Exploring Factors that Affect Reliability of Open Pit Heavy Mining Dump Trucks: A Case of Bisha Mining Share Company, Eritrea

Dr. Dyson Galatia, PhD

Abstract: *Achieving high production and productivity target is one of the core focus areas ofthe mining industry today in order to stay in business. As such, it entails proper performance management of the huge and capital intensive equipment which is utilised in the industry. Dump Trucks are one of the most critical equipment in the movement of material and their reliability has a great influence on the mine output. Unplanned downtime results intoundesirable indirect cost of maintenance due to losses in production and the idleness of other machines in the production system. This paper therefore, aims at identifying potential causes of Dump Truck downtime in orderto establish a Framework that could be used as a tool by management to proactively identify breakdown causes and make informed decisions.Reliability and Maintainability characteristics; Meantime Between Failure (MTBF) and Meantime To Repair (MTTR)as well as failure mode patterns have been examined in order to identify the keysources of Truck downtime.To help with the research, a case study was conducted at BMSC. Data collection was through document review (time series analysis), questionaires, personal interviews with key subject matter experts as well as through participant observation. Pragmatisim was the philosophical view that underpinned the study with a maltimethods approach. Additionally, a covergent paralle strategy of mixed research methods approach was applied. Qualitative data was analysed through the inductive process of building from the data to broad themes and then proceeding to interpretation. Further, quantitative data was analysed by the use of descriptive statistics from the Likert scale and graphs and tables have been used to highlighttrends of data results.The findings from the study show that Maintenance personnel and Truck Operator skills, staffing levels, supervision, the mode of loading trucks and environmental conditions have a significantimpact on the reliability of mining Dump Trucks.*

Keywords: Reliability, Meantime To Repair (MTTR), Meantime Between Failure (MTBF), Availability, Maintenanbility, Key Performance Indicator (KPI)

1. Introduction

Dump Trucks play an important role in the mining industry in the movement of material and its cost proficiency at efficient operation and maintenance practices centered on reliability can lead to substantial reduction in equipment breakdown and operating cost. Morad, Mohamad and Sattarvand (2014) echoed that, loading and hauling equipment is considered as the most precious assets of an open pit mine which correspond to the vast amount of capital invested and that maintenance of these vehicles is critical to the movement of ground. From another platform, Yadav, Gupta and Kumar (2020) indicated that, Dump Trucks are one of the most widely capital intensive heavy duty equipment used in the mining industry and that continuous monitoring of the equipment’s performance is essential for a mining system. They further commented that, it is necessary to have a well-defined performance measure (PM) to monitor performance. From this conceptual theory, they proposed a maintenance approach which unites time performance, capacity performance and environmental performance, criticizing the traditional maintenance practice which is based on the internal losses and neglects the operational effect beyond the system boundary, that is, external losses. From these ideologies and concepts, it can be established that,low equipment reliability is a cost to an organization and a major concern for Mine management.To this effect, this kind of equipment should be maintained and operated efficiently. However, though various maintenance activities have been adopted to ensure high equipment reliability, unplanned breakdowns usually occur as explained by Tananwari, Abbasi and Rashid (2006) who said, equipment of whatever type no mater complex or simple, however, cheap or expensive, is liable to breakdown, therefore, not only procedures should be considered for equipment maintenance, but also the possibility of breakdowns and disruption of operation must be considered during capacity planning and activity scheduling.As such, to achieve better results, the main aspects of Dump Truck reliability must be considered.

2. Background

The aim of every mining operation is to produce at a lower unit cost where production performance depends on the availability and utilization of the mining equipment. Therefore, equipment must operate efficiently and when a breakdown occurs, the repair reaction time (MTTR) must be minimal and recorded for further analysis. In many situations, the reaction time to breakdowns is often short, thus, if a trained and experienced labor-force is exist,nevertheless, the impact of downtime no matter how small it may be has significant implications on productivity.In mining, operations are collateral, a delay in one section affects the other and finally the whole production cycle.For that reason, every production area in mining is as effective as the performance of the weakest section. On the other hand,Jula et al (2006) explains that, there are a lot of reasons why mining equipment goes wrong and this includes selection of equipment, the manner in which the equipment is used or applied, maintenance practices, inadequacies in technical skills, lack of mid-life equipment rebuild, quality of equipment and component refurbishment, quality of replacement parts as well as the maintenance organization structure.

Further, the impact and frequency of equipment downtime has a negative effect on an organizations’ productivity and profitability.Most of the time, breakdown of equipment is only viewed as mere downtime to operations, however, this has a triple cost implication on the organization, production cost in not meeting the output target, maintenance cost, the more breakdowns experienced, the more parts will be required to repair broken down equipment as well as maintenance labor cost which usually arises from unplanned work and finally,fixed cost associated with mining operations such as power.

Hence, it is always important to ensure that,equipment failure is prevented or kept to a bearable minimum, this can be made possible by ensuring that management and the rest of the workforce develop a culture of managing equipment with a sense of care, understanding that, maintenance activities undertaken before failure are less disruptive to production and easy to correct.

In order to keep mining equipment such as Dump Trucks running effectively, most of the companies have invested inundertakings such as:

1) Planned maintenance – where equipment is maintained after a specified period of time (usually in hours). By definition, maintenance is a combination of all technical, administrative and managerial related activities carried out at stated intervals throughout the life cycle of a piece of equipment, system or subsystem intended to retain it in its operating state, or restore it to, a condition in which it can perform the required function. Maintenance practices are grouped into two major categories, namely Preventive and Corrective Maintenance. If maintenance is carried out correctly, it leads to decreased downtime and subsequent reduced maintenance cost with a high profit margin. Maintenance represents a significant proportion of the overall operating cost, contributing around 15 to 40% of the total mine production cost, this margin may even be higher if maintenance is neglected. Additionally, Tripathy claims that, maintenance represents a significant proportion of the overall operating cost in the mining industry and despite the large cost of maintenance; management has only given passing attention to the optimization of the maintenance process.
2) Major component change out – major components are tracked using operating hours and when the component reaches its maturity, it is replaced before failure occurs. This has a duo benefits, it is cheaper to recondition the component which has not failed and there is less interruption to operations since the downtime is planned in advance. A major component may be defined as that part of a machine that is taken to have a longer life cycle and usually of a higher value. The replacement of components is usually planned and determined by operating hours or distance covered, except in cases of equipment breakdown. Following the major component replacement plan has been a challenge for most of the mining companies due to cost associated with the replacement (management usually wants to draw maximum benefit from components) and lack of effective planning.Lack of manpower to replace the components equally poses a challenge, unless reliable systems are in place.
3) Condition monitoring – the wear or deterioration of certain parts such as engines and associated drive units is monitored through oil analysis(Tribology) to avoid unexpected failure.Condition Based Maintenance (CBM) can be defined as amethod of maintenance where the operating state of components on a machine, system or subsystem is monitored for wear or deterioration. When a fault is identified, corrective action is immediately taken or deferred to a later date depending on the severity of wear or deterioration. However, in most cases, determining the replacement point is not accurate and despite monitoring the deterioration, unexpected failure occurs.
4) Tyre management – one of the critical areas. A good tyre management plan clearly defines the selection, operation, maintenance and disposal (i.e. whole life cycle) of tyres, rims and wheel assemblies. Hence, the management of these items requires an integrated risk-based strategy from key personnel on the mine, including Management, Production, Maintenance, Supply Chain, Occupational Health and Safety, and Environment. Tyre condition and life is monitored to avoid unexpected failures which may be catastrophic. Further, working with off-the-road tyres for earth-moving machinery such as mining Dump Trucks can be potentially dangerous because of their large size and mass, magnitude of air or gas pressures, and the presence of combustible materials. The uncontrolled release of stored energy can have serious, even fatal, implications. Therefore, management of such vessels reqyuires maximum attention to avoid unforeseen failure.
5) Lubrication – some organisations have put in place lubrication programs to ensure consistency in lubrication of heavy equipment.In today’s heavy mining equipment world, the driving power in new product development is to enable the mining units to have lower operating cost. Therefore, equipment manufacturers have replied by increasing equipment efficiency, primarily by increasing equipment size, load carrying capacity and operating speeds while continually pushing to reduce both equipment cost and weight. Increasing equipment size has triggered the increase in the engine’s size and horsepower, which in turn has placed more demand on the drivetrain hardware components (i.e. transmission, axles, hydraulics and gears) and correspondingly on the fluids that lubricate these components and keep the equipment running optimally for their expected useful life cycle. Typically, there have been increases in power, power density and torque with each successive model. Concequently this increase in power density generates more heat, raising oil sump temperatures throughout the drivetrain and other corresponding links. Transmissions, differentials and final drives are subjected to increasingly higher loads as machines become capable of shifting larger quantities of material and much faster. The surface finish of components, their design and metallurgy have steadily improved, but they still require the highest level of lubrication to deliver maximum performance and remain durable. To this effect, lubrication becomes a very important aspect in minimising failure of such critical parts and subsequently achieving high reliability of heavy mining equipment .

