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ORIGINAL CONTRIBUTION

An OEE-Based Approach to Identify Impact of Vulnerable Sub-Systems on the Continuity of Coal Mining Operation

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Abstract Mining in India is having long history, since ancient age; however, nowadays India is implementing some of the cutting-edge coal production technologies; such as Continuous Miner (CM) dedicated to mass production of coal from underground without drilling and blasting. In this paper, the Overall Equipment Effectiveness (OEE) of the CM system was observed for a period of six months and found to be alarmingly low. This encouraged for detailed study through reliability analysis of different sub-systems of the CM-based operation to identify potentially vulnerable sub-systems contributing to unwanted stoppages of the equipment. Reliability of each subsystem was analysed for a period of fifteen thousand minutes with an interim time gap of one thousand minutes. This has depicted mine conveyor as most vulnerable subsystem followed by ram car, electrical attachments, cutter and feeder breaker, respectively. Further, Failure Modes and Effects Analysis (FMEA) was applied on these five sub-systems to identify and select significant failure modes based on subsequent field observations. Finally, appropriate actions were suggested to alleviate those failure modes.

Keywords Continuous miner · Reliability analysis · Failure Modes and Effects Analysis · Availability · Overall Equipment Effectiveness · Goodness-of-fit test

Introduction

India is one of the global leaders in coal production sector; more specifically India is third largest coal producer globally, with 715.13 Mt of coal production in the year 2018–2019 as reported by Ministry of Coal, Government of India [1]. Opencast mining technique in India extremely dominates the underground mining; as reported by Indian Bureau of Mines [2] in 2017–2018 only 6.3% of annual coal production is accomplished through underground mining method. The complex geo-mining condition and restricted implementation of cutting-edge technologies is considered to be the main hindrance in underground mining in India. According to Ghose. M.K. [3] with higher depletion of the seams near the surface, concerns related to environmental pollution and degradation are forcing the government to think for some alternatives to opencast mining; one of the most feasible solution to this is large scale implementation of cutting edge underground mining technologies; such as Continuous Miner (CM) and Longwall technology.

Following Table 1 depicts the percentage of coal produced from underground mining out of total coal produced annually by major coal producing countries.

Table 1 delineates that except India other countries are far ahead in contribution of underground mining for coal production; this is basically feasible with implementation of cutting-edge technologies as stated above.

This is evident that the CM technology is effective with those major coal producers globally, though the scenario may be different in Indian geo-mining conditions; this opens a huge avenue for research in pre-commissioning and operational stage of these machines.

Government of India has already adopted this technology in some of the selective underground coal mines of the

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Table 1 Contribution of underground mining in overall coal production for different countries

Sl. No	Country	Percentage of underground coal Production	Source of Information
1	India	6.3%	Indian Bureau of Mines [2]
2	Australia	20%	Geoscience Australia, Australian Government [4]
3	USA	35%	US Energy Information Administration [5]
4	South Africa	51%	Department of Energy Republic of South Africa [6]
5	China	90%	Chu, Jain et.al. [7]

Table 2 Geo-mining condition of the mine site under study

Depth of Cover	Pillar size	Gradient	Height of working	Gallery width	Thickness of seam
320 m during study	70 m × 60 m	General 1 in 4 (1 in 7.5 apparent gradient)	3.4–3.5 m	5.5 m	7 m (where only 3.5 m is extracted)

country; few of which are working satisfactorily but majority of them demands further research and observations.

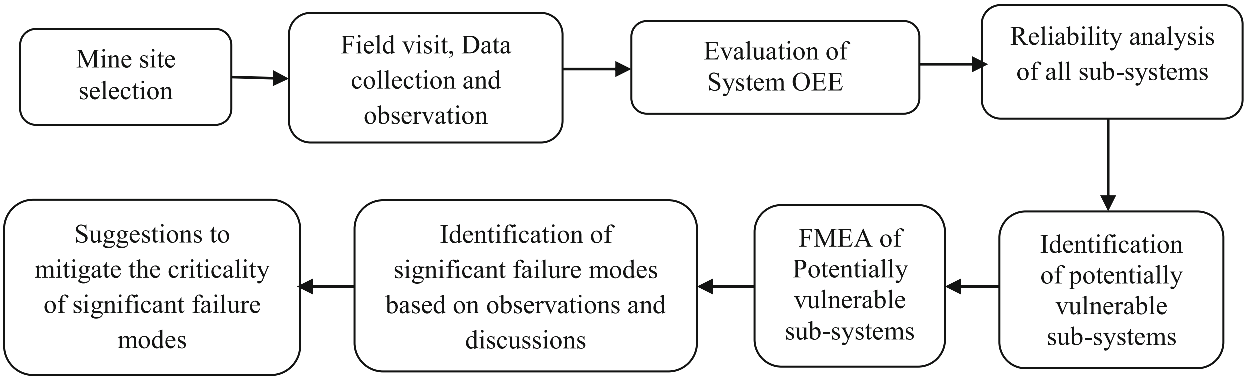
This paper actually deals with the evaluation of Overall Equipment Effectiveness (OEE) of a CM-based project in southern India for a period of six months; to understand the scenario of effectiveness and utilization. From OEE calculation, an alarming situation was recognized; which encouraged for conducting further in-depth analysis of reliability of each sub-system with the purpose of identification of potentially vulnerable sub-systems. Further, FMEA technique was used on identified vulnerable sub-systems to describe significant failure modes or causes of failure and further few actions with controls were suggested on significant failure modes to mitigate their criticality.

