The Use of Productivity Improvement Tools at a Mineral Processing Plant

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Abstract

This study investigates the applicability and effectiveness of continuous improvement tools in mineral processing plants. The gold mining sector in South Africa in 2021 contributed about 8.2% towards the GDP, which is a lower percentage compared to the 21% of the 1980s. Mineral processing is the 2nd phase of mineral extraction and processing activities (from the 1st stage, the ore extraction process). As such, productivity improvement is important as it also improves the output the minerals extracted. It is essential that mining houses continuously looks at ways to improve productivity. Due to the nature of the process, it is also important to note that any change or improvement on productivity should be considered holistically and be efficient, as increases are usually in the range of 5 to 10%. The research looked at various productivity improvement tools including lean, six sigma, kaizen, and applicability of these tools. The research that has already been done on productivity improvement were also investigated, with the aim of establishing what has not been covered, which revealed that productivity in the mineral processing industry has had less research. Improvement tools applicable to the gold processing plants were then investigated and recommendations made on implementation of such.

Keywords
Productivity, Reliability, Availability, Productivity, Mineral Processing

1.Introduction
Production is one factor that is available in every industry and in the mining industry it is all about the amount of product, usually semi-processed which is achieved within a specified period. In gold mining, the amount of gold processed from the production plant is usually stipulated in ounces and is a representation of the input into the plant as well as the effectiveness of the classification process. Countries like South Africa, Tanzania and Ghana are major plyers in the gold mining business and as such each country aims to obtain maximum benefit from this giant economic contributor. However, there is need to proper governance to control and regulate the mining so that it benefits the country and the locals where the operations take place. Increasing production of this precious mineral therefore positively affects the nation (Elbra 2017).

Employing mining design and processing techniques is critical to boosting productivity in the mining sector (Lynn and Hanson 2015). This helps in reducing use of manpower thereby shortening process time. New technology has brought about simpler ways in condition monitoring and equipment reliability monitoring techniques. One such technology is called Synetrex condition monitoring system develop by Weir group. While modern technology helps to improve and maintain production levels, the area of equipment capabilities was not addressed by this author. Acquiring international assistance in terms of technology is also vital for productivity improvements.

The gold mining and processing industry in Tanzania is growing and quite competitive due to availability of ore that bears the precious metal around the country, with Barrick Gold having two major mines in operation in the country. To maintain their position as one of the top gold producers in Tanzania, continuous improvement is key. The researcher is involved in these operations as a service provider in the field of mining equipment supply and specialist services, mainly on the pump and pumping solutions. This therefore availed the opportunity to the researcher to be part of the productivity improvement research It has appeared to the researcher that while the management might be focusing on getting more throughput, they might omit vital considerations in terms of equipment capabilities. This is mainly because not all top-level management comprehend the engineering side of running the processing plant. The omission(s) will have an effect of the intended production throughput and might lead to the bottlenecks downstream.

The mineral processing plant that the study was conducted on has two mining locations the ore is transported to the gold processing plant using heavy haulage trucks. The plant then processes the ore to produce the final product using the Carbon in Leach process (CIL). The mine has been operating at a production rate of feeding an average of 105 tons of primarily crushed ore per hour into the processing plant. In a quest for continuous improvement, the mineral processing plant has decided to increase the production throughput to an average 120 tons per hour feed to the plant. This has necessitated the need to investigate the processing equipment capacities and capabilities so as to establish what modifications and upgrades need to be done to achieve the production increase. The company is already at an advanced planning stage for the productivity improvement projects hence this study is critical for the purposes of budget allocation and project planning. This research should highlight the most viable tools applicable to mineral processing plant and should benefit the company by enabling the implementation of continuous improvement strategies to achieve required throughput and can be duplicated to other plants. The mineral processing plant is also involved in numerous community development projects in the region where its operating. These includes supply of clean water to the surrounding community, building of schools and assisting with education material for the schools. By increasing productivity at the mine, it enables the organization to continue with these community beneficiation projects.

