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A Critical Investigation into the Real Cause of the Low Heavy Mining Equipment Reliability: A Case of AZ Open Pit Mine, West Africa

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Abstract: ***Miningis heavily dependent on large and expensive equipment, therefore, it is important to efficiently manage the performance of the capital intensive equipment to remain productive. The performance of the major mining equipment (Dump Trucks and Excavators) at AZ Mine, not the real name, was continuously below budge from 2019 to 2020, a condition that adversely affected productivity of the mine. The mine management attributed the low equipment reliability to poor supervision in the Heavy Mining Equipment (HME) department and extended lead-time of maintenance spares, however, this assumption was not supported by any formal investigation or research. It is for this reason that the study was conducted to investigate the actual cause of the low reliability of the HME at the mine. Reliability and Maintainability characteristics; Meantime Between Failure (MTBF) and Meantime To Repair (MTTR) as well as failure mode patterns of the equipment are studied. Data collection is through document review from planning office, participant observation and through views of key informants (subject matter experts). Tables and graphs are used to present data trends and their characteristics. The study has therefore, concluded that, the major contributing factors to the low equipment reliability of the HME at the mine are lack of Heavy Equipment Repair skills to work on the high technology equipment. The Local Technicians, though constituted the largest number compared with the skilled Expatriates, were not adequately trained and the onsite training provided was not sufficient. Further, there was no established spares management plan to assist in prioritising and forecasting parts acquisition. The maintenance infrastructure did not support the HME operations and the department run without a formalised maintenance strategy. To summarise the factors responsible for downtime, a framework to show the main causes of the low equipment reliability with intervening variables was developed. Finally, various recommendations were made and in certain areas implementation commenced immediately, however, recruiting of qualified and experienced staff faced a serious challenge due to the worldwide travel restriction of personnel imposed by various nations due the COVID 19 pandemic.***

Keywords: Reliability, Meantime to Repair (MTTR), Meantime Between Failure (MTBF), Availability, Maintainability

1. Introduction

Equipment plays an important role in the mining industry 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. Therefore, low reliability of this equipment always becomes a major concern for the mine management.

The reliability of the major mining equipment, Dump Trucks and Excavators at AZ Mine began declining by April 2019 and continued into 2020 without any significant improvement and management attributed this trendto the long maintenance parts lead-time and poor supervision. However, this assumption by management was not supported by any formal investigation or research. It is for this reason that this study was conducted to validate management's views on the low reliability and further explore the actual cause of the low reliability of the HME at the mine.

2. Methodology/ Data Collection

To mitigate the cause of the low equipment reliability, Reliability and Maintainability characteristics; Meantime Between Failure (MTBF) and Meantime To Repair (MTTR), failure mode patterns of the core mining equipment as well as staffing levels and quality were examined. Additional data were collected through document review from planning office, participant observation and from views of key informants. Tables and graphs were used to present data trends and their characteristics.

Document Review

The data used in this section were obtained from HME Planning office where all equipment performance data was assembled and analyzed for further decision making. Performance trends for the major equipment for the period January 2019 to February 2020 are illustrated in Figure 1, 2, 3 and 4.

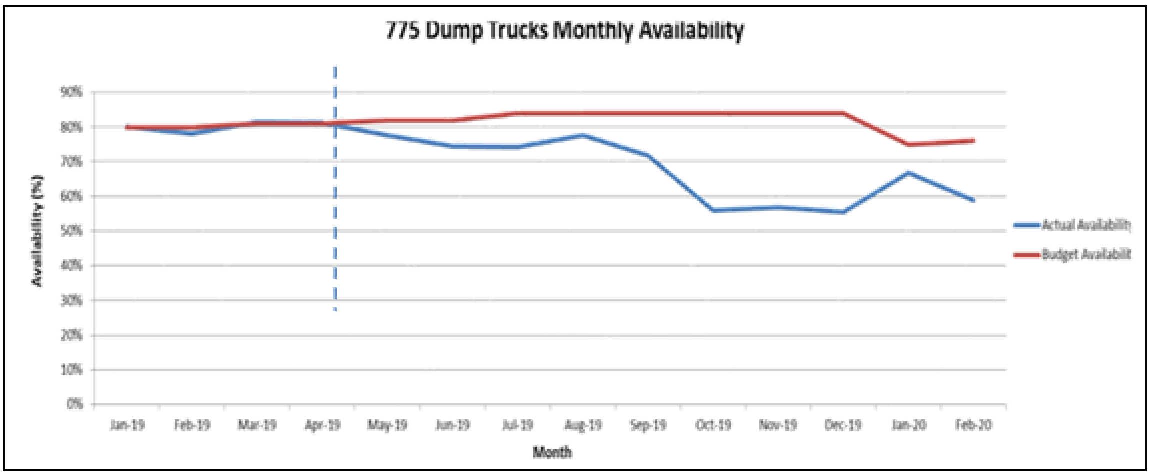

Figure 1: CAT 775 Dump Trucks Performance

The data in Figure 1 show that the performance of the CAT 775 Dump Trucks began falling from April 2019 and this trend continued through to February 2020 when the study was being conducted. However, there was no document available to indicate the probable cause of the low equipment availability. The planning office chats only showed performance trends without any explanation relating to the trends behavior. Figure 2 shows the monthly availability trend for the CAT789 Trucks.

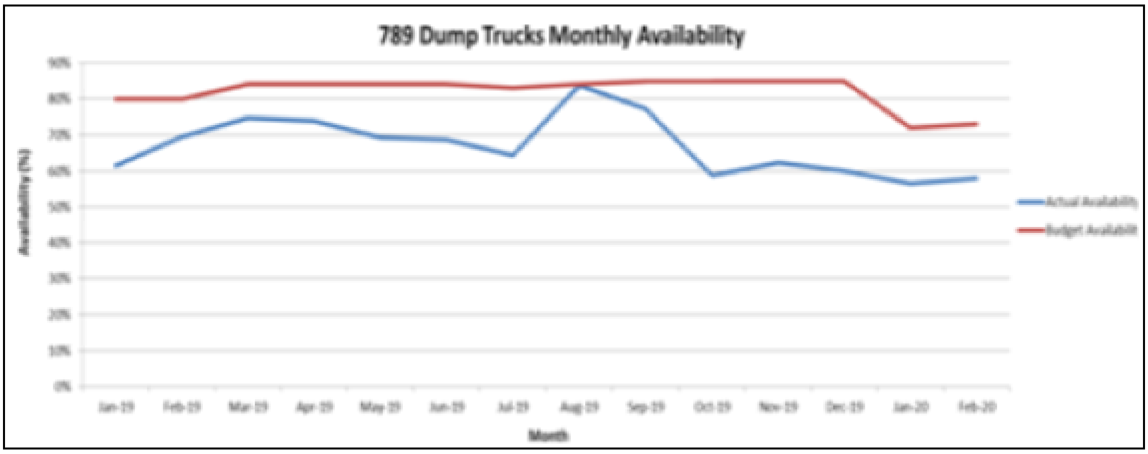

Figure 2: CAT 789 Dump Trucks

Figure 2 displays the performance trend of the CAT 789 Dump Trucks. The performance of the equipment was below budget from commissioning to the time the study was conducted, taking a steeper trend from August 2019. No written records were available to explain the cause of the poor reliability of the newly acquired (refurbished) production equipment. The only relevant information available was that, the equipment was purchased in 2019 from an outside contractors as 'good' rebuild machines and the mine expected to achieve above 85% availability per month from the machines, however, this was never attained. Figure 3 shows the availability of the Primary Excavators CAT 6015 and 6018.