Many statistical models have been developed to assist in predicting equipment failure and reliability which can be expressed as a probability, and affected by variation. In principal, the approaches are applicable, however, these methods may not always give satisfatory results for mining equipment as most of the equipment failures display a stochastic pattern. Mining equipment reliability is affected by factors that may not be easily predicted through such models, never the less, these models are essential in guiding maintenance activities. Factors such as operator behavior, attitude of maintenance personnel and other operating conditions may render model prediction inacurate.Hall (1997) claimed that, in the mining industry, specialised equipment, more especially mobile equipment is affected by various factors under which the equipment operate. Therfore, in order to manage reliabilty of this equipment, it is important to first understand and manage the key (silent) causes of failure.Niklin (2013) implied that, failure causes of production systems need to be identified for effective solutions and root-cause failure analysis used to identify the failure causes. Mohammadi, Quoquab and Alias (2011) on the other hand, gave caustion by saying, human factors play an important role in the operation of the mine in supporting equipment maintenance practices. Therfore, human behaviour has a great impact on equipment reliability.

The aim of this reasearch is to identify factors that contribute to low reliability of the heavy open pit Dump Trucks in the mining industry and to propose a model that could assist mine management in making informed decisions. A case study was carried out at BMSC to help identify the major causes of Dump Truck downtime and to validate reliability aspects.

3. Case Study

Many writers on mining equipment have indicated that it is important to have a well defined maintenance plan to keep the equipment running efficiently throughout its life-cycle and to achieve this, a number of maintenance modules and schedules have been developed. Dump Trucks are one of the most important equipment in an open pit mine for moving material and therefore, to achieve set production targets, Trucks must be reliable at all times.

The data used in this study comes from BMSC Planning office. The mine runs a series of heavy mining equipment, however, for the sake of this study, the performance of twenty seven (27) CAT775B/F Dump Trucks has been used to help in determing some of the major causes of Dump Truck breakdowns in an open operation. This equipment operated both during the day and night and planned maintenance was carried out by the maintenance department. The mine had a team of operators under the mining department and maimntenance personnel under the Heavy Mining Equipment (HME) departement. The maintenance planning personnel kept all equipment performance records and were responsible for planning and scheduling of equipment maintenance as well as planning for repair of unscheduled failures.

The equipment performance data for the Trucks were collected from planning office and the information relevant to the study was reogarnised for used in anlysing equipment reliability parameters and identifying the behaviour of failure causes.

4. Methodology

The overall objective of the study was to identify the main causes of open pit Dump Truck breakdowns and develop a model that coud be ised in identifying potential downtime causes. The study sought to answer the general research question: What are the major causes of Dump Truck breakdown in open pit mines? The study was therefore, underpinned on a pragmatic view point and applied a multi-methods approach. For collecting data, a questionnaire was developed and administered to both maintenance and mining personnel. Further, an interview guide was used to collect information from key informants who were selected using a purposive sampling technique. Additionally, documents from Heavy Equipment Maintenance Planning office provided significant equipment performance data which included among others, MTTR, MTBF and Availability. Qualitative data was analyzed using the inductive process of building from the data to broad themes and then to a generalized model or theory, participant observation was used to collect data from the filed. Quantitative data was analysed by using descriptive statistics and equipment performance data was collected from machine history files and analyses through tables and graphs.

Document Review

All the data used in this section were obtained from HME Planning office where all equipment history files and maintenance plans were developed and kept.

The performance of twenty seven (27) CAT 775 Dump Trucks for a period 1st January 2019 to 30th April 2020 was observed. This included reviewing both maintanability (MTTR) and reliability (MTBF) attributes as well as equipment availability figures. Different failure modes were analysed and the frequency of major component failure ocurrance recored.

a) Equipment Availability

In this study, equipment availability is defined as the duration of time a piece of equipment, system or sub system is in an operable condition and readily available for use when required, it excludes all repair time. The units are expressed in hours. Hillon (2008) expresses availability as the probability that a piece of equipment is functioning satisfactorily at a specified time, when used according to specified conditions, where the total time includes operating time, logistical time, active repair time, and administrative time. Pinto and Xavier (2001) on the other hand, describe availability as the ratio of possible working hours to calendar hours and that it is an important indicator for reliability analysis.

The availability of the twenty seven (27) Dump Trucks at BMSC from 1stJanuary 2019 to 30thApril 2020 is as shown in Figure 1.

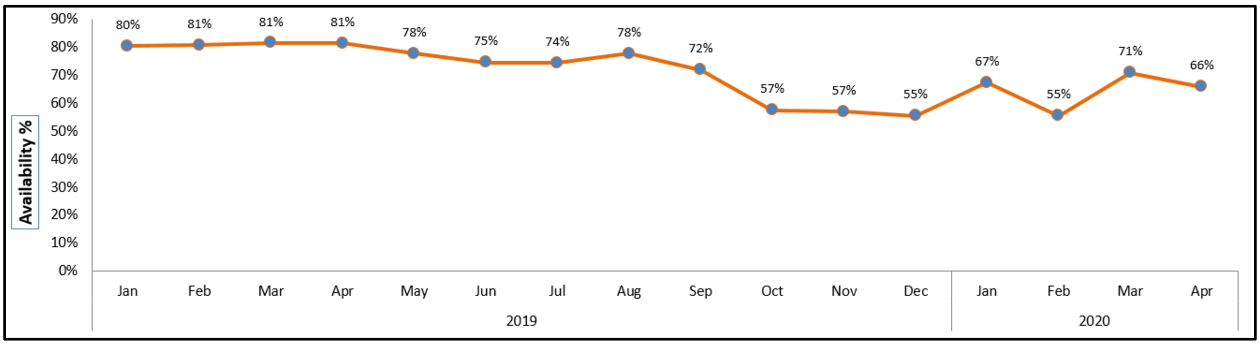


Figure 1: Availability

The availability of the total fleet was averaging 80.75% in the first four (4) months of 2019, however, from May 2019 the availability began declining to an average of 64.75% into the first four (4) months of 2020. In July 2019, the contractor who was engaged in carrying out maintenance was terminated and the mine started using the local labor force with a few relatively cheap expatriates.

