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Assessing Drill Rig Availability Through Maintenance and Mean Time to Repair

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Abstract

Drill rig availability is essential in the mining industry's value chain. Ensuring transparency and traceability in the performance of the drill rig availability is critical. The purpose of this study is to evaluate the effectiveness of the drill rig availability rate based on maintenance compliance, mean time to repair, and mean time to failure. The studies were carried out using literature analysis and other scientific methodology including Pareto charts. A capability analysis was undertaken by collecting data on weekly planned maintenance, daily mean time to repair of drill rigs, and mean time to failure of drill rigs. The goal of using the analytical tool was to check the central tendencies of the data and process variation. This analytical tool also helped us identify what level each process is at in terms of sigma. A cause-and-effect diagram and failure mode and effect analysis were used to conduct a more in-depth root cause investigation. The goal of the cause-and-effect diagram was to examine the elements that contributed to the poor drill rig availability, including service and mean time to repair (MTTR). The FMEA was used to assess the effectiveness of the present controls for process failure and to define new actions to close all process gaps. Recommendations have been made to bridge the gaps with the most significant contributors to the low drill rig availability. This study collects data using the case study methodology. The contribution of the study is based on the assessments have been done to the mining industry that has not been addressed by current literature.

Keywords
Maintenance, Process optimization, Industrial Engineering

1. Introduction and background
System dependability and availability in mining operations are critical performance indicators (Barabady, 2005). Researchers have focused their work on increasing asset availability. The study will primarily focus on the availability of underground mine drill rigs at one of the diamond mines. Drill rig availability has a direct impact on the mine's value chain because, without drilling meters, there would be no blasting, which means no production to process in the plant. By focusing solely on sublevel cave drilling, the mine has four drill rigs, one of which must be in service while the other three are active during normal working hours. There are several factors that influence the availability of these three drill rigs, either directly or indirectly. Regarding planned maintenance, there is also an acceptable maintenance downtime, which ranges from 55 to 6% per industry norm. Indirectly, capabilities in asset maintenance and drill rig operations may have an impact on how the drill rig performs throughout operations. This research aims to analyse in different studies on how they determine how the performance of mean time to repair and effective in servicing the machinery can have a positive impact on the overall performance of the drill rig. For this purpose, there were considered the academic bases published in the scientific literature between 2011 and 2022.

2. Literature Review

2.1 Mean Time Before Failure

Reliability in general is the ability of a system or component to perform its required functions under stated conditions for a specified period (Torell and Avelar, 2010). The higher the mean time between failures, the higher the reliability, in simple terms is that the longer the asset takes the time before it fails, the more reliable it is. Companies focus more on the MTBF because they will get more production time and create more revenue from their assets.
Many complex systems are designed to perform missions that consist of phases or stages in which deterioration of the components and configuration of the system changes dramatically from phase to phase (Çekyay, B. and Özekici 2010). Any competitive company would rather have a part that fails at the required time than a part that the part that does not meet is the service level agreement. The mean time between failures (MTBF) principle is mostly used or rather followed in the power generation plant, whereby the incremental of MTBF is one of the most critical concepts in order to generate the power supply effectively.

2.2 Mean Time To Repair

Mean-Time-to-Repair (MTTR) is a measure of the average downtime. MTTR takes the downtime of the system (or assets) and divides it by the number of failures. MTTR can be impacted by the response time to failure, the skills of the mechanics, the seriousness of the failure (sometimes it may be a major component), and the frequency of failure in an asset (Çekyay, B. and Özekici,2010). For constant failure intensity, approximating the mean time to repair by one-half of the test interval is valid when the product of failure intensity and test interval is small. The handling time during unplanned breakdowns needs to be minimized so that the equipment availability can be improved significantly. Design activities can be considered as factors that can improve availability, however, operational factors such as environment, logistics support, maintenance facilities, and maintainability (Gupta et al. 2013). Mining companies have a historical background of having distant residential areas from the mine itself and that normally increases the mean time to repair of equipment, normally if the breakdown must be done by personnel on standby. So, distance is one of the factors that can impact the duration of unplanned maintenance (Ozkirim and Imrak 2001).

2.3 Planned Maintenance

To meet the demand from the mine's value chain and to minimize the constant breakdown of assets, a proper maintenance needs to be done accordingly. Assets need to be maintained by means of preventive maintenance. With the development of preventive and predictive maintenance strategies, studies that deal with policies for planning, inspection, maintenance activities, and renewal according to asset status have been developed (Roda and Macchi, 2021). The industry standard suggests that 80% should be allocated for planned maintenance while 20% should be for unplanned breakdowns. Maintenance comprises activities, which are carried out during the life cycle of a system to retain it in or restore it to a state in which it functions as originally intended (Hassanain 2002). Planned Maintenance eliminates unnecessary engineering downtime failures and aligns business goals with the overall strategy. For planned maintenance to be effective must be done by an authorized and certificated maintenance personal according to the maintenance instructions (Ozkirim and Imrak 2001). Organizations are basing their operations in a more efficient and effective way to have sustainable businesses. With that in place, operations need the correct number of people in place, the correct processes in place, the correct tools, and the compatible working place for conducting planned maintenance.

2.4 Availability

When assessing a system performance, it is always important to understand how its availability is determined and calculated. Firstly, by determining what availability is, availability is a function of how the system fails. Generally, availability can be defined as the probability that the system will be ready to perform its mission or function under the stated conditions when called upon to do so (Barabady 2005). Availability can be modified based on the ideal support components such as unlimited spares and no delays. Availability can be calculated as follows.

$$Availability = \frac{Uptime}{Uptime + downtime}$$

In the mining environment or any other industry, asset availability is always tied to the financial health of the company. You cannot have your assets always to breakdown while they are supposed to be working. That will not make the company profitable. Therefore, availability is used to measure and investigate the effectiveness of assets like trackless mobile machinery in the mining environment, and how they can be improved (Fourie,2016). Availability in the trackless mobile machinery concept is taken as subtracting the total breakdown hours and the planned maintenance hours from the total time. Availability of any working machinery is impacted if any specific part of that machinery goes into a breakdown while the machinery is operational. The system fails when the total damage exceeds some threshold level (Çekyay B. and Özekici 2010). Effective inspections are the most important factors that can detect any possible system failure so that the system can be fixed or repaired before failing. If failure is detected, then the system is repaired to a state as good as new (Çekyay B. and Özekici 2010). Availability of any asset is the output of the overall equipment efficiency and machine reliability. To confirm the reliability of the asset, one must be satisfied with the asset's overall equipment effectiveness. OEE can also be improved in any company through the implementation of an innovative maintenance strategy and reduced operating costs of the mining industry as well (Gupta et al. 2013). Modern manufacturing company uses total productive maintenance to improve asset reliability. TPM is an innovative approach used to enhance the output of the asset overall equipment effectiveness (Gupta et. al. 2013). Jain et al. (2015) suggested eight pillars of the TPM model within the Indian industry context that helps to improve the asset reliability.

