Scientific Mining Journal, 2023, 62(2), 67-76

SCIENTIFIC MINING JOURNAL

The Publication of the Chamber of Mining Engineers of Türkiye

www.mining.org.tr

Original Research

Analysis of Bottleneck using Mine Production Index and Ishikawa Diagram: A Case of Indian Coal Mine

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Received: 10 August 2022 • Accepted: 18 July 2023

ABSTRACT

The traditional way of coal production and management is still predominant in the Indian coal mining industry which has led to a widespread waste of resources both materials and humans. Operational loss of the mining machinery and equipment is one of the key factors for the low performance and productivity of mines. This research presents an application of the integrated approach of the Mine Production Index (MPi) and Ishikawa Diagram in an Indian coal mine to study the bottleneck equipment in the mining operation among the fleet of shovels, trucks (dump trucks), and dozers. Mine Production Index (MPi) identifies the bottleneck equipment in the mining operation, and Ishikawa Diagram presents the Root Cause Analysis of bottleneck equipment. The Fuzzy Analytical Hierarchy Process (FAHP) is used to determine weights for MPi calculation using information gathered from a group of 11 experts through structured interviews. The study found that the dozer fleet is the bottleneck equipment and the ineffectiveness of the dozer fleet can be grouped into 4 categories as enumerated on the Ishikawa diagram. The study proposes that the ineffectiveness of the dozer fleet can be improved with an increase in its performance rate. The study is based on the judgments of the experts for the case mine, which may limit the external validity. This paper is an original contribution to the analysis of mining equipment using the Mine Production Index and Ishikawa Diagram in an Indian coal mine.

Keywords: *Indian Coal Mining Industry; Mine Production Index; Ishikawa Diagram; Fuzzy Analytical Hierarchy Process.*

Introduction

The traditional way of the coal production process is still predominant in the Indian coal mining industry which has led to widespread waste of resources for both materials and humans. Operational losses for machinery and equipment such as losses due to breakdown, waiting time during set-up, adjustments and small stops, defects, over-processing, and rework are the main factors affecting the performance and productivity of the machines and equipment. Operational loss is one of the major factors for the low productivity of the Indian coal mining industry despite augmenting investment, introducing updated equipment, and improving labor intensity. The Indian coal mining industry is no exception; despite augmenting investment, introducing updated equipment, and improving the labor intensity in recent years. The management of bottlenecks is key to reducing costs and remaining competitive in the global market. The concept of "lean mining" in the Indian coal mining industry is put forward in this paper through the application of the Mine Production Index (MPi) and Root Cause Analysis (RCA) using the Cause and Effect Diagram (Ishikawa diagram). Although there is considerable literature available about lean application in the mining industry, a few authors address the practical applications of lean in mines.

MPi addresses the issues of poor performance and low productivity by identifying bottleneck equipment in mining operations. MPi was introduced in 2014 and is an extension of Overall Equipment Efficiency (OEE) with the introduction of weight for each factor considering some operational constraints in the mining industry (Lanke *et al.*, 2014). OEE is a Key Performance Index (KPI) that can be used to determine the overall performance of an industry. Availability, utilization, and performance rate are the parameters that form the product of MPi and are calculated as follows:

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https://doi.org/10.30797/madencilik.1160266

$= (Av^a \times Ut^b \times Pp^c)$ (1)

where Av is Availability, Ut is utilization and Pp is performance of the equipment.

a, b, and c are weights such that $0 < a, b, c < 1$ and $\sum(a, b, c) = 1$

Several Multi-Criteria Decision Making(MCDM) tools such as the Analytical Hierarchy Process (AHP), Fuzzy Analytical Hierarchy Process(FAHP), Weighted Sum Model(WSM),Technique for Order of Preference by Similarity to Ideal Solution(TOPSIS),ELimination and Choice Expressing REality (ELECTRE), etc. can be used for determining the weights of the factors used in the MPi formula. In this study, Fuzzy AHP is used to calculate the weights of the factors for calculating the MPi of mining machines to study its overall effectiveness.

There are many productivity-related issues in the mining industry due to the inherent mining work environment and varying degrees of assignable causes such as inefficiency of manpower or machinery. RCA for productivity-related issues is an essential step for any multi-stage production process (Wilson *et al.*, 1993). RCA is a step-by-step process of identifying causal factors using comprehensive and system-based review techniques aimed to provide the focal root causes of problems and to develop action plans with measurement strategies to resolve the problem. Cause and Effect Diagram (CED), also known as Fishbone or Ishikawa Diagram, is an RCA tool that can be used to identify and organize the possible causes for a particular single effect (Wilson *et al.*, 1993).

The main objectives of this paper are:

· To identify the bottleneck equipment in a mining operation in an Indian coal mine through the application of MPi.

· RCA of bottleneck equipment using a cause and effect diagram.

The subsequent sections present a literature review on the background of MPi to concisely describe its key advantages over OEE. This is followed by the background of AHP, Fuzzy AHP, Root cause Analysis, and Ishikawa diagram. In section 3, the methodology adopted for the study is discussed where the stepwise determination of weights of the factors using FAHP is shown which is followed by steps of cause and effect diagram in the subsequent section. The next section presents the illustration of a case study. The final section presents discussions on the key results followed by the conclusions, limitations, and directions for future research.