Availability was driven from the formular:

$$Availability\ Time\ \% = \frac{AAT}{TT}\ x\ 100$$

Where:

i. AAT = Actual Available Time
ii. TT = Total Time

The Actual Available Time was derived from the computation:

Actual Availability Time (AAT) = TT - (P + R + D + L + S + O) x Number of days

Where:

i. Pre-start Inspections (P)
ii. Refueling of the Machine (R)
iii. Daily Inspections (D)
iv. Breaks -Tea/Lunch (L)
v. Shift Change-Over (S)
vi. Others Activities (O)
vii. Hours per Shift (H)
viii. Total Time (TT) = H x Number of days

It is also import to note that management time such as bad weather should not negatively affect the availability calculation. This should not be considered as downtime.

MTTR and MTBF are all linked to equipment availability, therfore, these two matrices were equally collected to help validate availability outcomes.

b) Meantime To Repair (MTTR)

Meantime To Repair is a maintainability measure of repairable items and represents the time a piece of equipment or system breaks down to the time it is put back into operation. It is mathematically expressed as total downtime divided by the number of failures in a specified period of time. It takes into account notification, diagnosis and repair time. If such activities as cooling down of parts, adjustments, set-up and testing apply, this downtime is considered as repair time.

Esmaeili (2016) describes Mean Time to Repair as the average time required to repair a piece of equipment or system and is expressed as the total repair time divided by the total number of repairs.

Figure 2 shows MTTR for the same equipment within the same period of time.

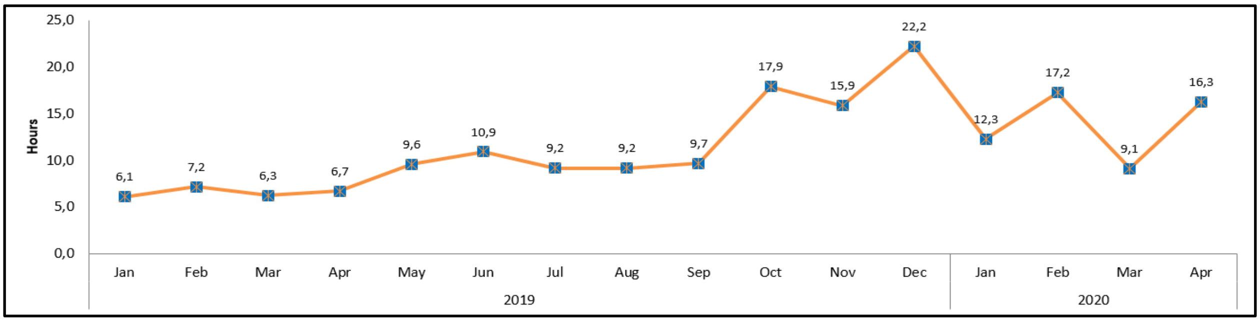


Figure 2: MTTR

MTTR during the first four (4) months of 2019 was averaging 6.58 hours which was within a reasonable magine, however, the repair time began increasing from May 2019 to an average of 13.73 hours during the first quarter of 2020.MTTR was calculated using the formular:

$$MTTR = \frac{TDT}{NF}$$

Where:

MTTR = Meantime To Repair
TDT = Total Downtime
NF = Number of failure

c) Meantime Between Failure

Meantime Between Failure is the predicted elapsed period of time between inherent failures of equipment or system during normal operation. Esmaeili (2016) expresses Mean Time Between Failures (MTBF) as the mean time of the failure distribution of a machine or component and for a constant failure rate, it is expressed as the total operating time divided by the total number of repairs.The data in Figure 3 show the MTBF durning the same period under review.

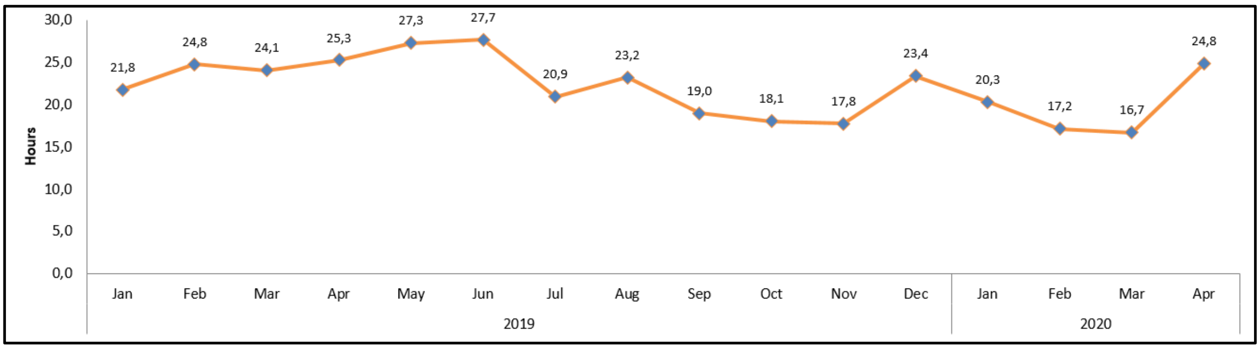


Figure 3: MTBF

MTBF took an almost linear trend throughout the period under review and it was caculated as:

$$MTBF = \frac{TOH}{NF}$$

Where:
MTBF = Meantime Between Failure
TOH = Total Operated Hours
NF = Number of failures

It was therefore important to validate the Key Performance Indicators (KPIs) as it is common practice in certain operations to calculate equipment availability and then make up MTTR and MTBF figures from no background information. Table 1 validates the two matrices against availability:

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

Where:
A = Availability
MTBF = Meantime Between Failure
MTTR = Meantime To Repair

Table 1: KPI Validation

	2019												2020			
DT 775F/G	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Actual Availability	80%	81%	81%	81%	78%	75%	74%	78%	72%	57%	57%	55%	67%	55%	71%	66%
MTBF	21,8	24,8	24,1	25,3	27,3	27,7	20,9	23,2	19,0	18,1	17,8	23,4	20,3	17,2	16,7	24,8
MTTR	6,1	7,2	6,3	6,7	9,6	10,9	9,2	9,2	9,7	17,9	15,9	22,2	12,3	17,2	9,1	16,3
Derived {MTBF/(MTBF+MTTR)}	78%	78%	79%	79%	74%	72%	70%	72%	66%	50%	53%	51%	62%	50%	65%	60%
% Variance	2%	3%	2%	2%	4%	3%	5%	6%	6%	7%	4%	4%	5%	6%	6%	5%

The average variance in avalability (4.38%) is not significant, therefore, this indicates that the data collected is reliable and can be trusted for use in this study.

Further, an analysis was conducted to determine the frequency of major component failure. Figure 4 shows the failure frequency of the top ten major components.

