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Defining main prioritized remedial actions of maintenance using root cause analysis on mining equipment

Bachelor Thesis

by
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Statutory Declaration

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I hereby affirm in lieu of an oath that I provided the submitted bachelor thesis

Defining main prioritized remedial actions of maintenance using root cause analysis on mining equipment

I did not use any sources other than those stated. In case that the work is additionally submitted on a data medium, I declare that the written and the electronic form are completely identical. The work was not submitted in the same or similar form to any examination authority.

Ulaanbaatar, 2022.05.16
Place, Date

Signature

Acknowledgment

First of all, I would like to express my sincere gratitude to all the professors and staff at the German Mongolian Institute for Resources and DAAD for their continuous support over the years. Moreover, I convey my deepest gratitude to my supervisors, Prof. Manfred Hampe and Prof. Enkhzaya Chuluunbaatar, for their guidance and wisdom throughout my thesis work.

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Last but not least, I am very thankful to my family and friends for enabling me to be here and for supporting and encouraging me during my bachelor’s studies.

Abstract

Maintenance accounts for the largest portion of mining's controllable operating cost. In this thesis, a methodology to define prioritized remedial actions for failures using FMEA, as root cause analysis, is proposed, covering 4 main phases: Problem area identification, Downtime priority determination, Candidate equipment selection, Determination, and analysis (FMEA) of failure modes for selected equipment. The data used in the thesis was real-time data of Monnis Mining LLC, one of the Mongolian coal mining companies.

Multiple failure analysis techniques can be found in the literature. In this thesis, the logarithmic scatter plot of mean time to repair vs failure frequency was employed to categorize failures into acute and chronic failures. Through the use of a logarithmic scatter plot, the identification of problems affecting fleet availability, reliability, and maintainability was determined. To determine maintenance priority, the economic consequences of failure were considered. Due to the fact that, at the time of writing, the coking coal price was at a five-year high, production was prioritized over maintenance cost, hence availability and reliability over maintainability. The maintenance priority was then used to define a prioritized list of component failures and these failures were considered to be critical component failures. The most critical components were steering and final drive, having the highest downtime contribution.

The critical component failures were used as a base for selecting candidate equipment for FMEA and TR3105 was chosen for the purpose as it was contributing one-third of total downtime caused by braking system failure for the whole fleet and had the highest number of critical component failure frequency. From the analysis, the notable thing was that most of the critical failures were occurring on specific equipment. Therefore, it can be concluded that these failures were not common characteristics for the whole fleet and it could be desirable to mitigate the effects of critical failures equipment by equipment for the case study, instead of taking an action for the whole fleet.

After the equipment was chosen for the analysis, the FMEA worksheet was used for the analysis. In the worksheet, the failure modes of candidate equipment were determined and

for each of them, the risk priority number (RPN) was calculated to prioritize these failure modes. But the remedial actions for these failure modes were not identified since the goal of the thesis was to only propose a methodology to define prioritized remedial action, moreover, the FMEA is a team-based project and needs a variety of perspectives and experience, especially on mechanical engineering in which the writer lacks knowledge. But having a prioritized list of failure modes means having a prioritized list of remedial actions. Thus, the thesis work did not go further as it reached the goal.

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1 Introduction

Maintenance in the mining sector has been extremely relevant for decades. For this sector equipment downtimes can involve considerable amounts of time, effort and financial losses. Thus, defining maintenance priority and remedial actions for cause of failure has been implemented to help allocate resources effectively, especially it can be essential for low budget small companies that are starting to shape their own maintenance management. In this thesis a method to prioritize remedial actions for equipment failures is proposed to cover the stages of an effective maintenance prioritization strategy for the case of mining equipment of Monnis Mining LLC which operates in Tavantolgoi Coal mine in Mongolia.

1.1 Company background

In this subchapter the intent of the company. Moreover, an overview of Monnis Mining LLC (MM) and failure prioritization of the equipment Terex 60 dump truck will be presented.

MM is Mongolian coal mining contract company of Erdenes Tavantolgoi JSC in the Tavan Tolgoi open pit mine. The company conducts its operations with mining and earthmoving equipment such as Terex 60, Liebherr T264 dump trucks, Liebherr R996, R9350 excavators and PR776 bulldozers.

1.2 Problem statement and motivation

The company suffers from low equipment availability which has an adverse impact on profitability. To increase its availability, decreasing downtime caused by unplanned failure could be one solution. Thus, the thesis has a goal to propose methodology to mitigate the effects of unplanned downtime and determine prioritized remedial actions.

1.3 Objectives of the thesis

The fundamental idea behind this thesis work is to propose methodology that allows to determine prioritized remedial actions using root cause analysis.
For this end, a set of objectives are defined as follows.

1. To decompose the truck system into subsystems.

    a. The decomposition of the truck system into subsystems will help facilitate the failure analysis by categorizing the failures.
2. To determine component failures responsible for most downtime and get a prioritized list of component failures.
    a. The determination of critical subsystems will narrow down the focus of analysis.
3. To select candidate equipment for further analysis
    a. The information from the prioritized list of critical components will be used to select candidate equipment.
4. To perform root cause analysis
    a. Root cause analysis will be performed to determine the prioritized remedial actions
5. To determine prioritized remedial actions

1.4 Expected outcome

As an outcome of this thesis work, a practical method that can be used for problem solving and prioritizing remedial actions is developed.

1.5 Assumptions and Limitations

The data used in this thesis has several assumptions which limit its application.

On one hand, the estimates of repair time obtained from maintenance personnel were not reflected accurately due to improper repair time recording. Because some recorded repair time was incorporating repair time of different system failures in it and had to be separated which distorted the accurate repair time.

On the other hand, there could be factors, other than repair time itself, dominated equipment downtime, such as delays caused by lack of resources (spare parts, labor, tools or shop space).

2 Theoretical background

In this chapter most relevant concepts that provide groundwork of the thesis are outlined, For each section, a brief description and review of the related work is described, and finished by a conclusion that justifies why they are selected and used for the thesis.

2.1 Maintenance management methods

Maintenance accounts for 30-60% of the total operating cost for a typical mining company and takes a dominant portion of the company's controllable operating costs.[2] This, coupled with the fact that the mining industry today is facing a more demanding marketplace, inevitably has increased an interest in methods to reduce maintenance costs. There are several types of maintenance management strategies for the cause. According to Mobley[1], four main categories of maintenance management are:

1. Run-to-Failure management
2. Preventive maintenance
3. Predictive maintenance
4. Other maintenance improvement methods

2.1.1 Run to failure management

Since the first manufacturing plant was built, it has been one of the most commonly used maintenance managements. The logic behind run to failure management is pretty simple. When a machine breaks down, fix it[1]. In this way, maintenance efforts are minimized and does not spend any money on maintenance, allowing the asset to operate until it cannot provide more service. However, it is the most expensive method of maintenance strategy. The major associated expenses for this maintenance strategy are high spare parts inventory cost, high labor costs, high machine downtime and low equipment availability.

This reactive maintenance method forces the maintenance department to maintain extensive spare parts inventories due to its nature that it must be able to react to all possible failures. The other possible alternative is to rely upon equipment vendors that provide expedited delivery which makes the cost of repair parts and downtime required to correct machine failures increase substantially.

2.1.2 Preventive maintenance

Preventive maintenance has many definitions, but one thing in common among them is that all preventive maintenance management programs are time-driven. Expressly, maintenance tasks are defined using elapsed time or hours of operation. Figure 1 illustrates the bathtub curve which indicates that a new machine has a high probability of failure because of improper installation during the early time of operation. After this period, the probability of failure becomes relatively low during the normal machine life period. After this normal life period, the probability of failure surges up with elapsed time.

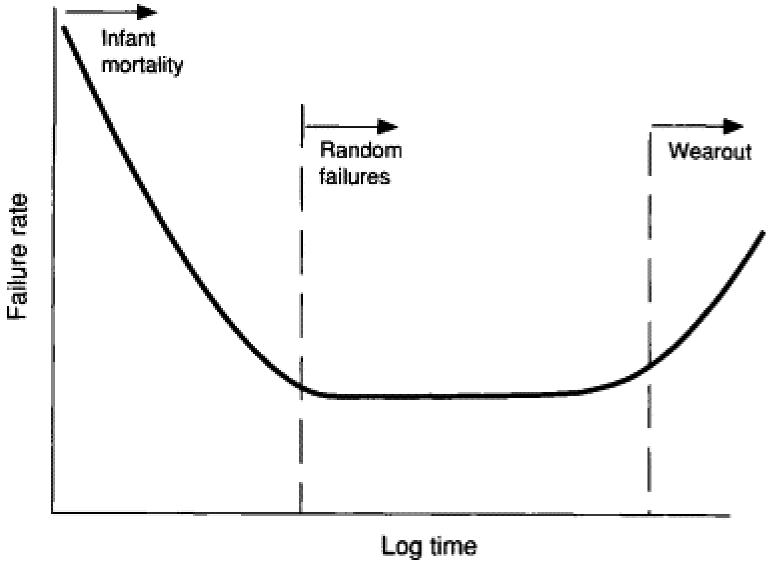

Figure 1. Bathtub curve[11]

More specifically, in preventive maintenance management, mean-time-to-failure (MTTF) statistics are used to schedule machine repairs or rebuilds and the management assumes that machines will degrade within a time frame typical of their particular classification. But the problem with this approach is that the operating life of equipment is directly affected by the mode of operation and system variables. The mean-time-between-failures (MTBF) is not the same for equipment with different operating conditions. The common consequence of using MTBF statistics to schedule maintenance can be unnecessary repairs or catastrophic failure.

2.1.3 Predictive maintenance

As R. Keith Mobley stated in his book, “predictive maintenance is a philosophy or attitude that, simply stated, uses the actual operating condition of plant equipment and systems to optimize total plant operation.” A comprehensive predictive maintenance management obtains the actual operating condition of critical plant systems using the most cost-effective tools and based on the result schedules all maintenance activities in accordance with needs. The benefits of implementing predictive maintenance as part of a comprehensive maintenance management program optimizes the availability of equipment and greatly reduces the maintenance cost. Other mentionable benefits include improvement of product quality, productivity, and profitability of manufacturing and production plants.

Unlike the preventive maintenance program relying on average life statistics, predictive maintenance or condition-based maintenance uses direct monitoring of the mechanical condition, system efficiency, and other indicators to determine the actual MTTF or loss efficiency for each machine-train and system in the plant.

Five nondestructive techniques that are used for predictive maintenance are as follow:

1. Vibration monitoring
2. Process parameter monitoring
3. Thermography
4. Tribology
5. Visual inspection

2.1.4 Other maintenance improvement methods

Over the past 10 years, a variety of management methods have been developed and touted as panacea for ineffective maintenance.[1] The two of the methods are reliability-centered maintenance (RCM) and total productive maintenance (TPM) which are quick-fix methods in an attempt to compensate for recognized maintenance shortcomings.