2. Literature Review

2.1. Mine Production Index

Mine Production Index is an operational measure for the mining sector which is an extension of the OEE concept by assigning different weights to the traditional OEE components (Lanke *et al.*, 2014). It helps in identifying the bottleneck and its root causes in mining operations reliably. The literature review reveals that MPi evaluates not only effective equipment but also the effect of assessment factors on the effectiveness (Lanke *et al.*, 2016). Availability, utilization, and performance rate, which are considered important criteria for determining mining equipment productivity, form the product of.

The availability rate is defined as the ratio of the available shift/planned time for production to the total available shift/planned time (Elevli and Elevli, 2010). It considers the downtime such as breakdowns and waiting times due to set-ups, maintenance actions, adjustments, etc.

Availability=(Total available shift or planned time for production - total downtime)/(Total available shift or planned time for production) (2)

Performance rate is defined as the ratio of actual output from a machine to the rated output (Elevli and Elevli, 2010). It is used for the assessment of decreased performance and operational efficiency of machines due to reduced machine speed or delays in cycle time, etc.

Performance rate= (Actual output from a machine (satisfying quality standard)/(Rated output (during the time machine is operating)) (3)

The utilization of equipment is defined as the ratio of the time in hours the machine is used in a year to the total hours which can be either total annual Scheduled Shift Hours (SSH) or total Machine Available Hours (MAH) in a year (Arputharaj, 2015).

Utilisation= (Actual hours used in a year)/(Total annual SSH or total MAH in a year) (4)

2.2. Analytic Hierarchy Process

The Analytic Hierarchy Process was developed by Saaty (1980) and is one of the most widely used MCDM tools to assist complex decision-making. AHP is a method that structures the decision problem into a hierarchical level by eliciting pair-wise comparison that indicates the relative importance of all criteria or alternatives using a 9-point scale (Saaty, 1980). AHP has been applied in various decision-making environments like to prevent child sexual abuse in schools (Lundberg and Dangel, 2019); develop weighting system (Kamaruzzaman *et al.*, 2018); management effectiveness (Pendred *et al.*, 2016), and machine tool configurations (Farhan *et al.*, 2016).

2.3. Fuzzy Analytic Hierarchy Process

In AHP, the relationships of the factors are based on the subjective judgment of the experts which are expressed in crisp values. Thus, the relationships may be imprecise as it is hard to estimate our judgments by specific numerical values and the results may misguide in decision-making. Although AHP is an accomplished tool for the assessment of problems, Fuzzy theory can be integrated into AHP to increase the sensitivity of the AHP method with fuzziness situations. The combination of fuzzy concepts and AHP is called fuzzy AHP (FAHP).

2.3.1. Fuzzy Set Theory

The fuzzy set was introduced by Zadeh in 1965 (Zadeh,1965) as an extension of the classical notion of a set whose elements have degrees of membership. A classical bivalent set, called a crisp set, evaluates in binary terms according to a condition i.e. an element either belongs or does not belong to the set while a fuzzy set defines a degree of belonging to the possible individual in the universe of discourse by assigning a value representing its degree of membership in the fuzzy set. So, fuzzy set theory can be used in solving complex problems to measure uncertainty in human insight and implication.

2.3.2. Triangular Fuzzy Number

Let X be a universe of discourse having its generic elements Y, or $Y = \{y_1, y_2, y_3.....,y_n\}$. A fuzzy set F in Y is characterized by a membership function, (Y), which maps Y to the membership space

[0, 1]. A fuzzy number F is defined as a triangular fuzzy number (TFN) parameterized by the triplet (p, q, r) with peak value q, left width p > 0, and right width r > 0, if its membership function has the following form (Khaba and Bhar, 2017; Cheng, 1999):

$$\mu_F(Y) = (y-p)/(q-p) \quad p \leq y \leq q$$
$$(\beta-p)/(\beta-q) \quad q \leq y \leq r \tag{5}$$

The membership function is defined in Figure 1.

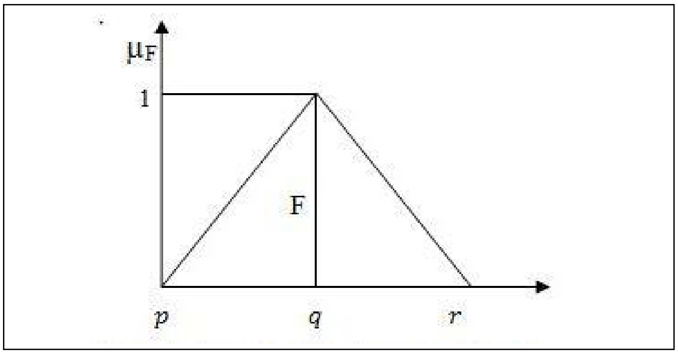

Figure 1. *A triangular fuzzy number F.*

Fuzzy AHP has been applied in various decision-making environments like raw material criticality assessment (Kim *et al.*, 2019); network access of mobile applications (Mowafi *et al.*, 2019); health symptom checking system (Huang *et al.*, 2018); clinical decision support system (Nazari *et al.*, 2018); prioritizing the solutions of lean implementation (Belhadi *et al.*, 2017); water loss management (Zyoud et al., 2016); analysis of reverse logistics implementation (Prakash *et al.*, 2015); machine tool evaluation (Ayag and Gurcan Ozdemir, 2012); failure modes and effects analysis (Kutlu and Ekmekçioğlu, 2012); supplier selection (Beikkhakhian *et al.*, 2015; Shaw *et al.*, 2012, Yu *et al.*, 2012); partner's selection within a green supply chain (Lee *et al.*, 2011); mining equipment selection (Kesimal and Bascetin, 2002). The extent analysis method is one of the extensively used fuzzy weighing and prioritizing methods due to its simplicity and efficiency (Chang, 1996) while the centre of gravity is one of the widely used methods of defuzzification (Kang *et al.*, 2010), and both the approaches are applied in this study. Other methods include centroid (Lee *et al.*, 2010) and α-cut (Buckley and Qu, 1990).

