A STUDY OF THE EFFECTS OF THE MAINTENANCE SYSTEM AT AN OPEN CAST IRON ORE MINE

Kevin Anthony Setzkorn (0712364P)

A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science in Engineering

Johannesburg 2017

Abstract

The study assesses the drilling, loading and trucking stages of the mining cycle of an iron ore mine situated in the Northern Cape province of South Africa for the period of 1 January to 30 June 2011. The purpose of this study is to investigate the effect of increasing reliability and maintainability of mining equipment in an effort to increase throughput of iron ore. The data processing indicated that both availability and utilisation are contributing to the sub-optimal performance of the mine. Data regarding reliability (MTBF), maintainability (MTTR), planned and unplanned maintenance was analysed, and this provided input for the simulation model. The intention of the simulation model is to simulate scenarios of proposed improvement in MTBF and MTTR through increasing planned maintenance activities. A simulation model provides insight regarding where to invest in interventions. It is determined that the drilling equipment is the problem area.

Acknowledgements

I would like to acknowledge my supervisor Ian Campbell and co-supervisor Philip Haupt for their support throughout this research. Lastly, I would like to thank my family and friends who supported me through this journey.

Declaration

I declare that this dissertation is my own unaided work. It is being submitted as due requirement to the University of the Witwatersrand, Johannesburg, in partial fulfilment for the degree of Master of Science in Engineering (Industrial) (50/50).

____

Kevin Setzkorn

This the______day of______________2017

Table of Contents

List of Figures

List of tables

Outline of chapters

This research report consists of six main chapters:

- Chapter 1 provides background to the problem that leads to the problem statement and the central research question. The research objectives, methodology and limitations are discussed.
- Chapter 2 discusses literature on the topic and includes an overview of opencast mining equipment maintenance practices and a background to maintenance management approaches and strategies.
- Chapter 3 discusses the objectives
- Chapter 4 provides a description of the data and sample calculations that form part of the research methodology.
- Chapter 5 presents the results.
- Chapter 6 contains the discussion.
- Chapter 7 draws conclusions and provides recommendations.

Chapter 1 – Introduction

1.1 Introduction

The reliability of production systems is an important issue in industry. The successes of process-orientated manufacturing techniques like just-in-time and highly automated production processes depend on the reliability of the equipment. At the same time, a growing interest can be observed in the literature concerning the modelling of reliability of production systems and the analysis of the impact of disruptions on performance and potential financial losses. However, in some of the literature, preventative maintenance has been overlooked. Preventative maintenance has the potential to significantly reduce the occurrence of breakdowns and improve the performance of the system (Van der Duyn Schouten & Vanneste 1995). Dhillon (2008) suggests there are many reasons for improving equipment reliability. These include maximising profit, reducing the cost of poor reliability, minimising downtime and improving short to medium term forecasts of operating hours.

In the context of performance of mining machines, the performance thereof depends on the reliability of the equipment used, the operating environment, the maintenance efficiency, the operation process and the technical expertise of the miners/operators. As the size and complexity of mining equipment and the mines themselves continue to increase, the implications of equipment failure become more critical (Barabady & Kumar 2008). The high productivity and capital costs of modern machinery as well as the high maintenance costs dictate an intensive approach to maintenance management. Maintenance departments are also expected to improve quality, cycle and set-up time, reduce costs and expand capacity (Oke 2006). The attention that maintenance receives is often unplanned and haphazard in nature (Coetzee 1999). Reliability analysis is required to: identify the causes of bottlenecks in the systems; find the components or subsystems with low reliability for a given designed performance; enhance and direct the maintenance procedures; and to give direction to the maintenance strategy.

A mine production system consists of many subsystems. The optimisation of each subsystem in relation to one another is imperative to make the system profitable and viable for operation. Effectiveness of the mining equipment is mainly influenced by the availability, reliability and maintainability of the system, and its capability to perform as expected. Reliability analysis and the techniques thereof have been progressively recognised as tools that can be useful in complex mining environments. Since failure cannot be prevented entirely, it is important to minimise both the probability of occurrence and the impact of failures when they do occur. To maintain the desired reliability, availability and maintainability characteristics and to achieve expected performance, an effective maintenance programme is imperative. The costs associated with maintenance programmes constitute a major part of the total operating costs of all manufacturing or production plants, and depending on the specific industry, maintenance costs can represent between 15% and 60% of the cost of the goods produced. A major part of the mining system's operating costs may be due to unplanned system stoppages for unscheduled repair of the entire system or of components (Barabady & Kumar 2008).

1.2 Background to the problem

Iron Ore Futures is situated approximately 30km south of the town of Khatu, in the Northern Cape Province of South Africa. The Iron Ore Futures mine has been designed to produce 10 million tonnes of export quality iron ore each year, a figure that will eventually rise to 16 million tonnes upon completion of an expansion project. The mine, comprising two operations, is operating at a 2.6 stripping ratio, meaning that for every 1 tonne of ore processed, 2.6 tonnes of waste rock has to be removed. The planned expansion includes development of the mining platform on the property, material handling systems, stockpiles, stackers and re-claimers, a local railway siding, an additional rapid load-out station, a waste disposal facility, haul roads and other supporting facilities. The iron ore mined at Iron Ore

Futures will initially only be exported. However, with future expansions it will also be supplying the local South African steel market (Burger 2014). In 2005 a feasibility study for the expansion project was completed. The mining rights were approved and construction began in June 2006. It was planned to have 1.2 million tonnes (MT) transported via rail by the end of June 2008 and 7.2 MT on rail between June 2008 and July 2009. This project would conclude with 10 MT on rail for the following year. During the expansion, Iron Ore Future's senior management experienced significant challenges in consolidating and stabilising the operational processes and practices such that they remained at a state of optimal efficiency. These challenges included low utilisation of the drills and loading equipment compounded with high unplanned maintenance and low planned maintenance percentages. There are three high level processes occurring at this mine, namely resource development, rail and mine operations.

- Resource development comprises the following steps;
    - Exploration;
    - Assessment; and
    - Planning.

- Mine operations comprise the following steps;
    - Drill and blast;
    - Load and haul;
    - Process (milling); and
    - Stock pile and load out.

- Rail operations comprise the following steps;
    - Rail transport;
    - Ore car dumping; and
    - Stockpiling.

The availability and utilisation of the equipment had a compound effect on the utilisation of the process plant which is seen to have low utilisation. An operations review (Appendix A) established that there are significant challenges concerning the availability, utilisation and high levels of unplanned maintenance of the drilling and loading equipment at the mine. Production for both operations during the 2011 financial year was 30 MT as per Table 1.

Table 1 Monthly production of both mines for the period 1 July 2010 to 30 June 2011 (financial year 2011)

Month	**Tonnes**	
	Mine A	**Mine B**
July	417 850	2 162 498
August	359 878	2 263 369
September	81 526	2 135 262
October	456 385	2 267 924
November	451 055	2 120 670
December	937 410	2 206 569
January	676 173	1 179 932
February	995 357	1 102 990
March	1 225 564	1 724 551
April	1 145 636	1 564 177
May	905 852	1 451 697
June	985 780	1 410 244
Total	**8 638 466**	**21 589 883**

The scope of this research report is based on 6 months production for Mine B for the period 1 January to 30 June 2011. This is quantified in Table 1 as being 8.4 MT of total production.

Figure 1 shows the traditional approach for appraising new equipment, as well as assessing the suitability of existing equipment, for a given production scenario (Hall & Daneshmend 2010).

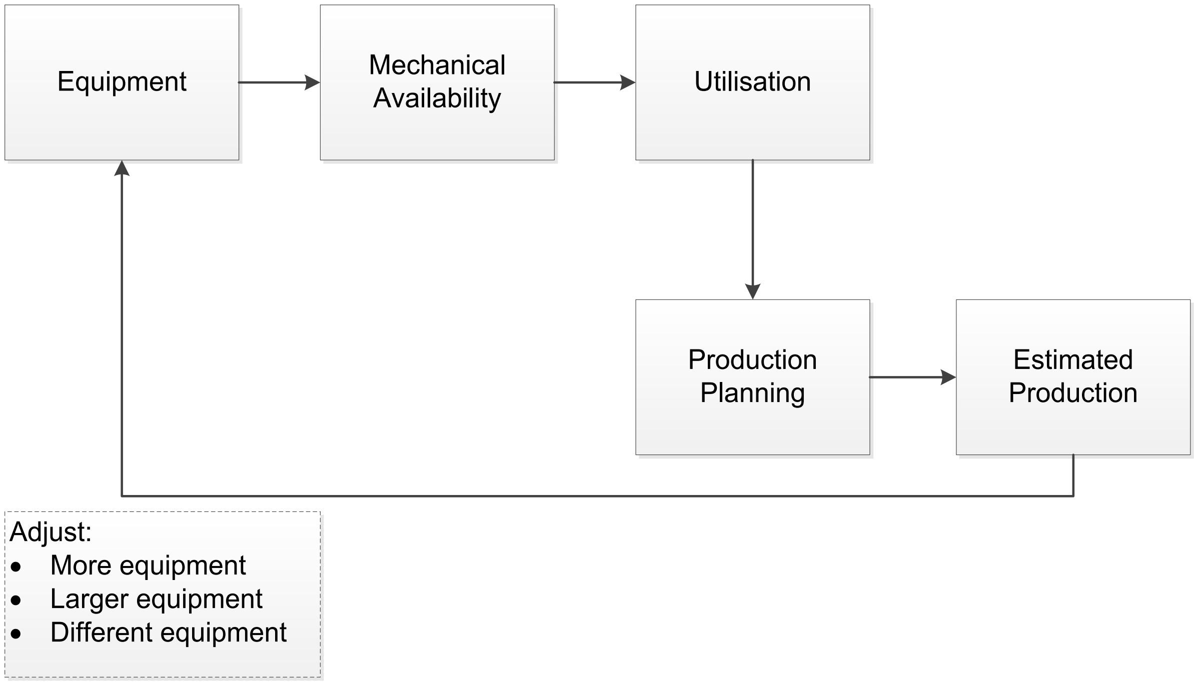


Figure 1 Traditional method of assessing effects of equipment decisions on production

1.3 Problem statement

The problem statement is:

"The mine is suffering from low output due to low availability and utilisation of drilling and/or loading equipment"

Further refining the above formed the research objectives:

- *What will the effect be of influencing the characteristics of planned and unplanned maintenance on some of the equipment in terms of the output?*

Chapter 2 – Literature Review

2.1 Introduction

In this research there is a need for a detailed understanding of the Mean Time Before Failure (MTBF) and the Mean Time to Repair (MTTR) indicators and the failure characteristics of the equipment. The objectives set out formulate the need for a discussion on the possibility of increasing utilisation and indirectly the availability of the equipment by addressing the maintenance issues and each of the concepts will be discussed.

2.2 Maintenance

Maintenance is defined as the following:

"The combination of all technical and associated administration actions intended to retain an item in or restore it to a state in which it can perform its action required. This required function might be defined as a stated condition" (Mishra 2006).

Maintenance is a repetitive process to ensure that equipment remains in a state of operation without breakdown, resulting in none or minimal lost time in production. The emphasis is on enabling machinery to operate and be utilised according to the designed capacity. Due to the size and intricacy of current day industrial installations, the scope and responsibility of maintenance engineers and practitioners has increased.

In the case of an iron ore mine, it's output is a commodity and, as such, is subject to fluctuations in price, which can dramatically affect revenue and profit. Therefore, planned maintenance is even more important. All equipment is exposed to some form of failure and there needs to be a system in place to ensure the equipment can be returned to operational capacity in the event of a breakdown.

The system or function to complete this is known as maintenance and the reasons for this include (Dhillon 2002):

- Increased sophistication of production equipment;
- The need for return on investment;
- The high cost of maintenance; and
- The complexity of the maintenance function.

Up to 1940, maintenance was considered an inescapable cost. The only maintenance activity performed was corrective maintenance i.e. repair upon failure. Maintenance was not taken into consideration during the design phase nor was it considered in terms of business continuity aspects. Operations research evolved during the Second World War and subsequently led to the concept of preventative maintenance. During the 1970s a more integrative approach developed and life-cycle costing was taken into consideration as maintenance had a significant impact on the total costing of equipment. It was in the civilian aviation, industry that the connection between reliability and maintenance was first recognised resulting in the concept of reliability centred maintenance (RCM). In this approach, maintenance focused on the individual parts and its function on the reliability of the system as whole. The approach uses failure mode and effect analysis (FMEA) and is in principle measurable (Igba et al. 2013). The Japanese, in the context of manufacturing, developed total productive maintenance (TPM) (Eti et al. 2006). Poor maintenance will ultimately impact negatively on manufacturing through poor availability, low production rate and poor quality output (Murthy et al. 2002).

2.3 Objectives of maintenance

The maintenance function is complex and a detailed understanding of the fundamental objectives is required (Coetzee 2004). The objective of maintenance is to support the production process with adequate levels of availability, reliability and operability at an acceptable cost. This objective consists of four sub-objectives and these include:

- *Availability* – The proportion of time that equipment is in an operational state. It is the function of the maintenance department to ensure that an acceptable level of availability is achieved to support the production plan.
- *Reliability* – The number of instances equipment experiences operational difficulties. This measure indicates the continuity of the production process. A machine can have high availability without being reliable. A low level of reliability can have an adverse effect on stoppages. For continued success on production plans, high availability and reliability are necessary.
- *Operability* – This is a measure of a machines ability to sustain an adequate production rate. Availability and reliability are important for production but the required results cannot be produced without the required levels of operability.
- *Cost* – The cost of the maintenance action needs to be at an acceptable level.

2.4 The changing role of maintenance

"For any system in operation, it is necessary to maintain it in a predetermined level of performance. The tasks or activities required to achieve this purpose is termed maintenance" (Lau 1983). Maintenance of equipment has always been regarded as repair work. In the past machines were in operation until breakdown, with little or no method of prevention. It wasn't until the 1950s, together with the development of the 'reliability field' that the concept of preventative maintenance emerged. Time-based maintenance (TBM) was founded on the bathtub curve representing the increase in the failure rate of products after a certain period of operation (Takata et al. 2004). This curve indicated in Figure 2 has three categories; "A" represents a decreasing failure rate period in the life cycle, "B" represents a constant failure rate period in the life cycle and "C" is near the end of the useful life, with the failure rate increasing. By applying statistical techniques it is possible to determine where on the curve a piece of equipment is operating (Jardine & Tsang 2013).

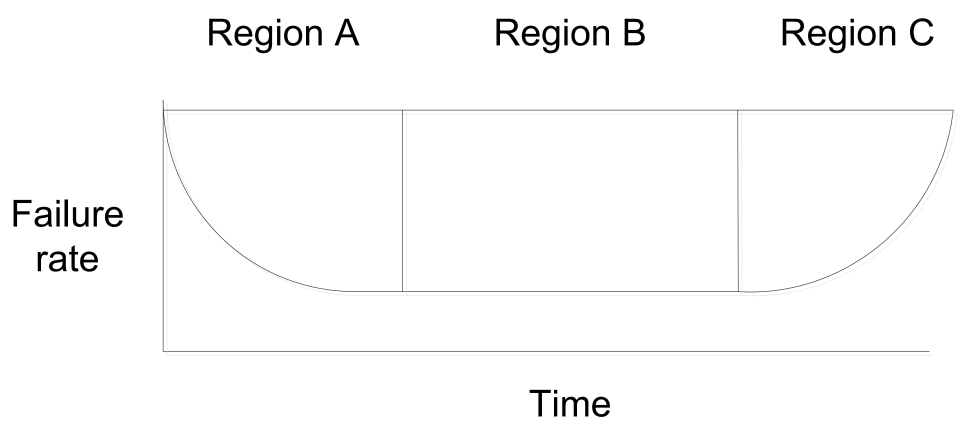


Figure 2 Life Cycle Curve (Greyling 2004)

There are some limitations associated with TBM and after these surfaced the notion of condition based maintenance (CBM) was proposed, based on the development of machine diagnostic techniques in the 1970s. "In the case of CBM, preventive actions are taken when symptoms of failures are recognized through monitoring or diagnosis. Therefore, CBM enables the taking of proper actions at the right timing to prevent failures, if there is a proper diagnostic technique" (Takata et al. 2004).

CBM is not always the only route to follow when there are breakdowns. If on assessment, the breakdowns are non-critical then breakdown maintenance (BM) can subsequently be applied. TBM can be preferable where reliable statistics are available to indicate lifespan of certain machines or their components. Since the second half of the 1980s it has become essential to select the most appropriate maintenance strategy for each situation. Whilst there have been significant improvements around the concepts and methodologies, a maintenance department is still regarded as a cost centre which does not generate profit (Takata et al. 2004).

RCM and TPM are both broadly focused on the link between component failure and business output. There is however an assumption that an optimal maintenance strategy is in place and these do not take into consideration the degradation caused by loading. RCM and TPM do not deal with long term maintenance strategies as their primary focus is on short to medium term business needs. These strategies are more scientific as there is reliance on modelling, a sound understanding of the operating conditions and field data. Those responsible for maintenance are divided into two categories when it comes to applying RCM. Those who do not favour its use firstly question whether the technique is based on science, although they do not have an alternative that does not rely on the structures of RCM. Secondly, RCM has had bad publicity caused by unprofessional salesmen who have not emphasised its scientific strengths and rely solely on a mathematical approach to maintenance without taking into account other factors such as human behaviour and the interaction between systems, equipment and components, where intervention by a management team which understands the entire process is essential (Coetzee & Claasen 2002).

2.5 Strategic Maintenance Management

The strategic maintenance management (SMM) approach has two guiding concepts (Murthy et al. 2002):

- It is paramount for the sustainability and profitability of a business that maintenance management is dynamic and strategic in nature; and
- Effective maintenance management needs to be based on measurable business models that incorporate maintenance with other management decisions such as production.

In the SMM approach, maintenance is viewed as a multi-faceted activity and involves:

- Scientific comprehension of deterioration mechanisms, relating them to data collection and breakdowns to evaluate the state of the equipment;
- Building measurable models to forecast the effect of diverse maintenance operations on equipment deterioration; and
- Managing maintenance from a calculated viewpoint that is more strategic in nature.

Considering total operating costs at a mine, maintenance of equipment and associated costs are substantial proportions. Both corrective and predictive maintenance can contribute 40-50% of operating costs on a mine. It is imperative that maintenance be viewed through a strategic lens in terms of business continuity – without machinery operating there is no means of generating product for market.

Therefore, SMM can be viewed as a multi-disciplinary approach with the following features;

- It takes both commercial and technical factors into account;
- It uses mathematical models to measure the maintenance management required;
- It makes sure all relevant information is taken into account; and
- It continually seeks and improves maintenance programmes.

Modern mines, together with industrial societies, are characterised by a dependence on technology. This technology is crucial to producing goods and services and is required for output. Over the years, advances and technological development have given rise to improvement in output through increased productivity and efficiency. This improvement has come at a financial cost and increased complexity. There are high penalties and losses when equipment is not operational. As an example, an open cast mine could lose between $0.5 – 1 million per day (Murthy et al. 2002). High industrial productivity can only be achieved where there is equipment reliability and plant availability. Repairs, instead of routine maintenance, can affect spare part inventory control and the resultant crisis management impacts on the direct costs of maintenance. RCM enables the main causes of equipment failure to be controlled, thus making optimum use of resources to prevent failure disruptions which in turn lead to decreased output (Fore & Msipha 2010).

Equipment in operation degrades with usage and age and will ultimately become non-operational. There are many factors that determine the rate of degradation which include design, the operating environment, and the intensity of use and skill level of operators. This degradation can be mitigated through sound operating practices and correct preventative maintenance. Corrective maintenance at the point of failure can restore equipment to original operating condition. These direct costs are associated with keeping equipment operational whilst the indirect costs could potentially result in lack of company confidence, market challenges and delays to customers. It is therefore implied that these elements need to be managed effectively (Murthy et al. 2002).

2.6 Maintenance in mining environments

The use of more mechanisation and automation in the industry has emphasised the need for reliable operating systems. In terms of economics, systems with high reliability are favoured to reduce maintenance costs. In times gone by maintenance wasn't considered a problem as the cost and consequences were considered negligible (Eti et al. 2006). Statistics from research done in Swedish mines in recent times have revealed that maintenance costs, both direct and indirect, make up between 50-60% of the operating costs. "The indirect maintenance cost is due to the incidence of random equipment failures. These result in indirect costs of maintenance due to losses in production and forced idleness of other equipment in the operating systems. The area of maintenance is identified as strategic for cost reduction in mechanised mines by the Swedish mining industry" (Kumar et al. 1989).

As per Barabady & Kumar (2008) the following can be said regarding a mine production system:

- There are many subsystems that are incorporated into a mine production system;
- To ensure profitability it is vital to ensure that any optimisation programme that is installed must take into account all the subsystems;
- The overall effectiveness of mining equipment is influenced by availability, reliability and maintainability and its capability to perform as anticipated;
- Since the mid 1980s reliability analysis has steadily gained acceptance as a method for planning and operation;
- 100% of failures cannot be prevented. It is however important to manage their anticipated occurrence and to mitigate occurrence;

- An effective maintenance programme must be adopted and installed to manage the risks of availability, reliability and ultimately the maintainability of systems; and
- An improvement in the production system should first concentrate on the reliability and availability of the equipment hindering the production process in achieving the desired output.

Furthermore, effective maintenance leads to lower operational costs. In the manufacturing and industrial fields maintenance costs can represent anything between 15% and 60% in terms of the operations budget (Mobley 2002). The following are factors that could potentially affect mining equipment reliability (Sharma et al. 2011):

- The suitability of the design can negatively impact on dependability;
- The quality of any repairs to the machinery, planned or unplanned, can impact on the period between breakdowns; and
- Operating conditions

2.7 Types of maintenance systems

There are generally two types of maintenance systems, namely unplanned and planned. Unplanned maintenance allows for machines or components to run until a failure occurs. Maintenance activities are considered to take place in an unplanned manner and can be ***corrective*** in nature. The opposite is experienced with planned maintenance where a plan/schedule is followed to ensure activities take place at given intervals and this can be considered ***preventative*** in nature. Figure 3 provides a graphical representation of the different types of maintenance (Kothamasu et al. 2006).

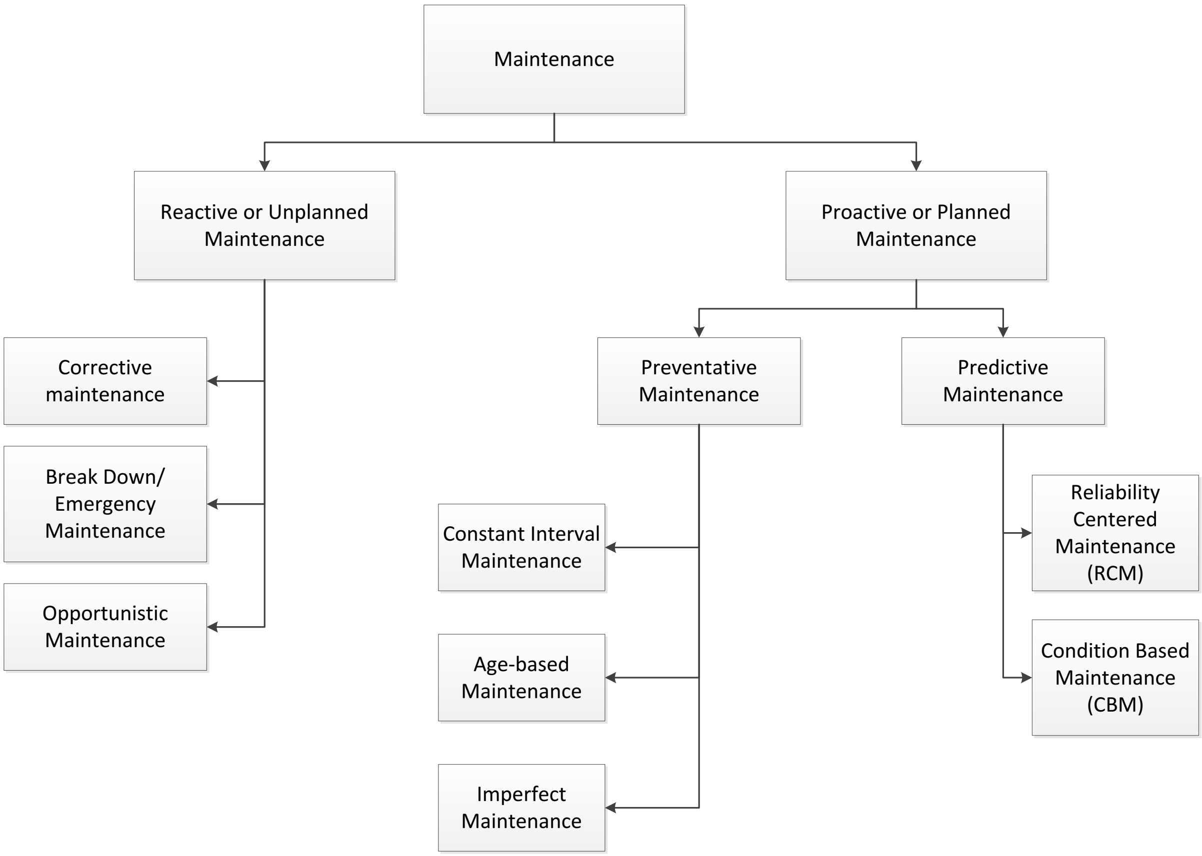


Figure 3 Taxonomy of maintenance philosophies (Kothamasu et al. 2006)

2.7.1 Reactive/unplanned maintenance systems

The equipment/system operates until it stops working and requires repairs in order to make the machine functional again. It can be defined as “The maintenance carried out after a failure has occurred and is intended to restore an item to a state in which it can perform its required function” (Mishra 2006).