1.1. Objectives

The objectives of this study are to:

- gain a thorough understanding of the current production throughput and the equipment running parameters
- determine the bottlenecks to throughput increase
- establish the best continuous improvement tools to achieve the desired production with minimal cost

2. Literature Review

Production is one factor that is available in every industry and in the mining industry it is all about the amount of product, usually semi-processed which is achieved within a specified period. In gold mining, the amount of gold processed from the production plant is usually stipulated in ounces and is a representation of the input into the plant as well as the effectiveness of the classification process. Countries like South Africa, Tanzania and Ghana are major plyers in the gold mining business and as such each country aims to obtain maximum benefit from this giant economic contributor. However, there is need to proper governance to control and regulate the mining so that it benefits the country and the locals where the operations take place. Increasing production of this precious mineral therefore positively affects the nation (Elbra 2017).

Vanek et al. (2015) mentioned that, for continuous improvement, there has to be a change in managerial approaches consistent with changing technological and economic systems. Changes that come like this project at The mineral processing plant are considered as sudden and fundamental since they require a substantial amount of investment. This then means the outcome should also reflect the investment injected. Singh and Singh (2015) studied the various ways implementation for continuous improvement and the evolution that has been happening to this methodology.

However, the research was not specifically for the mining industry hence it did not have the depth within the mining field. There are several success factors for continuous improvement projects, Aleu and Van Aken (2016) identified more than fifty of these factors and looked at their success levels on different organisations and projects. There has been various evolutions and improvements on CI methodologies, one of the main ones being the Six Sigma-Lean-Lean six sigma. The researcher feels these methodologies have not been applied sufficiently in the mineral processing field and therefore would like to have a deeper look into the possibilities of these tools being a success in mining.

Employing mining design and processing techniques is critical to boosting productivity in the mining sector (Lynn and Hanson 2015). This helps in reducing use of workforce thereby shortening process time. New technology has brought about simpler ways in condition monitoring and equipment reliability monitoring techniques. One such technology is called Synnetrex condition monitoring system develop by Weir group. While modern technology helps to improve and maintain production levels, the area of equipment capabilities was not addressed by this author. Acquiring international assistance in terms of technology is also vital for productivity improvements.

Research has also shown that there is still more that can be done in utilising the correct equipment for the right applications in the mining industry. Global average equipment effectiveness has been established to be 69% in the crushing and grinding sections (Durrant-Whyte et al. 2015). This indicates that equipment utilisation can still be improved thereby improving productivity, especially in this era of lean manufacturing. Through the use of a lean principle, Value Stream Mapping, results have shown that production lead times can be significantly reduced, e.g., from 8.5 days to 6 days while value added time decreased from 68 to 37minutes (Rohani and Zahraee 2015). Lean manufacturing mainly seeks to reduce waste, which automatically translates to improved productivity. While there is a lot of waste that occurs in mineral processing due to spillages, their impact on the overall productivity is very minimal, since there are recovery systems in place in form of sumps that collect spillages, and these are then pumped back into the process.

Durakovic et al. (2018) observed that lean manufacturing tools puts organisations at a competitive advantage, and also mentioned the versatility of the tools to different industries. The effectiveness on implementation was what distinguished the success of the tools within different organisations and the level to which the personnel in the organisation understood lean manufacturing. This translates to then fact that even in mineral processing organisations, if implemented effectively, lean manufacturing tools can enhance productivity and minimise operational costs. Palange and Dhatrak (2021) also reiterated the importance of lean manufacturing in enhancing productivity in manufacturing industries. The most important factors according to the two authors is having the right lean manufacturing tool, realistic data collection. Some of the benefits of correct implementation of lean principles include but not limited to, improved productivity, more organised work environment and minimal down time. This will ultimately lead to reduced manufacturing costs which is the main objective of lean manufacturing. The researcher observed again that the observations are more directed to other manufacturing industries besides the mineral processing, hence the decision to look at lean manufacturing in mineral processing.

DMAIC is used for optimization of business processes and is applicable to other methodologies over and above the lean six sigma. The steps are:

- **Define:** the problem the process is facing must be clearly defined to be able to understand what needs to be done. In this case the mine is facing a productivity deficit which needs to be covered
- **Measure:** establish the process parameters. The running parameters for the processing plant must be gathered and they indicate the current status quo
- **Analyze:** have an investigative look into the process data to establish the bottlenecks and causes thereof. The production data and equipment data indicate the production achieved and the equipment capabilities, especially the grinding circuit machines namely the mills, pumps, and hydro cyclones.
- **Improve:** implement process improvement methodologies in line with the challenges observed. The researcher looked at the probable productivity improvement tools applicable to the mineral processing plants, especially the gold plant.
- **Control:** the improved process needs to be governed for consistence and to be able to improve from there in the future

The involvement of machine operators and the maintenance personnel in ensuring improved equipment availability is the core of Total Productive Maintenance (TPM) (Agustiady and Cudney 2018). The operators of equipment are on the ground always and are usually the first to notice an anomaly with the machine, after which they will report to the maintenance department. This set-up applies to almost all manufacturing and processing industries, though with improved automation in the recent years, problems are also reported remotely through machine intelligence. Having the operators as part of maintenance activities enhances effective machine maintenance and reduces the probabilities of unplanned stoppages.