2.1.4.1 Total productive maintenance

The TPM concept was developed by Deming in the late 1950s and, as adapted by the Japanese, stresses absolute adherence to the basics, such as lubrication, visual inspections, and well-known best practices in all aspects of maintenance.

At the core of TPM is a new partnership among the manufacturing or production people, maintenance, engineering, and technical service to maintain and improve the integrity of production, quality and what is called overall equipment effectiveness (OEE). It is program of being effective at improving or eliminating the following six crippling shop floor losses:

- Equipment breakdowns
- Setup and adjustment slowdowns
- Idling and short-term stoppages
- Reduced capacity
- Quality-related losses
- Startup/restart losses

It is difficult to come up with a concise definition of TPM, but one can say it is about improving effectiveness.

2.1.4.2 Reliability centered maintenance

According to R. Keith Mobley, the basic premise of RCM is that all machines must break down and have a finite life-span, but neither of these assumptions is well grounded. If equipment and any system are properly designed, installed, operated and maintained, there will not be failure, consequently their life-span is almost infinite. And the cause of the failures would be random and caused by outside influence such as operator error or improper repair. If all instantaneous failures caused by aggregate operator error or any abnormal outside influence are taken as exceptions, the detection, isolation and prevention of system failure can be achieved through the operating dynamics analysis methodology.

Because RCM is founded on the belief that all machines will degrade and fail according to the P-F curve (see figure 2), failure modes and effects analysis (FMEA) and Weibull distribution analysis are commonly used to anticipate failure occurrence. These two theoretical methods are based on probability tables that presume genuine design, installation, operation and maintenance of equipment. But neither of these methods is able to adjust for abnormal deviations.

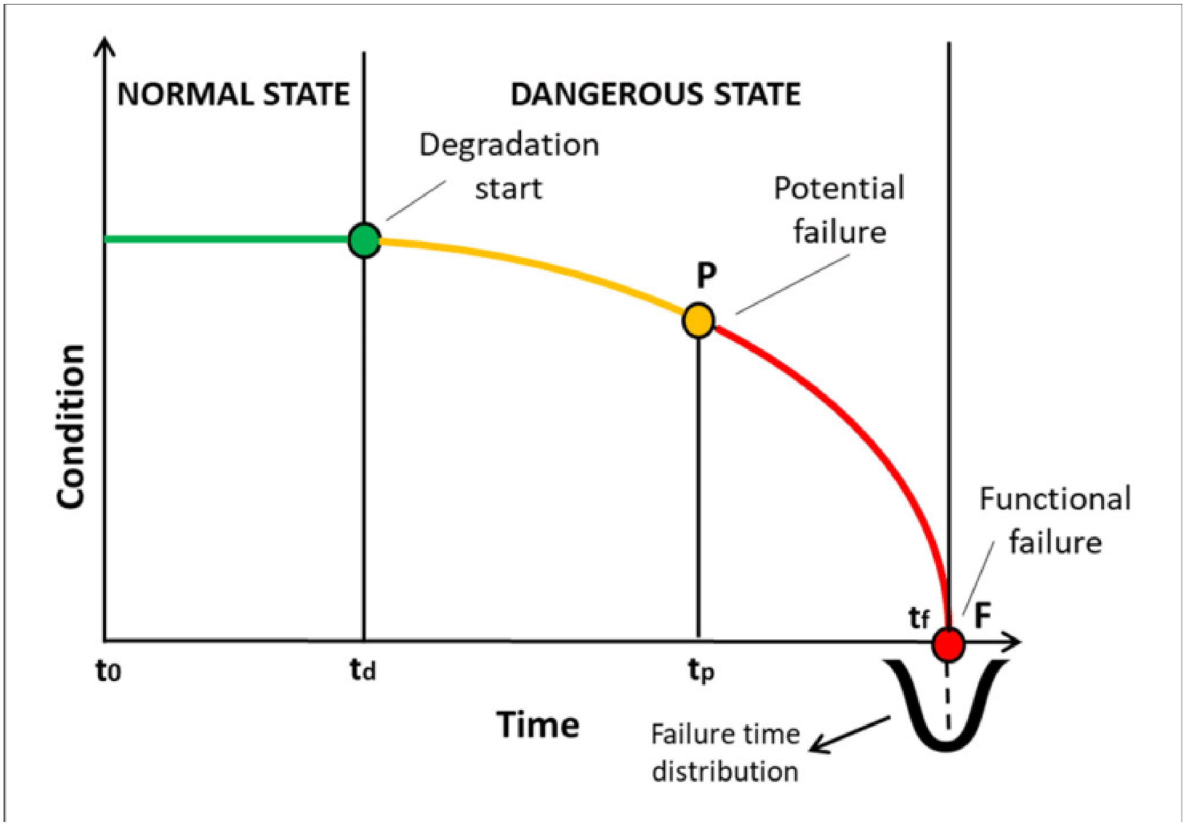

Figure 2. P-F curve[12]

More generally RCM is a systematic method to keep a balance between preventive and corrective maintenance activities. This method chooses the right preventive maintenance activities for the right component at the right time to reach the most cost-efficient solution. RCM is characterized by maintaining system function, identifying failure modes, prioritizing functions and choosing efficient maintenance. RCM is a technique that is used to develop cost-effective maintenance plans and criteria so that operational capability of equipment is achieved, restored or maintained. Accordingly, the main objective of RCM is to reduce the maintenance cost by focusing on the most important functions of the system. The following basic steps for RCM analysis:

1. Defining the system and/or subsystems and boundaries.
2. Defining the functions of each system or subsystem identifying functionally significant item (FSI).
3. Identifying the pertinent FSI functional failure causes.
4. Predicting the effects and probability of these failures
5. Using a decision logic tree to categorize the effects of the FSI failures.
6. Identifying applicable and effective maintenance tasks which comprise the initial maintenance program.

7. Redesign of the equipment or process, if no applicable tasks can be identified.
8. Establishing a dynamic maintenance program, which results from a routine and systematic update of the initial maintenance program and its revision assisted by the monitoring, collection and analysis of in-service data.

2.2 Pareto analysis

Vilfredo Pareto (1842-1923), an Italian engineer, created histograms of the distribution of wealth in Italy and concluded that 80 percent of the country's wealth was owned by 20 percent of the Italian population. This trend was later well known and became representative of the distribution of other data populations. The 80:20 rule, or an ABC analysis which uses an 80:15:5 classification rule, is now routinely used in many fields of study as being useful for analysis where many possible courses of action are competing for attention.

2.2.1 Pareto analysis in maintenance application

To reduce maintenance costs, companies seek to optimize its maintenance function and identify areas of improvement in the maintenance process, seeking to find failure codes responsible for the majority of equipment maintenance cost or downtime. For that reason, mostly, Pareto analysis is commonly used for identifying such codes. However, Pareto histogram does not readily show:

1. which factor or factors are dominant in contributing to the downtime or cost of maintenance
2. which individual events have high associated costs or downtime or failure frequency of the codes

In order to overcome such shortcomings, the thesis work used a logarithmic scatter plot which preserves an order of priority observed in Pareto histogram and, moreover, shows which factor – failure frequency or mean downtime – is dominant.[2]

2.2.2 Logarithmic scatter plot as establishment tool for defining problem area

In order to overcome shortcomings of Pareto histogram, Peter F. Knights[2] proposed a logarithmic scatter plot which preserves an order of priority observed in Pareto histogram and, moreover, shows which factor – failure frequency or mean downtime – is dominant for corresponding failure codes (See figure 2).

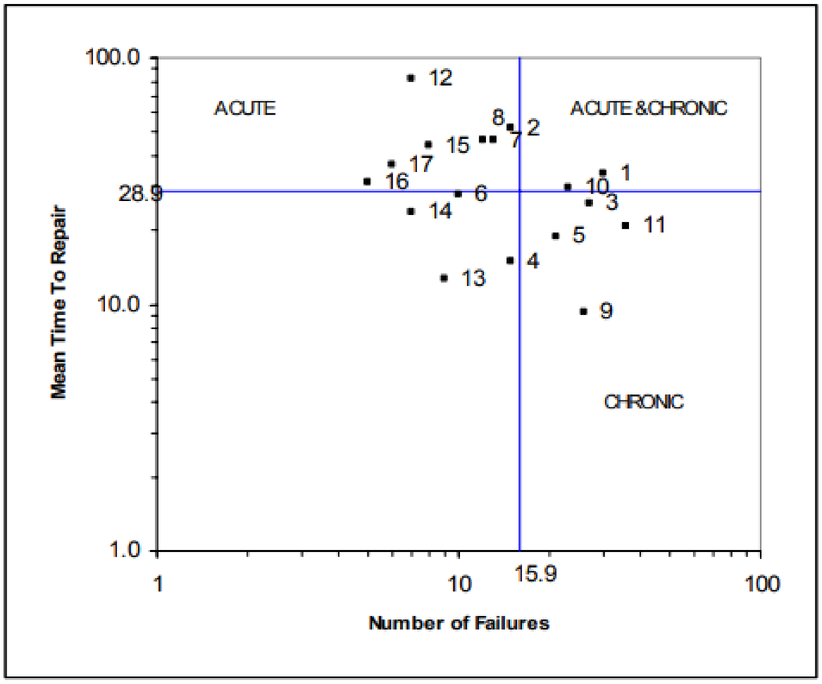

Figure 3. Log dispersion plot of mean repair times versus number of failures[3]

In figure 3, Peter F. Knight used threshold limit values, which are MTTR for all failure codes (28.9) and mean number of failures (15.9), in order to distinguish which failure codes are which kind of failures (e.g. acute, chronic and acute & chronic) by dividing the figure into quadrants. Moreover, by setting the limits, logarithmic scatter plots make it easy to identify reliability, availability and maintainability problems.[2] Jack-Knife limits can be established in order to determine failure priority. The Jack-knife limit considers the relative importance of repair costs to the economic consequences of downtime in its orientation, which is affected by change in the business cycle. How the threshold limits and jack-knife limit are established in the scatter plot will be discussed in the methodology section.

The use of logarithmic scatter plots does not mean it should replace traditional Pareto analysis techniques for they can be beneficially used in parallel. More specifically the information provided by scatter plot can be usefully adapted for use in conventional Pareto analysis.

