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ASSESSMENT OF PRODUCTION EFFICIENCY AT TATAMA MINE

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ABSTRACT

It is important to assess mining productivity to ensure optimal mining production performance. Mining productivity is achieved through proper management, monitoring and evaluation of invested resources and operations to increase production efficiency. This paper assesses the production efficiency of an underground coal mine called Tatama Mine (TM) by identifying and evaluating the factors that influence production levels using statistical methods. The parameters used include equipment availability, equipment engineering availability, equipment mean time to repair (MTTR) and mean time between failure (MTBF), equipment engineering availability (ENA) and equipment availability (EQA). The results show that the EQA for the continuous miners and MTTR for shuttle cars influenced the production outputs by 77.00% and 96.36% respectively. The MTTR for continuous miners (CMs) influenced production performance by 59.68% while the ENA and MTBF for CMs and EQA, ENA and MTBF for shuttle cars affected production output by < 50%. It is recommended that technological advances should be adopted and integrated into the production system to respond immediately to problems with production units and improve the entire production system. Also, CMs and shuttle cars should be frequently examined within their equipment reliability periods (using their current MTTR values) to maximise their equipment uptimes (MTBF values).

Keywords: underground coal mine, equipment availability, production efficiency, production equipment.

1. INTRODUCTION

Mining productivity measures the effectiveness of mining resource inputs computed as a ratio of production output per input resources. Productivity is defined as a single factor, multi-factor and total factor productivity [1]. Factors affecting productivity can be grouped as economic, technical or a combination of the two factors.

Humphreys [2] states that mining productivity is inherently cyclical as evidenced during mining booms. Generally, during periods of high commodity prices mining entities focus on volume while productivity declines and during periods of low prices, they focus on maximisation of resource utilisation. A decline in productivity characterises a mining boom season as production efficiency is neglected to have high returns. Consequently, the cost of production gradually increases, commodity prices gradually drop with time and investor confidence also drops from high to low [3]. As a result, during periods of mining booms, the focus of the mining industry shifts to maximising productivity to address declining commodity prices, the decline in investor confidence and escalation in production inefficiencies. This means that during periods of high commodity prices mining performance is often overlooked or neglected as profit margins are usually high and these eventually cost the company when the prevailing conditions change. Therefore, mine managers must maintain high operational performance of the mining processes across distinct production faces based on the scale of production and prevailing conditions (e.g., change in mineral market price and technology).

Tatama Mine (TM) is an underground mine that uses room and pillar mining method to extract the coal. In this research, the factors affecting mine production were identified and the causes of productivity losses classified according to a scale of impact at TM. Over the years, the mine has been experiencing challenges in achieving optimal production performance. This is evident from the varying daily and monthly production levels that are generally below set targets. The performance of TM indicates the existence of possible production uncertainties which may be critical to the performance of input resources.

2. LITERATURE REVIEW

This section contains the literature review on mining productivity, production improvement techniques and analysis of the methods.

2.1 Production Efficiency

The efficiency of a production unit is a comparison between the actual values of its output and input [4]. A 100% efficiency means that a production process has achieved the maximum amount of physically achievable output with current technology and given a fixed number of inputs [5]. Production efficiency enables mine management to re-evaluate the mine's strategies, plans and practices to achieve high output values with minimal input resources. The effectiveness of a mining production system expresses the level of resource utilisation [6]. Mining efficiency aims to ensure that the supply and demand ratio is balanced at the current market prices that input resources are efficiently utilised, mining costs are minimised and profits maximised.

The production operations in mining include fragmentation and materials handling. The unit mining operations in surface mining are drilling and blasting or cutting, loading, hauling and dumping the broken ore or waste. The unit operations may differ for underground

ARPN Journal of Engineering and Applied Sciences

mines depending on the mining methods utilised (e.g., use of continuous miners or longwall systems in underground coal and potash mines), ventilation and ground support requirements. Various factors influence mine production efficiency [7 - 9]. The magnitude of these factors either minimise or maximise the production output. Their evaluation indicates to the mine planning and management teams the need to maintain or change and implement strategies to achieve the set production targets.

According to Fried [10] variances in the production results may be attributed to the differences in the technology applied, scale of production, operational efficiency and the environment where the production occurs. Therefore, the production variances must be evaluated to maintain or define a production scale by assessing the existing aspects of production that will ensure that appropriate measures are considered to monitor the production scale.