Mine Description

The mine site is located in the southern part of the country and working with continuous miner for development purpose using room and pillar method of working for coal extraction. The geo-mining condition of the mine site is depicted in the following Table 2.

The geo-mining condition depicts some adversity for deploying Continuous Miner such as very high gradient of 1 in 4. Rhombus-shaped pillar design is adopted to partially overcome the problem arising from high gradient. This create another problem of higher exposed roof area at the junctions, inducing high stress, demanding furthermore dense roof support at the junction for safety purpose. It is also worthy to mention that the Rock Mass Rating (RMR) value of the panel was evaluated as 37 by one of the statutory bodies in the country. This indicates really poor characteristics of immediate roof and makes it unsuitable to work out with Continuous Miner.

Other adverse conditions are low gallery width and high seam thickness. Therefore, unexplored strata induce enormous production loss and results in low return on investment. In addition, very high gradient (around 1 in 12) in strike direction poses an unusual and adverse condition for the operation of shuttle cars.



Methodology

Mine site with a Continuous Miner (CM) working was selected for development of the coal panel. Working time and downtime related data were collected for a period of six months, for CM and allied machines. A digital stopwatch was used to record the time related data. Using this downtime, working time and production data the system availability and performance were evaluated, which were used to calculate the OEE of the system. OEE of the CM machine was found alarming for a period of six months of study. Subsequently, reliability analysis of different subsystems of CM was performed to identify potentially vulnerable sub-systems. Further, FMEA was applied to those potentially vulnerable sub-systems to recognize different failure modes based on field observations and discussions. Afterward, these failure modes were categorized as significant or not using Pareto chart. Finally, few actions were suggested to alleviate those significant failure modes.

Overall Equipment Effectiveness (OEE) Analysis

Overall Equipment Effectiveness (OEE) is an important technique for evaluation of the effectiveness of a production system. The article "Calculate OEE" depicts that OEE is actually a combination of three individual parameters, these are: availability, performance and quality [8, 9].

The quantification of these three parameters for CM-based underground coal production system is elaborated as follows:

Availability

It is basically the ratio of the time for which the machine is actually available (Actual Operation Time) to perform its desired task to the Net Available Time [9]. The Net Available Time is the time remaining after deduction of scheduled maintenance and planned stoppages from the overall planned production time.

Therefore, the Availability of a machine is given by; $\text{Availability} = \frac{\text{Actual Operation Time}}{\text{Net Available Time}}$.

Availability of CM based production system is calculated similarly.

Performance

It is the ratio of the actual output to the planned output [9].

The calculation of performance for CM based production system is done by evaluating the ratio of number of shuttle car load actually produced in a day to the number of shuttle cars load targeted to be produced in that same day under same condition.

Quality

Quality is the ratio of the number or quantity of product qualified in the quality benchmarking to the number or quantity of products actually produced [9].

For factory-based products, it is easy to determine how many products are actually defective within the total number of products produced in a specified time domain, from which the quality can be evaluated as a ratio of number good quality products and total number of products produced.

However, for coal mining this is very difficult to quantify good quality and inferior quality in a similar way like factory made products. Therefore, as suggested by Elevli and Elevli [10] that the bucket filling factor of the hauling or loading machine should be considered as the quality parameter for coal mining industries, as a result, the average bucket filling factor of the shuttle cars is considered as the quality parameter in this study, which is also supported by a paper by Banerjee. [9].

Bucket Filling Factor is basically the ratio of actual load carried by a hauling machine to maximum carrying capacity of that machine. Here average bucket filling factor is considered as quality parameter.

Overall Equipment Effectiveness (OEE) of machine can be calculated as follows:

$\text{OEE} = \text{Availability} \times \text{Performance} \times \text{Quality}$

From Table 3, the calculated OEE for CM system for a period of six months can be seen, which depicts alarmingly low value as compared to maximum possible value of 1. It is a potential reason to further research into the vulnerable sub-systems.

Reliability Analysis

Reliability of a system or sub-system describes the probability of a machine that; it will perform its desired task after a specified time since inception of working. This helps in identification of vulnerable sub-systems; contributing to lower equipment availability and OEE.