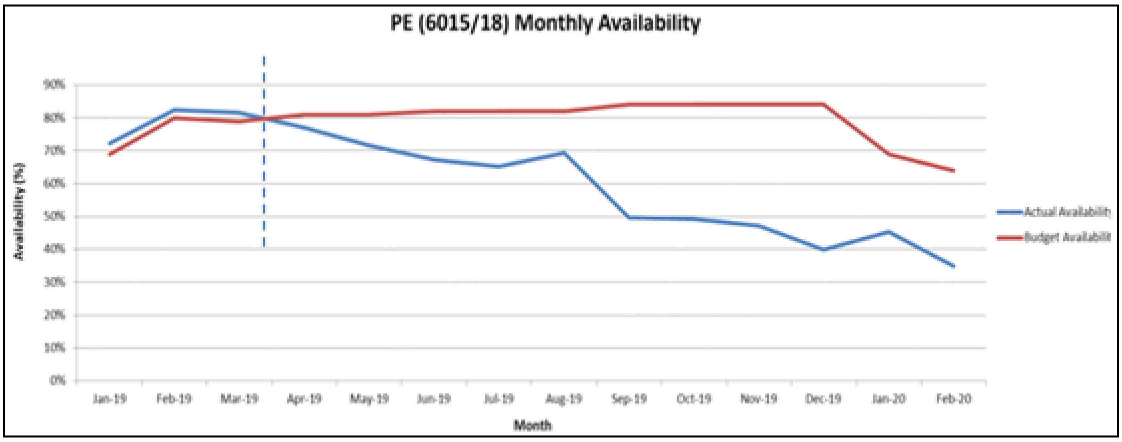

Figure 3: CAT6015/6018 Excavator Performance

The reliability of the CAT 6018 and 6015 Excavators equally started to decline from March 2019 with no much improvement. From planning office reports, no justification was given for the low equipment reliability, only performance trends were displayed. Figure 4 illustrates the performance trend of the CAT6040 Excavator.

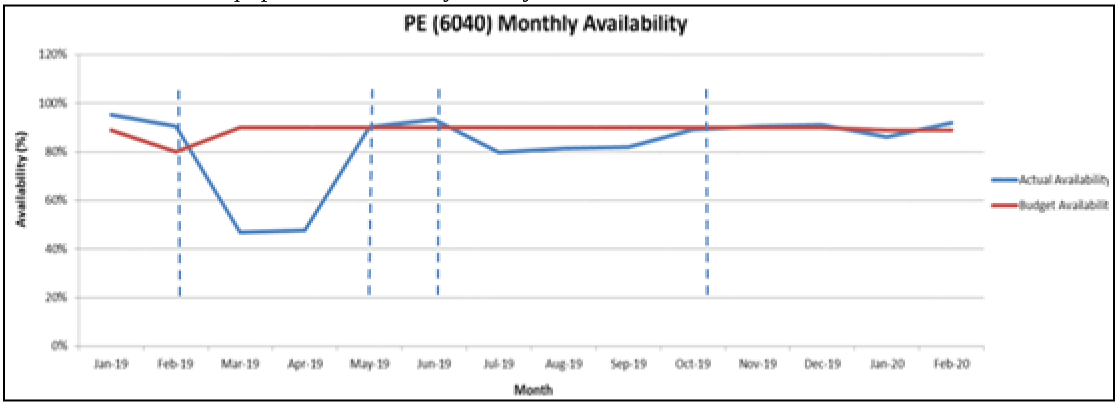

Figure 4: CAT6040 Excavator Performance

From Figure 4, the performance of the Excavator CAT 6040 is generally within budget though in March and April 2019, the availability was low. The documented explanation to this was that, the machine was down for a failed fan motor and a travel motor respectively. Both components failed prematurely and warranty was granted by the supplier of the machine. After, the two repairs, the reliability of the machine was continuously with budget.

Though Jula et al (2006) states that, there are a lot of reasons why mining equipment goes wrong such as 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, AZ Mine did not investigate the real cause of the numerous equipment breakdowns. As such, it was difficult for the mine to develop a strategy to improve reliability of the heavy mining equipment.

Participative Observation

Through exploratory survey, various areas of the HME department were investigated in order to determine the real cause of the low equipment reliability.

Equipment

The mine had different types of equipment associated with mining activities as shown in Table 1.

Table 1: Main Production and Ancillary Equipment List

Count of Fleet Plant Type	Model	Total
Front End Loader	Front End Loader - CAT 966	7
	Front End Loader - CAT 980H	1
	Front End Loader - CAT 990	4
Articulated Dump Truck	Articulated Dump Truck - CAT ADT 740	2
Blast hole Drill	Blast hole Drill - Atlas Copco D65	3
	Blast hole Drill - CAT MD6290	2
Bobcat	Skid Steer Loader - CAT 262	1
	Bobcat 232b skid steer loader	1
	Bobcat 2268 skid steer loader	1
Compactor	Compactor	3
Dozer	Dozer - CAT D10T	3
	Dozer - CAT D8R	1
	Dozer - CAT D9R	3
Dump Truck	Dump Truck - CAT 775F	18
	Dump Truck - CAT 775G	10
	Dump Truck - CAT 789B	6
Explosive Truck	Explosive Truck - Iveco	2
	Explosive Truck - Kenworth	1
Fuel Truck	Fuel Truck - CAT 775	1
	Fuel Truck - Iveco	2
Grade Control Drill	Blast hole Drill - Atlas Copco D55	1
Grader	Grader - CAT 14M	2
	Grader - CAT 16G	2
Hiab Truck	Hiab Truck - Iveco	2
Lube Truck	Lube Truck - Iveco	2
Manitou	Telehandler - Manitou MT-X 1440 SLT	1
Mobile Crusher	Terex-Finlay C-1540RS Cone Crusher	1
	Terex-Finlay J-1175 Jaw Crusher	1
Primary Excavator	PE CAT 6015 Backhoe	3
	PE CAT 6015 Face Shovel	1
	PE CAT 6018 Backhoe	2
	PE CAT 6018 Face Shovel	1
	PE CAT 6040 Backhoe	1
RC Drill	Schramm T450GT DRILL RIG	1
	Schramm T450WS Drill Rig	1
Small Excavator	Excavator - CAT 320	4
Tipper Truck - Iveco	Tipper Truck - Iveco	3

The data in Table 1 only shows equipment related to mining operations and does not cover all equipment used on the mine as the other equipment did not have a major influence on mining productivity. In all, the mine had about 140 pieces of equipment managed by the HME department.

Staffing
Among the major roles, the department was managed by:

Table 2: Staffing Level

Item	Description	Number
1	Maintenance Engineer	1
2	Superintendent	1
3	Supervisor/ Foreman	3
4	Maintenance Planner	2
5	Technicians- Expatriate	35
6	Technician- Local	98

In terms of the Local Technicians, records showed that there was no formal training in Heavy Equipment Repair, most of them only had basic engineering courses. Further, no Local Technician had undergone any form of OEM training on any equipment. However, to improve the skills of the Local Technicians, in August 2019, the mine started an onsite Heavy Equipment Repair Fast Tracking Program managed by the Mine Training Department.

The Expert Technicians were meant to coach the Local Technicians after the onsite training, however, this was found not to be practical as the Expert Technicians were always tied up with either maintenance or breakdown work with backlog work usually left unattended due to lack of manpower.

