

The present work was submitted to the Faculty of Engineering

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# **Optimal Service Inspection and Maintenance for Highway Dump Truck**

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**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

### OPTIMAL SERVICE INSPECTION AND MAINTENANCE FOR HIGHWAY DUMP TRUCK

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.

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Many thanks,  
Nomintuya Bold

# Abstract

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The periodic maintenance and optimal service inspection become important to prevent any failure of all mining machines. Among a lot of mining machines, I chose a highway dump truck. The highway dump trucks are large vehicles used in heavy cargo transportation. Due to the heavy loads carried by dump trucks, the maintenance of those vehicles should be performed periodically. Frequently the components of the engine and transmission fail along with damages. Therefore, periodic maintenance is important.

The period of service inspection is scheduled for every 350 service hours in “Burdel Mining LLC”. However, the standard service hours in which an inspection is needed is 250 hours. The selection of service hours should consider operating time, working environment, and service life of the machinery. It needs to be determined to guarantee not only the highest benefit with respect to the economy and lifetime of the dump truck but also the occupational health and safety-related to the failure of the dump truck.

Using the collected data in the field, the possibility of minimizing the dump truck failure was studied in this research. Time-based maintenance, which has the same interval for all mining equipment, is not able to use due to mining environmental conditions and usage of technique. Thus, condition based maintenance is thought as the most efficient method to do the service inspection based on the S.O.S analysis, fault codes and service inspections. It increases the lifetime of heavy dump truck.

# Table of contents

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<b>Statutory Declaration</b>	2
Acknowledgment	4
Abstract	5
Chapter 1 Introduction	9
<b>1.1 Problem Statement</b>	9
<b>1.2 Objective of Research</b>	11
Chapter 2 Literature Review	12
<b>2.1 Overview of Preventive maintenance</b>	12
Chapter 3 Methodology	17
<b>3.1 Selected Truck Model for Research</b>	17
3.1.1 Oyu Tolgoi LLC	17
3.1.2. Burdel Mining LLC	17
3.1.3 Comparison of CAT-772 and CAT-773 OFF dump truck	18
<b>3.2 Research principle and Strategy</b>	19
3.2.1 Time-based maintenance	19
3.2.2 Condition-based maintenance	23
(1) Oil sample analysis	25
(2) Product link analysis	26
(3) Mechanical inspection	26
Chapter 4 Result	28
<b>4.1 Burdel Mining LLC</b>	28
<b>4.2 Oyu Tolgoi LLC</b>	36
Chapter 5 Conclusion	40
<b>Appendix A:</b>	41
	44
<b>Appendix B:</b>	45
<b>References:</b>	51

# List of Figures

---

Figure 1 "Highway dump truck" ..... 9

Figure 2 "Present maintenance strategies" [2].....10

Figure 3 "Total productive maintenance" .....12

Figure 4 "Types of maintenance" .....14

Figure 5 "P-F curve" [5].....15

Figure 6 "Uncertainty propagation for time-dependent system reliability" .....20

Figure 7 "Time-based Maintenance Strategy" .....22

Figure 8 "Weibull distribution" .....23

Figure 9 "Framework of FCPB" .....24

Figure 10 "Framework of FCPB" .....24

Figure 11 "Mechanical inspection" .....27

Figure 12 "Date of taking oil sample" .....29

Figure 13 "Content of Si and Na" .....30

Figure 14 "Content of Mo, Ca, P and Zn" .....31

Figure 15 "Status due to tire problem" .....32

Figure 16 "The reason of downtime" .....33

Figure 17 "Comparison of total costs" .....35

Figure 18 "Costs for fault codes" .....36

Figure 19 "The faultiest techniques" .....37

Figure 20 "Frequency of failure" .....38

# List of Tables

---

Table 1 "Difference between CAT-772 and CAT-773" ..... 18

Table 2 "The closest dump truck" ..... 28

Table 3 "Sequence of PM" ..... 28

Table 4 "HT-69, severity of oil" ..... 29

Table 5 "Oil sample result" ..... 33

Table 6 "Status of HT-109" ..... 34

Table 7 "Result of oil sample" ..... 39

Table 8 "Parts to be replaced at 350 SMU" ..... 41

Table 9 "Parts to be replaced at 700 SMU" ..... 41

Table 10 "Parts to be replaced at 1400 SMU" ..... 42

Table 11 "Parts to be replaced at 2800 SMU" ..... 43

Table 12 "Indication of hydraulic cylinder" ..... 45

Table 13 "Signs of engine" ..... 46

Table 14 "Indication of transmission" ..... 47

Table 15 "Indication of differential" ..... 48

Table 16 "Indication of final drive" ..... 49

Table 17 "Indication of wearing parts" ..... 50

# Chapter 1 Introduction

---

## 1.1 Problem Statement



*Figure 1 "Highway dump truck"*

The trucks were failing constantly and randomly, in mid-travel. Frequent failures resulted in increased downtimes, loss in production, and a focus on preventive maintenance and reactive maintenance. Preventive maintenance (PM) is the regular and routine maintenance of equipment. This is a successful maintenance strategy that requires planning and scheduling maintenance of

*Figure:1 "Highway dump truck"*

equipment before a problem occurs. [1]

The optimal service inspection is scheduled maintenance, because we understand that a small problem can turn into a larger and more expensive one down the road. We may fail to bring in a vehicle for scheduled maintenance, believing it will save money and time. But failing to properly maintain a vehicle can lead to a breakdown, which is ultimately more expensive and time intensive to deal with than a simple maintenance visit. The longer a vehicle is neglected, the greater the chances are it will result in a larger problem, such as damage to the engine, requiring even more costly repair work, or even the need to replace the engine. Therefore, the scheduled maintenance is important to the economy and lifetime of the vehicle.

Approximately 200 manufacturing facilities were involved in a survey of advanced technology services, which specialized in outsourced industrial maintenance services and found preventive maintenance as well as parts solutions. According to industrial maintenance strategy, 88% of manufacturing facilities follow a preventive maintenance strategy, 52% have performed a computerized maintenance management system (CMMS), and 51% use a run-to-failure method. [2]

## PRESENT MAINTENANCE STRATEGIES AND TOOLS

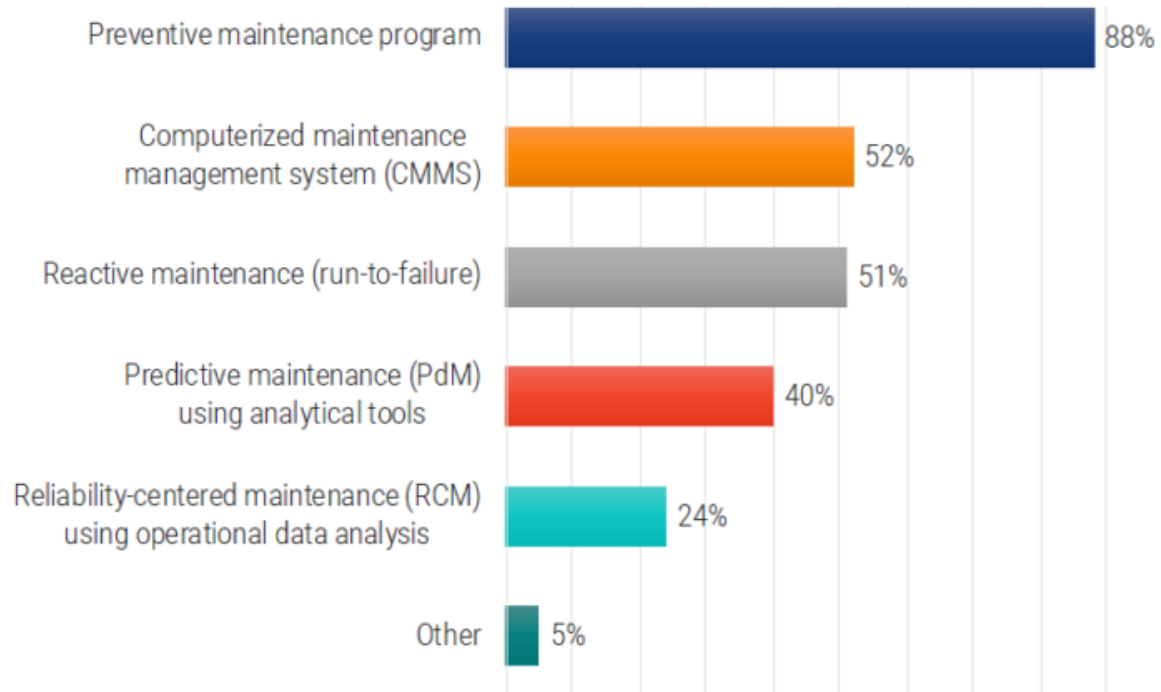


Figure 2 "Present maintenance strategies" [2]

Figure 2 shows today's typical maintenance program.

The normal preventive maintenance is scheduled 250 PM from Caterpillar inc. However, some companies schedule it differently including the operating time, working environment, and service life of the equipment. On the other hand, the coal mine dust is hazardous for heavy machinery, as it has a negative effect on the life, health, and safety of miners. Because the filters clog very quickly and then the engine and transmission will be damaged. "Oyu Tolgoi" LLC scheduled the service inspection at 250 PM, but "Burdel Mining" LLC is scheduled at 350 PM. Planning and scheduling maintenance needs to be determined to guarantee not only the highest benefit with respect to the economy and lifetime of the equipment but also the occupational health and safety related to the failure of equipment.

Based on the information and my interest following research questions were developed:

1. When do we need to do preventive maintenance and how does it affect the condition of equipment to time-based maintenance?
2. How preventive maintenance does affect to the economy? Which solution is more effective?
3. What are the most frequent problems of equipment and Why?

## 1.2 Objective of Research

The objective of this research work is to find out the solutions and answers of the above questions. To determine the optimal preventive maintenance for highway dump trucks.

Mongolia has a lot of mining companies and manufacturers. The preventive maintenance belongs to all companies, which have equipment and need to do maintenance. Thus, I choose the following targets:

- Only CAT 772 and 773 OFF-Highway trucks
- Burdel Mining LLC, which is gold mining company
- Oyu Tolgoi LLC, which is copper and gold mining company

This thesis research work has two main objectives. The first objective is to explore the corrective maintenance interval for highway dump trucks. The second objective is to discuss their effectiveness, which means minimizing failure costs and machine downtime, and increasing product quality. Brief reviews of the concepts, general processes toward maintenance decision making are described in Chapter 2. The methodology and definitions of TBM and CBM are presented in Chapter 3. Chapter 4 is about data analysis. Finally, conclusions are made in Chapter 5.

