Comparative Analysis of RPN and Criticality Index for Assessment and Prioritization of Dumper Breakdowns

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Abstract. Dumper is a repairable equipment which is used to carry and dump the coal in open cast mining (OCM). Due to the enhanced demand for thermal power, the consumption of coal has increased to generate electricity. To meet the demand, coal must be produced and supplied at right time in right quantity. Dumpers, which act as load transport system, carry the coal from the mine to the power plant. Interruptions in the dumpers in the form of failures may result in improper and delayed delivery of coal to the power generating unit. In the interest of proper delivery and production of coal, failures are to be minimized and the reliability of the dumper should be maximized. In this paper, a well-known reliability enhancement metric, i.e., failure mode effect and criticality analysis (FMECA) is used to identify the risk and criticality level of dumper breakdowns. Initially, FMEA is carried out to find out all potential failure modes of functionally significant components of dumpers and thereafter, risk priority number (RPN) and criticality index is computed for each identified failure mode. Further, a comparative analysis of RPN and criticality index is performed to find out the convenient approach to conduct criticality analysis in FMECA.

1. Introduction
Coal mining is the process of extraction of coal deposits from the surface of the earth and from the underground. Open Cast mining is a method in which coal is excavated by removing a seam of overlying soil and rock bed. A variety of equipment is used in open cast mining right from the removal of overburden to the unloading of the coal to the central storage area. Bucket wheel excavator, dumper, dragline, bull dozer and drill rig are few of the equipments used in open cast mining. In order to achieve the established production targets, mining organizations are demanding higher equipment reliability. Reliability indicates the performance of overall machine condition and it can be defined as the probability that a component or a system will perform its required function satisfactorily for a given time period when used according to stated operating conditions [1]. Approximately 10% to 15% of production time is wasted by unscheduled maintenance in open cast mining [2] and also the cost of maintenance is more than 60% of the operation cost [3]. Thus, reliability of mining equipment is a complex issue that needed to be addressed. There are many factors that impact directly or indirectly on the reliability of mining equipment. Some of these factors are shown in the figure 1. So, the reliability of the mining equipment should be improved for the following reasons.
To maximize profit of the organization
To minimize the cost of poor reliability
To provide accurate short-term forecasts for operating hours of the equipment
To enhance the productivity by making equipment available in the field
To overcome challenges imposed globally

FMECA is proved to be one of the prominent reliability enhancement techniques, which prevents the sudden failures from occurring. Significant contributions have been made in the reliability literature to apply FMECA technique for various fields and systems. Xiaoqing Cheng et al. [4] assessed reliability of metro door unit by FMECA approach. The study revealed that EDCU and Limit switch failures are having highest criticality. Rundong Yan et al. [5] carried out reliability analysis of AGV’s using FMECA and FTA. After the analysis, it was found that all AGV components are critical except manual button. Dobrivoje Ćatić et al. [6] performed criticality analysis of steering tie rod joint components. FMECA approach was applied to investigate the failure modes, causes and effects and also their criticality. Ball pin and cup are found to be the highest critical components of tie rod joint. Sheng-Hsien Teng et. al. [7] developed an approach to integrate FMECA, process design and process control in order to establish an effective quality control plan. Marcantonio Catelani et al. [8] applied FMECA method on photovoltaic module with an objective to eliminate & reduce the impact of potential failure modes before the completion of the design. D. Ćatić et al. [9] analyzed the degree of criticality of motor vehicle drum brake components. A relation between various events that lead to system failure was built using FTA. After analysis, shoe linings have found to be having highest critical degree. Mehrzad Ebrahimzadeh [10] assessed potential hazards by FMECA method in Yazd Steel Complex. Risks were evaluated for different parts of the complex using FMECA worksheet. Fall basket Netscape and infrared light are the failure modes showing highest risk.

It is observed that FMECA is a powerful tool to analyze the criticality of a system. It is also observed that, in the literature very few researchers have devoted their work to develop FMECA for mining equipment. This paper is devoted to apply FMECA technique to enhance mining equipment reliability. Moreover, among all the equipments used in OCM, dumpers are found to be most unavailable equipment due to their breakdowns. Hence, in the present work, FMECA is used to analysis the criticality of dumpers breakdowns. However, there are two ways to find out the criticality of a failure mode i.e., by (i) RPN (ii) Criticality Index. In this paper, these two methods are adopted to find out the criticality. Further a comparative analysis is done in order to find the better approach among the two.