The log scatter plots and jack-knife diagrams have shown they are strong analysis tool as they have been employed by a number of mining companies and mining equipment suppliers.[3]

2.3 Root cause failure analysis

Reliability engineering and predictive maintenance have two main objectives:

- Preventing catastrophic failures of critical plant production systems
- Avoiding deviations from acceptable performance levels

that result in injury related safety issues, environmental impact, capacity loss, or poor quality of product.[4] Unfortunately, these events will happen no matter the effectiveness of the reliability program you have. Consequently, a process for fully understanding and correcting the root causes that lead to any critical events must be included in a viable maintenance program.

The purpose of root-cause-failure-analysis (RCFA) is to determine and fix problems that have an impact on plant performance.[4] It provides comprehensive classification of problems and the common problem classifications are:

- Equipment damage or failure
- Operating performance
- Economic performance
- Safety
- Regulatory compliance.

The classification establishes a knowledge base for analysts to deal with problems related to process reliability, availability and maintainability. With respect to inadequate training, human (operator and maintenance engineer) errors and attitude, can contribute to unreliability and machine related problems such as, poor calibrations or misalignments may result in low operational efficiency.

Chemweno, P.[4] distinguishes three broad categories in which RCA can be divided:

- Qualitative
- Semi-quantitative
- quantitative techniques.

2.3.1 Qualitative RCFA

In qualitative-based approaches, they represent causes based on descriptions and representations in diagrams and the commonly used ones are Ishikawa cause-and-effect diagrams and the ‘5-whys’ analysis. These techniques are based on quality-management methodologies and are used along with other techniques such as Pareto histogram representation.[6]

2.3.2 Quantitative RCFA

Quantitative approaches, on the other hand, use context and behavioral data for analysis. Mostly it is used when big data is available.

2.3.3 General analysis techniques

There are a number of general techniques useful for problem solving. This subchapter provides a brief overview of common techniques that are used to perform an RCFA. Mobley[4] defined the general techniques as follows:

1. Failure mode and effect analysis
2. Fault tree analysis
3. Cause and effect analysis
4. Sequence of events analysis

2.3.3.1 Failure mode and effect analysis

Failure mode, effect and criticality analysis (FMECA) is mostly done when performing an RCM analysis[7] and it is one of the common RCFA methods. As a tool it is used to evaluate potential failure modes, their effects and causes systematically. Failure modes mean the ways in which something could fail. Effects analysis relies on examining the consequences of those failures. The main purpose of the FMECA is to eliminate or reduce failures by taking remedial actions, starting with the highest-priority ones. The analysis can be done either qualitatively or quantitatively. Basic steps in performing a FMECA could be:

1. Define the system to be analyzed and it includes defining of system boundaries, identification of internal and interface functions, expected performance and failure definitions.

2. Identify failure modes for each system failure.
3. Identify potential effects of failure modes. Here the main question would be: what happens when the failure occurs?
4. Determine how serious each effect is and rank them.
5. Determine all the potential root causes for each failure mode.
6. Identify available detection methods and rank them based on defined criteria.
7. Identify remedial actions for each cause that can reduce the severity of each failure.

To evaluate failure modes, the usual parameters of the FMEA is used and the parameters are the frequency O, which characterizes occurrence failure modes, the severity S, which characterizes the duration of the outage caused by the failure mode detectability and D, which characterizes the probability of detecting the failure before it starts to take corrective or preventive actions. From the three previous parameters the criticality C or risk priority number (RPN) is calculated as shown in equation 1. It allows analyzing the risk and can be used to set the threshold of acceptability for each failure mode.

$$S \times O \times D = RPN \qquad (1)$$

Figure 4 shows a typical logic tree that results with a FMEA.

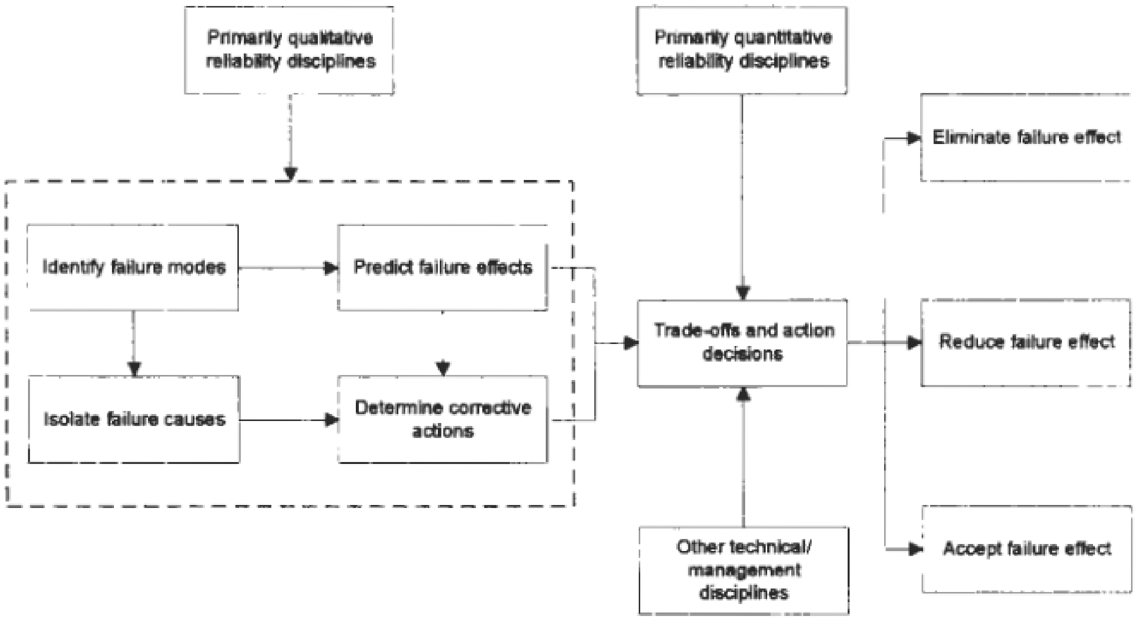

Figure 4. Typical failure mode and effects analysis flow diagram.[1]

2.3.3.2 Fault tree analysis

Fault tree analysis is mostly used to analyze system reliability and safety. It is different from a FMEA as it identifies system elements and events that lead to one particular failure and it does not go any further.

Fault tree analysis is one of the detailed deductive analysis that requires a large amount of information about the system to be analyzed and makes it simple to understand system failures deductively and points out the aspects of the system that are important with respect to the failure of interest. More generally, it provides insight into system behavior. Typical fault tree process is shown in Figure 5.

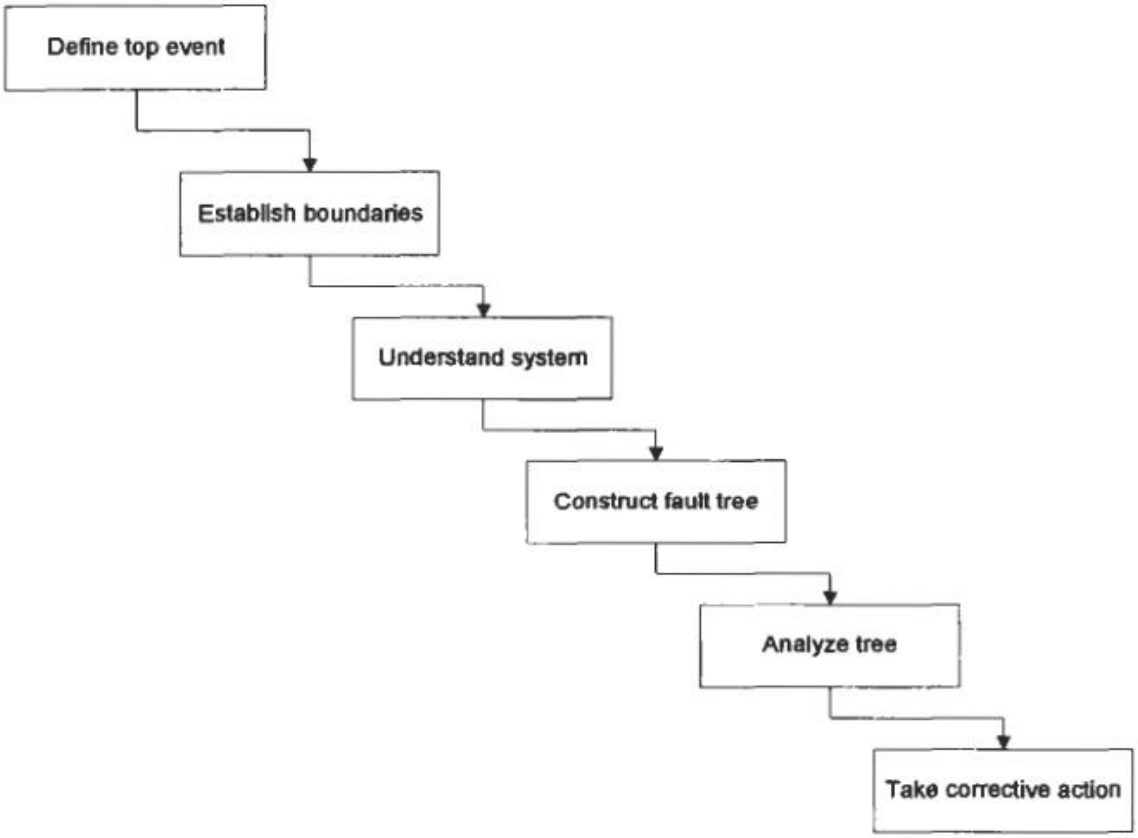

Figure 5. Typical fault tree process.[1]

A fault tree model graphically and logically determines the various combinations of possible events that lead to the top event in the associated system. The term event indicates a dynamic change of state in a system element, including hardware, software, human and environmental factors.

2.3.3.3 Cause and effect analysis

Cause and effect analysis or fishbone analysis is one of the graphical approaches to failure analysis. In most cases the cause and effect analysis plots four major classifications of potential causes: human, machine, material and method. Figure 6. Illustrates a simple analysis.