# Chapter 2 Literature Review

---

## 2.1 Overview of Preventive maintenance

The preventive maintenance (PM) is a part of total productive maintenance (TPM) strategy. The total productive maintenance has been developed based on the productive maintenance concepts and unique Japanese philosophy. M/s Nippon Denso Co. Ltd. of Japan, which is a supplier of M/s Toyota Motor Company, introduced for the first time in the year 1971. This concept is an innovative approach to maintenance that optimizes equipment effectiveness, eliminates breakdowns and promotes autonomous maintenance by operators through day-to-day activities involving total workforce [3]. The basic practices of total productive maintenance are called the pillars or elements of TPM. It has 8 pillars:

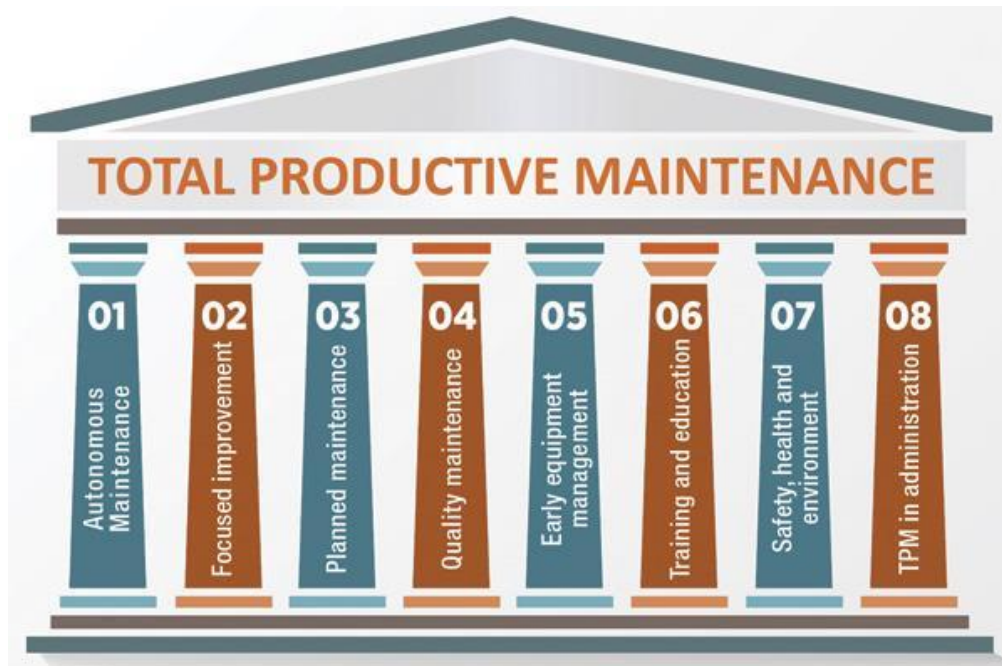


Figure 3 "Total productive maintenance"

**Pillar 1** is Autonomous maintenance (AM). This pillar is developing operators to be able to take care of small maintenance tasks. The main goal of this pillar is to maintain the machine in new condition and freeing up the skilled repairman to spend time on more value added activity and technical repairs.

**Pillar 2** is Kaizen, "Kai " means change and "Zen" means good and the principle behind this pillar is that a very large number of small improvements are more effective in an organizational environment than a few improvements of large value". The main goal is reducing losses and improving efficiency.

**Pillar 3** is Planned maintenance (PM), which is aimed to achieve and sustain availability of machines, optimum maintenance cost, reduce spares inventory, and improve reliability and maintainability of machines. This pillar is divided into four groups, preventive maintenance, breakdown maintenance, corrective maintenance and maintenance prevention. PM targets are zero equipment failure and break down, improve reliability and maintainability by 50 percent, reduce maintenance cost by 20 percent, and ensure availability of spares all the time.

**Pillar 4** is quality maintenance (QM), which achieves and sustains customer complaints at zero, reduces in-process defects by 50 percent, and reduces cost of quality by 50 percent. It focuses on eliminating non-conformances in a systematic manner, much like focused improvement.

**Pillar 5:** 5S /Early equipment management/, which is a systematic process of working environment and involving the employees with a commitment. Cleaning and organizing the workplace helps the team to uncover problems.

**Pillar 6** is training which is aimed to have multi-skilled revitalized employees. This pillar focuses on improvement of knowledge, skills and techniques.

**Pillar 7:** The final pillar is Safety, health and environment, which focuses on creating a safe workplace and a surrounding area that is not damaged by our process or procedures.

A result of this 8 pillar is an indication of increase in equipment availability, decrease in rework, rejection and increase in rate or performance.

**Pillar 8** is Office TPM, which should be started after four other pillars which are AM, Kaizen, PM, and QM. It is followed to improve productivity and efficiency. The benefits are involvement of all people in support functions for focusing on better plant performance, better utilized work area, reduced repetitive work, reduced administrative costs, reduced inventory carrying costs and so on. [4]

## 2.2 Types of preventive maintenance

Maintenance is moving from an equipment repair service to a business process for increasing reliability and ensuring plant capacity. It has two main types into preventive maintenance and corrective maintenance, which are divided into subcategories.

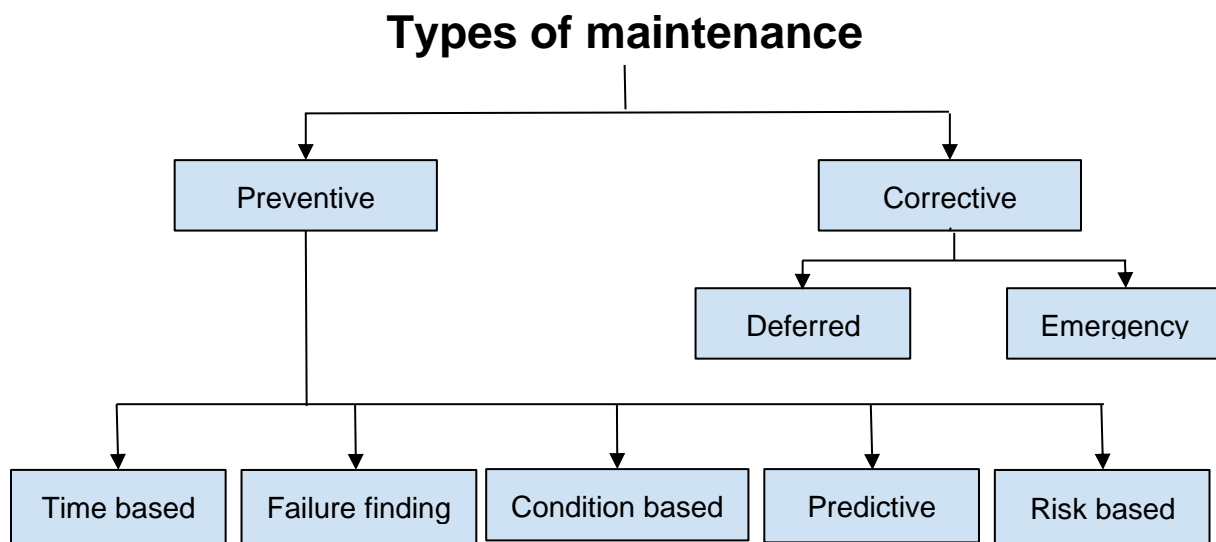


Figure 4 "Types of maintenance"

Preventive maintenance is done before a failure occurs and consists of some types like:

Time based maintenance, Failure Finding Maintenance, Risk based, Condition based, and Predictive maintenance

**Time based maintenance (TBM)** is a type of maintenance that is done at a regular interval while the equipment is still functioning with the objective of preventing failure or reducing the likelihood of failure. It can also be based on every week, every month or every three months. The preventive maintenance can also be based on usage every 150 cycles, every 10000 hours or service every 10000 km.

**Risk based maintenance (RBM)** is essentially preventive maintenance where the frequency and scope of the maintenance activities is continuously optimized based on the findings from testing or inspection and a thorough risk assessment.

**Failure finding maintenance (FFM)** is aimed at detecting hidden failures typically associated with predictive functions. It is conducted at fixed time intervals typically derived from legislation or risk based approaches.

**Condition based maintenance (CBM)** is maintenance based on the failure modes. Most failure modes do give some sort of warning that they are in the process of occurring or are about to occur. This method uses the P-F curve, it has three main sections. As we can see from Figure. 2, at the first section, the curve runs smoothing. Then a failure starts manifesting, the equipment deteriorates to the point at which it can possibly be detected (Point "P"). If the failure is not detected and mitigated, it continues until a functional failure occurs at point "F". The time range between P and F, commonly called the P-F interval, is the window of opportunity during which an inspection can possibly detect the imminent failure and give you time to address it.

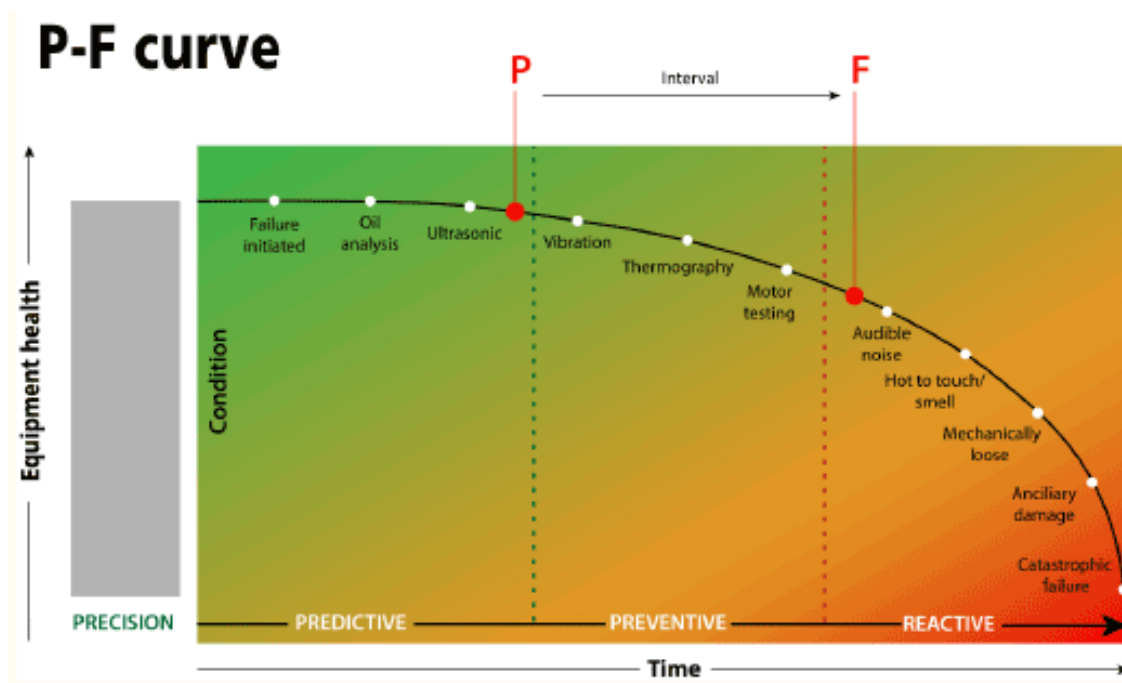


Figure 5 "P-F curve" [5]

Technologies and tools used to detect failure can include oil analysis, ultrasound, vibration, thermography, motor testing, and physical inspection. Each of these methods of testing has something to say about an asset's operation, and the timing information has even more to say about the future of the asset. Using these modes of inspection and methods of detection can provide an early warning of decreased performance.

**Predictive maintenance (PDM)** is to predict when the failure is going to occur and then determine the appropriate time for maintenance intervention. Essentially, it is a synonym for condition based maintenance. The predictive maintenance approaches need to be underpinned by sound reliability principles and understanding.

**Corrective maintenance (CM)** restores only the function of an item after it has been allowed to fail. It is based on the assumption that failure is acceptable and preventing failure is either not economical or not possible. This maintenance is divided by two types: Deferred Corrective Maintenance and Emergency Maintenance.

**Deferred Corrective Maintenance** refers to corrective actions that are scheduled for later.

**Emergency Maintenance** typically leads to longer equipment outages and more production impact. It is less safe and expensive, various sources have suggested that Emergency Maintenance is three to five times as expensive as normal preventive maintenance. [5]

## Chapter 3 Methodology

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### 3.1 Selected Truck Model for Research

#### 3.1.1 Oyu Tolgoi LLC

“Oyu Tolgoi LLC” is one of the largest known copper and gold deposits in the world. The Oyu Tolgoi underground development consolidates our position as a leading global producer of copper, a material essential for decarbonization and electrification. When the underground is fully operational, it will be the world’s fourth-largest copper mine. Open-pit mining began at Oyu Tolgoi in 2011 and the copper concentrator, the largest industrial complex ever built in Mongolia. [6]. The resources of Oyu Tolgoi LLC are defined until 2041. But it can be extended 2 times by 20 years.[7] The Oyu Tolgoi uses some types of Caterpillar Off-Highway dump trucks (also called “haul trucks”) and Komatsu dump trucks for transporting the deposits along haul roads to different locations within the mine. I selected CAT-773 OFF dump trucks from Oyu Tolgoi LLC.