2.2 Technical Function of Production

The production function refers to the maximum output levels achieved with a given amount of input using a given production technology, processes or operations [11]. It is also described as a relationship between the output volume produced per input volume change. The production function (Y) is given by equation (1):

$$Y = f(X_1, X_2, \ldots, X_n) \tag{1}$$

where: $X_1, X_2, \ldots, X_n$ are input variables

The inputs to the production function are known as production factors as they contribute to the efficiency of the production operations. These are parameters that can be strategically planned and controlled to achieve maximum production efficiency. As such, production analysis needs to be carried out to optimise the production scale to ensure that there are no wide variances in production levels from the set targets so that the company's production performance is not hampered. Frequent drops in production levels that are less than the targeted values are likely indicators of possible inefficiencies in the invested resources. The production efficiency measures are production success indicators that lead to identifying controllable and uncontrollable sources that cause production variances [10].

2.3 Measures of Mining Productivity

The productivity of an operation is classified either as a single or multi-factor productivity [12]. Single factor productivity, also known as partial factor productivity, is a measure of production output per unit measure of a single resource input e.g., labour productivity, equipment productivity or capital productivity. Multi-factor productivity is a description of production output per grouped units' measure of resource inputs in a production system. Also, computation of the total productivity factor can be applied, which refers to a measure of the total output per all resource inputs, not per grouped input units as in multi-factor productivity.

2.4 Determinants of Underground Coal Mine Productivity

Many factors affect the level of mine production. These include the type of equipment used, quality of labour, available capital, health and occupational safety work environment conditions/practices and availability of raw materials. Productivity reflects the degree of utilisation of the production factors [6]. According to Topp [7], the factors that determine production efficiency are technology, management, skills and work practices. Fourie [9] defines the factors affecting productivity in mining as the selection of appropriate equipment, operator competency, haul road profiles and work scheduling including the short-term to long-term planning by the management.

According to Malhotra [13] the factors that influence an underground coal mine's productivity are seam thickness, mine roof and floor conditions, annual production capacity, period of operation, quality of the finished product (coal preparation), presence of water, the quantity of methane and other strata gases emitted, management philosophy and mining equipment performance. Other factors that affect underground coal mining productivity are the availability of skilled personnel, shift in demographics and regulatory inspection [14]

2.5 Equipment and Maintenance Performance Availability

The assessment of underground production performance is measured by the equipment availability, equipment engineering availability, equipment mean time to repair (MTTR) and mean time between failure (MTBF). Equipment availability (EQA) is the ratio of equipment uptime and total work period excluding time lost due to uncontrollable events such as power and water outages. This is expressed mathematically by equation (2):

$$EQA = \left\{\frac{(WT - UET) - (UMT + SMT + OPT)}{(WT - UET)}\right\} = \left\{1 - \frac{(UMT + SMT + OPT)}{(WT - UET)}\right\} \tag{2}$$

where: WT = Work time; UET = Uncontrollable events time; UMT = Unscheduled maintenance time; SMT = Scheduled maintenance; OPT = Operational time losses; CTL = Consequential time loss; STL = Standby time loss; OTD = Operational delays

Equipment engineering availability (ENA) is the sum of the difference between work time and equipment downtime and uncontrollable events time divided by work time excluding uncontrollable events period as expressed in equation (3):

$$ENA = \left\{\frac{WT - (UET + UMT + SMT)}{(WT - UET)}\right\} \tag{3}$$

VOL. 17, NO. 18, SEPTEMBER 2022 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

Equipment downtime refers to consequential time lost; standby time and operational delay lost time or refers to unscheduled and scheduled maintenance and operational delays.

Equations (4) and (5) are used to calculate the mean time between failure (MTBF) and equipment mean time to repair (MTTR) of critical underground production equipment:

$$MTBF = \frac{\text{Total run hours}}{\text{Number of breakdown occurrences}} \tag{4}$$

$$MTTR = \frac{\text{Total downtime hours}}{\text{Number of breakdown occurrences}} \tag{5}$$

3. DATA COLLECTION AND ANALYSIS

Data was collected from the mine records and reports covering the period 2015 to 2020.Descriptive and inferential statistical methods were used to analyse the mine's operational data to determine the variances in the shifts and yearly production and the impact of resources used on the mine's productivity. In the data analysis, production variants and cause-effect of production changes were identified. Figure-1 shows the yearly actual and planned production outputs of the mine from 2015 to 2020.