2. Failure mode effect and criticality analysis (FMECA)
A wide variety of techniques are available to identify the risk associated with the failures modes. The process of risk management includes different steps such as risk identification, risk analysis, risk evaluation and implementation of action plan. The classifying steps of risk management are shown in the figure 2. The degree of risk of a failure mode can vary and evaluated differently based on the objective of
the analysis. The risk can be in the form of damage to the environment, safety of employees, loss of production or availability of a machine. FMECA is a qualitative risk assessment technique, which can be used to assess the risk associated with each failure modes. The origin of FMECA was initiated by US Army in 1949 to enhance and inspect the reliability of the military systems [11]. The MIL-STD-1629A developed the rules and requirements to perform FMECA in order to evaluate failure modes, their causes and effects on the mission, persons and system safety [12]. FMECA basically predict the catastrophic failures and prioritizes the failure modes based on their associated risk. It further suggests preventive measures to enhance the reliability of the system [13]. Identification and prioritization of risky and critical failure modes can be done in two ways in FMECA, i.e., through Risk Priority Number (RPN) and through Criticality Index (CI). These two criterions are briefed in the preceding sections.

\[ \text{Risk Priority Number} = (O_i \times S_i \times D_i) \]

Here, \( O_i \), \( S_i \) and \( D_i \) refers to the occurrence, severity and detection of \( i^{th} \) failure mode of \( j^{th} \) component.

\[ C_{ij} = \alpha_{ij} \times \beta_{ij} \times \gamma_{ij} \times t_{ij} \]

Where, \( \alpha_{ij} \) = Failure frequency ratio, \( \gamma_{ij} \) = Failure rate, \( \beta_{ij} \) = Effect probability and \( t_{ij} \) = component working time of \( i^{th} \) failure mode of \( j^{th} \) component.

2.1 Risk priority number (RPN)

In traditional FMECA, the risk of a failure can be measured by a metric called Risk Priority Number (RPN). It is the generalized method to determine the priority of failure modes in terms of their risks. This is achieved by multiplying three indexes i.e., Occurrence (O), Severity (S) and Detection (D). These three factors are evaluated for each failure mode on a ten point scale, usually from 10 to 1.

\[ \text{Risk Priority Number} = O_i \times S_i \times D_i \]

Here, \( O_{ij} \), \( S_{ij} \) and \( D_{ij} \) refers to the occurrence, severity and detection of \( i^{th} \) failure mode of \( j^{th} \) component.

2.2 Criticality index (CI)

Criticality Index is another mathematical formulation to analyze the criticality of a failure mode. It is used to find the perniciousness of a component breakdown. The consequence of a breakdown on the lucrative operation and safety of a machine is determined by Criticality Index. For this, it is necessary to have the data regarding failure rate, failure modes, severity categories, operating time etc., The criticality index of each failure mode is computed by using the following relation

\[ C_{ij} = \alpha_{ij} \times \beta_{ij} \times \gamma_{ij} \times t_{ij} \]

3. Field investigation

FMECA is carried out on dumpers working at Open Cast Project – II (OCP-II), Ramagundam. Dumpers are used to handle and transport the coal from mine to the storage area. Figure 3 shows a typical dump truck used in open cast mine. Before conducting the analysis, relevant documents related to the failure history of the dumpers are collected from the maintenance shop. Data inconsistencies and errors are removed and refined data is arranged in a chronological order. All the failure modes are classified under seven functionally significant components of dumpers as depicted in figure 4.
4. FMEA of dumper

For the convenience of the analysis the entire system of dumper is divided into seven sub-systems (components). These include brake, suspension, engine, transmission, steering, hydraulic and radiator. Failure modes are identified for each component and their cause and effects have been studied. The FMEA table for seven dumper components is shown in the table 1.

![Dump truck at Open cast mine](image1.jpg)

**Figure 3.** Dump truck at Open cast mine

![Seven functionally significant components of dumper](image2.jpg)

