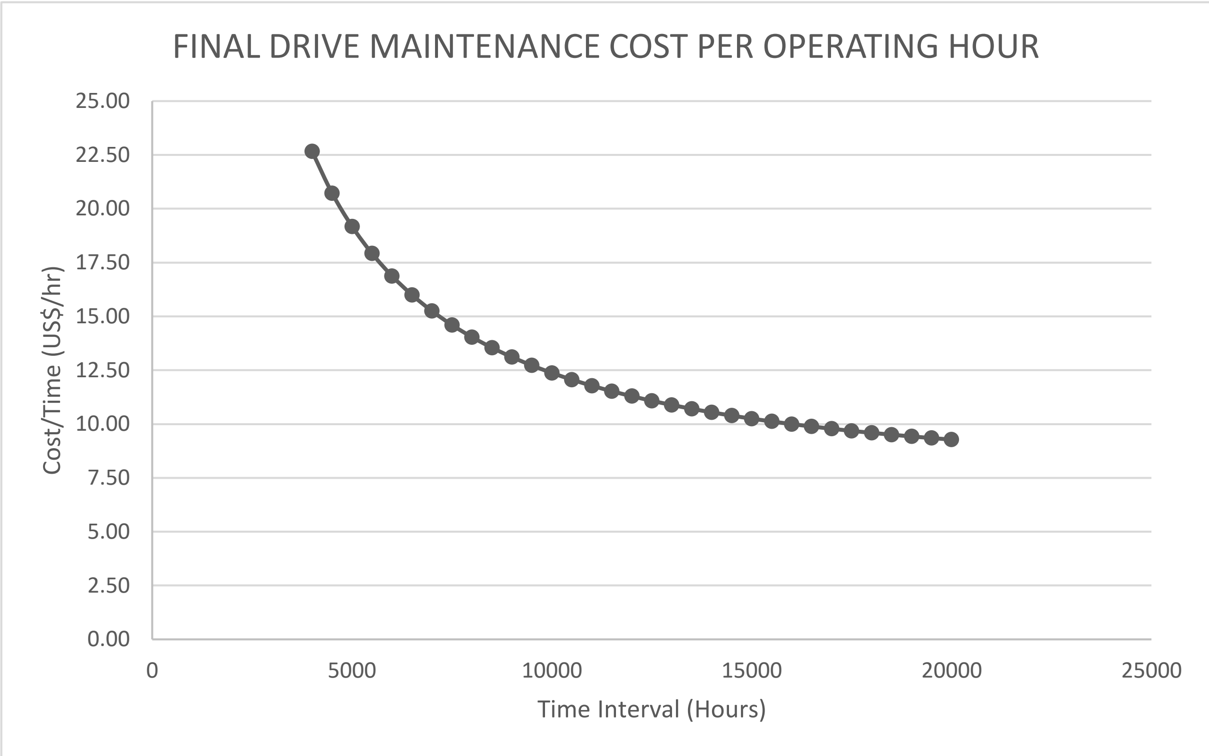


Figure 16: Final Drive Maintenance Cost

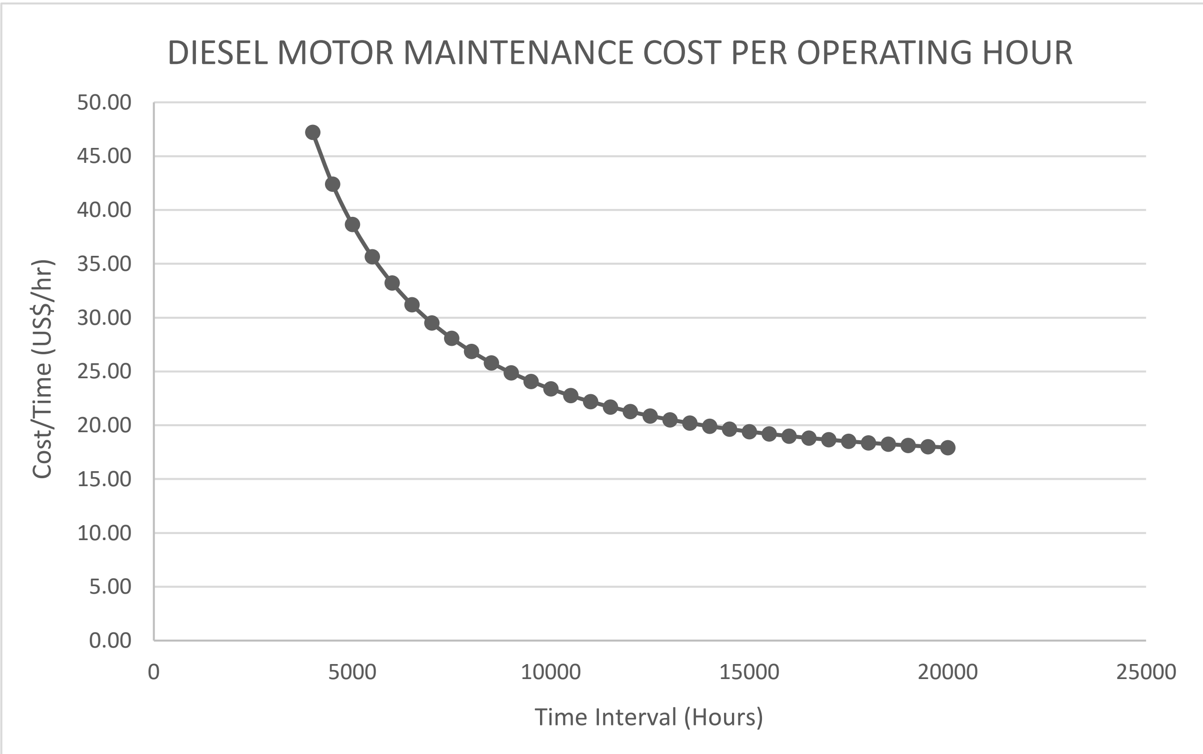


Figure 17: Diesel Motor Maintenance Cost

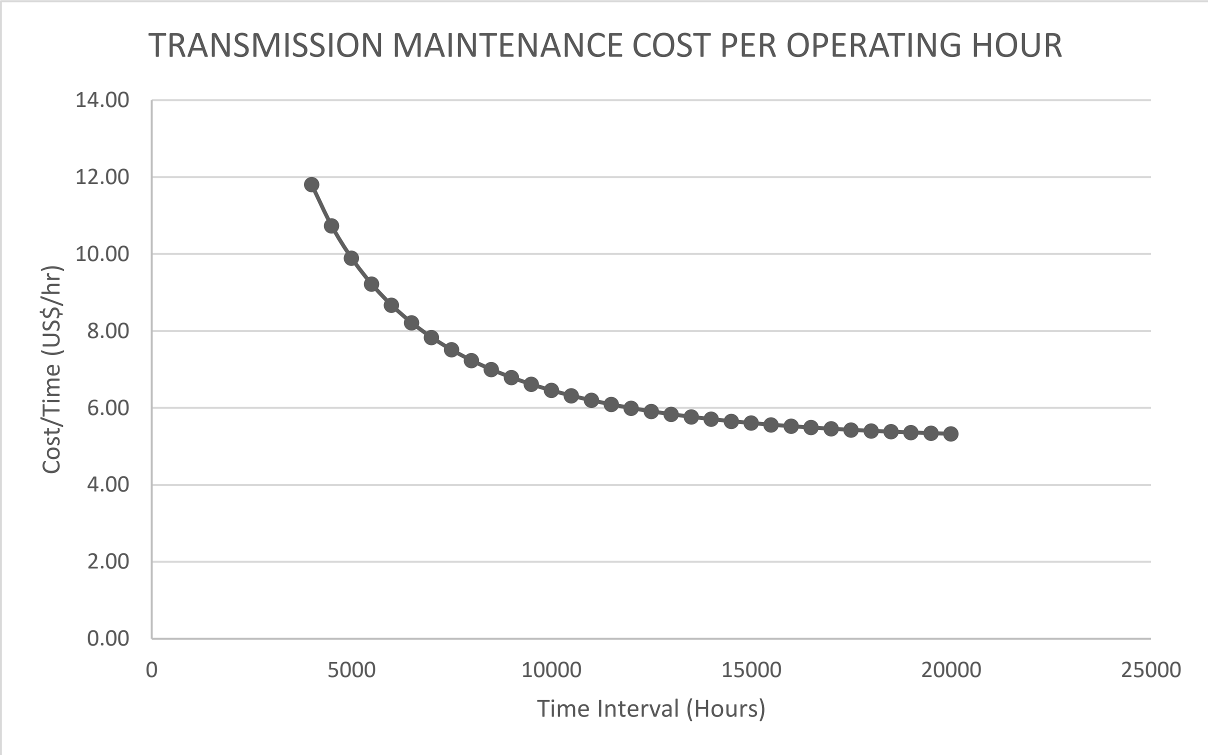


Figure 19: Transmission Maintenance Cost

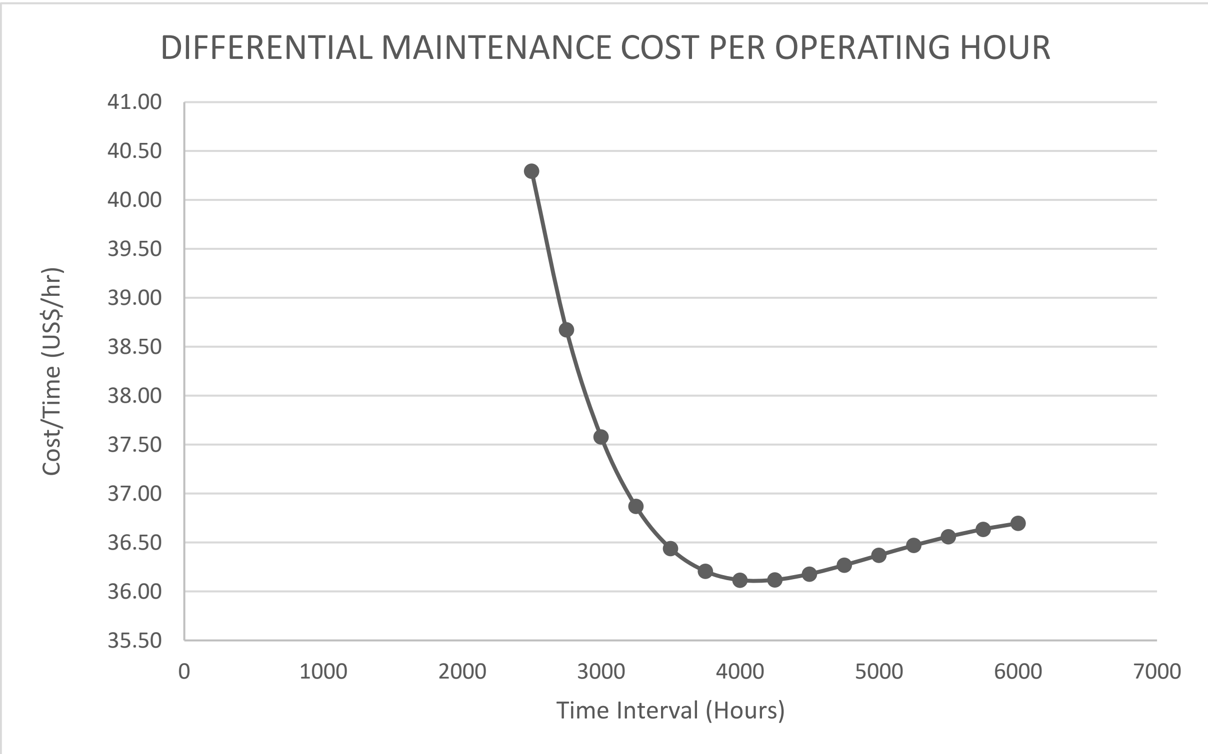


Figure 18: Differential Maintenance Cost

APPENDIX B: PROJECT PLAN

PRIMARY TASKS

The execution of the project consists of four primary phases that are outlined in the following section. Within each phase are multiple tasks which are either considered as necessary or optional. Within the overall project's Gantt chart, presented below, only necessary tasks have been identified. The tasks that are considered optional advantages and are recommended for completion, however if required to meet timelines they can be reduced or removed without impeding the goals and objectives of the investigation. Task prioritisation has been implemented in order to account for this time management risk.