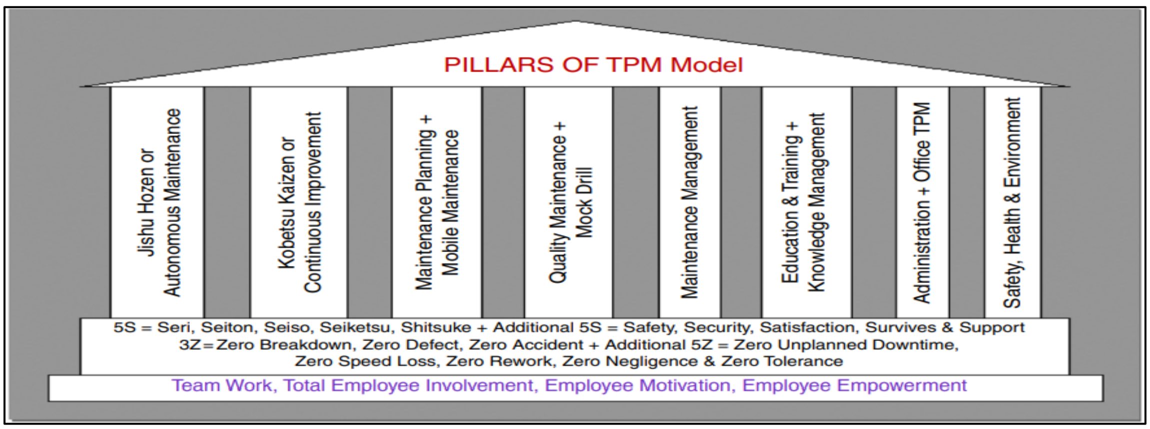


Figure 1. The 8 Pillars of the TPM methodology (Source: (Gupta et al. 2013).

TPM is one of the world class manufacturing tools that is used to seek to manage assets by involving everyone in the manufacturing organization (Ozkirim and Imrak,2001). The TPM methodology is a methodology to improve the OEE concept. On the other hand, the OEE concept was developed as a quality rating to ensure that every equipment is rated to improve its efficiency by ensuring that it has low breakdowns, less idling and stop time, and lower quality defects.

2.5 Planned Maintenance

To meet the demand from the mine's value chain and to minimize the constant breakdown of assets, a proper maintenance needs to be done accordingly. Assets need to be maintained by means of preventive maintenance. With the development of preventive and predictive maintenance strategies, studies that deal with policies for planning inspections, maintenance activities, and renewal according to asset status have been developed (Bhebhe 2020). The aim for any profitable organization is to decrease failures and increase system reliability. So that needs a robust planned maintenance adherence to schedules. Maintenance schedules assist planners to plan the parts replenishment accurately and identify which are the parts that break down the most (fast moving parts in terms of procurement) and be able to predict the usage for the future. The industry standard suggests that 80% should be allocated for planned maintenance while 20% should be for unplanned breakdowns. Maintenance comprises activities, which are carried out during the life cycle of a system to retain it in or restore it to a state in which it functions as originally intended (Hassanain 2002).

Planned Maintenance eliminates unnecessary engineering downtime failures and aligns business goals with the overall strategy. For planned maintenance to be effective must be done by an authorized and certificated maintenance personal according to the maintenance instructions (Sar and Garg 2012). Organizations are basing their operations in a more efficient and effective way to have sustainable businesses. With that in place, operations need the correct number of people in place, the correct processes in place, the correct tools, and the compatible working place for conducting planned maintenance.

Planned maintenance gains significance in terms of the scope of work, the size of the business, work relevance, operational, and maintenance costs (Raposo and de Brito 2013). It is relevant to manage the planned maintenance to avoid cost impact downstream in a production environment. The analysis aspect of the planned predictive maintenance helps to track and improve on the key performance indicators of the planned predictive maintenance. Raposo and de Brito (2013) suggest an analytical tool for conducting a planned maintenance, especially when focusing on different sites.

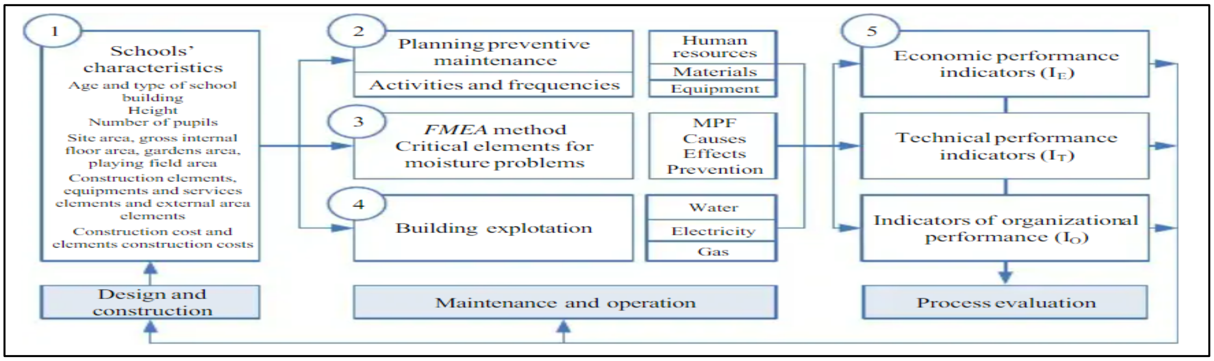


Figure 2. Analytical tools that assist in integrating integrated key performance indicators
(Source: Raposo and de Brito)

The complexity of systems is determined by multiple-component units that may vary from one product to the other and that may have a different preventive maintenance approach. It is important for any system performing a specific work while its lifecycle to be available when required to ensure material and personnel safety. With all of that being mentioned above, only preventive maintenance approaches can allow the personnel to be able to improve the safety, product and availability that will satisfy both internal and external customers of the business.

