Overall equipment effectiveness optimisation for a reserves constrained underground coal mine in South Africa

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Abstract

The aim of the research is to investigate factors that optimize Overall Equipment Effectiveness (OEE) of an underground Bord and Pillar coal mine that has limited coal reserves and unfavorable geological conditions. The mine consists 10 CM sections, mining both high and low seams with equipment-suits that comprises the Continuous Miner (CM), Shuttle Cars, Feeder Breaker, Conveyor Belts and Roof Bolter. Three elements making up the OEE equation (Availability, Performance Rate, Quality), are reviewed to establish factors that influence OEE improvement. The research paper employs deductive, quantitative research methods, analyzing 18 months performance data. The main source of data is the mine's Enterprise Resource Planning (ERP) system. Average OEE figures are 45%. Quality and productivity rate figures are 85% and 103%. Availability figures average 52% and presents opportunity for OEE improvement. Geological conditions inherently contain mining inefficiencies leading to losses of direct operating hours (DOH), which affects the availability component of OEE. OEE improvement results are obtained through analysis of CM sections that have shown a positive shift in OEE performance. The results demonstrate that DOH improvement leads to optimized equipment uptime, thereby increasing availability. DOH improvement is achieved through effective operational downtimes management and good equipment maintenance management practices.

Keywords
Overall Equipment Effectiveness (OEE), Bord & Pillar Coal Mining.

1. Introduction
The current outlook in the mining sector has been challenging with the evident drop in commodity prices leading to downscaling and a lack of capital investment in Greenfields and Brownfields mining projects. The situation has forced mining companies to review current maintenance and productivity related practices to maximize the Return on Capital Employed (ROCE) of existing assets. A review of current industry's best practices on OEE improvements, underground Bord and Pillar coal mining layout and equipment-suit deployment is key in addressing productivity challenges and constrains on a Bord and Pillar coal mining operation. The research case is for an underground coal mine that consists of two shaft complexes that comprises 10 continuous mining sections which employ the conventional Bord and Pillar extraction method to produce thermal coal. The current mining challenge is the decline in CM productivity which comes as a result of reduced underground mining coal seam height and poor geological conditions. These constraints lead to lower productivity and higher mining cost per ton. The one method used for realizing productivity objectives in a Bord and Pillar coal mining operation is through measurement and optimization of OEE (Hedman et al. 2016)

The mine has 10 CM sections that consist of 2 Seam and 4 Seam mining operations which has varying seam height, different seam thickness and parting/ Dyke intersections with inherently difficult geological conditions. The research paper investigates answers to the following questions:

- At a Bord and Pillar multi-seam operation, what is the optimal equipment-suit deployment required to ensure maximum productivity?

- What are key factors that can improve the equipment-suit's OEE of a reserve constrained Bord and Pillar operation?

2. Literature Review

In South Africa, coal was first mined on a commercial basis in 1857 and South Africa is currently the 6th largest producer of coal worldwide. The two types of underground coal mining are the conventional mining system and continuous mining system. Continuous mining is the most common form of underground coal mining method and accounts for about 60% of world production (Hancox and Gotz 2014). The mechanized machine used on a Bord and Pillar operation is a continuous mining machine. The CM is a self-propelled machine that cuts into the full thickness of the coal seam by following a series of Rooms and leaving solid support Pillars in development panels (Ghasemi et al. 2012). The CM's cutting operation and movement has to be properly coordinated as the Conveyor/ Shuttle Car has to permanently follow the CM to enable a continuous efficient mining process (Beitler et al. 2013). OEE as a concept for measuring progress achieved through improvement initiatives in Total Productive Maintenance (TPM), was first introduced and pioneered by Nakajima (Hedman et al. 2016). Gibbons (Gibbons and Burgess 2010), describes OEE as a measure of using resources while focusing on maximizing Production Equipment Effectiveness (PEE) by delivering high amounts of capital productivity in organizations. Companies use OEE for internal performance improvements and benchmarking purpose with the intention of identifying underperforming pieces of equipment for TPM focus (Jain et al. 2014). OEE is an indication of a system and its subsystem's capacity. The three factors making up the OEE equation (Availability, Production Rate, and Quality) can have their impact measured by estimating each element's contribution to a production system (Tang 2019). OEE enhancement is achieved by minimising equipment downtime (availability increase), decreasing rework and rejections of material produced (quality increase) and speed losses occurring from process related activities (performance rate increase). TPM is the best maintenance strategy for improvement of OEE on production equipment through the three major parameters (availability, performance and quality rate) which are critical in calculating OEE (Saleem et al. 2017). Vilarinho (Vilarinho et al. 2017), further describes TPM as a maintenance management methodology consisting of eight pillars of which one of the pillars focuses on improvements in equipment and processes, this pillar forms the basis of the OEE indicator.