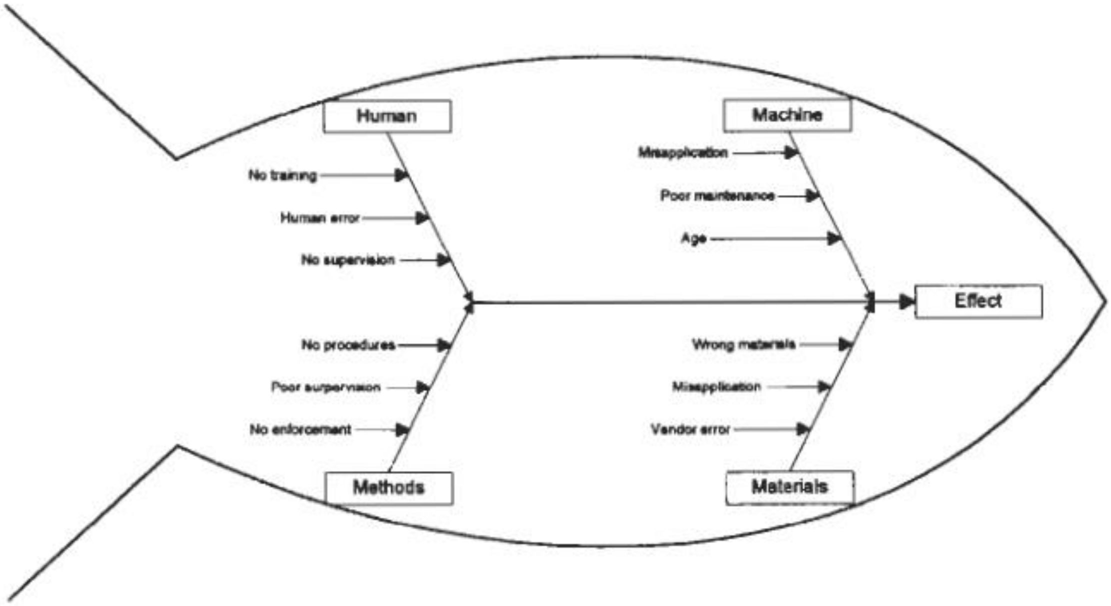

Figure 6. Typical fishbone diagram that plots four categories of causes.[1]

The main feature that sets it apart from any other analysis method is that it uses the fish-shaped graph to plot the cause-effect relationship between specific actions and the end result. But it has one series limitation and that is it does not provide a clear sequence of events that leads to failure. Instead it presents all possible causes and does not isolate the specific factors that caused the event.

2.3.3.4 Sequence of events analysis

There are a number of software programs that can be used to generate a sequence of events diagrams. One example could be Microsoft's Visio. In the diagram each event that is investigated should be included. Consequently, It helps to organize the information collected, identify missing or conflicting information and improve the understanding by showing relation between events and the incident, and calls attention to potential causes of incident. Figure 7 is shown to provide an example of the diagram.

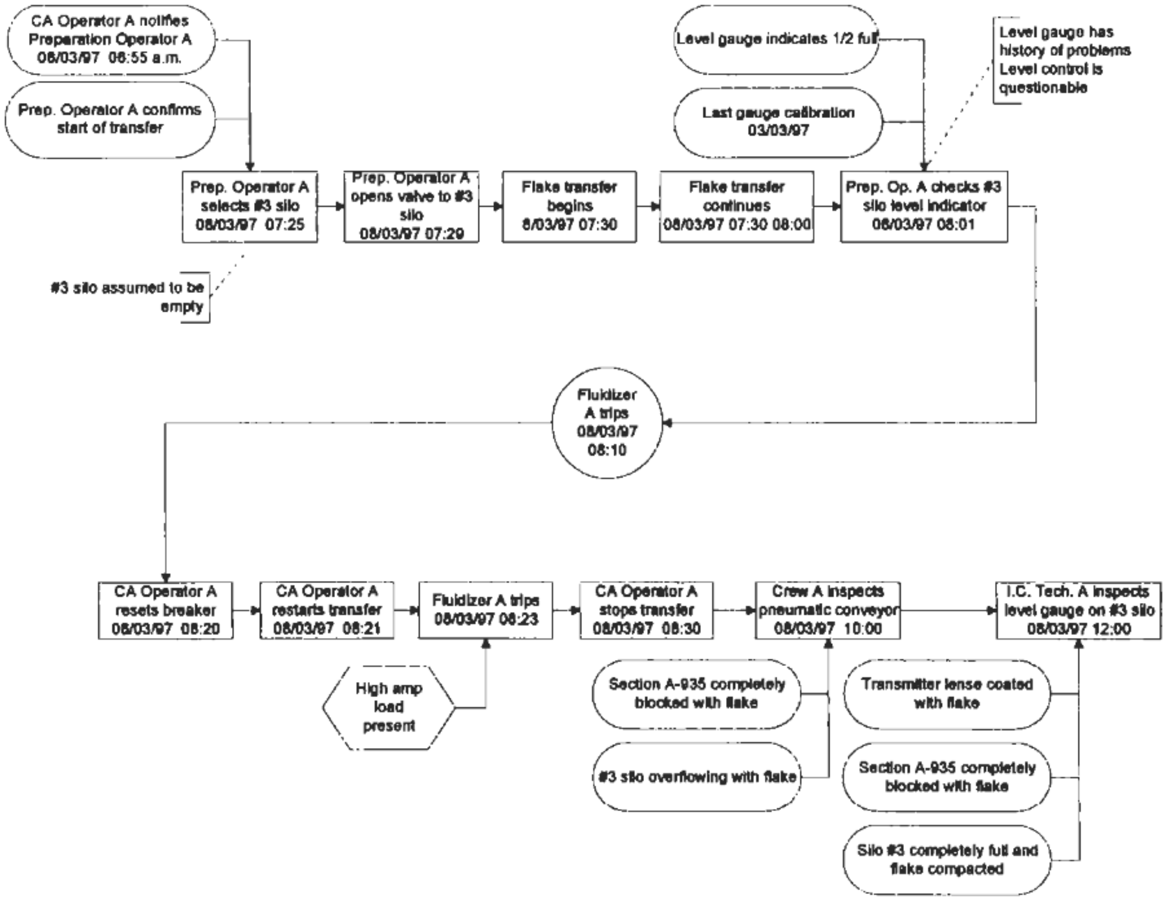

Figure 7. Typical sequence of events diagram.[1]

2.4 Conclusions and remarks

This thesis focuses on providing means for Reliability Centered Maintenance. Considering that the company does basic Preventive Maintenance (PM) services for equipment which is suggested in the maintenance book and there is a significant amount of unplanned downtime, the RCM could be a suitable maintenance method for the company to keep balance between preventive and corrective maintenance. For that reason, the RCM method is considered to be desirable.

When it comes to analysis of data to get deep understanding of equipment condition or fleet condition, Pareto analysis tool is simple yet powerful tool to define system which causes the most downtime or maintenance cost and the use of logarithmic scatter plot in the analysis provides more detailed information on classification of failure and their respective problem areas: availability, reliability and maintainability.

For the main analysis of root cause analysis, FMECA is a practical tool when performing an RCM analysis[7] and it is one of the common methods used to perform an RCFA. Moreover, it defines recommended actions or remedial actions for each failure mode.

3 Methodology

The methodology proposed in the thesis work aims to meet the stages of RCM and the data used here is from the fleet of Terex 60 dump trucks of Monnis mining LLC. The main stages specified in this thesis for this maintenance methodology are: Problem area identification, Downtime priority determination, Candidate equipment selection, Determination and analysis (FMEA) of failure modes for selected equipment.

There is one thing that should be noted that the information in FMEA worksheet filled by thesis work lacks knowledge specially on cause and remedial actions, since the FMEA is a team-based project, needs a variety of perspectives and experience, on top of that the analysis was done by industrial engineering student who has lack of experience in mechanical engineering. The purpose of this thesis is to propose a method, that was practiced and implemented in the field, to define prioritized remedial actions.

3.1 Problem area identification

In order to prioritize remedial actions, we have to know fleet conditions and define what failures most happen in which system and what main problem areas are. For that purpose, first, we have to decompose the equipment system into subsystems.

3.1.1 Decomposition of equipment into sub-system

The first step in the pareto analysis was to decompose the mining equipment into appropriate subsystems to analyze system and component reliability. The decomposition of the truck system model defined by Morad A. et al was used for the thesis work (See figure 8).

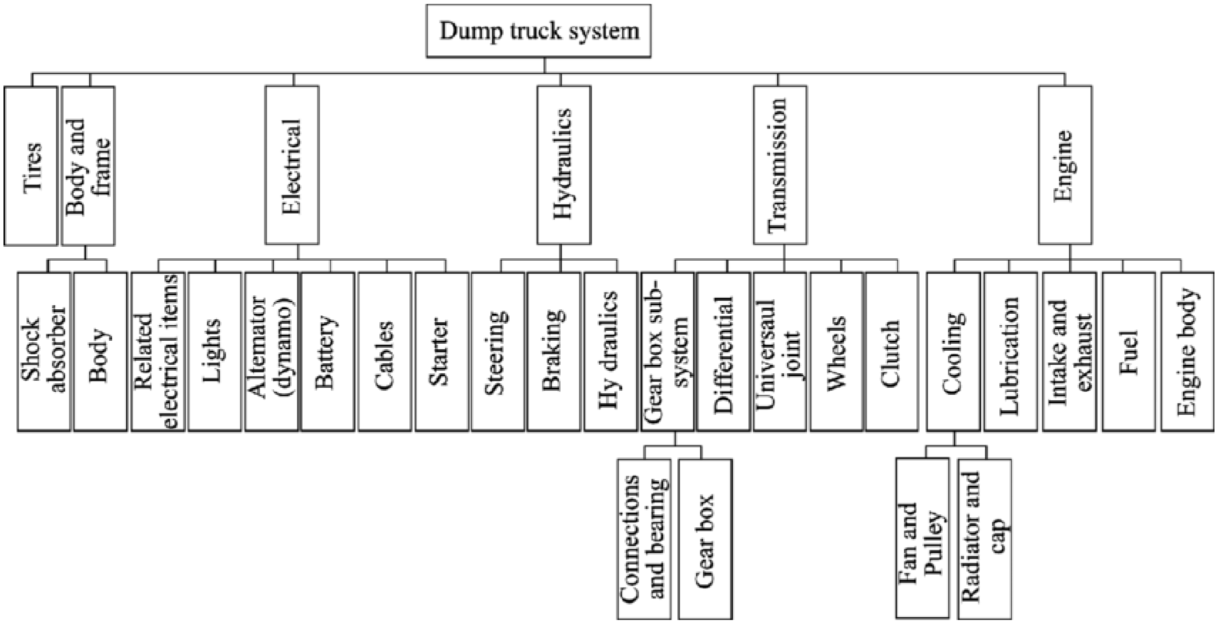

Figure 8. Dump truck system decomposition[8]

The figure 8 shows the hierarchical decomposition of the dump truck system into main sub-systems and their corresponding components. Based on the decomposition model, the recorded failure data and repair time for the associated failures in each subsystem were then used to plot cumulative percentage of downtime (Pareto histogram) to identify which system has the most downtime contribution to the fleet of Terex 60 dump trucks. It is typical to find that approximately 80% of the downtime is a result of 20% of the failures and maintenance efforts should focus on these failures.

3.1.2 Identification of reliability, availability and maintainability problems

To define significant problems, the reliability, availability and maintainability problems were defined and for that purpose the logarithmic scatter plot of MTTR vs failure frequency was used and the methodology used here follows steps Peter F. K. has defined.[3] To calculate MTTR, downtime data and the Equation 2 were used. The Maintenance downtime can be calculated by the equation:

$$Downtime_i = n_i \times MTTR_i \qquad (2)$$

where $Downtime_i$ is the downtime related to the ith failure code and n_i and $MTTR_i$ represent the number of failures and mean time to repair correspondingly.