2.4. Cause and Effect Diagram

Cause and Effect Diagram (CED), 5 Whys, Interrelationship Diagram (ID), Multi Vari Analysis, and the Current Reality Tree (CRT) are some of the RCA tools that help in identifying the root causes of problems (Duggett, 2004). RCA tools have been used for studying failure to improve patient safety (Kellogg *et al.*, 2017); factors contributing to cancer-related suicide (Aboumrad,*et al.*, 2018). Cause and effect diagram (CED), also known as Fishbone or Ishikawa Diagram is used to identify and organize the possible causes for a particular single effect (Wilson *et al.*, 1993). In the CED, the potential causes are often organized into 4 key groups for identifying the root cause- manpower, materials, machinery, and methods in the manufacturing sector while people, policies, equipment, and procedures for the service sector. Many studies have used the Ishikawa diagram for diagnosing the root causes of different industrial problems such as productivity losses in mining equipment (Papic *et al.*, 2016); minimizing rejection of raw materials (Ahmed and Ahmad, 2011), equipment unreliability (Sharma and Sharma, 2010), etc. The drawbacks of the Ishikawa diagram are highly expert-driven, considerable manpower requirements in the form of expert teams to conduct the analysis, and insufficient explanation of possible strategies for mitigating the root causes (Guerin, 2015; Reid *et al.*, 2012).

3. Research Methodology

In this study, an integrated approach of FAHP for MPi calculation and CED for RCA has been used. The structured interview is used to collect information and knowledge from the experts for developing the pairwise comparison matrices to determine the weights for MPi evaluation of mining machines. A total number of 11 experts, 8 from the mining sector (from the case study mine) and 3 from academic institutions with substantial experience were consulted and asked to respond to the importance of each factor on a scale of 1 to 9 using an interview questionnaire. In the next stage, the cause and effect analysis method are done to integrate experts' knowledge for a possible solution to the bottleneck. In this study, cause and effect analysis is done through personal observations, consensus building, and semi-structured interviews with a cross-functional team of 15 employees from different departments of the mine.

3.1. Steps of Fuzzy AHP

The various steps adopted in this study are discussed below:

Step 1: The first step of FAHP is to construct a pairwise comparison matrix with the data collected from z experts for the n factors using Saaty's 9-point scale. For each expert, an nxn non-negative pairwise comparison matrix is constructed. Each pairwise comparison matrix is also checked for consistency.

Step 2: The pairwise comparison matrices are converted into fuzzy comparison matrices using the corresponding characteristic (membership) function as shown in Table 1.

Table 1. *Characteristic function of the fuzzy numbers.*

Fuzzy number	Characteristic (membership) function
$\tilde{1}$	(1, 1, 2)
$\tilde{x}$	(x-1, x, x + 1) for x = 2, 3, 4, 5, 6, 7, 8
$\tilde{9}$	(8, 9, 9)
$1/\tilde{1}$	(1/2,1, 1)
$1/\tilde{x}$	[{1/(x+1)}, (1/x), {1/(x - 1)}] for x = 2, 3, 4, 5, 6, 7, 8
$1/\tilde{9}$	(1/9, 1/9, 1/8)

The membership function is TFN and thus requires fuzzy aggregation to achieve a favorable result from the responses of experts. In our study, fuzzy comparison matrices are aggregated by the geometric mean method. The aggregated fuzzy comparison matrix for Z number of experts is represented by $A_{ij} = (p_{ij}, q_{ij}, r_{ij})$, where

$$p_{ij} = \left(\prod_{t=1}^{Z} p_{ijt}\right)^{\frac{1}{Z}} \quad , \forall\, t = 1,2,3 \ldots , Z \tag{6}$$

$$q_{ij} = \left(\prod_{t=1}^{Z} q_{ijt}\right)^{\frac{1}{Z}} \quad , \forall\, t = 1,2,3 \ldots , Z \tag{7}$$

$$= \left(\prod_{t=1}^{Z} r_{ijt} \right)^{\frac{1}{Z}} \quad , \forall\, t = 1,2,3 \dots , Z \tag{8}$$

Step 3: The next step is the defuzzification of the aggregated fuzzy comparison matrix into crisp scores using the defuzzification method for testing consistency. In this study, the Centre of Area (COA) method is applied for defuzzification by using the following equation:

$$F_i = \frac{[(r_i - p_i) + (q_i - r_i)]}{3} + p_i \tag{9}$$

Step 4: Fuzzy synthetic extent analysis is used for determining the weight of the aggregated fuzzy comparison matrix. According to Chang (1996), if X={x_1,x_2,x_3,...,xn } be the objects set, U={u_1,u_2,... .,u_m } be a goal set and M_{gi}^1,M_{gi}^2,...,M_{gi}^m be the values of extent analysis of i^{th} object for m goals, then the fuzzy synthetic value of the i^{th} object can be determined by using equations (10) - (12) as follows:

$$F_i = \sum_{j=1}^{m} M_{gi}^{j} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right]^{-1} \tag{10}$$

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right]^{-1} = \left(\left[\sum_{i=1}^{n} \sum_{j=1}^{m} p_{ij} \right]^{-1}, \left[\sum_{i=1}^{n} \sum_{j=1}^{m} q_{ij} \right]^{-1}, \right| \tag{11}$$

$$\left. \left[\sum_{i=1}^{n} \sum_{j=1}^{m} r_{ij} \right]^{-1} \right) \tag{12}$$

Step 5: After calculating the fuzzy synthetic value (F_i) for the i^{th} object, the F values are compared.