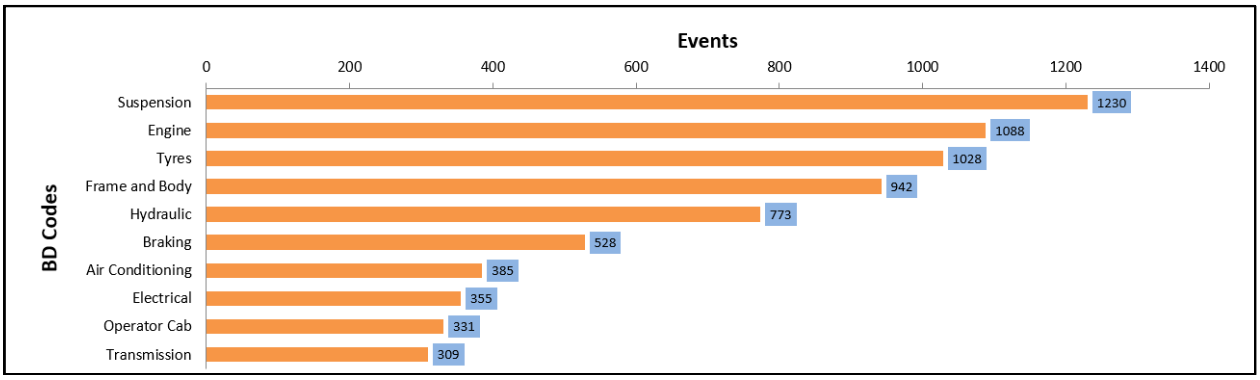


Figure 4: Major Component Failure Frequency

From Figure 4, it can be seen that suspension failures have the most failure events with 1,230 breakdowns indicating 45.55 times per machine in 16 months. This can be interpreted as each machine going down 2.85 times in a month as a result of a suspension problem. The same goes for the other components.Figure 5 shows downtime of the same equipment in hours.

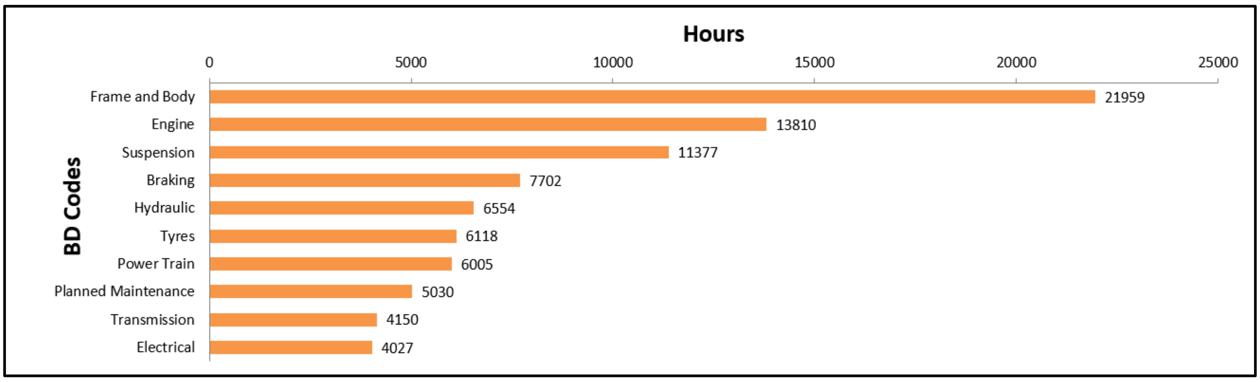


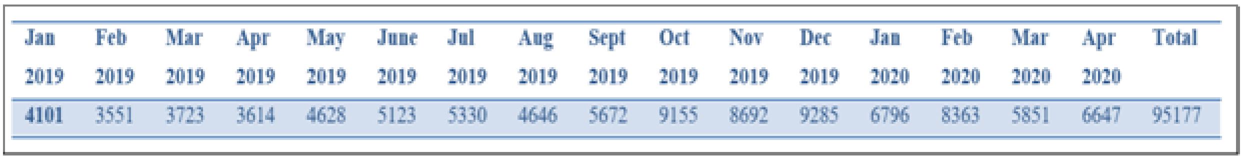
Figure 5: Major Component Downtime

The total downtime from body and frame breakdowns amounted to 21,959 hours in 16 months, implying 50.83 hour of downtime per machine per month.

Productivity Analysis

From the economic point of view, mining equipment should be fully utilized to realize the intended benefits, therefore, downtime arising from failure of the ten major components was equally studied to determine its effect on productivity. Table 2 shows the downtime in hours for the twenty seven (27) Trucks during the period under investigation.

Table 2: Downtime



Jan 2019	Feb 2019	Mar 2019	Apr 2019	May 2019	June 2019	Jul 2019	Aug 2019	Sept 2019	Oct 2019	Nov 2019	Dec 2019	Jan 2020	Feb 2020	Mar 2020	Apr 2020	Total
4101	3551	3723	3614	4628	5123	5330	4646	5672	9155	8692	9285	6796	8363	5851	6647	95177

The expected daily availability of each Truck is 85% (determined by management), therefore, theoretically, each Truck is intended to operate for 20.4 hours in a day.

Therefore;
1) 20.4 x 30 = 720 hours/machine/month
2) 720 x 16 = 9,792 hours/machine/in 16 months
3) 9,792x27 = 264,384 hours/27machines/16 months

Thus, the total expected availability (total available time) for the 27 machines in 16 months is 264,384 hours. This is what may be termed as engineering projected availability, it does not consider mining downtime such as breaks.

The total breakdown hours being 95,117, the available time from the 27 machines is:
i. 264,384 – 95,177 = 169,207 hours (total time after subtracting breakdown hours)
ii. $\frac{169,177}{264,384} = 64.0\%$

Due to breakdown of the major components, the fleet was available for operation for 64.0% with 36.0% of downtime.

With the average fragmentation of 4.5 (density), one CAT775 Dump Truck is expected to hoist 112 tonnes per hour (based on site specific distances) and operates for 15 hours per day, thus taking out breaks and other associated management time. Therefore, analysing the productivity in 16 months:

Planned Productivity:
i. Calculated equipment availability for 27 Trucks in 16 months = 264, 328 hours
ii. Planned utilization of 15 hours per machine/day
iii. 15 x 30 = 450 hours/machine/month
iv. 450 x 27 = 12,150 hours/27 Trucks/month
v. 12,150 x 16 = 194,400 hours/27 machine/16 month
vi. @112t/h
194,400 x 112 = 21,772,800 tonnes of ore.

Actual productivity:
i. Total time available after subtracting breakdown hours = 169,207
ii. @112t/h
169,207 x 112 = 18,951,184 tonnes
∴ 21,772 – 18,951,184 = 2,821,616 tonnes (loss)
In other words, an average of 176,351 tonnes of ore per month was lost theoretically.

From this analysis, it is clear that during the period under review, 2,821,616 tonnes of ore was lost due to breakdown of equipment components. Hence, it can be concluded that equipment downtime has a significant impact on productivity, to this effect, effective and efficient maintenance and operation of production equipment becomes necessary to reduce production cost and increase productivity.Barabady and Kumar (2008) explained that, breakdown of capital intensive equipment and its consequences have a strong impact on production cost. Therefore, it was stressed that, since failure cannot be prevented entirely, it is important to minimize both the probability of occurrence and the impact of failures when they occur.

Participant Observation

From Figure 4, it is observed from the top ten failures that suspension had the highest frequency of failure. The main function of suspension is to provide support and cushion the load, it protects the machine frame from shock that is generated during loading and travel. Otherwise, if the suspension cannot take up the shock, all the shock-load is absorbed by the machine frame, eventually, causing failure and maintenance concerns. Therefore, understanding the application and performance demands of the machine suspension should be one of the first steps to good operating standards of a machine.