These scatter plots provided easy means of identifying which failures are in which problem for the whole fleet and based on this information we could select the problem area, by having identified the threshold limits. In order to create these scatter plots the following equations were used.

With strict attention to detail, reliability is a probability of survival and a function of time. Mean time between failures (MTBF) are mostly used as a measure of reliability. The MTBF is calculated as;

$$MTBF = \frac{Operating\ time}{N} \tag{3}$$

Truck availability and reliability are interrelated by the approximation;

$$Availability \cong \frac{MTBF}{MTBF+MTTR} \tag{4}$$

There are two values that determine threshold limits: absolute values determined by company policy, and relative values that depend on the relative magnitudes and quantity of data. In this thesis work, the thresholds were determined by using relative values which use average values using equations 7 and 8. And these 2 thresholds divide the scatterplots into quadrants and define maintainability and reliability problems (see figure 6, 7 and 8).

The total downtime, D, caused by unplanned failures is calculated as:

$$D = \sum_i Downtime_i \tag{5}$$

The total number of failures is:

$$N = \sum_i n_i \tag{6}$$

The threshold limit for acute problems which belong to the maintainability problem (acute failures) is defined as:

$$Limit_{MTTR} = \frac{D}{N} \quad (7)$$

and the threshold limit for reliability problem (chronic failures) can be defined as:

$$Limit_{n} = \frac{N}{Q} \quad (8)$$

where Q is the number of distinct failure codes used to categorize the downtime data.

To determine the availability limit, for ease of construction, the constant downtime equal to the product of the two threshold limits calculated in equations (7) and (8) was used. Here the availability limit effectively divides the quadrants of acute and chronic into two areas, acute A and B and chronic A and B correspondingly. The expression that was used for the availability limit is:

$$n_i \times MTTR_i = \frac{D}{Q} \qquad where \quad 0 < n_i < \infty \quad (9)$$

The result of determining threshold limits will be shown in the “Results” section of the thesis.

3.2 Downtime priority determination for failure codes

Maintenance priority was determined on the basis of the economic consequences of failures, which includes opportunity cost of lost production, fixed costs which must be paid irrespective of equipment downtime, the cost of maintaining an increased number of spares and redundant equipment capacity to mitigate the effects of lost production. The priority was used only to prioritize maintenance problems; hence the prioritized list of failure codes would be defined.

In the mining industry, the economic consequence of mining equipment downtime far outweighs repair and maintenance costs and its industry is subject to highly cyclical commodity prices. On one hand, when commodity prices are currently at five-year high the opportunity cost of lost production will far exceed the maintenance and repair cost, hence it is desirable to prioritize production, more specifically equipment availability and reliability over maintainability. On the other hand, when the price troughs, the cost of production becomes more important to pay attention to and significance of controlling and reducing the maintenance and repair related costs will be as high as maintaining availability and reliability.

Based on current market conditions, the coking coal price was at a five-year high (see Figure 9) and the thesis work assumed that the opportunity cost of lost production would significantly exceed the direct cost of repair and maintenance and prioritized production. And the additional prerequisite in the case study was that the low availability was a problem the company was facing. Hence the equipment availability and reliability took priority over maintainability.[3]

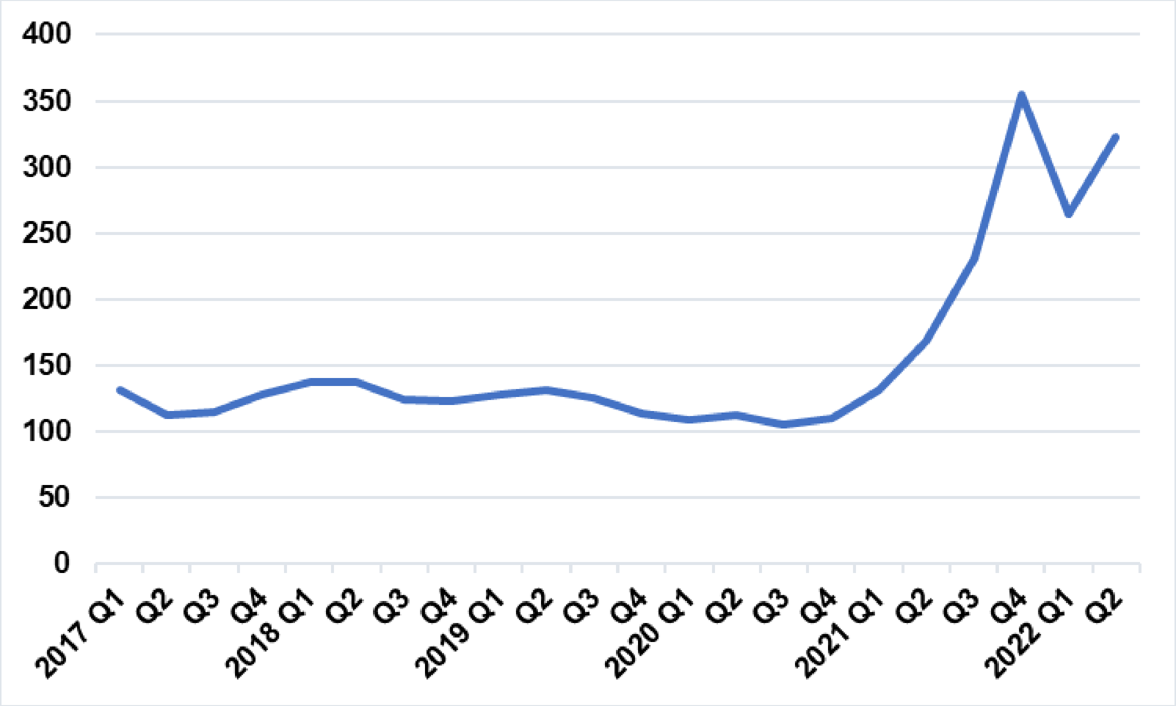

Figure 9. The average coking coal price informed by Mongolian mineral resources and petroleum authority.

To have more accurate data on coking coal price, the figure 10 was plotted by using data of international market price information for exported mineral products as Mongolian mineral resources and petroleum authority informed on the monthly basis on their website.

3.3 Candidate equipment selection

By prioritizing availability and reliability, failures associated with them were defined using a logarithmic scatter plot. Using the information from the scatter plot, the remedial actions for the whole fleet could have been determined since it used whole fleet data. But instead this thesis used the information as base for candidate equipment selection for FMEA. The reason why one equipment was selected was that in fact each individual equipment condition and aging could be different due to different operating and maintenance conditions and the equipment here considered was not from the same generation. Thus, it was ideal to tailor remedial actions for each equipment. Moreover, in FMEA, traditionally, one candidate equipment is selected for the FMEA.

To choose the candidate equipment, the prioritized list of failure codes was used. The prioritized failure codes would show what failures were critical and from the information we could track the responsible equipment.

3.4 FMEA on selected equipment

This subchapter has 3 main phases: Listing failure modes, assigning severity, occurrence and detection ranking, Determining prioritized remedial actions.

3.4.1 Listing failure modes

For the listing of failure modes, for each function all the ways failure could happen should be considered. But in this thesis, the unreliable components were prioritized and others with low priority were neglected. Only those selected components were considered here for the ease of analysis and more focus on critical components.

To list all the failure modes, some of the contents of the FMEA analysis worksheet[10] model was used to determine a prioritized list of remedial actions by defining effects of failure, cause of failures and current condition of equipment and calculating respective RPN. (see Table 8)

3.4.2 Assigning severity, occurrence and detection ranking

After defining all the failure modes, it is essential to assign severity, occurrence and detection ranking to each of them. To assign each of them the following tables of evaluation criteria were used (see Table 1-3). Each of these three evaluation criteria is based on 10-point scale ranking. It is important to have clear descriptions for the points on each scale, so that team members have the same understanding of the rankings. There were several different ranking systems having different criteria in the papers and to make it more suitable for the thesis the ranking model that was used in the study of real cases on the transportation machines was employed.[7]

3.4.2.1 Severity ranking

The severity ranking indicates how serious the effects would be if the failure occurs. For the severity ranking, the past data of recorded actions was used to assign ranking for each effect of failure mode. The criteria consider not only the performance of equipment, but also the safety issues. The failures with safety issues or any accidents are considered to have a rank of 10, since safety should take highest priority.

Criterion	**Severity**	**Value**
No effect	Very small	1
Has a very mild effect on performance	Small	2
Has little effect on performance	Very minor	3
Has relatively little effect on performance	Minor	4
Has a moderate effect on performance	Significant	5
Product performance declines but still operates properly and is safe	Medium	6
Product performance has dropped dramatically but is still useable and safe	Serious	7
The product does no work but is safe	Very serious	8
The system stops without a dangerous accident	Catastrophic	9
Breakdown with sudden danger	Very catastrophic	10

Table 1. Severity evaluation criteria[7]

3.4.2.2 Occurrence ranking

To determine the occurrence ranking, actual data from the process was used for each failure mode.

Effect	**Possible rate of occurrence**	**Value**
An error is unlikely to occur	The average distance between two failures is more than 25920 h	1
	The average distance between two failures is between 17280 and 25920 h	2
Very few errors	The average distance between two failure is between 8640 and 17280h	3
	The average distance between two failure is between 4320 and 8640 h	4
	The average distance between two failure is between 2160 and 4320 h	5
Average number of errors	The average distance between two failure is between 720 and 2160 h	6
	The average distance between two failure is between 240 and 720 h	7
Lots of errors	The average distance between two failure is between 72 and 240 h	8
	The average distance between two failure is between 24 and 72 h	9
The occurrence of an error is inevitable	The average distance between two failure is less than 24 h	10

Table 2. Occurrence evaluation criteria[7]

3.4.2.3 Detection ranking

The detection ranking is about how likely the failures or the effects of failure are detected. The actual data of failure codes were used for each failure mode.

Level of detectability	**Criterion of detectability**	**Value**
There are reliable detection methods	Immediate corrective action	1
There are reliable computer analysis	Immediate	2
There is modeling or simulation	Easy	3
There are high-precision tests for system components	Late	4
There are medium-precision tests for system components	Low	5
There are low-precision tests for system components	Occasional	6
There are low-precision methods	Not sure	7
There are very low-precision methods	Very late	8
There are unreliable methods	Very difficult	9
There is no detection method	Impossible	10

Table 3. Detectability evaluation criteria[7]

3.4.3 Determining prioritized remedial actions

To obtain a prioritized remedial action list, RPN for each failure mode was calculated and used for the purpose. But since the FMEA is a team-based project and needs several different perspectives and experience, the remedial actions were not determined. Instead the recommended action in the FMEA worksheet was written as “Determine remedial actions” and the determination priority was defined based on RPN of failure modes. The ones with highest RPN should be determined first and be implemented to eliminate or reduce failure effects.