There are three types of maintenance systems under reactive/unplanned maintenance:

- **Corrective Maintenance:** Activities for correcting or restoring failed units. This is usually carried out in four steps (Tsarouhas & Arvanitoyannis 2010):
    - 1st step: Collection of data, information and analysis;
    - 2nd step: Identifying the causes;

- 3rd step: Find out the best possible solution to eliminate likely causes; and
- 4th step: Implement those solutions.

Corrective maintenance can be considered volatile. The immediate reaction to a product or system failure is to repair or restore the fault to minimise production time loss.

- **Breakdown/Emergency Maintenance system:** Repair is undertaken only after failure of system. Lubricating and minor adjustments are done during the period (Takata et al. 2004).
- **Opportunistic Maintenance system:** In multi component systems it is often advantageous to follow opportunistic maintenance. When equipment or a system is not operational for maintenance of one or a few worn out components, the opportunity can be utilised for maintaining or changing other worn out components, even though they have not failed (Sharma et al. 2011).

2.7.2 Proactive/planned maintenance systems

Preventative maintenance is an organised type of maintenance and management has a forecast of maintenance activities and views these as necessities and not as a cost increasing activity. Two types of planned maintenance exist, preventative and predictive. The objective of preventative maintenance is to reduce the probability of failure in the period following maintenance.

1) Preventative Maintenance

Preventative maintenance is also referred to as use-based maintenance (Swanson 2001) It is mainly associated with a set of activities undertaken after a specific time interval and the estimated probability of failure after a set amount of time or use. Preventative maintenance is performed routinely to accomplish the following three goals (Smith & Hinchcliffe 2003):

- Avoid or moderate failure;

- Identify the onset of a breakdown and by performing this can enable the responsible engineer to take preventative actions before a catastrophic failure occurs; and
- Determine the cause of failure which can then be mitigated to prevent future failure(s).

There are three type of preventative maintenance as indicated in Figure 3:

- **Constant interval maintenance:** This is performed at predetermined intervals in addition to any maintenance prompted by failure. These intervals are determined to balance risks and costs (Kothamasu et al. 2006).
- **Age-based maintenance:** In this strategy, preventative maintenance at fixed intervals is carried out only after the system has reached a specific age.
- **Imperfect maintenance:** The system is not returned to as good as new condition but is in better condition than it was at the time of failure (Pascual et al. 2008).

The success of preventative maintenance depends on the adherence to detailed maintenance schedules. The Original Equipment Manufacturer (OEM) will publish maintenance schedules for established systems or machinery.

2) Predictive Maintenance

Predictive maintenance involves monitoring the condition of equipment with an appropriate means which allows for the detection of a problem in a predictive manner to stop the defect from occurring or to manage and minimise the consequence (Moore 2011).

- **Reliability Centred Maintenance:** Reliability-centred maintenance was developed in the aviation industry to determine scheduled maintenance policies for civil aircraft. This approach utilises reliability estimates of the system or components to assist in scheduling for maintenance activities (Igba et al. 2013).
- **Condition Based Maintenance:** The decision to perform maintenance is based on the observed condition of the system or its components and the decision is supported

by means of a monitoring mechanism. Vibration monitoring in the mining industry is an example of such a monitoring technique (Takata et al. 2004).

2.7.3 Cost implications

It is evident that replacing a component before it fails, in a preventative manner, may under certain circumstances, make better economic sense than replacing the component when it fails in random manner (Moore 2011).

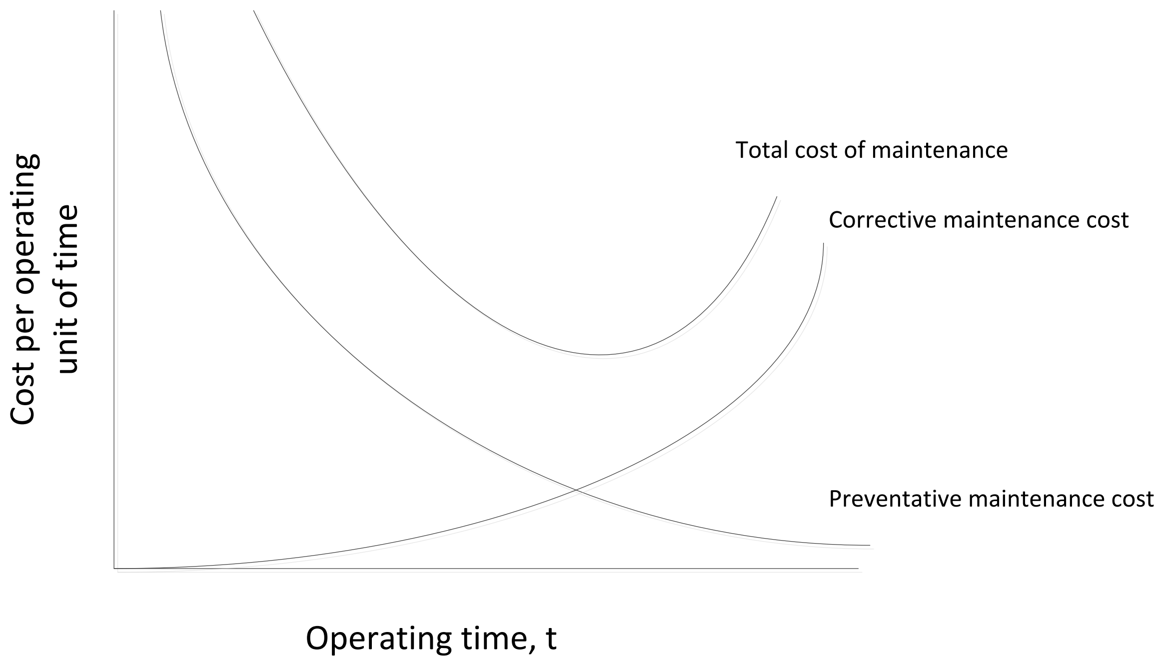


Figure 4 Total, PM and CM costs as a function of time (Bergsman 2010)

It is evident in Figure 4 that the corrective replacement costs increase as the operating time interval increases. In other words, the less often you perform a PM action, the higher your corrective costs will be. The longer a component operates, its failure rate increases to a point and becomes more likely and will ultimately require corrective action. The opposite is true for the preventive replacement costs. The longer you wait to perform a PM, the less the costs; while if you do PM too often, the higher the costs. If both these costs are combined there is an optimum point that minimises these and achieves a balance between the risk associated with a failure while maximising the time between PM actions (Bergsman 2010).

2.8 Maintenance concepts

2.8.1 Availability

Availability is the amount of time a piece of equipment is available at its design capacity whenever it is required to perform a function availability is represented as follow (Mishra 2006). The formula to calculate availability is:

Availability = (Available Time / Total Time) x 100% (1)

2.8.2 Utilisation

Machinery or equipment that is available for work is not always utilised during its available time. As an example, a piece of equipment is selected as back-up/standby or may be sitting idle caused by operational changes or no operator (Paraszczak 2005). The formula to calculate utilisation is:

Utilisation = (Utilised Time / Available Time) x 100% (2)

Utilisation will increase as more operating hours are logged during the machine's available time. Paraszczak (2005) goes into further detail and defines utilisation as the use of the availability. A machine will be available for work, and utilisation in essence measures the percentage of this time that machine is actually productive.

2.8.3 Failure and failure rate

A failure is defined as the system not functioning. Occurrences of reduced availability are not included in failure data, but they do adversely affect production. A failure is regarded as a state of unsatisfactory condition and failure rate is the rate at which a system or component fails or breaks down. It is represented as the number of failures per hour and improving reliability decreases the failure rate (Samanta et al. 2004). Failure rate is defined as the number of failures per unit of time e.g. 1 failure per 1000 hours of operational or utilised time.

The formula to calculate failure rate is:

Failure Rate = Number of Failures / Utilised Time (3)

2.8.4 Pareto Theory

This forms an important step in any intervention or improvement exercise so that the correct resources can be directed to the source of the problem. Pareto Theory states that a few failures are responsible for the bulk of low availability (Chua & DeFeo 2006).

2.9 Maintainability and Reliability

2.9.1 Concepts

Reliability predictions form the groundwork for reliability analyses. They are used to compute the predicted failure rate or mean time between failures (MTBF) of a system. MTBF is usually expressed in terms of hours. For example, if a system has a predicted MTBF of 1000 hours, this means that, on average, the system experiences one failure after 1000 hours of operation.

MTBF is defined as the probable period that an item will function without failure (Lau 1983). The formula to calculate MTBF is:

MTBF = 1 / Failure Rate (4)

Maintainability analysis is a method that identifies failure modes, the predicted failure frequency (MTBF) and the maintainability, which is expressed by the indicator Mean Time to Repair (MTTR), and includes the total, planned and unplanned times to repair. As such, MTTR has been defined as the expected time to repair. Planned maintenance MTTR is the average time it takes to repair a component or system at a planned point in time. Unplanned

MTTR is the average time it takes to repair a component or system after a breakdown (Marten 2010). The formula to calculate MTTR total is:

MTTR Total = ((Unplanned Maintenance Time + Planned Maintenance Time) / 3600) / (Number of Unplanned Maintenance Actions + Number Planned Maintenance Actions) (5)

The formulae to calculate MTTR Unplanned Maintenance Time and MTTR Planned Maintenance Time is as follows:

MTTR Unplanned Maintenance Time = ((Unplanned Maintenance Time) / 3600) / (Number of Unplanned Maintenance Actions) (6)

MTTR Planned Maintenance Time = ((Planned Maintenance Time) / 3600) / (Number of Planned Maintenance Actions) (7)

2.9.2 Reliability Analysis

Hall & Daneshmend (2010) suggest three factors affecting the reliability of mining equipment:

- The reliability of the equipment must be measured against its original design and component materials;
- The quality of the maintenance carried out on the equipment which must take into account the quality of the workmanship and replacement parts; and
- How the equipment is used. A piece of equipment abused by its operator is going to fail long before one which is used by an operator who understands its limitations.

There are many sources of data that are of significance to reliability modelling of equipment. In addition to the reports that are generated from the maintenance and production functions, it is the raw data from which these reports are generated which must also be obtainable. Reliability modelling is therefore an integral part of analysis with information flows (Figure 5) including:

- Data from sensors on mobile equipment;
- Data and information from operator interfaces;
- Historical operational maintenance information; and
- Current operational and maintenance information.

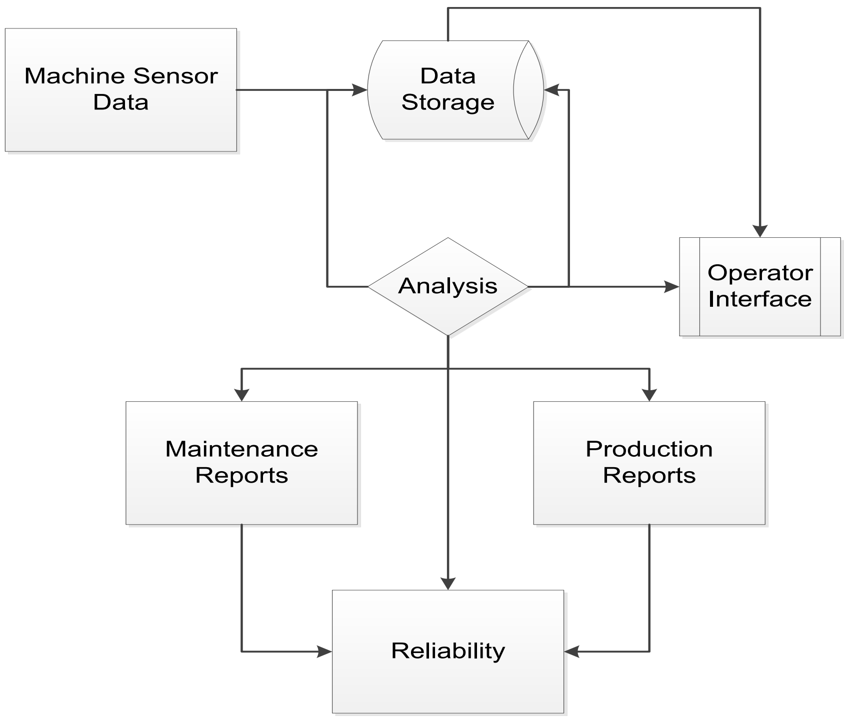


Figure 5: Data flows for reliability modelling (Hall & Daneshmend 2010)

Maintenance data was usually of poor quality and more recently there has been an increase in the quantity and quality of this data due to monitoring technology (e.g., the Caterpillar VIMS technology). In the context of surface mining, the communications and networking infrastructure to facilitate these data flows is provided by the mine dispatch system, e.g., Modular Mining's DISPATCH/INTELLIMINE or Caterpillar's MINESTAR systems. These technologies enable proper management of the equipment, monitoring production, operator behaviour and assisting in productivity and efficiency improvements (Caterpillar Inc. 2015).

2.9.3 Performance benchmarks

Benchmarking is the process in which a company compares its business processes and performance metrics to best practice. The application of benchmarking is important as it allows an organisation to compare itself to other companies operating within the same industry. This allows the organisation to form improvement plans generally to improve performance. In the case of Iron Ore Futures the benchmark indicators are availability, utilisation, unplanned and planned maintenance, as indicated in Table 2. The targeted benchmark indicators were chosen to initiate the drive towards world-class standards. The following are the selected benchmarks (Burger 2014):

- Availability - 90%. Each piece of equipment is to be available for work for 90% of total time.
- Utilisation – 80%. Each piece of equipment is to be utilised for 80% of the time that it is available for work.
- Unplanned Maintenance – 10%. With availability benchmarked at 90%, this indicates that total maintenance time should not exceed 10%, with unplanned maintenance time or failure time not exceeding 10% of that time.
- Planned maintenance time – 90%. With availability benchmarked at 90%, this indicates that total maintenance time should not exceed 10%, with planned maintenance time not being below 90% of that time.

Table 2 Benchmark indicators (Burger 2014)

Indicator	Benchmark Indicator
Availability	
Drills	90%
Loaders	90%
Haulers	90%
Utilisation (As a % of available time)	
Drills	80%
Loaders	80%
Haulers	80%
Unplanned Maintenance (As a % of total maintenance time)	
Drills	10%
Loaders	10%
Haulers	10%
Planned Maintenance (As a % of total maintenance time)	
Drills	90%
Loaders	90%
Haulers	90%

2.10 Why use simulation modelling?

"Simulation is an indispensable problem-solving methodology for the solution of many real-world problems. Simulation is used to describe and analyse the behaviour of a system, ask "what if" questions about the real system, and aid in the design of real systems" (Banks 2000).

Some of the benefits of simulation include (Banks 2000):

- It provides users with practical feedback regarding the effectiveness and the efficiency of the design before the system is constructed.
- The cost of simulation can be less than the cost of redesign or the modification of a process or part thereof.
- It allows the user to evaluate alternative designs and explore new control philosophies, operating procedures and methods.

- Simulation helps to establish where constraints and bottlenecks lie and to ensure these are managed properly.
- It can inform the user why certain phenomena are occurring in the real system.
- Illustrative and animated models can be used as an effective means for illustrating concepts relating to the system.

Chapter 3 – Objectives

The rationale for increasing availability and utilisation of mining equipment is to be able to extract and process more ore and generate increased profit. Compromising the maintenance of the equipment will have a negative effect on the reliability thereof. The objectives of this research are:

- To calculate the utilisation, availability, reliability and maintenance indicators of the drilling, loading and hauling equipment in precise quantitative terms;
- To create a validated simulation model and run a series of scenarios demonstrating the effect of influencing planned and unplanned maintenance activities on the drilling fleet.

This research and analysis is governed by some assumptions, which include:

- The data provided to the author was collected and verified by mine management and was collated in accordance with internal operating procedures. The author therefore assumes the data is accurate, reliable and complete;
- A planned maintenance strategy is in effect at the mine;
- A maintainable (repairable) system is studied; and
- The simulation developed is applied to demonstrate principles in maintenance management and is based on assumptions put forward by the author.

Chapter 4 – Methodology

The methodology involved an investigation of relevant processes and then a simulation was used to investigate proposed changes in maintenance philosophies. The methodology is illustrated in Figure 6 and comprises 5 steps that were performed in sequence. The steps will be described in further detail in this section.

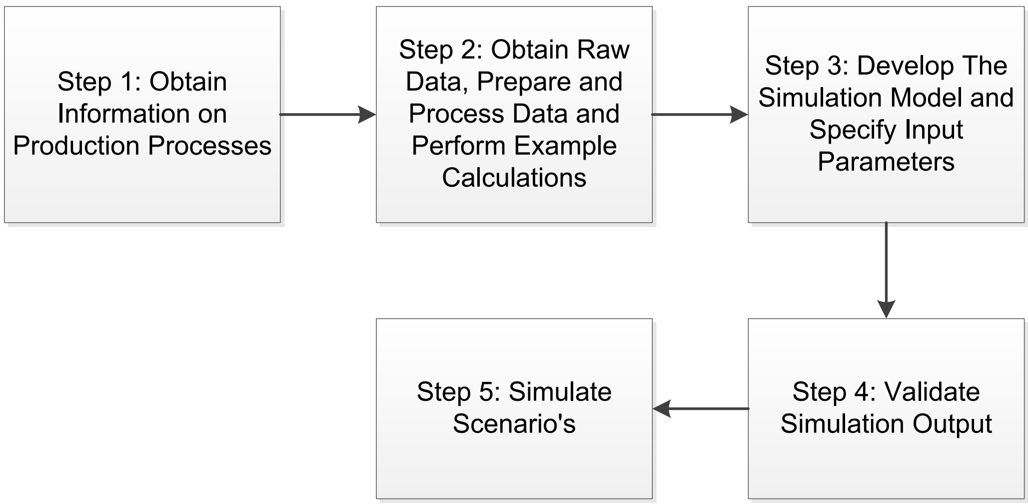


Figure 6: Methodological steps

4.1 Obtain background information

The introduction (Section 1.1.1) provides an overview of the mine used in this investigational study and this step involves obtaining information on the production processes. Step 1 entails understanding background information in terms of the equipment in use at the mine:

- The drilling equipment: Iron Ore Futures makes use of seven mobile drills. There are four Sandvik Titon DI600 RC Drill Rigs and three Atlas Copco Pit-viper 271 Drill Rigs (Figures A.4 and A.5 in Appendix A).

- The loading equipment: The broken and fractured material is loaded for transport by front-end loaders into haulers. Iron Ore Futures makes use of four Caterpillar 994D front-end loaders (Figure A.6 in Appendix A).
- Hauling equipment: Haul trucks are the 190 tonne class and are used to transport waste rock to the dumps and iron ore to the processing plant. Iron Ore Futures makes use of twelve Caterpillar 789C haul trucks (Figure A.7 in Appendix A).

4.2 The mining process

The mining process begins with block planning. A block is a section of rock that is planned for drilling and the tonnage planned for each block is 100 000 tons of material. The drill plan is 200 holes at 11 metres each, which equates to 2200 metres per block. After the 200 holes are completed, the holes are prepared for blasting - an external service provider performs this function. A blast takes place and releases 100 000 tons of material. The process of loading and hauling removes the material to the processing plant which crushes the material and separates the iron ore from the rock material. Further information pertaining to drilling, loading and hauling rates is described in Section 4.4.1 Table 7 pertaining to the setup of the simulation model.

The Minestar system is integrated into all equipment which tracks activity. There is a panel inside the cab that the operator uses. For example, if the machine is waiting for a load, the operator will push a button indicating this activity. Table 3 provides a summary of all equipment with commission dates and decommission dates (Burger 2014). Only the decommission dates of the Titon DI 600 drills were available.

Table 3 Summary of asset ages and decommission dates

Equip Code	ASSET DESCRIPTION	Commission date	Decommission date
DT90010	Dump Truck,789C(DT90010)	Apr-09	Still in operation
DT90011	Dump Truck,789C(DT90011)	Apr-09	Still in operation
DT90020	Dump Truck,789C(DT90020)	Aug-09	Still in operation
DT90021	Dump Truck,789C(DT90021)	Aug-09	Still in operation
FE90010	Front End Loader(FE90010)	Dec-08	Still in operation
DL90006	DI600 RC Drill Rig(DL90006)	Jun-09	Aug-12
DL90010	DI600 RC Drill Rig(DL90010)	Dec-09	Sep-12
DL90007	DI600 RC Drill Rig(DL90007)	Jun-09	Nov-12
DL90008	DI600 RC Drill Rig(DL90008)	Jun-09	Nov-12
DL90001	Pitviper,Drill Rig 271,DL90001	Jan-08	Still in operation
DL90002	Pitviper,Drill Rig 271,DL90002	Jan-08	Still in operation
DL90003	Pitviper,Drill Rig 271,DL90003	Apr-08	Still in operation
DT90004	Dump Truck,789C(DT90004)	Oct-07	Still in operation
DT90005	Dump Truck,789C(DT90005)	Nov-07	Still in operation
DT90006	Dump Truck,789C(DT90006)	Nov-07	Still in operation
DT90007	Dump Truck,789C(DT90007)	Sep-08	Still in operation
DT90008	Dump Truck,789C(DT90008)	Mar-09	Still in operation
DT90009	Dump Truck,789C(DT90009)	May-09	Still in operation
DT90015	Dump Truck,789C(DT90015)	Sep-09	Still in operation
DT90022	Dump Truck,789C(DT90022)	Aug-09	Still in operation
FE90003	Front End Loader(FE90003)	Oct-07	Still in operation
FE90005	Front End Loader(FE90005)	Apr-08	Still in operation
FE90012	Front End Loader 994F(FE90012)	Sep-09	Still in operation

4.3 Obtain Raw Data

Step 2 of the methodology is obtaining appropriate data for this study.

4.3.1 Time delay structure

The MineStar system described in Section 2.9.2 ensures the collection of operational data for each piece of machinery. A time delay structure is required in order to understand how time data was populated in the database and this is described below:

- **Total time:** Total quantity of time per shift or per specific period;
- **Available time:** Total quantity of time the equipment is available for work;
- **Utilised time:** Quantity of operating time performing work;
- **Delay time:** Quantity of time that the equipment experienced delays from performing work;
- **Standby time:** Deliberate or unplanned quantity of time lost; and
- **Downtime**: Quantity of lost production time
    - **Planned Maintenance:** Quantity of time spent performing planned maintenance activities
    - **Unplanned Maintenance:** Quantity of time spent performing breakdown maintenance

A graphical outline of the above time delay structure is represented in Table 4. Each category of time has the corresponding database reference point i.e. Total time is represented by BKMTOTALTIME.