Consider two convex fuzzy numbers F_1=(p_1,q_1,r_1) and F_2=(p_2,q_2,r_2) as shown in Figure 2. The degree of possibility of F_2 greater than F_1 is defined as

$$V(F_2 \geq F_1) = 1 \text{ if } p_1 \geq p_2, q_1 \geq q_2 \text{ and } r_1 \geq r_2 \tag{13}$$

$$\text{Or } V(F_2 \geq F_1) = \text{hgt}(F_1 \cap F_2) =$$

$$(p_1 - r_2) / (q_2 - r_2) - (q_1 - p_1) \tag{14}$$

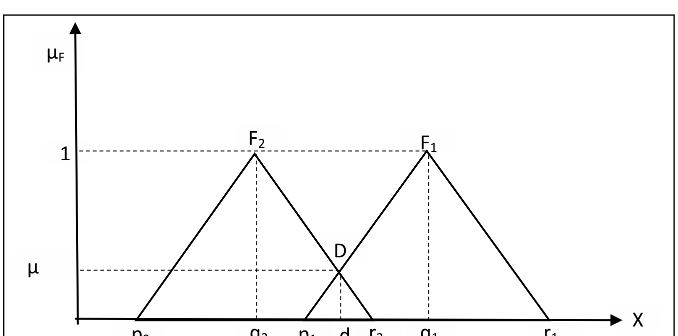

Figure 2. *Two triangular Fuzzy numbers F_1 and F_2 (Cheng, 1999).*

The degree of possibility of a convex fuzzy number F greater than k convex fuzzy numbers is defined as

$$V(F \geq F_1, F_2, \dots, F_k) = V[(F \geq F_1)\text{and}(F \geq F_2)\text{and}$$
$$(F \geq F_2)\text{and } (F \geq F_3) \dots (F \geq F_k)]$$
$$= \min V(F \geq F_i) \forall\, i = 1, 2, \dots k \tag{15}$$

$$\text{Consider } d(F_i) = \min V(F_i \geq F_k) \forall\, k = 1, 2, \dots t \text{ and } k \neq i \tag{16}$$

The weight vector is calculated as

$$\bar{W} = [(d(F_1), d(F_2), \dots, d(F_t)]^T \text{ where } F_i \ (i = 1, 2, \dots t) \text{ are elements} \tag{17}$$

Step 6: The priority weight vector is obtained after normalization as follows $W = [(d'(F_1), d'(F_2), \dots, d'(F_t)]^T =$ $(w1, w2, w3, w4, \dots wt)$ where W is a nonfuzzy number (18)

3.2. Calculation of MPi

MPi is calculated using Equation 1 by assigning the weights for each parameter that has been identified using the FAHP.

3.3. Steps of Cause and Effect Diagram

The steps of the CED adapted from the literature (Ishikawa, 1990; Sharma and Sharma, 2010; Papic *et al.*, 2016) are shown below:

1. Select a multi-disciplinary Cross-Functional Team (CFT) or inter-departmental team

2. Define the problem

3. Collect data implementing the '3W2H' tool (what, when, where, how, how much) to categorize the characteristics of the cause

4. Study every possible causal factor

5. Check all the consistent and reliable causes and eliminate all inconsistent causes, thus identifying the root cause(s)

4. Case Study

The study of the application of MPi for evaluation of the mining equipment productivity is carried out in an Indian open-pit mine operated in eastern India. The mine is operated for 24 hours 7 days a week in 3 shifts of 8 hours each day. The poor performance of key mining machinery is the main problem of this mine in the production process resulting in low productivity The purpose of using MPi in the process is to identify the significant bottleneck and measure the effectiveness of the machine which is followed by root cause analysis of the bottleneck equipment. The productivity of the fleet of 3 mining equipment is being studied using MPi. The data collection for availability (total working duration, standby hours), performance, and utilization (idle time and downtime time, etc.) of the shovel, truck, and dozer was performed for a period of 12 months from November 2015 to October 2016.The production performance is measured in terms of total output by each fleet of equipment operated in the mine and hence the output data are also collected. In this mine, the shovel fleet consists of 14 shovels, a dozer fleet of 17 dozers and the trucks fleet consists of 38 trucks with three different capacities.

4.1. Data Collection and Development of the Hierarchy

In this study, a structured interview was used to collect information and knowledge from the experts for developing the pairwise comparison matrices to determine the weights for MPi evaluation of mining machines. An interview questionnaire was designed for data collection and evaluation to ensure the content validity of the questionnaire. A total number of 11 experts, 8 from the mining sector (from the case study mine) and 3 from academic institutions with substantial experience were consulted and asked to respond to the importance of each factor on a scale of 1 to 9 using an interview questionnaire followed by elicitation of experts and semi-structured interviews with a cross-functional team of 15 employees from different departments of the mine and personal observations for the cause and effect analysis for a possible solution to the bottleneck.