TPM is a holistic maintenance approach that involves all personnel working with or around equipment. Figure 1 below shows an example of a maintenance instruction from the Original Equipment Manufacturer which is quite instrumental in achieving TPM. Another way of promoting TPM on the mineral processing plant is the carrying out of Root Cause Failure Analysis (RCFA). This is when investigations are done to find out the cause of equipment failure and it's also another form of Failure Mode and Effect Analysis (FMEA). The most common wat that the mine is currently using is called the "five whys" where the why are basically asking why a particular failure happened. Attached is the RFCA form in use. The analysis is critical in TPM in that it helps to identify the failure trends and hence the possible solutions, if recurring failures occur on the same equipment, a FMEA, if done correctly, should unveil the most probable causes and the applicable solutions to the challenge. The RCFA process follows the following steps.

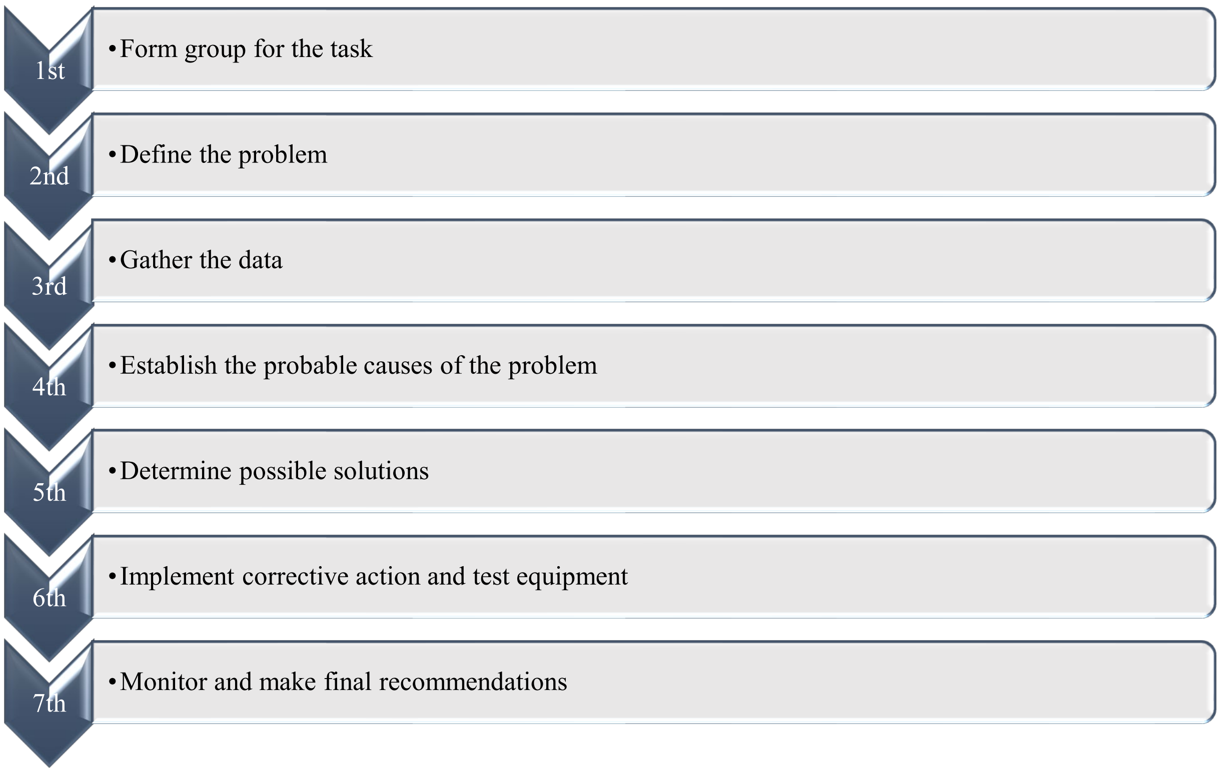

Figure 1. The RFCA process

3. Methods

The study necessitated the use of a quantitative study approach since equipment and process information was the critical information in determining the best solution. However, a bit of qualitative information was necessary to complement the quantitative information. This data was obtainable from the process plant control room and the plant planning department. MJ Goertzen (2017) reiterates the fact that statistical analysis of quantitative data is made effective by the accuracy and reliability of the information gathered. It is therefore imperative that data is obtained from reliable sources, which in the researcher's case was through the SCADA system information.

The following are some of the advantages of quantitative research and the reasons why the researcher decided to employ it.

- ❖ The research can be repeated, and the same data gathered again
- ❖ The information can be shared, and similar information produced
- ❖ The results can be considered to represent similar situations, like a similar gold processing plant with similar equipment and similar ore will give more or less the same data
- ❖ The outcome can be applied to replicate circumstances

4. Data collection

In this research the quantitative data gathered include production figures, equipment parameters. The qualitative data includes the input of the operators and maintenance personnel which is vital especially when it comes to Total Productive Maintenance. It is imperative to also look into the process facilities layout, as this also has an effect especially on the processing time. The layout involves a of conveyer belts, which however does not negatively affect the processing times but determine the quantity of ore to be transported at a particular instance. Other data collected include tonnage feed to the processing plant and feed from the Run-Off Mine (ROM) to the processing plant. The ROM is done by use of apron feeder and rubber conveyors, passing through secondary and pebble crushers both reducing the size of the ore. This throughput goes through the processing stages until the gold is extracted and the residue (tailings) is pumped to the Tailings Storage Facility (TSF). The feed is measured in tonnes per hour and is the main contributor to the ounces produced over a specified time. The mine has been running at 405 Tonnes per hour of dry ore being fed into the SAG mill. To improve productivity, this rate will also have to be increased.