In recent years, the business world has evolved in a way that makes the business more agile. Planned preventive maintenance is now scheduled using effective systems that have decreased more paperwork because now planning is done systematically. Systems are now compatible to cater for complex components and subcomponents when doing planned maintenance schedules and that works well when maintaining medical equipment (Moghaddam and Usher, 2011). According to Wu (2011), there have been researches that have classified preventive maintenance models. These models are more focused on age or hazard reduction or the combination of both models (Wu, 2011). The age reduction model aims at decreasing the maintained system's age to a younger age, while the hazard reduction model assumes the role of decreasing the hazards in the system that is being maintain. Both models are used in the mining industry as they are in line with the regulations in terms of the hazard reduction model, which focuses on the safety aspect of the mine performance. Then, the age reduction model is in line with the production aspect of the business because there is no mining company that would like to perform with an ageing machinery.

2.6 Component Replacement Strategies

Each component in a trackless mobile machinery has a certain life span. As for mining underground drill rigs, their life span before major component replacement is 20 000 hours and it is of importance to have ageing equipment management systems to better track and monitor the conditions of the assets.

Managing physical ageing of major components is important to safety requirements and predicting or detecting when a component will have degraded to the point that requires replacement and taking appropriate corrective actions. The study will investigate what is considered as a major component replacement on drill rigs and what is the relevant replacement interval as per the OEM standards. There haven't been much research on the impacts of major component replacement based on the trackless mobile machinery. Most of the research are based on nuclear plants or power stations and airline companies.

In the mining industry, the ageing of machinery influences the major component change, but it is different in the airline or any other production industry. Cost of managing that particular asset may be the most influential factor. Maintenance costs are directly linked to any company's annual expenditure (Sillivant 2015). The effectiveness of any modification needs to be assessed by the cost of implementation and the benefits. Normally, companies use the original equipment manufacturer and the alternative suppliers as a comparison to decrease maintenance costs.The mining industry involves machinery operating in a very extreme condition that may have an impact on the way components may behave or shorten the lifespan of a particular product. In the underground mining, there is a lot of water and hot conditions, so normally moisture and temperature can have an influence in terms of how the product may behave mechanically. Moisture and temperature affect the chemical, biological, and mechanical processes of decay (Moncmanova 2007).

Some of the factors, such as continued improvements in technology, are likely to influence in the prolonged decision to change the components of a certain machinery mainly. Methods of mining goes with the type of technology that is adapted in the recent markets. Finsch diamond mine in the Northern Cape was one of the first mines in South Africa to change from the block cave mining method to the Sub Level Cave mining method. So, such technological changes can have an influential factor to either change components in the machinery to replace the machinery with the new type of machinery that will be more compatible with the new method of mining operation.

Every component in the machinery has its own lifespan and the cycle time of how it should be in operation before it can be maintained. For any continuous operating unit, the production loss is often very large when unexpected shutdown occurs (Laggoune 2009). It is evident that if any large operation such as a chemical plant or mining company goes to a prolonged unexpected shutdown, it may suffer a large profit loss or gaining. Every company needs to follow the strategy of component change and always abide to the required component lifespan of every component to minimize unexpected plant breakdowns. Aligned component replacement strategies will have to follow the entire company's planned shutdown strategy to minimize costs and optimizing machine uptime and utilization by operators. A departmental shutdown cost is often much higher than the cost of one company, so it is advisable to follow a suitable maintenance policy that caters the whole company.

Research Methodology

In this work, a systematic review was carried out to locate relevant studies based on previously formulated research questions, to evaluate and synthesize how drill rig maintenance compliance and effective mean time to repair can contribute to the drill rig reliability (Sar and Garg 2012). The research is an explanatory type of research target mining industry to explore more studies with Industrial Engineering tools. The study data source focused on secondary data from related mining industry or literature. According to Christopher et al. (2021), the systematic review of the literature is a form of research that uses as a source of information data from the literature on a given topic and that allows the researcher to identify in an agile and summarized way the outstanding theories, in the area of interest, identify key concepts, the most outstanding authors, the methodologies that have been used, the most important findings and that provides a summary of the evidence related to a specific intervention strategy, through the application of explicit and systematic search methods, critical appraisal and synthesis of the selected information.

Statistical methods were employed to determine the sigma level at which each process operates. In terms of the failure mode and effect analysis and the cause-and-effect diagram, an additional root cause analysis was carried out. The mean time to repair (MTTR) and other factors that contribute to the poor drill rig availability were examined in the cause-and-effect diagram. Data was processed using the Minitab application. Data processing was used to define the control limits on the control chart and assess process capability.

Statistical data analysis is the methodology for analysing data. The statistics represent the scientific part which involves the collection of data, the handling of data, and the sorting of data using a structured approach that may lead to new results. The primary goal of statistics is information extraction from the data with an intention to gain an understanding of what the data is representing at a particular moment. Sarmento and Costa (2019) suggest that statistics is a science of using theoretical concepts to learn data. Learning what the data is representing is one of the most important things an analyst can do because without understanding what the data means can lead to a company focusing on the wrong things. Data can then be analysed using the central tendency to check where most of the data is centred. The measure of central tendency in analysis uses the mean, median, and mode. The mean will be used to check the overall idea of the data sets. The median is used to measure the data distribution in terms of skewness and outliers. The mode will then be used to repetitive numbers in a data set.

Measures of variability are used to check the data spread from its central value. Variability is used to check how is the data varying. If the analysis shows that there is a high variability, then this shows that there is a widespread in terms of the data or process. The range, standard deviation, and variance are statistical tools used for the measures of variability. The range measure, the difference between the largest and the smallest value, the standard deviation is used to check of each data point from the mean.The objective of the FMEA was to demonstrate its validity for a scientific protocol of basic research, thus producing valuable proposals for the improvement of research performance, process control and the overall working environment (Mascia et al.2020).