#### 3.1.2. Burdel Mining LLC

“Burdel Mining” LLC was founded in 2013 years in Bulgan aimag, Bureg Khangai soum. That company is a gold deposit and open-pit mining company and has 4 branch-company. Although that has not been the deposit in one place for a long time like Oyu Tolgoi LLC, the company migrates between where they find out the gold deposits. Therefore, the resources aren't defined. Burdel Mining has a total of 374 pieces of heavy machinery, which includes excavators, Off-Highway dump trucks, loaders, bulldozers, and graders. Also, the company uses Caterpillar Off-Highway dump trucks and Komatsu dump trucks for carrying the gold deposits and soil along haul roads to different locations within the mine. I chose a CAT-772 OFF dump truck from Burdel Mining LLC. [8]

### 3.1.3 Comparison of CAT-772 and CAT-773 OFF dump truck

Table 1 "Difference between CAT-772 and CAT-773"

<b>Nº</b>	<b>Definition</b>	<b>CAT-772G</b>	<b>CAT-773G</b>
<b>1</b>	Nominal Payload Class	51.6 ton (US)	61 ton (US)
<b>2</b>	Engine Model	CAT C18	CAT C27
<b>3</b>	Top Speed - Loaded	49.2 mile/h	41.6 mile/h
<b>4</b>	Saving fuel	0.5 - 15%	0.15-15%
<b>5</b>	Rated engine speed	1800 r/min	1800 r/min
<b>6</b>	Gross Power	605 HP	775 HP
<b>7</b>	Displacement	1105 in <sup>3</sup>	1648 in <sup>3</sup>
<b>8</b>	Transmission (Reverse)	10.4 mile/h	8.7 mile/h
<b>9</b>	Brake standards	ISO 3450:1996	ISO 3450:2011
<b>10</b>	Standard Tire	24.00R35 (E4)	24.00R35 (E4)
<b>11</b>	Changing parts of PM	same	same

Although CAT-772 and CAT-773 OFF dump trucks are different models and engine models, the changing parts of PM and standards are the same. I selected these 2 different models due to the number of dumps in mining and proximity. [9], [10]

## 3.2 Research principle and Strategy

As aforementioned that preventive maintenance is five main types. I have chosen condition based maintenance and time based maintenance. The service inspection of “Oyu Tolgoi” LLC is 250 hours and “Burdel Mining” LLC is 350 hours. Therefore I will compare each day's state and failure as well as an oil sample report. First of all, working hours are important for comparison. If the working hours are different, then the research work will fail.

### 3.2.1 Time-based maintenance

Time-based maintenance is like periodic-based maintenance. The maintenance decisions of TBM are determined based on the failure time analyses. On the other hand, the aging (expected lifetime),  $T$ , of some equipment is estimated based on failure time data or used-based data.

From Jing Li and Zissimos Mourelatos's research work, reliability is an important engineering requirement. It usually degrades with time increasing, thus the lifecycle cost due to more frequent failures which result in increased warranty costs, costly repairs and loss of market share. A customer's buying decision is the total lifecycle cost which can be included by a high maintenance cost. Quality and reliability are very important parts of requirements. The quality measures the conformance to design specifications as the product leaves the factory to begin its life cycle. The probability that the system will perform its intended function for a specified interval of time, under stated operating and environmental conditions is defined as reliability.

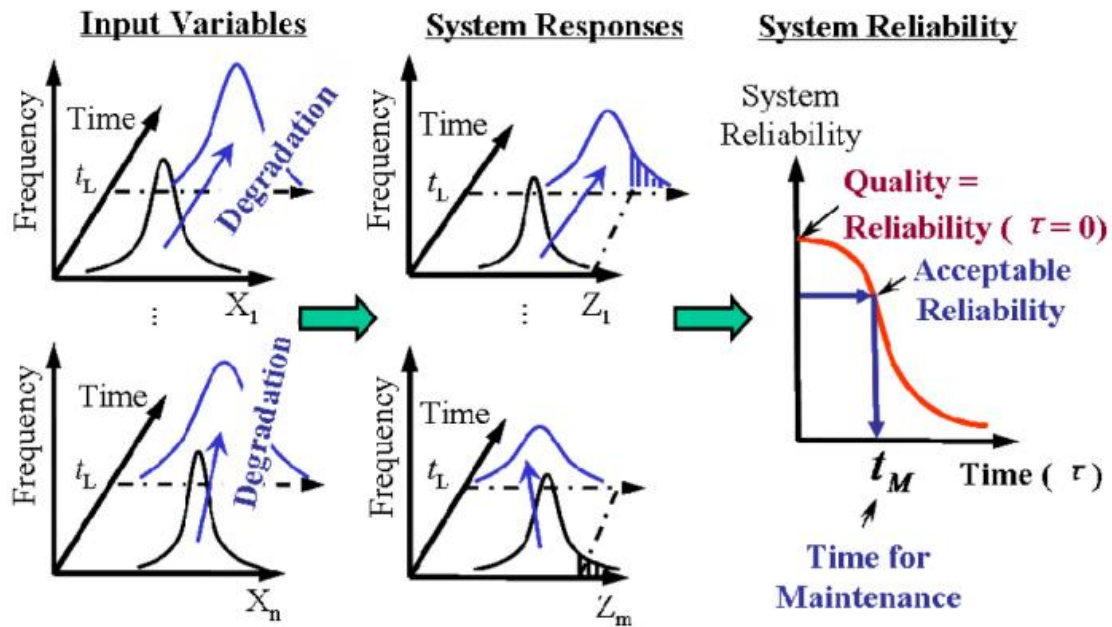


Figure 6 "Uncertainty propagation for time-dependent system reliability"

**Figure 6** shows a probabilistic view of this process over time. The probability density functions of the input random variables  $X_1$  change over time due to degradation. The system response distributions also change over time due to the changes in the inputs. The system reliability versus time is shown at the left of **figure 6**. It is indicated over time by calculating the system time-dependent reliability or probability of conformance. If an acceptable reliability level is prescribed, the time to maintenance  $t_m$  can be determined. Therefore, the key to determining the time to maintenance is the efficiency estimation of the time dependent reliability. An automatic roller clutch example illustrates the approach of this paper and provides details on the usefulness and practicality of the proposed methodology for optimal preventive maintenance. In reliability analysis, a time-independent limit state function  $g(X)$  is used:

### Equation: 1

$$P_f = P(g(X) < 0) = \int \dots \int_{g(X) < 0} f(X) dx \quad \text{Equation 1}$$

This equation illustrates the probability of failure.  $g(X)$  is a time-independent limit state function, where the vector  $X$  represents the input random variables with a joint probability density function  $f_X(x)$ . As we can see, the multi-dimensional integral is difficult to evaluate. Thus, it isn't used in this paper. However, a time-dependent reliability function is used in this paper. The system response is described by a random process  $g(d, X, \tau^*)$  and it depends on time.  $X$  represents random variables and for each realization of the input deterministic variables  $d$ , the output is a time-dependent sample function. The probability of failure within time interval  $[t_{min}, t_{max}]$  is defined as:

### Equation: 2a Time-dependent reliability estimation

$$P_f^c(d, X; t_{min}, t_{max}) = P(\exists t \in [t_{min}, t_{max}], g(d, X, t) < 0) \quad \text{Equation 2}$$

The conceptual difference between the cumulative and the instantaneous probabilities of failure is very important. The **equation 1** related to time-dependent reliability estimation, which indicates cumulative probability of failure. Thus we need to determine the failure probability at any time, to prevent any failure. However, **equation 2** belongs to time-independent reliability estimation. On the other hand, that is the instantaneous probability of failure. To prevent this type of failure, time-dependent and data analysis are very important. [11]

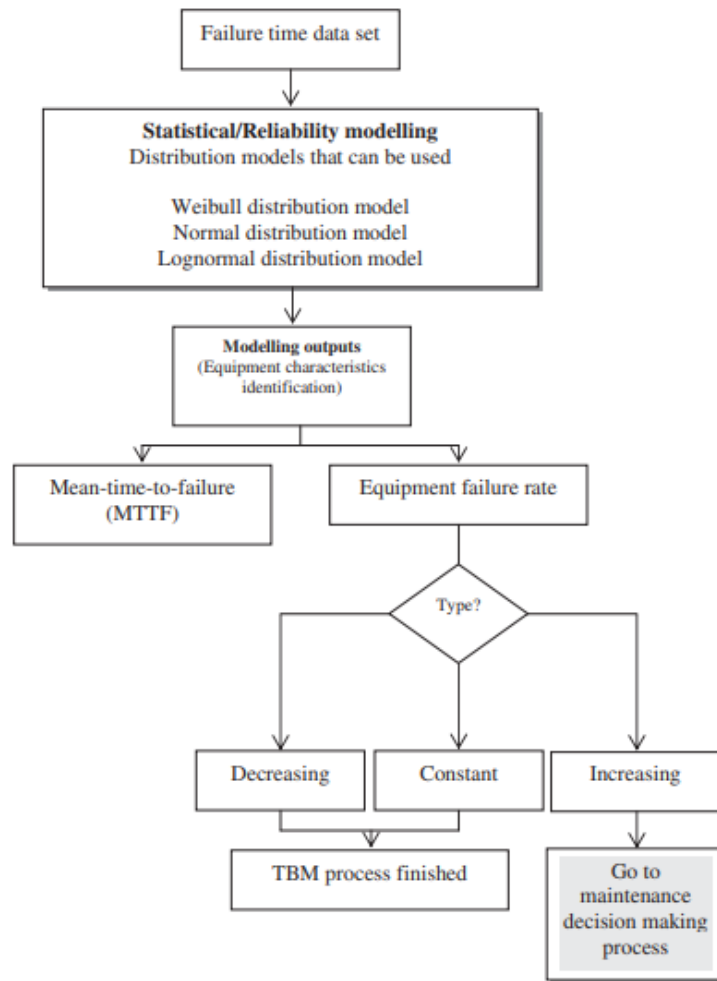


Figure 7 "Time-based Maintenance Strategy"

Usually maintenance decisions are defined in TBM based on failure frequency, and failure time data.

Due to its ability to model various aging classes of life distributions, including increasing, decreasing, or constant failure rates, Weibull-distribution has been widely used to model the failures of many materials and in numerous other applications.

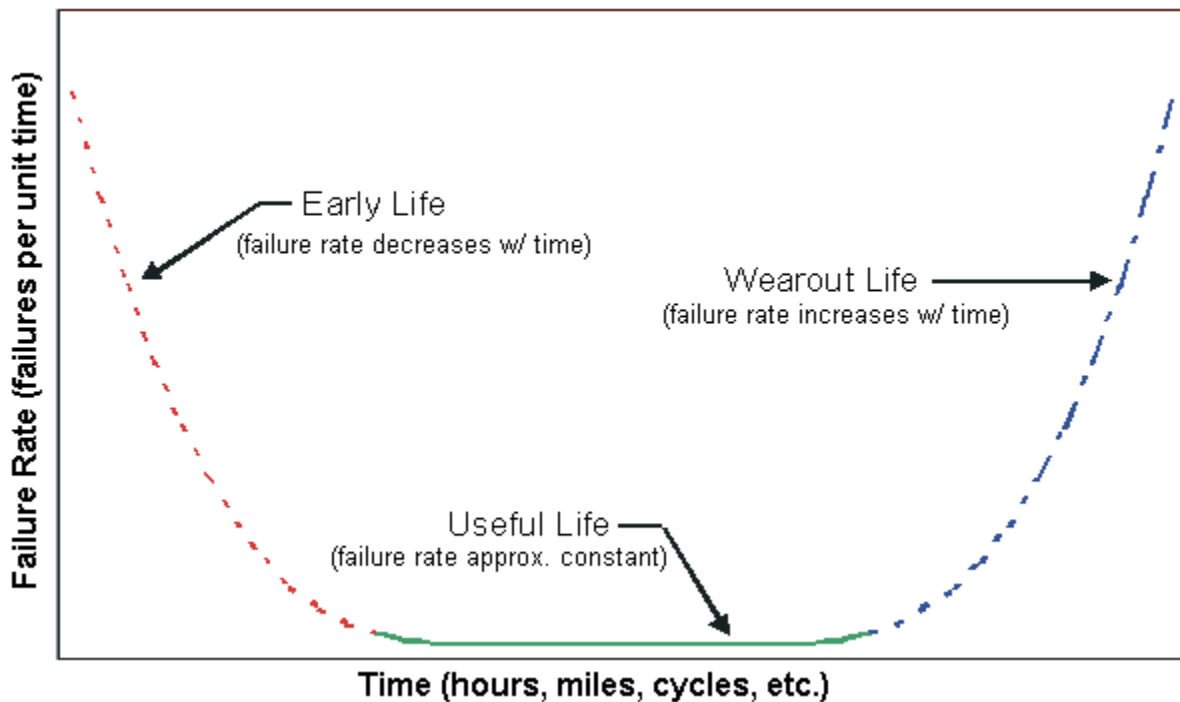


Figure 8 "Weibull distribution"

