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Performance augmentation of continuous miner based system in India: a reliability based approach

A Continuous Miner (CM) is a globally competitive machine, capable of boosting the production of underground mines, which is imperative for future production growth. However, the geological factors and other mining parameters of all underground mines do not always support the best performance from the equipment. In this article, the effects of mining parameters like pillar size, gradient, number of headings and equipment fleet on CM-based production system have been observed and a forecast regarding trend analysis has been done. Furthermore, this study enlightens the effects of breakdowns of CM and its allied equipment; the breakdown times for CM and its related equipment are quantified collectively. The percentages regarding the reliability and probability of these types of failures have been considered within the scope of this paper. Corresponding study shows that conveyor breakdown affects the system productivity the most and other failures affecting the production significantly are electrical failure, shuttle car breakdown, hydraulic breakdown, gathering problems, cutter breakdown and traction breakdown. The reliability analysis of each group of components will function as a forecast of the maintenance schedule and inspection frequency of different components in order to decrease failures and increase available time.

Key words: *continuous miner, pillar size, number of headings, reliability, percentage of failure*

1. INTRODUCTION

Coal reserves near the surface are nearing exhaustion due to the higher exploitation rate, tending a necessity to produce coal from deeper seams in the near future. Until now, underground mining has been the only economic technique for producing coal from reserves at greater depths from the Earth's crust. India is one of the top-five coal producers in the world, with a production of 639.23 MT of coal in 2015–2016 [1]; though, it is far away from being able to be an effective exporter or even meet its own indigenous demand. This indigenous demand is expected to increase to 1373 MT by 2021–2022 [2]. Therefore, India has planned to increase total coal production to at least 1 BT by 2020 [3]. This plan necessitates the exercise of underground mining to exploit the deeper seams of the Earth's crust.

In India, most of the underground mines operate with the Bord and Pillar method (a variety of room and pillar) with conventional drilling, charging and blasting for coal production and SDL or LHD for loading. Few projects of the major coal producing public sector company of the country are already working with Continuous Miner (CM) and are further planning to introduce new CM-based projects, as CMs are globally accepted machines for their high performance in underground mining (Fig. 1). The compatibility of CMs in all of the existing projects is low; because of the insufficient reserve to support production for a long duration, old mine layouts and presence of geological disturbances etc. The annual coal production of the whole world was 3400 Mt in 1977 [4] and this reached 7861 Mt by 2017 [5] with the introduction of advanced new-age technologies.

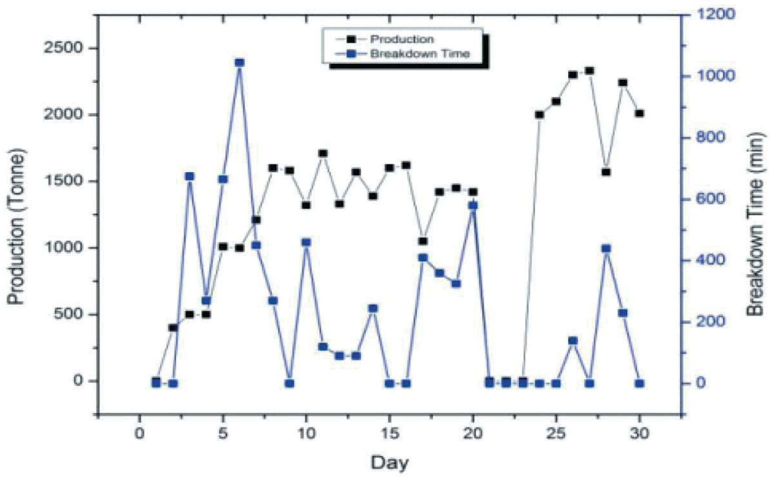

Fig. 1. Production and Breakdown trend of CM-based underground mine for one month

This paper is concentrated on a study conducted in two mines situated in the eastern part of the country that deploy total of three CMs. The first mine (Mine-A) deploys two CMs (one for development and another for depillaring) and the second (Mine-B) operates with one CM for development purpose only.