The field survey reviewed that the most common failure mode of the suspension was discharging of the suspension cylinders.

Impact during loadingwas also observed, in certain situation, the Truck was loaded using a CAT6040 excavator of a bucket capacity of $22.0m^3$. This capacity was believed to be big and could put a higher shock-load onto the cylinders and subsequently damaging the cylinder seals. At the same time, Trucks were found to negotiate bends at high speed. This action is likely to put more force on one side of the machine resulting into damage to suspension parts.

Additionally, some flaws were observed when charging suspension cylinders, at times the nitrogen-oil mixture was not correct, this mainly arose due to lack of experience in charging the cylinders.

Frames and body was another area with a high frequency of failure events.Frame failures were mainly associated with collapsing of A-frame bearings and excessive wear of the A-frame bearing housing. Truck pans for some machines had liners completely worn out with further damage to the body.

Engine failures were high with 1088 failure events during the period under review. These failures included overheating of the engine, engine failing to start and failure of other engine parts such as injectors, vee belts, starter motors and other minor engine parts.

The frequency of failure of hydraulic components was also high, 773 failure events were recorded during the period under review. These failures included hydraulic pumps, valves, motors and hoses. The oil dispensing area was also visited to look at the decanting process and it was noticed that a number of machines were fitted with widget type coupling which were good enough to prevent oil contamination while filling the vehicle.

Tyres also significantly contributed to the downtime. Upon inspection, various failure modes were identified with tyres, these failures ranged from belt separation, side cut, penetration and normal wear. The condition from which the Trucks operated were also investigated thus the loading and dumping areas as well as the roadways. Housekeeping was a concern.

Most of the machines were on breakdown awaiting labour as the available manpower was committed to planned maintenance and breakdowns. The number of backlog work was also high. At the time of the study, the section had one engineer, one superintendent, two planners and three Foremen.

Questionnaire Responses

As a way of gathering data from different stratum of the production section, a questionnaire was developed and administered to both maintenance and mining personnel. All responses were recorded and analyzed. Table 3 shows the responses on whether respondents believed that loading of trucks using bigger capacity excavators contributed to Dump Truck failure of the suspension section.

Table 3: Suspension

Loading with bigger excavators damages Truck suspension	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
	16	4	2	2	1
	64%	16%	8%	8%	4%

The majority of the respondents 64%) indicated strong agreement to the view that loading with bigger excavators damaged Truck suspension. Few of the respondents 12% were not in agreement with the statement while 8% were undecided.

Table 4 indicates how respondents reacted to the question of whether loading of trucks using bigger capacity excavators contributed to A-frame bearing failure.

Table 4: A-Frame Bearings

Loading with bigger excavators damages Truck A-frame bearings	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
	13	7	3	1	1
	52%	28%	12%	4%	4%

When asked whether loading with bigger excavators damaged Truck A-frame bearings, most of the respondents 52% indicated strong agreement while few of them 8% were in disagreement. Three 12% of the respondents were undecided.

In this study, it was important to get the general view of the respondents on whether the conditions of the roadways contributed to truck tyre failure. Table 5 shows how respondents reacted to this question.

Table 5: Condition of Roadways

The condition of road damages Truck tyres	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
	17	2	1	3	2
	68%	8%	4%	12%	8%

Respondents were asked to give opinion on whether the condition of roads damaged Truck Tyres. In responding to this statement, the majority of the respondents indicated strong agreement that indeed, the condition of roads damaged Truck Tyres. Five 20% of the respondents indicated disagreement that the condition of roads did not damage Tyres

Further, Table 6 shows respondent’s views on whether lack of skill contributed to Dump Truck breakdown.

Table 6: Maintenance Skills

Lack of skills contribute to truck breakdowns	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
	19	3	2	0	1
	76%	12%	8%	0%	4%

The study also wanted to get the opinion of the respondents as to whether lack of skills contributed to Truck breakdown. It was found out that the majority of the respondents 76% indicated strong agreement to the statement while only one 4% respondent was in disagreement.

Procurement delay has equally been cited as one of the contributing factors to Truck breakdown. Table 7 highlights responses from the selected respondents.

Table 7: Procurement Delays

Procurement delays contribute to truck breakdowns	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
	16	2	1	3	3
	64%	8%	4%	12%	12%

When asked whether procurement delays contributed to Truck breakdown, most of the respondents 64% indicated agreement while few of them 24% were in disagreement. One 4% of the respondents remained undecided.

Operator practices were also highlighted as one of the factor that could contribute to Dump Truck breakdown. Table 8 shows the level of response in this area.

Table 8: Operator Practices

Operator practices contribute to truck breakdown	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
	18	2	2	3	0
	72%	8%	8%	12%	0%

Respondents were inquired to give their opinions on whether operator practices contributed to Truck breakdown, it was found out that the majority of respondents 72% strongly agreed that Operator practices contributed to Truck downtime.

Effective maintenance is significant to minimizing equipment breakdown, with the high frequency of engine breakdowns, respondents were asked to give their views on whether inadequate maintenance was one factor which contributed to Truck breakdown. Table 9 highlights the responses given by the selected respondents.

Table 9: Engine Failures

Engine failures are due to inadequate maintenance	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
	8	3	2	6	6
	32%	12%	8%	24%	24%

Respondents were asked to give their opinions on whether engine failures were due to inadequate maintenance, it was discovered that though the majority, 32% indicated strong agreement,the overall scale showed disagreement that engine failures were not due to inadequate maintenance.

Table 11 gives a picture of responses to whether contamination of oil contributed to failure of hydraulic system components.

Table 11: Hydraulic System Failures

Hydraulic system failures are due to oil contamination	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
	15	6	1	2	1
	60%	24%	4%	8%	4%

When respondents were asked whether hydraulic system failures were due to oil contamination, the majority of the respondents 60% indicated strong agreement to the statement while few 12% were in disagreement.

Lack of maintenance skills was also considered to be one of the causes of Truck breakdown at the mine. Therefore, the data in Table 12 show respondent’s views on whether lack of skills contributed to equipment downtime.

Table 12: Lack of Skills

Truck breakdowns are due to lack of skills	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
	18	3	1	2	1
	72%	12%	4%	8%	4%

On whether lack of skills contributed to the Truck downtime, the majority 72% of the respondents indicated strong agreement to this view, while few 12% were in disagreement.

The staffing level of Technicians was yet another factor that was worthy considering as a factor that could contribute to the Truck breakdowns. Table 13 shows the views from respondents on the adequacy of maintenance Technicians.

Table 13: Adequacy of Technicians

The no. of technicians is not adequate	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
	21	1	0	1	2
	84%	4%	0%	4%	8%

On whether the number of technicians was not adequate, most of the respondents 84% indicated strong agreement to this statement compared to 12% respondents who were in disagreement.

Supervision is one aspect of maintenance which is significant in managing maintenance activities, therefore, views were sought from respondent to find out whether the number of Supervisors was adequate to manage the fleet. Table 14 gives responses to this investigation.

Table 14: Supervision

Supervision is not adequate	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
	22	2	0	1	0
	88%	8%	0%	4%	4%

Respondents were asked to give their opinions on whether supervision was not adequate, the majority indicated strong agreement to this view while 16% respondents were in disagreement.

Table 15 shows how respondents responded to the question on the adequacy of workshop facilities.