**Figure 4.** Seven functionally significant components of dumper

**Table 1.** FMEA of Load Hauling Dumper

| Component  | Component Function                                                                 | Failure modes | Failure effect description                                                                 | Failure Cause(s)                                      |
|------------|-------------------------------------------------------------------------------------|---------------|-------------------------------------------------------------------------------------------|------------------------------------------------------|
| Brake      | Impede motion by absorbing energy                                                   | 1-a. Brake oil leak | Loss of Brake pressure                                                                     | Oil seal failure                                      |
|            |                                                                                    | 1-b. Air leak from the brake | Reduced stopping efficiency                                                               | Damaged brake lines                                   |
|            |                                                                                    | 1-c. Brake Jam      | Motion can’t be stopped                                                                     | Development of hotspots                               |
|            |                                                                                    | 1-d. Brake wear     | Improper function of brakes                                                               | Worn out brake pads                                  |
|            |                                                                                    | 1-e. Brake Anchor Leak | Reduced performance of braking system                                                     | Distorted brake shoe                                 |
| Suspension | Reduces the abrupt impact and excessive bouncing                                    | 2-a. Suspension bolt broken | Entire vehicle may vibrate                                                                | Excessive bouncing                                   |
|            |                                                                                    | 2-b. Suspension Oil Leak | Motion may become bouncy                                                                  | Oil seal failure                                      |
| Engine     | To convert thermal/chemical energy into mechanical energy                            | 3-a Exhaust leak    | Decreased fuel efficiency                                                                  | Wear of piston rings                                 |
|            |                                                                                    | 3-b Engine replaced | Unavailable service & loss of production                                                  | Contamination of fuel                                |
|            |                                                                                    | 3-c Engine head failed | Coolant and oil leak                                                                      | Rust/scale formation                                 |
3-d. Engine vibration
4-a. Toe in toe out
4-b. Gear shifting problem
4-c. Transmission oil leaked
5-a. Steering oil cylinder leak
5-b. Steering box bolts replaced
5-c. Steering ball bearing broken
6-a. Hydraulic oil leak
6-b. Hoist not working
7-a. Water boil in radiator
7-b. Water pump leak
7-c. Radiator hose problem
7-d. Radiator fan damaged

Noisy function
Minimized turning tendency
Delayed gear engagement
Loss of power efficiency
Unsafe driving
Interruption of service
Poor turning tendency
Inefficient operation
Stoppage of service
Increased water pressure
Improper circulation
Loss in heat transfer
Slow cooling effect
Detonation
Bumpy roads
Worn out gears
Wear of parts
Improve maintenance
Constant vibration
Seal damage
Running too hot
Thermostat malfunction
Damaged water pump
Over heating
Improper maintenance

5. FMECA analysis using risk priority number (RPN)
RPN is a metric used to prioritize all failure modes in a system to decide preventive measures that may reduce the risk and minimize the failure occurrences. This metric can also help in establishing the control mechanisms for detecting the failure. The influence of three indexes, occurrence, severity and detection are used to evaluate the RPN. Occurrence represents frequency of component failure, severity reflects the estimate of how strongly the consequence of failure impacts availability of service and detection estimates the chances of identifying/detecting a breakdown before it occurs. All these three parameters are measured on a 10 point scale, where 1 indicates lower risk and 10 indicates higher risk. The ranking criteria for each of these three parameters are shown in the table 2. Based on these, RPN is calculated and ranks were allotted as per the RPN value. The score of \( O_{ij} \), \( S_{ij} \) and \( D_{ij} \) for each failure mode and resulting RPN values are shown in table 3. It is observed that, failure mode 3-c is having highest value of RPN and failure mode 5-b is having least value of RPN. It is also noted that, few failure modes are having similar value of RPN. In such cases ranking was done based on the severity level of the failure mode. Further, in table no 3 the values of O, S and D are allotted based on the data pertaining to a group of dumpers. If one considers another group of dumpers there will be different failures with different frequencies. In such cases, the values of O, S and D varies and hence RPN also. Thence, for different systems, there may be different values of RPN. However, judgment can be made based on the rankings of RPN.

Table 2. Evaluation criteria for severity, occurrence and detection

| Rank | Severity Ranking Criteria | Occurrence Ranking Criteria | Detection Ranking Criteria |
|------|---------------------------|----------------------------|---------------------------|
| 1    | Interruption is less than 2 hours | Once in two years | Almost certain to detect |
| 2    | Interruption is more than 2 hours and less than 5 hours | Once in 18 months | Very high chance of detection |
| 3    | Interruption is more than 5 hours and less than 10 hours | Once in a year | High chance of detection |
Table 3. RPN and its ranking for failure modes