2. METHODOLOGY

The study was conducted for about 120 shifts of working for each CM panel. The effects of the geological conditions were compared in the two mines working with three CMs in different panels. Permissible values of these variables and effects of the actual geological conditions were observed. How these variables affect the productivity and equipment efficiency were broadly explained.

The down-time and working-time data for subsystems of CM and its allied equipment was collected from the mines and the Mean Time Between Failure (MTBF), Mean Time to Repair (MTTR) and Availability of each subsystem were calculated using the raw data collected from the mines. The following formulae were used to calculate the above-mentioned parameters [6–8]:

$$\text{MTBF} = \frac{\text{Total Acutual Working Time}}{\text{Total Number of Failures}} \quad (1)$$

$$\text{MTTR} = \frac{\text{Total Time To Repair}}{\text{Total Numbers of Repairs}} \quad (2)$$

$$\text{Availability} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} \quad (3)$$

The percentage of failure of each subsystem with respect to the total failure time was also evaluated.

Then, trend test and serial correlation tests were performed for each CM-based failure data prior to fitting the appropriate probability distributions; these tests verify the Identical Distribution and Independence of the data set. The classical statistical techniques are useful for the independent data set [8]. The best-fit probability distribution was then selected, and the reliabilities of the subsystems were obtained graphically. Here, different probability distributions were performed using MATLAB 2013a. The best-fit probability distribution was used to measure the reliability.

In this paper, the three least- available subsystems for each CM and its allied equipment were considered. The other subsystems have an overly negligible record of downtime to impact on production loss.

3. VARIABLES AFFECTING UNDERGROUND MINE PRODUCTION

Underground mine production depends on several mining variables that have noteworthy impact on coal production. According to the Coal Mines Regulation of 1957, some of these variables can range within a specified limit for safety and productivity purposes. A few of these factors are as follows [9]:

3.1. Thickness of seam

This characterizes the volume of extractable coal present in the panel (the working place for the CM).

Lower seam thickness results in a low amount of coal production from a single heading in a single pass of cutting and movement of a continuous miner. This results in considerable production loss. An extremity in higher as well as lower thicknesses of the seams does not result in a better utilization; hence, it negatively affects productivity. A seam thickness between 3.5–6.0 m is the optimum range to get the best performance of a CM. For thicknesses of 2.5–4.6 m, the utilization is medium and seams with thicknesses less than 2.0 m are not suitable to work with a CM [10].

3.2. Pillar size

Pillar sizes in underground coal mines vary depending mainly on the depth of cover and other geological factors. Panels with smaller pillar dimensions may cause less duration for cutting, causing the frequent movement of a continuous miner between faces. Whereas, the panels with higher pillar sizes causes considerable transportation delay. Therefore, the selection of proper pillar dimension is important from both the mine safety and production purposes. Pillar sizes ranging from 20.0 to 30.0 m centers are optimum for the best performance of the CM-based mine operation and pillar sizes ranging from 30.0 to 45.0 m allows for a moderate operational performance with CMs [10].

3.3. Gallery width

CMs are large machines to be fitted and operated within a maximum permissible gallery width of 4.8 m as per the Coal Mines Regulation. A standard CM has a 3.6 m cutter width, demanding a relatively larger gallery width for efficient operation. Depending on the strata condition, these machines can be safe and productive at higher gallery widths of 5 m to 6.6 m. For higher gallery widths, a Continuous Miner gets more volume of coal at a single heading. In India as per the Coal Mines Regulation 1957, 4.8 m is the maximum permissible gallery width, though the optimum performance of a CM can be achieved at this gallery width while moderate performance is achieved up to a width of 4.0 m; a further lowering of gallery width is not at all suitable for CM-based working.

3.4. Gradient

The transportation equipment speed and efficiency get drastically reduced with an increase in the gradient; this adversely affects the transport equipment cycle time and disrupts overall productivity. A gradient of not steeper than 1 in 10 is optimum for a CM-based production system [10]; a gradient of 1 in 8 results in a lesser efficiency of the transport equipment and hence reduces the overall efficiency of the CM-based production system, whereas a gradient of 1 in 5 or higher severely affects the efficiency of a CM-based system. The values of the parameters discussed above are presented in Table 1.