PHASE ONE: PROJECT PLANNING & LITERATURE REVIEW

Table 5: Task for Completion in Phase One

TASK	GOAL	COMPLETION	PRIORITY
Project Plan	Develop in depth project plan with outlined milestones	18/10/18	Necessary
Literature Review	Develop and collate a baseline knowledge of relevant material	18/10/18	Necessary
Risk Analysis	Thorough risk assessment completed with mitigation strategies identified	18/10/18	Necessary

The initial phase of the project has been commenced and has concluded with the submission of this report. It consists of a formulation of the literature review and option assessment boundary conditions. Existing models and processes have been identified and limitations are present. Furthermore, the risks have been outlined in APPENDIX C: RISK ASSESSMENT to ensure that appropriate actions are taken to ensure smooth project execution.

PHASE TWO: DATA ANALYSIS & MODEL FORMULATION

Table 6: Task for Completion in Phase Two

TASK	GOAL	COMPLETION	PRIORITY
Preliminary Data Analysis	Weibull distribution function comparison between components	30/10/18	Necessary
Graphic Data Representation	Graphical representation of distribution functions	30/10/18	Necessary
Development of Model	Development of adjustable variable models to permit "what if" studies.	30/10/18	Necessary

The execution of phase two commenced with preliminary data compilation and analysis. Additionally, the initial development of the mathematical models was completed in alignment to the schedule outlined in the Gantt chart. Further development of the project was dependent, primarily on the data analysis and model formulation.