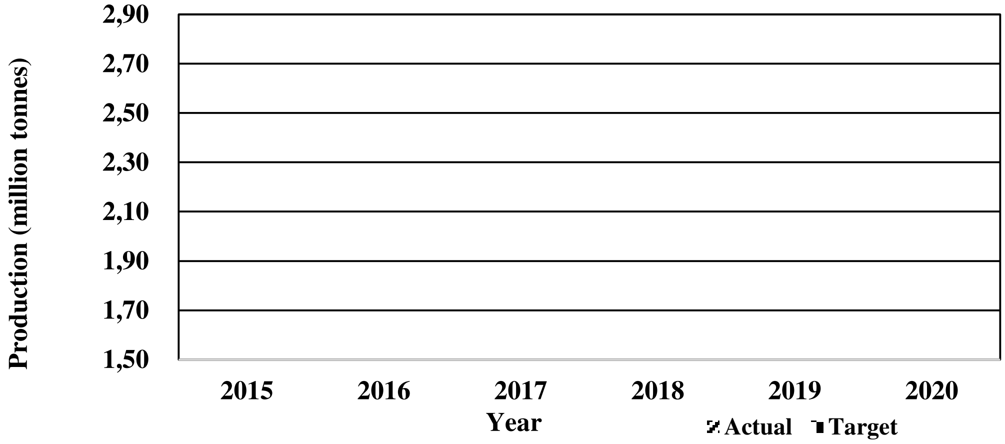

Figure-1. Actual and planned production performance from 2015 to 2020.

From Figure-1, the planned production targets of the mine were met only in 2017 and 2018. Figure-2 shows the percent variances between actual and targeted production from 2015 to 2020.

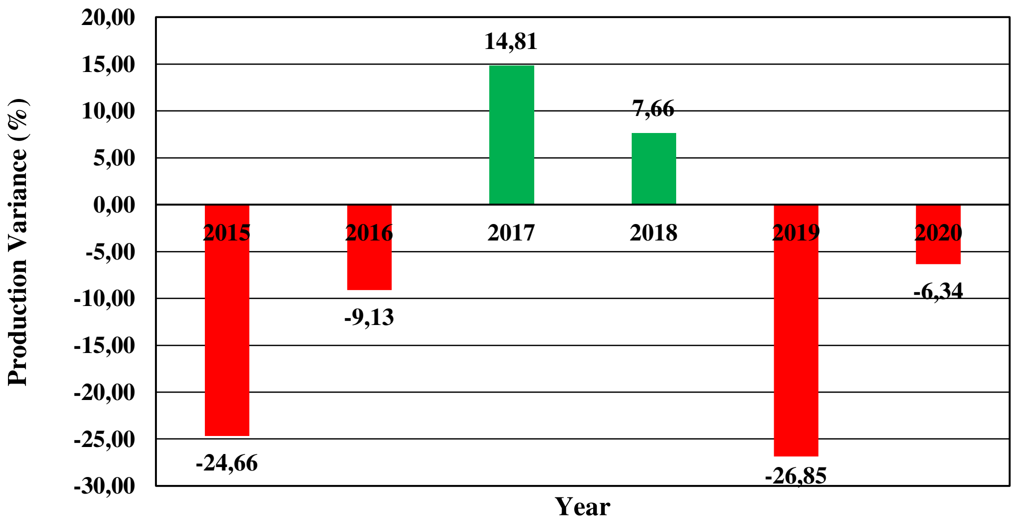

Figure-2. Yearly production variance 2015 to 2020.

ARPN Journal of Engineering and Applied Sciences

From Figure-2, the difference between the actual and targeted production values varied from -26.85% in 2019 to 14.81% in 2017.

Figure-3 shows the total yearly production during the morning, afternoon and night shifts (including data from the weekend shifts) from 2017 to 2020. It is important to note that there is only one day shift on Saturdays. The daily target production per shift varied yearly throughout study period. It is observed that higher production outputs were always achieved during the morning shifts than in the afternoon and night shifts. Night shifts are usually reserved for the maintenance of underground equipment but occasionally some minimal production is done during the night shifts to supplement the production from the morning and afternoon shifts.