Table 1

Geo-mining condition of mines under study

Mine	Seams working with CM	Thickness of seam [m]	Pillar Size [m]	Gallery width [m]	Gradient
Mine-A	2	4.0–5.0	32 × 32	6.0	1 in 16
Mine-B	1	4.75	34 × 34	6.0	1 in 15

4. RESULT AND DISCUSSION

In the corresponding study, the overall system is broadly divided into several subsystems; some of them are integral parts of the CM and others are important in respect to the overall performance of the CM-based system. Therefore, failure of any of these subsystems disrupts the CM-based production; namely, the subsystems are- the electrical parts of the CM and its allied equipment, traction of the CM, gathering arm of the CM, cutting drum, hydraulic systems, feeder breaker, conveyors of the CM and overall mine conveying system. The percentage of downtime caused by any of the subsystems among the overall downtime and availability of each subsystem is presented in Table 2.

Table 2 indicates that, outbye Conveyor, CM Conveyor, Electrical systems have the lowest equipment availability for CM-1based systems. For CM-2 based systems, the conveyor, electrical systems and gathering arm have the least availability; whereas for the CM of Mine-B, the subsystems with least availability are – the Conveyor, Electrical and Shuttle car.

The reliability analyses of three subsystems with the least availability for each of the CMs are presented in the scope of this paper. At first, the relationship between the cumulative failure number and cumulative Time Between Failures were plotted graphically to see the trend; if the plotted graph is almost linear it signifies no trend in failure rates [8]. Then, Time Between Failures for the i^{th} time vs. the $(i–1)^{th}$ time were

Table 2

Percentage of total downtime and availability of all associated subsystems of CMs

Name of Subsystem	CM-1 of Mine-A		CM-2 of Mine-A		CM of Mine-B	
	Percent DT.	Availability	Percent DT.	Availability	Percent DT.	Availability
Electrical	3.69	98.53	8.34	95.77	32.18	93.85
Cutter	0.34	99.87	1.28	99.35	0.88	99.83
Gathering	0.96	99.62	7.55	96.17	6.04	98.85
Traction	3.27	98.70	1.90	99.04	0.00	100.00
Hydraulic	1.30	99.48	2.01	98.98	2.34	99.55
Chassis	0.08	99.50	0.13	99.93	0.70	99.87
S/C	2.16	99.14	5.19	97.36	8.79	98.32
Maint.	4.09	99.30	13.09	93.36	3.34	99.36
Conveyor	76.57	69.56	55.02	72.96	41.50	92.07
F/B	0.93	99.63	0.18	99.91	1.41	99.73
CM Con.	6.62	97.37	5.32	97.30	2.81	99.46

Legend: Percent DT. = Percentage Downtime among Overall Downtime; S/C = Shuttle Car; F/B = Feeder Breaker; Maint. = Extended Maintenance Time; CM Con. = CM Conveyor

scatter plotted to verify any correlation between them; if there is no specific trend in the scatter plot, this signifies that the data is free from any correlation [8].

4.1. Statistical significance and mathematical relationship

Subsequently, the proper probability distributions were fitted to the data to determine the reliability of the subsystems. In the reliability analysis of the repairable systems, three types of probability distributions are generally used: Weibull Distribution, Lognormal Distribution and Exponential Distribution. The goodness of fit was measured by the Chi-Square test. The failure data related to an individual subsystem was fitted to the appropriate distributions and the reliability was obtained and presented here graphically.

Figure 2 represents the results of the trend and serial correlation tests of CM-1 in Mine-A. The trend test is the line plot between the cumulative failure number and cumulative Time Between Failures [8]. The serial correlation test is a scatter plot between the i^{th} Time Between Failure and $(i–1)^{th}$ Time Between Failure [6, 8].

The trend test plot shows a linear trend; hence there is no trend present in the failure data. The serial correlation test shows no specific trend through the scattered data plot; hence, no correlation is present. This signifies the absence of any trend and serial correlation in the failure data of CM-1 in Mine-A. Similar tests were also performed on the other two CM-based failure data and shows similar results as the CM-1.

After this, the data sets were analyzed using compatible probability distributions for their reliability analysis.