5. Results and Discussion

Given that the mine management and stakeholders always focus on upping the throughput, the need to investigate and implement continuous improvement tools is critical for the present as well as future benefit. The mining houses needs to apply a holistic approach to effectively address productivity increase. Productivity improvement is more effective when the correct areas are addressed, and the right resources used. Digital innovation is one of the tools that can significantly improve productivity in the mining and mineral processing industries (Durrant-Whyte et al. 2015). With the advancement in technology in the current revolution, technology is making industrial operations quicker and smarter with minimal human interaction. Productivity improvement can be in the following was: Process improvement, Equipment upgrades, Resources improvement and Cost Management. As investigated earlier, the following factors need to be considered when implementing productivity improvement in the gold processing plant.

5.1. Continuous Improvement

An organisation that stays stagnant losses its competitive advantage and subsequently its market share. In the mineral processing field, new hydro cyclones are being introduced which are more efficient in the classification process and are also durable. New slurry pumps with rubber lining technology and throat bush adjustment system avoid the replacement of the more expensive metal casings and the traditional adjustment of the bearing assembly which posed a safety risk. Electrical drive systems are being modified to eliminate chances of unexpected equipment shut offs, and therefore clear warnings are sent to the concerned personnel either through texts to cell phone or emails.

These changes contribute towards improved productivity. The processing plant in question should aim at adapting these changes for the betterment of the production figures. Embracing technology is also inevitable if a mineral processing plant needs to achieve Total Productive Maintenance. Condition monitoring systems assist in capturing live data if equipment health and thereby making it easy and quick to be able to analyse information and take immediate action where necessary.

5.2. Bottlenecks

Figure 2 below shows the process flow shows the main equipment and their capacities. This clearly indicates that the cyclone feed pumps (410T/Hr) are the bottleneck in the process when only capacity is considered. While the SAG mill can handle 420T/Hr, after the grinding the pumping of the slurry will not be achievable due to the equipment limit. Therefore, to produce within equipment capacities, the operations department would have to run the operation at the capacity of the cyclone feed pump. This then implies that there is need to upgrade the pumping system so as to be able to increase feed and production. When other equipment has to be upgraded, like mills and hydro cyclone clusters, there is a lot of design and cost factors that have to be considered. Since the equipment is at an elevated platform, the structural layout is affected by any modifications hence feasibility studies have to be carried out first. The structural strength can also be a restriction to equipment upgrade or feed increase to the equipment. The conveyors and conveyor structures must be taken into account whenever the load they carry has to change. This however does not affect the mineral processing plant as the design of the current equipment was overdesigned in anticipation of future adjustments.