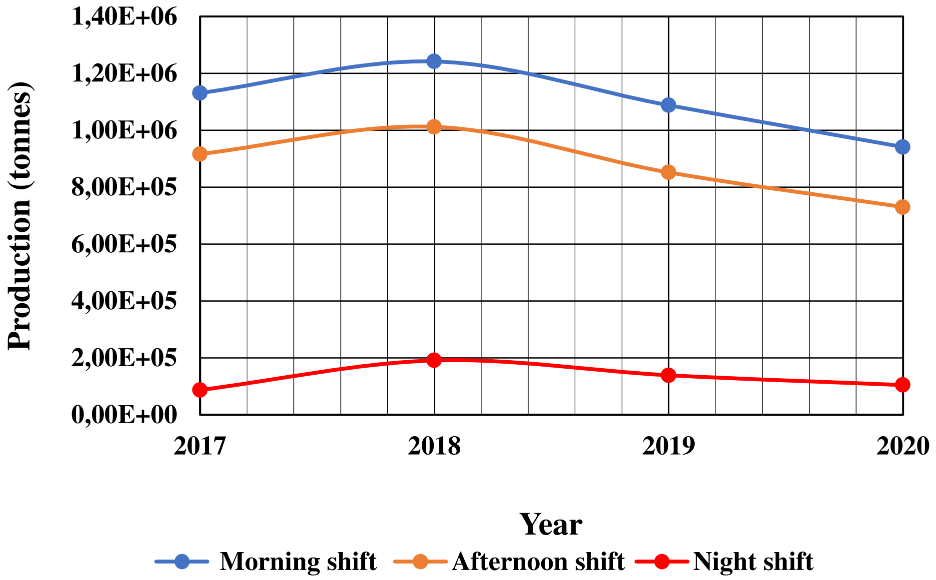

Figure-3. Overall shift performance from 2017 to 2020.

The production efficiency of TM was assessed using parameters such as equipment availability, equipment engineering availability, mean time to repair and mean time between failure. The evaluation of the mine's equipment was done on the four CMs, 12 shuttle cars, 4 roof bolters, 4 feeder breakers, 4 section conveyor belts and 4 loading centres. Figures 4 and 5 show the yearly equipment availabilities (EQA) and equipment engineering availabilities (ENA) from 2017 to 2020 respectively. The threshold targets for EQA and ENA are set at 85.0% in TM for all equipment. In general, all the equipment achieved the targeted EQA and ENA over the years except the CMs and shuttle cars (see Figures 4 and 5).

