DEDICATED TO MY BELOVED PARENTS

FOR THEIR LOVE, SUPPORT AND ENCOURAGEMENT

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SYMBOLS USED

A: Availability

P: Performance

Q: Quality

U: Utilization

C: Capacity Performance

E : Environmental Performance

A_i: Inherent Availability

R: Reliability Characteristic of the System

M: Maintainability Characteristic of the System

ABBREVIATIONS USED

PM	Performance Measurement
OEE	Overall Equipment Effectiveness
OEPI	Overall Equipment Performance Indicator
PEE	Production Equipment Effectiveness
TEEP	Total Equipment Effectiveness Performance
OAE	Overall Asset Effectiveness
OPE	Overall Production Effectiveness
OFE	Overall Factory Effectiveness
OTE	Overall Throughput Effectiveness
ORE_{ft}	Operational Resource Effectiveness
MTBM	Mean time between corrective and preventive maintenance actions
MAMT	Mean active maintenance time
MTTF	Mean time to failure
MTTR	Mean time to repair
AT	Available time
UT	Utilization time
IT	Idle time
MNT	Maintenance time
BDT	Breakdown time
TT	Total time
CL	Capacity loss

PREFACE

The ever-increasing demand for coal/minerals has forced the surface mines to consistently upgrade the level of mechanization for increasing production. For transporting coal and ore in open pit mines, most commonly used vehicles are dump trucks. In an open pit coal mine, transportation subsystem for coal/overburden is the backbone of production system and a fleet of dump trucks are critical component of this subsystem. Dump trucks are capital intensive equipment. Hence, improving the overall effectiveness and performance of the dump trucks are important for sustainable mining operation.

Indian coal mines deploy dump trucks of different sizes. The most commonly used dump trucks in Northern Coal Fields (NCL) are 85T, 100T, and 120T dump trucks of BEML, Caterpillar, and Komatsu. Sustaining high performance of these equipment is one of the challenging tasks for the mining authority. Monitoring of performance involves measurement of performance with a suitable metric and devising counter measures in case of underperformance. Proper maintenance is very necessary and hence performance measurements are done of these equipments. Performance measurement is the first stage of improving it in any field or organization because without measuring it one cannot know whether that the performance is above or below the standard performance level and there is any scope of improving it or not.

Review of the existing literature on performance measurement of mining equipment reveals that prevailing methods of performance evaluation of mining equipment are primarily based on the concept of measurement of availability and utilization. Although, these performance measurement metrics have been used in many

mining projects for diagnosis of ill-performance but they provide only a tunnel view to the scope of the problem by considering the equipment in isolation from the system and, as such, are unable to address the performance measurement in a holistic manner. In this research, a holistic approach has been presented by considering all the aspects.

The specific objectives of the present research are

1. Analysis of the OEE concept and modify it for the performance measurement of mining dump trucks including their operational impact on environment. Call this modified performance measure as Overall Equipment Performance Indicator (OEPI).
2. Evaluation of field data about the dump truck operations and suggest a methodology for computing components of OEPI.
3. Development of a suitable methodology of fixing benchmark values for OEPI and its components.
4. Diagnosis of the problem areas of case study dump truck subsystem and suggest suitable measures for improving the performance of the case study dump truck subsystem.

Field studies were conducted in Northern Coalfields Limited (NCL) and Bharat Coking Coal Limited (BCCL), India to collect relevant data about the dump truck subsystem.

In this research, the performance measurement of dump trucks has been defined through the translation of Nakajima's concept of Overall Equipment Effectiveness (OEE), a widely used technique for measuring the performance in the manufacturing industry. Nakajima has considered six internal losses occurring within the system for explaining the OEE. The performance of mining equipment is measured using various

performance measurement metrics in the industry. Initially, availability was used as the performance metrics, later on many researchers such as Jonsson and Lesshammar (1999); Jeong and Phillips (2001); Elevli and Elevli (2010); Norden and Ismail (2012) applied Nakajima's concept of OEE also. Elevli and Elevli (2010) used OEE concept for measuring the performance of shovels. Translation of the OEE for mining dump trucks has not been fully explored.

This research is an attempt to translate OEE into the mining industry for the dump trucks by considering internal as well as external losses. Operation of dump trucks degrade environment which may be regarded as external losses.