Table 4 Time delay structure (Burger 2014)

Equipment	Total time -BKMTOTALTIME				
	Available time -Available Time			**Downtime** - Sum of planned and unplanned shutdowns	
	Utilised time (Operating time) - Utilised time	**Delay Time** -BKMPLANNEDLOSTOPERTIME -BKMNONOPERATINGDELAYTIME -BKMOPERATINGDELAYTIME	**Standby Time** -BKMSTANDBYTIME	**Planned Maintenance** -BKMPLANNEDMAINTENANCETIME	**Unplanned Maintenance** - BKMUNPLANNEDMAINTENANCETIME
Trucks	Travel full at source Dumping Travel full	Blasting Change operator Crusher Delay Mid shift Break Operator Break Pre-start check Refueling Shift Change	Accident/emergenecy Cleaning Dust No material No operator Not required S/By after Workshop Supervision/Support Training Weather	Daily check Planned GET/Bowl Planned Service Planned Tyres/Tracks Wash before maintenance	Accident damage Breakdown Down GET/Bowl Down Tyres/Tracks
Loaders	LHD Loading	Blasting Change operator Crusher delay Mid-shift Break Operator break Pre-start check Refueling Shift change	Accident/emergency Cleaning Dust No material No operator No truck available Not required S/By after workshop Training Weather	Daily check Planned GET/Bowl Planned Service Planned Tyres/Tracks Wash before maintenance	Accident damage Breakdown Down GET/Bowl Down Tyres/Tracks
Drills	Drill	Blasting Change operator Filling water GET Sandvik Mid shift break Operator break Pre-start check refuliing Rod stuck Shift Change	Accident/emergency Cleaning Dust No operator No pattern No sample Not required S/by after workshop Supervision/Support Training Weather	Daily check Planned service Planned Tyres/tracks Wash before maintenance	Accident damage Breakdown Down GET/Bowl Down Tyres/Tracks

4.3.2 Database structure

The data provided to the author was extracted from the Minestar System. The machine operators log the activity manually on a digital panel within each piece of equipment. The data was obtained for the following production processes: Drill and blast, load and haul. The processing plant's data was not obtained as it does not form part of this investigation. The data is presented as a summation of the time related activities (see Appendix B for an example of the extract). The data is grouped into the following categories:

- PRIMARYMACHINECATEGORYNAME;
- CYCLEOID;
- CALENDARSHIFTSTARTTIME;
- STARTTIME;
- BKMPLANNEDMAINTENANCETIME;
- BKMUNPLANNEDMAINTENANCETIME;
- BKMTOTALTIME;
- BKMSTANDBYTIME;
- BKMPLANNEDLOSTOPERTIME;
- BKMNONOPERATINGDELAYTIME;
- BKMOPERATINGDELAYTIME;
- Available Time;
- Utilised Time;
- Payload;
- Hours to failure;
- Planned Shutdown; and
- Unplanned Shutdown

4.3.3 Data preparation

The data was sorted and grouped into a table using a pivot table in Excel 2010. The maintenance indicators calculated include:

- Sum of total time (BKMTOTALTIME);
- Sum of standby time (BKMSTANDBYTIME);
- Sum of planned maintenance time (BKMPLANNEDMAINTENANCETIME);
- Sum of unplanned maintenance time (BKMUNPLANNEDMAINTENANCETIME);
- Sum of planned lost operating time (BKMPLANNEDLOSTOPERTIME);
- Sum of non-operating delay time (BKMNONOPERATINGDELAYTIME);
- Sum of operating delay time (BKMOPERATINGDELAYTIME);
- Payload (Load and haul);
- Sum of available time (Available Time);
- Sum of utilised time (Utilised Time);
- Sum of unplanned shutdowns; and
- Sum of planned shutdowns

Tables 5 provides a summary for January 2011 of all performance indicators. Apart from the sum of planned/unplanned shutdowns, all values are in seconds:

Table 5 Summary of maintenance indicators for all equipment (January 2011)

PRIMARY MACHINE NAME	Sum of BKM TOTAL TIME	Sum of BKM STANDBY TIME	Sum of BKM PLANNED MAINTENANCE TIME	Sum of BKM UNPLANNED MAINTENANCE TIME	Sum of BKM PLANNED LOST OPER TIME	Sum of BKM NON OPERATING DELAY TIME	Sum of BKM OPERATING DELAY TIME	Sum of PAYLOAD	Sum of Available Time	Sum of Utilized Time	Sum of Unplanned Shutdown	Sum of Planned Shutdown
DL90001	2 147 881	-	51 977	358 784	219 211	806 502	99 895		1 737 120	611 512	22	3
DL90002	2 127 282	11 554	33 766	127 949	256 667	592 802	98 689		1 954 013	1 005 855	19	4
DL90003	2 251 516	-	50 190	508 628	198 059	515 521	128 447		1 692 698	850 671	40	4
DL90006	2 160 000	79 626	-	1 039 308	188 076	334 742	41 075		1 041 066	477 173	39	-
DL90007	2 160 000	33 800	15 256	395 653	255 917	586 852	73 510		1 715 291	799 012	30	2
DL90008	2 371 106	142 105	124 950	264 798	438 709	653 589	44 593		1 839 253	702 362	26	5
DL90010	2 148 479	59 228	168 304	511 897	171 664	449 668	84 458		1 409 050	703 260	41	10
Grand Total	**15 366 264**	**326 313**	**444 443**	**3 207 017**	**1 728 303**	**3 939 676**	**570 667**	**-**	**11 388 491**	**5 149 845**	**217**	**28**
FE90003	2 160 143	2 576	42 680	770 182	161 162	292 841	31 814	377 730	1 344 705	858 888	51	6
FE90005	2 160 087	4 064	51 063	302 778	219 985	363 813	53 985	239 938	1 802 182	1 164 399	28	16
FE90010	2 159 623	-	39 570	1 742 103	48 068	116 359	8 505	72 543	377 950	205 018	47	4
FE90012	2 166 162	2 325	66 695	503 575	182 379	329 451	47 071	352 599	1 593 567	1 034 666	77	7
Grand Total	**8 646 015**	**8 965**	**200 008**	**3 318 638**	**611 594**	**1 102 464**	**141 375**	**1 042 809**	**5 118 404**	**3 262 971**	**203**	**33**
DT90004	2 160 000	265 288	21 198	154 912	444 482	658 127	32	57 066	1 718 602	615 961	11	2
DT90005	2 159 047	330 850	9 603	153 852	372 210	604 153	-	56 923	1 664 742	688 379	10	2
DT90006	2 158 659	178 181	51 918	91 841	303 228	407 627	-	90 813	1 836 719	1 125 864	9	4
DT90007	2 160 000	171 702	7 493	30 710	262 028	459 810	-	97 407	1 950 095	1 228 257	6	2
DT90008	2 157 578	211 135	30 170	116 262	221 374	530 332	332	87 688	1 800 011	1 047 973	14	1
DT90009	2 160 000	144 559	29 883	542 459	149 403	458 150	-	67 388	1 443 099	835 546	19	4
DT90010	2 158 757	259 726	26 453	48 198	238 622	338 960	-	104 204	1 824 380	1 246 798	6	3
DT90011	2 160 000	243 505	47 209	439 769	188 241	531 640	-	58 792	1 429 517	709 636	23	3
DT90015	2 160 000	197 158	2 261	6 030	275 028	478 252	-	106 727	1 954 551	1 201 271	3	3
DT90020	2 157 180	603 098	3 268	18 741	233 273	474 227	-	68 833	1 532 073	824 573	5	1
DT90021	2 160 000	232 694	32 882	727 741	266 847	330 017	-	46 059	1 166 683	569 819	29	3
DT90022	2 419 081	310 568	48 904	22 032	242 168	401 881	-	111 974	2 037 577	1 393 528	12	7
Grand Total	**26 170 302**	**3 148 464**	**311 242**	**2 352 547**	**3 196 904**	**5 673 176**	**364**	**953 872**	**20 358 049**	**11 487 605**	**147**	**35**

4.3.4 Example calculations

The January 2011 data as discussed in Section 4.3.3. is populated in Table 5 and the calculated maintenance and reliability indicators based on formula presented in Section 2.8 are presented below for demonstrative purposes for the drilling fleet. The complete sets of maintenance and reliability indicators calculated for the 6-month period for all equipment are in Appendices C-G. The following performance metrics as calculated per piece of equipment:

- Failure rate;
- MTBF;
- MTTR Total;
- MTTR (Planned Maintenance);
- MTTR (Unplanned Maintenance);
- Availability; and
- Utilisation.

Equation (3) to calculate Failure Rate:

Failure Rate = Number of Failures / Utilised Time

Where:
Unplanned shutdowns: = 217
Sum of utilised time: = 5 149 845 seconds

Therefore:
Sum of Utilised time in hours = 5 149 845 / 3600
= 1431.51 hours

Failure Rate = 217 / 1431.51
= 0.152 failures per hour of utilised time

Equation (4) to calculate MTBF:

MTBF = 1 / Failure Rate

Where:
Failure Rate: = 0.152

Therefore:
MTBF = 1 / 0.152
= 6.59 hours

Equation (5) to calculate MTTR Total:

MTTR Total = (Unplanned Maintenance Time + Planned Maintenance Time) / (Number of Unplanned Maintenance Actions + Planned Maintenance Actions)

Where:
Sum of Unplanned Maintenance Time: = 3 207 017 seconds
Sum of Planned Maintenance Time: = 444 443 seconds
Sum of Unplanned Maintenance Actions: = 217
Sum of Planned Maintenance Actions: = 28

Therefore:
MTTR Total = ((3651460/3600)/245
= 1014/245
= 4.14 hours

Equation (7) to calculate MTTR Planned Maintenance Time:

MTTR Planned Maintenance Time = ((Planned Maintenance Time) / 3600) / (Number of Planned Maintenance Actions)

Where:
Sum of Planned Maintenance Time: = 444 443 seconds
Sum of Planned Maintenance Actions: = 28

Therefore:
MTTR Planned Maintenance = ((444 443/3600)/28
= 123/28
= 4.41 hours

Equation (6) to calculate MTTR Unplanned Maintenance Time:

MTTR Unplanned Maintenance Time = ((Unplanned Maintenance Time) / 3600) / (Number of Unplanned Maintenance Actions)

Where:
Sum of Unplanned Maintenance Time: = 3 207 017 seconds
Sum of Unplanned Maintenance Actions: = 217

Therefore:
MTTR Unplanned Maintenance = (3 207 017 / 3600) / 217
= 890/217
= 4.11 hours

Equation (1) to calculate Availability:

Availability = (Available Time / Total Time) x 100%

Where:
Available Time: = 11 388 491 seconds
Total Time: = 15 366 264 seconds

Therefore:
Availability = (11 388 491 / 15 366 264) x 100%
= 74%

Equation (2) to calculate Utilisation:

Utilisation = (Utilised Time / Available Time) x 100%

Where:
Utilised Time : = 5 149 845 seconds
Available Time: = 11 388 495 seconds

Therefore:
Utilisation = (5 149 845 / 11 388 495) x 100%
= 45%

The 6-month summaries for all equipment are in Appendices C-G

4.4 The Simulation model and Input data

The software chosen for this experiment is Simul8 version 20. The software was chosen for its suitability when dealing with a process example such as the one found in open cast mining.

4.4.1 Design

Phase 1 - Problem formulation and definition:

A subsidiary goal of this investigation was to design a simulation which represents as closely as possible the actual operations at Iron Ore Futures for the period under consideration. The purpose was to run different scenarios to determine what the effects would be of manipulating planned and unplanned maintenance

Phase 2 - Define the boundaries

The boundary of the simulation is limited to the drilling, loading and hauling activities of the mining operation. The layout is visually presented in Appendix H.

Phase 3 - Input data requirements

The MTBF and MTTR input variables were calculated in Section 3.3.2 and have been summarised in Table 6. There are other data requirements and these are equipment specific and relate to the shift patterns and operating time of the mine, the drilling, load and hauling benchmarks and are summarised in Table 7. The MTBF and MTTR values were input for each piece of machinery. This is performed through the "Efficiency" functionality in Simul8. These input windows in Simul8 are represented in Figure's 7 and 8 for MTBF and MTTR respectively. The results/output of the model are displayed in percentages and are in four key categories; waiting (idle time), working (utilisation), stopped (breakdown time) and maintenance (scheduled planned maintenance time). Figure 9 serves as an example.

Table 6 MTBF and MTTR values for the period 1 January to 30 June 2011

Equipment	**MTBF**	**MTTR Unplanned**
	Mean (Hours)	
DL90001	5,58	2,95
DL90002	13,91	1,50
DL90003	7,10	3,21
DL90006	5,90	6,65
DL90007	6,18	6,88
DL90008	7,24	4,36
DL90010	5,28	5,49
Total	**6,89**	**4,61**
DT90004	19,34	3,44
DT90005	24,61	2,74
DT90006	22,37	3,64
DT90007	13,81	6,90
DT90008	19,87	3,36
DT90009	9,08	6,71
DT90010	17,47	4,57
DT90011	23,26	3,48
DT90015	33,69	2,08
DT90020	28,64	1,36
DT90021	19,50	3,37
DT90022	29,34	3,20
Total	**20,26**	**4,10**
FE90003	4,86	4,96
FE90005	9,51	2,62
FE90010	5,72	5,00
FE90012	5,31	2,84
Total	**6,10**	**3,85**

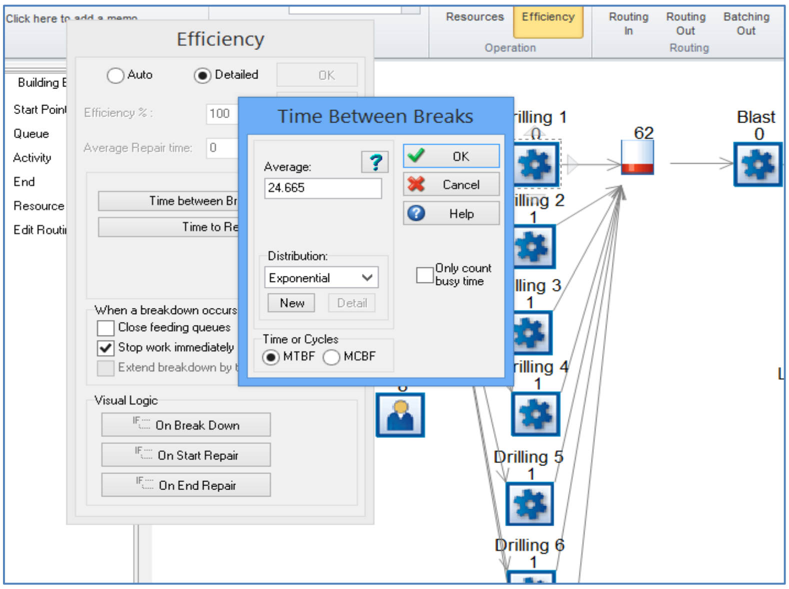


Figure 7 MTBF input variables

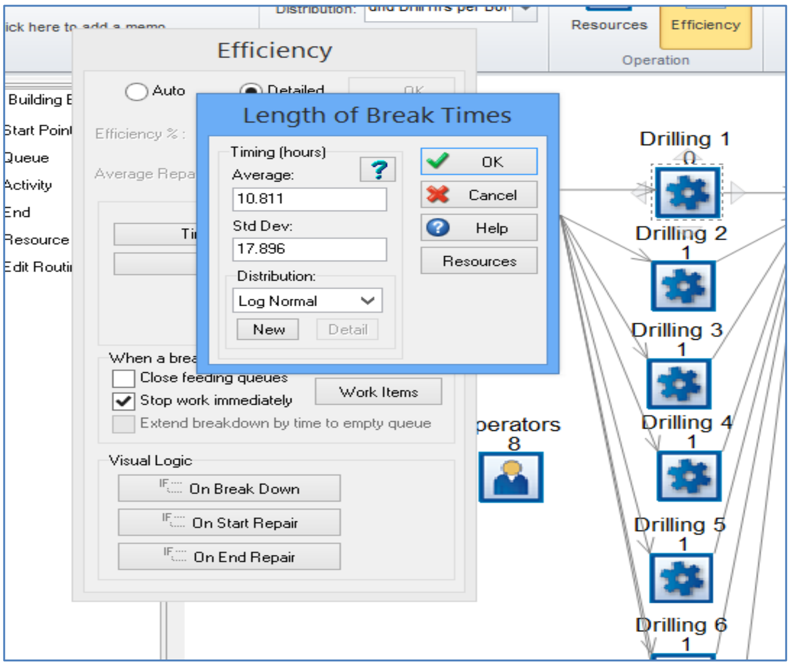


Figure 8 MTTR input variables

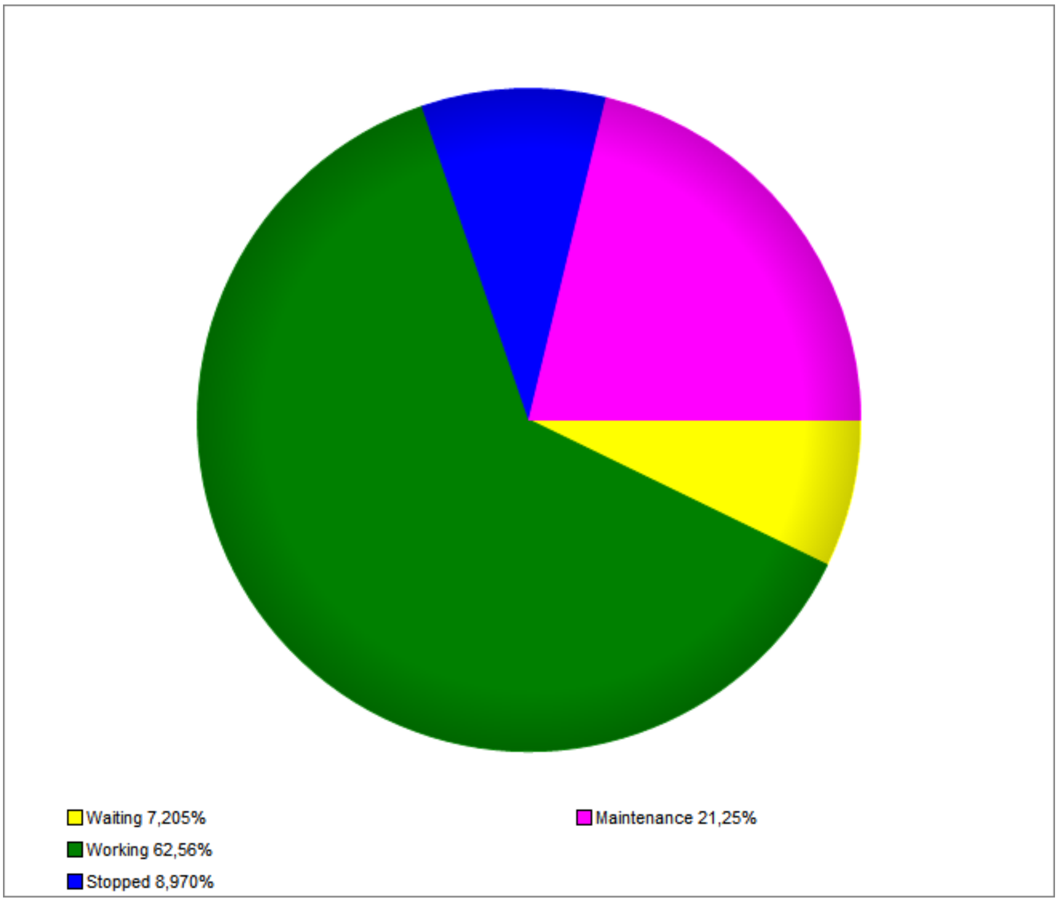


Figure 9 Example of Simulation Output

Table 7 Simulation parameters and setup

Step	Element	Description	Parameters	Reference
Setup	Shift	Each shift is 11 hours	2 per day Each shift is 11 hours	Burger 2014
	Drilling	7 Drills	Metres per hour = 80.05 Metres per hole = 11 Holes per hour = 7.28 Holes per block = 200 Block per hour = 0.04 Hours per hole = 0.317 Tonnes per block = 100 000	
	Loading	4 Loaders	Tonnes per loader/hour = 1100 Hours per tonne per loader = 0.000909 Appendix K	
	Hauling	12 Trucks	Tonnes per truck/hour = 315 Hours per tonne per truck = 0.003175 Appendix K	
	Model	Runtime	4406 Hours = BKMTOTALTIME 51 runs of simulation determined by Simul8 for adequate number runs per scenario	
1		Start point	Unlimited feed Each red ball in the simulation represents one hole to be drilled	
2		Start next drill session	Batching out function selected at 200 as this is the number of holes required per block	
3		Queue for drilling	The size of the queue is infinite	
4		7 drills are linked to the queue for drilling	Each drill is set to an "Average" of 0.317 Hours per hole MTTR/MTBF set as per Table 6 MTTR: Log Normal Distribution MTBF: Exponential Distribution Work stops immediately when failure occurs	
5		Queue for blast	Capacity of the queue is 200 indicating that once this point is reached a blast will take place	
6		Blast	Once 200 holes are drilled, a blast will release 100 000 tons of material	
7		Queue for loading	Infinite	
8		4 loaders are linked to the queue for loading	Each loader is set to "Average" of 0.000909 Hours per tonne MTTR/MTBF set as per Table 6 MTTR: Log Normal Distribution MTBF: Exponential Distribution Work stops immediately when failure occurs	
9		Queue for hauling	Infinite	
10		12 Haulers are linked to the queue for hauling	Each hauler is set to "Average" of 0.003175 Hours per tonne MTTR/MTBF set as per Table 6 MTTR: Log Normal Distribution MTBF: Exponential Distribution Work stops immediately when failure occurs	
11		Arrive at plant	Total material arrived at Processing plant	

4.5 Validate simulation output

An important component of the simulation is to ascertain whether the model in fact represents the real life-mining environment. Total mine output for the period under consideration is 8.43 MT

The validation of the model was considered from three points of view:

1) Total output of the validation run is 8.74 MT. The difference is 4% to actual production and this is deemed acceptable for the purposes and objective of this investigation.
2) As per the simulation input variables in Table 7, each drill operates at 11 metres per hour, and indicates that, based on utilised drilling time (working hours) of 16694 hours, 8.67 MT would be produced. This difference is only 3% and is deemed acceptable for the purposes and objectives of this investigation.
3) As per the table below, maintenance time (planned maintenance) at 922 hours is 8% and stopped time (unplanned maintenance) at 10794 hours is 92% of total maintenance time.

Table 8 Simulation output indicators for validation purposes

Validation	Waiting (Hours)	Working (Hours)	Stopped (Hours)	Maintenance (Hours)	Total (Hours)
7 Drills	2088	16694	10794	922	30498

4.6 Simulate scenarios

Through the process of running various scenarios in Simul8, it was possible to estimate how changes in planned and unplanned maintenance time affect tonnes produced. The following scenarios were constructed as experiments:

- **Scenarios 1-4:** Increasing planned maintenance time from the validated scenario of 922 hours and decreasing unplanned maintenance time of 10794 hours of the drilling fleet. The foundation for these simulation runs is based on the validation scenario laid out in Table 8. Planned maintenance time will be increased without reducing or increasing MTBF.
- **Scenario 5-13:** Increasing planned maintenance time of the drilling fleet whilst increasing MTBF. The foundation for these simulation runs is based on the validation scenario in Table 8. Scheduled maintenance time will be increased whilst increasing MTBF at intervals beginning at 5% as indicated in Table 10.

Table 9 Scenario descriptions

Scenario	**Description**				
	Planned Maintenance %	**Hours**	**Unplanned Maintenance %**	**Hours**	**MTBF Increase %**
Validation	8	922	92%	10794	-
1	16	1884	84	10040	-
2	31	3821	69	8514	-
3	57	7549	43	5619	-
4	80	11921	20	2920	-
5	8	886	92	10666	5
6	16	1868	84	9738	7,5
7	30	3609	70	8307	10
8	57	7246	43	5386	12,5
9	80	11438	20	2835	15
10	81	11371	19	2645	20
11	82	11269	18	2558	25
12	82	10643	18	2309	50
13	84	9834	16	1834	100

Table 10 MTBF indicators per scenario for the drilling fleet

Equipment	MTBF	MTTR Unplanned	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Scenario 11	Scenario 12	Scenario 13
	Mean (Hours)		5%	7,50%	10%	12,50%	15%	20%	25%	50%	100%
DL90001	5,58	2,95	5,86	6,00	6,14	6,28	6,42	6,70	6,98	8,37	11,16
DL90002	13,91	1,50	14,61	14,96	15,30	15,65	16,00	16,69	17,39	20,87	27,82
DL90003	7,10	3,21	7,45	7,63	7,81	7,98	8,16	8,51	8,87	10,64	14,19
DL90006	5,90	6,65	6,20	6,35	6,49	6,64	6,79	7,08	7,38	8,85	11,81
DL90007	6,18	6,88	6,49	6,64	6,80	6,95	7,11	7,42	7,72	9,27	12,36
DL90008	7,24	4,36	7,61	7,79	7,97	8,15	8,33	8,69	9,05	10,86	14,49
DL90010	5,28	5,49	5,54	5,67	5,80	5,94	6,07	6,33	6,60	7,91	10,55

Chapter 5 – Results

There are three sections within the results:

1) The maintenance and reliability indicators;
2) The pareto analysis; and
3) The simulation model;

5.1 The maintenance and reliability indicators

5.1.1 Drilling Equipment

The highest number of failures experienced for the drilling fleet was in April at 319 and the lowest in January at 217. This is graphically presented for the two different types of equipment in Figure 10. The linear trend line is the line of best fit and is used to determine if there is a pattern in the data and for indicative purposes the number of failures in on an increasing trend. The Pitviper drills experience a higher MTBF in Figure 11 of 8.15 hours in comparison to the Titon at 6.05 hours and the trends indicate consistency even though there are monthly variations. In Figure 12, MTTR Total suggests that total maintenance time for the Titon drills is on an increasing trend and above the upper limit of 6 hours whilst the Pitviper is relatively more constant and below the lower limit line. This may indicate that the drills are taking longer to repair each time there is a failure but also taking longer to perform planned maintenance activities. Out of the total maintenance time, 92% was allocated to unplanned and only 8% was allocated to planned maintenance activities. Planned and unplanned maintenance for the Pitvipers appears to be more constant and no significant increases and decreases are apparent whilst the opposite can be said for the Titons. Planned maintenance repair time is on a downward trend and unplanned is on an upward trend. This is likely to suggest that failures are requiring longer repair time and less time is being spent performing planned maintenance. In terms of availability in Figure 15 the Titon drills are indicating a downward trend in availability whilst the Pitvipers have relatively higher availability which is more constant without abnormal monthly fluctuations. There are no conclusive deductions made regarding utilisation except for the fact that during March lower failures and higher reliability were experienced.