### 3.2.2 Condition-based maintenance

At the first time, condition-based maintenance was introduced in 1975. The main purpose of this maintenance model is maximizing the effectiveness of PM decision making. The method of CBM is to recommend and make decisions based on the information collected through the condition monitoring process. The important parameters are vibration, temperature, lubrication oil, contaminants, and noise levels as well as other sensors. The CBM process is divided by 2, first, it collects the condition data of the equipment as TBM. Second, It increases knowledge of the failure causes and effects and the deterioration patterns of equipment. Decision making can be carried out based on two methods:

1. Current evaluation-based (CCEB)
2. Future condition prediction-based (FCPB)

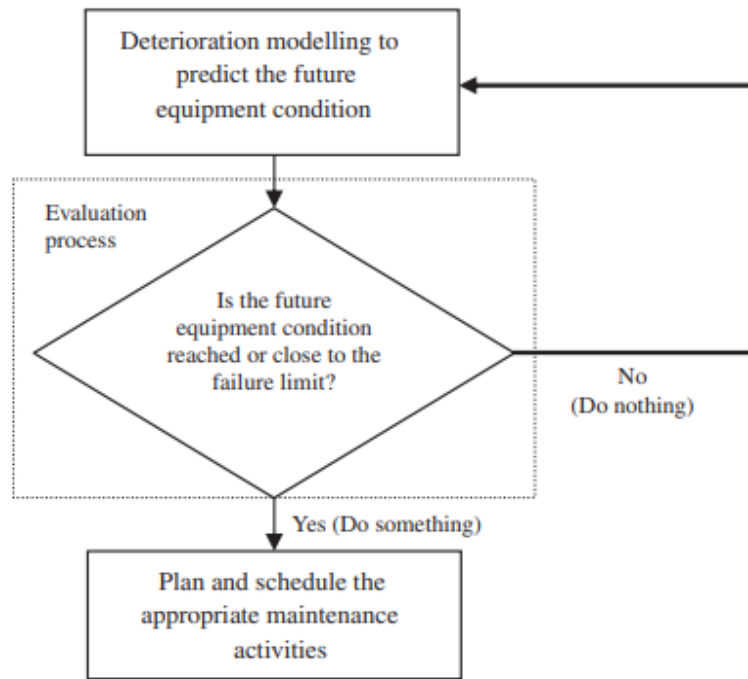


Figure 9 "Framework of FCPB"

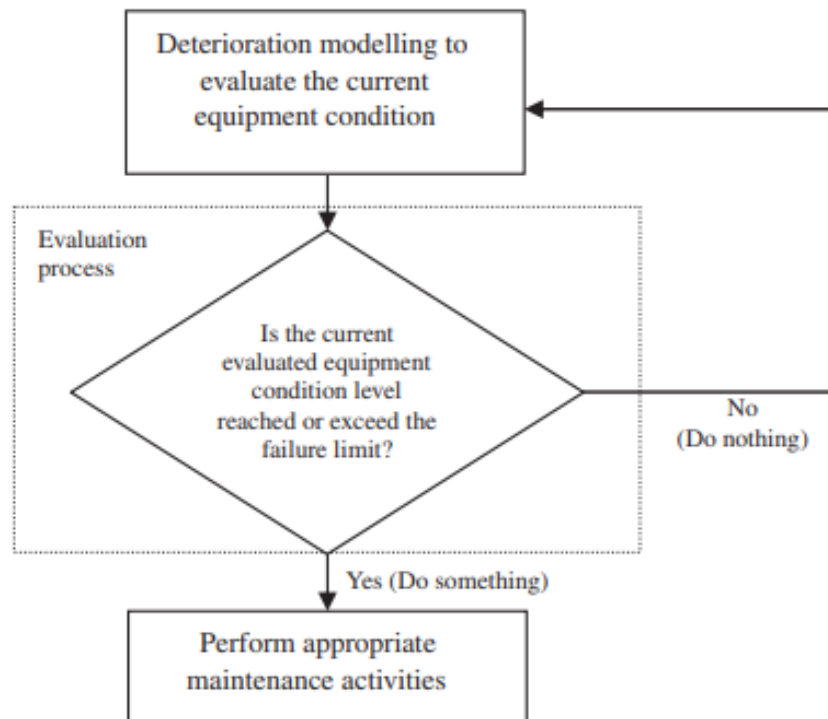


Figure 10 "Framework of FCPB"

The CCEB estimates the actual equipment condition at present. If the equipment condition level reaches or exceeds the limit, the equipment will be called for maintenance. Otherwise, the equipment is assumed to be in good condition and it can be used. [12]

Following three analyses are used for caterpillar equipment to do condition based maintenance.

#### (1) Oil sample analysis

Oil sample is also called S.O.S fluid analysis, which monitors equipment health to prevent downtime and improve the lifetime. This analysis uses the caterpillar verified and ASTM (American Society for Testing and Materials) laboratory methods, which are designed to identify wear and contamination in fluid samples. The S.O.S program provides oil, coolant, and diesel fuel analysis. The sampling benefits are to offer recommendations that are unique to equipment's needs by carefully monitoring equipment performance. Identifying early signs may prevent equipment downtime and extend component life. There are three categories of oil analysis: fluid properties, contamination and wear debris. The fluid properties focus on identifying the oil's current physical and chemical state. [13]

The Caterpillar suggests that when evaluating engines with a 500-hour recommended oil change. But, some applications and conditions, which includes working conditions and dusts, may allow for oil drain interval extensions, but some extreme conditions may require more frequent oil changes. Firstly, we need to determine that wear rate and oil condition are satisfactory at the recommended intervals. Then, extend to the recommended interval plus 50 hours. After that analyze the S.O.S fluid program in the interval, if wear results remain acceptable, proceed again to a plus 100 hour interval.

The oil sample indicates the viscosity of oil and contents of chemical elements. On the other hand, that defines the condition of parts, which is normal, warning and action. As a result of that, equipment can prevent any failure and use the right maintenance.

As you can see from the above tables, the chemical elements indicate some reason for defects and warning. On the other hand, the S.O.S analysis indicates how much metals are contained in the oil. As a result, it can determine wearing out parts and pollution of the oil. Elements such as sodium, potassium or silicon indicate contamination by road salt, hard water, glycol antifreeze or dust. Comparing the amount of organometallic additive elements (such as calcium, magnesium, phosphorous, zinc, sulfur, or boron) in the used oil to fresh oil provides an indication of changes to the oil, such as additive depletion or possibly the mixing of different types of oil. [14]

The **table 7** defines the action required content of the chemical elements, on the other hand, if these elements are contained up to the level, the equipment would require any actions and be in a warning condition.

## (2) Product link analysis

Product link is wireless technology of caterpillar to connect equipment and customers. It can give us valuable information into how our machine or fleet is performing. The information includes such as location, service hours, fuel consumption, productivity, idle time, and diagnostic codes. That can maximize efficiency, improve productivity, and lower the cost of owning. All sensors of heavy machinery connected with product link, thus it gets the data from all sensors.

## (3) Mechanical inspection

Mechanical inspection checklists are tools used to determine some problems or failure, which didn't indicated by S.O.S analysis and product link. All inspections need to be done by mechanics and some testers.

										
no.	part Item	inspection method	S	S	M	T	W	TH	inspection photo	
①	Operators Induction form	Operators Safety Induction Form should be signed by the operator.							 Rear view camera	Controller
②	Controller & brake	Controller, clutch and brakes should work fine and seat belt needs to be attached								
③	Rear view mirror & alarm	Rear view mirror should be properly attached and alarm device needs to work normally								

Figure 11 "Mechanical inspection"

# Chapter 4 Result

## 4.1 Burdel Mining LLC

The SMU (service management unit) of the dump truck of “Burdel Mining LLC”, and “Oyu Tolgoi LLC” are a lot different from each other. The difference of SMU includes my result, thus I choose the closest dump trucks.

Table 2 "The closest dump truck"

No	Company	Equipment ID	SMU	Date
1	Burdel Mining LLC	HT-69	27367	Jan-2021
2		HT-69	27822	Feb-2021
3	Oyu Tolgoi LLC	HT-67	27702	Feb-2021
4		HT-67	28214	Mar-2021

As you can see from **table 2**, the equipment ID HT-69 of Burdel Mining LLC is the closest dump truck to HT-67 of Oyu Tolgoi LLC. The interval of service inspection is 350 hours and the sequence of PM is shown in the **table 3** below. The spare parts to be replaced at the time are shown in the **Appendix A**.

Table 3 "Sequence of PM"

SMU	350	700	1050	1400	1750	2100	2450	2800
Type of service inspection	PM1	PM2	PM1	PM3	PM1	PM2	PM1	PM4

Firstly, I compared these dump trucks by S.O.S analysis. Although the parts are changed at the right time, the oil sample does not have a certain sequence. The **figure 12** below shows the time sequences of taking oil samples from the engine.

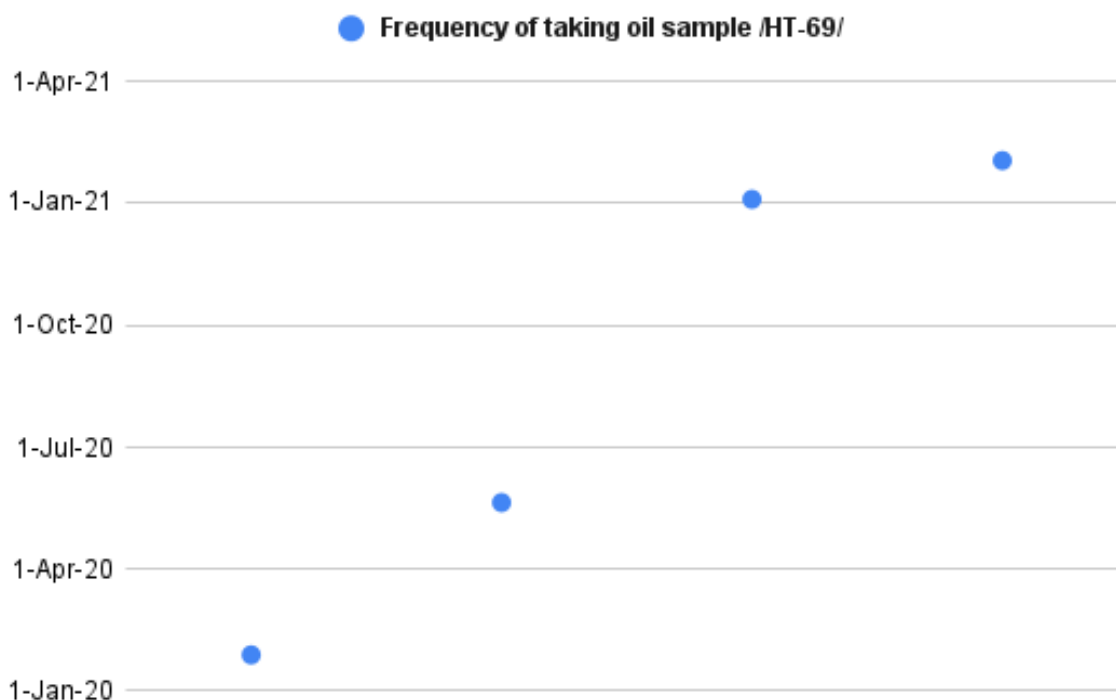


Figure 12 "Date of taking oil sample"

As we can see from the **figure 12**, between 21st May 2020 and 3rd January 2021 didn't take any oil samples. The below **table 4** shows S.O.S analysis date and SMU of the equipment, however the yellow highlighted analysis is severity 2, which means that some pollution is indicated from oil. The mechanics or the planners need to plan maintenance and do the service inspection. The red highlighted analysis is severity 3, which means red alarm, thus the maintenance would be done emergency. However, the green highlighted indicates severity 1 and it is normal.