The translation and requisite modification of OEE for the mining dump trucks are done here to define Overall Equipment Performance Indicator (OEPI) which categorises entire array of losses into three clusters, namely time losses, capacity losses and environmental losses. OEPI is expressed as a product of three components as given below:

$$\begin{aligned} &Overall\ Equipment\ Performance\ Indicator\ (OEPI) \\ &= Time\ performance\ (T) \times Capacity\ performance\ (C) \\ &\times Environmental\ performance\ (E) \end{aligned}$$

All the events of dump truck operations and various losses in the dump truck operations were identified through literature review, field observations and interactions with field personnel. Various time losses identified in different operational events of dump truck operations were classified to translate OEE concept of performance evaluation of dump truck.

Time performance is calculated as the multiplication of availability and utilization. Availability takes into account "lost time" which includes any event that

stops planned production for an appreciable length of time due to maintenance, failures, and inspection of equipment. It is calculated as the ratio of available time to total time. Second component of time performance is utilization. Utilisation refers to the extent up to which a machine is being utilised for given available hours. Utilization of available hours can be expressed as the ratio of UT and AT.

Second term of Overall Equipment Performance Indicator (OEPI) is capacity performance. The term "capacity" in the perspective of a dump truck can be defined as the amount of material it can transport from one place (loading point) to another place (dumping point) in case of a coal mine. Capacity losses have been estimated through questionnaire survey, field observation and discussion with the field personnel.

The third component of OEPI measures the environmental performance of dump truck operation. The environmental performance has been indirectly calculated by measuring the CO_2 percentage of the dump truck engine exhaust. It indirectly accounts the effect of dump truck operation on the environment. It is expressed as

$$Environmental\ Performance\ (E\ ) = \frac{Percentage\ of\ CO_2\ in\ the\ engine\ exhaust}{12}$$

It indirectly indicates the health of the engine and its efficiency. When an engine is in good condition, it will exhaust more CO_2 due to better combustion of fuel. With increasing operating hours, the percentage of CO_2 in the engine exhaust will decrease and the percentage of other pollutants such as CO, unburnt fuel, NO_x, and hydrocarbons will increase in the exhaust. The percentage of CO_2 in the exhaust is nearly 12% in case of a diesel engine of the excellent condition [Khair et al., 2006]. If the engine is of excellent condition then the value of E will be near to 1.

The real benefit of performance measurement can be realised when it helps in diagnosing the problem of underperformance. This may be achieved through comparison with a standard level of performance. This research also discusses fixing the benchmark values of availability, utilization and OEPI so that one can compare it with the current performance value and if needed improvement can be done accordingly. It has been observed that there is an urgent need to develop a structured methodology for standardising performance of mining dump trucks that can be acceptable to the industry. In this study, a benchmarking methodology has been developed using K-means clustering and support vector machine.

By using the K-means clustering algorithm availability, utilization, and Overall Equipment Performance Indicator (OEPI) have been divided into five clusters, namely poor, marginal, average, moderate and good. The demarcation of the cluster boundaries has been done by using support vector machine (SVM). Benchmark has been fixed by considering the average of goods (AOG) in each case separately. AOG has been calculated from the average of all the data points which belongs to the good quality clusters.

By using the performance measurement metrics described above, the comparison of the performance of same capacity dump trucks of two different mines have been done and reasons for the low performance has been discussed. It was found that availability of Mine-I dump trucks is better but utilization and OEPI are poor as compared to Mine-II dump trucks.

The present work has been organized in seven chapters. A brief description of each chapter is presented in the following section:

Chapter 1 is an introductory chapter which lays down the relevance of the study. It summarizes the main objectives of this research. **Chapter 2** covers the related available literature on the subject area and deals with the different aspects of performance measurement of manufacturing industry and other industries in which OEE and its benchmark value was used as performance metrics as well in mining industries. **Chapter 3** discusses the methodology for measuring the OEPI and its components of the dump trucks. It also details the methodology of fixing the benchmark of the different components of performance measurement i.e., availability, utilization and OEPI. **Chapter 4** consists of field study and data collection. **Chapter 5** is dedicated to results and discussions. Results and discussions have been illustrated in the forms of graphs, figures and tables. **Chapter 6** discusses the application part of the developed methods. **Chapter 7** consists of conclusions and suggestions for the future work. References, appendices and drawings are compiled at the end.