Maintenance personnel were not allocated specific sections, they were distributed by the Superintendent according to daily needs. As such, a miss-match in skills allocation was eminent.

Maintenance Infrastructure
The mine had two workshops, one for repair and maintenance of heavy equipment and the other for Boiler making and Fabrication work. Crowding of equipment parts was seen inside and around the Fabrication workshop. However, major equipment such as welding machines was readily available. Coupled with the Fabrication shop was a small Machine shop fitted with a lathe and pressing machine.

The maintenance workshop had six bays of a reasonable size (able to accommodate big Trucks). The workshop was equipped with oil and grease dispensing facilities, compressed air and there was a small apartment within the shop where hydraulic hoses were fabricated. Though the workshop was big enough, there was no provision for a pit or rump to enable the maintenance personnel easy access for checking the bottom part of equipment.

Though Heavy Equipment tyres were assembled and repaired on site, there was no dedicated workshop for tyres, only a small areas was demarcated outside the workshop for tyres.

Supply Side
The mine had one Central Store which catered for all departments at the mine with all issues made on demand from the end user department.

The lead time for most major equipment components was somehow uncontrollable, in certain situations, in excess of 160 days. However, the availability of routine maintenance parts (consumables) was consistent. The data in Table 3 show a comparison of the number of broken down equipment awaiting parts against those waiting for maintenance labor.

Table 3: Parts and Labor Status

Plant Type	Equipment down as of Feb'20	Awaiting Labor	Awaiting Parts	Work in Progress
PE (615/18)	5	2		3
DT 775	8	3		5
DT 789	2		1	1
Track Dozer	5	2	1	2
Wheel Dozer	1		1	
Lube Truck	1	1		
FL 990	2	2		
FL 966	3	1	1	1
Bobcat	3	3		
Compactor	1	1		
Fuel Truck	1	1		
Small Excavator, 3200	1	1		
Water Tank	2	1	1	
Graders	3	2		1
Iveco Tipper Truck	2	1		1
Iveco Trakker Horse	1		1	
Manitou Forklift	3	1	1	1
Mobile Crane	1		1	
Scout 350piccini Self loading concrete mixer	1	1		
30t Boom Truck (maintex 35100c), SN: 161870)	1	1		
	47	24	8	15
		51%	17%	

As seen from the data in Table 3 (taken at the time of the study), 51% of the long breakdowns were waiting for labor, whereas 17% were waiting for parts.

Maintenance Systems
There was no dedicated Computerized Maintenance Management System (CMMS), the one used was more of a financial accounting software. It did not provide for such processes as maintenance trigger or equipment life cycle monitoring. However, I could provide all the stores information such order status, inventory level, cost and material and spare part sources as well as final statements. Additionally, the department had no approved maintenance strategy.

3. Literature Review

To understand the main cause of the low reliability of the major HME at AZ Mine, maintenance strategies and systems employed by other operations arestudied.This is critical as the mining equipment technology has continued becoming sophisticated and expensive to produce and maintain, therefore, maintenance management is facing even more challenging situations to maintain effectively such equipment in today's dynamic environment. To manage this, most mining operations are coming up with various philosophies to support equipment performance and remain in business.

Mohammedi et al (2015) indicates that, achieving productivity is one of the biggest challenges of the mining industry considering the huge capital investment involved. Therefore, to fully understand the performance of mining equipment, it is important to appreciate the critical attribute of equipment performance; reliability.

Sondalini and Witt (2015) echoed that, equipment reliability,which is defined by Katukoori et al (2014) as the probability that an item will operate satisfactorily at a given point in time when used under stated conditions in an ideal support environment, needs to be seen as more than just a chance time span. It is about building great businesses that are world-class performers. High-reliability organizations expect equipment to last a longer time and are unhappy when it does not. Not only are they unhappy, but they take effective measures to learn and improve from the failures. In the case of AZ Mine, management noted that the reliability of the HME was low, however, no immediate studies was conductedto find out the main cause of the low equipment reliability. The idea of poor supervision and long lead time of parts was not supported by any form of technical analysis or research, though measures were being sought to address the two phenomenon.

Training of main earthmoving equipment and hauler operators, though not the core discussion in this study, 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 centers 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". Additionally, maintenance and repair Technicians should also be trained by the instructors of OEM both in classroom and on the machine (preferably on simulators) as well as hands on training on the machine (Ozdogan, 2015). AZ Mine however, did not have simulators for operator training, all practical lessons were undertaken from production equipment, nevertheless, this did not significantly contribute to equipment failure as only a few machines were identified for training, though due to the numerous equipment breakdown, these machines were often in production to make up for the broken down machines.

Additionally, even if all the factors cited above are favorable, if the mine is not administered and managed by talented and educated people properly, the costs of unit operations will be affected negatively. Properly trained and educated managers adequately equipped with contemporary management techniques and skills as well as trained and competent technical personnel 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 significant as the quality of the earth moving equipment fleet in terms of cost per tonne produced. Due to the dynamic technological advancement in mining equipment, there is a serious need for the mining operations to provide training to their maintenance personnel to up their skills in line with the new technology machines. Most operations have opted for the OEM to provide such training as many training schools, colleges and universities may not provide such equipment specific training.

Nights (2005) undertook a maintenance benchmarking study of six open pit copper mines having mill capacities varying between 18,000t/d and 156,000t/d, which collectively was responsible for 58% of Chilean copper production. The study found out that, on average, maintenance was responsible for 44% of the mine production costs. From the same study, percentage planned maintenance of equipment fleets was noticed to be low by world standards, averaging 35%, 56%, and 44%, respectively, for blast hole drill, shovel, and haul truck fleets. Further, fleet availabilities were found to be significantly influenced by the percentage of planned maintenance achieved, while maintenance cost per equipment was found to decrease non-linearly with increases in percentage planned maintenance. Investment in technical training (including planned maintenance practice) was also observed to be low by global standards. Maintenance compliance is key to attaining high equipment reliability in the mining industry. This is only made possible with adequate number of maintenance personnel who are at the same time well trained and experienced in both planning and actual execution of maintenance and repair work.

Paraszczzak (2015) explains that, a piece of equipment that is in an 'up-state' (capable of performing the work it is designed to do) is rarely used throughout all of its available time. This he says is due to factors such as the use of stand-by equipment where applicable, site preparations, lack of operators etc. This scenario however, occursas described when the fleet is running efficiently, otherwise parking of equipment becomes difficult if there are a lot of breakdowns. Any piece of equipment that is made available is immediately utilized on production to make up for the downtime created by broken down equipment.

McCaherly (2014) explains that, maintenance is the factor that offers mining companies the best opportunity to influence and control the performance and availability of their equipment. Therefore, to keep the machines running efficiently, an effective maintenance plan is required coupled with a trained, competent and experienced workforce.

Additionally, from the CAT website (https://www.cat.com), it is stated that, there are three critical factors that affect equipment availability, these being, design of the machine, the application of the machine and the kind of maintenance the machine goes through during its life cycle. It is further emphasized that, of the three factors, maintenance offers the greatest opportunity for improvement. However, this is only made possible in the presence of a trained, competent and experienced maintenance workforce guided by effective maintenance strategies and systems.

From the study conducted by Kumar and Barabady (2008), it is concluded that, the performance of mining machines depends on the reliability of the equipment used, the operating environment, the maintenance efficiency, the operation process, the technical expertise of the miners, etc. As the size and complexity of mining equipment continue to increase, the implications of equipment failure become ever more critical. Therefore, reliability analysis is required to identify the bottlenecks in the system and to find the components or subsystems with low reliability for a given designed performance. To achieve this, the maintenance personnel must be well abreast with the technological advancement in the modern mining equipment world available on the market today.