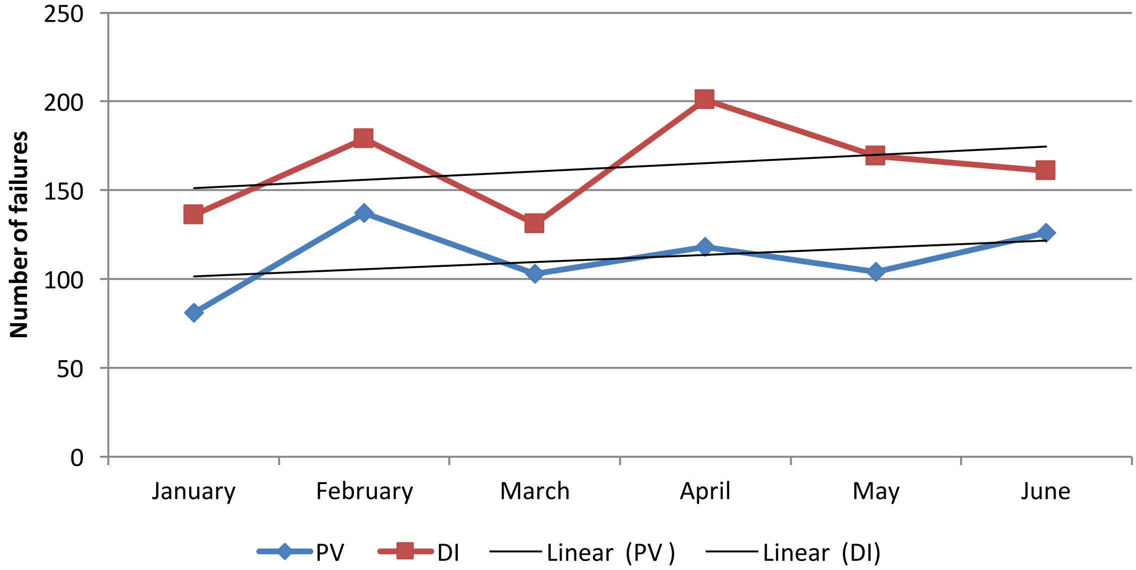


Figure 10 Failures (Drills)

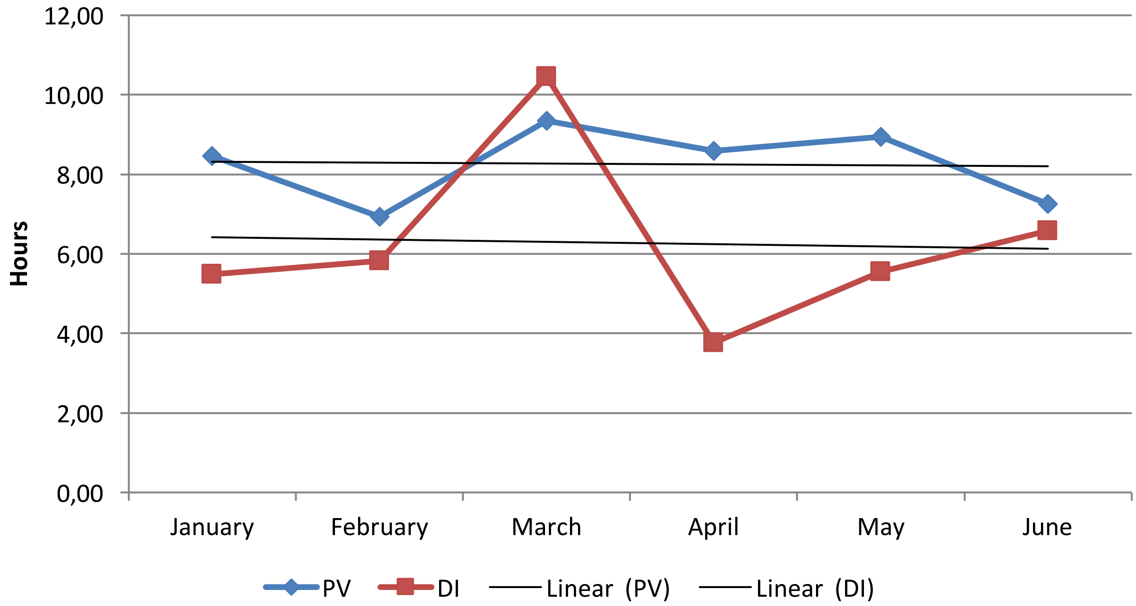


Figure 11 MTBF (Drills)

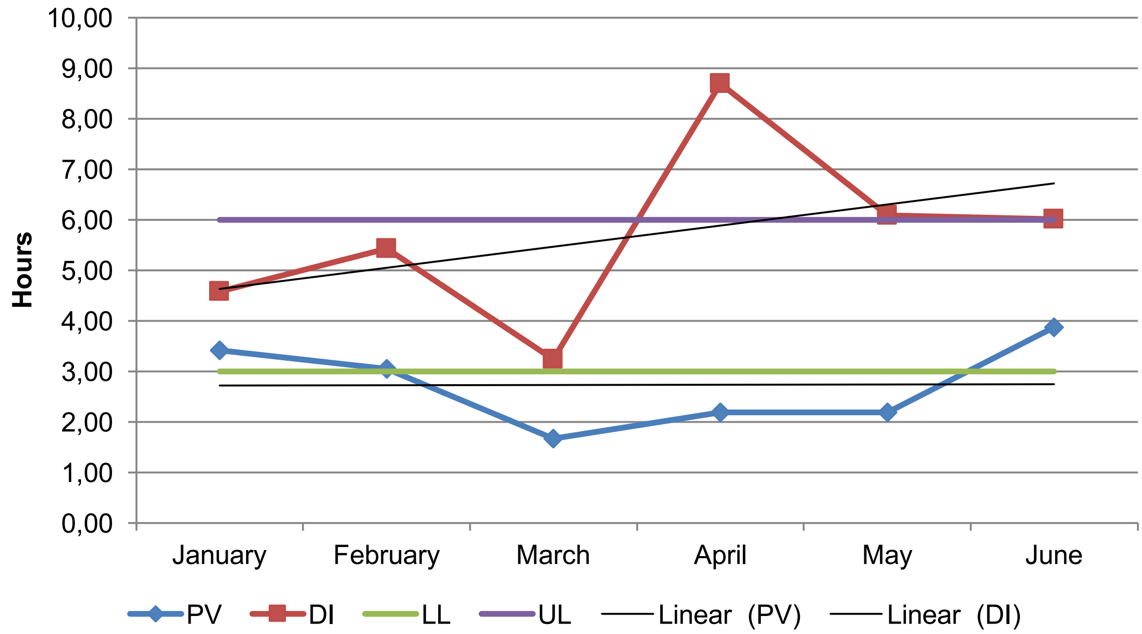


Figure 12 MTTR Total (Drills)

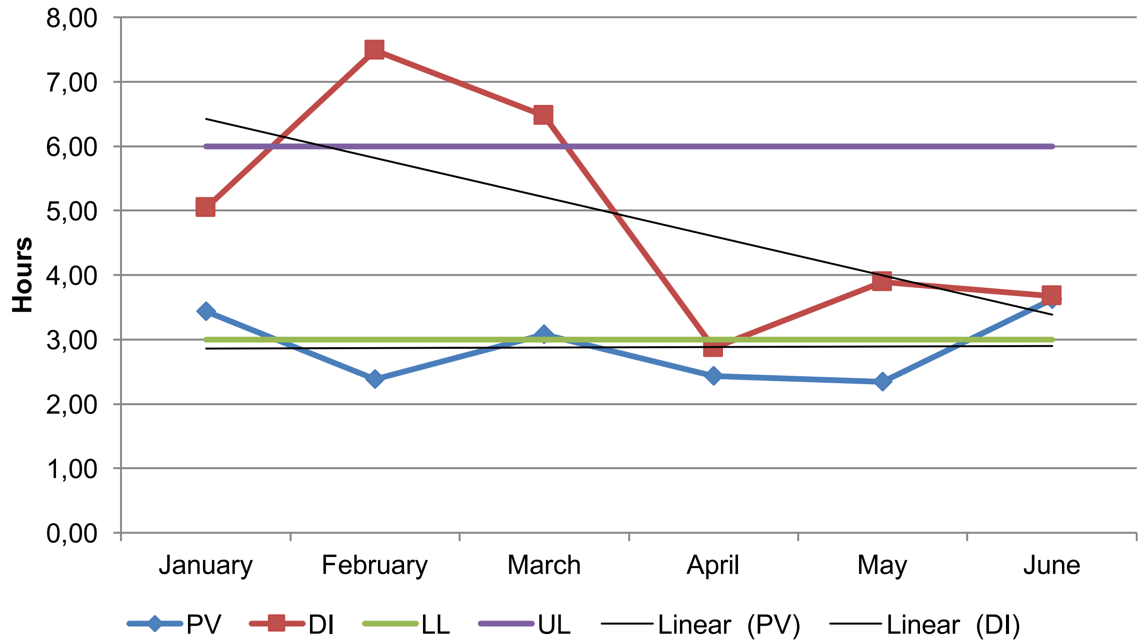


Figure 13 MTTR Planned maintenance (Drills)

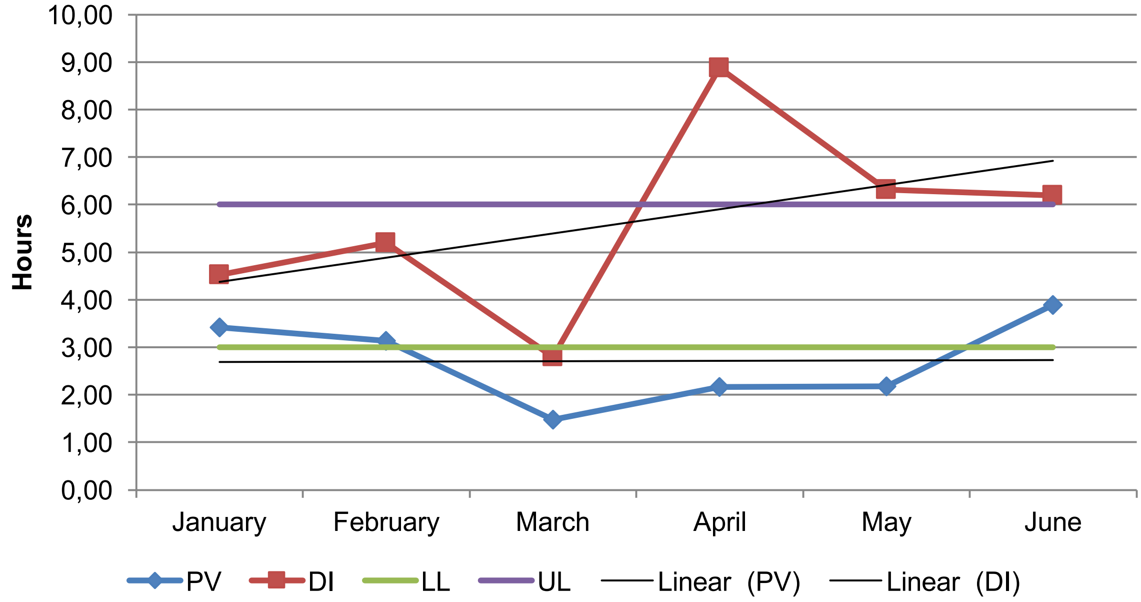


Figure 14 MTTR Unplanned maintenance (Drills)

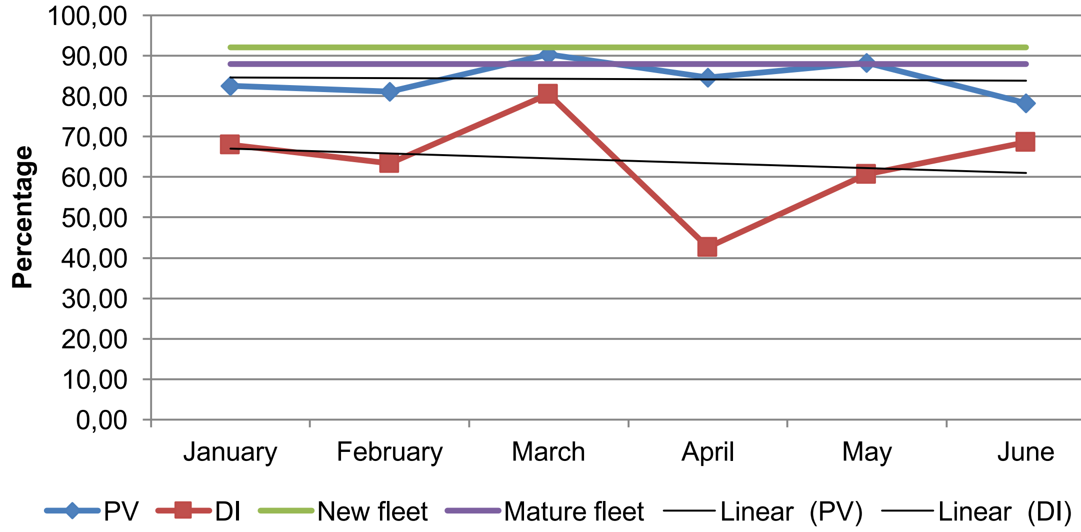


Figure 15 Availability (Drills)

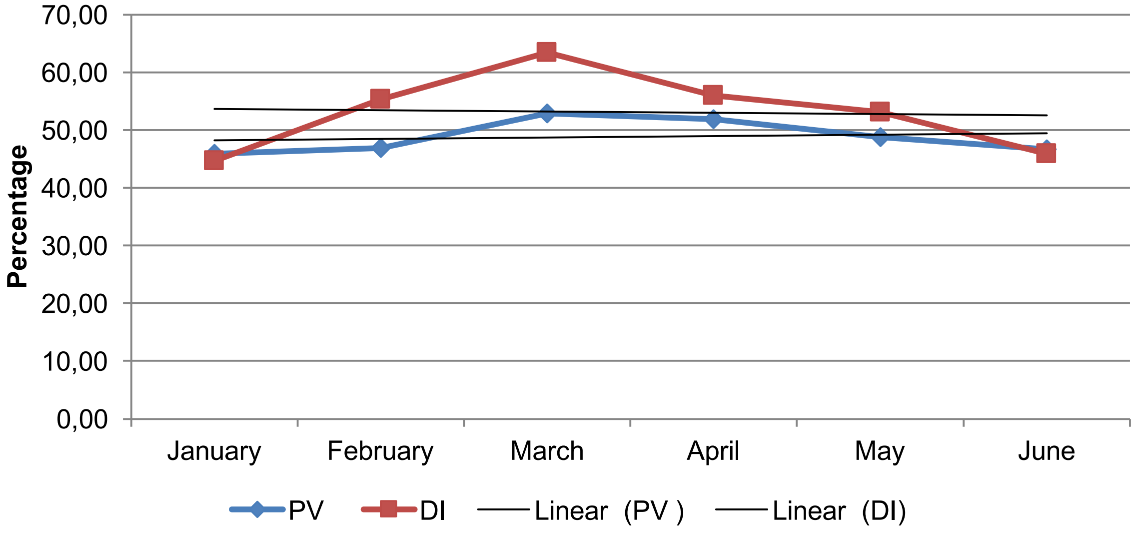


Figure 16 Utilisation (Drills)

5.1.2 Loading and hauling equipment

The highest number of failures experienced was in February at 326 and June for the loaders and haulers respectively. This has been graphically represented in Figure 17. In terms of MTBF in Figure 18, the trends are suggesting the loaders are becoming more reliable with increased gaps between failures whilst the haulers are becoming less reliable. Total MTTR is constant, whilst MTTR planned maintenance time for the haulers is on an increasing trend and the opposite is experienced for the loaders. The converse relationship is evident for MTTR unplanned maintenance. Availability of the haulers is decreasing slightly and this correlates to the increase in failures per month whilst the loaders are experiencing increased availability. Utilisation of both the haulers and loaders is gradually increasing.

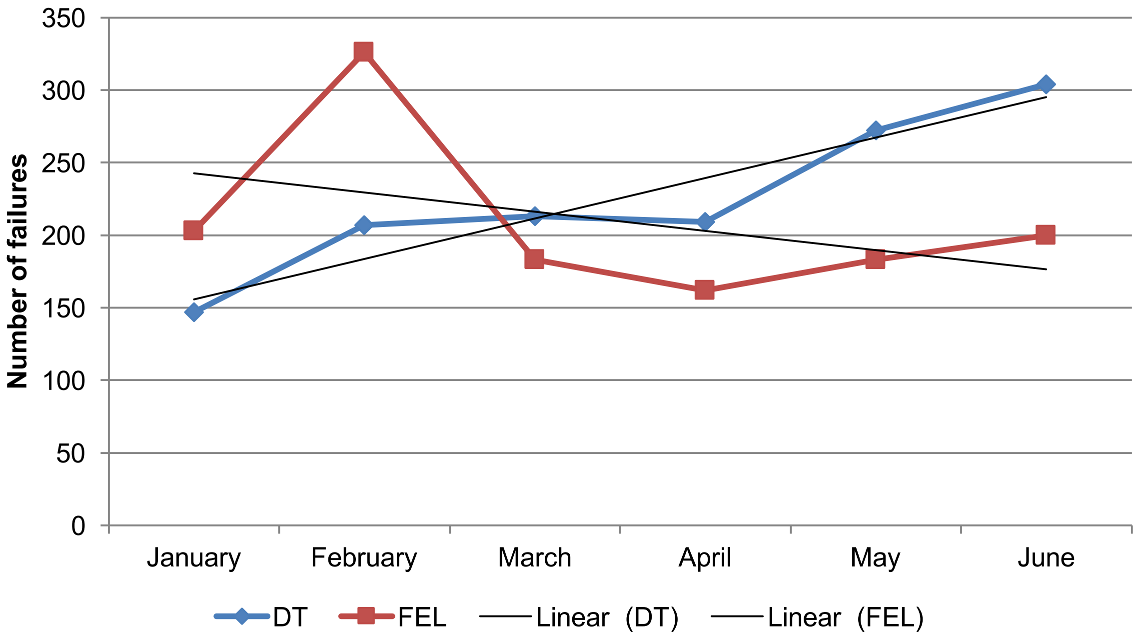


Figure 17 Failures (Loaders and haulers)

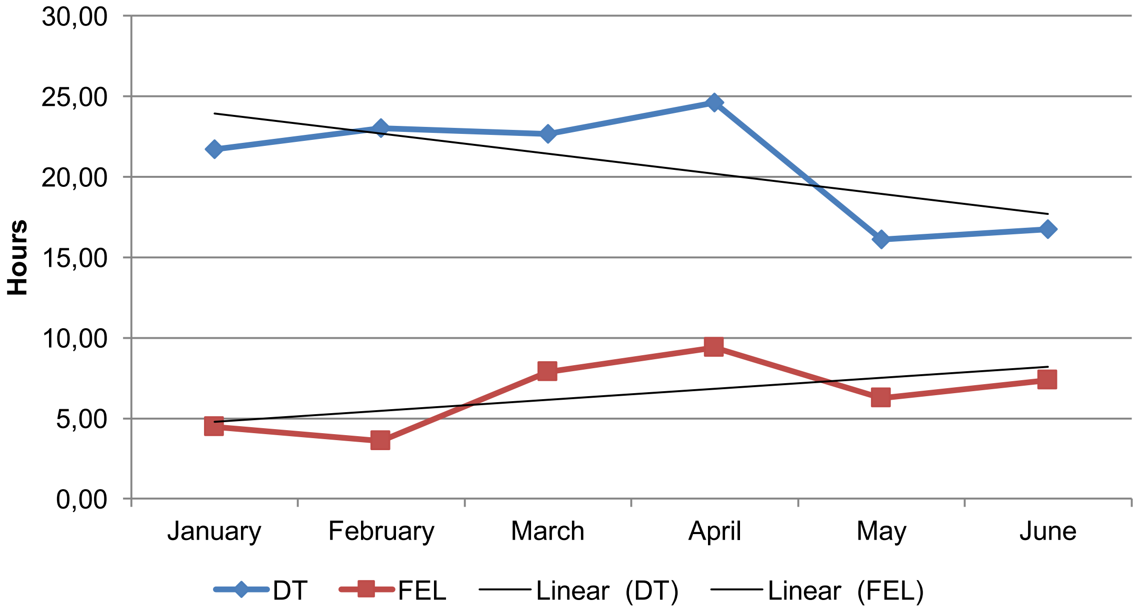


Figure 18 MTBF (Loaders and haulers)

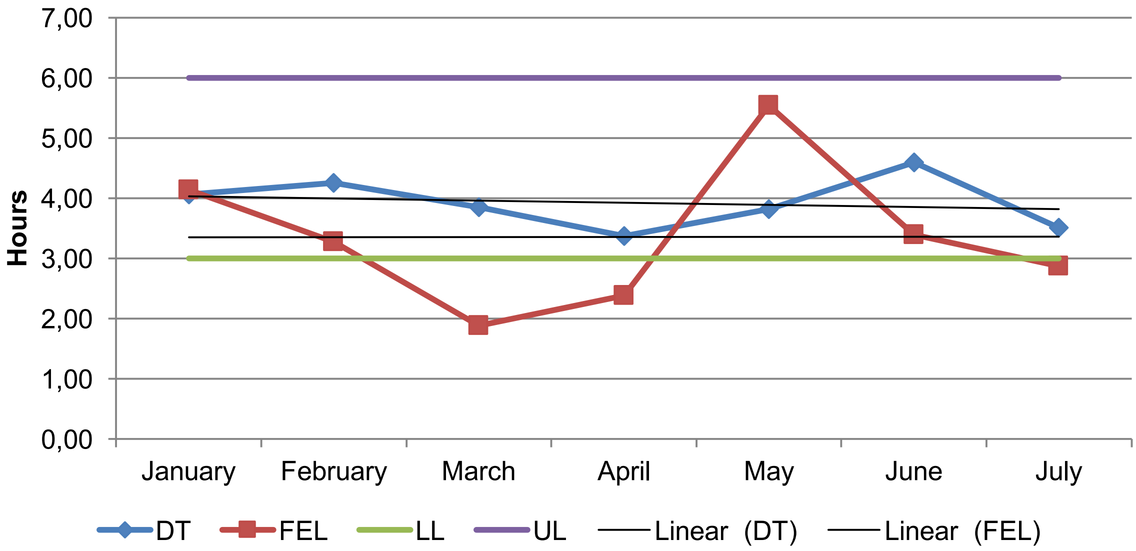


Figure 19 MTTR (Loaders and haulers)

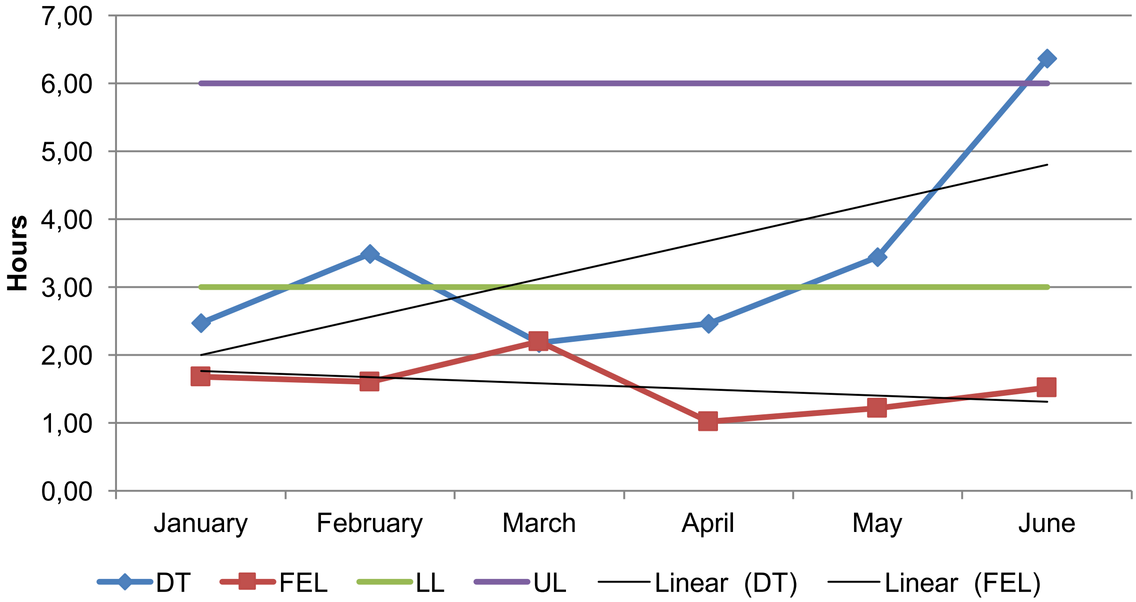


Figure 20 MTTR Planned maintenance (Loaders and haulers)

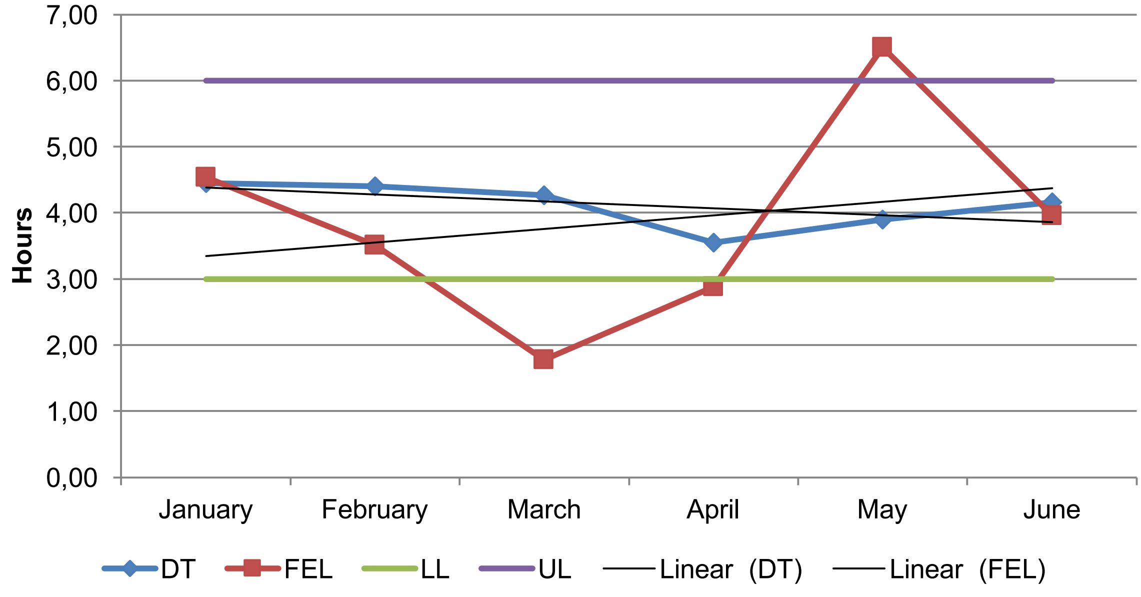


Figure 21 MTTR Unplanned maintenance (Loaders and haulers)