As the research is based on drilling operations and has components that have been discussed earlier on (MTBF, MTTR, and Planned Maintenance). A systematic approach called lean six sigma was followed to analyse each component in terms of process capability. The aim of that approach was to check how capable is the process to the customer specification. Then a time series plot was used to analyse how the process is behaving overtime. Lastly, a root cause analysis was conducted in terms of the fishbone diagram and failure mode and effect analysis to understand what the root causes of the process failure are.

Results and discussion
Mean Time before failure (MTBF)

The I Chart
The I-Chart was used to in the analysis phase. The I-chart helps to identify the common and assignable causes in the process. It also displays the individual data points and monitors mean and shifts in the process when the data points collected at regular intervals of time. The secondary data of 137 data points was used for the I-chart. The figure below (Figure 3) illustrates the analysis of the daily MTBF of the drill rigs. The figure shows that there was no data point that was over the upper control limit, 43% of the data was above the average, and 57% of the data was below the average. The mathematical calculations used on the i-chart were as follows.

$\bar{x} = \frac{\sum x}{n}$,
$UCL = \bar{x} + 3\sigma$, and
$UCL = \bar{x} - 3\sigma$

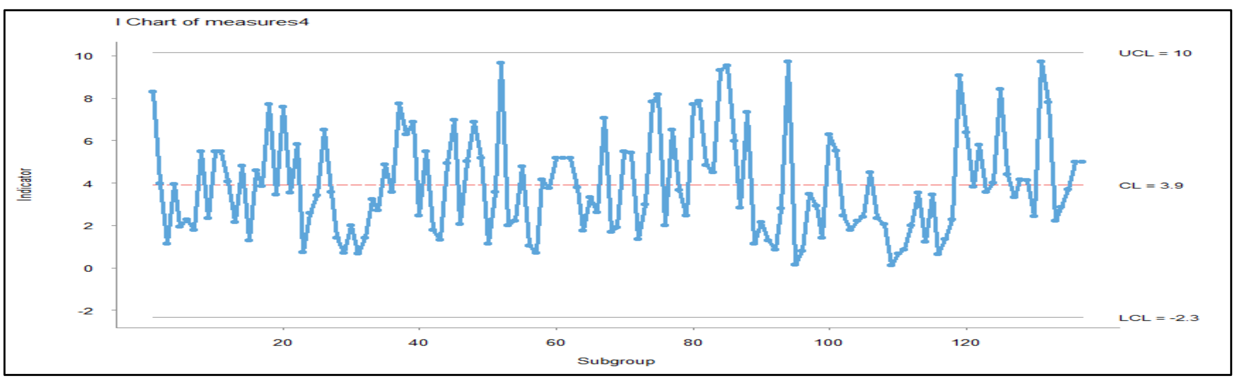


Figure 3. I-Chart for Mean time before failure (MBTF)

The Capability Analysis
The process capability analysis was used to check how well the process is meeting the customer specifications. In this case, the requires every drill rig to operate from 4.4 hours to 10 hours without going into breakdown. The current process shows that every drill rig operates for 3.9 hours and then goes into breakdown. Looking into the analysis of Figure 2, it is evident that 60% of the data points are lying outside the lower specification limit (LSL) and the upper specification limit (USL). With an average of 3.9 hours daily, there is a standard deviation of 2.4 hours, and this means that the process varies between 6.3 hours and 1.7 hours. The process capability index (C_{pk}) is -0.07 against the industry target of 1.33, so this shows that the process requires an improvement.

The process capability index (C_p) is 0.94 against the industry target of 1.33, so this shows that the process is not capable of meeting the business requirements. Furthermore, it is evident that the process is not centred between the LSL & the USL due to C_{pk} and C_p not being equal. The statistical calculations used on the capability analysis were as follows.

$$C_p = \frac{(USL-LSL)}{6\sigma} = \frac{18-4.4}{6(2.40)} = 0.94 \ ,$$

Calculating C_{pk};

$$CPU = \frac{(USL-\bar{x})}{3\sigma} = \frac{18-3.91}{3(2.40)} = 0.94$$

$$CPL = \frac{(\bar{x}-LSL)}{3\sigma} = \frac{3.91-4.4}{3(2.40)} = 0.07$$

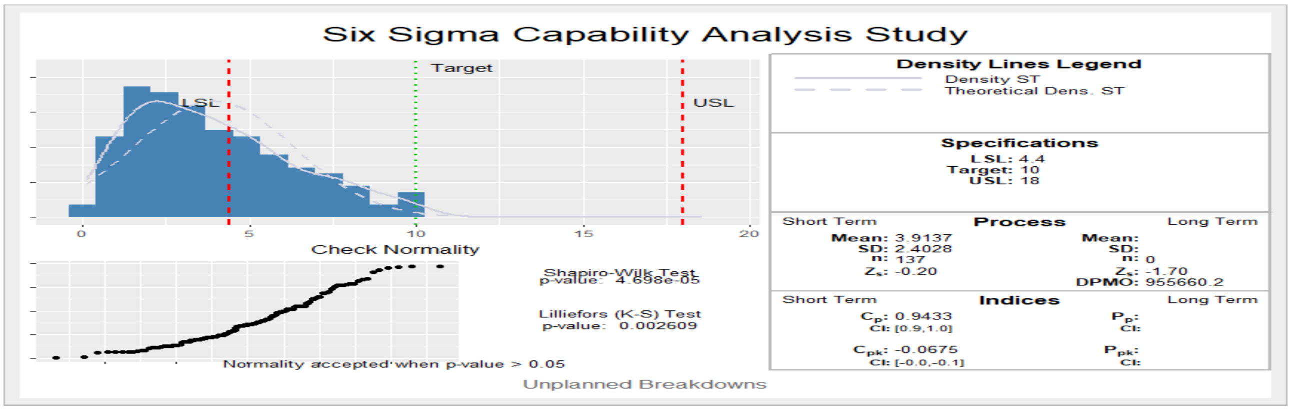


Figure 4. Process capability analysis for Mean time before failure (MBTF)

Mean time to failure

The I-chart

The I-Chart was used to in the analysis phase. The I-chart helps to identify the common and assignable causes in the process. It also displays the individual data points and monitors mean and shifts in the process when the data points collected at regular intervals of time. The secondary data of 372 data points were used on the I-chart. The figure below (Figure 5) illustrates the analysis of the daily MTTR of the drill rigs. The figure shows that 19 days were over the upper control limit, 45% of the data was above the average and 55% of the data was below the average. The statistical calculations used on the i-chart were the same as the one's for MTBF.