| Failure Mode | Occurrence | Severity | Detection | RPN | Rank |
|--------------|------------|----------|-----------|-----|------|
| 1-a          | 3          | 3        | 2         | 18  | 21   |
| 1-b          | 3          | 4        | 7         | 84  | 7    |
| 1-c          | 4          | 5        | 5         | 100 | 5    |
| 1-d          | 3          | 3        | 3         | 27  | 18   |
| 1-e          | 4          | 3        | 3         | 36  | 16   |
| 2-a          | 4          | 3        | 7         | 84  | 8    |
| 2-b          | 6          | 5        | 5         | 150 | 5    |
| 3-a          | 3          | 3        | 7         | 63  | 11   |
| 3-b          | 4          | 7        | 7         | 196 | 2    |
| 3-c          | 4          | 7        | 8         | 224 | 1    |
| 3-d          | 3          | 3        | 4         | 36  | 17   |
| 4-a          | 4          | 3        | 2         | 24  | 19   |
| 4-b          | 4          | 3        | 4         | 48  | 14   |
| 4-c          | 5          | 4        | 5         | 100 | 6    |
| 5-a          | 5          | 3        | 4         | 60  | 12   |
| 5-b          | 3          | 1        | 6         | 18  | 23   |
| 5-c          | 3          | 1        | 7         | 21  | 20   |
| 6-a          | 7          | 5        | 5         | 175 | 3    |
| 6-b          | 5          | 3        | 5         | 75  | 10   |
| 7-a          | 4          | 4        | 5         | 80  | 9    |
| 7-b          | 3          | 3        | 5         | 45  | 15   |
| 7-c          | 3          | 2        | 3         | 18  | 22   |
| 7-d          | 3          | 3        | 6         | 54  | 13   |

6. FMECA analysis using criticality index

Criticality index is a relative measure of consequence of failure mode that has on the safety and operation of the system. The system or component failure data is essential for quantitative analysis of criticality index. The magnitude of criticality index for each failure mode is computed by the product of α, β, γ, t. Alpha (α) is used to express the item failure probability and beta (β) is used to define the failure effect probability. γ and t are the failure rate and duration of component working time respectively. The α, β, γ and t values for individual failure modes are shown in the table 4. The value of alpha is taken as the ratio.
of number of failures observed to the total number of failures of the component. The value of beta is identified based on the consequence of the failure mode on the system. $\beta = 1$ represents that the system certainly fails, $\beta = 0.5$ represent that the system may fails, $\beta = 0.1$ indicates that the system rarely fail and $\beta = 0$ means there is no effect on the system. The gamma value reflects the failure rate of the component which can be obtained by dividing total number of component failures by operating time of the component. The variable $t$ indicates the duration of component operating hours. It is observed that, failure mode 2-b is having highest value of criticality index and failure mode 5-b is having lowest value of criticality index. For the similar values of criticality index, ranking was done based on the failure frequency.

Table 4. Criticality index and its ranking for failure modes

| Failure Mode | $\alpha$   | $\beta$ | $t$    | $\gamma$ | Criticality Index | Rank |
|--------------|------------|---------|--------|----------|------------------|------|
| 1-a          | 0.238095   | 0.1     |        |          | 0.5              | 19   |
| 1-b          | 0.095238   | 0.5     |        |          | 1                | 13   |
| 1-c          | 0.238095   | 1       | 7168   | 0.00293  | 5                | 4    |
| 1-d          | 0.142857   | 0.5     |        |          | 1.5              | 10   |
| 1-e          | 0.285714   | 0.1     |        |          | 0.6              | 16   |
| 2-a          | 0.263158   | 0.1     |        |          | 0.5              | 18   |
| 2-b          | 0.736842   | 1       | 7175   | 0.002648 | 14               | 1    |
| 3-a          | 0.133333   | 0.5     |        |          | 1                | 12   |
| 3-b          | 0.266667   | 0.1     |        |          | 0.4              | 20   |
| 3-c          | 0.4        | 0.1     | 7092   | 0.002115 | 0.6              | 14   |
| 3-d          | 0.2        | 0.5     |        |          | 1.5              | 9    |
| 4-a          | 0.263158   | 0.1     |        |          | 0.5              | 17   |
| 4-b          | 0.315789   | 0.1     | 7185   | 0.002644 | 0.6              | 15   |
| 4-c          | 0.421053   | 1       |        |          | 8                | 3    |
| 5-a          | 0.636364   | 0.5     |        |          | 3.5              | 5    |
| 5-b          | 0.181818   | 0.1     | 7188   | 0.00153  | 0.2              | 23   |
| 5-c          | 0.181818   | 0.5     |        |          | 1                | 11   |
| 6-a          | 0.631579   | 1       | 7184   | 0.002645 | 12               | 2    |
| 6-b          | 0.368421   | 0.5     |        |          | 3.5              | 6    |
| 7-a          | 0.333333   | 0.5     |        |          | 2                | 7    |
| 7-b          | 0.25       | 0.1     |        |          | 0.3              | 21   |
| 7-c          | 0.166667   | 1       | 7175   | 0.001672 | 0.2              | 8    |
| 7-d          | 0.25       | 0.1     |        |          | 0.3              | 22   |