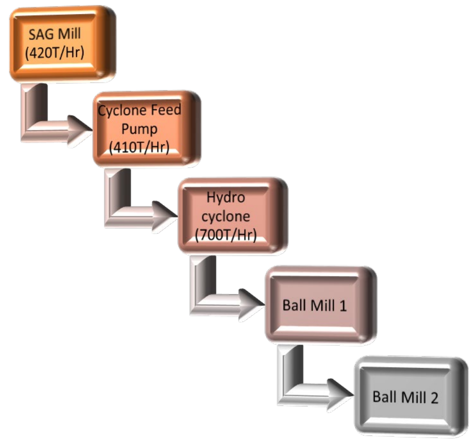

Figure 2. Process Flow for the main equipment

5.3. Equipment upgrades

There are three options when it comes to equipment improvement which are upgrading, replacing, and adding. The choice now is determined by the comparison of the cost involved against the benefit to be realised. The figure 16 below shows a system used to perform a pump duty calculation when selecting a pump for a particular application. This ensures that a pump selected is capable of performing the duty for which it is installed. All the details of the system set up are considered, which include the pipework and the tanks associated with the pump. When a correct size and type pump is selected and installed, pumping efficiency will be high thereby contributing to improved productivity. A change from the current 350MCR pump to the 400MCR pump constitutes an increase in maximum achievable flow of 30% (2800m3/hr to 4000m3/hr). This will leave the mine with more room for further expansion in the future with the same equipment.

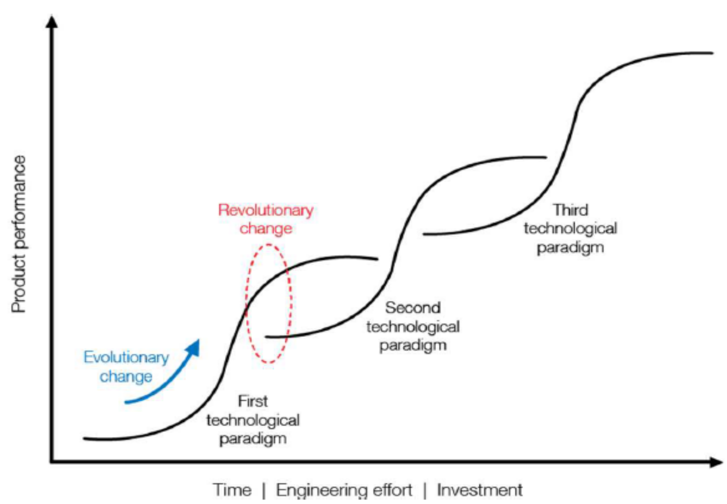

Figure 3. S Curve of product performance . Source: Juan Cols

Figure 3 above indicates the stages that a product goes through during operation where technological advancements keep the product in operation by improving its performance in line with other products/equipment. In the mineral processing plant, this applies to the equipment used in the process where if the organisation keeps a piece of equipment for far too long, it begins to struggle to meet operational needs. A good example is in pumps where the mine was using 14/12 AH pumps and later upgraded to the MCR pump, which had been developed from the same 14/12 pump principle and improved to best suit mill circuit operations. The first pump can be considered as the 1st technological paradigm and the MCR pump the 2nd. Most probably there will be an advanced model from the MCR pump at a later stage and this will be the 3rd paradigm. This equation helps in pump selection as the selected pump should overcome the static head and the frictional energy loss.

Darcy Equation:

$$Hf = fLv2/ 2Dg$$

Where,

Hf	=	Head loss (Frictional)
f	=	Darcy friction Factor
L	=	Pipe Length
D	=	Diameter of pipe
V	=	Average Velocity
g	=	Gravitational acceleration

For the cyclone feed application the flow rate is measured using a flow meter and averages 1800m3/hr, converting to m3/s.