Kumar (1989) studied in detail, the Time To Failure (TTF) and Time To Repair (TTR) data for major subsystems for evaluating performance and effectiveness analysis of Load-Haul-Dump (LHD) machines. The data was collected from Kiruna mine, the largest and most modern underground iron ore mine in the world. Mean of TTF and TTR data was calculated for the best fit distribution, with the aim of analysis of inherent availability. Knowing the availability trends of mining equipment is significant, however, reliability assessment becomes a vital component to mining productivity if the reliability analysis results give a detailed account of the factors responsible for major downtime causes. In certain situations, the availability of a machine may be within budget, but its reliability may be poor. A good example is a machine which is left in production with an overheating engine. The operator may be leaving the machine to cool for a few minutes and continues working, despite being unreliable, such kind of a machine may register good availability figures. In many operations, this has brought a major battle between maintenance and production personnel.

Vagenas et al. (1994) deployed graphical, analytical and statistical tools in RAM analysis to study the failure and repair characteristic of the system and its subsystems. They further used these tools for enhancing the availability of mine Trucks. Such analysis help in improving the reliability of mining equipment, however, a well-trained and competent workforce is required to manage such analytical systems. Further, buy-in from management is essential as certain mining organizations take such initiatives as a waste of production time and an unnecessary cost to the company.

Paraszczak (2002) identifies reliability and maintainability as key constraints to improve the availability and hence productivity of LHDs. He proposed that MTTF can also serve for benchmarking of mining equipment performance. Maintainability and reliability are key drivers in the running of mining equipment and it is significant to benchmark these parameters with other operations to weigh performance and identify areas requiring attention.

Hall et al. (2000) states that reliability and inherent availability are the design characteristic of an equipment and therefore, much space is not available to improve them from user's viewpoint. As such, it should be taken care of during design and users should put reliability as a criterion in the selection and evaluation of surface mining equipment. It should however, be pointed out that, it's the responsibility of each mining organization to maximize and sustain the mine determined operational availability of each equipmentthrough effective maintenance systems and careful utilization of the equipment. To achieve this, an adequate number of trained, qualified and experienced personnel is required to manage the fleet.

Grujic et al. (2000)explains that, operating environment has a significant role on the system's reliability and efficiency. Observing the dynamic nature of the operating environment and quality of repair, a genetic algorithm based reliability assessment has been proposed by Nuziale and Vagenas (2000) for mining equipment. The operating environment of mining equipment encompasses the physical environmental conditions, operations which includes operator practices and the maintenance environment, therefore, to attain desired operational availability, these variables must be balanced to an appropriate level through well-established systems and processes.

Gupta et al. (2005) discusses the methodologies to evaluate the effectiveness of the active maintenance polices to frame an importance measure based maintenance and replacement schedule for availability improvement of long-wall shearer. Effective maintenance and a firm component replacement schedule are key to running Heavy Mining Equipment, however, most mines present reluctance in following a replacement program, mainly on the basis of cost, insufficient labor to carry out component replacement tasks and lack of proper planning due to lack of skills.

Tregelles and Worthington (1983) supports the importance of reliability assessment of mining equipment throughout its life starting with specification and design, through manufacture and testing and finally during installation, commissioning and operation. Usually, more effort is put into the selection of equipment to ensure the machine is fit for purpose, however, the operational reliability of the equipment relies on the life cycle management of the equipment.

For an effective maintenance organization, Nights (2005) suggests a ratio of 1:24 for Planner to Technician and 1:16 for Supervisor to Technician, whereas, Nyman (2006) states a 1:20 for Planner to Technician and 1:10 for Supervisor to Technician. These assumptions are closely related to the suggested ratios of David (2015) of 1:15 to 1:20 for Planner to Technician. For the Engineer to maintenance personnel, Nyman proposes a 1:40 ratio. However, the reliability of these ratios is anchored on the availability and quality of maintenance personnel and systems available.

Tsang, (1999) indicates that, a better maintenance process should be guided by the integration of critical success business factors, which should be derived from the overall organisational strategy. This should then be drilled down to individual departments for effective operation.

Ljungberg (1998) explains that, human factor represented by maintenance technicians and other related staff is the backbone of the maintenance system in any organization. As such, the effectiveness of the different facet of the performance system is very much dependent on the competency, training, and motivation of the overall human factor in charge of the maintenance system. Further, Cabahug (2004) comments 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 a maintenance system.

Barabady (2017) states that, maintenance cost is a significant part of production costs and that logistics and spare part management should be considered early in the design. He further indicates that, the operational phase and reliability characteristic of a piece of equipment can be used effectively to determine spare part prediction (SPP). As such, spares projection can assist in holding economical stock levels and avoid stock run-outs which results in prolonged equipment downtime and in certain cases, the use of alternate parts. The accuracy of an economical stock holding may be compromised as some parts could be subjected to stochastic failure caused by factors such as operating conditions and human factors. Therefore, safety margins must be considered where possible.

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 engineers and as managers. At the same time, the limitations of maintenance systems are becoming increasingly apparent, no matter how much they may be computerized. Dynamic training in the ever changing equipment technology should always be made available to all personnel involved with the HME which has seen several technological changes in recent years.

Basic Requirements for an Effective Maintenance Organization

Maintenance and repair of mining equipment play a significant role in assuring productive capacity and equipment capability. Hence, effectiveness of maintenance relies on the amount and quality of maintenance resources available of which labor is key as it is at the helm of practical work and decision making. To ensure an effective maintenance organization, certain critical factors are necessary:

Staffing

The maintenance personnel must be adequate, qualified and well experienced to manage the available fleet. Some mining organizations resort to using the OEM through Maintenance and Repair Contract (MARC) to ensure effective maintenance of equipment. MARC allows for:

1) Maximizing production or increasing facilities availability at the lowest cost and at the highest quality and safety standards.
2) Reducing breakdowns and emergency shutdowns.
3) Optimizing resource utilization.
4) Allows mine management to concentrate on other needs.
5) Relieves management of budgeting constraints.

Further, maintenance labor may have other critical characteristics in a mining operation:

1) Agility - is essential for labor demand over time as what was sufficient the previous year or years may be insufficient the following year. There is an opportunity for most sites to better align the size of their maintenance labor team with demand to avoid backlogs that impact on machine reliability, or an oversupply of labor for the work required that leads to higher costs.
2) Total requirements for maintenance labor changes over the life of equipment - in the beginning, labor intensity could be low, building over time to the longer-term sustaining rates around the first major rebuild. This may present an opportunity for sites with new equipment to have a relatively low labor workforce in the initial years, and only ramp up as demand builds up.
3) Labor skills requirements change significantly over time - at the start of equipment life, semi-skilled resources may be sufficient for most tasks required. As the equipment ages, the skill levels are likely to increase and specialist skills maybe required. As the demand for labor fluctuates over time, there could be an even greater shift in the specific skills required to complete the work to a high quality with reduced time to repair.

Maintenance Infrastructure

In the context of this study, infrastructure refers to the basic systems and services that the HME department needs in order to function properly. This includes among others:

1) Workshops
2) Offices
3) Satellite stores for fast moving parts
4) Equipment
5) Maintenance Resource Management tools, such as computerized maintenance systems
6) Emergency services
7) Energy sources
8) Communication facilities
9) Other utilities.