The fundamental building blocks of OEE, as a performance indicator, is to improve and sustain equipment efficiency (Hedman et al. 2016). OEE is widely used as a quantitative tool used for productivity measurements. The primary aim of OEE is to identify and eliminate losses in a manufacturing environment (Heng et al. 2019). OEE is generally computed as a product of Availability Efficiency, Performance Efficiency and Quality Efficiency (Garza-Reyes 2015). The world class OEE ranges between 85% and 92% for non- process industries (Andersson and Bellgran 2015). In the manufacturing industry, the figure is reported to be around 50% while the world class figures are known to be in the 85% range (Ylipää et al. 2017). To achieve real production availability that is essential to meet customer demand, the optimal OEE figure must reach an average of 86% (Antonioli et al. 2017). The desired values for OEE measures are 1) availability over 90% 2) performance efficiency over 95% and 3) quality rate over the 99% mark (Mansour et al. 2013). OEE is used to measure effectiveness of a single piece of equipment or a pieces of equipment that function collectively on a manufacturing line. It is usually used for evaluating performance of the most problematic pieces of equipment in an organization (Wudhikarn 2016). OEE identifies losses by taking into account the six big production losses and categorize them into 3 efficiency baskets known as downtime losses, speed losses and quality losses (Foulloy et al. 2019). Figure 1 shows the six big production losses used for the computation of OEE.

Downtime losses are used to determine actual availability values of a machine. Speed losses determine the performance rate of a machine which are a result of a machine performing at less than its optimal condition. Quality losses determine the quality rate of a machine by measuring defects produced (Hedman et al. 2016).

Availability is the ratio between actual production time and scheduled production time (Anvari et al. 2010).

$$\text{Availability (A)} = \frac{\text{Planned Production Time} - \text{Downtime}}{\text{Planned Production Time}} \text{ x } 100 \qquad (1)$$

Performance Rate (also known as Operational Efficiency) is the ratio between expected and actual production of a machine over a specified time (Anvari et al. 2010).

$$\text{Performance Rate (R)} = \frac{\text{Design Cycle Time x Produced Amount}}{\text{Actual Running Time}} \text{ x } 100 \qquad (2)$$

Quality is an indication of the amount of defective units produced against the total volume produced It is the quantity of produced items that fit the correct specification (Anvari et al. 2010).

$$\textbf{Quality Rate (Q)} = \frac{\textbf{Produced Amount} - \textbf{Defect Amount}}{\textbf{Produced Amount}} \textbf{ x 100} \tag{3}$$

OEE is the result obtained when multiplying the three factors of availability, performance rate and quality rate

$$\textbf{OEE} = \textbf{Availability x Operational Efficiency x Quality Rate} \tag{4}$$
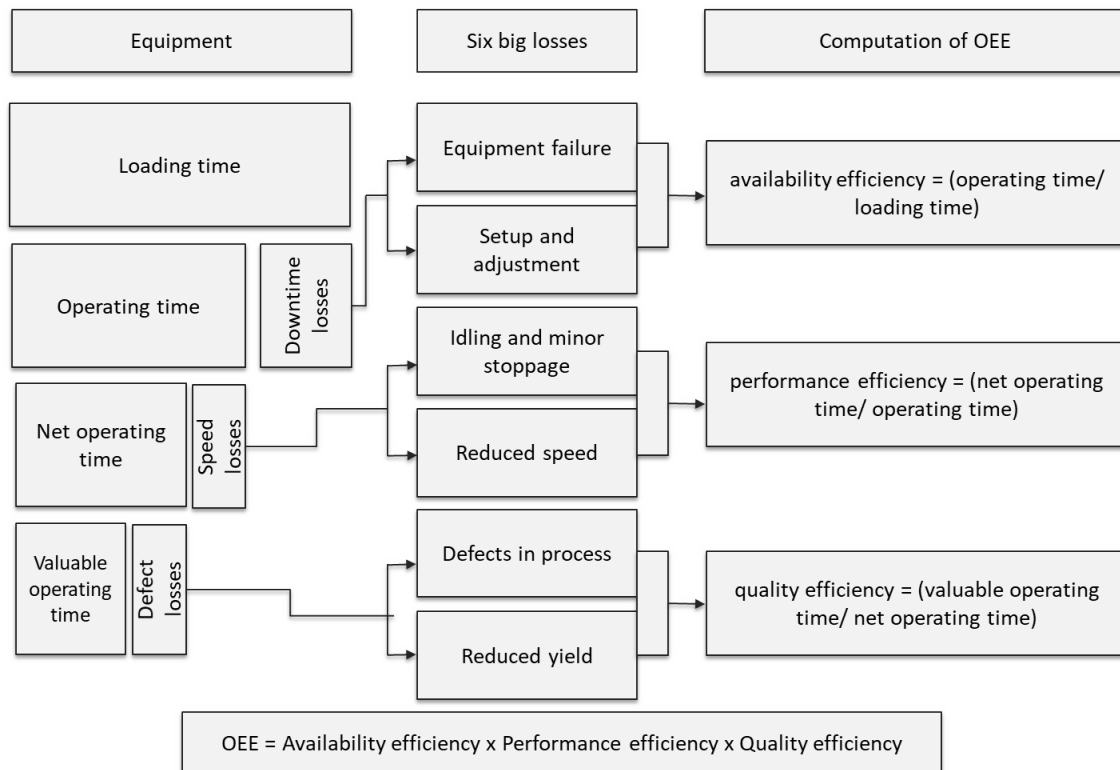
Figure 1. Six equipment losses for OEE computation (Anvari and Edwards 2011)