4.1.1. Development of the Pairwise Comparison Matrix

The first step of FAHP is to construct a pairwise comparison matrix with the data collected from 11 experts for the 3 factors using a comparison scale of 1-9. For each expert, a 3 x 3 non-negative pairwise comparison matrix is constructed. Thus, the importance levels were obtained for availability, performance, and utilization. Each pairwise comparison matrix is also checked for consistency. The pairwise comparison matrices are converted into fuzzy comparison matrices using the corresponding characteristic (membership) function using Table 2.

4.1.2. Integration of the Fuzzy Comparison Matrices:

The fuzzy comparison matrices from 11 experts are incorporated into a final comparison matrix by the geometric mean process which is shown in Equations (6), (7), and (8). For example, the aggregated fuzzy number F_{12} in the fuzzy comparison matrix for the dozer is represented as, (p_{12},q_{12},r_{12}), where,

$$p_{12} = (4*2*1*2*4*1*4*2*2*1*1)^{1/11} = 1.88$$
$$q_{12} = (5*3*2*3*5*2*5*3*3*2*2)^{1/11} = 2.98$$
$$r_{12} = (6*4*3*4*6*3*6*4*4*3*3)^{1/11} = 4.02$$

The aggregated fuzzy comparison matrices for the shovel, truck, and dozer are shown in Tables 2, 3, and 4, respectively.

Table 2. *Aggregated fuzzy comparison matrices for shovel.*

	Availability	Utilization	Performance
Availability	(1,1,1)	(1.95,2.9,4.02)	(1.29, 2.32,3.33)
Utilization	(0.25,0.33,0.51)	(1,1,1)	(0.33,0.50,0.90)
Performance	(0.30,0.43,0.78)	(1.11, 2,3.03)	(1,1,1)

Table 3. *Aggregated fuzzy comparison matrices for truck.*

	Availability	Utilization	Performance
Availability	(1,1,1)	(2, 3.06,4.09)	(1.2, 2.23,3.24)
Utilization	(0.24,0.32,0.50)	(1,1,1)	(0.31,0.45,0.85)
Performance	(0.31,0.45,0.83)	(1.18, 2.21,3.23)	(1,1,1)

Table 4. *Aggregated fuzzy comparison matrices for dozer.*

	Availability	Utilization	Performance
Availability	(1,1,1)	(1.88,2.98,4.02)	(1.07, 1.61, 2.66)
Utilization	(0.24,0.33,0.53)	(1,1,1)	(0.27, 0.37, 0.62)
Performance	(0.4,0.62,0.94)	(1.61,2.66,3.68)	(1,1,1)

4.1.3. Defuzzification of the aggregated Fuzzy Comparison Matrix

For the defuzzification of the aggregated fuzzy comparison matrix, the COA method is used. Using Equation (9), the aggregated fuzzy comparison matrix of the factors was defuzzified.Then the consistency ratio of the defuzzified integrated comparison matrix is checked.

4.1.4. Calculation of the Fuzzy Synthetic Value

The fuzzy synthetic value of assessment factors is calculated from the aggregated comparison matrix by using Equations (10) - (12). The fuzzy synthetic value of the dozer is shown below:

$$\sum_{i=i}^{n}\sum_{j=1}^{k} M_{gi}^{j} = (8.47, 11.57, 15.45)$$

$$F_1 = \sum_{j=1}^{k} M_{g1}^{j} \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{k} M_{gi}^{j}\right]^{-1}$$

$$F_1 = (3.95, 5.59, 7.68) \otimes (0.06, 0.09, 0.12)$$
$$F_1 = (0.24,0.50,0.92)$$

F_1 = (3.95,5.59,7.68) ⊗ (0.06,0.09,0.12)

F_1 = (0.24,0.50,0.92)

Similarly, the fuzzy synthetic value of the remaining factors is calculated as

F_2 = (0.09,0.15,0.26) and F_3 =(0.18,0.39,0.68)

4.1.5. Comparison of the Fuzzy Synthetic Value:

The fuzzy synthetic values of the factors are compared by using Equations (13) - (16)

The degree of possibility for the factors

$$V[(F_1 \geq F_2)\text{and}(F_1 \geq F_3)] = 1$$
$$V[(F_2 \geq F_1)] = \frac{(0.24 - 0.26)}{(0.15 - 0.26) - (0.50 - 0.24)} = 0.054$$
$$V[(F_2 \geq F_3)] = 0.44, V[(F_3 \geq F_1)] = 0.8 \text{ and } V[(F_3 \geq F_2) = 1]$$

The degree of possibility that F_1 is greater than F_2 and F_3 is $(F_1 \geq F_1, F_2,) = \min(1,1) = 1$

Similarly, $V(F_2 \geq F_1, F_3,) = \min(0.054, 0.44) = 0.054$
$V(F_3 \geq F_1, F_2) = \min(1, 0.8) = 0.8$

4.1.6. Calculation of the Weights:

- Using the possible value of the criteria, the weight of the criteria is calculated by using Equations (17) and (18):