This must be well organized for easy access to avoid delays.

Maintenance Strategy

A maintenance Strategy is a plan of action designed to achieve a long-term or overall aim in terms of equipment maintenance with the ultimate aim of ensuring high equipment reliability. Additionally, Kelly (1997) states that, a Maintenance Strategy is a systematic approach to upkeep the facilities and equipment and it varies from facility to facility. It involves identification, researching and execution of many repairs, replacement and inspection decisions and is concerned with formulating the best life plan for each unit of the plant, in coordination with production and other functions concerned.

Selecting a successful maintenance strategy requires a good knowledge of maintenance management principles and practices as well as knowledge of specific facility performance. There is no one correct formula for maintenance strategy selection and, more often than not, the selection process involves a mix of different maintenance strategies to suit the specific facility performance and conditions.

There are a number of maintenance strategies available today that have been tried and tested throughout the years. These strategies range from optimization of existing maintenance routines to eliminating the root causes of failures altogether, to minimize maintenance requirements. Ultimately, the focus should be on improving equipment reliability while reducing cost of ownership.

As earlier stated, a maintenance strategy involves the identification, resourcing and execution of different types of repair, replace and inspect decisions. To achieve this, the following may be required:
1) Formulating optimal equipment life cycle management. This is a comprehensive program of maintenance procedures – repair/replace/inspect at various frequencies – spanning the expected life of the unit or units.
2) Formulating a maintenance schedules for equipment. This should be assembled from the programs of work contained in the equipment life plan, but should however, be dynamic. For example, it should be readily adjustable in the light of changes in production schedules.
3) Establishing the organization to enable the scheduled, and other, maintenance work to be resourced, which also shows that maintenance strategy and capital replacement policy are interrelated, thus, maintenance cost influences unit replacement decisions and vice versa.

Spare Parts Management

All mining operations across the globe deal with heavy equipment which consumes maintenance materials, therefore, spare parts management is one of the most significant considerations to take into account. Having a solid spare parts planning system in place can offer benefits across many different aspects of operations.

Effectively, there are two major areas that need to be addressed when it comes to spare parts management:
1) An accurate and complete set of data related to the items using the parts and,
2) A strong forecasting process.

The two concepts create a foundation of an effective spare parts management plan. Further, the availability of spares is key to running a smooth maintenance process. To minimize spares run out, a critical spares audit may be required and a list of critical spares to be submitted to the Supply department. A daily monitoring of this list could be essential and scheduled meetings between Supply and maintenance usually help in tracking parts.

Site Build Equipment Specification

This document should be developed by the mine and should define the minimum requirements for the supply of any major equipment to be used at the mine. It is sent to the supplier of equipment before any commitment by the mine is made. This document:
1) Enables the mine to purchase correct equipment, fit for purpose.
2) Helps maintenance personnel to prepare in advance material and parts for the machine.
3) Allows for adjustments before delivery of the equipment.
4) Avoids delays in the manufacturing and delivery of the equipment.
5) Minimizes commissioning time of the equipment.
6) Prevents disputes between buyer and supplier of equipment at the point of delivery.

With these basic maintenance organization requirements in place and well managed, the maintenance department should be able to operate proactively and positively manage equipment reliability to a desired standards. However, all this requires support from top management.

4. Discussion, Results and Decisions

Maintenance of mining equipment can make up between 20 and 35 percent of the total mining operation, however, this average cost may be higher if the maintenance systems and processes are not managed effectively. Utilizing a proper mining maintenance system with close focus on optimizing scheduled maintenance operations can reduce these costs substantially by deferring non-essential maintenance, reducing maintenance manpower and controlling spare part inventory.

To assist identify the cause of the low reliability of the HME at AZ Mine, certain specific areas were investigated.

Staffing

At the time of the study, the engineers' role was under a Technician who was only acting in the position, the section had no dedicated Engineer. The main duties of the engineer were carried out by the Engineering Manager. On the other hand, the whole section was managed by a single Superintendent, covering the Maintenance Workshop, Tyre Management Section, Field Service, Electrical Workshop, Light Vehicle Workshop and Fabrication. The three Supervisors available were not adequate to manage the whole fleet. To create an effective HME department, a senior leadership (Engineers, Superintendents and Supervisors) is required to influence the whole functional activity. Maintenance performance can never rise above the quality of its leadership and supervision. From good leadership stems the teamwork which is the essence of success in any enterprise. Talent and ability must be recognized and fostered; good work must be noticed and commended; and carelessness must be exposed and addressed. Without a firm leadership, all this may not be practical. Superior leadership shapes nearly every facet of the maintenance organization.

Further, the backlog work of 18,000 hours was very high to be easily handled in the midst of breakdowns and planned maintenance as well as the lean labor force. If the backlog is too large, a lot of material may be tied up and the backlog may be difficult to control. Additionally, there may be a loss of confidence that work would ever be done, and "emotional emergencies" occasionally emerge. It may even become easier to submit a new work order than to try to find an existing work order in a large backlog situation. A large backlog is of little help for work scheduling, ideally, the backlog should be of such a size that key Maintenance and Operations personnel, including Supervisors and Planners have a good enough "feel" for what is in the backlog to be able to immediately recognize duplicate work requests. Moreover, large backlog work coupled with the numerous equipment breakdowns led to the HME department at AZ Mine create an artificial manpower shortage, leading to:

1) The quality of work not being guaranteed as most of the jobs were rushed due to lack of labor. Further, some high technology tasks were carried out by inexperienced personnel in trying to reduce the backlog work.
2) The component change-out plan, which is essential for HME not being executed as scheduled as the available labor was usually tied up with maintenance and breakdown work. This resulted into catastrophic failure of major equipment components affecting the OEE and subsequently, mine productivity.
3) The Superintendent and Supervisors not carrying out their administrative work, but fell into the hands of day to day work of Technicians. The Superintendent spent 91% of his daily time in the field attending to breakdowns.
4) Stress of employees. This led to employee ineffectiveness and high labor turnover. The effects of chronic job stressors on the individual leads to burnout (Aswathappa, 2009, Gill et al, 2006, Schaufeli et al., 2008). Burnout as a state of physical, emotional and physical exhaustion as well as cynicism to one's work is found to lead to lower levels of performance by the employee. Additionally, the low levels of performance by the employee is translated into reduced profitability of the organization at large. The labor turnover was evident in the department and an average of eight (8) Technicians was out each day on sick off.

As seen from the contents of the literature review, one Maintenance Planner with his assistant and assisted by two Data Clerks observed on the mine was not adequate to handle the day to day workload of the department. Planning plays an important role in the running of heavy mining equipment and prevents reactive maintenance where the machine is only checked if it breaks down or seen to be at the verge of failing. Therefore, an optimized maintenance system at AZ Mine was required to allow for effectiveness in planning. However, to achieve this, the mine required to invest in a correct number of qualified and experienced personnel to manage the planning section.