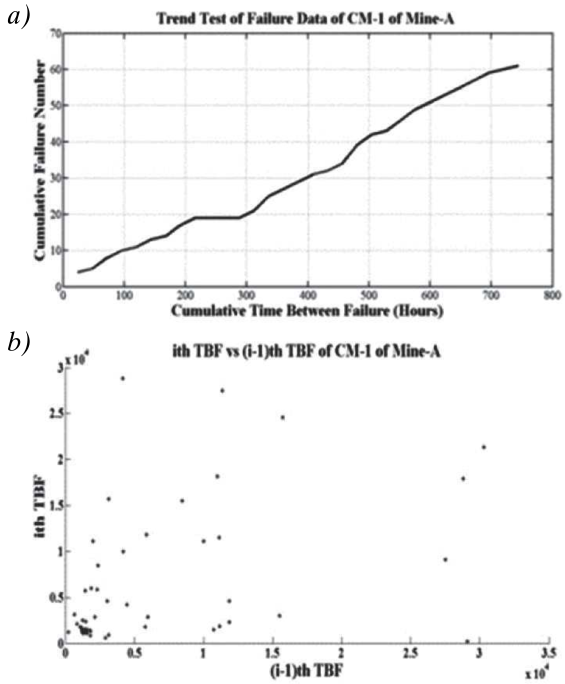

Fig. 2. Trend Test (a) and Serial Correlation Test Plots (b) of CM-1 in Mine-A

Figure 3 depicts the reliability of the electrical systems associated with the three CMs and their allied equipment; as the electrical system was found to be common among the three subsystems with a lower availability for all three CMs. A similar study was also conducted for the other two lower availability systems of each CM. Initially, the reliability of each subsystem was 100%, with an increase in operating time reliability generally decreases. From the analysis, CM-1 based system of Mine-A shows the lowest reliability of the mine conveyors; reaching 50% reliability in just 1500–1600 minutes of operation, and its electrical and CM conveyor reaching 50% reliability after 4500–4600 and 7200–7300 minutes of operation. A similar low reliability trend was also observed for the conveyor associated with the CM-2 based production system of Mine-A, whereas, the electrical system of CM-2 and its allied equipment reaches 50% reliability after 2000–2200 minutes of operation and the gathering arm of CM-2 depicts 50% reliability after 7500–7700 minutes of operation. The conveyor in Mine-B described a better reliability trend, reaching 50% reliability after 3500–3800 minutes of operation, whereas the electrical system takes 3300–3500 minutes to reach 50% reliability and the reliability of the shuttle car reaches to 50% after 6000–6500 minutes of operation.

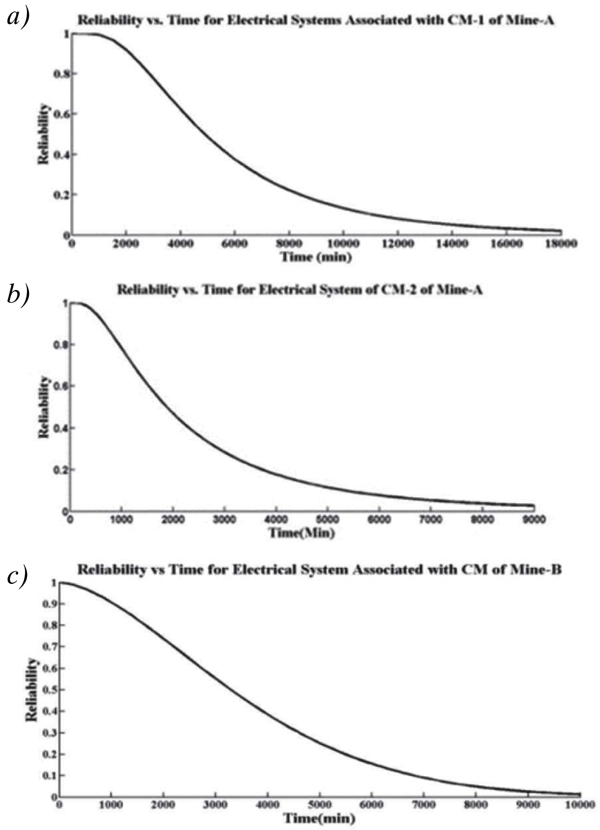

Fig. 3. Reliability of Electrical Systems Associated with CM-1 (a), CM-2 of Mine-A (b), and CM of Mine-B (c)

A statistical analysis of the CM-2 of Mine-A and CM of Mine-B are presented in Table 3. Where, the hydraulic systems and conveyors of the two CMs depicted significant variation for their corresponding working conditions.