Table 4 "HT-69, severity of oil"

Equipment ID	Date	SMU on oil	SMU
HT - 69	28-Jan-20	350	24363
HT - 69	21-May-20		25444
HT - 69	03-Jan-21	350	27367
HT - 69	01-Feb-21	700	27822

## Highest chemical elements

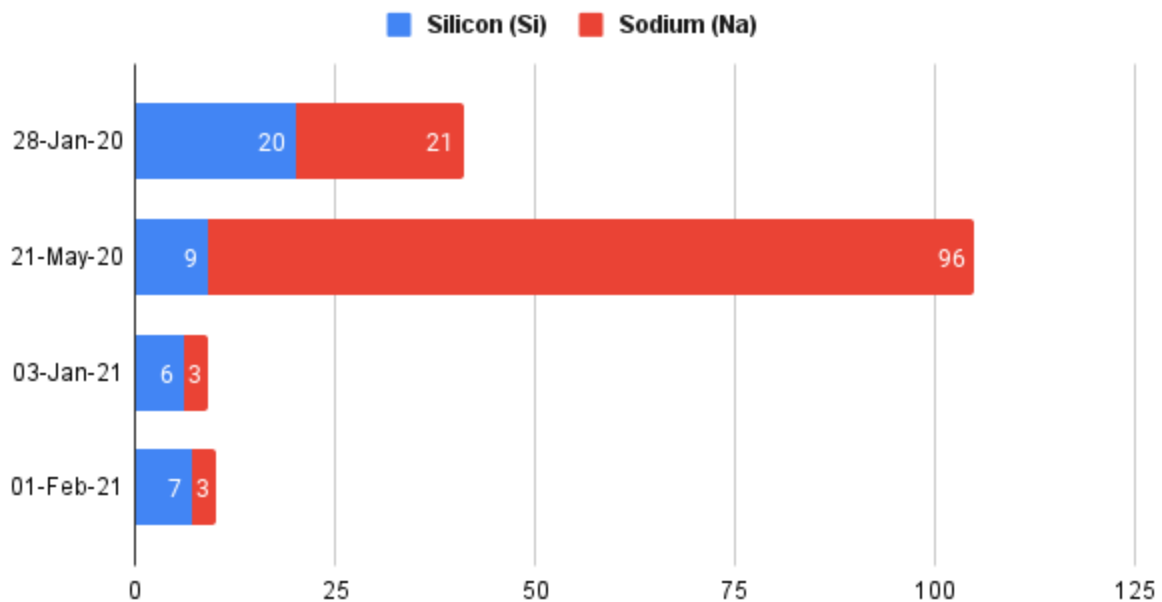


Figure 13 "Content of Si and Na"

As you can see from **figure 13**, the contents of sodium and silicon are high from normal. It means dirty coolant and using the wrong oil. The reason and defect identification is in **table 13**.

The contents of molybdenum, phosphorus, and zinc are indicated high from all machines of Burdel Mining LLC. /**Figure: 14**/ These elements don't affect machine parts, but it shows high due to geographical features, content of soil or fuel additives. The reason why, the molybdenum is important for plants and animals. Some contents of chemical elements are high due to geological features of mining. However, in some conditions, the molybdenum, calcium, and phosphorus are fuel additives in order to increase the benefits of fuel and decrease the corrosion. These fuel additives also can indicate entering the coolant to the engine oil. In order to distinguish these reasons, the other contents of chemical elements are important.

Comparison of above two techniques wasn't possible, because the working conditions and usage are different. Although the service management units are approximately the same, the HT-69 didn't work for six months due to the absence of an operator. Whereas, HT-67 worked for that six months. Thus, it wasn't possible to compare two techniques, which work another mining.

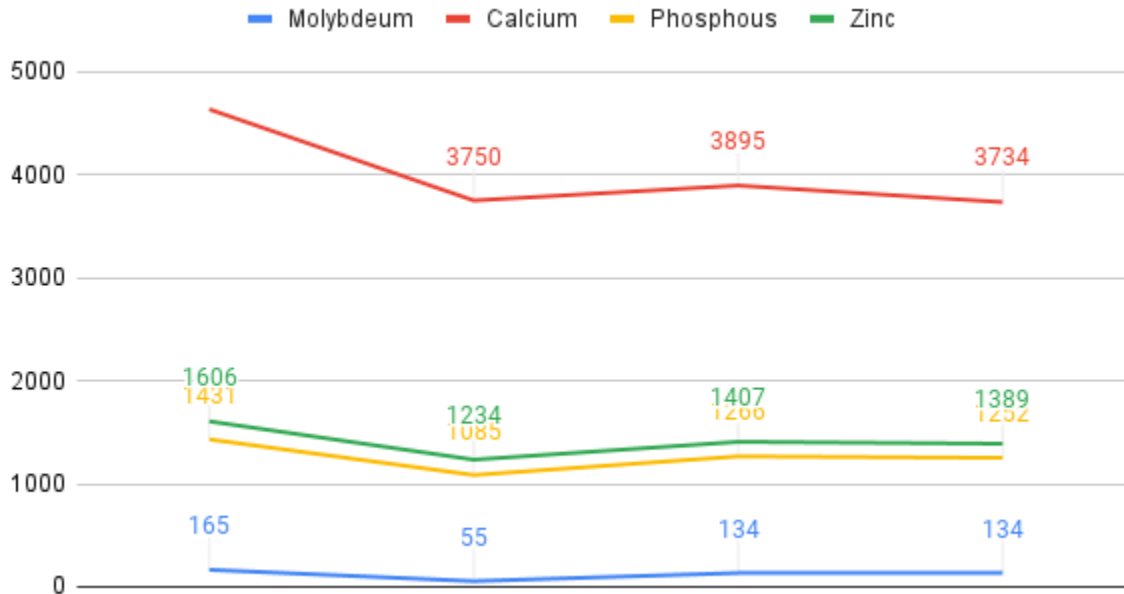


Figure 14 "Content of Mo, Ca, P and Zn"

Downtime lasts at least for 6 months due to engine damage and tire damage. From the data analysis, engine, tire, hoist and suspension cylinder, as well as transmission failure repeats a lot of times and it becomes the main reason for idle.

In the below pie chart (Figure 16), you can see the total idle for some reasons. The statistics clearly illustrate that 100% of ifle for 6 months. As it is shown, engine failure is the highest reason of downtime with 42.3%, and then other failures are found to be second highest with a percentage of 34.3%. It includes seal or o-ring problems and other small parts problems. Whereas, tires failure have a percentage of 16.9% and further the miscellaneous expenses such as the transmission and suspension cylinder.

## Downtime due to tires

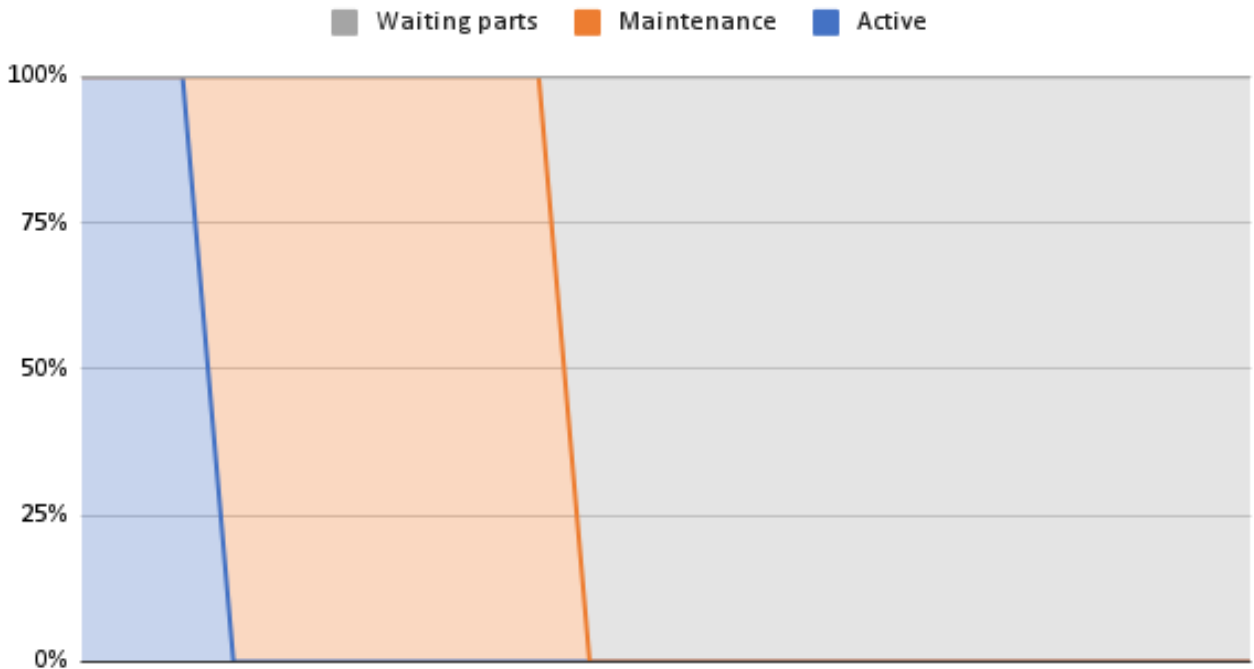


Figure 15 "Status due to tire problem"

The tire and engine failures continued for a long time, as you can see from **Figure 15**. The machine had 83.3% idle for 6 months due to tire failure. The engine and tire failures are a big problem for Burdel Mining LLC.

The reason for the tire, suspension cylinder and hoist cylinder is firstly exceeded load. A payload of CAT 772 is 45.3kg. When the dump truck is loading, the excavator or loader loads exceed the normal. Otherwise, a combination of techniques can be wrong. The combination of techniques needs to be 3-4 times. On the other hand, the excavator or loader, which is unloaded to the dump truck, must be unloaded 3 or 4 times in order to fill out the bucket of the dump truck. Thirdly, the condition of the road is bad and the company doesn't follow and check the lifetime of tires. It is important to be safe and reduce the cost.

## Maintenance & Waiting parts

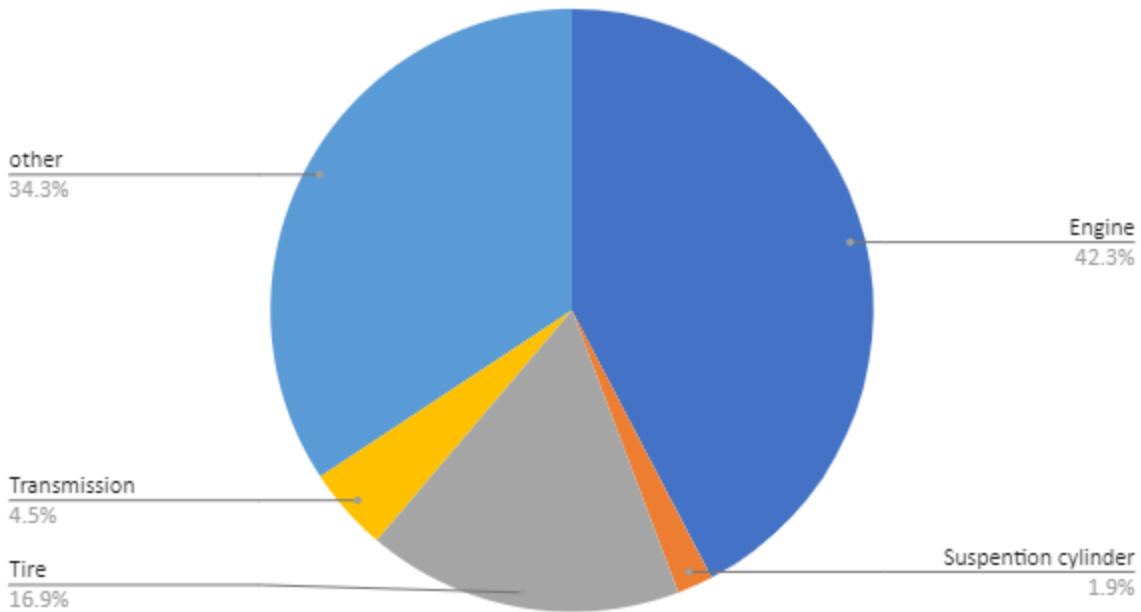


Figure 16 "The reason of downtime"

The engine failure, and injector failure have repeated a lot of times. As you can see from **table 5**, which shows us the result of the engine oil sample, this result was severity 2 (yellow) due to the content of iron being high on the 20th of May 2020 of HT-109 truck. At that date, the SMU was 11539. The main reason for indicating iron is pollution of fuel filter, low quality fuel, wearing out parts, damaging the nozzle, and pollution of air filter from **table 17**.