The other important finding at the mine was that, the Local maintenance Technicians did not undergo any OEM training. With the ever changing technology in mining equipment, Technicians must have sufficient technical training backed up by OEM courses.OEM training presents a prime opportunity to expand the knowledge base of Technicians, though a number of operations in the current environment find these development opportunities expensive. It is a well-known dictum in many operations to believe that employees attending OEM training courses do not participate directly to the mine productivity. However despite these potential drawbacks, training and development through the OEM provides both the individual and organizations as a whole with benefits that make the cost and time a worthwhile investment. Training of employees has several benefits and could assist AZ Mine:

1) Increase productivity - To attain maximum productivity, there is need for the workforce to have the skills needed to do their job. This way, employees do not waste time in trying to figure out work or systems that they should already know. The more skilled the employees are, the more efficient they will be and the more they will be able to produce.
2) Create innovation and creativity - Employees who have the skills to carry out the task they have been assigned to will spend less time worrying about how they will do it. This, in turn, frees up their minds to think about better ways of getting the job done. As a result, a skilled workforce will always be able to come up with innovative and creative solutions even for new problems due to the confidence they have from possessing the skill to work in a certain field rightfully.
3) Save the organization money - This may be challenged by certain sources since a skilled workforce usually calls for higher salaries than the unskilled, but in fact, it's not. Workers who have very little knowledge about what they are doing will generally make a lot of errors and serious errors were seen at the mine during the time of the study. Some Technicians with less experience on equipment were found to be replacing expensive components from equipment which in actual fact had not failed, but because they assumed that specific part was the cause of the breakdown. These mistakes evidently cost the mine money. Having a skilled workforce, although it may cost more at face value, would help reduce the amount of errors and improve safety within a workplace.
4) Increase profitability and stronger growth - Having a skilled workforce as opposed to an unskilled one implies that the organization can get more output with the same number of employees, sometimes even less. This could help enhance the organization's productivity and consequently the bottom line.
5) Improve health and wellness within the workplace - Unskilled workers usually struggles to perform tasks, more especially specialized tasks. Such workers would constantly feel drained, worried, and generally overwhelmed. Eventually, the stress could surpass their ability to cope and start causing damage to their minds, bodies and equipment. As a result, employees would ask for more sick days, and employee turnover is likely to increase.

Though AZ Mine had an Artisan development program, the content was not adequate to develop a full HME repair Artisan. Further, major teaching aids were not available, trainees could only dismantle and assemble a light vehicle differential, steering links and small hydraulic cylinders. Personnel conducting training had no much experience in the maintenance and repair of heavy mining equipment. The other challenge was that, when these trainees graduated and allocated to the workshop, there was no period of orientation on machines as all experienced Technicians were always busy attending to either planned maintenance or breakdown work. To this effect, the study recommended the involvement of the OEM in training and development of Artisans.

To assist AZ Mine determine the desired number of maintenance personnel, the number of equipment and associated maintenance tyres were reviewed. This data were obtained from the HME planning office, rearranged and tabulated for easy analysis. The number of Mechanical Technicians was calculated and determined as shown in Table 4.

Table 4: Proposed Number of Mechanical Technicians

Machine Type	PE 6018	PE 6040	PE 6015	DT 775	DT 789B	DR 65	MD 6290	DZ D8R	DZ D9R	DZ D10T	Total
Personnel	4	4	4	5	4	4	4	4	4	4	41
Machine Type	MT 95	FL 990	FL 966	WD 824H	GR 14M	GR 16G	ADT 740B	EX 320D 2L	IVECO Truck	SINO Truck	Total
Personnel	3	2	1	2	2	2	2	2	1	1	18
Grand Total											59

The computation in Table 4 is only for the Mechanical Technicians and does not include planning, management, supervision and other support fields such as boiler making and machining. Further it does not take into account the Roster leave, these are dealt with separately.

The approach adopted in determining the maintenance staff levels from equipment maintenance type is equally supported by the Bluefield Asset Management study (2018) and this was enough evidence to conclude that the method used was ideal for determining the number of maintenance personnel required for the HME at the mine.

AZ Mine being an off-site operation with employees coming from various countries and towns, personnel worked on rotation basis and through an onsite survey of the HME, it was noted that at least one third of the labor force was always out on roster leave. Therefore, allowing for Rotation, the required number of Technicians (Mech.):

i. $\frac{1}{3} \times 59 = 19.66 \therefore$ ~20 Technicians were always out.

ii. $\mathbf{59} + 20 = 79$

Seventy nine (79) Maintenance Technicians (Mech.) were therefore, required taking rotation into consideration.

The number of light vehicle mechanics was derived from the industry standard ratio of 1 Technician to 12.3 vehicles which is supported by Boyce (2009). Bibona (2011) from his series of ratios recommended a 1:10 ratio for transit buses which is not far from the industry standard highlighted by Boyce. Vehicles at AZ Mine did not cover substantial distances; the majority of them cover a range of 790Km to 1,000Km per month. A sample of vehicle mileage was collected from the Light Vehicle Workshop and analyzed for use in this study.

The total number of light vehicles at the mine was 150, therefore the number of Technicians (mechanics) required to maintain these vehicles was calculated as:

i. $\frac{150}{12.3} = 12.195$

Thus, the required number of Light vehicle Technicians was found to be **13**. This number only took into account Auto-Electricians and Auto-Mechanics for the light Vehicle Workshop. Table 5 shows the proposed number of Auto-Mechanics and Auto Electrical Technicians as well as other support staff.

Table 5: Other HME Support Staff

Item	Designation	Number
1	Boilermaker	13
2	Coded Welder	2
3	Machinist	2
4	Automotive Machine (LV)	10
5	Auto- Electrical (HME)	9
6	Auto- Electrician (LV)	3
7	Type Fitter	8
8	Wash bay Attendant (LV)	2
9	Wash bay Attendant (HME)	3
10	Crane Operator	2
11	Tool Crib and Hose Fabricator	3
12	Helper (HME)	3
13	Wash bay Attendant (LV)	2
		55

The number of personnel in fields such as Machinists, Boilermakers and helpers was derived from a review of previous workload as these tasks were not fixed.

With planning personnel, adopting the 1:24 Planner to Technician principle, the number of planning personnel was determined as:

i. NP= $\frac{59}{24} = 2.458$

$\therefore$ NP=3

Where:

NP = the number of Planners

Therefore, the number of planning personnel for the 59 Technicians was proposed to be three (3). Two (2) Data input administrators were required for data collection and filing. The data input administrators could equally carry out other tasks such as flight bookings and other HR data input tasks. Other personnel recommended under planning were quality controllers and inspectors.

The Planner to Technician ratio of 1:24 by Nights (2005) and adopted for AZ Mine can closely be supported by David (2015) whose study concluded that the ideal ratio for planner to maintenance Technician should range from 1:15 to 1:20.

For Supervisors, a standard ratio of 1:16 was adopted, the number of Supervisors was calculated as:

i. NS= $\frac{59}{16} = 3.867$

$\therefore$ NS=4

Where:

NS = Number of Supervisors

From this computation, the number of Supervisors suggested was 4.

The 1:16 Supervisor to Technician ratio adopted by Night (2005) and used in this study can closely be supported by assumption made by Cleveland (2012) of 1:20.

The final proposed number of personnel for the HME at AZ Mine was drawn as shown in Table 6.

Table 6: HME Staffing

Management and Supervision	Planning	Loaders and Dozers	Trucks	Rigs and Diggers	Ancillary	Light Vehicles	Type Management	Total Manpower
13	12	25	46	29	12	13	10	160

From the data in Table 6, a labor structures with respective responsibilities was developed and presented to the mine management for review and possible implementation.