$W = (1, 0.05,0.8)^T$

W'_{Dozer}= (0.54,0.03,0.43)

Similarly, the weights of the assessment factors for the shovel and truck are calculated.

$$W'_{Shovel} = (0.60, 0.05, 0.354) \quad (19)$$

$$W'_{truck} = (0.60, 0.04, 0.36) \quad (20)$$

$$W'_{Dozer} = (0.54, 0.03, 0.43) \quad (21)$$

4.2. Calculation of MPi

The information for availability, utilization, and performance of the shovel, truck, and dozer at the mine for the period under study are presented in Figures 3-5. The average percentage of availability, utilization, and performance for shovel, truck, and dozer is taken for MPi calculation. The average percentage of the factors for each machine along with the permissible norms of the Government of India for this mine, represented within the parenthesis, is shown in Table 5:

Table 5: *Average percentage of availability, utilization, and performance of shovel, truck, and dozer.*

	Shovel	Truck	Dozer
Availability	74 (80)	56 (67)	35 (70)
Utilization	54 (58)	27 (50)	29 (45)
Performance	42	34	31

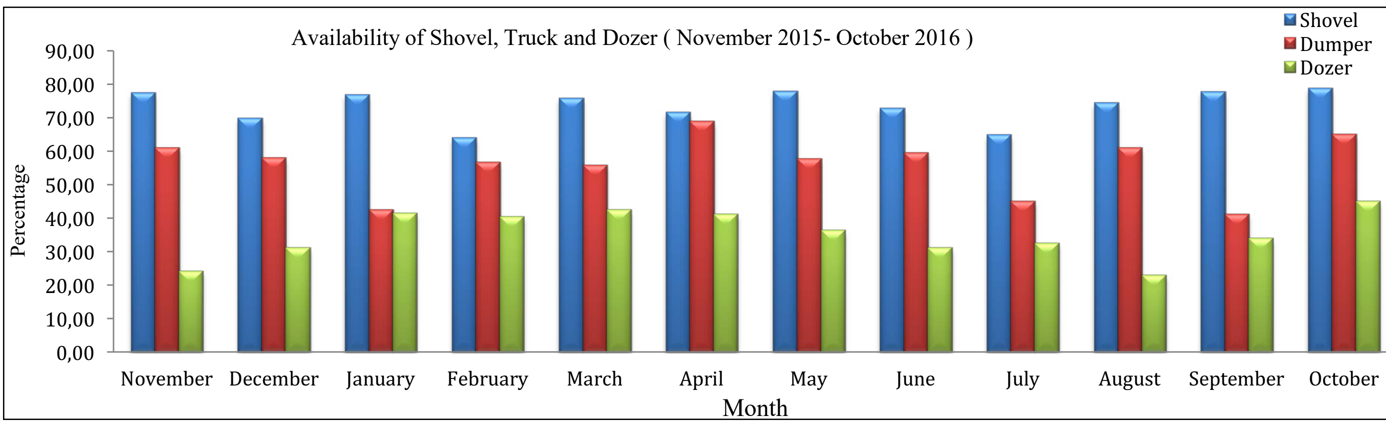

Figure 3. *Availability of Shovel, Truck, and Dozer*

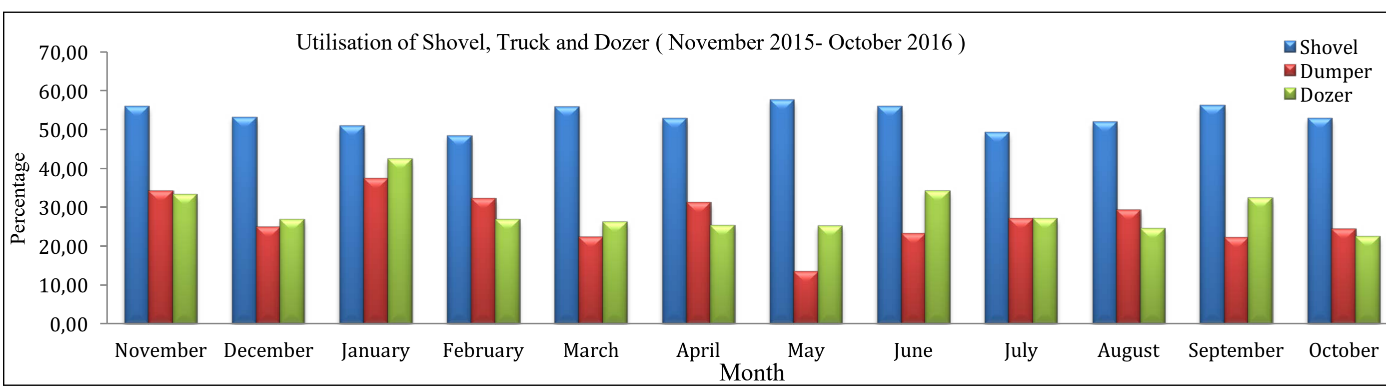

Figure 4. *Utilisation of Shovel, Truck, and Dozer*

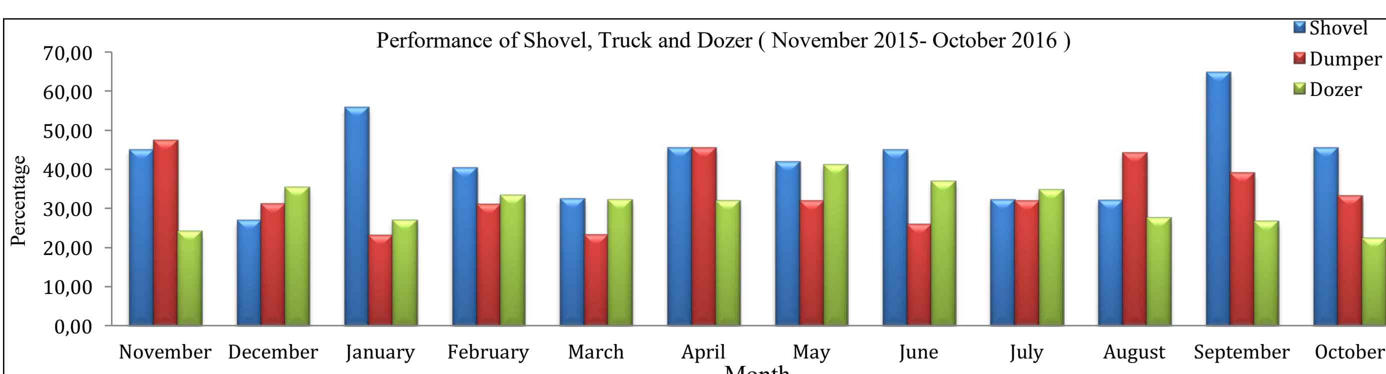

Figure 5. *Performance of Shovel, Truck, and Dozer*

Using the weights presented in Equations (19) - (21) the value of MPi for each machine is calculated using Equation (1) as follows:

$$MPi_{Shovel} = Av^{0.60} \times Ut^{0.05} \times Pp^{0.34} = 74^{0.60} \times 54^{0.05} \times 42^{0.34} = 57.55\ \%$$

$$MPi_{Truck} = Av^{0.60} \times Ut^{0.04} \times Pp^{0.36} = 56^{0.60} \times 27^{0.04} \times 34^{0.36} = 45.45\ \%$$

$$MPi_{Dozer} = Av^{0.54} \times Ut^{0.03} \times Pp^{0.43} = 35^{0.54} \times 29^{0.03} \times 31^{0.43} = 33.03\ \%$$

4.3. Root Cause Analysis

Root cause analysis is best accomplished by a multidisciplinary cross-functional team of experts in different sectors as it would provide complementary skills (Guerin, 2015). In the study, data collection is done through personal observations, consensus building, and semi-structured interviews with a cross-functional team of 15 employees from different departments such as mining (excavation), electrical and mechanical engineering, safety, and personnel at the worksite and area office of the mine. The mine visits help to examine the physical environment and the usual work processes through direct interaction