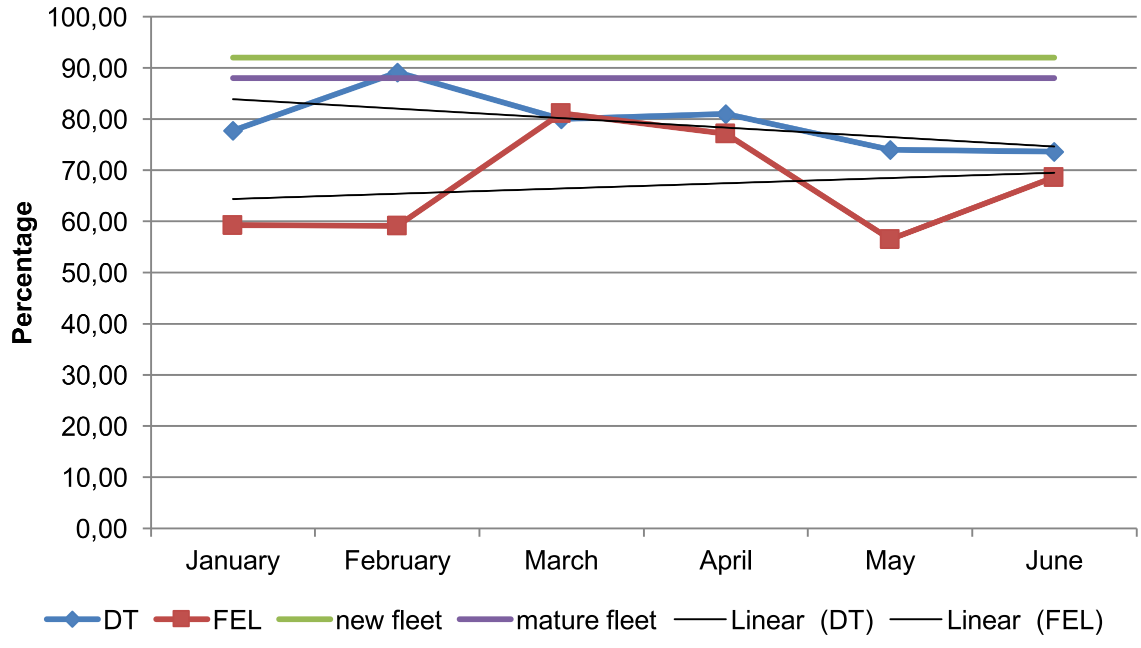


Figure 22 Availability (Loaders and haulers)

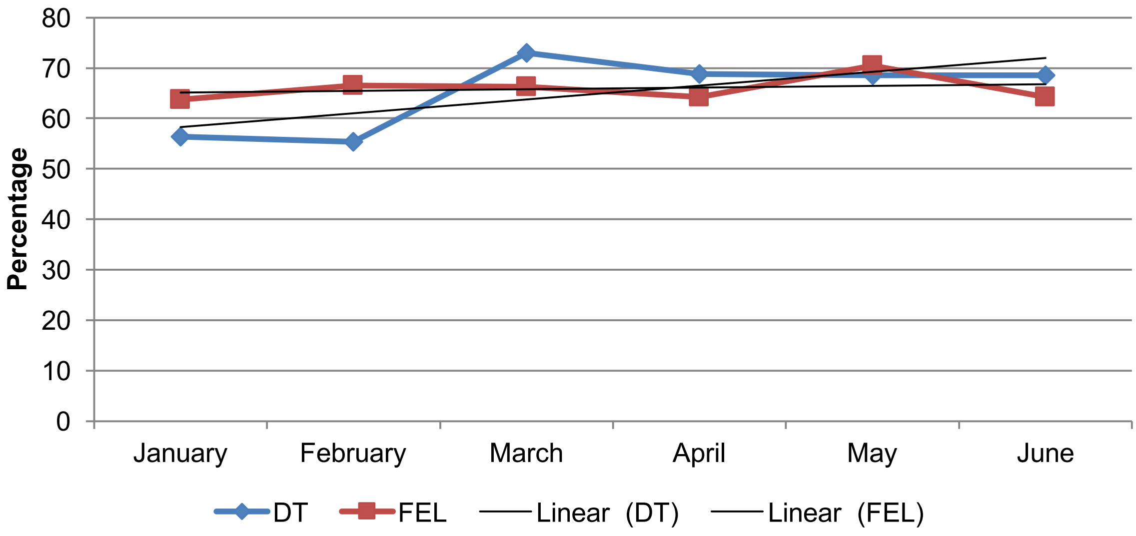


Figure 23 Utilisation (Loaders and haulers)

5.1.3 Result Summary

Table 11 Summary of the results

	MTBF	MTTR	Availability	Utilisation
Drills	6,9	4,57	72%	51%
Pitviper	8,15	3,59	84%	49%
Titon	6,05	5,84	63%	53%
Loaders	6,1	3,41	67%	66%
Haulers	20,27	4,03	79%	65%

The summary of the results in Table 10 indicates there are potential problems associated with the MTBF and the MTTR indicators, which is having an impact on the availability of the equipment. Table 10 indicates that planned maintenance is between 8% and 17% of total maintenance time and unplanned maintenance is between 83% and 92% of total maintenance time. MTTR and MTBF will influence the availability of the equipment.

Table 12 Summary of maintenance indicators for the drills

Indicator	**Benchmark Indicator**	**Mine Actual**
Availability		
Drills	90%	72%
Loaders	90%	67%
Haulers	90%	79%
Utilisation		
Drills	80%	51%
Loaders	80%	66%
Haulers	80%	65%
Unplanned Maintenance		
Drills	10%	92%
Loaders	10%	91%
Haulers	10%	83%
Planned Maintenance		
Drills	90%	8%
Loaders	90%	9%
Haulers	90%	17%

The percentages for unplanned and planned maintenance are benchmark percentages for the amount of time that should be allocated to those maintenance activities as discussed in Table 2 in section 2.9.3.

5.2 Pareto Analysis

A pareto analysis as indicated in the three figures that follow has been used to identify the top issues or failure types which have been causing the low level of reliability experienced by the drills, loaders and haulers. The failure code on the x-axis corresponds to a specific failure. For example: EN equates to an engine related failure and a complete list of codes and corresponding failures is in Appendix I. The limitation of the data is evident at this point as the engine is a large system made up of many complicated components all working together and it is not possible to deduce which exact component is the cause of the failure. However, what this type of analysis does is direct management to the source of the problem.

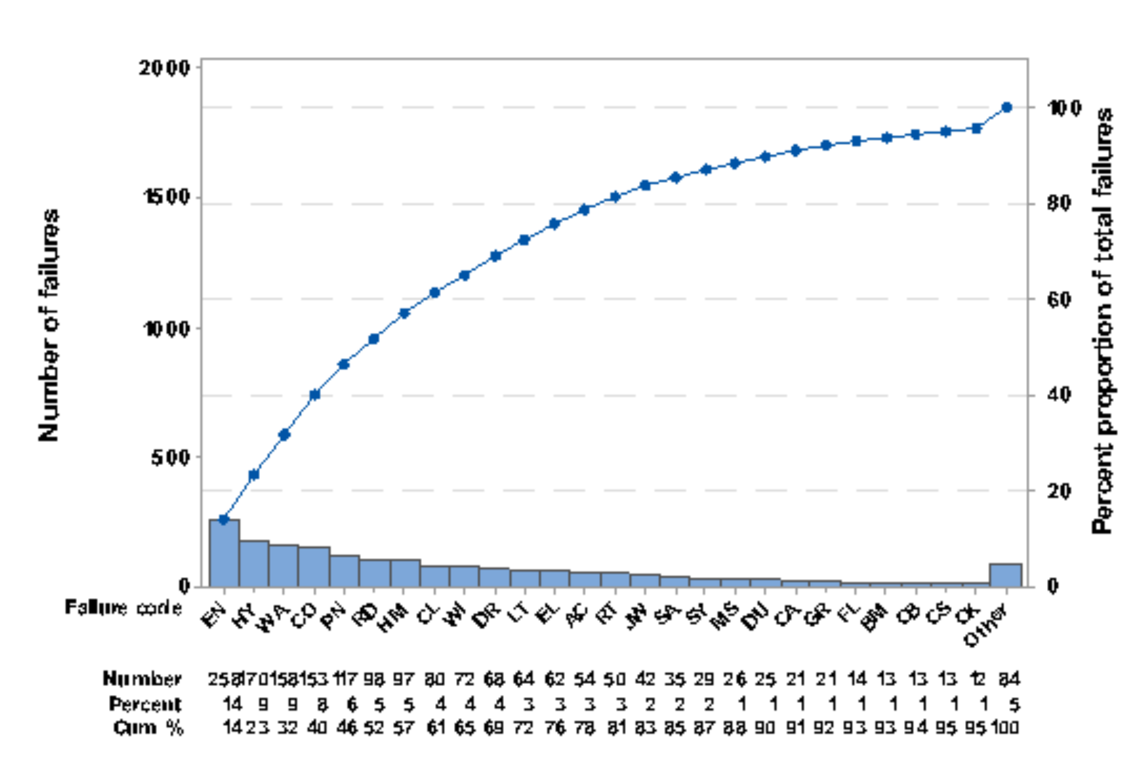


Figure 24 Pareto of drill failures

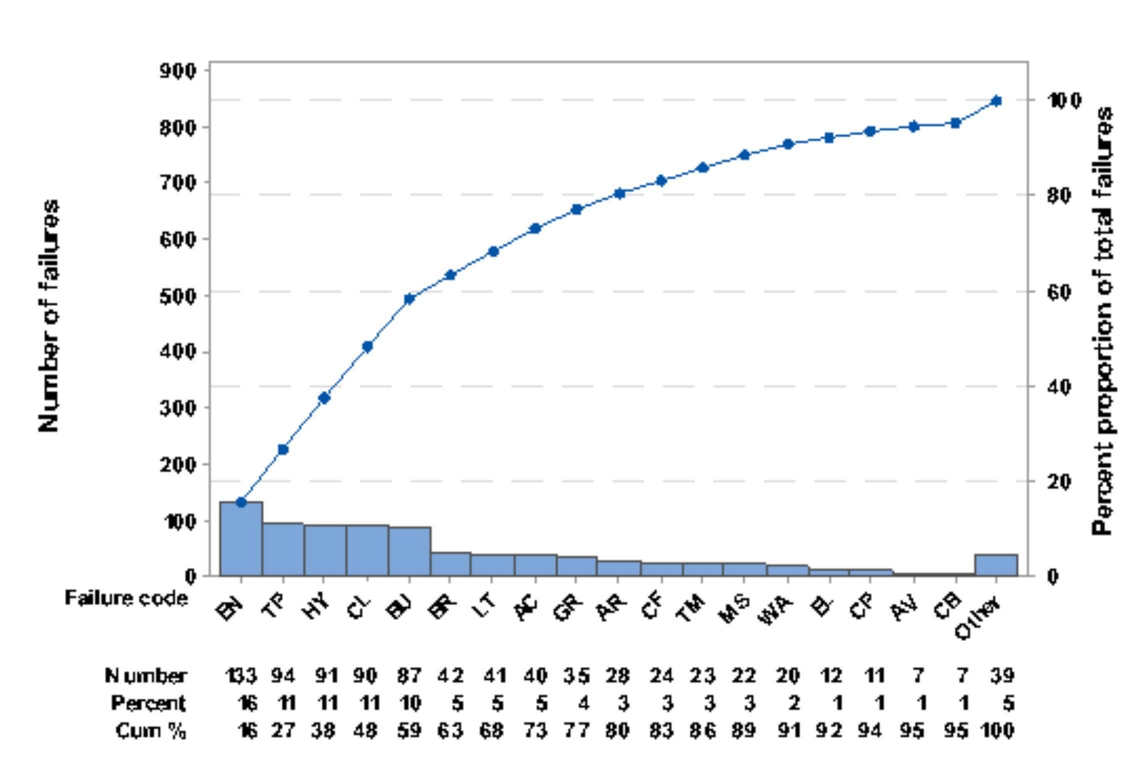


Figure 25 Pareto of loader failures

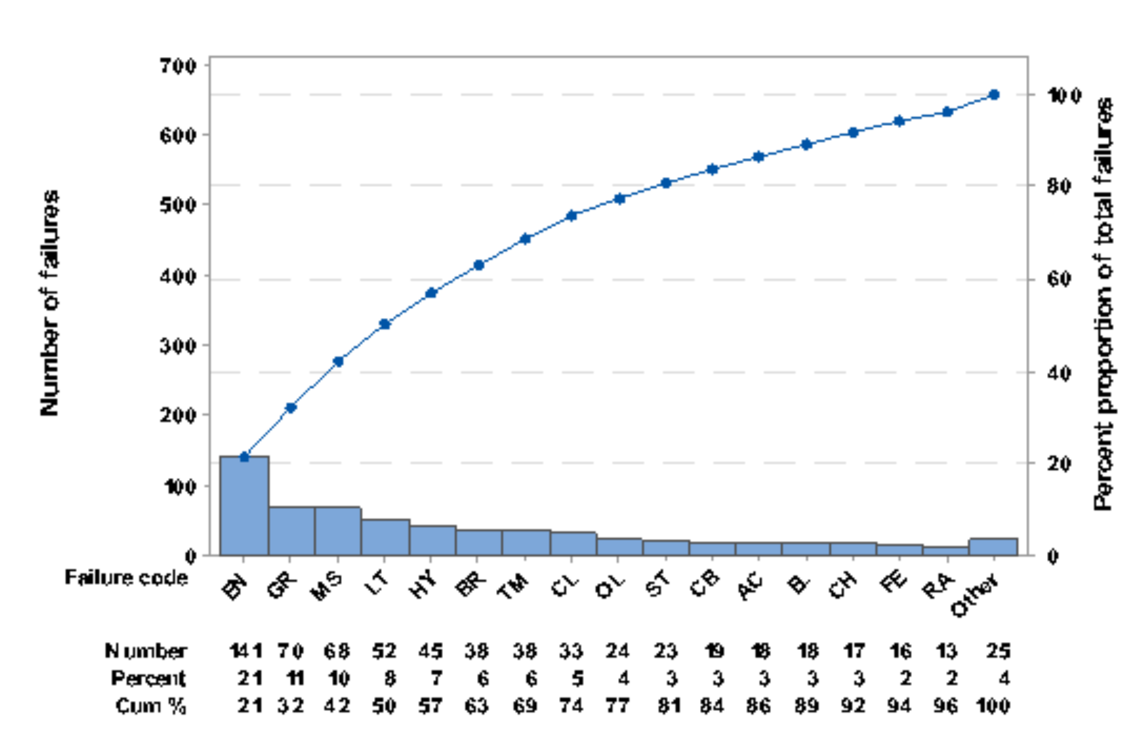


Figure 26 Pareto of hauling failures

5.3 The simulation model results

The starting point for the simulation is the validation scenario. This scenario was validated from various points and was discussed in Section 4.5. This validation scenario formed the bases for the scenario's simulated. As is evident in Figure 27, increasing planned or scheduled maintenance removes the machine from production and this is indicative of the downward trend of tons produced which is represented by the blue line. This suggests that through the process of increasing planned maintenance time there is less time available for the drills to work, therefore less drilling time and decreasing the number of holes drilled for blasting purposes. Additionally, in Figure 28, there is sufficient evidence to suggest that a converse relationship exists between planned and unplanned maintenance, in that with increasing planned maintenance activities there should be evidence to suggest that unplanned activities will decrease. Scenarios 1-4 have been applied to demonstrate the effect of increasing planned maintenance without having any influence on the reliability of the equipment.

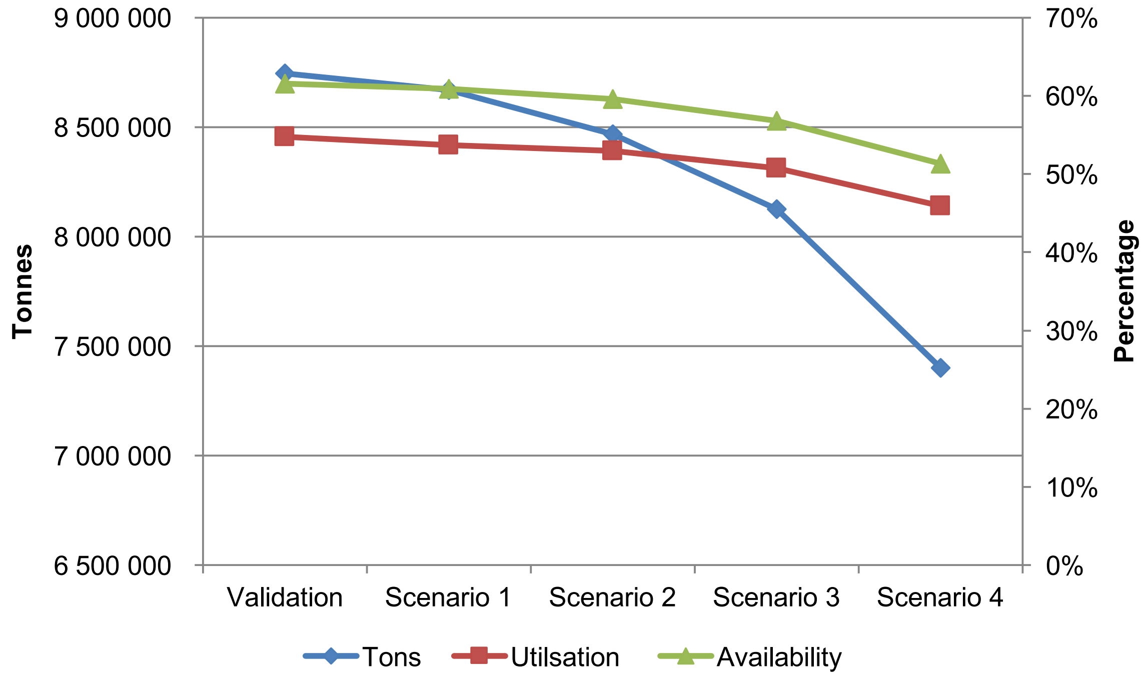


Figure 27 Tons, utilisation and availability: Validation run and scenario's 1-4

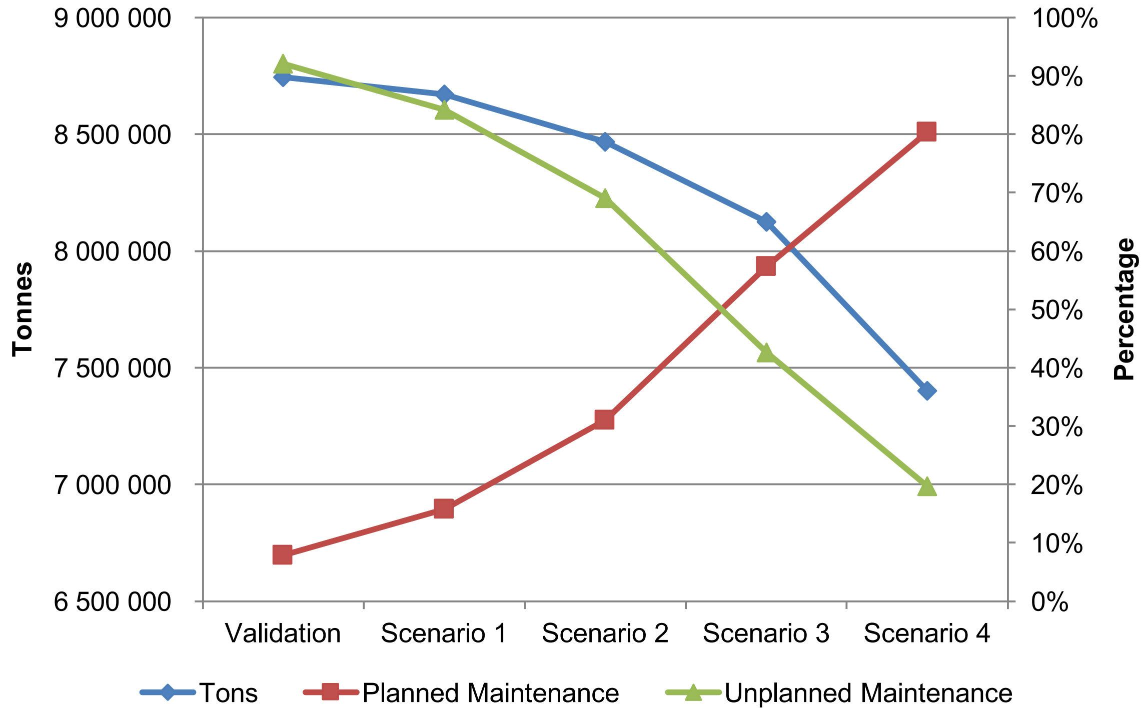


Figure 28 Tons, planned and unplanned maintenance: Validation run and scenario's 1-4

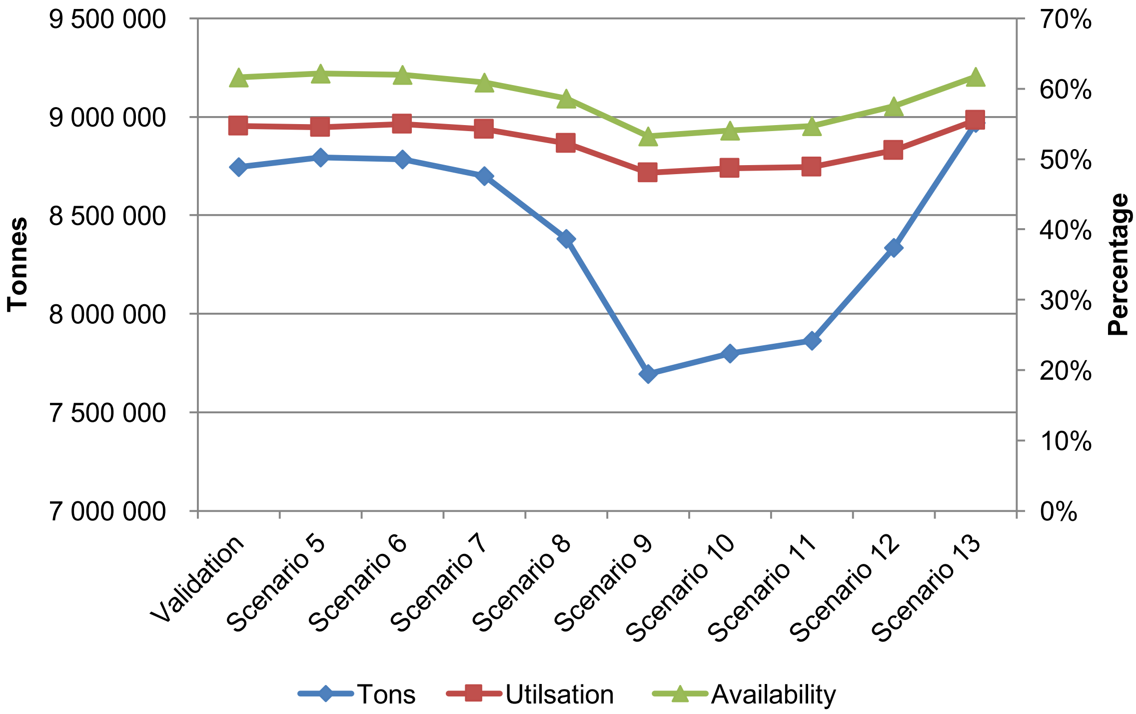


Figure 29 Tons, utilisation and availability: Validation run and scenario's 5-13

In Figure 29, the same validation starting point was applied. Increasing planned maintenance whilst increasing MTBF has been simulated concurrently. Initially it is evident that up to scenario 9 as MTBF has only been increased gradually, the increase in planned maintenance time is having little to no impact on production output. Only from scenario 10 does production increase whilst at the same time unplanned maintenance is decreasing towards an end objective of 10% total maintenance time, thus indicating that planned maintenance is increasing the reliability of the equipment.