Table 15: Adequacy of Workshop Facilities

Workshop facilities are adequate	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
	16	4	1	3	1
	64%	16%	4%	12%	4%

On whether workshop facilities were adequate, the majority of the respondents 64% were in agreement compared to 16% respondents who indicated disagreement.

The age of equipment is one aspect which was equally explored and Table 16 shows how respondents replied to this interrogation.

Table 16: Equipment Age

The old age of machines contribute to failure	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
	22	1	0	2	0
	88%	4%	0%	8%	0%

On whether the old age of machines contributed to equipment failure, most of the respondents 88%showed agreement with the statement while few 8% indicated disagreement.

Lack of employee motivation has also been highlighted as one of the contributing factors to equipment breakdown. Table 17 shows the nature of responses from questionnaires.

Table 17: lack of Motivation

Lack of Motivation contributes to truck breakdowns	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
	13	2	3	1	5
	52%	8%	12%	4%	20%

Respondents were asked to give their opinion on whether motivation contributed to truck breakdowns, it was found out that the majority 52% indicated strong agreement compared to 34% who indicated disagreement.

Fatigue is one factor that affects employee performance, therefore, the selected respondents were asked to give their views on fatigue in relation to equipment breakdown. Table 18 shows responses on how employees related fatigue to equipment downtime.

Table 18: Employee Fatigue

Employee fatigue contribute to breakdowns	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
	17	1	1	2	4
	68%	4%	4%	8%	16%

Respondents were asked whether employee fatigue contributed to breakdowns, it was revealed that, themajority of the respondents 68%specified strong agreement compare to 24% respondents who showed disagreement.

From the findings, it is evident that all the factors identified in the study contributed to equipment downtime and needed interventions. Figure 6 shows the trend of finding graphically.

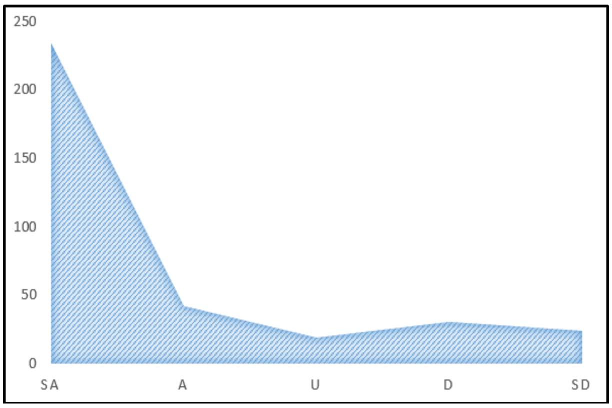


Figure 6: Sum of Breakdown Contributors

From Figure 6, SA denotes Strongly Agree, A stands for Agree, U states Undecided, D indicates Disagree and SD for Strongly Disagree. The biggest area from the graph signifies that most respondents agreed with the fact that the identified factors contributed to the Dump Truck breakdown, therefore, these required interrogation. To validate the findings, views of key informants who were subject matter experts were sought.

Key Informant Responses

A total of 10 key informants were selected and interviewed and all respondents indicated that the factors identified significantly contributed to Dump Truck breakdowns and that it was important to find mitigating measures to these problems in order to improve and sustain the reliability of Trucks.

5. Discussion of the Findings

From the equipment reliability data collected, thus, MTTR and MTBF, Failure Frequency Analysis (FFA), onsite observations, questionnaire responses and views of key informants, the most prominent causes of Dump Truck downtime could be described.

It was noticed from onsite observations that in most instances, the CAT775 Trucks were loaded usinga bigger capacity excavator (CAT6040), the dealer, CAT recommends either a CAT988K or 990K wheel loader for loading this size of a Truck. The effect of loading with a bigger machine was seen from regular failure of the suspension cylinders and centre section part (A-frame).

When loading with bigger machines, the frame bearings took excessive impact-load and started deforming the bearing housing. This action latter resulted into rocking of the bearings inside the housing and eventually breaking due to shock loading, in certain cases where the play was not noticed in time, the bearing housings wore out excessively with the frame requiring line-boring to bring back the housing to standard dimensions. Lack of greasing was one of the contributing factors to bearing failure, however, by the time of the study, a lubrication program had been put in place and managed by a dedicated team from the maintenance department. However, post effects were still being addressed as a number of machines were affected by previous lubrication issues.

The other aspect which was responsible for failure of centre section and suspension parts was the overloading of Trucks and the bad condition of roads. The overloading was mainly caused as a result of using a bigger machine as this made it difficult for the operator to judge the volume of ground in the bucket by sight. As a result of overloading, both the suspension cylinders and the centre section took extra load. Since the pressure was too high for the cylinders, seals usually failed, hence the machine loosing stability. Trucks were also seen to over speed around bends, this action resulted into overloading of the suspension cylinders as too much pressure was exerted on cylinder seals and eventually leaks along the seal lips developed. Incorrect charging of suspension cylinders was also noticed, the effect of low charging of cylinders is that it increases the cylinder stroke and consequently creating high pressure inside the cylinder which causes the seals to fail. On the other hand, over charging of cylinders restricts the movement of the cylinder ram and most of the impact is then taken by the vehicle frame. The result of this is failure of frame parts and axles.

A number of engine related failures were noticed and these included:

1) Harness Failure – this was mainly due to running harnesses for a longer period without replacing. In some areas, harnesses were inappropriately secured, shorting down due to lost insulation as a result of rubbing against the vehicle frames and other vehicle structures.
2) Fatigue – breaking or failure of engine parts such as rocker arms. These failureswere associated with cycle fatigue coupled with heat from the engine which weakened the material structure of parts. A planned replacement program was been lacking to replace the parts before they failed.
3) Injector failure – a number of injectors were replaced. Injector failure was mainly as a result of fatigue as there was no replacement plan for injectors, they were replaced as they failed. Injectors are supposed to be replaced at stated intervals.
4) Shut offs on warning – there was equally a number of engine cut off mainly as a result of low coolant level. This kind of breakdown arose as a result of coolant leaks either from failed hoses, cores or deteriorating seals.
5) Drive belt failure – this was mainly as a result of running belts beyond the replacement period (cycle fatigue). In isolated cases, belts failed as result of oil from leaking sections.

Hydraulic system failures were equally prominent and the main failures comprised:

1) Pump and motor failure – cavitation was observed as one contributing factor to pump failure. This usually happened when there was an unnoticed oil leak or when the leak was ignored for future repair. The other contributing factor to pump failure was contamination from metal chip from failed hydraulic components like pumps themselves. When catastrophic failure of hydraulic component occurred, the system was not flushed before replacing the failed unit. These metal particles would then cause seizure to spools.
2) Hose failure – hoses also had a high rate of failure. Most of the hoses failed prematurely as a result of poor quality of fabrication. The mine had a hose making crew, but the skills were not to standard to guarantee good quality. Lack of correct fittings was also observed and in isolated cases, fittings were modified to suit the application.
3) Contamination – contamination of oil was observed though not to a greater extent as the equipment was fitted with widget couplings. However, as indicated, contamination from failed hydraulic components was observed.