4 Results

4.1 Problem area identification

4.1.1 Decomposition of equipment into sub system

Using the model from Figure 9, the truck decomposed into 6 systems and the respective downtime contribution, failure frequency and MTTR were calculated and the results are illustrated in table 4.

	System	Duration	Duration %	Cum%	Quantity	MTTR, h
1	Transmission	1251.6	36.0%	36.0%	44	28.4
2	Hydraulics	1134.4	32.7%	68.7%	53	21.4
3	Engine	567.3	16.3%	85.0%	56	10.1
4	Body and Frame	290.3	8.4%	93.4%	11	26.4
5	Tires	162.8	4.7%	98.1%	15	10.9
6	Electrical	66.1	1.9%	100.0%	10	6.6
	Total	3472.6	100.0%		189	

Table 4. Pareto analysis calculation results for the fleet of Terex 60 dump trucks

In table 4 and 5 total time to repair each system and mean time to repair (MTTR) per failure for the fleet are shown. According to table 4, the most unreliable systems for the trucks were transmission, hydraulics and engine, accounting for 80% of total downtime for the fleet. In order to get more deep insight for the equipment failures, each subsystem was broken down into component level to diagnose the root cause of the significant problem. (see Table 5).

Code	Description	Quantity	Duration/h	%Time	%Cum	MTTR/h
1	Steering	18	579	16.7	16.7	32.2
2	Final drive	6	434	12.5	29.2	72.3
3	PTO	9	425.2	12.2	41.4	47.2
4	Braking	15	303	8.7	50.1	20.2
5	Transmission	11	275.6	7.9	58.1	25.1
6	Cooling (Radiator and cab)	19	210.2	6.1	64.1	11.1
7	Body and frame	7	192.6	5.5	69.7	27.5
8	Tires	15	162.8	4.7	74.4	10.9
9	Driveshaft	11	146.7	4.2	78.6	13.3
10	Hydraulic hose	26	130.2	3.7	82.3	5.0
11	Intake and exhaust	16	127.4	3.7	86.0	8.0
12	Fuel	11	99	2.9	88.9	9.0
13	Suspension	4	97.7	2.8	91.7	24.4
14	Axle	1	92.3	2.7	94.3	92.3
15	Cooling (Fan and pulley)	7	79.1	2.3	96.6	11.3
16	Related electrical items	4	44.7	1.3	97.9	11.2
17	Engine body	1	35.8	1.0	98.9	35.8
18	Lubrication	2	15.8	0.5	99.4	7.9
19	Starter	1	11.5	0.3	99.7	11.5
20	Lights	5	10	0.3	100.0	2.0
	Total	189	3472.6	100.0		18.3

Table 5. Decomposition of dump truck system into component level subsystems

Unlike table 4 in which the most unreliable system was transmission, in table 3, further decomposition into component level indicates that the steering subsystem has the most downtime contribution and it is incorporated in the hydraulic system which was the second most downtime contributed system.

4.1.2 Identification of reliability, availability and maintainability problems

To determine threshold limits of problem areas, total downtime (D), total failure frequency (N), distinct failure number (Q) were used: D=3472 hours, N=189 and Q=20. By applying equations 2-8, the limit value for acute failures was 3472/189=18.4, which was illustrated as blue line in Figure 10, and the limit value for chronic failures was 189/20=9.45 repairs, which was illustrated as yellow line.