PHASE THREE: TOOL DEVELOPMENT & OPTIMISATION

Table 7: Task for Completion in Phase Three

TASK	GOAL	COMPLETION	PRIORITY
Prototype Development	Initial development of tool	31/12/18	Necessary
Tool Refinement	Continual iterative process until satisfactory results are achieved	16/01/19	Necessary
Optimisation of Tool	GUI development via macro functions and minor technical adjustments	31/01/19	Necessary

Phase three primarily consists of development and optimisation of the budgeting tool. With completion of the models in phase two, the tool development can be initiated with the integration of the models. The execution of phase three was a time intensive process, with tool refinement and optimisation tasks requiring an iterative approach to achieve a desired result.

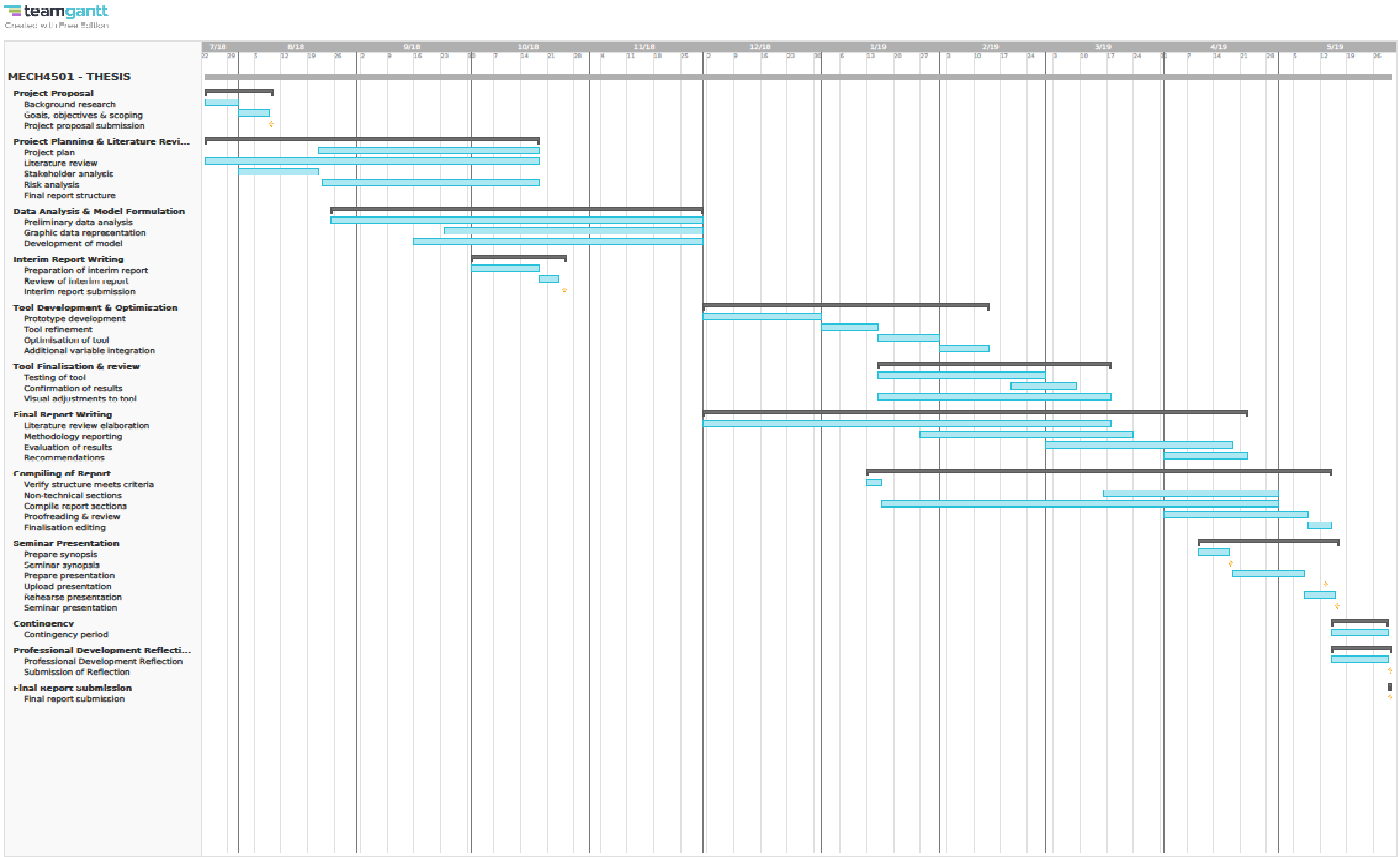
PHASE FOUR: FINALISATION & REVIEW

Table 8: Task for Completion in Phase Four

TASK	GOAL	COMPLETION	PRIORITY
Testing of Tool	Application to industry scenario	01/03/18	Necessary
Finalisation of Tool	Confirmation and minor visual adjustments	18/03/19	Necessary
Report Findings	Present findings of investigation and potential benefits or disadvantages	30/05/19	Necessary