7. Comparative analysis of RPN and criticality index

The rankings of RPN and criticality index for each failure mode is compared and analyzed using Spearman’s rank correlation coefficient. The comparative analysis of RPN and criticality is shown in the table 5. Spearman correlation measures correlation between the ranks and assesses the relationship between two variables. The value of Spearman correlation occurs between +1 and −1. If the rank between two variables is similar, then correlation value will be high (positive correlation). If there are dissimilar ranks between two variables, then the correlation will be low (negative correlation). Spearman’s rank correlation coefficient is computed using the formula as given below.
\[ \rho = 1 - \frac{6 \sum d_i^2}{n(n^2 - 1)} \]

Where \( n \) = number of observation
\( d_i \) = difference between two ranks

\[ \rho = 1 - \frac{6 \times 1257}{23(23^2 - 1)} = 0.38 \]

From the above calculation, it can be noted that, there is a positive correlation between RPN and criticality index. That is, as the values of RPN increases, the criticality index also increases. If the result shows negative value, it indicates that the two entities are inversely proportional as there is no correlation between them. If the spearman correlation value in close to 1, then it indicates that the rankings of criticality index and RPN are very nearer.

From spearman’s rank correlation results, it can be observed that both the methods will yield similar results indicating the suitability of both the approaches in finding criticality of failure modes. However, when compared to criticality index approach, RPN method provides ease and flexibility in finding the criticality. Calculation of criticality index involves failure probability, failure rate and effect probability. All these values will be obtained in decimals. For the data involving large number of failure modes, it may become quite difficult and may lead to confusions in calculating criticality index, as decimal values are involved. Also, precise data and expert opinions are required for accurate results. Therefore, RPN method is suitable approach in finding the criticality of a system.

Table 5. Comparison of RPN and Criticality index Rankings

| Sl. No. | Failure Mode | RPN Rank | Criticality Index Rank | \( d \) | \( d_i^2 \) |
|---------|--------------|----------|------------------------|--------|-----------|
| 1       | 1-a          | 21       | 19                     | 2      | 4         |
| 2       | 1-b          | 7        | 13                     | -6     | 36        |
| 3       | 1-c          | 5        | 4                      | 1      | 1         |
| 4       | 1-d          | 18       | 10                     | 8      | 64        |
| 5       | 1-e          | 16       | 16                     | 0      | 0         |
| 6       | 2-a          | 8        | 18                     | -10    | 100       |
| 7       | 2-b          | 5        | 1                      | 4      | 16        |
| 8       | 3-a          | 11       | 12                     | -1     | 1         |
| 9       | 3-b          | 2        | 20                     | -18    | 324       |
| 10      | 3-c          | 1        | 14                     | -13    | 169       |
| 11      | 3-d          | 17       | 9                      | 8      | 64        |
| 12      | 4-a          | 19       | 17                     | 2      | 4         |
| 13      | 4-b          | 14       | 15                     | -1     | 1         |
| 14      | 4-c          | 6        | 3                      | 3      | 9         |
| 15      | 5-a          | 12       | 5                      | 7      | 49        |
| 16      | 5-b          | 23       | 23                     | 0      | 0         |
| 17      | 5-c          | 20       | 11                     | 9      | 81        |
| 18      | 6-a          | 3        | 2                      | 1      | 1         |
| 19      | 6-b          | 10       | 6                      | 4      | 16        |
| 20      | 7-a          | 9        | 7                      | 2      | 4         |
| 21      | 7-b          | 15       | 21                     | -6     | 36        |
| 22      | 7-c          | 22       | 8                      | 14     | 196       |
8. Conclusion

In this paper, FMEA is conducted on dumpers to identify the potential failure modes and explore their causes and effects. Criticality analysis of failure modes is performed through RPN and criticality index approach. The FMECA through RPN revealed that engine head failure has the highest risk and the steering box bolts failure has the lowest risk. Further, FMECA through criticality index shows that suspension oil leak has the highest criticality index value and steering box bolts failure has lowest. Regular monitoring and maintenance of the equipment by focusing on the highest risk and critical failures may improve the overall performance of the dumper. In order to suggest best suitable approach for criticality analysis, RPN and Criticality index are compared using Spearman’s rank correlation coefficient. Results revealed that, both have a positive correlation that indicates the suitability of both the methods in finding criticality.

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