ARPN Journal of Engineering and Applied Sciences

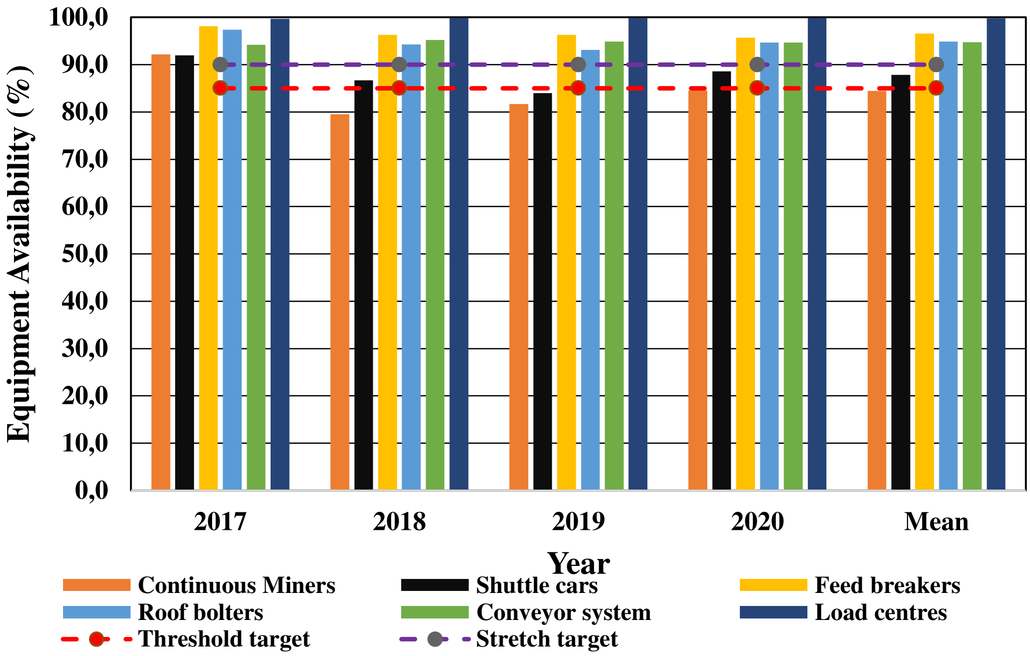

Figure-4. Equipment Availability (EQA) from 2017 to2020

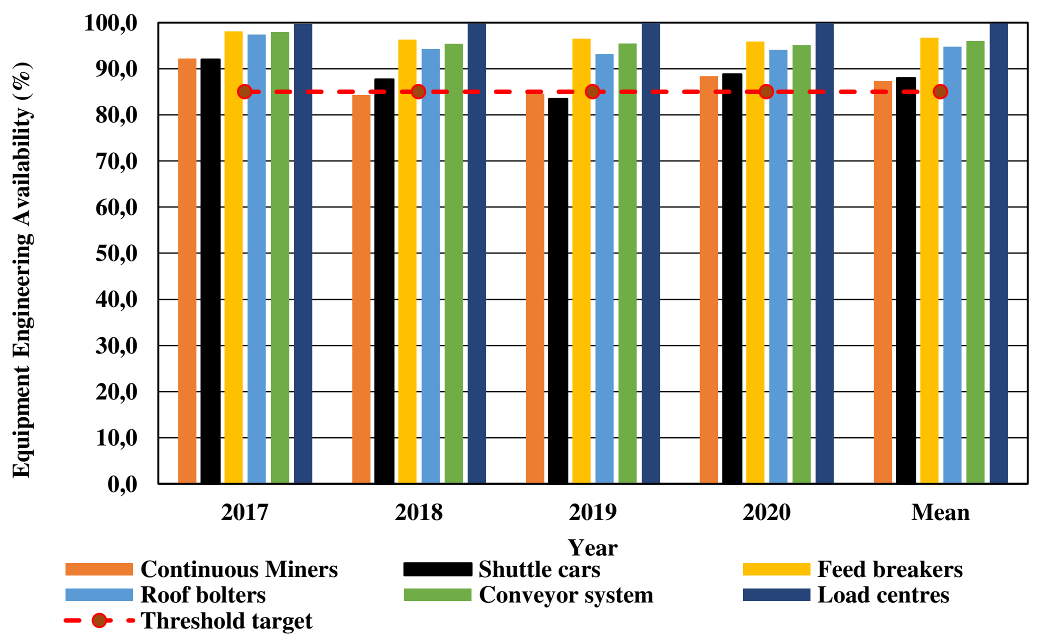

Figure-5. Equipment Engineering Availability to Uptime from 2017 to 2020.

Figures 6 and 7 show the yearly Mean Time between Failure (MTBF) and Mean Time to Repair (MTTR) values for the underground mining equipment from 2017 to 2020 respectively.

From Figure-6, all the equipment achieved the mine's targeted MTBF in all the years except the CMs. Also, from Figure-7, apart from the shuttle cars (in 2019), the equipment mean time to repair of all the other equipment were below the threshold and stretch targets.

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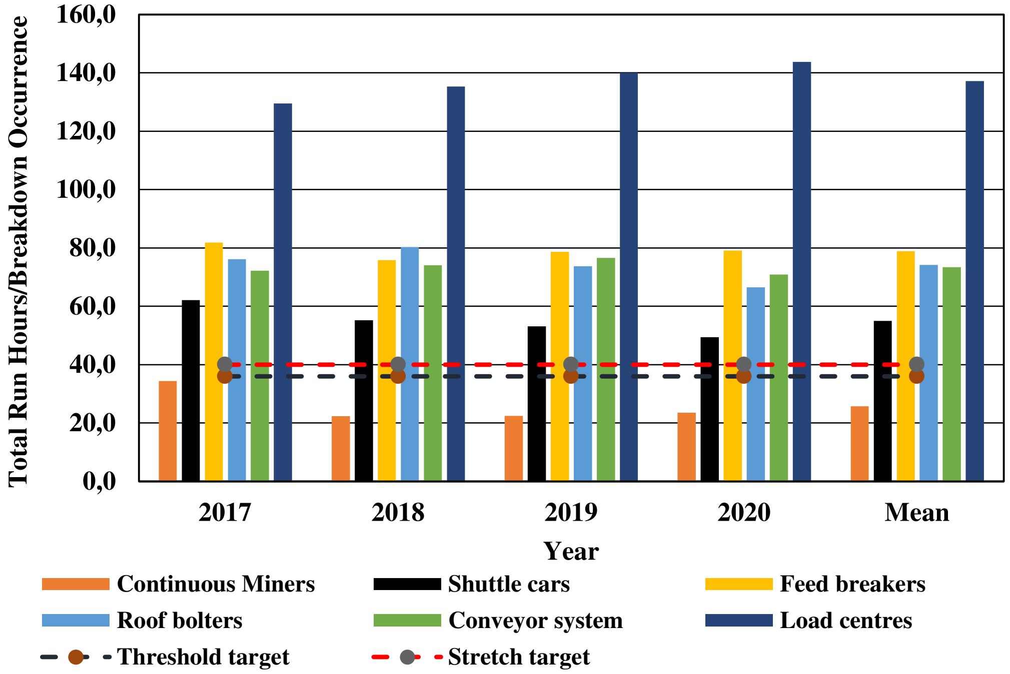