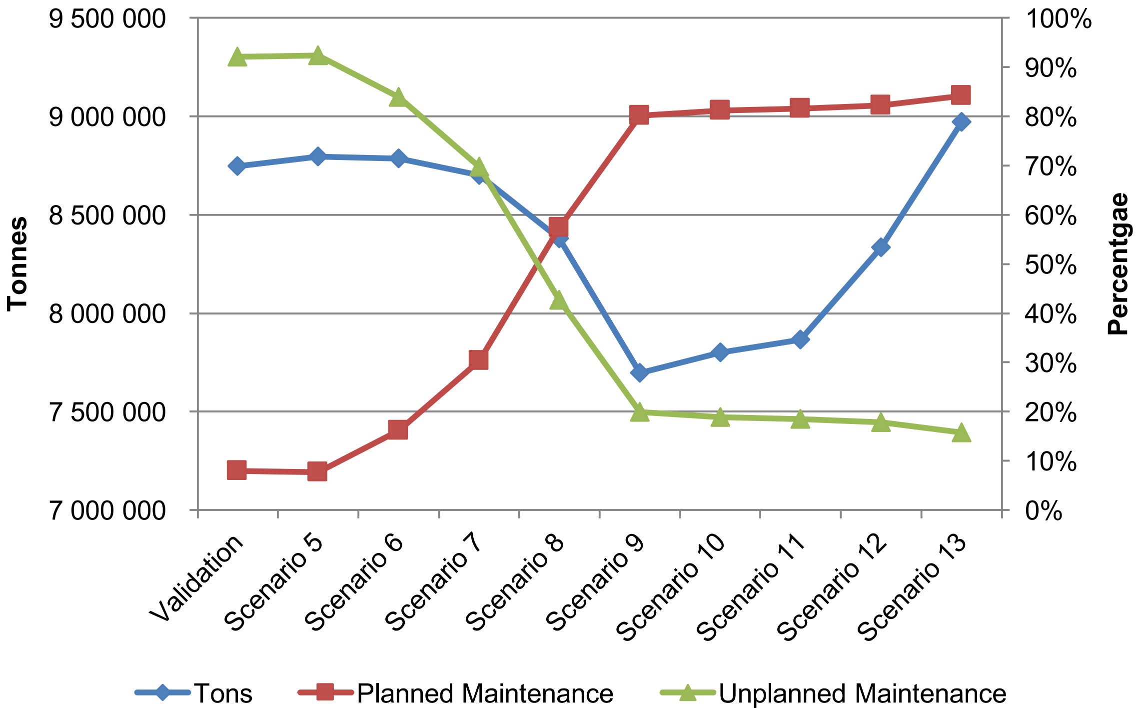


Figure 30 Tons, planned and unplanned maintenance: Validation run and scenario's 5-13

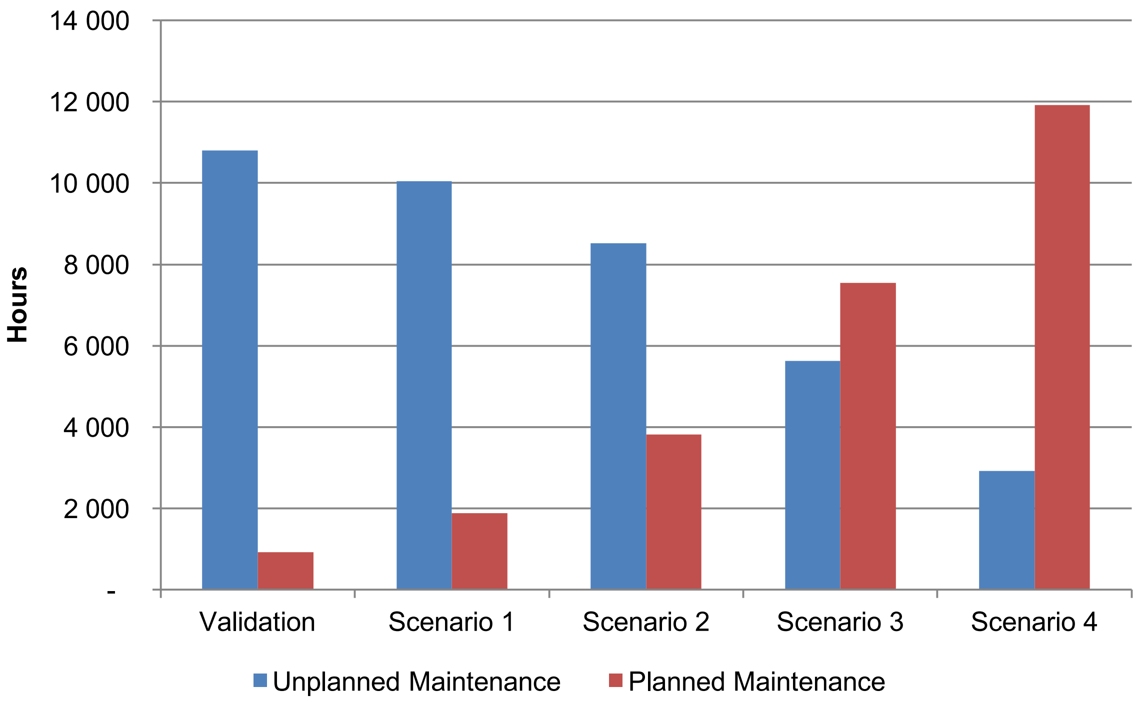


Figure 31 Total hours of planned and unplanned maintenance: Validation and scenario's 1-4

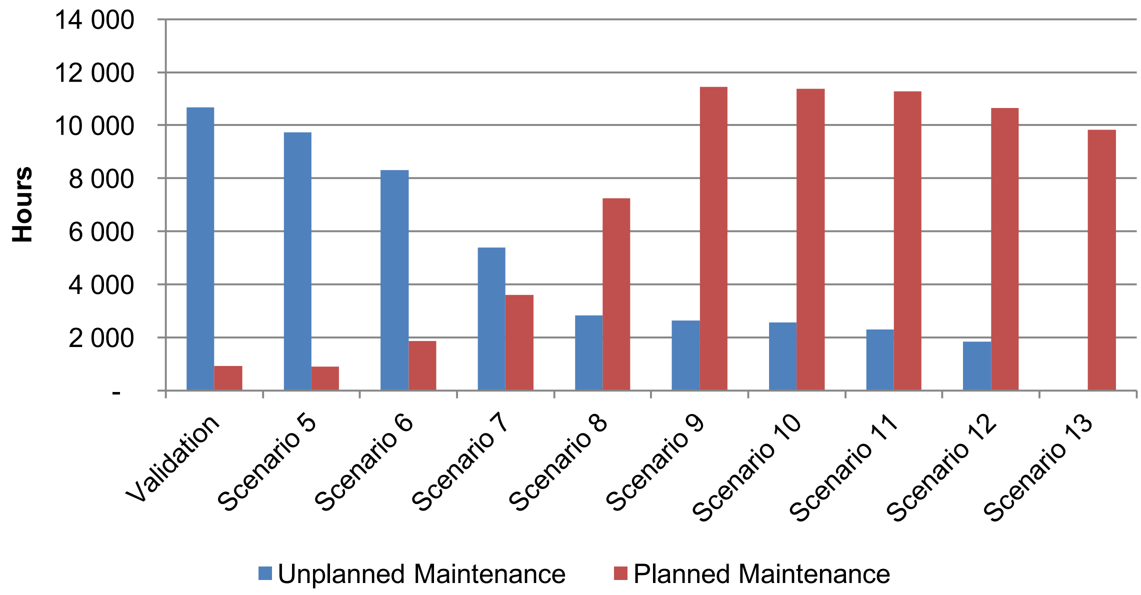


Figure 32 Total hours of planned and unplanned maintenance: Validation and scenario's 5-13

Figures 28, 30, 31 and 32 are directly related to each other, however Figures 31-32 graphically represent the total number of hours related to planned and unplanned maintenance. The following graphic of the mining environment is put forward by the author in Figure 33, and in conjunction with Figure 1, does not indicate that higher availability of mining equipment has the potential to drive higher utilisation. However, utilisation is dependent on a number of unknown, but controllable variables and these include:

- Production planning: The mine plan needs to adequately cater for drilling space, loading areas and expected tonnages; and
- Utilisation: The maintenance department makes preparations and performs necessary maintenance to provide the mining department with machinery with high availability. Utilisation is also dependent on resource availability to use the machinery for production purposes.

The utilisation of the equipment drives the production process and the output of the production process is tons of ore. The yield is dependent on the ore body and the quality thereof. The price of the ore is driven by macroeconomics and profit earned is therefore also driven by the same market forces.

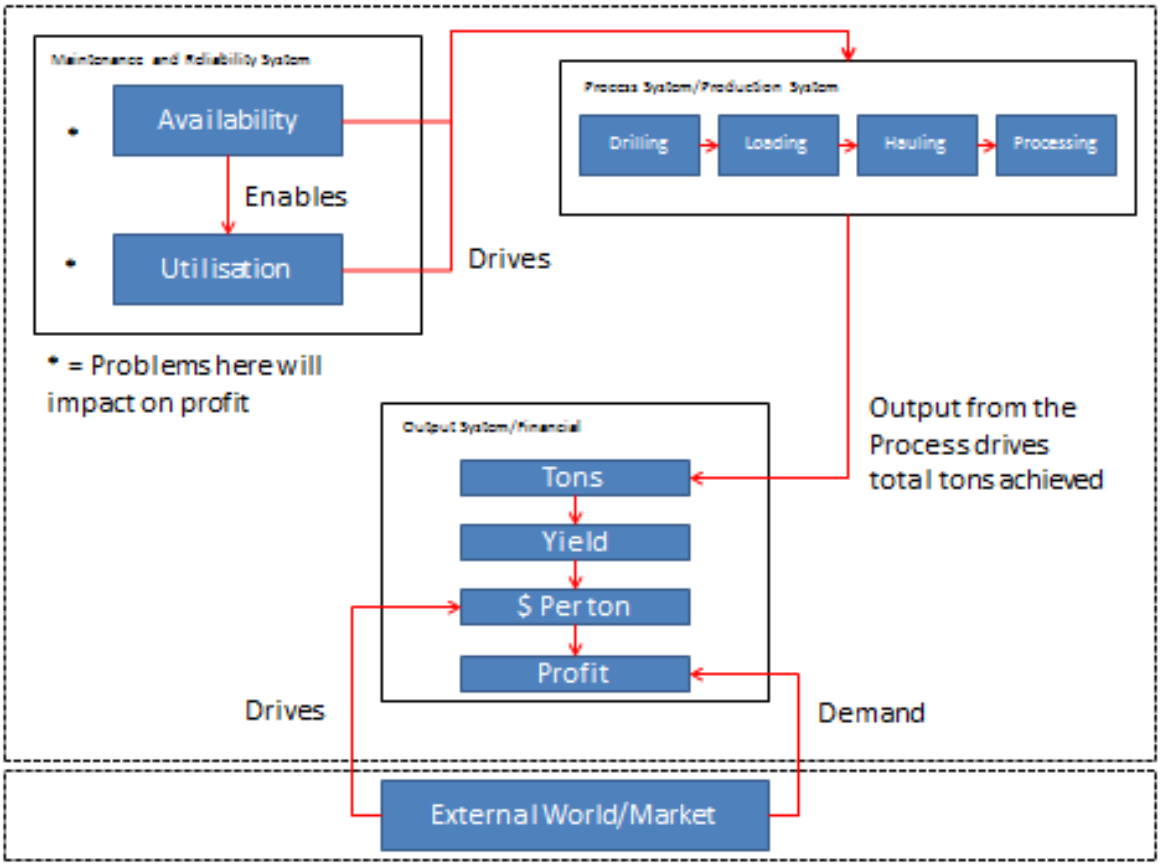


Figure 33 Theoretical model of the mine

Chapter 6 – Discussion

The problem statement is:

"The mine is suffering from low output due to low availability and utilisation of drilling and/or loading equipment".

As we have seen, availability and utilisation of machinery is a function of several variables, including (but not limited to): maintenance activity; skills; scheduling of resources and utilisation of these resources. The key question to answer from this problem statement is what the effect would be on mine output of increasing planned maintenance, decreasing unplanned maintenance, increasing MTBF and decreasing MTTR. The results show that the impact on output of decreasing unplanned and increasing planned maintenance with hypothesised reliability increases is positive. The author established that there is a link between availability, utilisation, maintenance time and production output. High availability together with minimal downtime increases the expected utilisation and throughput of material to the process plant.

The literature suggests that high levels of productivity can only be achieved with high equipment availability and reliability. To ensure this high level of performance, maintenance must be preventative, planned and proactive. If preventative maintenance time is low, as it is with Iron Ore Futures, available resources are diverted to corrective (reactive) maintenance activities instead of preventative (proactive) maintenance activities and this negatively affects the reliability. This diversion has a cost caused by overruns on unplanned activities. This can also have a negative effect on inventory and parts management in that parts are potentially not available for maintenance activities when the time arises for their need. The results of this study support the overall principles of the literature review.

There were two objectives to this research report; both of these objectives were achieved:

- To calculate the utilisation, availability, reliability and maintenance indicators of the drilling, loading and hauling equipment in precise quantitative terms;
- To create a validated simulation model and run a series of scenarios demonstrating the effect on output of increasing planned and decreasing unplanned maintenance activities on the drilling fleet.

To estimate the utilisation, availability, reliability and maintenance characteristics of the equipment in precise quantitative terms

- Chapter 4 outlined the structure of the methodology and introduced the reader to the formula applied as well as example calculations. The raw data as described in section 4.3.1 required the author to manipulate the data into a useable format (Table 5);
- Example calculations using the manipulated data were presented in section 4.3.4. The indicators presented quantified the utilisation and availability of each piece of equipment. In addition, reliability indicators were presented in the form of failure rate and MTBF and maintenance indicators in the form of MTTR;
- The results of all these indicators for the period under consideration were presented in section 5.1. The results presented in graphical format provide a retrospective view of the indicators, and trends in the data were observed and discussed.

To create a validated simulation model and run a series of scenarios

The author created a simulation using Simul8 software and the simulated production related to actual production as presented in section 4.6. The data indicated that more maintenance time is spent on reactive/unplanned maintenance activities rather than planned/proactive maintenance activities.

The author proposed a number of scenarios to be run in the simulation model. It was decided only to focus the scenarios on the drilling fleet as this is the starting point for the mining process. **The author established that there is a link between availability, utilisation, planned maintenance time and production output.** High availability together with minimal downtime increases the expected utilisation and throughput of material to the process plant. The author established that the mine was suffering from a high amount of unplanned maintenance time with low planned maintenance time and this factor was having a negative impact on availability and output.

It was evident from the simulation that initially increasing planned maintenance activities decreases output; failure rates are still high and equipment is being subjected to planned maintenance. As the reliability improved with increased levels of planned maintenance the output began to increase while unplanned maintenance reduced. During the six-month period the scenarios showed that management would be able to transform the maintenance function into one that embraces proactive, preventative and planned maintenance philosophies and practices.

Key elements to a research report of this nature are data reliability, accuracy and completeness as stipulated in the research objectives. The author was provided with a dataset and the methodological approach as described in Chapter 4 was followed. The author allowed for assumptions pertaining to drilling, loading and hauling rates (Table 7). These assumptions were applied in a simulation model and verified against actual production. Thus the model was an accurate representation of actual production levels.

The simulation model was designed to demonstrate a key concept: the impact on output of increased planned maintenance will be positive, with lost time due to unplanned maintenance decreasing. The simulation was able to demonstrate this.

A further limitation was the time frame. Utilised time and total available time for the period of 6 months was applied. This provided a granular view of the scenario's impact on production over the period. Whilst this granular view is rich in information, a production shift or weekly output view would more than likely produce a better picture of the impact of planned maintenance. Shorter time periods with runtime and cycle times would be able to demonstrate shift based changes on production levels as opposed to a six month view. Changes or recommendations could be implemented more quickly.

Chapter 7 – Conclusion

The source data as described in section 4.3 was assumed to be accurate as this was the very data applied in monthly reporting by both management and the engineering teams at the mine. The first part of the report investigated and calculated the reliability and maintenance KPIs for the selected machinery. A number of conclusions were deduced about the operating conditions during the time period of 1 Jan - 30 June 2011. The simulation applied assumptions and standards (Table 7) and it calculated MTTR and MTBF values. It was expressed to the author that the maintenance philosophy was preventative but the results quite clearly contradict that. A true preventative maintenance philosophy or strategy would indicate planned maintenance at 90% and unplanned 10%, whereas the actual percentages at Iron Ore Futures were opposite to these numbers – unplanned maintenance at 90% and planned at 10%. These values would inform any third party that the preventative maintenance philosophy is not entrenched. Data in the quantitative form was not a limitation and the qualitative data detailing the maintenance philosophy was not an objective of this report. This presents a rich area for future research; a more detailed understanding of the maintenance philosophy would be of great interest to gain insight into the management and leadership challenges at the mine.

This research report suggests that in the absence of increased planned maintenance time, production output is going to be negatively affected. The literature review, in relation to this, supports this notion. The maintenance function is complex and a detailed understanding of the fundamental objectives is required. The objective of maintenance is to support the production process with adequate levels of availability, reliability and operability at an acceptable cost. The use of more mechanisation and automation in the industry has emphasised the need for reliable operating systems. In terms of economics, systems with high reliability are favoured to reduce maintenance costs.

The relationship between production (mining) and maintenance is complex. It was described in Chapter 1 that the mine's maintenance management was governed by preventative and proactive measures. However, upon investigation it is evident that more maintenance time is spent on reactive/unplanned activities rather than proactive/planned activities. This factor is one of several that are having a negative impact on mine output. The author proposed a number of scenarios to be run in the simulation software and it was decided only to focus the scenarios on the drilling fleet as this is the starting point for the mining process. The author established that there is a link between planned, proactive maintenance and availability, utilisation, and production output. High availability together with minimal downtime increases the expected utilisation and throughput of material to the processing plant.

Available time, utilised time, unplanned and planned maintenance time for the period under consideration were some of the KPIs driving the formulation of the simulation. Future research may wish to investigate the following:

- Time based studies for individual equipment for shorter time frames i.e. per shift;
- The cost-benefit impact of the expense of a properly installed planned maintenance system against the pay-off of increased throughput and therefore increased profitability; and
- Qualitative studies on management practices and attitudes in order to investigate the potentially deleterious impact of these on the levels of planned and unplanned maintenance at the mine, and the consequent adverse impact on throughput and eventually profitability.

References

Atlas Copco, 2013. Atlas Copco Blasthole Drills. Available at: http://www.atlascopco.com/Images/Brochure PV-271 Low res %28A4%29_tcm795-3434016.pdf.

Banks, J., 2000. Proceedings of the 2000 Winter Simulation Conference J. A. Joines, R. R. Barton, K. Kang, and P. A. Fishwick, eds. , pp.9–16.

Barabady, J. & Kumar, U., 2008. Reliability analysis of mining equipment: A case study of a crushing plant at Jajarm Bauxite Mine in Iran. *Reliability Engineering & System Safety*, 93(4), pp.647–653.

Bergsman, J., 2010. *Improving maintenance efficiency at AstraZeneca through increased use of TPM*. Linkoping University.

Caterpillar, 2011. 789 C. Available at: http://www.hsegroup.com.au/uploads/res/CAT789C.pdf.

Caterpillar, 1998. 994 D. Available at: http://www.witraktor.lt/pdf/E1-994D-Specalog.

Caterpillar Inc., 2015. Caterpillar. Available at: http://www.cat.com/en_US/products/new/by-industry/mining.html [Accessed February 5, 2015].

Chua, R.C.H. & DeFeo, J.A., 2006. *Juran's quality planning and analysis: for enterprise quality* Fifth., Tata McGraw-Hill Education.

Coetzee, J.L., 1999. A holistic approach to the maintenance "problem." *Journal of Quality in Maintenance Engineering*, 5(3), pp.276 – 281.

Coetzee, J.L., 2004. *Maintenance*, Trafford.

Coetzee, J.L. & Claasen, S.J., 2002. Reliability Centred Maintenance for Industrial use: Significant advances for the new millenium. *SA Journal of Industrial Engineering*, 13(2), pp.97–129.

Dhillon, B.S., 2002. *Engineering Maintenance - A Modern Approach*, CRC Press.

Dhillon, B.S., 2008. Mining Equipment Reliability. *Mining Equipment Reliability, Maintenance and safety*, Chapter 4, pp.57–70.

Van der Duyn Schouten, F.A. & Vanneste, S.G., 1995. Maintenance optimization of a production system with buffer capacity. *European journal of operational research*, 82(2), pp.323–338.

Eti, M.C., Ogaji, S.O.T. & Probert, S.D., 2006. Strategic maintenance-management in Nigerian industries. *Applied Energy*, 83(3), pp.211–227.

Fore, S. & Msipha, A., 2010. PREVENTIVE MAINTENANCE USING RELIABILITY CENTRED MAINTENANCE (RCM): A CASE STUDY OF A FERROCHROME MANUFACTURING COMPANY. *SA Journal of Industrial Engineering*, 21(1), pp.207 – 235.

Greyling, M., 2004. A METHODOLOGY FOR EVALUATING THE IMPACT OF ROTARY MILL INSTALLATIONS ON THE RELIABILITY PROFILE OF SOUTH AFRICAN PLATINUM CONCENTRATOR PLANTS.

Hall, R.A. & Daneshmend, L.K., 2010. Reliability Modelling of Surface Mining Equipment : Data Gathering and Analysis Methodologies Reliability Modelling of Surface Mining. *International Journal of Surface Mining, Reclamation and Environment*, (September 2012), pp.37–41.

Igba, J. et al., 2013. A Systems Approach Towards Reliability-Centred Maintenance (RCM) of Wind Turbines. *Procedia Computer Science*, 16, pp.814–823.

Jardine, A.K.S. & Tsang, A.H.C., 2013. *Maintenance, replacement, and reliability: theory and applications*, CRC press.

Kothamasu, R., Huang, S.H. & VerDuin, W.H., 2006. System health monitoring and prognostics — a review of current paradigms and practices. *The International Journal of Advanced Manufacturing Technology*, 28(9-10), pp.1012–1024.

Kumar, U., Klefsjo, B. & Granholm, S., 1989. Reliability Investigation for a Fleet of Load Haul Dump Machines in a Swedish Mine. *Realiability Engineering and System Safety*, 26, pp.341–361.

Lau, H., 1983. Reliability, maintainability and cost effectiveness. A bibliographic note. *Microelectron Reliability*, 23(I), pp.21–40.

Marten, F.A., 2010. Reliability Centered Maintenance : A Case Study of Railway Transit Maintenance to Achieve Optimal Performance. *Mineta Transportation Institute*.

Mishra, R.C., 2006. *Reliability and Maintenance Engineering*, New Age International.

Mobley, R.K., 2002. *An introduction to predictive maintenance*, Butterworth-Heinemann.

Moore, R., 2011. *Selecting the right manufacturing improvement tools: what tool? when?*, Butterworth-Heinemann.

Murthy, D.N.P., Atrens, A. & Eccleston, J.A., 2002. Strategic maintenance management. *Journal of Quality in Maintenance Engineering*, 8(4), pp.287–305.

Oke, S.A., 2006. Maintenance Performance Reasearch - Part 1: A Review of models and issues. *SA Journal of Industrial Engineering*, 17 (1)(May 2006), pp.149–172.

Paraszczak, J., 2005. Understanding and assessment of mining equipment effectiveness. *Mining Technology : IMM Transactions section A*, 114(3), pp.147–151.

Pascual, R., Meruane, V. & Rey, P. a., 2008. On the effect of downtime costs and budget constraint on preventive and replacement policies. *Reliability Engineering & System Safety*, 93(1), pp.144–151.

Samanta, B., Sarkar, B. & Mukherjee, S.K., 2004. Reliability modelling and performance analyses of an LHD system in mining. *The Journal of the South African Institute of Mining and Metallurgy*, (February), pp.1–8.

Sandvic, 2007. Sandvik DI600 Always a hole ahead Enjoy the power and precision. Available at: http://mc.sandvik.com/sandvik/0120/Internet/Global/S003715.nsf/GenerateTopFrameset?ReadForm&menu=&view=http%3A//mc.sandvik.com/sandvik/1281/Internet/MANorway/se03605.nsf/Alldocs/Products*5CDrill*rigs*and*rock*drills*5CSurface*DTH*drill*rigs*2ADI600&banner=/sandvik/0120/Internet/Global/S003715.nsf/LookupAdm/BannerForm%3FOpenDocument.

Sharma, A., Yadava, G.S. & Deshmukh, S.G., 2011. A literature review and future perspectives on maintenance optimization. *Journal of Quality in Maintenance Engineering*, 17(1), pp.5–25.

Smith, A.M. & Hinchcliffe, G.R., 2003. *RCM--Gateway to World Class Maintenance*, Butterworth-Heinemann.

Swanson, L., 2001. Linking maintenance strategies to performance. *International Journal of Production Economics*, 70(3), pp.237–244.

Takata, S. et al., 2004. Maintenance : Changing Role in Life Cycle Management. *CIRP Annals - Manufacturing Technology*, 53(2), pp.643–655.

Tsarouhas, P.H. & Arvanitoyannis, I.S., 2010. Assessment of operation management for beer packaging line based on field failure data: A case study. *Journal of Food Engineering*, 98(1), pp.51–59.

Appendix A: Operations Review

This review took place between January and February 2011, and assessed the operational aspects relating to drilling and blasting, loading and hauling. There is a fourth leg to the mining process, the processing plant, and this area has not been included in this review. For each of the phases the following descriptors were assessed:

- Total Available time;
- Planned maintenance;
- Unplanned maintenance
- Standby time;
- Available time;
- Operating delays;
- Non-operating delays;
- Planned lost time; and
- Utilisation.

1. Drilling and Blasting

For the month of January and February, the total available time is 15,366,264 and 19,670,317 seconds respectively. This translates to 4,266.41 and 5,463.98 hours respectively, see Tables L.1 and L.2. There are some noticeable discrepancies in the total time (Sum of BKMTOTALTIME) and this can be attributed to January only having 50 shifts (25 days) and February 62 shifts (31 days).

Table A.1 Drilling rigs, January 2011

Primary Machine Name	Sum of Available Time (Seconds)	Sum of Utilised Time (Seconds)	Sum of Total Time (Seconds)
DL90001	1737120	611512	2147881
DL90002	1954013	1005855	2127282
DL90003	1692698	850671	2251516
DL90006	1041066	477173	2160000
DL90007	1715291	799012	2160000
DL90008	1839253	702362	2371106
DL90010	1409050	703260	2148479
Grand Total	11388491	5149845	15366264

Table A.2 Drilling rigs, February 2011

Primary Machine Name	Sum of Available Time (Seconds)	Sum of Utilised Time (Seconds)	Sum of Total Time (Seconds)
DL90001	2038080	902694	2678384
DL90002	3109002	1501073	3626233
DL90003	2143454	1015881	2676686
DL90006	365170	191265	2678400
DL90007	2071740	1211125	2678400
DL90008	2225206	1083590	2678400
DL90010	2116391	1264253	2653814
Grand Total	14069043	7169881	19670317

From Figure L.1, it is quite evident that there are problems with the unplanned maintenance and non-operating delays. It is observed that these two elements are significantly affecting the utilised time.