Table 5 "Oil sample result"

Equipment ID	Date	SMU	Type of oil	Iron /Fe/
HT - 109	20-May	115390	10W40 Fuchs	86

However **table 6** shows us the status of HT-109 for 4 months. HT-109 stopped from the 27th of September 2020 to July 2021 due to engine failure. The dirty fuel filter can cause erratic fuel flow and the abnormal wearing out parts can cause overheating, and leaking. After the S.O.S analysis, the dump truck HT-109 was working for 1025 hours, but nobody took any required action for the engine severity.

Table 6 "Status of HT-109"

DATE OF STATUS	No	MODEL	PARK NUMBER	Active	Maintenance	Waiting parts	STATUS	LOCATION	STOP DATE	SMU
1/1/2021	1	CAI772	HT-109			1	Engine maintenanca	Maintenance shop	2020.09.27	12564
1/10/2021	2	CAI772	HT-109			1	Engine maintenanca	Maintenance shop	2020.09.27	12564
1/20/2021	3	CAI772	HT-109			1	Engine maintenanca	Maintenance shop	2020.09.27	12564
1/30/2021	4	CAI772	HT-109		1		Change the tire /4/	Maintenance shop	2020.09.27	12564
2/1/2021	5	CAI772	HT-109		1		Change the tire /4/	Maintenance shop	2020.09.27	12564
2/10/2021	6	CAI772	HT-109		1		Change the tire /4/	Maintenance shop	2020.09.27	12564
2/19/2021	7	CAI772	HT-109		1		Coolant enters to engine oil	Maintenance shop	2021.02.15	12564
2/27/2021	8	CAI772	HT-109			1	Engine maintenance, to UB	Maintenance shop	2021.02.15	12564
3/1/2021	9	CAI772	HT-109			1	Engine maintenance, to UB	Maintenance shop	2021.02.15	12564
3/10/2021	10	CAI772	HT-109			1	Engine maintenance, to UB	Maintenance shop	2021.02.15	12564
3/20/2021	11	CAI772	HT-109			1	Engine maintenance, to UB	Maintenance shop	2021.02.15	12564
3/30/2021	12	CAI772	HT-109			1	Engine maintenance, to UB	Maintenance shop	2021.02.15	12564
4/1/2021	13	CAI772	HT-109			1	Engine maintenance, to UB	Maintenance shop	2021.02.15	12564

As a result, this dump truck stopped for 10 months and the company spent 98,139,000 tugrik for only the engine parts and lost a lot of profits. The total profits of the company is confidential. If the engine was checked by someone, after the S.O.S analysis, this dump truck wouldn't stop for a long time and lost the profits. It costs 926,793 tugrik for only parts of service inspection. The reasons, which are overdue of preventive maintenance or recommendations were not followed, lost 106 times more profits. But this calculation didn't include the salary of technicians, running costs, and transportation costs. **(Figure: 17 "Comparison of total costs")**

### Cost of preventive maintenance VS reactive maintenance

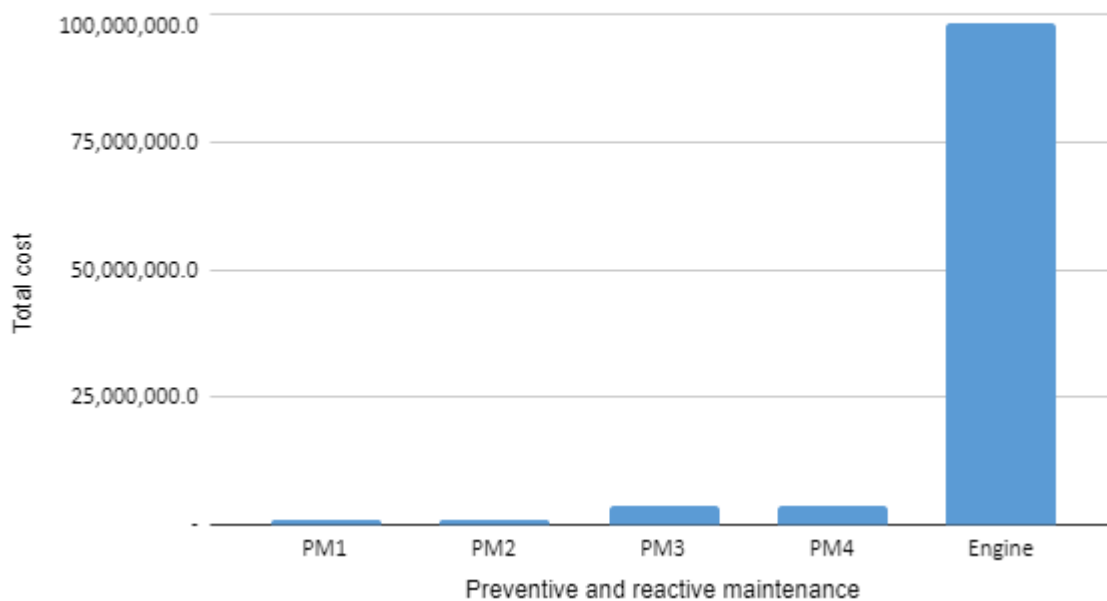


Figure 17 "Comparison of total costs"

## 4.2 Oyu Tolgoi LLC

Oyu Tolgoi LLC did the S.O.S analysis every month. Thus, the company can avoid any failure, which relates to wear parts, and dirty oil.

Costs for fault codes

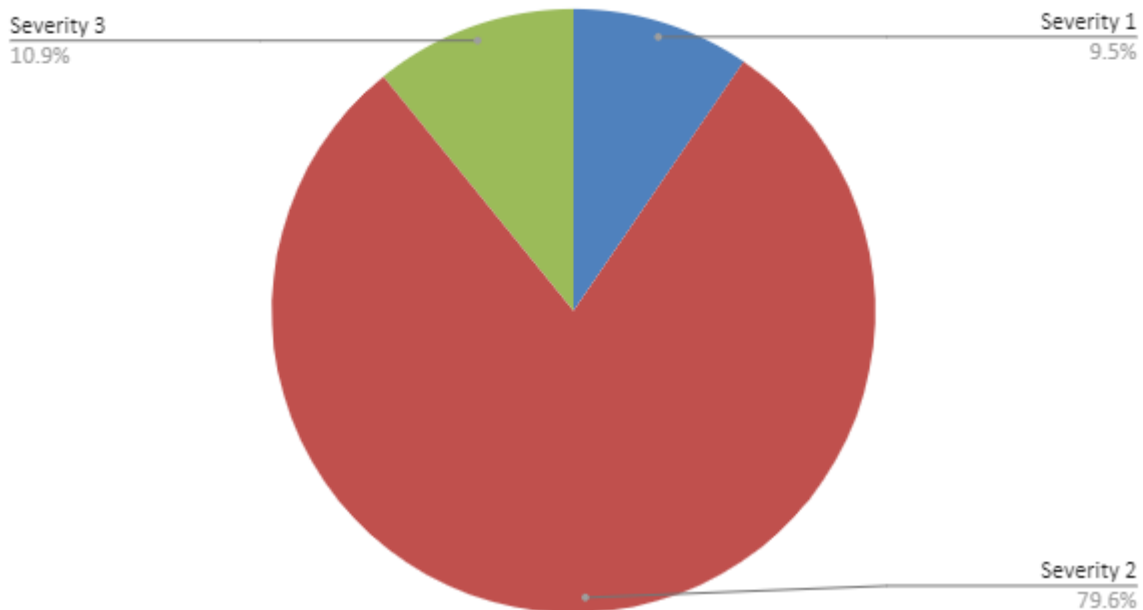


Figure 18 "Costs for fault codes"

From the data of 4 years, the company did any action for a fault code at severity 2. As you can see from **figure 18**, 79.6% of total expenses conquer action for severity 2. It can show us, company can diagnose the problem early. On the other hand, when you did action for technique after severity 3 fault code, it spent more money than severity 2 action like HT-109.

The HT066, HT067, and HT068 techniques have more failures **in figure 19**. The service monitoring units of these machines are 39329, 33358, and 31625. Normal lifetime of a dump truck is 7 to 10 years such as 30000 SMU. The reason for more frequency failure is probably overdue usage or lifetime of techniques. As aforementioned, a failure rate is high when the techniques are new and old. At the first time, new parts rubbing is poor, thus the failure rate decreases at the early life. After that, the failure rate becomes constant. However, the failure rate increases after overdate.

## The most faulty techniques

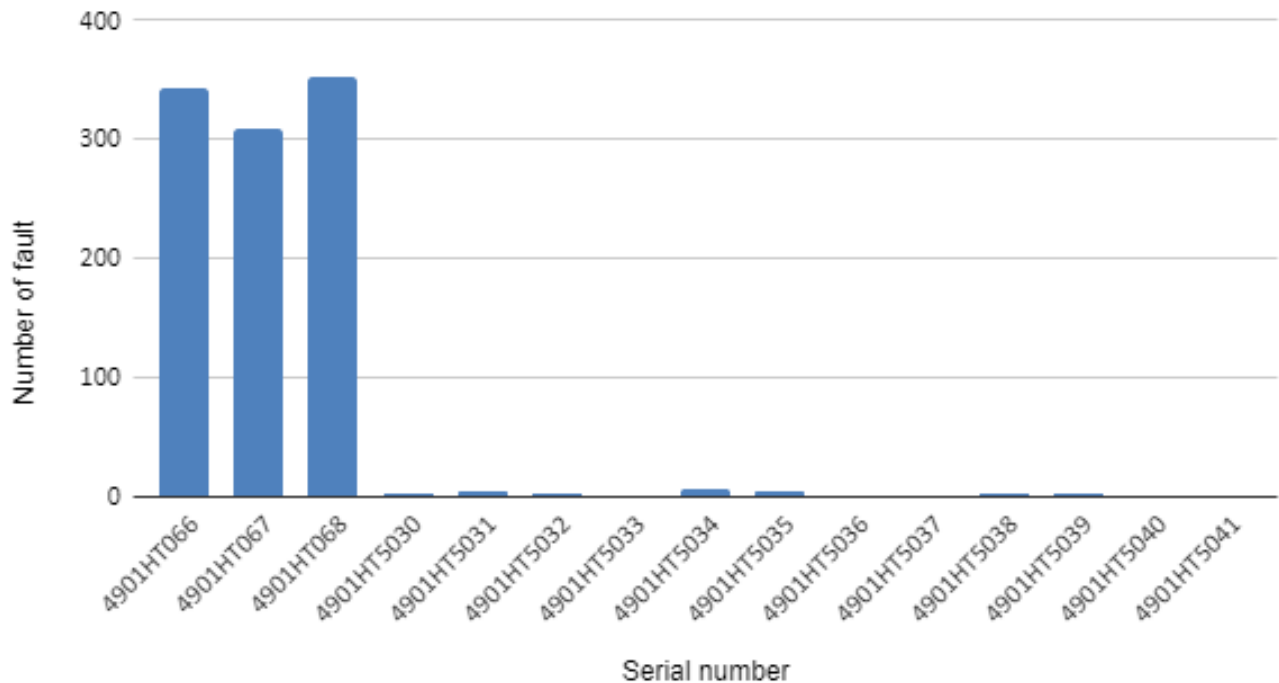


Figure 19 "The faultiest techniques"

The 99.8% of severity 2 total cost is related to these three dump trucks, but another 0.2% is related to other dump trucks. To conclude, the expenses were spent on only the old three techniques for 4 years. On the contrary, other techniques, such as HT-5030, HT-5031 and so on, had a failure due to operators' wrong usage. 98% of all failures of four years are related to tires. The major cause of this is the bad condition of the mining road. **Figure 20** shows us which type of failure repeated more. Action required failure has repeated once for 4 years. However, the severity 2 failure has repeated 4 times, the tire failure has repeated 24 times.