Figure-6. Equipment mean time between failures from 2017 to 2020.

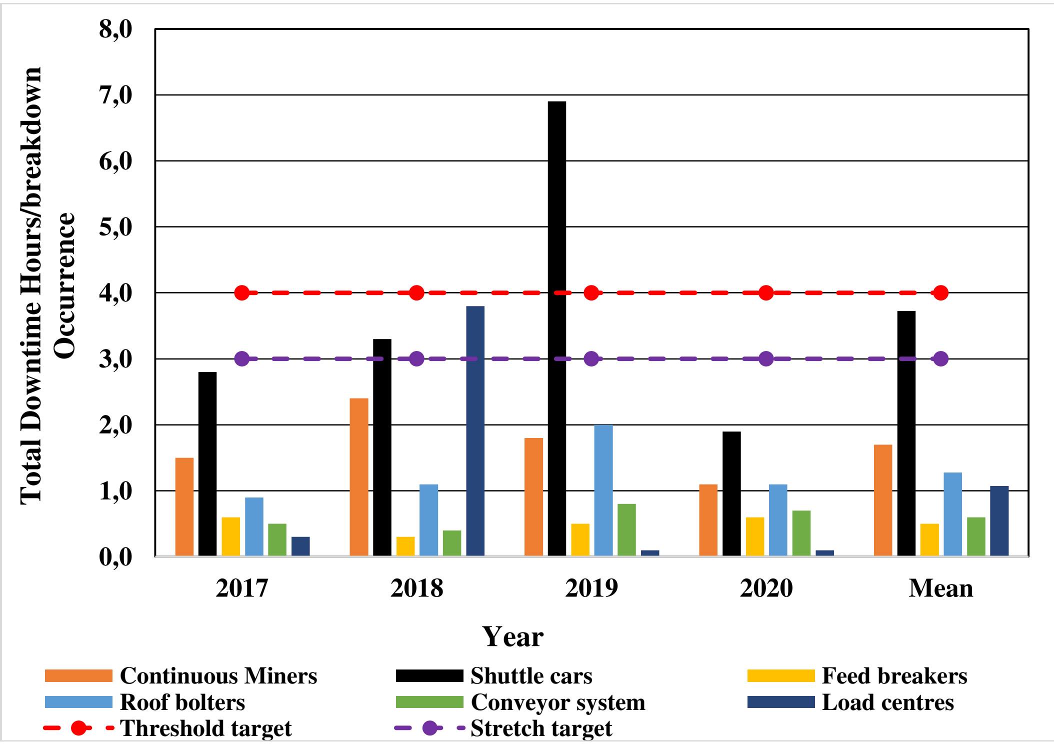

Figure-7. Equipment mean time to repair from 2017 to 2020.

4. DISCUSSION OF RESULTS

From the EQA and ENA evaluations in Figures 4 and 5, the CMs and shuttle cars were the lowest available equipment in the fleet of production equipment at TM and are the only equipment that did not achieve the threshold targets of equipment and engineering availabilities over the period from 2017 to 2020. This was due to numerous mechanical, electrical and hydraulic fluid flow problems (e.g., bursting of hose pipes). These are the cause-effect for production losses and resulted in equipment unscheduled maintenance/unplanned downtime,

VOL. 17, NO. 18, SEPTEMBER 2022 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

operational and consequential time delays and losses including equipment scheduled maintenance time losses.