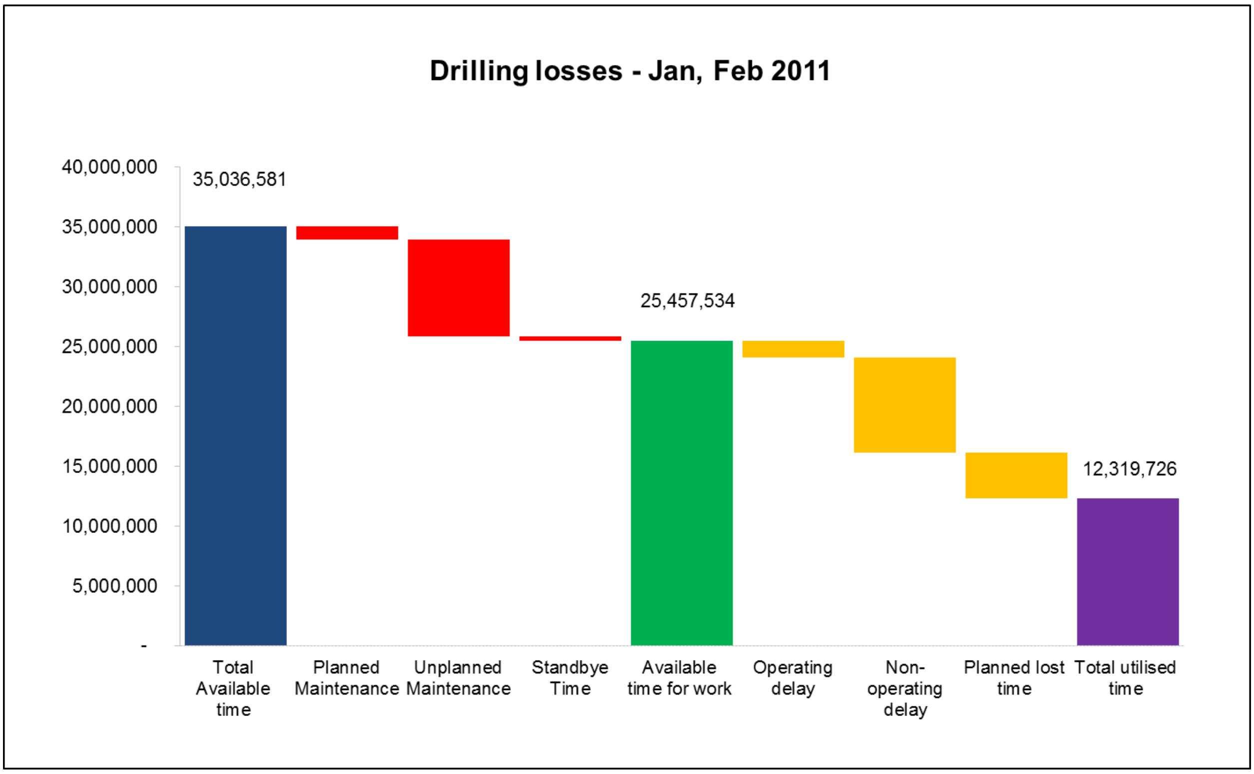


Figure A.1 Drilling fleet delays

Some initial maintenance indicators include:

- Availability: 60.00%
- Utilisation: 48.00%
- Unplanned maintenance and non-operating delays impacts negatively on equipment availability and utilisation.

2. Loading

For the months of January and February, the total available time is 8,646,015 and 10,714,357 seconds respectively. This translates to 2,401.67 and 2976.21 hours respectively, see Tables L.3 and L.4 below. There are some noticeable discrepancies in the total time (Sum of BKMTOTALTIME) and this can be attributed to January only having 50 shifts (25 days) and February 62 shifts (31 days).

Table A.3 Loaders, January 2011

Primary Machine Name	Sum of Available Time (Seconds)	Sum of Utilised Time (Seconds)	Sum of Total Time (Seconds)
FE90003	1344705	858888	2160143
FE90005	1802182	1164399	2160087
FE90010	377950	205018	2159623
FE90012	1593567	1034666	2166162
Grand Total	5118404	3262971	8646015

Table A.4 Loaders, February 2011

Primary Machine Name	Sum of Available Time (Seconds)	Sum of Utilised Time (Seconds)	Sum of Total Time (Seconds)
FE90003	1880099	1263199	2678913
FE90005	1978509	1318082	2678394
FE90010	414338	286437	2678400
FE90012	2064386	1351029	2678650
Grand Total	6337332	4218747	10714357

From Figure L.2, it is quite evident that there are problems with the unplanned maintenance.

It is observed that this element is contributing significantly to low levels of utilised time.

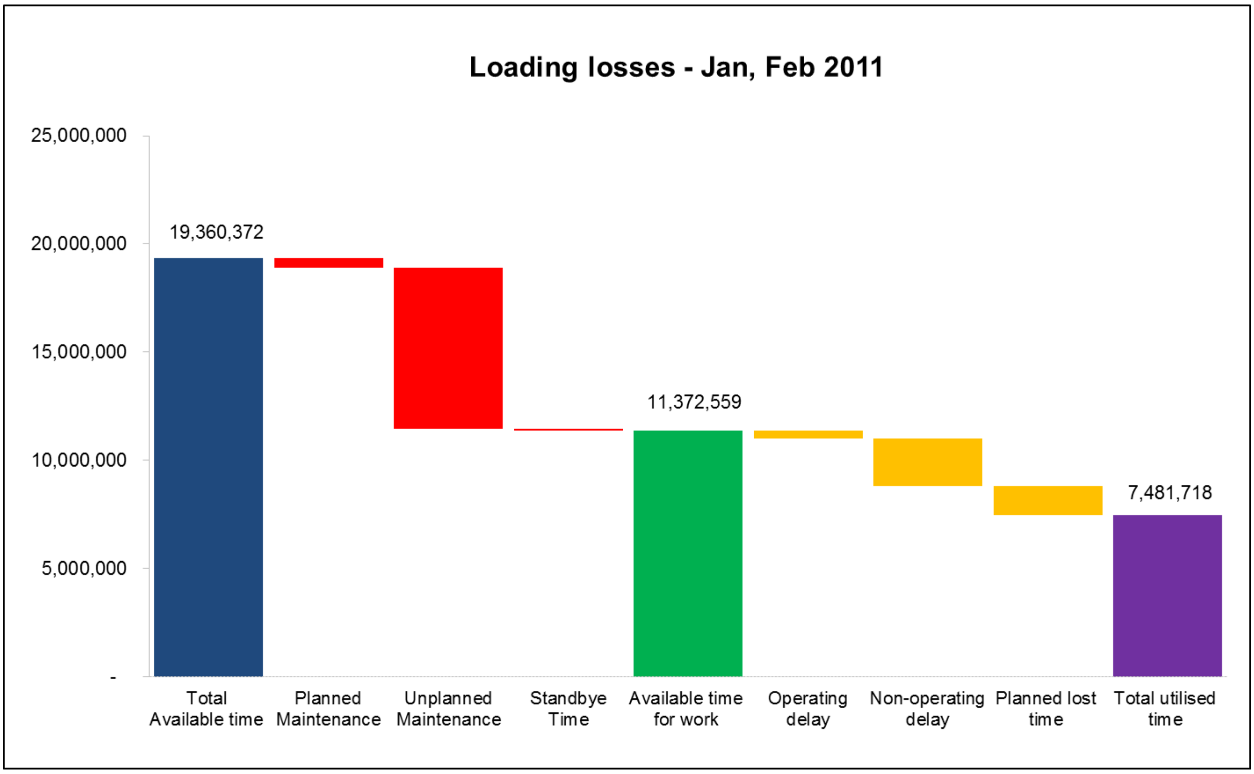


Figure A.2 Mine Loader delays

Some initial maintenance indicators include:

- Availability: 52.00%
- Utilisation: 65.00%
- Unplanned maintenance and non-operating delays impact negatively on equipment availability and utilisation.

3. Hauling

For the months of January and February, the total available time is 8,646,015 and 10,714,357 seconds respectively. This translates to 2,401.67 and 2976.21 hours respectively, see Tables L.5 and L.6. There are some noticeable discrepancies in the total time (Sum of BKMTOTALTIME) and this can be attributed to January only having 50 shifts (25 days) and February 62 shifts (31 days).

Table A.5 Haulers, January 2011

Primary Machine Name	Sum of Available Time (Seconds)	Sum of Utilised Time (Seconds)	Sum of Total Time (Seconds)
DT90004	1718602	615961	2160000
DT90005	1664742	688379	2159047
DT90006	1836719	1125864	2158659
DT90007	1950095	1228257	2160000
DT90008	1800011	1047973	2157578
DT90009	1443099	835546	2160000
DT90010	1824380	1246798	2158757
DT90011	1429517	709636	2160000
DT90015	1954551	1201271	2160000
DT90020	1532073	824573	2157180
DT90021	1166683	569819	2160000
DT90022	2037577	1393528	2419081
Grand Total	20358049	11487605	26170302

Table A.6 Haulers, February 2011

Primary Machine Name	Sum of Available Time (Seconds)	Sum of Utilised Time (Seconds)	Sum of Total Time (Seconds)
DT90004	2172826	1033879	2678400
DT90005	2553190	1548305	2678400
DT90006	2570879	1395672	2678400
DT90007	2448871	1071932	2676634
DT90008	2609686	1506041	2677508
DT90009	861213	291950	2678400
DT90010	2464071	1402670	2678400
DT90011	2490807	1487044	2678400
DT90015	2603429	1606627	2676801
DT90020	2565471	1368055	2677695
DT90021	2410598	1388678	2678400
DT90022	5266864	3061384	5356800
Grand Total	31017905	17162237	34814238

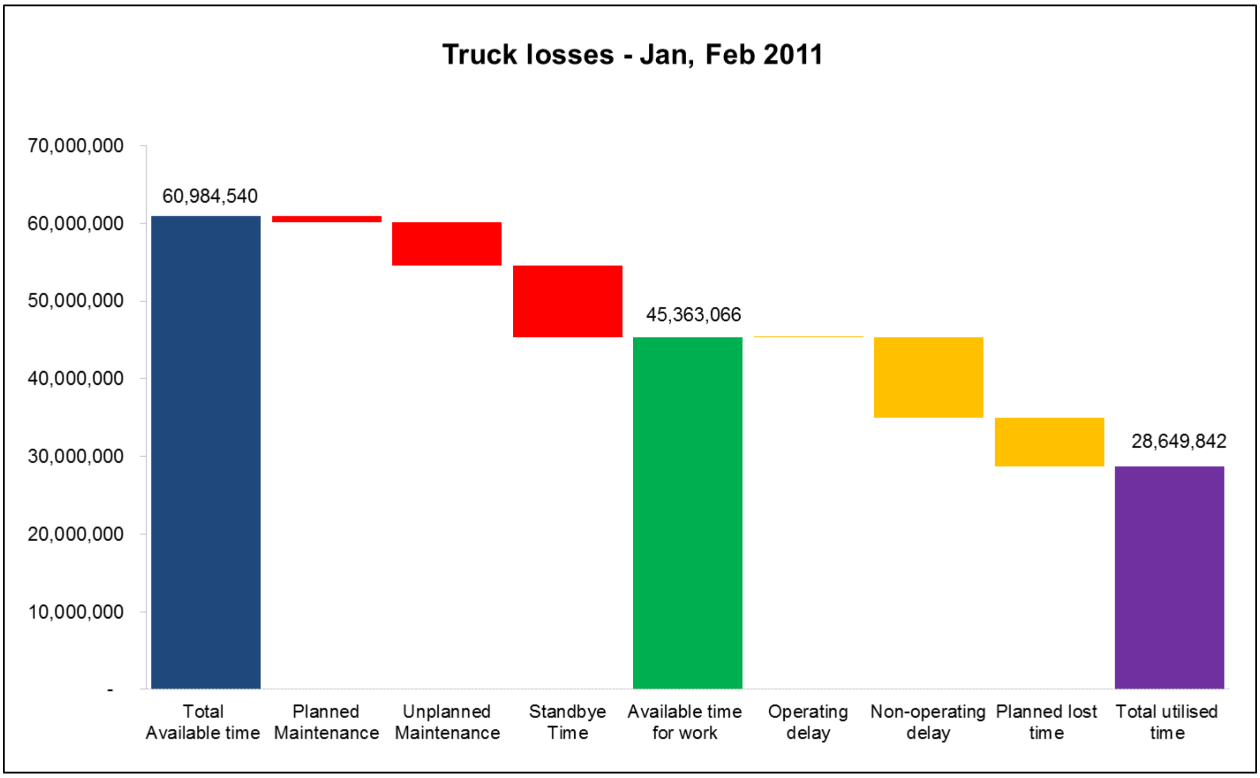


Figure A.3 Dump truck delay

Some initial indicators for Iron Ore Futures include:

- Availability: 88.35%
- Utilisation: 51.29%

4. Images of machinery types

Figure A.4 Image of Titon DI600 (Sandvic 2007)

Figure A.5 Image of Pit Viper 271 (Atlas Copco 2013)

Figure A.6 Image of Loader (Caterpillar 1998)

Figure A.7 Image of Dump Truck (Caterpillar 2011)

Appendix B: Example of source data from Minestar System (DL 90001)

PRIMARY MACHINE CATEGORY NAME	PRIMARY MACHINE NAME	CYCLEOID	CALENDAR SHIFT START TIME	START TIME	BKM PLANNED MAINTENANCE TIME	BKM UNPLANNED MAINTENANCE TIME	BKM TOTAL TIME	BKM STANDBY TIME	BKM PLANNED LOST OPER TIME	BKM NON OPERATING DELAY TIME	BKM OPERATING DELAY TIME	PAYLOAD	Available Time	Utilized Time	Planned Shutdo	Unplanned Shutdow	Hours to Failure
Track Drill	DL90001	195623125	1/1/2011 7:00	1/1/2011 7:00	0	0	43200	0	1584	41587	0		43200	29	0	0	29
Track Drill	DL90001	195623488	1/1/2011 19:00	1/1/2011 19:00	0	0	43200	0	6517	36580	0		43200	103	0	0	103
Track Drill	DL90001	195623580	1/2/2011 7:00	1/2/2011 7:00	0	0	5703	0	3866	0	0		5703	1837	0	0	1837
Track Drill	DL90001	195623626	1/2/2011 7:00	1/2/2011 8:35	0	0	2583	0	0	0	0		2583	2583	0	0	2583
Track Drill	DL90001	195623671	1/2/2011 7:00	1/2/2011 9:18	0	0	2815	0	0	0	0		2815	2815	0	0	2815
Track Drill	DL90001	195623694	1/2/2011 7:00	1/2/2011 10:05	0	0	1446	0	0	0	0		1446	1446	0	0	1446
Track Drill	DL90001	195623722	1/2/2011 7:00	1/2/2011 10:29	0	0	1424	0	0	0	0		1424	1424	0	0	1424
Track Drill	DL90001	195623770	1/2/2011 7:00	1/2/2011 10:52	0	0	4492	0	0	591	0		4492	3901	0	0	3901
Track Drill	DL90001	195623786	1/2/2011 7:00	1/2/2011 12:07	0	0	1500	0	0	0	0		1500	1500	0	0	1500
Track Drill	DL90001	195623899	1/2/2011 7:00	1/2/2011 12:32	0	0	12119	0	0	9509	0		12119	2610	0	0	2610
Track Drill	DL90001	195623908	1/2/2011 7:00	1/2/2011 15:54	0	0	1220	0	0	0	0		1220	1220	0	0	1220
Track Drill	DL90001	195623916	1/2/2011 7:00	1/2/2011 16:15	0	0	1276	0	0	0	0		1276	1276	0	0	1276
Track Drill	DL90001	195623934	1/2/2011 7:00	1/2/2011 16:36	0	0	1556	0	0	0	0		1556	1556	0	0	1556
Track Drill	DL90001	195623968	1/2/2011 7:00	1/2/2011 17:02	0	0	2028	0	0	0	0		2028	2028	0	0	2028
Track Drill	DL90001	195623989	1/2/2011 7:00	1/2/2011 17:36	0	0	1535	0	0	0	0		1535	1535	0	0	1535
Track Drill	DL90001	195624030	1/2/2011 7:00	1/2/2011 18:01	0	0	3503	0	1211	2092	0		3503	200	0	0	200
Track Drill	DL90001	195624078	1/2/2011 19:00	1/2/2011 19:00	0	0	3889	0	3889	0	0		3889	0	0	0	0
Track Drill	DL90001	195624429	1/2/2011 19:00	1/2/2011 20:04	0	0	39311	0	2165	19797	17312		39311	37	0	0	37
Track Drill	DL90001	195624498	1/3/2011 7:00	1/3/2011 7:00	0	0	14717	0	1811	10481	0		14717	2425	0	0	2425
Track Drill	DL90001	195624509	1/3/2011 7:00	1/3/2011 11:05	0	0	14676	0	0	12711	0		14676	1965	0	0	1965
Track Drill	DL90001	195624524	1/3/2011 7:00	1/3/2011 15:09	0	0	2950	0	0	0	0		2950	2950	0	0	2950
Track Drill	DL90001	195624536	1/3/2011 7:00	1/3/2011 15:59	0	0	1465	0	0	0	0		1465	1465	0	0	1465
Track Drill	DL90001	195624556	1/3/2011 7:00	1/3/2011 16:23	0	0	2806	0	0	0	0		2806	2806	0	0	2806
Track Drill	DL90001	195624572	1/3/2011 7:00	1/3/2011 17:10	0	0	3126	0	0	0	0		3126	3126	0	0	3126
Track Drill	DL90001	195624609	1/3/2011 7:00	1/3/2011 18:02	0	0	3460	0	2965	0	0		3460	495	0	0	495
Track Drill	DL90001	195624924	1/3/2011 19:00	1/3/2011 19:00	0	0	43200	0	4630	38533	0		43200	37	0	0	37

Appendix C: Drill data summary data

Month	January	February	March	April	May	June	Totals (Hours & Failures)	Failure Rate	Total MTBF
Time	5 149 845	7 169 881	8 395 467	6 375 519	6 724 315	7 100 333	11 365	0,14	6,90
Number of Failures	217	316	234	319	273	287	1 646		
Failure rate	0,15	0,16	0,10	0,18	0,15	0,15			
MTBF	6,59	6,30	9,97	5,55	6,84	6,87			
		MTTR Total					**Totals (Hours & Maintenance Actions)**	**MTTR Total**	
Total Maintenance Time	3 651 460	5 561 029	2 437 475	7 514 520	4 986 997	5 632 927	8 273	4,57	
Total Maintenance Actions	245	351	266	338	301	308	1 809		
MTTR Total	4,14	4,40	2,55	6,18	4,60	5,08			
		MTTR Planned					**Totals (Hours & Maintenance Actions)**	**MTTR PM**	
Total Planned Maintenance Time	444 443	667 372	574 247	175 737	331 250	276 520	686	4,21	
Total Planned Maintenance Actions	28	35	32	19	28	21	163	8%	
MTTR Planned	4,41	5,30	4,98	2,57	3,29	3,66			
		MTTR Unplanned					**Totals (Hours & Maintenance Actions)**	**MTTR UP**	
Total Unplanned Maintenance Time	3 207 017	4 893 657	1 863 228	7 338 783	4 655 747	5 356 407	7 587	4,61	
Total Unplanned Maintenance Actions	217	316	234	319	273	287	1 646	92%	
MTTR Unplanned	4,11	4,30	2,21	6,39	4,74	5,18			
		Availability and Utilisation					**Total Hours**		
Total Available Time	11 388 491	14 069 043	14 327 687	11 903 684	13 214 996	15 363 126	22 296		
Actual Working Time	5 149 845	7 169 881	8 395 467	6 375 519	6 724 315	7 100 333	11 365		
Total time	15 366 264	19 670 317	16 914 761	19 749 618	18 234 349	21 107 364	30 845		
Availability	74%	72%	85%	60%	72%	73%	72%		
Utilisation	45%	51%	59%	54%	51%	46%	51%		

Appendix D: Loader data summary data

Month	January	February	March	April	May	June	Totals (Hours & Failures)	Failure Rate	Total MTBF
Time	3 262 971	4 218 747	5 201 446	5 473 253	4 130 016	5 313 211	7 667	0,16	6,10
Number of Failures	203	326	183	162	183	200	1 257		
Failure rate	0,22	0,28	0,13	0,11	0,16	0,14			
MTBF	4,46	3,59	7,90	9,38	6,27	7,38			
		MTTR Total					**Totals (Hours & Maintenance Actions)**	**MTTR Total**	
Total Maintenance Time	3 518 646	4 392 380	1 648 109	1 903 868	4 464 617	3 184 001	5 309	3,41	
Total Maintenance Actions	236	373	243	222	224	261	1 559		
MTTR Total	4,14	3,27	1,88	2,38	5,54	3,39			
		MTTR Planned					**Totals (Hours & Maintenance Actions)**	**MTTR PM**	
Total Planned Maintenance Time	200 008	271 378	475 523	220 670	179 505	332 865	467	1,55	
Total Planned Maintenance Actions	33	47	60	60	41	61	302	9%	
MTTR Planned	1,68	1,60	2,20	1,02	1,22	1,52			
		MTTR Unplanned					**Totals (Hours & Maintenance Actions)**	**MTTR UP**	
Total Unplanned Maintenance Time	3 318 638	4 121 002	1 172 586	1 683 198	4 285 112	2 851 136	4 842	3,85	
Total Unplanned Maintenance Actions	203	326	183	162	183	200	1 257	91%	
MTTR Unplanned	4,54	3,51	1,78	2,89	6,50	3,96			
		Availability and Utilisation					**Total Hours**		
Total Available Time	5 118 404	6 337 332	7 846 610	8 526 598	5 865 530	8 279 689	11 659		
Actual Working Time	3 262 971	4 218 747	5 201 446	5 473 253	4 130 016	5 313 211	7 667		
Total time	8 646 015	10 714 357	9 677 627	11 059 988	10 369 535	12 060 878	17 369		
Availability	59%	59%	81%	77%	57%	69%	67%		
Utilisation	64%	67%	66%	64%	70%	64%	66%		

Appendix E: Hauler data summary data

Month	January	February	March	April	May	June	Totals (Hours & Failures)	Failure Rate	Total MTBF
Time	11 487 605	17 162 237	17 384 284	18 518 359	15 770 591	18 334 538	27 405	0,05	20,27
Number of Failures	147	207	213	209	272	304	1 352		
Failure rate	0,05	0,04	0,04	0,04	0,06	0,06			
MTBF	21,71	23,03	22,67	24,61	16,11	16,75			
		MTTR Total					**Totals (Hours & Maintenance Actions)**	**MTTR Total**	
Total Maintenance Time	2 663 789	3 796 333	3 684 907	3 037 219	4 559 215	6 271 136	6 670	4,03	
Total Maintenance Actions	182	248	266	250	332	379	1 657		
MTTR Total	4,07	4,25	3,85	3,37	3,81	4,60			
		MTTR Planned					**Totals (Hours & Maintenance Actions)**	**MTTR PM**	
Total Planned Maintenance Time	311 242	515 063	415 704	363 794	743 051	1 719 064	1 130	3,70	
Total Planned Maintenance Actions	35	41	53	41	60	75	305	17%	
MTTR Planned	2,47	3,49	2,18	2,46	3,44	6,37			
		MTTR Unplanned					**Totals (Hours & Maintenance Actions)**	**MTTR UP**	
Total Unplanned Maintenance Time	2 352 547	3 281 270	3 269 203	2 673 425	3 816 164	4 552 072	5 540	4,10	
Total Unplanned Maintenance Actions	147	207	213	209	272	304	1 352	83%	
MTTR Unplanned	4,45	4,40	4,26	3,55	3,90	4,16			
		Availability and Utilisation					**Total Hours**		
Total Available Time	20 358 049	31 017 905	23 839 985	26 899 713	23 011 340	26 725 464	42 181		
Actual Working Time	11 487 605	17 162 237	17 384 284	18 518 359	15 770 591	18 334 538	27 405		
Total time	26 170 302	34 814 238	29 804 488	33 218 115	31 091 724	36 272 616	53 159		
Availability	78%	89%	80%	81%	74%	74%	79%		
Utilisation	56%	55%	73%	69%	69%	69%	65%		