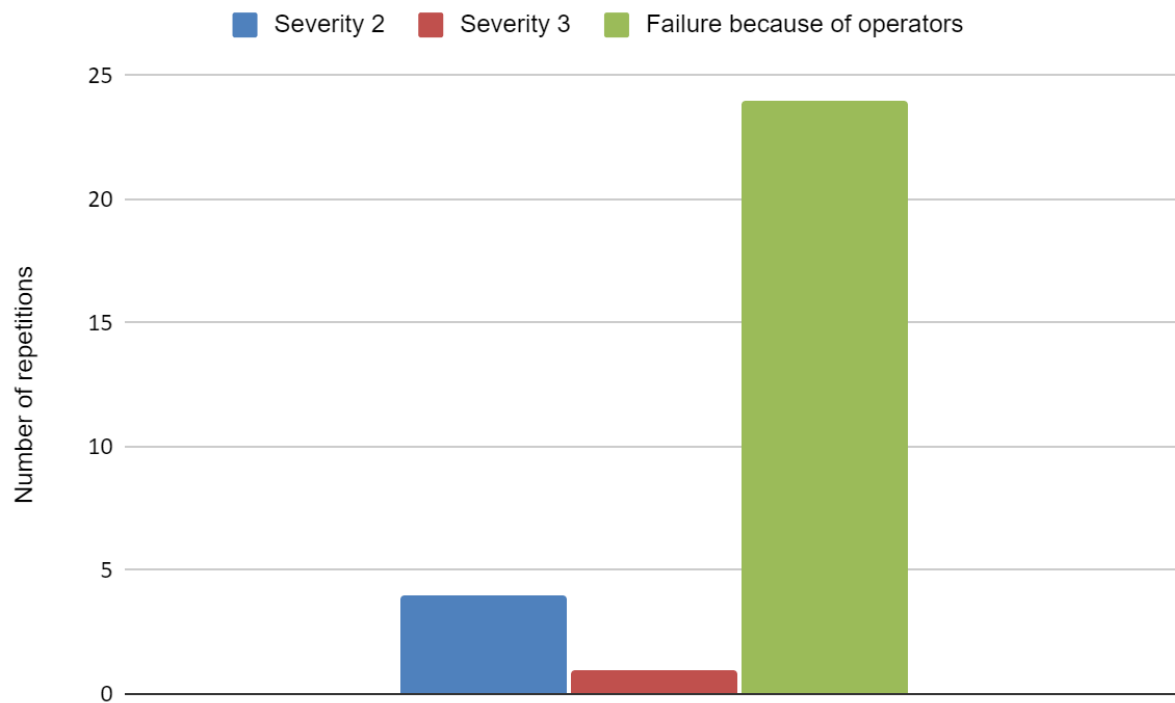


Figure 20 "Frequency of failure"

Now, let's look at the S.O.S analysis. As I mentioned that the time interval of service inspection is 250SMU. Thus, the company changes fuel and air filters every 250 hours. Below the table shows the results of the oil sample. /**Table 7**/

The main chemical contents are normal. It doesn't show any medium or red alert from the oil sample. It means that the engine oil is normal and filters are pure and normal. Thus, the time interval is approved.

Table 7 "Result of oil sample"

Cat 773E	HT066	250	Aluminium	1.1	ENGINE / ENG
Cat 773E	HT066	250	Copper	1	ENGINE / ENG
Cat 773E	HT066	250	Iron	11	ENGINE / ENG
Cat 773E	HT066	250	Magnesium	8	ENGINE / ENG
Cat 773E	HT066	2000	Aluminium	1.7	ENGINE / ENG
Cat 773E	HT066	2000	Copper	1.8	ENGINE / ENG
Cat 773E	HT066	2000	Iron	17.4	ENGINE / ENG
Cat 773E	HT066	2000	Magnesium	10.7	ENGINE / ENG
Cat 773E	HT067	0	Aluminium	1.3	ENGINE / ENG
Cat 773E	HT067	0	Copper	1.8	ENGINE / ENG
Cat 773E	HT067	0	Iron	22.8	ENGINE / ENG
Cat 773E	HT067	0	Magnesium	10.6	ENGINE / ENG
Cat 773E	HT068	500	Aluminium	1.3	ENGINE / ENG
Cat 773E	HT068	500	Copper	2.5	ENGINE / ENG
Cat 773E	HT068	500	Iron	15.5	ENGINE / ENG
Cat 773E	HT068	500	Magnesium	11.7	ENGINE / ENG
Cat 773E	HT067	250	Aluminium	2.1	ENGINE / ENG
Cat 773E	HT067	250	Copper	3.2	ENGINE / ENG
Cat 773E	HT067	250	Iron	61.2	ENGINE / ENG
Cat 773E	HT067	250	Magnesium	11.8	ENGINE / ENG

## Chapter 5 Conclusion

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As aforementioned, the preventive maintenance is the most effective solution to prevent major breakdowns and high running-costs. But, companies need to select most efficient service inspection for highway dump truck. Before beginning the research work, the time interval from 200 SMU to 400 SMU was selected for preventive maintenance. At this interval, all filters, oil and some basic parts were changed. Although it is a very simple strategy, it can help to avoid any big failure and decrease maintenance cost. Burdel Mining LLC uses the time interval 350 SMU, but this time period was recognized as too long to avoid any failure. During this period, oil or filters have become dirty and due to this some parts have worn out. In addition, although oil is analyzed, if no action is taken, the problem get worse in the equipment like HT-109. Meanwhile, Oyu Tolgoi LLC uses the time interval of 250 SMU and this period is not thought as a good one, since all chemical contents are normal and the condition of oil and filters has no problem. The company can use it continuously until 300 SMU to save maintenance costs. However, after 300 SMU, the oil condition need to be checked. The research work is suggesting 300 hours interval. Mining companies need to take oil sample and change the filters in every 300 hours. This SMU can avoid any failure and be techno-economical benefit.

From the results, the most important and right type of preventive maintenance is considered as the condition-based maintenance. The one time intervals cannot be suggested for all mining's dump trucks, because all mining or factories' environmental conditions and usages are different. Based on the analysis of data, the mining companies need to consider condition-based analysis and select own time interval for technique. More efficient time interval can be selected different from 300 SMU based on working conditions and condition-based analysis. It can lengthen the lifetime of dump truck.

# Appendix A:

## Tasks of service inspection

Table 8 "Parts to be replaced at 350 SMU"

<b>PM1 /350 SMU/</b>				
<b>Serial number of parts</b>	<b>Parts</b>	<b>Amount</b>	<b>Cost per an amount</b>	<b>Total costs</b>
1R-1808	Engine oil filter	1	140,879.20	140,879.20
423-8525	Fuel filter	1	126,831.00	126,831.00
1R-0762	Fuel filter	1	109,833.44	109,833.44
	Engine oil	65 liter	8450	549,250.00
<b>Total:</b>				926,793.64

Table 9 "Parts to be replaced at 700 SMU"

<b>PM2 /700SMU/</b>				
<b>Serial number of parts</b>	<b>Parts</b>	<b>Amount</b>	<b>Cost per an amount</b>	<b>Total costs</b>
1R-1808	Engine oil filter	1	140,879.20	140,879.20
246-5009	Air filter	1	219,702.51	219,702.51
423-8525	Fuel filter	1	126,831.00	126,831.00
1R-0762	Fuel filter	1	109,833.44	109,833.44
	Engine oil	65 liter	8450	549,250.00
<b>Total:</b>				1,146,496.15

Table 10 "Parts to be replaced at 1400 SMU"

<b>PM3 /1400SMU/</b>				
<b>Serial number of parts</b>	<b>Parts</b>	<b>Amount</b>	<b>Cost per an amount</b>	<b>Total costs</b>
1R-1808	Engine oil filter	1	140,879.20	140,879.20
246-5010	Primary air filter	1	94,457.87	94,457.87
246-5009	Air filter	1	219,702.51	219,702.51
423-8525	Fuel filter	1	126,831.00	126,831.00
1R-0762	Fuel filter	1	109,833.44	109,833.44
132-8875	Transmission filter	1	191,748.70	191,748.70
4T-6788	Steering system filter	1	91,424.30	91,424.30
126-1813	Steering system filter	1	256,769.00	256,769.00
134-0964	Brake oil filter	2	259,804.10	519,608.20
259-3222	Cabin air filter	1	116,118.73	116,118.73
9C-4937	Converter breather of fuel tank	1	84,874.50	84,874.50
8X-4575	Hydraulic tank breather	1	77,544.84	77,544.84
9T-1119	Differential breather	1	87,289.47	87,289.47
	Engine oil	65 liter	8,450	549,250.00
	Back reductor oil	18	7,640	137,520
	Final drive oil	10	14,870	148,700
	Steering hydraulic oil	10	8,400	84,000
	Hydraulic oil	25	8,400	210,000
	Coolant	18	7,740	139,320
<b>Total:</b>				<b>3,385,871.76</b>

Table 11 "Parts to be replaced at 2800 SMU"

<b>PM4 /2800SMU/</b>				
<b>Serial number of parts</b>	<b>Parts</b>	<b>Amount</b>	<b>Cost per an amount</b>	<b>Total costs</b>
1R-1808	Engine oil filter	1	140,879.20	140,879.20
246-5010	Primary air filter	1	94,457.87	94,457.87
246-5009	Air filter	1	219,702.51	219,702.51
423-8525	Fuel filter	1	126,831.00	126,831.00
1R-0762	Fuel filter	1	109,833.44	109,833.44
132-8875	Transmission filter	1	191,748.70	191,748.70
4T-6788	Steering system filter	1	91,424.30	91,424.30
126-1813	Steering system filter	1	256,769.00	256,769.00
134-0964	Brake oil filter	2	259,804.10	519,608.20
259-3222	Cabin air filter	1	116,118.73	116,118.73
268-6704	Cabin air filter	1	136,424.20	136,424.20
9C-4937	Converter breather of fuel tank	1	84,874.50	84,874.50
8X-4575	Hydraulic tank breather	1	77,544.84	77,544.84
9T-1119	Differential breather	1	87,289.47	87,289.47
	Engine oil	65 liter	8,450	549,250.00
	Back reductor oil	18	7,640	137,520
	Final drive oil	10	14,870	148,700
	Steering hydraulic oil	10	8,400	84,000
	Hydraulic oil	25	8,400	210,000
	Coolant	18	7,740	139,320
	Transmission oil	25	10550	263,750.00
<b>Total:</b>				<b>3,786,045.94</b>

Худалдан авагч 11343 Комкат Си Эл Эйч ХХК  
6594131

Үнийн саналын дугаар	Бэлтгэсэн ажилтан	Хэрэглэгч №	Серил №	Худалдааны тодорхойлолт
QTE0056974	WA\1646	CAT772 2674631 BLOCK AS-CYL 2298568		Counter Sales

№	Бараа материал	Тоо хэмжээ	On Hand	В/О	Захиалгын төрөл	Нийлүүлэх хугацаа	Discount Amount	Нэгжийн үнэ	Нийт үнэ
1	2674631 BLOCK AS-CYL 2298568	1.00	0	0	GRMSTCKS EA	45 days		47,988,402.00	47,988,402.00
2	10R4463 CRANKSHAFT A	1.00	0	0	GRMSTCKS EA	180 days		35,045,201.00	35,045,201.00
3	10R4463C CRANKSHAFT A	1.00	0	0		0		6,184,437.00	6,184,437.00