1800 ÷ 3600	=	0.5m3/s	
To find v, Q	=	Av	
Pipe diameter D	=	400mm	
Therefore Area A	=	π x 0.22	
		=	0.12568m2
V	=	Q/A	
	=	0.5m3/s ÷ 0.12568m2	
	=	3.978m/s	

Hf	=	fLv2/ 2Dg
	=	(0.02 x 30 x 42) ÷ (2 x 0.4 x 9.81)
	=	1.22m

So the pumping system will be experiencing a head loss of 1.22m, which is considerably reasonable with the duty the pump is doing. This will also be slightly reduced if the equipment is upgraded, and the pipework is changed to a larger size. The third main equipment to be looked at will be the hydro cyclone. This is a cluster of usually twelve cyclones assembled around a central overflow and underflow pipes. Due to the fact that the mine is only utilising half of the capacity of this equipment, an increased feed would work well in increasing cyclone utilisation. The engineering team should also look at installing condition monitoring instruments onto the pumps and cyclones which can be monitored remotely. This will enhance worker safety and convenient way to obtain and analyse machine condition. Earlier it was mentioned that lean manufacturing emphasizes on waste reduction and six sigma focuses more on defects minimisation. The combination of the two have pros that far outweigh their cons when implemented by an organisation. However, management involvement is also key to the success of this methodology. It has been observed during the research that sometimes there is accumulation of bearing units that have failed bearings which would have been removed from the pumps. These units can be refurbished by replacing the bearings and seals thereafter they will be just as good as new and can be reused on the pumps. This is a great step in waste reduction by recirculation. It is also a great cost saving measure and ultimately leads to improved productivity due to reduced process cost.

The implementation of JIT principles on all possible spares and equipment largely reduces cost by minimising inventory and elimination holding costs. In the case of North Mara, larger equipment such as pump, screens and hydro cyclones have always been delivered on a JIT principle. With proper planning, rubber material like liners and lining rubber for valves and pumps can also be delivered when about to be used. This is to avoid degradation if stored in open spaces where there is exposure to the sun or any other adverse weather conditions.

5.4. Overall Equipment Effectiveness (OEE)

This is generally the product of availability, performance and quality. OEE also indicates the use of the equipment up to its maximum capability, unlike efficiency which defines the useful work performed by a machine in comparison to the resources/energy consumed. Stamatis DH, 2017 recons system effectiveness can be said to be the numbers that show the level to which it performs against its intended best purpose.

Performance in this study is the times when the machine was reaching the expected running parameters against the total time in operation over a monthly period. The Mill performance was established to be 96%

Quality is this regard can be calculated as the amount of ore (slurry) exiting the mill to the pumps against the amount of ore fed into the mill. This is because there is always bad quality ore that can't be ground to the required sizes and is therefore expelled from the mill back to the pebble crusher. This has also been established to be averaging 98%

OEE = Availability x Performance x Quality
Mill OEE = 96.77 x 96 x 98%
= 91%

This is the effectiveness of this particular machine, however the OEE for the whole processing plant involves the various machines to include the pumps, hydro cyclones and ball mills. This measurement is very critical as it indicates the productivity of the processing plant as it involves the quality of the product as well. The higher the OEE, the better the productivity of the process. In essence the higher the availability, performance and quality, the better the productivity will be. It is therefore vital that the engineering and operations teams improves the OEE by implementing policies that enhances the three contributors to effectiveness.

6. Conclusion and Recommendations

6.1. Preventive maintenance

This aspect is considered to be the most effective and employed by many organizations. Maintenance is scheduled based on runtime. Each equipment is then stopped, and maintenance work carried out as per schedule. The scheduling is usually standardized and what changes is the scope of work, where additional issues have been picked. The mineral processing plant is also using this type of maintenance, with a single grinding circuit stoppage per month and most equipment in the section is then maintained. If executed effectively, preventive maintenance minimises unplanned equipment down time and the process plant has been realising the benefits. The researcher however feels TPM is not incorporated in this type of maintenance as mainly the engineering personnel carry out the work. The operations team could be involved in relatively simpler tasks like changing of valves and gaskets. This will assist during the running of the plant as the operators will have a basic understanding of the engineering side of the plant.

Predictive maintenance

The equipment healthy is monitored regularly by the condition monitoring technicians and data is recorded. Whenever the data obtained deviates from the standard, a closer monitoring is implemented and when the condition reaches the critical level, the equipment is stopped for maintenance. The mine has this type of maintenance in place, however the coordination with the maintenance and operations teams is weak hence sometimes unplanned downtime occurs on equipment that the CM technicians have recommended for immediate maintenance. When TPM principles are implemented, all departments work together for the betterment of maintenance activities.