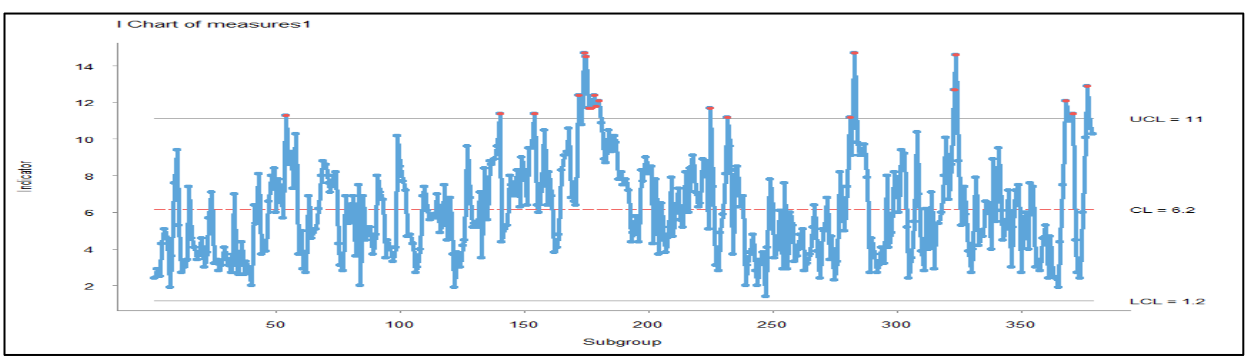


Figure 5. I-Chart for Mean time before failure (MTTR)

4.6 The Capability Analysis

The process capability analysis was used to check how well the process is meeting the customer specifications. In this case, the business requires every drill rig's breakdown to be fixed between 0.7 hours and 1.4 hours per day. The current process shows that every drill rig's breakdown duration averages at 6.2 hours per day. Looking into the analysis of figure 6, it is evident that 95% of the data points are lying outside the lower specifications limit (LSL) and the upper specifications limit (USL). With an average of 6.2 hours daily, there is a standard deviation of 2.7 hours, and this means that the process variates between 8.9 hours and 3.5 hours. The process capability index (C_{pk}) is -0.59 against the industry target of 1.33, so this shows that the process requires an improvement. The process capability index (C_p) is 0.04 against the industry target of 1.33, so this shows that the process is not capable of meeting the business requirements. Furthermore, it is evident that the process is not centred between the LSL & the USL due to C_{pk} and C_p not being equal. The statistical calculations used on the capability analysis were the same as the one's on MBTF.

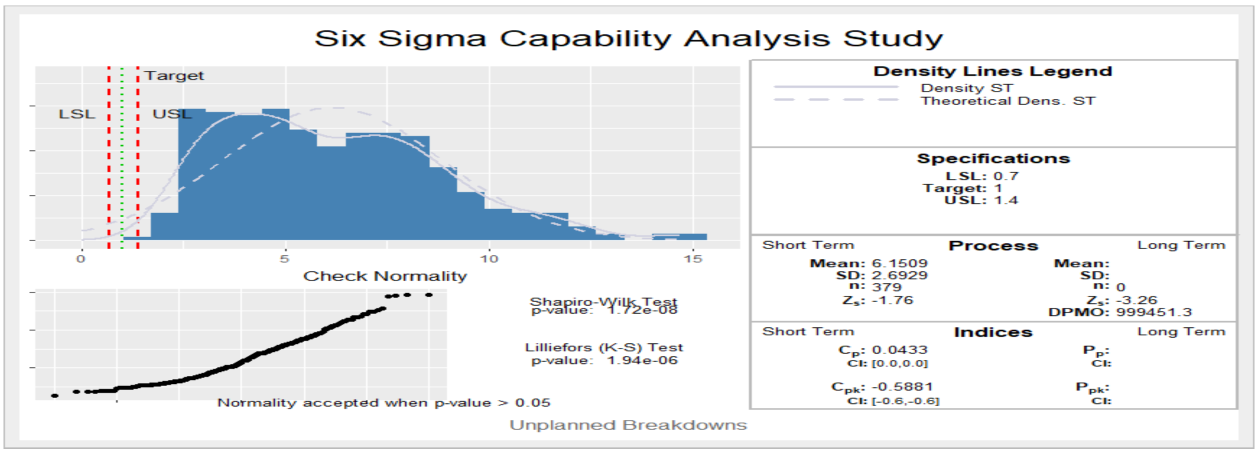
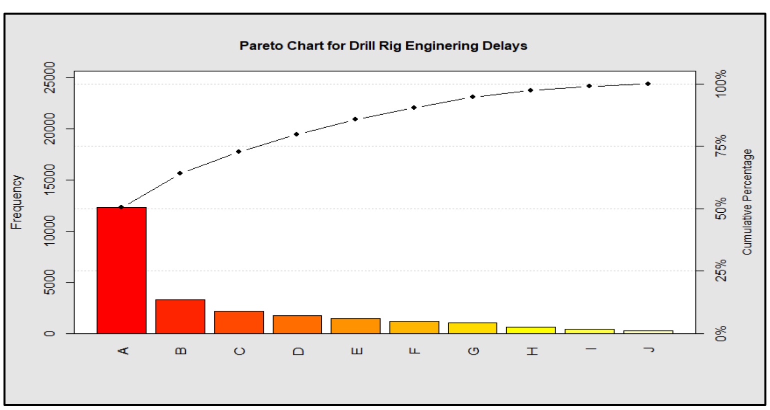


Figure 6. Process capability analysis for Mean time to failure (MTTR)

4.7 The Pareto Chart

The Pareto analysis was used as a form of a root cause analysis tool to identify the problem areas or tasks that will have the biggest payoff. The figure below (Figure 7) illustrates that 80% of the failures are the ones that are contributing to the average 6.2 hours of unplanned breakdowns daily for the 3 running drill rigs. The Pareto Chart below depicts that boom failure, which includes the drifter failure, oil leak challenge, and breaker challenges are the main process pain point. 80% of the mentioned failures contributed a total number of 19,461 hours delays out of the total 42,768 available hours over the past 3 years. This took approximately 45% of the total available time.