The Time Model serves as a basis for measuring equipment performance data that is used for calculating OEE. Each element of the time model provides context on how it fits to the computation of OEE in a mining operational environment that is specifically being considered for this paper.

Table 1. Time Model: (source: AATC – S – AM001)

Total Calendar Time			
Total Controllable Time (TOCO)			Non Controllable Time
Uptime		Equipment Downtime	Non Scheduled to Produced
Direct Operating Time Primary Production Secondary Non Production	Lost Time Delays Standby Consequential	Scheduled Maintenance Unscheduled Maintenance Production Stoppages	Uncontrollable Events

The use of variables from the Time Model, enables the evaluation of equipment-suit performance by setting up an equation that defines the OEE measurement. The various equations for computing OEE are detailed below:

UEA measures of amount of time, the equipment is utilised when it is available for production.

$$\text{Use of Equipment Availability (UEA)} = \frac{\text{Direct Operating Time (DOH)}}{\text{Uptime}} \text{ x } 100 \tag{5}$$

Equipment Availability (EqA) measures amount of time the equipment is available for production

$$\text{Equipment Availability (EqA)} = \frac{\text{Uptime}}{\text{Total Controllable Time}} \text{ x } 100 \tag{6}$$

Availability is an indicator of how much of available time is utilised for production

$$\text{Availability (A)} = \text{Use of Equipment Availability (UEA) x Equipment Availability (EqA)} \tag{7}$$

Production Rate (PR) is the ratio between expected and actual production of a machine over a specified time

$$\text{Production Rate (PR)} = \frac{\text{Production Material}}{\text{Primary Production Time}} \tag{8}$$

Quality Rate is the measure of actual coal qualities produced over the targeted planned qualities

$$\text{Quality Rate (Q)} = \frac{\text{Actual Quality}}{\text{Tartget Quality}} \tag{9}$$

OEE is the measure of how effectively the equipment is utilized

$$\text{Overall Equipment Effectiveness (OEE)} = \frac{\text{Actual Production Rate}}{\text{Target Production Rate}} \text{ x Availability x } \frac{\text{Actual Quality}}{\text{Tartget Quality}} \tag{10}$$

3. Underground and Pillar Equipment-suit Results

Mining equipment-suits consists of a continuous mining machine that extracts coal by cutting rooms in a predefined pattern and then leaving pillars that act as primary roof support underground. Coal then gets loaded onto Shuttle Cars for transporting material to the Feeder Breaker, where it gets crushed to suitably sizable lumps that enable easier transportation on conveyor belt (see Figure 2 below).
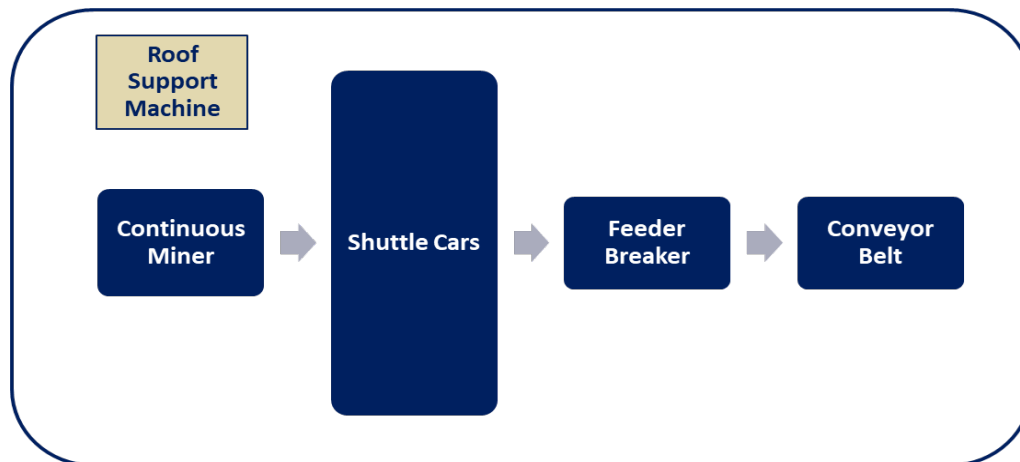