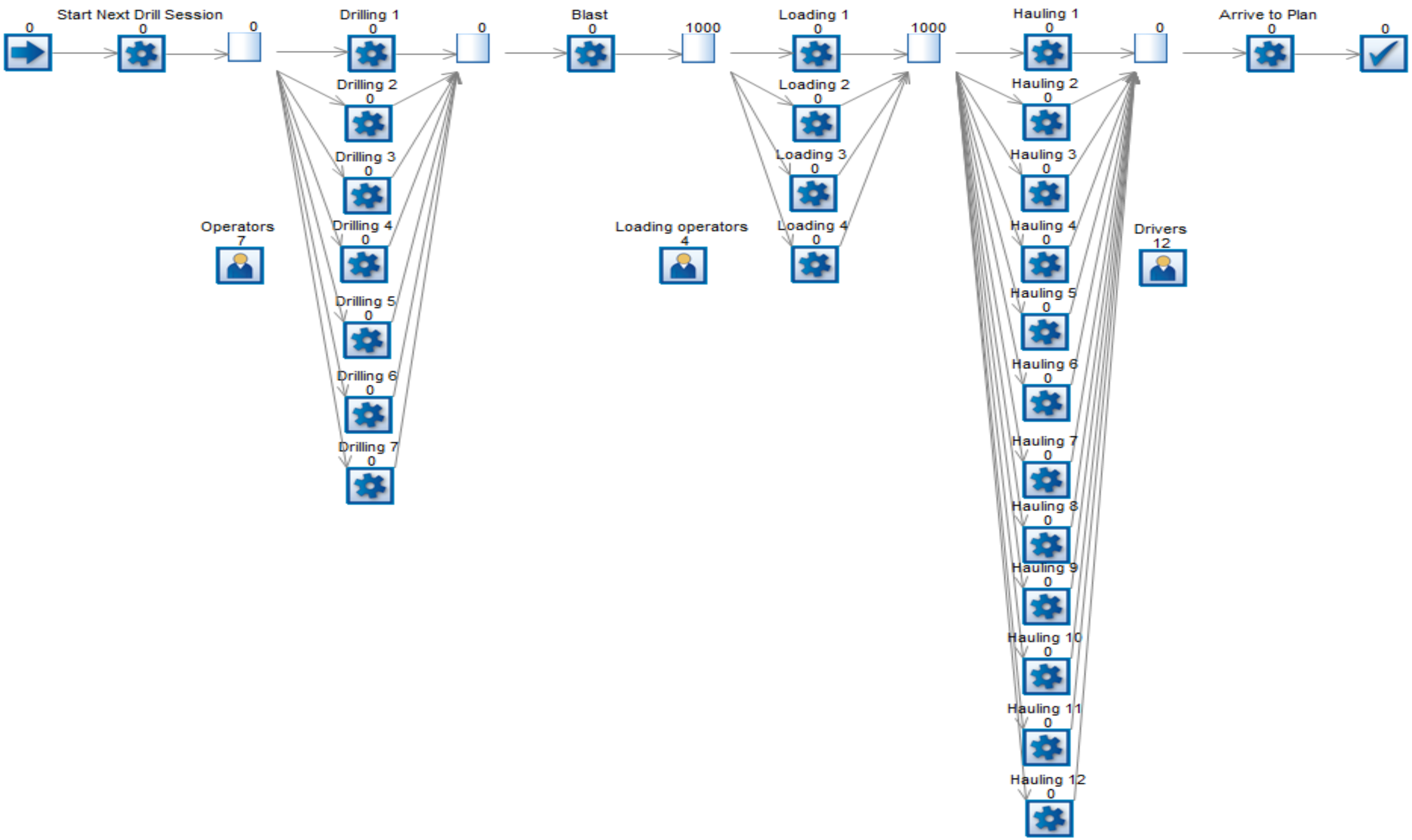
Appendix F: Pit-viper data summary data

Month	**January**	**February**	**March**	**April**	**May**	**June**	**Totals (Hours & Failures)**	**Failure Rate**	**Total MTBF**
Time	2 468 038	3 419 648	3 463 853	3 646 408	3 350 006	3 291 896	5 456	0,12	8,15
Number of Failures	81	137	103	118	104	126	669		
Failure rate	0,12	0,14	0,11	0,12	0,11	0,14			
MTBF	8,46	6,93	9,34	8,58	8,95	7,26			
MTTR Total							**Totals (Hours & Maintenance Actions)**	**MTTR Total**	
Total Maintenance Time	1 131 294	1 671 291	701 726	1 033 733	4 078 743	1 869 988	2 913	3,59	
Total Maintenance Actions	92	152	117	131	186	134	812		
MTTR Total	3,42	3,05	1,67	2,19	6,09	3,88			
MTTR Planned							**Totals (Hours & Maintenance Actions)**	**MTTR PM**	
Total Planned Maintenance Time	135 933	128 478	154 986	113 838	238 392	104 518	243	3,12	
Total Planned Maintenance Actions	11	15	14	13	17	8	78	8%	
MTTR Planned	3,43	2,38	3,08	2,43	3,90	3,63			
MTTR Unplanned							**Totals (Hours & Maintenance Actions)**	**MTTR UP**	
Total Unplanned Maintenance Time	995 361	1 542 813	546 740	919 895	3 840 351	1 765 470	2 670	3,64	
Total Unplanned Maintenance Actions	81	137	103	118	169	126	734	92%	
MTTR Unplanned	3,41	3,13	1,47	2,17	6,31	3,89			
Availability and Utilisation							**Total Hours**		
Total Available Time	5 383 831	7 290 536	6 554 372	7 024 235	6 863 422	7 063 076	11 161		
Actual Working Time	2 468 038	3 419 648	3 463 853	3 646 408	3 350 006	3 291 896	5 456		
Total time	6 526 679	8 981 303	7 256 808	8 292 710	7 771 676	9 016 257	13 290		
Availability	82%	81%	90%	85%	88%	78%	84%		
Utilisation	46%	47%	53%	52%	49%	47%	49%		

Appendix G: Titon data summary data

Month	January	February	March	April	May	June	Totals (Hours & Failures)	Failure Rate	Total MTBF
Time	2 681 807	3 750 233	4 931 614	2 729 111	3 374 309	3 808 437	5 910	0,17	6,05
Number of Failures	136	179	131	201	169	161	977		
Failure rate	0,18	0,17	0,10	0,27	0,18	0,15			
MTBF	5,48	5,82	10,46	3,77	5,55	6,57			
		MTTR Total					**Totals (Hours & Maintenance Actions)**	**MTTR Total**	
Total Maintenance Time	2 520 166	3 889 738	1 735 749	6 480 787	4 078 743	3 762 939	6 241	5,84	
Total Maintenance Actions	153	199	149	207	186	174	1 068		
MTTR Total	4,58	5,43	3,24	8,70	6,09	6,01			
		MTTR Planned					**Totals (Hours & Maintenance Actions)**	**MTTR PM**	
Total Planned Maintenance Time	308 510	538 894	419 261	61 899	238 392	172 002	483	5,31	
Total Planned Maintenance Actions	17	20	18	6	17	13	91	8%	
MTTR Planned	5,04	7,48	6,47	2,87	3,90	3,68			
		MTTR Unplanned					**Totals (Hours & Maintenance Actions)**	**MTTR UP**	
Total Unplanned Maintenance Time	2 211 656	3 350 844	1 316 488	6 418 888	3 840 351	3 590 937	5 758	5,89	
Total Unplanned Maintenance Actions	136	179	131	201	169	161	977	92%	
MTTR Unplanned	4,52	5,20	2,79	8,87	6,31	6,20			
		Availability and Utilisation					**Total Hours**		
Total Available Time	6 004 660	6 778 507	7 773 315	4 879 449	6 351 574	8 300 050	11 135		
Actual Working Time	2 681 807	3 750 233	4 931 614	2 729 111	3 374 309	3 808 437	5 910		
Total time	8 839 585	10 689 014	9 657 953	11 456 908	10 462 673	12 091 107	17 555		
Availability	68%	63%	80%	43%	61%	69%	63%		
Utilisation	45%	55%	63%	56%	53%	46%	53%		

Appendix H: Visual layout of simulation



Appendix I: Failure descriptors

Drills				Loaders				Haulers		
Failure descriptor	Code	Number		Failure descriptor	Code	Number		Failure descriptor	Code	Number
Engine	*EN*	*258*		*Engine*	*EN*	*133*		*Engine*	*EN*	*141*
Hydraulics	*HY*	*170*		*Tips*	*TP*	*94*		*Grease*	*GR*	*70*
Water System	*WA*	*158*		*Hydraulics*	*HY*	*91*		*Minestar*	*MS*	*68*
Compressor	*CO*	*153*		*Cooling*	*CL*	*90*		*Lights*	*LT*	*52*
Pneumatics	*PN*	*117*		*Bucket*	*BU*	*87*		*Hydraulics*	*HY*	*45*
Rod	*RD*	*98*		*Brakes*	*BR*	*42*		*Brakes*	*BR*	*38*
Hammer	*HM*	*97*		*Lights*	*LT*	*41*		*Transmission*	*TM*	*38*
Cooling	*CL*	*80*		*Air conditioner*	*AC*	*40*		*Cooling*	*CL*	*33*
Wipers	*WI*	*72*		*Grease*	*GR*	*35*		*Oil leaks*	*OL*	*24*
Drill bit	*DR*	*68*		*Arrows*	*AR*	*28*		*Steering*	*ST*	*23*
Lights	*LT*	*64*		Filter Change	CF	24		Operators Cab	CB	19
Electrical	*EL*	*62*		Transmission	TM	23		Air conditioner	AC	18
Air conditioner	*AC*	*54*		Minestar	MS	22		Electrical	EL	18
Rotator	RT	50		Water system	WA	20		Chassis	CH	17
Jaws	JW	42		Electrical	EL	12		Fire Extinguisher	FE	16
Sub-Assembly	SA	35		Clip - On	CP	11		Radio	RA	13
Parts - Supply	SY	29		Camera	AV	7		Exhaust	EX	7
Minestar	MS	26		Steering	ST	7		Bucket	BU	5
Dust	DU	25		Magnet	MT	7		Wheels/tyres	WH	3
Grease	GR	21		Operators Cab	CB	7		Injector	IN	3
Carousel	CA	21		Crocodile	CR	7		Windows	WN	2
Fuel	FL	14		Chassis	CH	5		Pneumatics	PN	2
Boom	BM	13		Wheels/Tyres	WH	4		Fuel	FL	1
Operators Cab	CB	13		Running gear	RG	3		Camera	AV	1
Casing	CS	13		Wipers	WI	2		Winch	WI	1
Tracks	TR	12		Parts - Supply	SY	1				
Chuck	CK	12		Fuel	FL	1				
Exhaust System	EX	10		Fire Extinguisher	FE	1				
Welding	WE	10		Hammer	HM	1				
Camera	AV	8								
Jacks	JK	8								
Joystick	JY	8								
Vertical Pin	VP	6								
Feet	FT	5								
Tower	TW	4								
Screen	SC	4								
Aiming	AM	3								
Oscillation	OS	3								
Winch	WH	2								
Fire Extinguisher	FE	1								

Appendix J: Total simulation results summary

Simulation Runtime	4357	Waiting	Working	Stopped	Maintenance
		Percentage (%)			
Validation					
Equipment	DL90001	7,5	60,4	30,6	1,5
	DL90002	10,4	79,0	9,4	1,1
	DL90003	7,6	62,0	28,7	1,6
	DL90006	5,0	41,1	49,8	4,1
	DL90007	4,9	40,3	49,6	5,2
	DL90008	7,1	57,4	32,7	2,8
	DL90010	5,4	42,9	46,8	4,9
Scenario 1					
Equipment	DL90001	8,0	59,4	29,5	3,1
	DL90002	11,0	77,5	9,2	2,3
	DL90003	8,8	60,5	27,6	3,1
	DL90006	4,7	41,0	46,5	7,9
	DL90007	4,8	39,9	44,6	10,7
	DL90008	7,4	56,2	30,5	5,9
	DL90010	5,6	41,6	42,5	10,3
Scenario 2					
Equipment	DL90001	7,3	59,0	26,9	6,7
	DL90002	10,0	76,7	8,8	4,6
	DL90003	8,1	60,5	25,2	6,2
	DL90006	4,8	40,1	37,8	17,3
	DL90007	4,5	38,9	35,1	21,6
	DL90008	7,0	54,8	26,9	11,2
	DL90010	4,4	40,8	34,7	20,1
Scenario 3					
Equipment	DL90001	7,1	57,4	22,0	13,6
	DL90002	9,4	73,5	7,9	9,2
	DL90003	7,4	59,8	20,1	12,7
	DL90006	4,4	39,0	20,5	36,1
	DL90007	4,0	36,8	19,4	39,8
	DL90008	5,9	52,3	18,2	23,6
	DL90010	4,4	36,5	20,9	38,2
Scenario 4					
Equipment	DL90001	6,5	54,2	12,9	26,3
	DL90002	8,3	66,9	6,4	18,4
	DL90003	7,1	57,0	12,0	23,8
	DL90006	3,9	36,2	9,5	50,4
	DL90007	3,2	32,4	8,6	55,8
	DL90008	5,4	45,4	8,4	40,8
	DL90010	3,7	28,9	9,2	58,1
Scenario 7					
Equipment	DL90001	8,3	57,4	32,6	1,7
	DL90002	10,8	79,1	9,0	1,2
	DL90003	8,8	62,0	27,7	1,5
	DL90006	5,5	41,9	48,7	3,9
	DL90007	4,9	41,7	48,8	4,7
	DL90008	8,5	57,1	31,5	2,9
	DL90010	6,6	42,5	46,5	4,4
Scenario 8					
Equipment	DL90001	7,9	57,8	31,1	3,2
	DL90002	10,5	78,5	8,8	2,2
	DL90003	8,5	62,4	26,1	2,9
	DL90006	5,3	42,3	43,3	9,1
	DL90007	4,6	41,8	43,6	9,9
	DL90008	7,4	57,8	29,1	5,7
	DL90010	5,0	43,9	41,4	9,8
Scenario 9					
Equipment	DL90001	7,8	57,5	28,1	6,5
	DL90002	10,1	77,2	8,1	4,6
	DL90003	7,7	62,8	23,7	5,8
	DL90006	5,4	41,6	36,7	16,2
	DL90007	4,6	40,9	35,3	19,2
	DL90008	6,4	57,1	25,7	10,8
	DL90010	4,7	42,6	33,0	19,7
Scenario 10					
Equipment	DL90001	7,2	56,6	22,9	13,3
	DL90002	9,6	74,1	7,1	9,2
	DL90003	8,0	61,5	19,0	11,5
	DL90006	4,4	41,6	20,4	33,6
	DL90007	4,1	39,1	18,4	38,3
	DL90008	7,0	53,4	17,3	22,2
	DL90010	4,4	39,0	18,4	38,2
Scenario 11					
Equipment	DL90001	5,8	54,7	13,5	26,0
	DL90002	7,6	68,5	5,7	18,2
	DL90003	6,5	60,3	11,4	21,8
	DL90006	3,9	38,8	9,3	48,0
	DL90007	3,6	34,5	8,4	53,4
	DL90008	5,2	47,8	8,0	39,1
	DL90010	3,4	31,7	8,7	56,1
Scenario 12					
Equipment	DL90001	5,6	55,5	13,3	25,5
	DL90002	8,0	68,6	4,9	18,4
	DL90003	6,5	60,9	10,8	21,7
	DL90006	4,7	39,1	8,9	47,3
	DL90007	3,9	35,6	7,2	53,3
	DL90008	5,5	48,4	7,4	38,7
	DL90010	3,3	32,6	8,2	55,9
Scenario 13					
Equipment	DL90001	6,8	55,3	12,2	25,6
	DL90002	8,4	68,1	5,1	18,3
	DL90003	7,0	61,4	10,0	21,6
	DL90006	4,8	40,0	8,3	46,9
	DL90007	3,6	36,2	7,5	52,6
	DL90008	5,7	48,8	7,1	38,4
	DL90010	4,0	32,5	8,4	55,1
Scenario 14					
Equipment	DL90001	7,4	58,1	11,4	23,2
	DL90002	8,9	68,9	4,1	18,0
	DL90003	8,0	63,2	8,8	20,0
	DL90006	4,4	43,7	7,5	44,3
	DL90007	4,3	39,0	6,6	50,1
	DL90008	6,4	50,9	6,5	36,2
	DL90010	4,5	34,9	8,2	52,4
Scenario 15					
Equipment	DL90001	7,2	62,6	9,0	21,3
	DL90002	8,1	71,1	3,1	17,6
	DL90003	7,7	67,3	7,3	17,8
	DL90006	4,7	48,9	6,4	40,0
	DL90007	4,9	44,1	5,5	45,5
	DL90008	6,4	55,3	4,9	33,4
	DL90010	4,4	39,3	6,1	50,2

Waiting	Working	Stopped	Maintenance	Total	Maintenance and Reliability indicators	%
Time (Hours)						
327	2 630	1 334	66		Utilsation	55%
452	3 444	412	49		Availability	62%
332	2 702	1 251	72		Planned Maintenance	8%
218	1 791	2 171	177	30 499	Unplanned Maintenance	92%
212	1 757	2 163	225		Tonnes	8 745 000
311	2 500	1 426	120			
236	1 870	2 039	212			
2 088	16 694	10 794	922			
348	2 587	1 287	136		Utilsation	54%
481	3 375	400	101		Availability	61%
382	2 637	1 204	134		Planned Maintenance	16%
205	1 786	2 024	343	30 499	Unplanned Maintenance	84%
207	1 738	1 945	467		Tonnes	8 670 000
322	2 451	1 328	257			
246	1 812	1 852	447			
2 189	16 386	10 040	1 884			
320	2 573	1 172	292		Utilsation	53%
434	3 340	384	199		Availability	60%
352	2 634	1 099	271		Planned Maintenance	31%
209	1 748	1 645	756	30 499	Unplanned Maintenance	69%
197	1 693	1 528	939		Tonnes	8 468 300
306	2 387	1 174	490			
192	1 779	1 512	874			
2 010	16 154	8 514	3 821			
309	2 500	956	591		Utilsation	51%
407	3 204	346	400		Availability	57%
322	2 605	875	555		Planned Maintenance	57%
191	1 697	894	1 575	30 499	Unplanned Maintenance	43%
173	1 602	847	1 735		Tonnes	8 125 000
257	2 281	791	1 028			
191	1 591	910	1 665			
1 851	15 480	5 619	7 549			
284	2 362	564	1 147		Utilsation	46%
363	2 915	278	801		Availability	51%
311	2 485	524	1 037		Planned Maintenance	80%
172	1 577	412	2 196	30 499	Unplanned Maintenance	20%
138	1 414	374	2 431		Tonnes	7 400 000
235	1 980	366	1 776			
161	1 261	402	2 534			
1 665	13 993	2 920	11 921			
361	2 500	1 422	74		Utilsation	55%
471	3 445	391	50		Availability	62%
382	2 702	1 207	67		Planned Maintenance	8%
238	1 825	2 121	172	30 499	Unplanned Maintenance	92%
211	1 815	2 126	205		Tonnes	8 795 000
371	2 488	1 371	127			
286	1 853	2 028	191			
2 320	16 628	10 666	886			
					Utilsation	55%
343	2 517	1 355	141		Availability	62%
457	3 421	385	95		Planned Maintenance	16%
371	2 720	1 137	128		Unplanned Maintenance	84%
230	1 845	1 886	396	30 499	Tonnes	8 785 000
202	1 821	1 902	432			
321	2 519	1 270	247			
216	1 911	1 803	427			
2 140	16 754	9 738	1 868			
					Utilsation	54%
341	2 507	1 226	283		Availability	61%
438	3 364	353	202		Planned Maintenance	30%
336	2 737	1 033	251		Unplanned Maintenance	70%
237	1 812	1 600	708	30 499	Tonnes	8 700 000
199	1 784	1 538	836			
280	2 488	1 118	471			
206	1 855	1 439	858			
2 038	16 545	8 307	3 609			
314	2 465	1 000	579		Utilsation	52%
419	3 229	310	400		Availability	59%
350	2 678	827	502		Planned Maintenance	57%
192	1 812	891	1 463	30 499	Unplanned Maintenance	43%
179	1 705	803	1 670		Tonnes	8 380 000
305	2 329	755	969			
191	1 700	802	1 664			
1 949	15 917	5 386	7 246			
254	2 381	588	1 133		Utilsation	48%
332	2 986	246	792		Availability	53%
282	2 629	497	949		Planned Maintenance	80%
169	1 689	407	2 091	30 499	Unplanned Maintenance	20%
159	1 505	367	2 326		Tonnes	7 695 000
224	2 082	348	1 702			
150	1 381	380	2 445			
1 571	14 655	2 835	11 438			
246	2 419	578	1 113		Utilsation	49%
350	2 990	214	804		Availability	54%
285	2 654	472	945		Planned Maintenance	81%
206	1 703	387	2 061	30 499	Unplanned Maintenance	19%
168	1 552	314	2 323		Tonnes	7 800 000
238	2 107	323	1 688			
143	1 421	356	2 437			
1 636	14 847	2 645	11 371			
296	2 410	533	1 118		Utilsation	49%
367	2 968	223	799		Availability	55%
306	2 673	436	942		Planned Maintenance	82%
208	1 743	363	2 043	30 499	Unplanned Maintenance	18%
158	1 579	327	2 293		Tonnes	7 865 000
247	2 126	312	1 673			
174	1 417	364	2 402			
1 757	14 915	2 558	11 269			
321	2 530	495	1 010		Utilsation	51%
389	3 004	180	784		Availability	58%
350	2 753	383	871		Planned Maintenance	82%
194	1 906	326	1 931	30 499	Unplanned Maintenance	18%
188	1 700	285	2 183		Tonnes	8 335 000
278	2 219	282	1 577			
196	1 519	356	2 285			
1 917	15 631	2 309	10 643			
314	2 726	391	926		Utilsation	56%
355	3 099	137	767		Availability	62%
334	2 933	316	774		Planned Maintenance	84%
205	2 131	280	1 741	30 499	Unplanned Maintenance	16%
214	1 922	238	1 983		Tonnes	8 970 000
278	2 407	214	1 457			
192	1 713	267	2 186			
1 891	16 931	1 843	9 834			

Appendix K: Total summary

PRIMARY MACHINENAME	Sum of BKM TOTAL TIME	Sum of BKM STANDBY TIME	Sum of BKM PLANNED MAINTENANCE TIME	Sum of BKM UNPLANNED MAINTENANCE TIME	Sum of BKM PLANNED LOST OPER TIME	Sum of BKM NON OPERATING DELAY TIME	Sum of BKM OPERATING DELAY TIME	Sum of PAYLOAD	Sum of Available Time	Sum of Utilized Time	Sum of Unplanned Shutdown	Sum of Planned Shutdown
DL90001	15 627 306	130 520	219 502	2 695 921	1 602 869	4 968 232	894 032		12 581 363	5 116 230	254	20
DL90002	16 511 383	99 733	339 891	1 024 961	1 920 319	3 903 410	1 048 687		15 046 798	8 174 382	167	33
DL90003	15 706 744	119 422	171 218	2 864 793	1 348 815	3 829 305	1 023 954		12 551 311	6 349 237	248	19
DL90006	15 634 738	186 379	282 549	5 867 140	1 224 173	2 472 379	395 666		9 298 670	5 206 452	245	15
DL90007	16 024 833	74 563	422 620	5 918 385	1 243 133	2 565 884	483 016		9 609 265	5 317 232	239	21
DL90008	15 860 856	309 291	393 450	3 075 405	3 490 186	3 075 954	397 353		12 082 710	5 119 217	196	17
DL90010	15 676 813	71 330	640 339	5 868 234	989 895	2 003 493	470 912		9 096 910	5 632 610	297	38
Grand Total	**111 042 673**	**991 238**	**2 469 569**	**27 314 839**	**11 819 390**	**22 818 657**	**4 713 620**		**80 267 027**	**40 915 360**	**1 646**	**163**
FE90003	15 639 847	582 198	232 868	5 733 625	1 175 579	1 998 207	310 927	1 773 843	9 118 903	5 608 511	321	58
FE90005	15 638 537	220 159	598 208	2 281 341	1 495 387	2 401 130	360 604	2 304 153	12 543 755	8 281 708	242	94
FE90010	15 604 832	487 838	401 089	5 362 994	1 192 277	1 727 164	294 924	1 777 673	9 353 491	6 138 546	298	69
FE90012	15 645 184	235 598	447 784	4 053 712	1 203 569	1 772 758	360 884	2 504 788	10 958 014	7 570 879	396	81
Grand Total	**62 528 400**	**1 525 793**	**1 679 949**	**17 431 672**	**5 066 812**	**7 899 259**	**1 327 339**	**8 360 458**	**41 974 163**	**27 599 644**	**1 257**	**302**
DT90004	15 634 439	1 931 513	1 777 201	1 114 293	1 547 642	3 002 480	32	566 567	11 293 478	6 261 278	90	57
DT90005	15 631 864	1 824 084	171 809	859 460	1 586 042	3 483 771	-	597 172	13 069 488	7 706 698	87	20
DT90006	15 638 604	1 792 927	198 037	1 323 274	1 526 179	2 670 890	243	684 327	12 915 655	8 127 054	101	27
DT90007	15 636 571	1 427 611	135 658	3 427 407	1 358 613	2 432 538	-	574 381	11 171 148	6 854 744	138	16
DT90008	15 640 753	1 791 478	189 521	1 438 387	1 430 572	2 283 610	332	712 979	12 635 922	8 506 853	119	20
DT90009	15 637 424	1 582 839	197 912	4 661 731	1 115 658	1 772 797	-	581 675	9 560 045	6 306 487	193	25
DT90010	15 634 395	1 889 451	227 387	2 118 878	1 283 177	2 011 312	-	700 663	11 898 089	8 104 190	128	23
DT90011	15 636 660	1 784 102	217 742	1 292 147	1 339 726	2 382 006	87	751 688	12 813 604	8 620 850	103	22
DT90015	15 658 900	1 526 996	150 764	576 691	1 555 303	2 517 660	-	849 918	13 838 882	9 331 486	77	15
DT90020	15 627 556	2 116 247	206 470	430 218	1 539 332	2 262 407	4	781 669	13 405 795	9 072 878	88	23
DT90021	15 641 062	1 547 220	321 348	1 491 191	1 573 764	2 077 109	1 733	758 963	12 732 080	8 628 697	123	26
DT90022	19 353 255	2 304 848	274 069	1 211 004	1 722 974	2 703 961	-	873 588	16 518 270	11 136 399	105	31
Grand Total	**191 371 483**	**21 519 316**	**4 067 918**	**19 944 681**	**17 578 982**	**29 600 541**	**2 431**	**8 433 591**	**151 852 456**	**98 657 614**	**1 352**	**305**

1) **Loading:** Total payload tonnage divided by utilised time indicates the hourly rate ranges between 1227 and 1583 tons per hour and an average of 1100 tons per hour.

2) **Hauling:** Total payload tonnage divided by utilised time indicates the hourly rate ranges between 289 and 334 tons per hour and an average of 315 tons per hour