6.2. Corrective maintenance

This happens when an equipment is faulty or has already broken down, also called breakdown or reactive maintenance. This type of maintenance needs to be avoided or reduced to the minimum possible since its affects production. The plant must be stopped for the machine to be repaired. At North Mara, they have managed to install standby units on most of the pumps. This assists in reducing downtime as when an equipment develops a fault, the standby unit is started up and then the faulty pump stopped for repair. This then avoids plant downtime, however it's not possible with the larger machines like the mills. The hydro cyclone is also another machine with options for countering breakdown maintenance because it has 12 cyclones and usually uses six, meaning if one develops a problem one standby one is opened and the problematic one shut off for maintenance. There is also the option of running one ball mill if the other one has a problem thereby avoiding total shutdown. In this case the mill feed must be reduced to a quantity safe for one mill. TPM also aims to reduce these stoppages whether there is a standby unit for the same application or not.

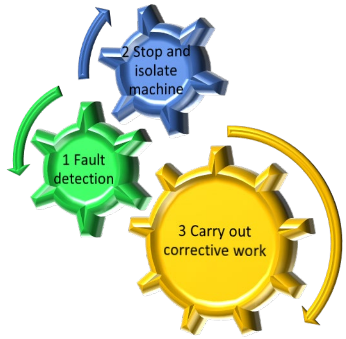

Figure 4. Corrective Maintenance Steps

TPM implementation is a gradual strategic process that brings numerous benefits, and there is also challenges that include having to bring the operations team to understand the value of them being part of maintenance activities. This is because the operators are using to be relaxing when its maintenance time. There is also need for basic training to non-engineering workforce in the process plant.

Total Quality Management

Quality is a critical part of an operation, and the effective implementation thereof positively impacts productivity. The process plant does not have a Quality department but do have metallurgists for monitoring the quality of the final product and processes. The researcher believes there should be a quality department that focuses on quality in the process flow and more on the engineering side of the process. The researcher has gathered that sometimes machine spares are delivered only to find out later during machine repair that the spares don't fit. This then affects the time of bringing the machine back into service. This can be simply avoided by having quality control team that checks all equipment and spares on delivery and confirms usability. It should however be noted that implementation of TQM comes with its own challenges, especially due to the general resistance to change that is found in most operations.
When it comes to procurement, most organisations are now having a person titled "supplier quality controller" who is there to ensure new spares and parts are fit for use and of the correct quality before being accepted into the warehouse. Most organisations attach a quality control sticker on their products as a sign that it has passed through a quality control process and passed. Proper storage practices also assist in reserving parts quality while waiting for use.

6.3. Lean Six Sigma

Waste elimination and process optimisation are great contributors to increased productivity. For effective implementation of Lean six sigma principles, the mine would have to engage qualified personnel for this activity as currently there is no such personnel. There is still a lot of waste that needs to be eliminated from the process system and also improvement on process optimisation The researchers also deduced that a holistic approach to the improvement objective would make the mission successful. It takes every employee's effort and understanding for productivity to improve; therefore, the change managers should ensure the goals and objectives are communicated clearly to the whole organisation and encompasses all the departments of the organisation from engineering, finance, procurement, operations and projects.

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Biographies

Prof Kem Ramdass has worked as a work-study officer, industrial engineer, production/operations manager and skills development facilitator in the clothing, electronics, and textile industries between 1981 and 1999. He joined the academic profession in 1999 as a lecturer with Technikon South Africa. He later moved to UNISA’S Department of Business Management in 2006 lecturing in operations management. He is currently a Professor in the Department of Industrial Engineering based as Unisa, Florida Campus. He has a passion for quality and firmly believes that the application of quality management methodologies will highlight deficiencies and instigate the implementation of improvement strategies. He has applied continuous improvement methodologies from an industrial engineering, quality, and operations management perspective. He is a process, performance and operations specialist with a driving passion for improving production, quality and competitiveness. He has authored and presented approximately 50 journal and conference papers both nationally and internationally and is a peer reviewer for numerous publications. He has achieved Fellow member status at SAIIE and is a member of PICMET and IEEE. He is registered as Pr Tech Eng at ECSA and is appointed as a member of the Code of Practice Steering at ECSA.

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