with the staff which is followed by reviews of relevant documentation and literature for formulating recommendations and actions. The semi-structured interview follows a deductive query technique in which a series of “why” and “caused by” questions were asked 3 or more times to identify the potential causes and various sub-clauses/factors that contributed to the potential causes. The query discontinues when no more causes can be attributed to the effect, hence here, the root causes are deduced. CED is done with suggestions from the literature (Papic *et al.*, 2016; Sharma and Sharma, 2010; Ishikawa, 1990) which is adapted for the study. The ineffectiveness of the dozer is enumerated and visualized on the Ishikawa diagram which is analyzed using the methodology proposed in Section 3. Hence, 5 root causes are identified based on 4 broad categories related to machine, material, manpower, and method as illustrated in Figure 6.

5. Discussions

The study explores the application of MPi and CED to examine the productivity of the fleet of 3 mining types of equipment through bottleneck identification and RCA. The study reveals that the dozer fleet is the bottleneck equipment. The effectiveness of the dozers may be improved with an increase in their performance. While the weight assessment suggests that utilization is the criteria that must be focused on strongly for improvement.

The study demonstrates to development of significant insights into the root causes of the ineffectiveness of dozers by exploring various failure factors. The finding from the RCA reveals a significant proportion of the causes are related to machine, material, manpower, and method. Several maintenance-related measures are proposed in the root cause analysis. The scheduling and planning of the dozer need to be checked for performance and productivity improvement. Maintenance outsourcing of the entire fleet of a dozer or some maintenance functions is one of the mitigation measures for maintenance managers and operators for the effectiveness of the dozer. Efficient maintenance can also be achieved by improved instructions on the maintenance of the dozer; continuous monitoring of the maintenance procedures such as cleaning or lubrication and appraisal of the inspection gap; and periodic inspection like minor servicing and repair, re-setting the machine to acceptable performance level and assessment of the quality of lubricants used.