Figure 2. Bord and pillar equipment-suit

The mine has a strategy of mining the higher seam mining suit and lower seam mining suit for both the North and South Shafts. The North shaft consists of 6 sections with one section on 2 Seam and the other 5 sections on 4 Seam. All of the 4 sections in the South Shaft consist of 4 Seam. The higher seam mining suite consists of a Continuous Miner rated for seam heights higher than 3.2 meters accompanied by three Shuttle Cars, a Roof Bolter and Feeder Breaker. The lower seam mining suite consist of a Continuous Miner and associated support equipment able to mine consistently down at average seam heights of 2 meters. The variation in the seam heights necessitates an equipment adaption strategy to ensure maximum productivity across the 10 CM sections. The correct equipment-suit is

determined by the mining application and technical specifications such as the established name plate capacities of the CM, Roof Bolters and Shuttle Cars. The equipment-suit deployment analysis is presented on Table 2.

All of the 10 CM sections are resourced with suitable machines for the seam height applications. The various CMs that are used in the 4 Seam, allow for ease of interchangeability as the CM's match the minimum and maximum seam height requirements. The cutter head widths are also suitable for cutting the required 7.2 meter standard bord widths to facilitate the correct mining layout. Only section N3 is on 2 Seam application and has limited flexibility on CM deployment. The Sandvik CMMC430 and Komatsu CM12HM37 CMs are suitable for use in 2 Seam applications. The roof support equipment-suit deployment is suitable across the 9 sections. The Roof Bolter in section N3 is not suitable for 2 Seam application. The incorrect application leads to inefficiencies and extended roof support delays. An HDDR 17C Rib access Roof Bolter may need to be deployed in the section with the same "T" Style TRS. The 14Ton Shuttle Cars utilised in section N3, are also not suitable for higher seam application. The 14Ton Shuttle Cars lead to reduced productivity rates and do not match the CMMC430 Sandvik CM.

Table 2. Equipment-suit deployment analysis

	OEM	Model	Section	Seam Height	Suitable
Continuous Miner	Komatsu (JOY)	CM12HM31AAA	Sec – S1, N1, N2, N4, N5	1600 - 3000mm	Yes
	Sandvik	CMMC430	Sec - N3	3000 - 4500mm	Yes
	CAT (Bucyrus)	CM35M	Sec - S2, S3	1584 - 3800mm	Yes
	Komatsu (JOY)	CM12HM37	Sec – S4, N6	2400 - 4500mm	Yes
Roof Bolter	OEM	Model	Section	TRS Type	Suitable
	Komatsu (Fletcher)	HDDR – 17	Sec - N1, N5, S1, S3	"T" Style	Yes
	Komatsu (Fletcher)	HDDR – 17C	Sec – N6	"T" Style	Yes
	Komatsu (Fletcher)	HDDR – 17C	Sec – N4	"L" Style	Yes
	Komatsu (Fletcher)	HDDR – 17	Sec - N2, S2, S4	"L" Style	Yes
	Komatsu (Fletcher)	HDDR – 17	Sec - N3	"T" Style	No
Shuttle Car	OEM	Model	Section	Min Seam Height	Suitable
	Komatsu (JOY)	10SC32 - 56C	Sec - N1, N4, N5, N6, S1, S2, S3, S4	2000mm	Yes
	Komatsu (JOY)	10SC22 - 56B	Sec - N2	1900mm	Yes
	Komatsu (JOY)	10SC32AB	Sec - N3	1600mm	No