#	Failure Type	Delay Hours
A	Boom	12298
B	Oil Leak	3315
C	Faulty Breaker	2132
D	Circuit Breaker Tripped	1716
E	Fail to start	1457
F	Pipe Burst	1137
G	Brakes	1050
H	Engine Failure	616
I	Aircon	419
J	Cabin	261

Figure 7. Pareto Analysis for Mean time to failure (MTTR)

4.8 Planned Maintenance

The I-Chart was used to be in the analysis phase. The I-chart helps to identify the common and assignable causes in the process (Sar and Garg 2012). It also displays the individual data points and monitors the mean and shifts in the process when the data points are collected at regular intervals of time. The secondary data of 75 data points were used in the I-chart. The figure below (Figure 7) illustrates the analysis of the weekly planned maintenance of the drill rigs. The figure shows that 6 weeks were over the upper control limit, 56% of the data was above the average, and 44% of the data was below the average. The statistical calculations used on the i-chart were the same as the one's for MTBF.

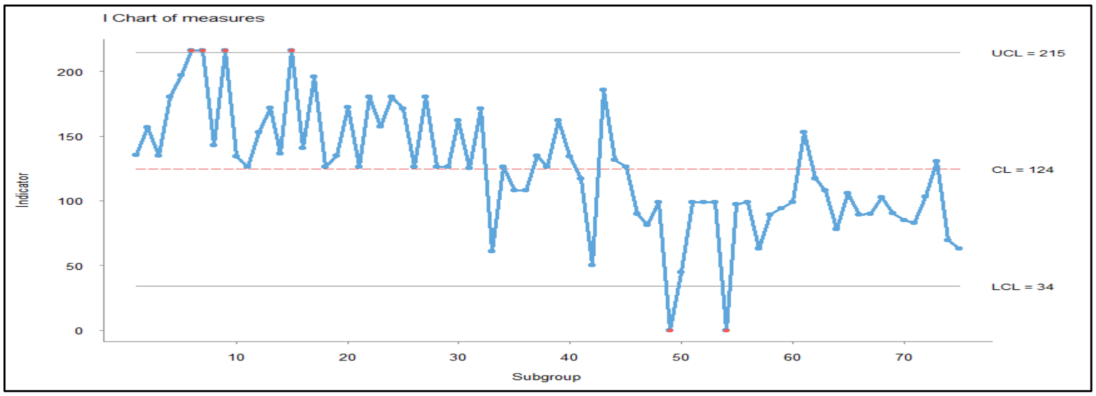


Figure 8. I-Chart for Planned Maintenance

4.9 The Capability Analysis

The process capability analysis was used to check how well the process is meeting the customer specifications (Kaya, and Kahraman, 2011). In this case, the business requires every planned maintenance to take between 81 hours and 99 hours per week. The current process shows that every drill rig's planned maintenance duration averages at 124.3 hours per week. Looking into the analysis of Figure 4, it is evident that 90% of the data points are lying outside the lower specification limit (LSL) and the upper specification limit (USL). With an average of 124.3 hours weekly, there is a standard deviation of 45.8 hours, and this means that the process varies between 170.1 hours and 78.5 hours. The process capability index (C_{pk}) is -0.18 against the industry target of 1.33, so this shows that the process requires an improvement. The process capability index (C_p) is 0.07 against the industry target of 1.33, so this shows that the process is not capable of meeting the business requirements. Furthermore, it is evident that the process is not centred between the LSL & the USL due to C_{pk} and C_p not being equal. The statistical calculations used for the ability analysis were the same as the one's on MBTF.

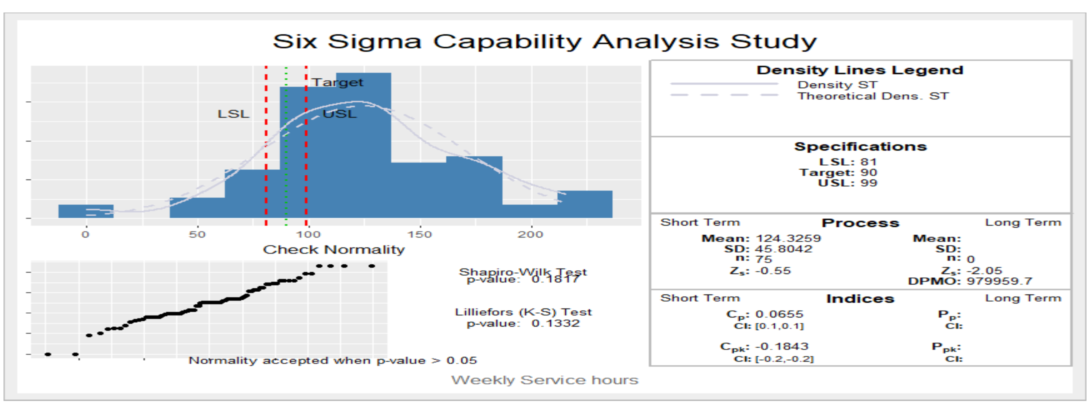
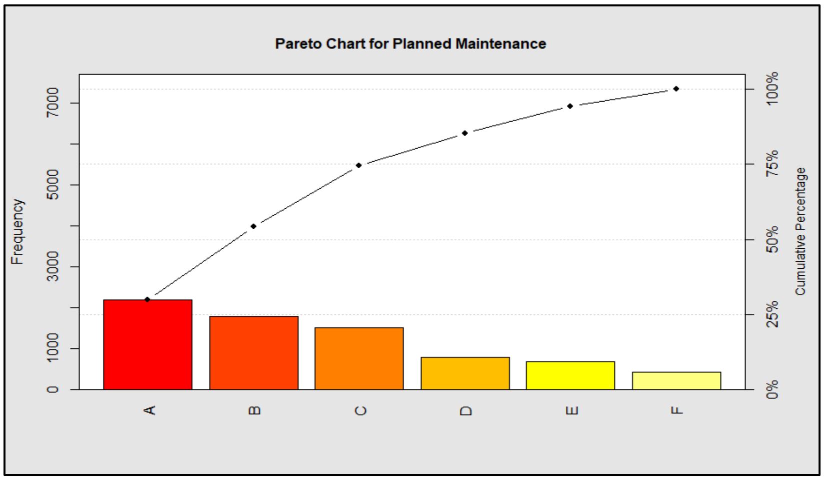