The final phase of the project will examine the budgeting tool and ensure it can be applied to industry scenarios. This will also represent a finalisation of the budgeting tool and investigate the impacts of implementation versus not implementation of the identified maintenance procedures.

GAANT CHART


teamgantt
MECH4501 - THESIS
Project Proposal
Background research
Goals, objectives & scoping
Project proposal submission
Project Planning & Literature Revi...
Project plan
Literature review
Stakeholder analysis
Risk analysis
Final report structure
Data Analysis & Model Formulation
Preliminary data analysis
Graphic data representation
Development of model
Interim Report Writing
Preparation of interim report
Review of interim report
Interim report submission
Tool Development & Optimisation
Prototype development
Tool refinement
Optimisation of tool
Additional variable integration
Tool Finalisation & review
Testing of tool
Confirmation of results
Visual adjustments to tool
Final Report Writing
Literature review elaboration
Methodology reporting
Evaluation of results
Recommendations
Compiling of Report
Verify structure meets criteria
Non-technical sections
Compile report sections
Proofreading & review
Finalisation editing
Seminar Presentation
Prepare synopsis
Seminar synopsis
Prepare presentation
Upload presentation
Rehearse presentation
Seminar presentation
Contingency
Contingency period
Professional Development Reflecti...
Professional Development Reflection
Submission of Reflection
Final Report Submission
Final report submission

APPENDIX C: RISK ASSESSMENT

RISK MATRIX

In order to understand and asses the hazards that have presented themselves in the development of this study, a risk matrix has been developed to quantify the risk in terms of likelihood and consequences. The product of the two values returns the overall risk rating of a hazard. This is illustrated in the risk matrix in Table 9. The risk classification can then be interpreted from Table 10, where a respective action has been identified.

Table 9: Risk Matrix

			Consequences				
			Insignificant	Minor	Moderate	Major	Catastrophic
Likelihood	5	Certain	5	10	15	20	25
	4	Likely	4	8	12	16	20
	3	Moderate	3	6	9	12	15
	2	Unlikely	2	4	6	8	10
	1	Rare	1	2	3	4	5

Table 10: Risk Classification

Classification	Colour	Action
Catastrophic		Stop
Problematic		Take Action
Acceptable		Monitor
Desirable		No action

POTENTIAL HAZARDS AND RISKS

The hazards associated with the undertaking of this thesis study have been identified in Table 11, and a mitigation strategy for each one has been elaborated. The result of the mitigating actions has reduced all risks to an acceptable rating in which only monitoring is required.

Table 11: Hazards and Mitigation

Hazard	Initial Risk			Mitigation	Revised Risk Rating
	C	L	RR		
Medical complications or illness	3	2	6	Ensure both physical and mental health are maintained and consultation with practitioner if health deteriorates	3
Poor time management	4	3	12	Meticulous application of the project plan, with regular updates on Gantt chart tasks and milestones	6
Electronic data loss	5	4	20	Application of an automatic updating software to regularly back-up progress to a cloud drive	5
Poor communication with supervisor	4	2	8	Regular contact maintained via email and face-to-face meetings at a minimum of fortnightly	4
Imbalance of work and university	3	3	9	Ensure employment is aware of tertiary requirements and hours appropriately	6
Misunderstanding of requirements	2	3	6	Regular updates with supervisor to ensure understanding, discuss results of interim report for direction	3
Academic misconduct	5	2	10	Referencing is completed extensively, and regular progress updates and source are recorded within log book	5
Transportation delay on milestone submission	4	3	12	Ensure extra time for travel on days when milestones must be submitted, or meetings are arranged	3
Time loss due to personal complications	3	2	6	Maintain task progression and account for contingency periods within the Gantt timeline	3
Low standard of work	5	2	10	Regular updates with supervisor to ensure standard of work is completed to the highest calibre	5
Failure to meet deadlines	5	2	10	Ensure deadlines are set realistically and milestones are continually being checked off	5