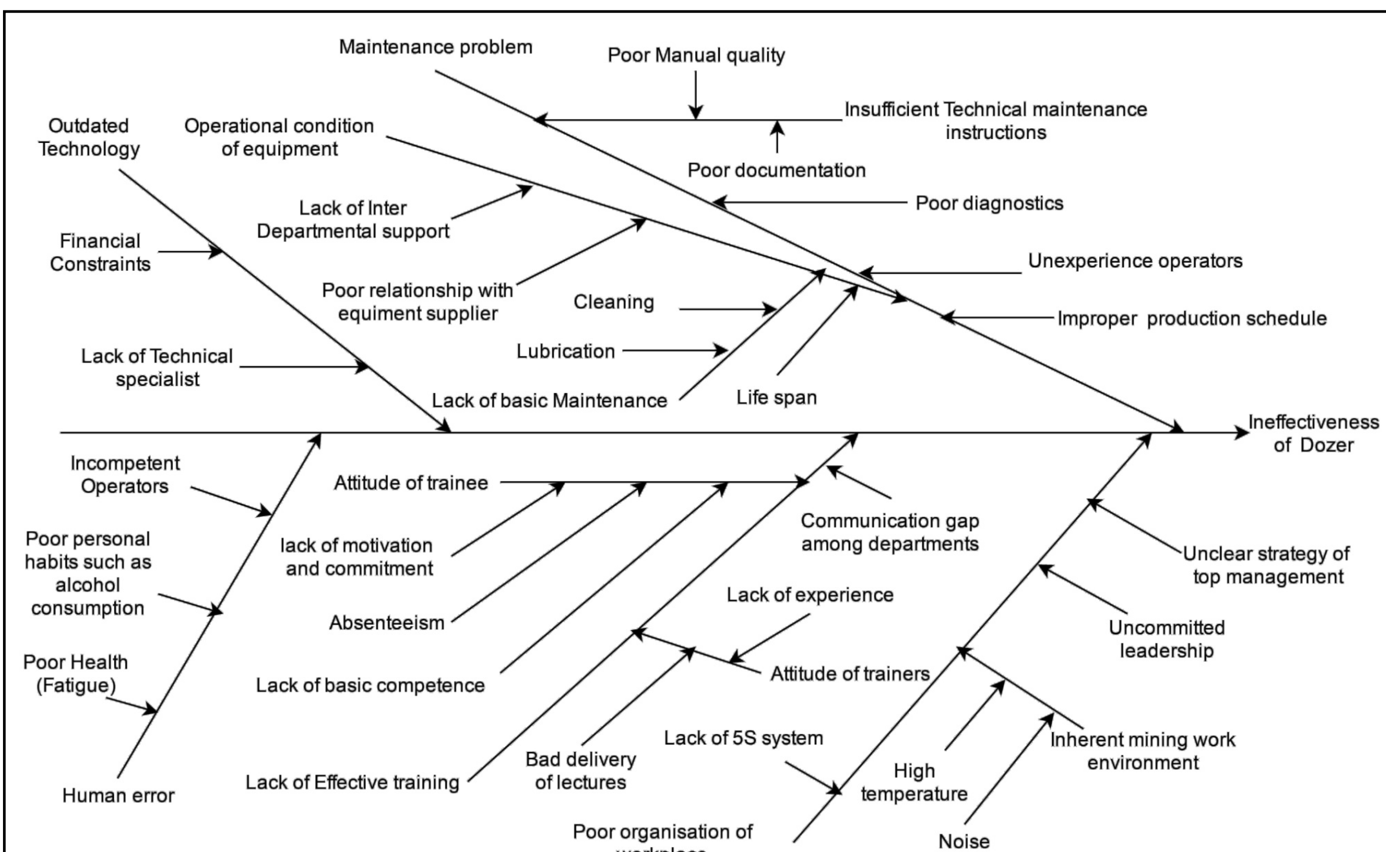

Figure 6. *Cause and Effect Diagram for Ineffectiveness of Dozer*

There is a significant need for the validation of theoretical knowledge and techno-managerial skills in the mine. Some of the mitigation measures for manpower-related causes such as lack of skill, working instructions, individual training and characteristics, and job experience would be personnel re-training; categorizing tasks based on complexity and assigning difficult task for more experienced personnel; developing task usage, inspection manuals and check-lists of equipment; educating operators about the importance of work standardization which helps in minimizing the consumption of resources; and augmenting employee motivation and commitment through participation in decision making.

Thus, exploring the root causes of the ineffectiveness of the dozers is important as it will avail the practitioners/employees with the opportunity of choosing and execute the maintenance strategies more effectively, thereby maximizing the equipment performance and productivity.

6. Conclusions

This study demonstrated a case analysis of a coal mine that can be applied for the productivity improvement of the Indian coal mining industry. In the study, the productivity of 3 mining equipment is analyzed using MPi. The study found that the dozers are the production bottleneck machine for the period of case analysis based on their MPi value. Thus, the dozers have less effectiveness for production as compared to the shovels and trucks. The result is validated with the secondary data from the mining department and personal management of the mine. The study reveals that not only productivity improvement but lean mining could be achieved by eliminating or reducing the inconsistency between the produced output and the desired output after bottleneck analysis. The improvement solutions and the mitigating measures are suggested based on the detected bottleneck and dominant factor through MPi comparison and evaluation using RCA. A CED was performed to eliminate the effect of bottleneck equipment. In this study, it has been observed that MPi and RCA can be implemented to improve the productivity of the equipment. The study identifies the root and contributory factors of the ineffectiveness of the dozer in the mine and suggests risk reduction strategies and the development of action plans to assess the effectiveness of the strategies.

The highly dynamic nature of the mining environment may constrain the evaluation of the process effectiveness using MPi thereby affecting the decision-making. The conclusion from the study is based on personal judgments of the experts and employees for the case mine which may limit the study to ensure external validity.

In RCA, the derived causal relations may not eMPirically link to the effect under examination owing to its predominantly expert dependence. Thus, semi-quantitative techniques such as Failure Mode and Effect Analysis (FMEA) can be employed in future studies. Moreover, the findings can be externally validated with multiple cases through real-world implementation or simulation.

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