The following trends were also observed in the operations at TM from 2017 to 2020:

a) The average availabilities of shuttle cars were generally below the set threshold targets. Generally, shuttle cars and CMs had the lowest equipment availabilities among all equipment from 2017 to 2020 (see Figure-4).
b) The average engineering availabilities of the mining equipment were above the set threshold targets except the CMs and shuttle cars which had low engineering availabilities over the period (see Figure-5).
c) The CMs, which are critical production machinery, had MTBF values below the mine's set threshold values compared to all the other equipment. This means the CMs broke down more often than the other mining equipment (see Figure-6).
d) The shuttle cars had high MTTR values. This means that they had longer downtimes per equipment breakdown. For example, the shuttle cars exceeded the set minimum times for a rapid/immediate repair to continue production operations in 2018 and 2019 (see Figure-7).

Correlation analysis was performed on the factors that affect production performance from 2017 to 2020 using MATLAB with the available data from a period of four years. The 2nd-degree polynomial regression was found to be a better fit for most of the data points. A higher polynomial was found to over fit the data points. The variations in production due to the independent variables were determined using MATLAB's curve fitting function. The regression model function and goodness of fit using measures such as the sum of square errors (SSE), R-square $(r_{ay})^2$ and root mean square errors (RMSE) were obtained. The sums of square errors, also known as the summed square of residuals, represent the total deviation of the values of the dependent variable from the curve of fit to the response variable values. The values of RMSE represent the standard deviation of residuals/spread of residuals around the curve of fit. Residuals are a measure of the difference between actual data points and regression line points/curve of fit points. A high R-square, high confidence bounds and low standard RMSE mean that the data points are close to the regression model curve points. It means the differences between the actual data points and regression model curve points are small (i.e., residuals are small). Table-1 summarises the results of the goodness of fit of the regression model/curves in terms of R-square and normalised RMSE for the various parameters.

Table-1. Goodness of fit measures.

Production Model Variables	R-square	RMSE
EQA of CM	0.7700	0.1197
MTTR of CM	0.5968	0.1585
MTBF of CM	0.3504	0.2012
ENA of CM	0.3302	0.2043
MTBF of shuttle car	0.4278	0.1888
ENA of shuttle car	0.2852	0.2111
EQA of shuttle car	0.1628	0.2284
MTTR of shuttle car	0.9636	0.0476

From Table-1, the normalised RMSE values range from 0 to 1. All the RMSE values are ≤ 0.2285 which indicates a good fit measure for the regression model.

The EQA of CMs and MTTR of shuttle cars influenced the production outputs by 77.00% and 96.36% respectively. This indicates a good fit for the model and a strong correlation between the variables and production performance. The MTTR for CMs influenced production performance by 59.68% which shows a moderate fit for the regression model and moderate strength of association between the variable and production performance. The ENA and MTBF for CMs and EQA, ENA and MTBF for shuttle cars had a < 50% impact on production output. This shows low strength of association between the variables and production output.

5. CONCLUSIONS

It is concluded that:

a) The equipment availabilities of the CMs were average and ranged from 79.5% to 92.2% while those of the shuttle cars were high (ranging from 84% to 92.0%). The average EQAs of the other production equipment were higher than their set threshold targets except for the CMs.
b) The engineering availabilities of the CMs and shuttle cars averaged 87.4% and 88.0%, respectively. These were higher than their set threshold targets but they were the lowest performing machinery.
c) The MTTR values of the shuttle cars were high (ranging from 1.9 to 6.9 downtime hours per breakdown) while the MTTR values for CMs ranged from 1.1 to 2.4 downtime hours with an average of 1.7 downtime hours per breakdown.
d) The actual run hours per breakdown for MTBF values of CMs varied from 14.7 to 25.9 running hours per breakdown. This indicates that it takes a long time (more than one 8-hour shift) to repair the CMs.
e) There were wide variances in the production outputs between morning, afternoon, and night shifts. The afternoon shifts generally had lower production outputs than the morning shifts.

f) The EQA and ENA of CMs and shuttle cars were generally low due to mechanical, hydraulic fluid and electrical faults/breakdowns.
g) The EQA of the CMs and MTTR for shuttle cars influenced production outputs by 77.00% and 96.36%, respectively showing a strong correlation between the variables and production performance. The MTTR of the CMs influenced production output by 59.68% while the MTBF and ENA of the CMs, MTBF, ENA and EQA of the shuttle cars impacted production output by < 50.00%.

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