The backlog hours as at the time of the study stood at 18,034, this data was collected from the HME planning office. Therefore, from this data, an estimation of the number of Technicians required was calculated as:
Number of hours per Technician per day = 12
=18034/12=1,502.83
Month=1502.83/30=50
Assuming three months 50/3=16.66

Therefore, seventeen (17) Technicians were required to complete the backlog work in three months. Allowing for rest (Rotation):
$1/3\times17=5.66 \sim 6$
$\therefore 17 + 6 = 23$

A total of twenty three (23) competent and experienced maintenance Technicians were required to complete the backlog work in three (3) months. It was therefore, proposed that this task be assigned to a contractor as the mine did have enough labor to allocate such tasks.

It should however, be noted that, all these ratios used may not be taken as a general rule for all entities or organizations, for each organization exists in its own unique environment and decision making processes are different. Therefore, the proposed numbers of personnel may equally be adjusted by AZ Mine management to suit their unique environment. The computations were a mere guide to provide direction to AZ Mine in resolving its staffing issues. Further, the number of personnel may be available, however, obtaining the right skills could be a challenge.

Maintenance Infrastructure

In terms of maintenance infrastructure, the maintenance workshop had only one oil dispensing unit to cater for all vehicles under breakdown and maintenance, this was not adequate. On the other hand, the design of the workshop was not appropriate, the building was at a lower elevation such that, during the rainy season, all the rain water found its way into the workshop. This caused suspension of work till all the water was physically cleared. The other constraint was that, the department had no component repair workshop or area, this situation caused the mine to send all components out of the mine for repair, this was time consuming and costly. The repair time was estimated at around three months for components such as the final drive of a CAT775 Dump Truck. If the mine had its own component repair shop, such jobs could be carried out onsite, quicker and cheaper. To augment this problem, there was no component change out workshop nor crew at the mine. This made it very difficult for the mine to maintain a smooth component change out plan. The data from planning office indicated that 86% of components for the 27 CAT 775 Dump Trucks were overdue. This condition allowed for unexpected breakdowns which pulled planned maintenance personnel from planned tasks as failure of components become stochastic due to age.

Equipment components are one of the key cost drivers in a mining operation and success in managing them (achieving expected life cycle and operational cost) is essential in meeting maintenance and production cost (cost/ton) of the equipment. While marginally small and repeated repairs primarily affect equipment availability, operational cost is directly influenced by major repairs, especially components. As such, it was suggested to AZ Mineto start forecasting component replacement and timely executing replacements to avoid unnecessary failure. The following was to be considered by the mine:

1) The component life goals to be well defined.
2) A strategy for component replacement to be defined.
3) The component inventory to be defined, thus, protective and normal PCR.
4) Repair kits to be well defined and incorporated into the inventory.
5) An effective component tracking system to be implemented.
6) Planned Maintenance to be adequately defined and executed.
7) Components to be kept clean and at the same time observing oil and fluid cleanliness specifications.
8) Condition Monitoring to be conducted to track the component health, this was to be apportioned into short-term (condition) and medium/long-term plans (target life projections).
9) Establish PCR forecast in medium and long term.
10) Planning and scheduling, standard jobs, backlog execution goals and PCR to be incorporated into maintenance and repair plans.
11) Define and apply pre-PCR inspections.
12) Follow recommended removal and installation (R&I) procedures.
13) Establish a performance baseline for all components installed on the machine.
14) Maintain consistent communication with repair centers by submitting accurate, complete, and timely information regarding components removed.
15) Produce and keep accurate records.

16) Evaluate performance of components and all steps of the process.
17) Apply immediate corrections to problems or pursue solutions through continuous improvement.

The Fabrication Workshop was small as seen from congestion of parts inside and out the shop. Usually, when a big item such as a bucket was brought for repair, time was wasted in opening up space. Further, the safe working load of the overhead crane was only 5 tons and this made it difficult to position bigger equipment parts as external lifting was to be sought. Additionally, the workshop was not demarcated to show stacking areas and walkways, this created confusion within the workshop as parts were placed all over the flow. As such, this posed a major safety hazard to personnel and the accountability of parts was made almost impossible.

Though heavy mining equipment tyres are critical components in that they cushion vehicles against the rigorous terrains, control stability, generate maneuvering forces and provide safety during operation, they are a safety hazard to both personnel and equipment if not properly managed. Therefore, they must be handled with care. Working with heavy mining equipment tyres is potentially dangerous because of their large size and mass, magnitude of air or gas pressures, and presence of combustible materials. The uncontrolled release of stored energy can have serious, even fatal, consequences. To the contrary, the mine did not have a dedicated workshop for tyres, tyres were repaired outside the Dump Truck workshop with no safety devices nor signs available.

There was need for the HME department at AZ Mine to have a dedicated tyre workshop and adopt a risk management approach backed up by appropriate tools and site specific equipment, with suitable controls to manage the risks. The following were suggested:
1) Competent people - training, knowledge, experience, assessment, fitness-for-work.
2) Safe systems of work - adequate procedures, information and instructions as well as good record keeping.
3) Fit-for-purpose equipment - safety-in-design, adequate capacity, well maintained and,
4) A safe and controlled working environment - adequate workshop facilities and services.

Further, proposals were made to AZ Mine to develop a safe and reliable tyre workshop with appropriate stacking areas as specified by the tyre manufacturers. The most important s recommendations made were:
1) New tyres (not mounted) to be subdivided and stack by size, tread pattern, machine type, or other characteristics.
2) New tyres (mounted) according to fitment.
3) Partly worn tyres (usually mounted) to be designated in one area for use on rear wheels only.
4) Repaired and re-manufactured (re-treaded) tyres to have their own section.
5) An inspection section to be provided for demounted, partly worn or fully worn tyres.
6) Scrapped tyre assemblies awaiting disposal section to be established.
7) Inflation cages to be provided.
8) A dedicated office to be constructed.
9) A tool room fitted with required support anchors to be constructed.
10) Provide safety signs around the workshop.
11) Develop procedures for managing the tyre section.

Additional advice was given to ensure that, the groupings (sections) were clearly designated and marked in the field to avoid potential confusion, and described in the site's tyre management plan. This was significant, more especially where the visual appearance of the tyre assembly components were similar.

Due to the ineffective tyre management system at the mine, tyre downtime was usually high and could be minimised if the points raised through the study were instituted and sustained.

Spare Parts Management

The responsibility of the Supply department as already indicated in the earlier section is to ensure the availability of material and spare parts. These have to be of the right quality and quantity at the right time and at a minimum cost. It is a service that supports the maintenance programs and its effectiveness depends to a large extent on the standards maintained within the stores system. However, though this may hold true, user departments have the responsibility to support the Supply department in forecasting of requirements and carrying out periodical auditing of inventory to avoid run outs and unnecessary inventory holding which is a cost to the company.

To ensure proper communication between the two departments was achieved, the study recommended that, the HME department formulate strong and clear systems and processes to assist in forecasting and monitoring the availability of maintenance parts. The proposal involved the HME department developing an accurate and complete data base for parts demand history, and a well-supported forecast of future needs. Further, the Supply and maintenance department, through the planning and service groups, were encouraged to coordinate activities and share information related to all repairs, repair plans, and parts logistics. Update meetings at specified intervals were proposed to achieve this scenario.

Based on the information provided by the maintenance department, the parts department would then design and implement the required functionalities, both on-site and off-site. Some of the elements suggested in considering the implementation of a parts management system at the mine were:
1) Parts supply channels or sources to be fully defined and established.
2) Supply communication channels with user departments and Suppliers to be clear and effective.
3) The availability of specialised labour to assist in coordinating activities to be made available.
4) Management support tools were required.
5) Facilities within the mine to be defined and provided.
6) Inventory management to be strictly considered.
7) Treatment of backlog parts to be prioritised.