Here the overall CM package is divided in few subsystems for the purpose of reliability analysis; these subsystems are namely: electrical, cutter, gathering, traction, hydraulic, chassis, feeder breaker, mine conveyor, CM conveyor, and ram car.

There are few steps involved in reliability analysis of any sub-system; these are described as follows:

Table 3 OEE of CM for a period of six months

Sl. No	Month	OEE of CM
1	First	0.144
2	Second	0.260
3	Third	0.311
4	Fourth	0.304
5	Fifth	0.234
6	Sixth	0.203

Estimation of Time Between Failures of Each Sub-Systems

For this purpose, the breakdown details were recorded for a period of six months and time between failures were calculated between each failure for every sub-system within the entire study period.

Check for Independence of Data

Time between failure (TBF) data are a prerequisite for evaluation of reliability of any system and sub-system. These TBF data are fitted to a suitable probability distribution. However, the TBF data must be free from any trend and correlation to qualify for getting fitted to any theoretical probability distribution.

As Vagenas et al. mention, there are basically two effective techniques utilized to evaluate the independence of the data set; these are trend test and serial correlation test [11].

Trend test is the scatter plot between the cumulative time between failure and cumulative failure number. The TBF data, which are free from any trend, depict linear plot. Here, the trend test plot for electrical sub-system is depicted in Figure 1, where the plot is depicting a linear trend to conclude that the TBF data for electrical sub-system are free from any trend.

Similarly, the trend test graphs for each sub-system were plotted and show almost linear trend in every case, which delineates that the TBF data set for all the sub-systems is free from any trend.

Serial correlation plot is the scatter one between (i-1)th TBF and ith TBF, where ith TBF is the TBF at any instance and (i-1)th is the just previous TBF to any corresponding ith TBF. For data sets free from any correlation, this scatter plot becomes random and does not show any specific trend.

The serial correlation plot of electrical sub-system is depicted in Figure 2, which is showing a random plot; hence it is free from any correlation. Similarly, the serial correlation plots for each sub-system were plotted and in every case, randomness was observed. This delineates that TBF data set for all the sub-systems is free from any correlation.

As TBF data for each sub-system are free from any trend and correlation, hence they qualify to be fitted to theoretical probability distributions.

Goodness-of-Fit Test to a Suitable Probability Distribution

For reliability analysis, there are three probability distributions, which are mostly accepted and widely used as mentioned by Vagenas et al. [11]; these are: Weibull distribution, log-normal distribution and exponential distribution.

Goodness-of-fit test is essential to identify the best fit distribution for TBF data of any specific sub-system.

There are two types of goodness-of-fit test techniques popular for this purpose; these are: Chi-square test and Kolmogorov–Smirnov test (K–S test). However, Vagenas et al. furthermore mention that K–S test is better suited for TBF data, as TBF is not discrete variable and K–S test is a versatile test technique [11]. Chi-square test is basically most suited to discrete variables. Therefore, K–S test technique is being used to evaluate the best fit probability distribution for TBF dataset of each sub-system.

Few assumptions for K–S test of this study are mentioned hereunder:

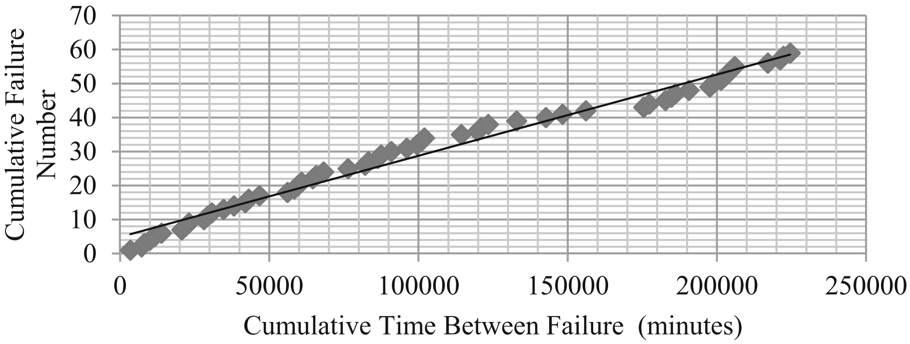


Fig. 1 Trend test plot for electrical sub-system

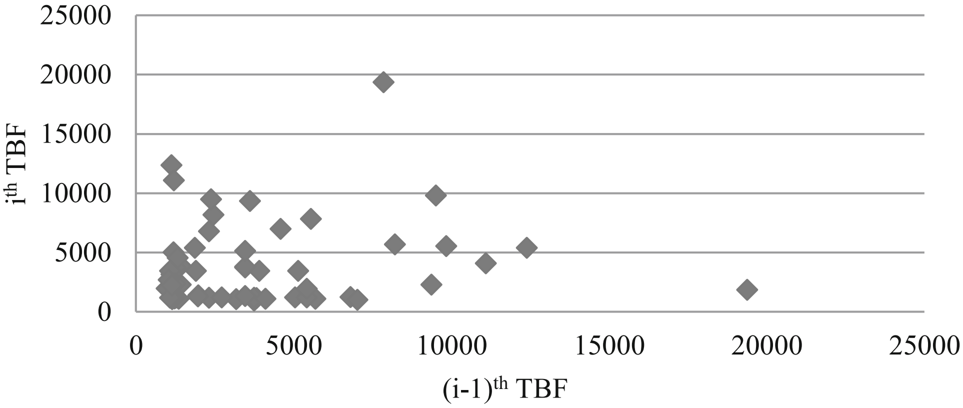


Fig. 2 Serial correlation plot of electrical sub-system

Table 4 K–S test goodness-of-fit result and best fit distributions for each sub-system