4. OEE Improvement Results

The product of availability, production rate and quality results, make up the OEE figure. OEE as a measure of how effective the equipment is utilized, gets calculated by combining availability, production rate and quality rate as depicted on equation 10. The OEE results for all 10 CM sections are shown on Figure 3 below. The 18 months percentage availabilities across the 10 CM sections range from 48% to a maximum of 57%. The production rate is affected by geological conditions where ground undulations and roof conditions affect the mining sequence. The average productivity rate values for all 10 CM sections, are in the region of 85%. In the North Shaft, the section with the lowest productivity rate is consistently trending at an average value of 57% which equates to about 174 t/h. The average quality rate figures for both the North and South Shafts are 85%.
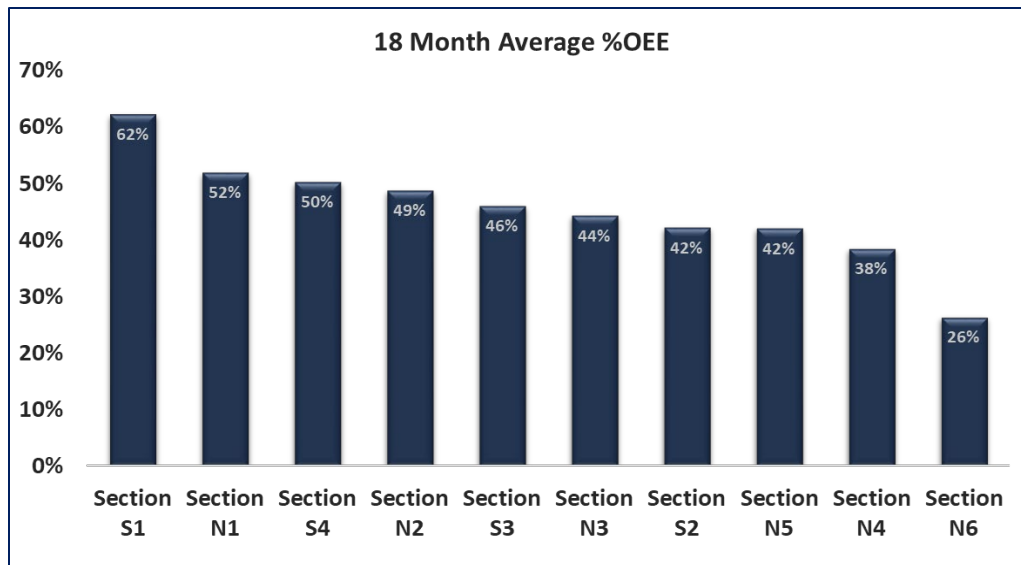
Figure 3. 18 months % OEE/ section

The OEE values across the 10 CM sections are at an average value of 45%. This is a norm for manufacturing industries where such values are reported to be in regions of 50% as opposed to the world class OEE figures of 85%. In order to establish factors for OEE improvement, an analysis is conducted on 3 sections that have values below the overall average OEE value of 45%. Each of the sections has demonstrated a positive shift in OEE at various stages along the 18 month period. The periods in months where a positive shift in OEE trend is seen, are demonstrated on Figure 4.
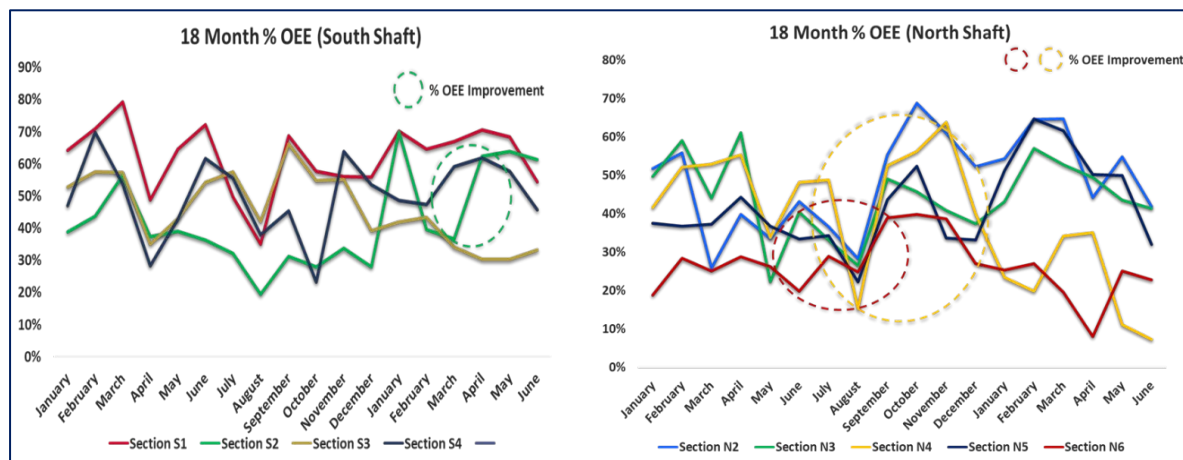