8) Procedures to support the system, and
9) The performance evaluation criteria to be instituted.

The other significant point emphasised was the storage of parts, the on-site storage of parts and components usually represents a challenge in terms of facilities and parts integrity preservation. Parts that are not stored properly are a source of equipment breakdown when installed on equipment. On the other hand, parts and components are expensive and must be in perfect condition when needed, contamination control practices must be fully observed. It was further stressed to the HME department that, it was important to consider the level-of-control of fleet maintenance and repair activities, which equally have a significant impact on the performance results of parts support. Measuring the "Percentage of Scheduled downtime" provides an indication of the control over the maintenance and repair activities of the fleet.

Maintenance Strategy and Systems

The HME department at the mime was found to have no firm maintenance strategy to guide its operations. A maintenance strategy is a plan of action designed to achieve a long-term or overall aim in terms of equipment maintenance with the ultimate aim of ensuring high equipment reliability. Additionally, Kelly (1997) defines a maintenance Strategy as a systematic approach to upkeep the facilities and equipment and it varies from facility to facility. Therefore, for successfully operation, the HME at AZ mine needed to set up its own strategy to involve identification, researching and execution of many repairs, replacement and inspection decisions and to be concerned with formulating the best life plan for each unit of the equipment, in coordination with production and other functions concerned.

Further, there was no dedicated Computerized Maintenance Management System (CMMS), the one used was more of a financial accounting software. It did not provide for such processes as maintenance trigger or equipment life cycle monitoring.

However, whilst an important part of an overall maintenance strategy an ERP - CMMS (Computerized Maintenance Management System) is essentially a data recording and reporting system, the usefulness of CMMS output (schedules, reports or performance indicators) is determined by the relevance and accuracy of the base data. Relevant base data starts with a "begin with the end in mind" approach to data collection and accurate base data requires robust business processes. Importantly, despite the name, a CMMS does not manage the work and does not manage the people, two critical ingredients for successful maintenance outcomes. Consequently, organizations often rely on the "tacit knowledge" of key people or that knowledge that comes with grey hair and experience to "keep things going". Tacit knowledge might appear to manage the system and asset failures in the short term, but any personality / individual driven approach is not a sustainable strategy for delivering safe reliable equipment consistently over time. Reliance on CMMS and tacit knowledge in the absence of a comprehensive work execution mechanism inevitably leads to crisis. The onset of crisis may be gradual and go unnoticed until the risk profile of the project or business is complicated by one or more outcomes of fire, accelerated asset impairment, catastrophic failure, and / or unreliable assets. Each of these outcomes can be traced back to the same or similar root cause and each can have a significant impact on the performance of the project, morale of the people and reputation of the organization.

Though strategy was identified as one of the critical elements for the success of the HME maintenance department at AZ Mine, the study did not conclusively discuss this element. Further studies may be required to determine a suitable maintenance strategy for the mine.

Summary

The factors affecting the reliability of the major HME at AZ Mine were summarised as shown in figure 5.

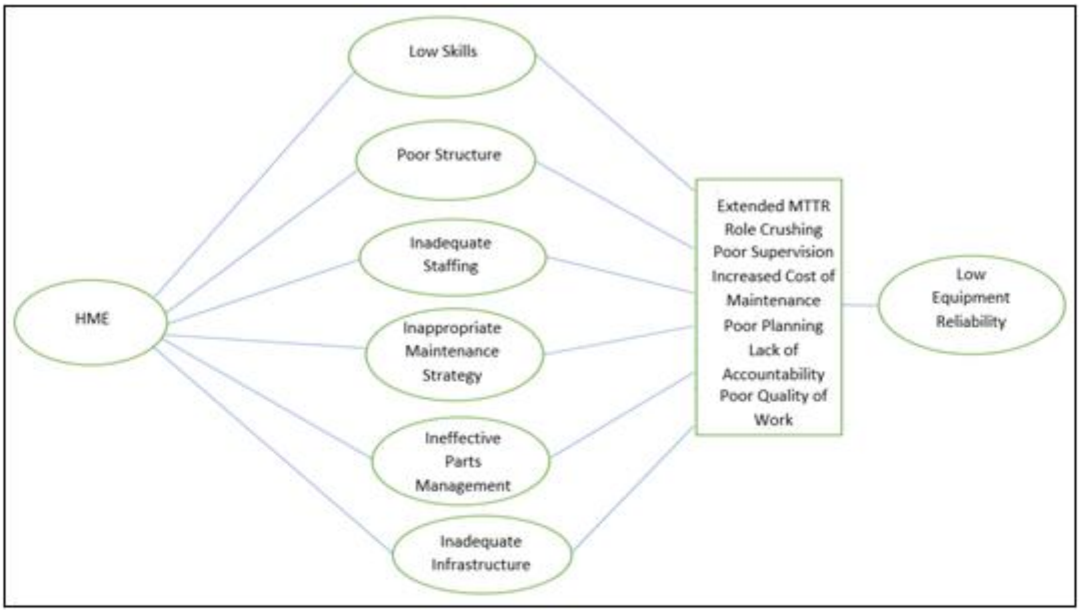

Figure 5: Contributing Factors to Low Equipment Reliability

As seen from Figure 5, the main factors affecting reliability of HME at AZ mine were:

1) Low Skills levels-the Local Technicians had not undergone the required HER training and yet they were the largest in number. This created a condition of poor fault diagnosis, extended mean time to repair and waste of parts as some tasks were carried out through try and error.
2) Poor Structure-this caused confusion among workers as they had no fixed supervisor to report to, therefore, accountability and defining of responsibilities was difficult.
3) Inadequate staffing-most tasks were not carried out and those carried out were rushed. This condition led to poor quality of work leaving the workshop. Additionally, it was not easy to formulate a workable structure with insufficient manpower.
4) Maintenance Strategy- due to not having a defined maintenance strategy, the department did not have a systematic way of operating, tasks and decisions were random and not consistent. This also led to other programs such as component change out plan not being carried as expected.
5) Inappropriate parts management - this led to extended lead time of parts as there was no proper forecasting of requirements and the Supply department was not given propriety lists of parts. The storage of major parts was not good resulting into most of the parts failing prematurely when installed on equipment.
6) Inadequate Infrastructure - led to most tasks not to be carried out appropriately and within time. Some areas like the tyre bay exposed personnel to serious hazards as all tyre repair work was done in open space.

5. Conclusion

Though AZ Mine management concluded that the major cause of the low reliability of the HME at the mine was poor supervision and extended spare parts lead time, the study conclusively found out that, the department was faced with various factors some of which were not considered by management. However, this situation may not only be unique to AZ Mine alone, many mining organizations ignore the root cause of poor equipment reliability and focus on minor contributing factors.

The main outcome from the study is that, the mine did not have appropriate skills to work on the high technology equipment. The Local Technicians, though constituted the largest number of Technicians on the mine compared with the skilled Expatriates, were not adequately trained and the onsite training provided was not sufficient. Further, there was no established spares management plan to assist in prioritising and forecasting parts acquisition. The maintenance infrastructure did not support the HME operations and the department run without a formalised maintenance strategy. To summarise the factors responsible for downtime, a framework to show the main causes of the low equipment reliability with intervening variables was developed.

Finally, various recommendations were made and in certain areas implementation commenced immediately, however, recruiting of qualified and experienced staff faced a serious challenge due to the worldwide travel restriction of personnel imposed by various nations due the COVID 19 pandemic.

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