Sl. No	Name of Sub-system	*p* value (K–S test)			Significance level (α)	Observation and Best fit distributions (Selected)
		Exponential	Log-normal	Weibull		
1	Electrical	0.004	0.055	0.077	0.05	$p > \alpha$ for Weibull and Lognormal but Weibull is selected as *p* is higher
2	Cutter	0.008	0.303	0.01	0.05	$p > \alpha$ for Lognormal; Lognormal is selected
3	Gathering	0.860	0.552	0.798	0.05	$p > \alpha$ for all three distributions; but Exponential is selected as p is highest
4	Traction	0.669	0.933	0.763	0.05	$p > \alpha$ for all three distributions; but Lognormal is selected as *p* is highest
5	Hydraulic	0.404	0.827	0.628	0.05	$p > \alpha$ for all three distributions; but Lognormal is selected as p is highest
6	Chassis	0.122	0.411	0.236	0.05	$p > \alpha$ for all three distributions; but Lognormal is selected as p is highest
7	Ram car	0.009	0.056	0.009	0.05	$p > \alpha$ for Lognormal, Lognormal is selected
8	Conveyor	0.002	0.054	< 0.0001	0.05	p > α for Lognormal, Lognormal is selected
9	Feeder breaker	0.324	0.393	0.242	0.05	$p > \alpha$ for all three distributions; but Lognormal is selected as p is highest
10	CM Conveyor	0.639	0.957	0.734	0.05	$p > \alpha$ for all three distributions; but Lognormal is selected as p is highest

Table 5 Best fit probability distributions and their relevant parameters

Name of sub-system	Best fit probability distribution	Parameter of relevant distribution
Electrical	Weibull distribution	**A** = 4118.69, **B** = 1.24313
Cutter	Lognormal distribution	$\mu = 8.02429$, $\sigma = 1.02383$
Gathering	Exponential distribution	$\mu = 24{,}324.3$
Traction	Lognormal distribution	$\mu = 8.87753$, $\sigma = 1.01364$
Hydraulic	Lognormal distribution	$\mu = 8.84057$, $\sigma = 1.03805$
Chassis	Lognormal distribution	$\mu = 9.30361$, $\sigma = 0.94891$
Ram car	Lognormal distribution	$\mu = 7.85405$, $\sigma = 0.86053$
Mine conveyor	Lognormal distribution	$\mu = 7.70443$, $\sigma = 0.802488$
Feeder breaker	Lognormal distribution	$\mu = 8.16352$, $\sigma = 0.977755$
CM Conveyor	Lognormal distribution	$\mu = 8.90622$, $\sigma = 0.991348$

Table 6 Reliability result for each sub-system

Time (mins)	Electrical	Cutter	Gathering	Traction	Hydraulic	Chassis	Ram car	Mine Conveyor	Feeder breaker	CM Con
0	1	1	1	1	1	1	1	1	1	1
1000	0.842	0.862	0.960	0.974	0.969	0.994	0.864	0.840	0.900	0.978
2000	0.665	0.660	0.921	0.896	0.884	0.964	0.616	0.551	0.717	0.906
3000	0.509	0.507	0.884	0.805	0.789	0.914	0.430	0.353	0.564	0.818
4000	0.381	0.396	0.848	0.718	0.701	0.856	0.305	0.231	0.447	0.732
5000	0.280	0.315	0.814	0.639	0.622	0.796	0.220	0.156	0.359	0.653
6000	0.203	0.255	0.781	0.570	0.554	0.738	0.163	0.107	0.292	0.583
7000	0.145	0.209	0.750	0.509	0.495	0.682	0.123	0.076	0.240	0.521
8000	0.102	0.173	0.720	0.457	0.444	0.631	0.094	0.055	0.200	0.467
9000	0.071	0.146	0.691	0.411	0.399	0.583	0.073	0.040	0.168	0.421
10,000	0.049	0.123	0.663	0.371	0.361	0.539	0.057	0.030	0.142	0.380
11,000	0.034	0.105	0.636	0.336	0.327	0.499	0.046	0.023	0.121	0.344
12,000	0.023	0.091	0.611	0.306	0.297	0.463	0.037	0.018	0.104	0.312
1300	0.015	0.079	0.586	0.279	0.271	0.429	0.030	0.014	0.090	0.284
14,000	0.010	0.068	0.562	0.255	0.248	0.399	0.025	0.011	0.079	0.259
15,000	0.007	0.060	0.540	0.233	0.228	0.371	0.020	0.009	0.069	0.237