Figure 4. 18 Month %OEE (North & South Shafts)

(i)   Section N6 OEE Improvement Analysis

The N6 %OEE improves from 20% to 39% in a period of 4 months. In this time, the availability losses have a 22% improvement which is primarily a result of 60% downtime reduction in the changing of CM's cutter head picks and sleeves. Availability losses are also affected by a 150 hrs downtime from a Section 54 instruction which is issued by the Department of Minerals Resources (DMR) following a safety incident. The section also contains a 150 mm floating stone within the coal seam. The stone affected rates until the month of July and it is also evident through the Feeder Breaker consequential downtime (26 hrs) lost on the feeder drum torque shaft as a result of crushing stone. The high quality losses in July and August are both as a result of high moisture content.
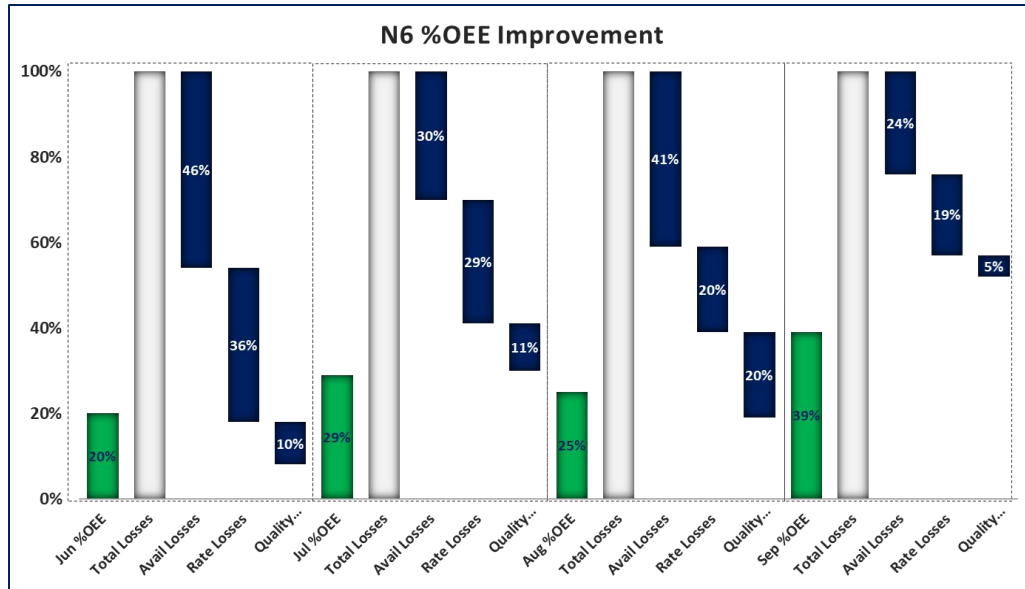
Figure 5. N6 %OEE improvement

(ii)   Section N4 OEE Improvement Analysis

The N4 %OEE improves from 15% to over 50% which gradually increases to 64% over a period of 2 months. In this time, the availability losses decrease from 56% to 13%. Consequential delays are also incurred as a result of Roof Bolter downtimes and the CM standing awaiting support. The Roof Bolter engineering downtimes are mainly due to hydraulic pipes and dust collector fan pumps, all of which accounts for 45% awaiting support downtime. The section also experienced an unplanned section move in the month of September. The high quality losses in August are a result of high inherent moisture content which also affected section N6.
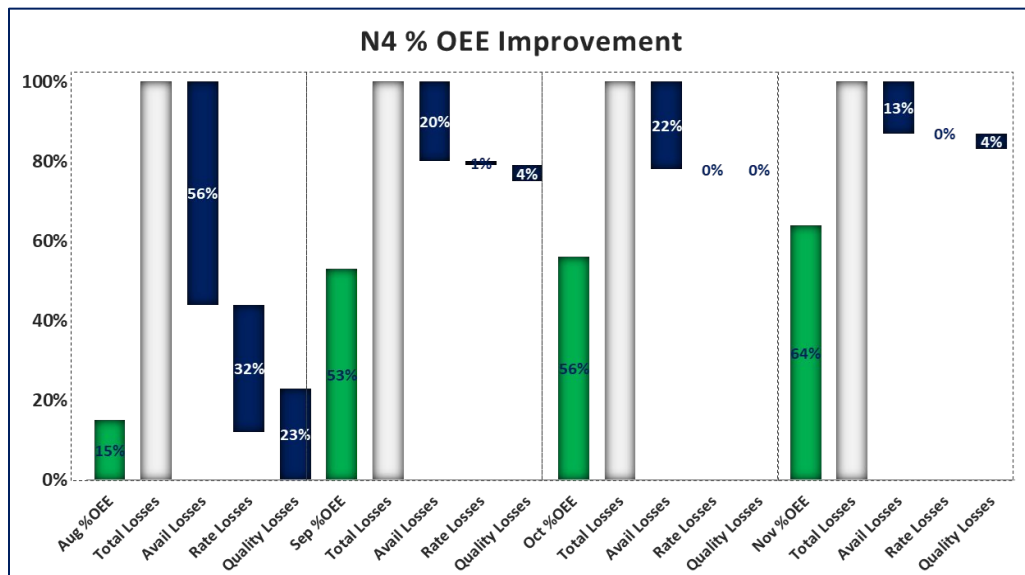