Үйлчилгээ	0.00
Бараа материал	89,218,040.00
Агаарын тээвэр	0.00
Нийт	89,218,040.00
Хөнгөлөлт	0.00
НӨАТ	8,921,804.00
Бүгд үнэ	98,139,844.00

## Appendix B:

Table 12 "Indication of hydraulic cylinder"

№	S.O.S performance	Reason	Defect indication
1	Cr, (Si, Al)	<ul style="list-style-type: none"> <li>● Bending or injure the cylinder rod</li> <li>● Entering dirt from wiper seal</li> </ul>	<ul style="list-style-type: none"> <li>● Leaking the oil</li> <li>● Increasing the drift of cylinder</li> </ul>
2	Si, Al	<ul style="list-style-type: none"> <li>● Decreasing a level of oil</li> <li>● Entering dirt</li> </ul>	<ul style="list-style-type: none"> <li>● Slowing down a frequency of rotation</li> </ul>
3	(Cu, Cr, Fe) or (Cu, Fe, Al)	<ul style="list-style-type: none"> <li>● Pump of vane</li> <li>● Pump of piston</li> <li>● Decreasing a level of oil</li> </ul>	<ul style="list-style-type: none"> <li>● Increasing the noise</li> </ul>
4	(Na, K, Cu)	<ul style="list-style-type: none"> <li>● Entering the coolant from oil cooler</li> <li>● Entering dirt</li> <li>● Using wrong oil</li> <li>● Decreasing a level of oil</li> <li>● Pollution of filter</li> <li>● Wearing the parts of system</li> </ul>	<ul style="list-style-type: none"> <li>● Heating the system</li> </ul>

Table 13 "Signs of engine"

№	S.O.S performance	Reason	Defect indication
1	Fe, Cr, Al, soot	<ul style="list-style-type: none"> <li>● Pollution of air filter</li> <li>● Much fuel</li> <li>● overloaded</li> </ul>	<ul style="list-style-type: none"> <li>● Emitting black smoke</li> </ul>
2	Fuel content, decreasing viscosity	<ul style="list-style-type: none"> <li>● Leaking fuel from injector</li> <li>● Decreasing additional element to improve quality</li> <li>● Pollution of air filter</li> </ul>	<ul style="list-style-type: none"> <li>● Increasing the consumption of fuel</li> </ul>
3	Fe, Cr	<ul style="list-style-type: none"> <li>● Damage for cooler of fuel</li> <li>● Wearing the seal of turbocharger</li> <li>● Exceeded usage of engine</li> </ul>	<ul style="list-style-type: none"> <li>● Emitting black smoke</li> <li>● Increasing the consumption of fuel</li> </ul>
4	Pollution of coolant, Na, K, Si, Cu	<ul style="list-style-type: none"> <li>● Entering coolant to engine</li> <li>● Broke the cap</li> </ul>	<ul style="list-style-type: none"> <li>● Emitting the white smoke</li> </ul>
5	Fe, Cr	<ul style="list-style-type: none"> <li>● Broke the cooler of oil</li> <li>● Wearing the seal of turbocharger</li> <li>● Exceeded usage of engine</li> </ul>	<ul style="list-style-type: none"> <li>● Increasing the consumption of fuel</li> </ul>
6	Cu, Pb, Al, pollution of fuel, decreasing the viscosity	<ul style="list-style-type: none"> <li>● Decreasing additional element to improve quality</li> <li>● Lower rod bearing</li> <li>● Rod eye bushings</li> <li>● Wearing bearing</li> <li>● Damaging the nozzle</li> </ul>	<ul style="list-style-type: none"> <li>● Increasing the noise</li> </ul>
7	Soot, Fe, Cr	<ul style="list-style-type: none"> <li>● Pollution of air filter</li> <li>● Low quality fuel</li> <li>● Damaging the nozzle</li> <li>● Pollution of fuel filter</li> </ul>	<ul style="list-style-type: none"> <li>● Loss the strength</li> </ul>
8	Fe, Pb, Al, Cu and soot	<ul style="list-style-type: none"> <li>● Gear</li> <li>● Bearing</li> <li>● Pollution of air filter</li> <li>● Cooler core</li> <li>● Wearing the belt</li> <li>● Decreasing coolant</li> </ul>	<ul style="list-style-type: none"> <li>● Overheating</li> </ul>
9	Soot, Fe, Cr	<ul style="list-style-type: none"> <li>● Low quality fuel</li> <li>● Pollution of air filter</li> <li>● Decrease the velocity of piston</li> </ul>	<ul style="list-style-type: none"> <li>● Shut down the engine</li> </ul>

Table 14 "Indication of transmission"

№	S.O.S performance	Reason	Defect indication
1	Si, Fe, (Ca, P, Zn)	<ul style="list-style-type: none"> <li>● Wearing out the disc</li> <li>● Wearing out the plate</li> <li>● Using wrong oil</li> <li>● Decreasing level of the oil</li> </ul>	<ul style="list-style-type: none"> <li>● Slow down transmission</li> </ul>
2	Fe, Cr, (Si, Al), (Ca, P, Zn)	<ul style="list-style-type: none"> <li>● Entering dust</li> <li>● Gear and bearing</li> <li>● Decreasing the level of oil</li> </ul>	<ul style="list-style-type: none"> <li>● Abnormal noise</li> </ul>
3	Fe, Cr	<ul style="list-style-type: none"> <li>● Bending the cardan shaft</li> <li>● Breaking down the gear</li> <li>● Breaking down the bearing</li> </ul>	<ul style="list-style-type: none"> <li>● Vibration</li> </ul>
4	Pollution of coolant, (Na, K, Si, Cu), increasing viscosity	<ul style="list-style-type: none"> <li>● Entering the coolant or dust</li> <li>● Overdue to change the oil</li> <li>● Using wrong oil</li> <li>● Wearing out the bearing and gear</li> </ul>	<ul style="list-style-type: none"> <li>● Overheating</li> </ul>
5	(Si, Al), (Ca, P, Zn), Fe, Cr	<ul style="list-style-type: none"> <li>● Using wrong oil</li> <li>● Entering the dust</li> <li>● Wearing out gear and bearing</li> </ul>	<ul style="list-style-type: none"> <li>● Pollution of filter and magnetic filter</li> </ul>
6	Si, Al	<ul style="list-style-type: none"> <li>● Entering the dust from seal</li> </ul>	<ul style="list-style-type: none"> <li>● Leaking the oil</li> </ul>

Table 15 "Indication of differential"

№	S.O.S performance	Reason	Defect indication
1	(Si, Al), Fe, Cr, increasing the viscosity	<ul style="list-style-type: none"> <li>● Entering the dust</li> <li>● Wearing out the bearing and gear</li> <li>● Overdue to change the oil</li> <li>● Using wrong oil</li> </ul>	<ul style="list-style-type: none"> <li>● Sawdust on the magnetic plug</li> </ul>
2	(Si, Al), Cr	<ul style="list-style-type: none"> <li>● Entering the dust</li> <li>● Wearing out bearing and seal</li> </ul>	<ul style="list-style-type: none"> <li>● Leaking the oil</li> </ul>
3	(Ca, P, Zn), Fe, Na, increasing viscosity	<ul style="list-style-type: none"> <li>● Using wrong oil</li> <li>● Decreasing the level of oil</li> <li>● Entering the water</li> </ul>	<ul style="list-style-type: none"> <li>● Overheating</li> </ul>
4	Fe, Cr, (Si, Al), increasing the viscosity	<ul style="list-style-type: none"> <li>● Wearing out the gear and bearing</li> <li>● Entering the dust</li> <li>● Decreasing the level of oil</li> </ul>	<ul style="list-style-type: none"> <li>● Abnormal noise (during straight ride)</li> </ul>
5	Fe	<ul style="list-style-type: none"> <li>● Wearing out gear</li> </ul>	<ul style="list-style-type: none"> <li>● Abnormal noise (during rotation)</li> </ul>
6	Fe, Cr	<ul style="list-style-type: none"> <li>● Wearing out gear</li> <li>● Breaking down the bearing</li> <li>● Breaking down the cardan shaft</li> </ul>	<ul style="list-style-type: none"> <li>● Vibration</li> </ul>

Table 16 "Indication of final drive"

№	S.O.S performance	Reason	Defect indication
1	Si, Fe, (Ca, P, Zn)	<ul style="list-style-type: none"> <li>● Wearing out the disc</li> <li>● Wearing out the plate</li> <li>● Using wrong oil</li> </ul>	<ul style="list-style-type: none"> <li>● The brake system works poorly</li> </ul>
2	Si, Al, Fe	<ul style="list-style-type: none"> <li>● Dust</li> <li>● Wearing out the disc</li> <li>● Wearing out the plate</li> <li>● Decrease the level of oil</li> </ul>	<ul style="list-style-type: none"> <li>● Abnormal noise</li> </ul>
3	Increasing viscosity, Fe, Na, water	<ul style="list-style-type: none"> <li>● Decrease the level of oil</li> <li>● Entering the water</li> <li>● Using wrong oil</li> </ul>	<ul style="list-style-type: none"> <li>● Overheating</li> </ul>
4	(Si, Al), increasing viscosity, (Al, Cu, Fe)	<ul style="list-style-type: none"> <li>● Wearing out gears and bearing</li> <li>● Wearing out Sleeve bushing</li> <li>● Entering the dust</li> <li>● Overdue date to change the oil</li> </ul>	<ul style="list-style-type: none"> <li>● Sawdust on the magnetic plug</li> </ul>
5	Fe, Cr, (Si, Al), (Cu, Pb)	<ul style="list-style-type: none"> <li>● Breaking down thrust washer</li> <li>● Entering the dust</li> <li>● Breaking down the bearing</li> <li>● Wearing out gear</li> </ul>	<ul style="list-style-type: none"> <li>● Vibration</li> </ul>
6	Si, Al, Cr	<ul style="list-style-type: none"> <li>● Breaking down the bearing</li> <li>● Entering the dust due to wearing out seal</li> </ul>	<ul style="list-style-type: none"> <li>● Leaking the oil</li> </ul>

Table 17 "Indication of wearing parts"

<b>Element</b>	<b>Upper warning level</b>	<b>Origin</b>
Iron (Fe)	80-180	Cylinder block, cylinder head, timing wheels and timing chains, valves, valve, tappets and guides, crankshaft, camshaft, rocker arm shaft, piston pins, roller bearings, oil pump, rare in residues of ferrocene, a fuel additive for soot reduction
Chromium (Cr)	4-28	Piston rings, crankshaft bearings, piston pins, exhaust valves, gaskets, guide bushes, chrome-plated parts and gears;
Tin (Sn)	12-24	Often together with lead or copper; running surfaces of connecting-rod bearings, rocker arm shaft and piston pin bearings, solder (consisting of lead and tin) in soldered radiator joints;
Aluminum	12-55	Primarily from pistons, oil pump housings, oil coolers, torque converter parts, turbocharger, guide bushes, plain bearings, cylinder blocks of all-aluminum engines
Nickel (Ni)	1-3	Alloy constituent of exhaust valves, valve guides, turbochargers, high-strength gears and turbine blades; instead of being chrome-plate;
Copper (Cu)	25-60	Main constituent of brass and bronze; as wear metal from oil pumps, connecting-rod bearings, piston pin bearings, rocker arm, shaft bearings, bronze worm gears, and sintered brake and clutch discs; resulting from the corrosion of oil coolers, piping and seals
Lead (Pb)	10-30	Usually in combination with tin and copper; connecting-rod bearings; nearly all running surfaces of plain bearings and soldered joints in combination with tin
Molybdenum (Mo)	4-20 /Up to 500 in fresh oil/	Contained in transmission synchronizer rings, piston rings and heat-resistant steels; component of an antioxidant and friction modifier additive package

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