Legend: CM Con. = CM Conveyor

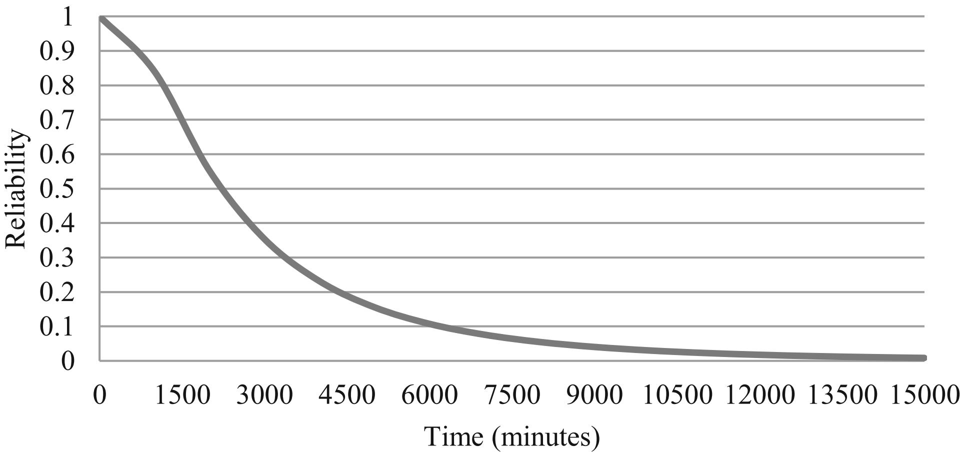


Fig. 3 Reliability trend of mine conveyor sub-system

H_0 = Data follow the specific distribution (this is null hypothesis).

H_a = Data do not follow the specific distribution (this is alternate hypothesis).

α is significance level (generally considered 5% or 0.05).

K–S test goodness of fit gives a p value, which along with α is considered for judgement of acceptance or rejection of the null hypothesis.

For every case where $p < \alpha$ the null hypothesis is rejected.

However, as per the selected null and alternate hypothesis as mentioned above; for fitting a distribution the null hypothesis should not be rejected and $p > \alpha$ is desirable.

The following Table 4 depicts result of K–S goodness-of-fit test as well as best fit probability distribution for TBF data of each sub-system. This goodness-of-fit test is performed using XLSTAT, which is a statistical add-in to MS-Excel.

Fitting a Suitable Distribution to TBF Data

TBF data of each sub-system are fitted to relevant distribution indicated by goodness-of-fit test. This is performed using distribution fitter application of MATLAB R2021a. During the distribution fitting in MATLAB, it provides

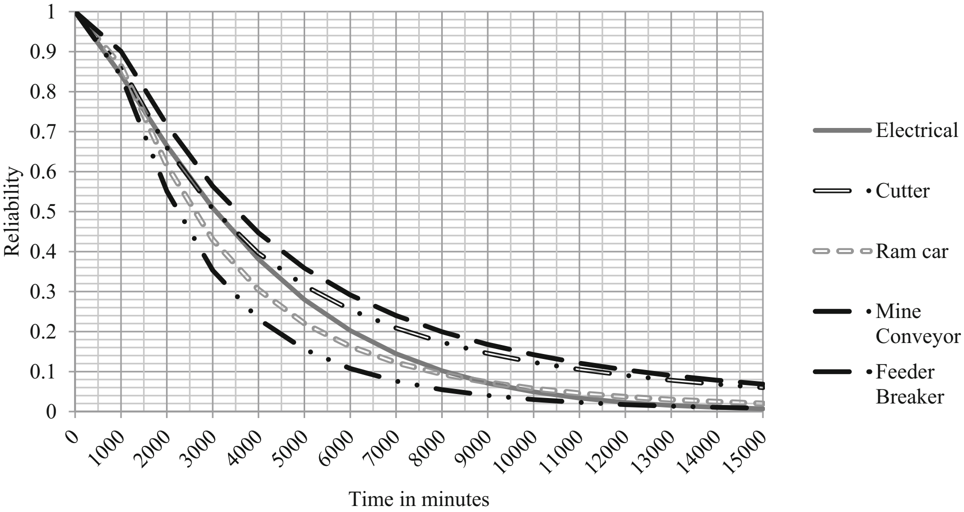


Fig. 4 Reliability depletion trend of vulnerable sub-systems

information related to relevant parameters with that distribution, which is helpful in calculation of reliability at any instance theoretically.

The following Table 5 depicts the best fit probability distribution for each sub-system, which is also indicated in the above-mentioned Table 4. Table 5 also provides values of all relevant parameters of those distributions under the effect of TBF data of assigned sub-system.