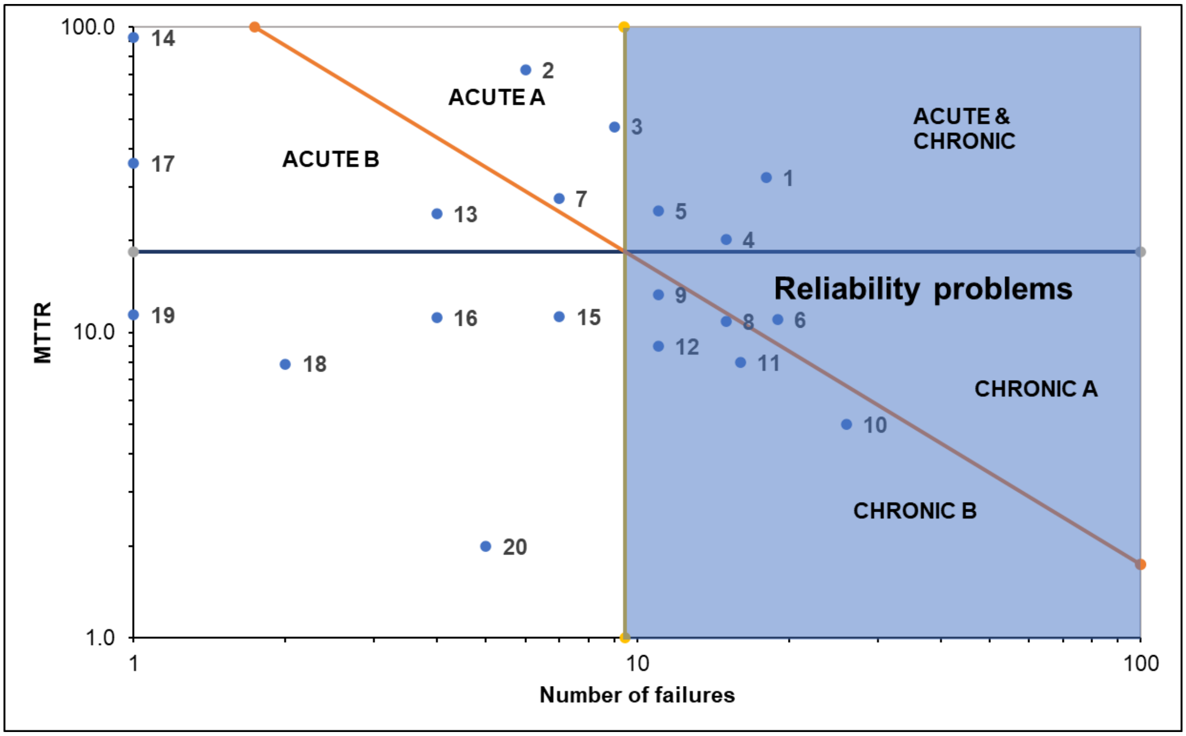

Figure 10. Truck fleet reliability problems

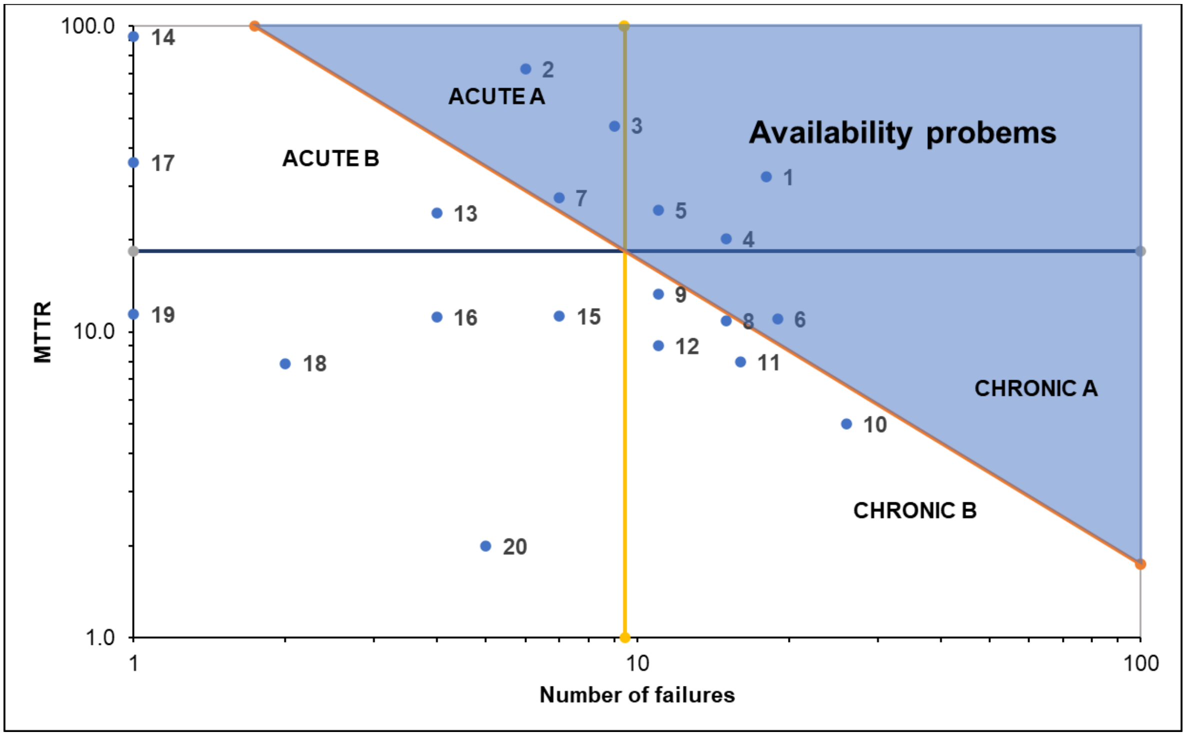

Figure 11. Truck fleet availability problems

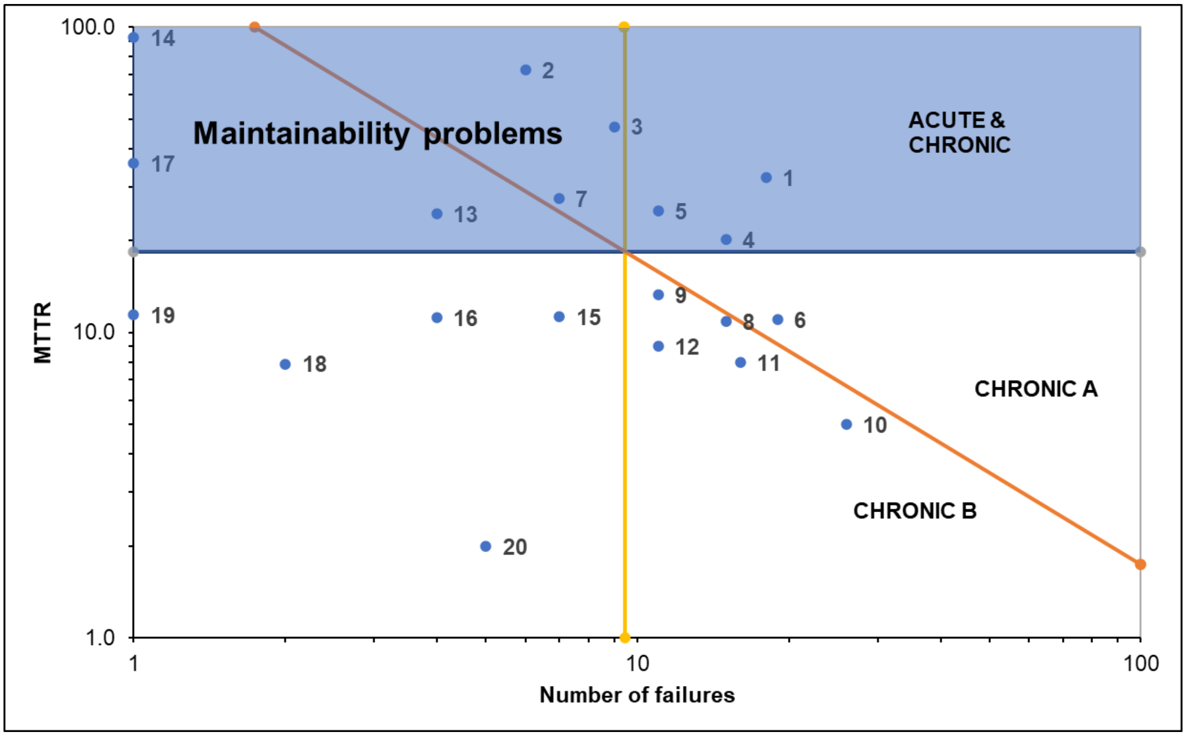

Figure 12. Truck fleet maintainability problems.

The chronic failures are those that contribute most to the number of observed failures and most affect the reliability of the fleet (see Figure 10). Finding remedial causes to these failures will most increase dump truck mean time between failure (MTBF). Comparably, Figure 11 shows those failures that most affect dump truck fleet availability.

Figure 12 shows the acute failures that most affect dump truck maintainability. From the figure, it can be seen that, if the root causes of failure codes 13, 14 and 17 are addressed, the MTTR for the fleet will be reduced. But the fleet availability will not be appreciably increased. Because even if the failure codes 13, 14 and 17 are eliminated, it will not significantly affect fleet MTBF due to their infrequent occurrence.

4.2 Downtime priority determination

The resulting graph that prioritized equipment availability and reliability was created to define which failures were significant to be analyzed (see Figure 13). This kind of graph is called a jack-knife diagram because of the inverted V shape of the limits.

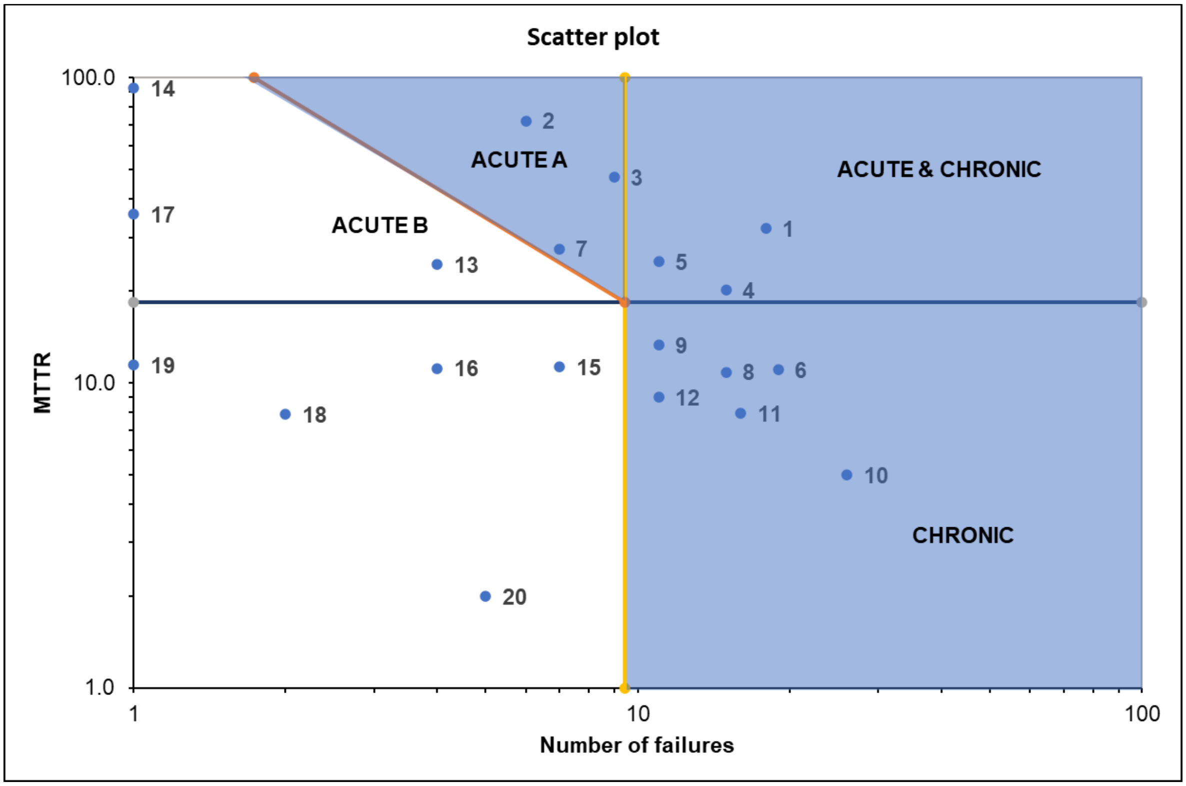

Figure 13. Jack-Knife diagram for commodity price cycle peaks

The jack-knife limits shown in Figure 13 were used to establish downtime priorities (see Table 6). In this table the component failures which most affect mining production adversely were shown. The failures with the highest priority were steering, braking and transmission component failures which were found in the intersection area of maintainability, reliability and availability in the upper right quadrant in Figure 10. These are both acute and chronic failures.

Code	Description	Quantity	Duration	% time	Av. Time
Acute & chronic failures					
1	Steering	33	579	16.7	17.5
4	Braking	22	417.06	12.0	19.0
5	Transmission	11	275.6	**7.9**	**25.1**
Sub total				**36.6**	**61.6**
Chronic failures					
6	Cooling (Radiator and cab)	19	210.2	6.1	11.1
8	Tires	15	162.8	4.7	10.9
9	Driveshaft	11	146.7	4.2	13.3
10	Hydraulic hose	26	130.2	3.7	5.0
11	Intake and exhaust	16	127.4	**3.7**	**8.0**
12	Fuel	11	99	2.9	9.0
Sub total				**25.2**	**57.2**
Acute A failures					
2	FINAL DRIVE	6	434	12.5	72.3
3	PTO	9	425.21	**12.2**	**47.2**

Table 6. Prioritized list of failure codes

The prioritized list in table 6 was based on only economic consequences of equipment downtime and this information could be used to define remedial actions for common failures for the whole fleet of Terex 60 dump trucks, assuming they have the same characteristics. But the mentioned idea was not considered here. Instead the prioritized list from Table 6 and its priority is used to select candidate equipment for the FMEA analysis. By eliminating or reducing these failures' effects equipment by equipment could reduce the most opportunity cost of lost production.

4.3 Candidate equipment selection

The list of equipment which were responsible for the prioritized failure codes was identified in Table 7.

Machine ’s code	**Steering**	**Steering hose**	**Braking**	**Disk brake cooling**	**Braking hose**	**Transmi ssion**	**Cooling (radiator and cab)**	**Tires**	**drive shaft**	**Intake and exhaust**	**fuel**	**Final drive**	**PTO**	**Total**
TR3105	0	1	5	3	1	1	3	2	2	0	0	1	1	20
TR322	3	2	1	2	0	1	0	2	0	1	0	2	0	14
TR326	5	1	1	0	1	1	1	1	0	2	0	0	0	13
TR3120	0	3	1	0	0	0	2	0	2	3	1	0	1	13
TR3116	1	1	0	0	1	1	2	0	1	0	3	0	2	12
Tr327	0	0	2	0	0	2	1	1	1	1	2	0	0	10
TR3125	1	1	2	1	0	0	0	3	0	2	0	0	0	10
TR324	0	0	1	0	0	0	1	1	1	0	2	0	2	8
TR3126	0	0	0	0	2	2	2	1	1	0	1	0	0	9
TR3131	1	4	0	0	0	1	1	0	0	2	0	0	0	9
TR3124	0	0	0	0	1	0	2	0	0	1	0	1	1	6
TR325	4	0	0	1	0	0	1	0	0	0	0	0	0	6
TR323	0	2	0	0	1	0	1	1	0	0	0	0	0	5
TR328	1	1	0	0	0	0	0	0	0	2	1	0	0	5
TR3101	2	0	1	0	0	0	0	2	0	0	0	0	0	5
TR3117	0	0	0	0	0	0	1	0	0	0	0	0	2	3
TR3114	0	0	0	0	0	0	1	0	0	0	0	1	0	2
TR3110	0	0	1	0	0	0	0	0	0	0	0	0	0	1
TR3121	0	0	0	0	0	0	1	0	0	0	0	0	0	1
TR3122	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	18	16	15	7	7	9	20	14	8	14	10	5	9	152

Table 7. Equipment list and respective frequency of failures of critical component according to prioritized list of failure codes

According to the table, there were no critical failures on the TR3122 truck, making it the most reliable one in the fleet. On the other hand, the most unreliable equipment was TR3105 which had the highest failure rate and was causing one third of the total downtime caused by braking system failure for the whole fleet. TR3105 was selected for FMEA analysis.

One thing that should be mentioned was that most of critical failures was happening mostly on one or two equipment (see Figure 14 and 15), meaning that the whole fleet of trucks tend to not have the same characteristics of failures, especially for the failures of braking and steering systems which contributed to 30 percent of total unplanned downtime of whole fleet.