Table 3

Significance test of TBF data of CM-2 of Mine-A and CM of Mine-B

Name of Subsystem	CM / Mine	Mean	Min	Max	Pearson's t-Test
Electrical	CM-2 Mine-A	2520.3	385.0	8585.0	NS
	CM Mine-B	3682.5	580.0	7200.0	
Cutter	CM-2 Mine-A	27217.5	25995.0	28440.0	NS
	CM Mine-B	30240.0	30240.0	30240.0	
Gathering	CM-2 Mine-A	6255.0	1285.0	19455.0	NS
	CM Mine-B	21840.0	480.0	43200.0	
Hydraulic	CM-2 Mine-A	5917.6	545.0	23645.0	S
	CM Mine-B	18267.5	13495.0	23040.0	
Chassis	CM-2 of Mine-A	18820.0	18820.0	18820.0	NS
	CM of Mine-B	21600.0	21600.0	21600.0	
Shuttle car	CM-2 of Mine-A	3407.69	510.0.0	11735.0	NS
	CM of Mine-B	7554.0	1880.0	20550.0	
Feeder breaker	CM-2 of Mine-A	7150.0	4940.0	9360.0	NS
	CM of Mine-B	8640.0	8640.0	8640.0	
Conveyor	CM-2 of Mine-A	1937.7	525.0	5400.0	S
	CM of Mine-B	3648.5	765.0	9265.0	

Legends: NS = Non-Significant (>0.05); S = Significant (<0.05); TBF = Time Between Failure

5. MAINTENANCE OF CM AND ALLIED SUBSYSTEMS

The current study shows a considerable production and resource loss due to equipment downtimes, imposing the requirement of a proper preventive maintenance schedule of the low-reliability subsystems of the CM-based mining operation. Preventive maintenance is carried out before the next forecasted failure occurs.

5.1. Conveyor

Conveyors are required to be inspected at least once daily by walking through the sides and looking for any abnormalities. The preventive maintenance includes inspection of the rollers, pulleys and wheels for their alignment, motor noise check and lubrication, sprocket alignment, lubrication of all moving parts and bearings as per manufacturer guidelines [11]. A proper strategic maintenance program should be designed for the overall equipment fleets.

5.2. CM

The operators should be assigned to inspect the machine condition before and after machine operation. A general inspection includes hydraulic-systems check, such as checking the cylinders for any leakages, checking of the cutter for any abnormality, gathering head assembly, gathering head motor, and control systems checks [12, 13].

5.3. Electrical Systems

The electrical failure was also significant in this study, causing power interruption for the working of vital machines. The regular inspection of the power transformer, gate end box, and supply cables are important. The handling of the power transmission cable during operation of the CM and shuttle car should be done with proper care.

6. CONCLUSION

The reliability and availability of equipment designates the dependability and sturdiness of production equipment. A reliability analysis of the CM-based underground mining operation describes that, the CM-based system in India has a considerable scope of improvement in the near future, along with the introduction of new CM-based projects in the country. In this paper, the reliability and availability analysis of three CMs working in two mines are studied; it shows that the maintenance program for the CM and its allied equipment has to be designed in a strategic way to improve the return on investment ratio. All of the subsystems of the overall CM-based system require attention for the proper maintenance. However, the reliability of the conveyor systems of all of the mine panels and electrical systems were found to be critical from a reliability point of view and needs more attention in regards to their maintenance aspect. The reliability criteria can be used to design a strategic maintenance schedule to prevent failures and improve utilization and productivity.

7. SUMMARY

This paper focuses on the effects of different geomining factors and downtime of a Continuous Miner (CM) and its allied equipment on underground coal mine production. The availability of the different subsystems of the CM and its associated equipment was determined. Subsequently, best-fit probability distributions were used to determine the reliability of the three least-available subsystems for each CM. Finally, a maintenance plan is prescribed to augment CM-based production.

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