Evaluation of the Reliability of Each Sub-System Based on Best Fit Distribution

As mentioned earlier, the TBF data are fitted to relevant best fit distribution through MATLAB R2021a and evaluated by selecting survivor function to assess reliability. The entire reliability analysis was performed for a time period of fifteen thousand minutes starting from zero minute with interim time gap of one thousand minutes. The identified potentially vulnerable sub-systems require further analysis for performance improvement through Failure Modes and Effects Analysis (FMEA).

Here, the reliability is evaluated using survivor function option of MATLAB distribution fitter. However, reliability of any sub-system can be calculated using the relevant formulae for the associated distribution using the parameter values mentioned in Table 5.

The reliability calculation formulae for different probability distributions are depicted in the following expressions [11, 12]:

$$\text{Reliability (Weibull)} = e^{-(t/A)^B}$$

Table 7 Occurrence, Severity and Detectability rating table

Occurrence (O)	Severity (S)	Detectability (D)	Rating
Extremely high ($\geq$ 1 in 2)	Hazardous without warning	Absolutely impossible to detect	10
Very high (1 in 3)	Hazardous with warning	Very remote chance of detection	9
Repeated failures (1 in 8)	Very high (system breaks down but no hazard to personnel)	Remote chance of detection	8
High (1 in 20)	High (system works but performance seriously affected)	Very low chance of detection	7
Moderately high (1 in 80)	Moderate (performance degraded)	Low chance of detection	6
Moderate (1 in 400)	Low (system works but requires maintenance to avoid further failure)	Moderate chance of detection	5
Relatively low (1 in 2000)	Very low (performance is less affected)	Moderately high detection	4
Low (1 in 15,000)	Minor (minor effect on system performance)	High chance of detection	3
Remote (1 in 150,000)	Very minor (very slight effect)	Very high chance of detection	2
Nearly impossible ($\leq$ 1 in 150,000)	None (No effect)	Almost certain chance of detection	1

Table 8 Failure modes; their corresponding RPN calculation and Ranking details

System	Sub-system	Failure mode	O	S	D	RPN	Ranking based on RPN	Rearranging failure modes on the basis of ranking (Starting from rank 1)	Rank
Continuous Miner	Mine Conveyor	Motor Breakdown	7	9	7	441	1	Motor Breakdown	1
		Gearbox related issues	6	7	8	336	2	Gearbox related issues	2
		Bearing problems	5	6	8	240	4	Power transmission failure	3
		Brakes and emergency brakes	3	10	7	210	7	Bearing problems	4
		Belt damage	6	8	4	192	10	Drive Failure	5
		Take up and sagging issues	7	6	4	168	13	Trailing cable rupture	6
		idler related issues	7	5	3	105	18	Brakes and emergency brakes	7
	Ram car	Drive Failure	5	8	6	240	5	Cutter induced vibration	8
		Engine related malfunction	5	8	5	200	9	Engine related malfunction	9
		Tyre and Rim failure	6	8	3	144	14	Belt damage	10
		Conveyor motor malfunction	4	8	4	128	15	Conveyor Drive failure	11
		Braking System problems	3	10	4	120	17	Cutting drum oil leak	12
	Electrical	Power transmission failure	8	8	4	256	3	Take up and sagging issues	13
		Trailing cable rupture	6	8	5	240	6	Tyre and Rim failure	14
		Pump motor Failure	6	7	3	126	16	Conveyor motor malfunction	15
		Traction motor failure	4	8	3	96	20	Pump motor Failure	16
		Load Center Failure	3	8	1	24	26	Braking System problems	17
		Controller and remote malfunction	2	8	1	16	27	idler related issues	18
	Cutter	Cutter induced vibration	7	5	6	210	8	Conveyor malfunction	19
		Cutting drum oil leak	5	6	6	180	12	Traction motor failure	20
		Cutter motor Failure	4	8	2	64	21	Cutter motor Failure	21
		Dust suppression failure	5	6	2	60	23	Lump breaker failure	22
	Feeder breaker	Conveyor Drive failure	6	8	4	192	11	Dust suppression failure	23
		Conveyor malfunction	5	7	3	105	19	Dust suppression spray failure	24
		Lump breaker failure	4	8	2	64	22	Discharge chute jamming	25
		Dust suppression spray failure	5	5	2	50	24	Load Center Failure	26
		Discharge chute jamming	3	8	2	48	25	Controller and remote malfunction	27

$$\text{Reliability(Exponential)} = e^{-(t/\mu)}$$

$$\text{Reliability(Lognormal)} = \left[1 - \Phi\left(\frac{\ln(t) - \mu}{\sigma}\right)\right]$$

Here, Φ represents normal cumulative distribution function.

And t = time in minutes for all above expressions.

The reliability result for each sub-system as obtained from MATLAB has been depicted in Table 6.