Figure 6: N4 %OEE Improvement

(iii)   Section S2 OEE Improvement Analysis

The S2 %OEE improves from 37% to 64% over a period of 3 months. In this time, the availability losses decrease by 50%. The availability losses are affected by engineering downtimes on the CM. The machine experienced a premature failure on a traction gearbox and a cutter head gear case. The two downtime events results in a total stoppage of 24 hrs on the gearbox and 17 hrs on the gear case. An RCA conducted on both machines points to excessive vibration & looseness on the cutter head and material defects on the non OEM traction gearing. The quality and productivity rates

are consistently trending in a positive direction during this specific period and they have no major effect on the %OEE improvement.
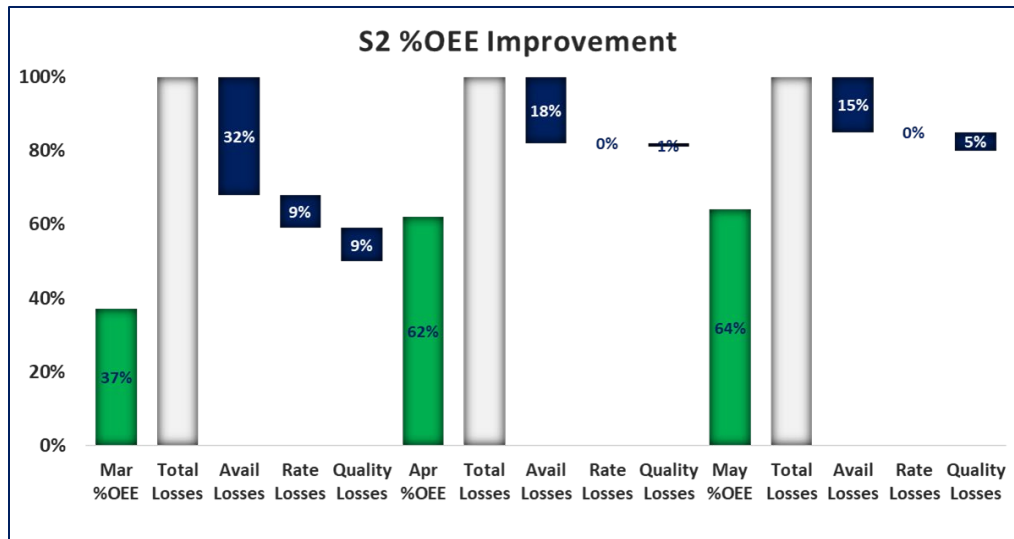

Figure 7: S2 %OEE Improvement

Results of the %OEE improvement analysis from the three sections demonstrates that each of the OEE variables (availability, production rate and quality), have an essential role in improving OEE of a Bord and Pillar mining operation. A review of the three variables also shows that the actual quality rate figures are more consistent with targeted quality rates and yields an improvement on the OEE value. The production rates across all 10 CM sections are also in line with de-rated productivity rate values as determined by the mine block ranking system that the mine employs for determining the production rate target values. Availability figures are much lower and plays a significant role in the improvement of OEE for a reserve constrained Bord and Pillar mining operation.