Downtime arising from tyre failure was also recorded and failure modes probed:

1) Belt edge separation – this kind of failure was observed and this was caused by low inflation of the tyres and overloading, however, no investigation was conducted on site to validate the cause of failure, though some trucks were observed to be overloaded.
2) Impact – this was mainly as a result of running over protruding rocks at a high speed. This was common when the machine was running empty and usually downslope.
3) Side wall cut – this is a failure associated with housekeeping. Tyres were damaged by rocks lying around work areas. Some tyres were also damaged when making turns too close to heaped ground or windrows. The cause of poor housekeeping was the constant failure of Bull Dozers and graders. These two machines are used for cleaning work areas and profiling roadways.
4) Normal wear – these is where tyres were removed due to normal wear and tear. However, some tyres were removed before getting worn-out completely and were kept for matching.
5) Penetration – the most common cause was rock penetration, this again was a result of housekeeping where loading areas as well the roadways were not cleaned of loose rocks.
6) Tonne-Kilometer Per Hour (TKPH) – though there was no evidence of the 775 Dump Truck tyres failing as a result of incorrect TKPH, this kind of failure was observed on the CAT789B tyres. TKPH represents the total load capacity of a tyre in relation to heat generation. The TKPH of a tyre can be provided by the tyre Supplier and the mine is expected to calculate its site specific TKPH value.

A skills gap wasequally noted, however, the mine had put in place a skills training programme on site. The lack of skills was seen in the long time taken to diagnose faults on equipment as well as the length of time in completing tasks. The frequency of repeat jobs also indicated a lack of competence and skills. In reference to Figure 1, the equipment availability began declining in July 2019 when the specialised maintenance contractor was terminated and the mine began using the local labour force and a few low cost expatriates. Repeat jobs are a cost to a company as production is delayed, correction cost involved and in some cases poor maintenance results into unnecessary failure of

equipment. Mobley (2002)states that, recent surveys of maintenance management effectiveness show that a third (1/3) of all maintenance costs is wasted as a result of unnecessary or improperly carried out maintenance.
From Ozdogan (2013) expression, it is certain that if the mine is not administered and managed by talented and educated people, the unit cost of operation will adversely be affected.Well-trained, well-educated managers fully equipped with contemporary management techniques and skills will have positive effect on the costs of the earth moved per tonne. In short, it may be said that, the quality of the people running the mine, is as important as the quality of the earth moving equipment fleet in terms of cost per tonne produced.

The number of Technicians, Supervisors and maintenance personnel was not adequate to manage the fleet. Maintenance staffing management is a critical area in the maintenance section of the mine as it is not easy to balance the maintenance labour force and thenumber of equipment operated. What makes this trade-off even more complicated is that, the extent of the impact of reactive maintenance delays vary significantly between bottleneck and non-bottleneck conditions. When the labour force is too high, the labour cost becomes unnecessary high due to idle labour, on the other hand, when the number of maintenance personnel is low, there is always a possibility that a given repair work will be delayed or not carried out altogether. The number of backlog work builds up and maintenance is rushed resulting into poor quality of maintenance. It is therefore, important to have some form of benchmark in determining labour statistics. In an HME Department where these Dump Trucks are maintained, the data in Table 19 may help determine the correct staffing level.

Table 19: Staffing Ratio

Item	Category	Staffing Ratio
1	Maintenance planner to Technicians	1: 24
2	Maintenance Supervisor to Technicians	1: 16
3	Engineer to Maintenance Personnel	1: 40

The number of Technician per specific planned maintenance type for a Dump Truck may be taken as shown in Table 20 to ensure quality ofmaintenance.

Table 20: Technician Machine Ratio

Item	Maintenance Type (hours)	Duration (hours)	Number of Technicians
1	500	24	3
2	1000	32	4
3	2000	40	4
4	4000	48	4
5	6000	90	5

Through participative observation, it was evident that the number of staff was not adequate. This was concluded from:

i. Backlog work – the number of backlog work was so high that the labor force on site could not manage clearing all of them in light of other activities such as planned maintenance and breakdown repairs.
ii. Planned Maintenance Compliance – PM compliance was quite low averaging 55%. This was as a result of not having enough personnel to carry out planned maintenance. This condition resulted into random equipment failure which drew more personnel from planned maintenance activities.
iii. Deferring of Work – it was also noticed that a lot of work from nightshift was deferred to dayshift, this was mainly because nightshift was not adequately manned in terms of personnel numbers.
iv. Management – there was only one Superintendent manning the workshop as well as the field. This made it very difficult for the Superintendent to allocate and inspect the jobs being carried out.
v. Equipment Inspectors – there was no equipment inspector on site. This deficiency contributed to substandard work leaving the workshop, hence, more equipment breakdown.

The other concern observed on site was the non-availability of an effective component replacement plan. The plan was available, but not executed and this was the basis for random failure of major components such as final drives and transmissions. On the other hand, only two machines underwent a mid-life refurbishment, this equally contributed to the unexpected failure of components and electrical systems. The average life of the remaining twenty five (25) Trucks was 27,000 hours. A CAT775 Dump Truck may require a mid-life rebuild at 16,000 hours and could be decommissioned at 45,000 hours. However, this will depend on certain specific site conditions.

As discussed earlier, planned maintenance assists in reducing the number of equipment failures, however, it is important to identify and understand factors that contribute to equipment breakdown in order to select an appropriate maintenance strategy. Figure 7 shows a model of major causes of Dump Truck breakdown and the associated relationships.