Table 6 delineates the reliability of any sub-system at any point of time, and it is really a handy tool to identify the sub-systems with rapid rate of reliability depletion; those sub-systems are basically considered vulnerable and contributing to lower availability trend of the system. Consequently, it reduces the Overall Equipment Effectiveness of the system.

Reliability trend of mine conveyor sub-system is depicted in Figure 3. However, the reliability trend of all

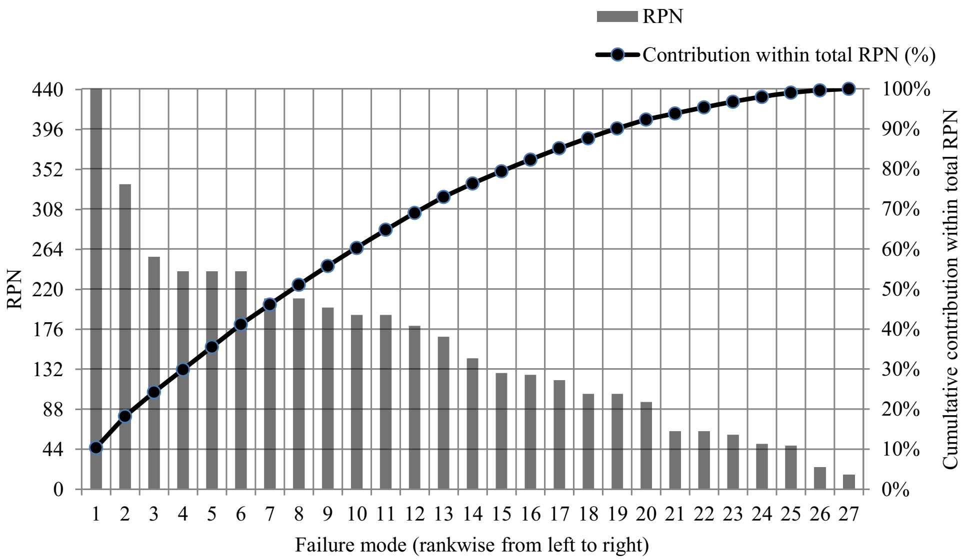


Fig. 5 Pareto chart to depict significant failure modes

the sub-systems showing similar trend of depletion of reliability, having increase in probability of failure with time is quite natural for any working machinery. The sub-systems depicting unusually fast reliability depletion trend when compared with other sub-systems of the same system can only be considered as vulnerable sub-systems.

Table 6 helps to easily identify the sub-systems reaching almost zero reliability after fifteen thousand minutes of operation; these sub-systems are electrical, cutter, ram car, mine conveyor and feeder breaker, respectively. These sub-systems can be considered potentially vulnerable, but their ranking can be determined from their reliability depletion trend. For the purpose of understanding the reliability depletion trend, the reliability trend of above mentioned potentially vulnerable sub-systems is plotted in a single plot (Figure 4). This Figure 4 helps to identify the ranking of vulnerable sub-systems ranging from most vulnerable to the next vulnerable sub-systems in descending order with mine conveyor being the most vulnerable sub-system, followed by ram car, electrical, cutter and feeder breaker respectively.

Failure Modes and Effects Analysis of these vulnerable sub-systems is important to identify most challenging failure modes; mitigating which may have positive impact on sub-systems as well as system availability and OEE.

Failure Modes and Effects Analysis (FMEA)

It is a technique to identify the failure modes or potential causes of failure of critical systems and sub-systems contributing towards overall system failure. This technique basically depends on evaluation of Risk Priority Number (RPN) for each failure modes. On identifying the critical or significant failure modes, some suitable controls are suggested to minimize the RPN value of significant failure modes.

The RPN value depends on three factors; namely: Occurrence (O), Severity (S) and Detectability (D). The RPN is calculated as follows:

RPN = Occurrence × Severity × Detectability.

Higher RPN number signifies higher criticality for corresponding failure mode; the target is to mitigate the criticality by reducing this RPN number through application of adequate engineering controls.

There are standard scales available for Occurrence (O), Severity (S) and Detectability (D) values as shown by Zuniga et al. [13], which are shown in Table 7. The ratings for all the parameters corresponding to each failure modes are selected from this table suitably.

This technique is applied on potentially vulnerable sub-systems as identified by reliability analysis. The following Table 8 depicts important failure modes associated with those sub-systems and their corresponding Occurrence, Severity and Detectability ratings as well as Calculated RPN values. Finally, rankings are provided to each failure modes based on RPN value in descending order (highest RPN assigned rank 1) and then these failure modes are rearranged based on ranking. These ranking details are given in the following Table 8.

From Table 8, it can be seen that RPN values for all the failure modes are not significantly high and thus can be excluded on taking special care. A Pareto chart as shown in Figure 5 is prepared to evaluate the significant failure modes.