Figure 9. Process capability analysis for Planned Maintenance

4.10. The Pareto Chart

The Pareto analysis was used as a form of a root cause analysis tool to identify the problem areas or tasks that will have the biggest payoff (Sar and Garg, 2012). The figure below (Figure 8) illustrates that 80% of the failures are the ones that contribute to the average 124 hours of weekly service. The Pareto Chart below depicts that sparing availability prior to service, Technician availability, tools like crane availability, and communication failure between the engineering team and the production teams are the main process pain points. 80% of the mentioned failures contributed a total number of 6,254 hours of delays out of the total planned maintenance time of 15,444 hours over the past 3 years.



#	Failure Type	Delay Hours
A	Spares Availability	2180
B	Technician Availability	1789
C	Crane Availability	1500
D	Communication Failure	785
E	Limited Workshop Space	667
F	Power Supply	409

Figure 10. Pareto Analysis for Planned Maintenance

4.11 Causes & Effect Diagram

A Cause-and-Effect Diagram is a tool that was used to help the researcher to identify, sort, and display possible causes of a specific problem (low availability) or quality characteristics (Coccia 2018). The figure below (Figure 9) graphically illustrates the relationship between low drill rig availability and factors that influence the low availability.

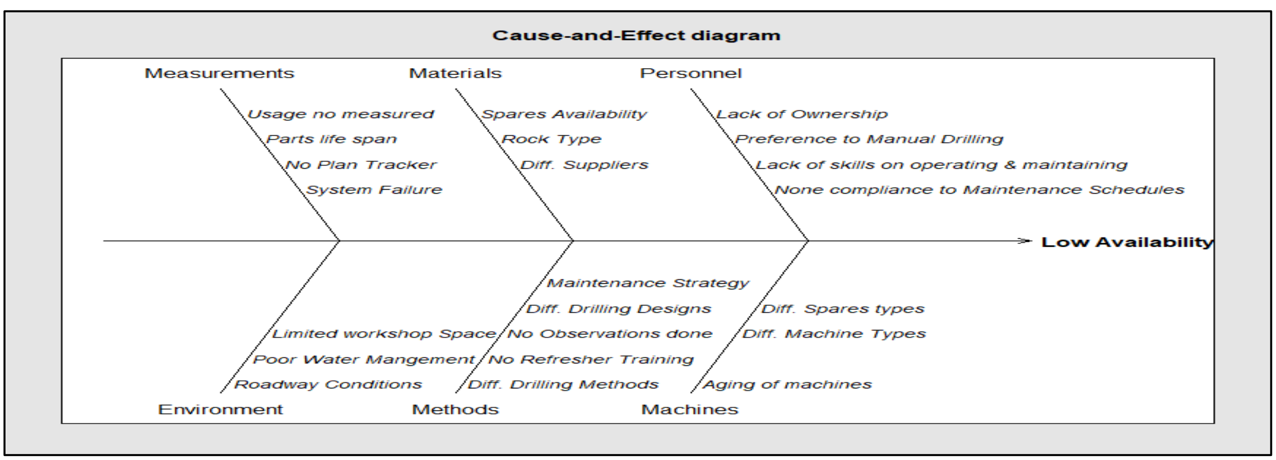


Figure 11. Cause and effect analysis for low drill rig availability.

4.12 Failure Mode & Effect Analysis

The Failure mode and effect analysis was used to evaluate the MTTR and the planned processes by identifying where and how the processes might fail. The analysis tool also assisted the researcher in terms of assessing the relative impact of different failures, to identify the parts of the process that are most in need of change (Labib et. al.,2021). After conducting the FMEA, the following potential causes were ranked high in terms of the risk priority matrix for MTTR.

- Ageing of machinery – 900

- Technician shortage – 540
- Manual drilling – 500

The following potential causes were ranked high in terms of the risk priority matrix for planned maintenance.

- Spares unavailability - 900
- Drill rig was not prepared for service – 900.
- Technician shortage – 500

The below table illustrates the FMEA that was conducted for planned maintenance and MTTR in order to address the low drill rig availability issues.

Table 1. Failure Mode and Effect Analysis (FMEA)

Process	Potential Failure Mode	Potential Failure Effect	SEV	Potential Causes	OCC	Current Process Control	DET	RPN	Action Recommended
What is the step?	In what way can the process go wrong?	What is the impact on the customer if the failure mode is not prevented?	How Servere is the effect on the customer?	What causes the process to go wrong?	How frequently is the cause likely to occur?	What are the existing control that eitherprevent the failure mode fromoccuring or detect it should it occur?	How probable is detection of the failure mode or its cause?	Risk priority number calculated as SEV x OCC x DET	What are actions for reducing the occurrence of the cause or for improving its detection? Provide action on all high RPNs and on severity ratings of 9 or 10
Attending to Machine breakdown (MTTR)	Longer machine downtime	Less machine upti	10	Operator taking time to report the machine	7	Logging in the downtime on the tablet inside the machine	3	210	Linking the reporting platform to the machine stoppage
			5	Network failure	3	Frequent Inspections	3	45	
			10	Spares Availability	9	Having multiple suppliers	1	90	Ensuring that the mine has critical spares inventory
			10	Technician taking time to respond to breakdowns	3	Allocation of service and breakdown crew	7	210	Adherence to call outs processes
			6	Technician Skills	5	Planned task observations	5	150	
			6	Operator skills	7	Planned task observations	5	210	
			10	Technician shortage	9	Prioritisation of breakdown work	6	540	Accelarate the recruitment of technicians
			5	Location of the Breakdown	5	Fixing of machines at any place by ensuring correct tools are brought on site	1	25	
			5	Manual Drilling	10	Standardising one-hole automation method of drilling	10	500	
			10	Limited Workshop Space	3	Fixing of machines at any place by ensuring correct tools are brought on site	9	270	Train technicians to be able to work on breakdowns anywhere.
			10	Machine Aging	10	Spares life span tracking after installation	9	900	Implementation of a real time Spares life span tracker.
Servicing Machines	Lower MTBF & Multiple breakdowns	low Machine availability or uptime	10	Spares Availability	10	Having multiple suppliers	9	900	Ensuring that the mine has critical spares inventory
			6	Technician Skills	5	Planned task observations & Refresher training	5	150	
			10	Operator not preparing the machine for service	10	Standadardised Process	9	900	Improve communications that will enable the transparency of machine activities
			10	Technician shortage	10	Prioritisation of breakdown work	5	500	Accelarate the recruitment of technicians
			10	None adherence to maintenance schedules	3	Standadardised Process	8	240	Improve communications that will enable the transparency of machine activities