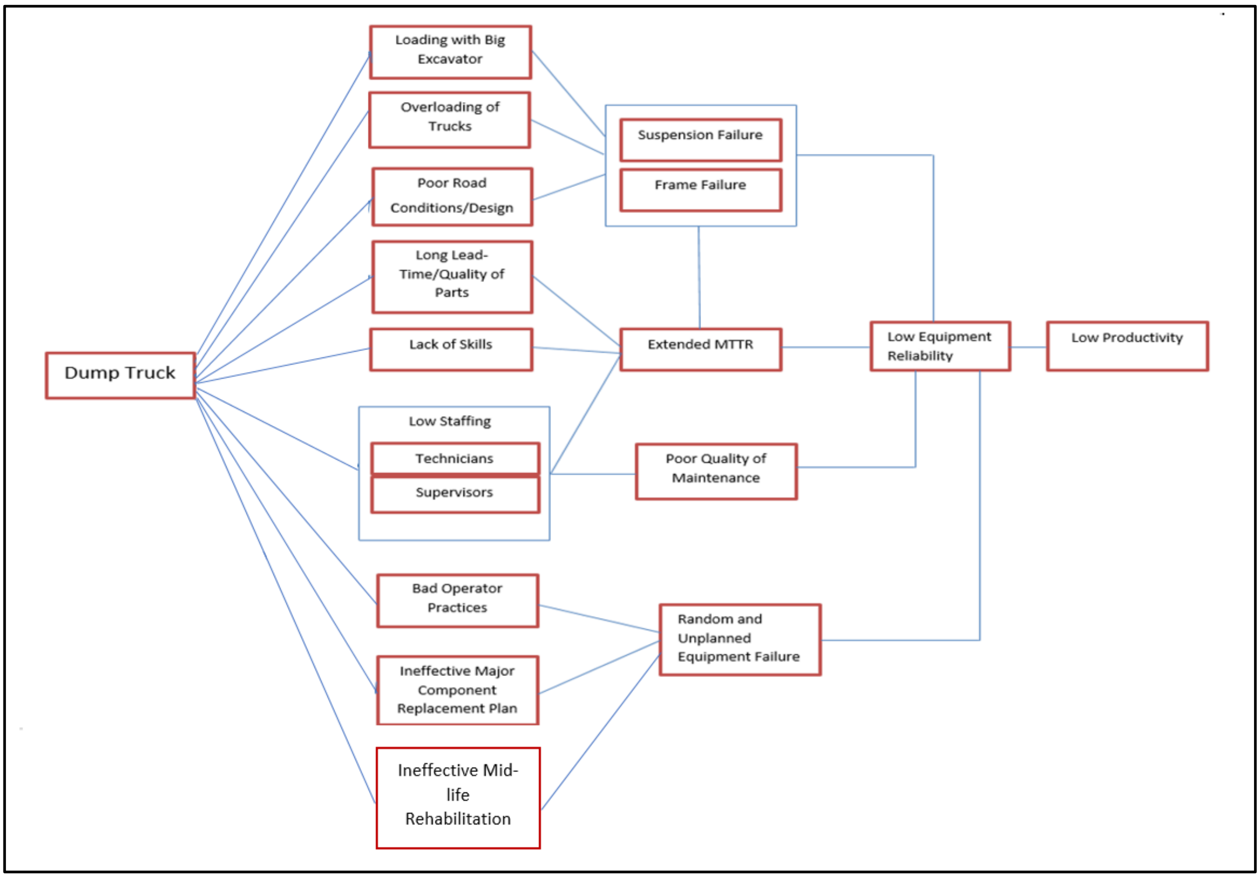


Figure 7: Breakdown Factor Model (BFM)

Model Operationalization

Whereasmaintenance has been upheldasthe underlying principlefor equipment reliabilityand that it has been termed as a factor that offers mining institutions the best opportunity to influence and control the performance and availability of their equipment, this paper also demonstrates that, to attain and sustain a satisfactory equipment reliability and reduce downtime, other reliability inhibiting factors must be identified, mitigated and managed accordingly.As such, in order to operate a reliable fleet of Trucks, it is essential for management to carry out an impact assessment of the factors that may compromise the reliability of the equipment.Therefore, the BFM may be used as a checklist by management to identify the potential causes of Truck downtime.

Dump Truck have specific load they can carry and this must be followed, the load cell readings must be followed to ensure the vehicle is not overloaded. Due to complacence, operators develop the habit of counting the bucket passes as a way of determining the load, however, this may result into either overloading or under-loading the machine as the density may not always be inform. Therefore, mere counting of bucket passes and the use of over specked loading machines should be avoided.

To avoid damage to tyres and suspension parts, work areas as well as roadways must always be kept clean. To ensure this is maintained, Dozers and Graders must always be available for maintain surfaces otherwise the roadways and operating areas become a hazard to equipment. The other important thing is to ensure that the road design suites the type of equipment being operated, tight corners have a serious impact on the vehicle suspension just as much as over speeding on bends.

Skills areessential and require close monitoring and administrating to ensure effective equipment operation.Here, both maintenance and operator skills are considered. Cabahug (2004) commented that, factors such as years of relevant work experience on a specific machine, personal disposition, operator reliability, work environment, motivational management, training and continuing education, are all relevant factors which tend to impact the effectiveness of the performance of the maintenance system. This can further be supported by the views of Ozdogan (2013) who gave caution by saying, if the mine is not administered and managed by talented and educated people, the unit cost of operation will be affected adversely. Well-trained, well-educated managers fully equipped with contemporary management techniques and skills will have positive effect on the costs of the earth moved per tonne. In short, it may be said that, the quality of the people running the mine, is as important as the quality of the earth moving equipment fleet in terms of cost per tonne produced. If operators do not take care of the equipment by not observing good operating practices, not conducting effective prestart inspections and not reporting faults or potential faults in time, unnecessary equipment breakdowns will occur. It is also important to have specific equipment or simulators for training, this may be equipment that has been retired from production or bought exclusively for training.

The training of mine earthmoving equipment and hauler operators is extremely important; these training courses should be repeated periodically and the use of operator simulators is essential. Prior to hands-on training on the equipment, the simulators are time and cost saving devices because of the fact that, the earthmoving and hauling equipment are very expensive capital equipment. Therefore, they should not be used as training tools by the new learners to prevent unnecessary equipment breakdown and damage. For this reason, mines are recommended to have operator training simulators and/or train the operators under the guidance of OEM training centres and instructors. Operators should also be briefly informed and trained on the structure, safety, operating and working principles of the equipment; pit safety and surface mining, geology (faults etc.) and slope stability etc. These courses should be repeated periodically [Ibid].

The advent of emerging technologies, the need to move more ground at a lower cost and a continued focus on safety and health has led to a development of high technology earth moving machines which require tested capabilities to maintain this kind of equipment. Therefore, to effectively maintain this equipment, the maintenance personnel should be highly qualified and competent. Most mining equipment dears now provide training to ensure the mine maintenance staff keeps up with the dynamics of the technological advancement.Taylor (1947) commented that in the modern age, the changes in maintenance practices are testing the attitude and skills of the maintenance personnel. Maintenance personnel have to adopt completely new ways of thinking and acting.

As stated in the study, equipment breakdown may not be completely eradicated, isolated breakdowns will occur, however what is significant is to reduce the downtime to a bearable minimum. If the maintenance personnel lack skills, they will take time in diagnosing the problem as well as in repairs and in most cases, rework becomes prominent. The low number of maintenance personnel will certainly result in extended downtime as some tasks will have to wait for labour. Therefore, staffing levels must be adequately matched with the number of equipment. The delay in procurement and supply of replacement parts also contribute to machine downtime, therefore, it is important for the Maintenance and Supply Chain Departments to plan ahead of usage.Barabady (2017) echoed that, maintenance cost is a significant part of production costs and that logistics and spare parts management should be considered early in the design. Further,the operational phase and reliability characteristic of a piece of equipment can be used to effectively determine spare part prediction (SPP) to avoid run-outs.

When running mining equipment, a major component replacement program is a necessity to avoid major parts failing stochastically and creating unnecessary downtime. The optimal replacement time or the component life cycle data may be obtained from the OEM. However, it is also important to factor in onsite experience when determining the replacement interval of components. Further, it pays to have a stand-alone workshop and personnel specifically for major component replacement. This move allows for a stable replacement program as there is no clash with other activities such as planned maintenance and breakdowns. Most replacement programs have failed because of using the same maintenance crew to carry out component replacement, preference is always given to maintenance and breakdown activities and the component replacement program is ignored.

In summary, if the staffing level is maintained according to the number of equipment, operators and maintenance personnel are well trained, competent and of good attitude, the work areas and road ways are properly maintained and maintenance carried out following the OEM recommendations, the equipment reliability will be high and subsequently increased productivity.

6. Conclusion

In this study, some common causes of mining Dump Truck downtime have been identified and the results discussed, with emphasis on the effect of downtime on mining productivity. Reliability and Maintainability characteristics, MTBF and MTTR including failure mode patterns have been examined in order to determine the main causes of downtime.The findings from the study show that Maintenancepersonnel and Truck Operator skills, staffing levels, supervision, the method of loading trucks and environmental conditions have a major impact on the reliability of mining Dump Trucks.It is also noted that, breakdown of Dump Trucks results into undesirable indirect cost of maintenance due to production loss and the unplanned idleness of other machines in the production system.Additionally, in order to assist maintenance management operate efficiently and minimize random failure of equipment, a model (BFM) has been proposed, this model can help management proactively focus attention on critical areas that may affect equipment performance. Finally, though through the search of literature, other areas of interest associated with the subject under study arose, such as the cost of downtime, tyre management and skills audit, however, these areas have notbeen handled conclusively in this study, they may be researched in later studies.

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