(iv)   DOH

To improve the availability of a section, the DOH value must be increased by reducing production downtimes and delays. The time losses outside the total controllable time are not considered for improvement as public holidays, industrial actions and unscheduled maintenances take place on non - production time as guided by the Time model. An analysis of factors that affect DOH across the 10 CM sections are presented on Figure 8.
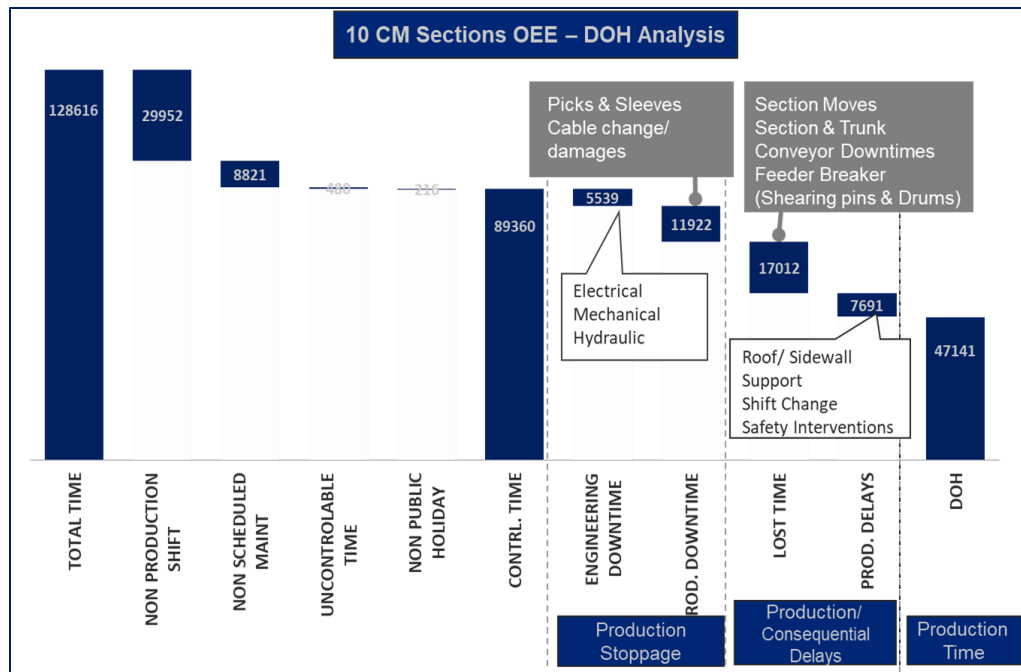
Figure 8: 10 CM sections OEE – DOH analysis

The DOH across all 10 CM sections is affected primarily by production stoppages, production delays and consequential delays. A reduction of these will increase DOH and improve both UEA and EqA, which leads in an increase of the overall OEE. The changing of picks and sleeves is excessive when cutting in areas of poor roof and floor conditions and results in excessive production downtime. Unplanned engineering stoppages have a negative effect of productivity. Engineering downtime analysis shows hydraulic hose leaks, mechanical component failures and electrical trips as major contributors. To reduce this:

- A root cause analysis must be conducted on major and repeat component failures
- A strict condition monitoring programme must be complied with
- A strict backlog management programme must be put in place and adhered to. Defects from inspections must be prioritized, resourced and planned for execution
- Equipment must be maintained as per the established onsite maintenance strategy.

Cable damages are affected by non-adherence to cable processes, cable standards not being followed (routing, suspension), excessive water in sections, substandard cable joints and a poor testing and inspection regime. The excessive roof and side wall support is compounded by failure to follow correct cutting sequence, thereby introducing CM waiting time as cutting behind the Roof Bolter introduces health and safety risks. Section and trunk conveyor belt downtimes are a result of excessive number of repair joints, drive and tail end spillages and non-adherence to inspections and proper preventive maintenance actions. Excessive section moves are a result of unfavourable mining conditions where panels are abandoned due to safety concerns as a result of poor geological conditions.

Conclusion

In the present study, the equipment-suit deployment is reviewed utilizing technical specifications and name plate capacities of each pieces of equipment. The results demonstrate that the equipment deployment is suitable for current seam applications, the higher seam (2 Seam) section does consist of unsuitable equipment-suit. Redeploying these pieces of equipment to lower seam applications (4 Seam), leads to optimized equipment-suit use for maximum productivity. The three elements making up the OEE equation (Availability, Performance Rate and Quality), are all reviewed to establish factors that influence the OEE value in this Bord and Pillar mining operation. Availability is a variable that significantly affects overall improvement in OEE. The main contributors being unplanned engineering and operational downtimes and consequential delays such as poor geological conditions. The OEE improvement results demonstrate that an improvement in DOH, leads to optimized equipment uptime, thereby increasing

Availability. The current Bord and Pillar mining operation study focuses on improving performance of individual pieces of equipment's that function as a single manufacturing line, thereby identifying reasons for overall poor line performance. There is opportunity for future bord and pillar OEE research to focus on integrating technological methods to provide practical solutions that address inherent mining inefficiencies such as geological challenges and conventional maintenance management systems. The future research work in 4th Industrial Revolution (4IR) for manufacturing can be replicated in applications of Bord and Pillar mining operations.

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