Table 1 showcase potential causes of low drill rig availability issues for planned maintenance and MTTR. The potential causes can be difficulty to exhaust in the FMEA, however, in order to identify as many potential causes as possible. The mining industry team or managers may need to acknowledge that they might not be able to capture all expected causes.

4.13 Mean time before failure

The analysis was based on a total number of 137 days MTBF occurrences. It is evident that the process is averaged at 3.91 hours per day. This means each drill rig takes for 3.91 hours before it fails. From the process capability point of view, there is more variation on the daily MTBF performance due to multiple factors. The standard deviation is showing that the process is deviating to 2.41 hours from the mean of which it is way above the standard deviation tolerance of 5% from the process mean. With that deviation in place, it is evident that the process shows 60 percent of the data points are out of the business specification limits of 4.4 hours and 10 hours per MTBF.

4.14 Mean time to repair

The analysis was based on a total number of 379 days MTTR occurrence. It is evident that the process is averaged at 6.2 hours per day. This means that each drill rig is being repaired for 6.2 hours when it is on breakdown. From the process capability point of view, there is more variation on the daily MTTR performance due to multiple factors. The standard deviation is showing that the process is deviating to 2.69 hours from the mean of which it is way above the standard deviation tolerance of 5% from the process mean. With that deviation in place, it is evident that the process shows 95 percent of the data points are out of the business specification limits of 0.7 hours and 1.4 hours per MTTR. The results from the Pareto illustrated the following.

a) The Boom

The boom failure represents the drifter challenge that the section experienced due to the contamination of oil and operator skill level.

b) Oil leak

Oil leaks were also the part of the 80% problem and that was caused by the operator skill level because some issues about oil leaks could've easily been fixed by the operator instead of waiting for the artisan.

c) Circuit breaker tripping

The prolonging electrical issues were caused by the shortage of auto electricians in shifts and the operator faultfinding skills.

d) Failing to start

The prolonging electrical issues were caused by the operator faultfinding skills.

e) Pipe burst

As per the process drivers, the pipe burst issues were mostly caused by the poor roadway conditions. The underground roadways have been identified as a problem child by the artisans because mud is clocking into the system that leads to the pipe burst.

4.15 Planned Maintenance

The analysis was based on a total number of 75 weeks of maintenance occurrence. It is evident that the process is averaged at 126 hours per week. This means that two or more drill rigs are being taken in for service. From the process capability point of view, there is more variation on the weekly maintenance performance due to multiple factors. The standard deviation is showing that the process is deviating with 45 hours from the mean of which it is way above the standard deviation tolerance of 5% from the process mean. With that deviation in place, it is evident that the process shows 90 percent of the data points are out of the business specification limits of 81 hours and 99 hours. The results from the Pareto chart are illustrated in the following.

Spares Availability

The spares availability is the most common problem because of the type and brand of of the drill rigs that the mine is having. With the pandemic impacting most of the businesses, there has been a global supply issue of spares across the country.

a) Technician Availability

There is a current shift model that that the company is currently utilizing is not suitable for the operating model. There shift structure and complement is coursing availability shortage in case one technician goes to leave training or is off sick.

b) The Workshop Crane Availability

The crane failure in the workshop prolonged the service hours because parts such as boom, gripper arm, or drifters cannot be removed without the crane being available.

c) Communication Failure

Communication failure was also identified as a common denominator because of the production department and the maintenance department being confused in terms of when is the drill rig supposed to be in for service.

Conclusions and Recommendations

5.1 Conclusions

The availability of drill rigs at Finsch Diamond mine is critical since ore must be removed from underground for the mine to continue operations. This study discovered that factors such as extended maintenance and repair times can have an impact on drill rig availability and reliability. Following a thorough review of the two components using root cause analysis, sparse availability and skill level were identified as common denominators. The availability of spare parts effects both the performance of the scheduled maintenance process and the mean time to repair procedures. Prolonged waiting times for spares cause the machines to remain in the workshops for prolonged periods of time. One of the contributing elements to spare unavailability was identified as a global supplier issue and an inefficient replenishment procedure.

5.2 Recommendations

Utilization of alternative suppliers to manage the availability of critical spares and fast-moving spares effectively. In addition, by utilizing alternative suppliers instead of the OEM, a proper service level agreement will have to be in place to monitor the efficiency of the suppliers. The internal management of the inventory needs to be integrated and the process needs to be streamlined to ensure transparency of the stock management. Adherence to the maintenance schedules needs to be a standardized process with a guideline from the annual asset management strategy, which must be formulated into a calendar. An integrated dashboard monitoring the next service cycle of every drill rig will have to be developed. Developing a dashboard that will monitor the life span of the critical parts. This will assist the maintenance planners to effectively manage the procurement process of critical spares. The skills improvement plan must be put in place so that gaps about the current and future gaps can be identified. All artisans/technicians must be trained in the two trades so that they can be able to conduct an effective faultfinding that will lessen the mean time to repair duration on drill rigs. This process will assist the artisans to be able to bring rightful spares and tools to the breakdown site.

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