The above Pareto chart in Figure 5 depicts one horizontal axis and two vertical axes. The horizontal axis depicts the rank of corresponding failure mode, left vertical axis depicts the RPN value for each failure modes, whereas right vertical axis depicts the cumulative contribution of each failure modes within total RPN.

Pareto chart depicted there are fifteen significant failure modes (rank 1 to rank 15) contributing to eighty percent of total RPN.

The concerned engineer along with marketing personnel and other experienced persons were involved in getting proper suggestions to mitigate RPN values of the identified failure modes. The related suggestions vis-à-vis fifteen failure modes are provided in Table 9. These may alleviate the criticality and improve the overall system reliability and effectiveness.

Discussion

The reliability depletion trend of the vulnerable sub-systems was plotted in a single graph depicted in Figure 4, for the purpose of their ranking based on reliability depletion trend. The mine conveyor with highest rate of reliability depletion was found most vulnerable, followed by ram car, electrical, cutter and feeder breaker.

Further, FMEA was applied on these vulnerable sub-systems to identify relevant failure modes. Subsequently, Pareto chart was used to identify the significant failure modes contributing to eighty percent of total RPN value.

In the Pareto chart depicted in Figure 5, a horizontal gridline passes through 80% mark intersecting the cumulative percentage curve at a point, from that intersection

Table 9 Failure modes and corresponding suggestions

Rank	Failure mode	Suggestions to mitigate
1	Motor Breakdown (Mine Conveyor)	Regular vibration and Noise monitoring, Maintain Proper motor sealing gaskets
2	Gearbox related issues (Mine Conveyor)	Regular oil analysis of the gearbox and replace if degraded Vibration analysis with VIBSCANNER and keep it within limit
3	Power transmission failure (Electrical)	Regular maintenance of transmission lines Use advanced fault detection equipment to easily locate the fault
4	Bearing problems (Mine Conveyor)	Install automatic lubrication system for bearings Regular vibration monitoring using VIBSCANNER and noise monitoring
5	Drive Failure (Ram car)	Regular vibration level monitoring using VIBSCANNER Pre operational check for unusual noise or performance variation
6	Trailing cable rupture (Electrical)	Ensure that cable is properly anchored to suitable anchor points and free to move Near the operational CM it must be monitored that trailing cable is not damaged by any operational machine
7	Brakes and emergency brakes (Mine Conveyor)	Introduce latest electro-hydraulic braking system along with existing mechanical brakes Regular inspection of braking components
8	Cutter induced vibration (Cutter)	Immediate stoppage of cutting for unusual behaviour or noise from cutter Prior knowledge of rock formation to ensure non presence of any high strength rock
9	Engine related malfunction (Ram car)	Regular engine oil analysis and replace if degraded Monitor the emission, it must be within stipulated limit set by DGMS Pre operational check for unusual noise and burning smell
10	Belt damage (Mine Conveyor)	Avoid overloading of belt and ensure transfer material is loaded at centre Regular visual inspection of belt condition
11	Conveyor Drive failure (Feeder breaker)	Regular inspection of the head and tail shaft assemblies and vibration monitoring Critical inspection of meshing components before Mean Time Between Failure (MTBF) and replace if necessary
12	Cutting drum oil leak (Cutter)	Regular inspection of oil level and if found decreasing immediate check for leakage
13	Take up and Sagging issues (Mine Conveyor)	Inspect catenary sag of belt during scheduled maintenance, for this catenary sag gauge can be used Proper lubrication and maintenance of take up pulleys
14	Tyre and Rim failure (Ram car)	Visual inspection of tyres and rims before starting the equipment Real time monitoring of tyre pressure using TPMS
15	Conveyor motor malfunction (Ram car)	Proper cleaning and lubrication of the system during maintenance Ensure proper sealing/ protection to the motor and shaft

point passing a vertical gridline meeting the horizontal axis. There are fifteen failure modes which are at left to that vertical gridline, contribute to eighty percent of total calculated RPN and can be termed as “significant failure modes”. These significant failure modes were considered for special controls to mitigate the RPN value and rest of the failure modes were excluded from further studies.

Further, FMEA analysis can be carried out after considerable time from implementation of recommended controls; to verify the improvement of system and sub-system performance as well as effectiveness.

Conclusion

This study identified fifteen potential failure modes from five sub-systems, contributing to overall system failure. A discussion among group of experienced personnel and engineers was conducted to find suitable solutions to these failure modes. The actions or controls suggested out of the discussion to reduce the criticality of failure modes are believed to be effective in improving the machine performance as well as Overall Equipment Effectiveness (OEE).

Evaluation of OEE, reliability analysis and FMEA of the system and sub-systems must be carried out in regular predefined interval to mitigate their further criticality.

Finally, it can be concluded that this paper may be a handy guide for stepwise procedures of reliability analysis and Failure Modes and Effects Analysis of Continuous Miner-based underground coal production system, which can be applicable to other machines as well.

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Declarations

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