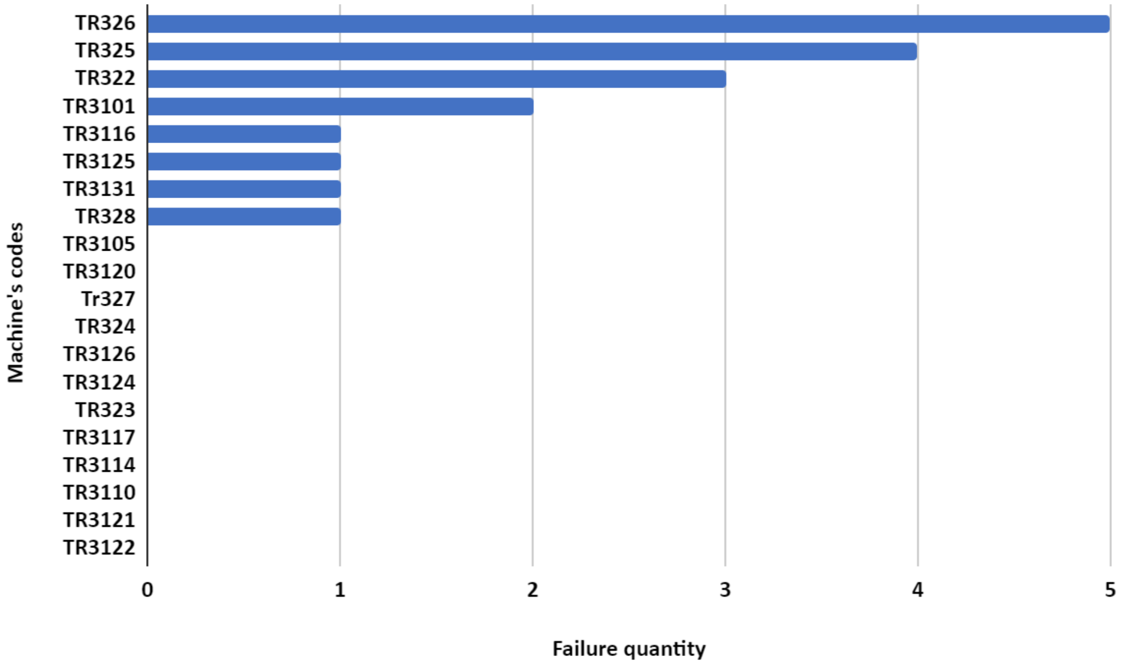

Figure 14. Number of steering system failures for each truck

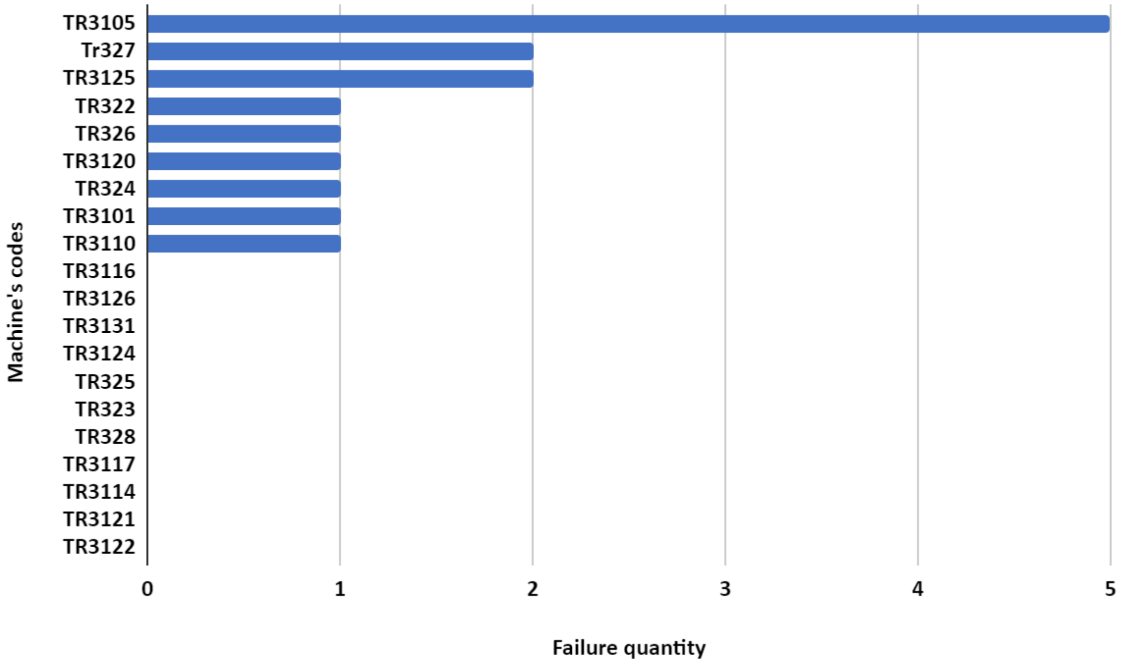

Figure 15. Number of braking system failures for each truck

4.4 The results of FMEA

The result of the 3 phases considered in FMEA was shown in the worksheet that was adapted for the thesis work purpose (see Table 8). There is one thing that should be noted that the information in FMEA worksheet filled by thesis work lacks knowledge specially on cause and remedial actions or recommended actions, since the FMEA is a team-based project and needs a variety of perspectives and experiences, on top of that the analysis was done by individual who has lack of experience in mechanical engineering.

The result of the FMEA worksheet suggests that the u-joint should take highest priority considering the respective RPN. It took one of the highest severity rates, because its failure could cause adverse effects on connected parts, increasing repair time, hence decreasing performance. More specifically, a bad or failed u-joint could cause vibration and influence other connected parts and cause other failures, such as transmission shaft seal failure or bolt loosening of connected components.

Line	Component	Potential failure mode	Potential effect(s) of failure	Severity	Potential cause(s) of failure	Occurrence	Current controls, prevention	Current controls, detection	Detection	RPN	Recommended action
1	U-joint	wear	Damage to other components	7	Wear	5	none	none	7	245	Determine remedial action
2	Brake caliper	Leak of brake fluid	Low hydraulic pressure	4	Failed seal	7	none	none	7	196	Determine remedial action
3	Monoblock	Brake seizure	Brake seizure Unbalanced system pressure	6	Wear and damage	4	none	none	8	192	Determine remedial action
4	Hydraulic oil cooler	Damage	Over temperature	4	Tube clogging, Damage	6	none	none	7	168	Determine remedial action
5	Retarder	retarder not working	Reduced performance	5	Failed seal	4	none	none	8	160	Determine remedial action
6	Coolant	Cooler needs to be changed	clogged tubes	5	Coolant not changed Breach in a system	4	none	none	8	160	Determine remedial action
7	Hub	damage	Wear and damage	5	failed bearing	4	none	none	8	160	Determine remedial action
8	Brake pedal	Not working	Reduced performance	5	Improper operating condition	4	none	none	7	140	Determine remedial action
9	Disk brake oil cooler	Needs check up	Brake over temperature	5	Tube clogging, Damage	4	none	none	7	140	Determine remedial action
10	Brake valve	Not working	Reduced performance	4	Improper operating condition	4	none	none	8	128	Determine remedial action
11	PTO	Not working	failed shaft seal	4	Wear	4	none	none	8	128	Determine remedial action
12	Hub	Seal failure	Oil leakage	4	Improper operating condition	4	none	none	8	128	Determine remedial action
13	Transmission oil cooler hose	Oil leakage	Oil leakage	4	Not secured	4	none	none	7	112	Determine remedial action
14	Sensor	Got dirty	Reduced performance	4	Dirt	3	none	none	8	96	Determine remedial action
15	Transmission filter	channeling	Contaminant	3	Wear of components	3	none	none	8	72	Determine remedial action
16	Coolant filter	Leakage	Reduced performance	3	Impropriety of maintenance procedure	3	none	none	7	63	Determine remedial action

Table 8. Adapted FMEA worksheet for the thesis purpose

5 Conclusions and remarks

In this thesis, a case of Monnis Mining LLC which operates in Tavantolgoi mine in Mongolia was considered to propose methodology to determine main prioritized remedial actions for unplanned failures of equipment.

5.1 Data processing

The data of repair time obtained from maintenance personnel were not reflected accurately due to improper repair time recording. Because some recorded repair time included repair time of different system failures in it and had to be separated which distorted the accurate repair time. And there could be factors, other than repair time itself, dominated equipment downtime, such as delays caused by lack of resources (spare parts, labor, tools or shop space). Better estimates of repair time could be acquired through more effective data gathering via a maintenance management information system.

5.2 Defining maintenance priority using logarithmic scatter plot

Thanks to the logarithmic scatter plot, the identification of problems affecting system reliability, availability and maintainability was easily done. Based on the circumstances the company is facing, maintenance priority should be changed accordingly. Different circumstances require different priorities. The considered circumstance was the business cycle in the thesis. At the time of writing, the commodity price was at a 5-year high, consequently production was prioritized over maintenance cost, hence availability and reliability over maintainability.

In conclusion, as the market condition is not stationary and could be changed by external factors, the maintenance priority should be changed and adapted accordingly to reach better effectiveness.

5.3 Candidate equipment selection for FMEA

The selected candidate equipment was TR3105 in the thesis. To select it, the prioritized list of failure codes was used and it facilitated the equipment selection process by defining a prioritized list of failure codes which decreased the inputs to consider. When the list of equipment responsible for the failure codes was identified, it was clear that some failures mostly occurred on certain equipment, meaning that the most types of failures were not common characteristics for the whole fleet of the same trucks. For example, TR3105 truck was solely responsible for one third of total downtime caused by braking system failure, which was the second most critical subsystem, and the critical failure frequency was high for the truck. The reason the certain failures were occurring on specific trucks could be due to the dissimilarity of equipment age, maintenance or operating condition.

It can be concluded that, since certain failures tended to occur on specific equipment, it could be desirable to mitigate effects of failure equipment by equipment instead of taking actions for the whole fleet to increase whole fleet performance.
Also, the determination of critical component failures could facilitate the FMEA analysis by narrowing criteria of equipment selection.

5.4 FMEA worksheet

FMEA worksheet was used to identify failure modes and determine remedial actions for the candidate equipment. For prioritizing the failure modes, RPN index was used. After determining remedial actions for the prioritized list of failure modes, we could get the prioritized list of remedial actions. But, even if the potential failure modes were identified, the respective remedial actions were not determined in the thesis. Because the FMEA is a team-based project and needs a variety of perspectives and experiences, and the analysis was done by an industrial engineering student who has a lack of experience in mechanical engineering. But having a prioritized list of remedial actions means having the prioritized list of remedial actions for failures.

Therefore, it can be concluded that the FMEA is valid and can be a support for maintenance engineers to determine main prioritized remedial actions for failures.

5.5 Final remark

The final conclusion that can be drawn from all this is that the proposed methodology can be used to achieve the goal set at the beginning of the thesis.

5.6 Future work

Some points that need to be addressed in the future were extracted after the completion of the thesis.

To apply the proposed methodology, an investigation into downtime factors should be done for the analysis. Because the repair time data used in the thesis could include delay time caused by lack of resources. Better estimates of repair time could be acquired through more effective data gathering via a maintenance management information system.

After identifying and implementing remedial actions, the performance evaluation needs to be done. To do that, after the remedial action is employed, the severity, occurrence and detection ranking should be reassigned to calculate new RPN. By comparing the previous RPN with the new one, the performance evaluation can be done

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