Performance Measurement of Mining Equipment

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Abstract-- Achieving the high production and productivity target is one of the biggest challenges for mining companies, in order to remain competitive in the global market. As such, it entails proper performance measurement of huge and capital intensive equipment which are deployed in mining industries. The present paper aims at reviewing the available pertinent literature in the subject field and deals with various aspects of performance measurement of excavating, loading and transporting equipment in the mining industry.

Keywords-- Availability, Dragline, Maintainability, Mining Equipment, Overall Equipment Effectiveness (OEE), Performance Measurement, Production Index, Reliability, Shovel, Utilization

I. INTRODUCTION

Minerals are one of our basic needs as they are used in tools, machines and provide us power and energy. The ever increasing demand for minerals, owing to rapid industrialization and population explosion has forced the surface and underground mines to produce more of it. As such, a large number of Bucket based Excavating, Loading and Transporting (BELT) equipment such as dragline, shovel, dumper, Side-Discharge-Loader (SDL), Load-Haul-Dump (LHD) and Low-Profile-Dump-Truck (LPDT) are deployed to meet the demand. With deploying these huge and capital intensive equipment, improving their overall effectiveness and performance are absolutely important in order to achieve high production and productivity target. As such, it entails proper measurement of equipment efficiency.

In this light, various indicators such as cycle time, bucket-fill factor, material-swell factor, reliability, availability, maintainability, utilization, and production efficiency have been in vogue since long for evaluating the performance of BELT equipment. The present paper aims at reviewing the available pertinent literature in the subject field and deals with various aspects of performance measurement of BELT equipment in the mining industry. These indicators which are used for evaluating the performance of BELT equipment are described herewith.

It is worthy to note that, the term of ‘BELT’ has been introduced as acronym, in the present work, to cover the entire variety of equipment that have bucket, which is capable of excavating, loading, hauling and dumping or even for transporting the excavated material (as in trucks).

II. AVAILABILITY AND UTILIZATION

Availability and utilization are the key performance indicators of equipment and this is a usual tool for decision-making by management in the mine operation. Rate of production is highly sensitive to the equipments’ availability and utilization [1,2,3,4]. Therefore, serious efforts should be made by the mining companies to achieve and maintain the level of higher availability and utilization for capital intensive equipment.

By closely scrutinizing the pertinent literature, field visits and investigations in the case study mines, various events in the BELT equipment operation were identified, and classified which are used in definition of availability and utilization concept (see figure 1).

FIGURE 1: Breakup of total calendar time under different time head
Operational availability is associated with the operation of an equipment or system. It can be represented by the total number of hours ‘within a period’ that machinery is fit for work [5, 6, 7, 8, 9, 10].

However, there are a few inconsistencies in the definition and utility of the term ‘within a period’, e.g. some researchers proposed calendar-time based approach which considers this period based on scheduled and non-scheduled time for operation [1, 7, 11]. Other researchers have propounded loading-time based approach which considers this period based on planned/scheduled operating time [12, 13, 14]. The main differences between the two approaches lie in the consideration of total accountable time for evaluating the operational availability. Mathematically, the difference between these two approaches can be understood by the equations 1 and 2.

\[
A_o = \frac{AT}{TT} = \frac{TT - (PSDT + BDT)}{TT} \quad (1)
\]

Where, \(A_o\) is operational availability (calendar-time based),

\[
A_o' = \frac{AT}{POT} = \frac{POT - BDT}{POT} \quad (2)
\]

Where, \(A_o'\) is operational availability (loading-time based).

Loading-time based approach provides higher availability values than calendar-time based approach. Therefore, it is important to be very clear about the selection and application of one of these approaches before proceeding for evaluation of availability. Besides, while scrutinizing the review of literature, it is found that there are some inconsistencies in the definition and classification of events that affect the value of availability and ability to compare results. For instance, the term "maintenance" has been invariably used to depict routine maintenance, planned maintenance or even corrective maintenance. It is important to make an exact definition of each event.

Anvari et al. [15] consider routine maintenance activities (such as cleaning and lubrication) as Planned-Shut Down-Time (PSDT), while CMPDI [11], considered them as preventive maintenance which comes under the Break Down Time (BDT). Shift changing, lunch break and non availability of operator are considered as idle time by Mirabediny [5], CMPDI [11] and Rai [16], while Zoltan [6], Anvari et al. [15] and Dal et al. [17] consider such activities as PSDT.

### B. Inherent Availability

Inherent availability (\(A_i\)) is associated with the in-built characteristic of the equipment or its parts. It ignores the downtimes due to other sources which are not directly caused by the equipment design and are generally beyond the control of the designer. Hence, it is recommended to assess design characteristics during the design process that can be used as an important tool for framing preventive maintenance schedule, spare parts management and optimal replacement strategies [8, 18, 19, 20]. Mathematically the \(A_i\) may be expressed as:

\[
A_i = \frac{MTTF}{MTTF + MTTR} \quad (3)
\]

Where, \(A_i\) is inherent availability, \(MTTF\) is Mean Time To Failure, and \(MTTR\) is Mean Time To Repair.

From the above definition, it is clear that the inherent availability is a function of reliability parameter (how often a unit fails) and maintainability parameter (how fast the unit can be restored after failure) [3, 19, 21, 22]. Hence, it can be expressed as:

\[
A_i = f(MTTF, MTTR) \quad (4)
\]

or,

\[
A_i = f(R, M) \quad (5)
\]

Where, \(R\) is reliability characteristic of item or system measured in terms of \(MTTF\), and \(M\) is maintainability characteristic of item or system measured in terms of \(MTTR\).

Reliability investigations are usually helpful in deciding the optimal maintenance intervals and the patterns of spare parts consumption. Therefore, one of the most effective ways of increasing equipment’s inherent availability is to improve its reliability and maintainability, either by reducing the number of unplanned shutdowns, or by minimizing the length of scheduled turnarounds [19, 23].
A lot of research related to Reliability, Availability and Maintainability (RAM) of mining equipment with the aim of improving inherent availability has already been reported. Tregelles and Worthington [24] pointed out the importance of reliability assessment of mining equipment throughout its life starting with specification and design, through manufacture and testing and finally during installation, commissioning and operation.

Kumar [18] studied in detail, the Time To Failure (TTF) and Time To Repair (TTR) data for major subsystem for evaluating performance and effectiveness analysis of Load-Haul-Dump (LHD) machines. The data was collected from Kiruna mine, the largest and most modern underground iron ore mine in the world. Mean of TTF and TTR data was calculated for the best fit distribution, with the aim of analysis of inherent availability.

Vagenas et al. [25] deployed graphical, analytical and statistical tools in RAM analysis to study the failure and repair characteristic of the system and its subsystems. They further used these tools for enhancing the availability of mine trucks.

Nanda [26] estimated the availability of a drilling system using Markov model assuming failure and repair rates to be constant. Paraszczak [27] identified reliability and maintainability are the key constraints to improve the availability and hence productivity of LHDs. He proposed that MTTF can also serve for benchmarking of mining equipment performance. Hall et al. [28] stated that reliability and inherent availability are the design characteristic of an equipment and therefore much space is not available to improve them from users’ viewpoint. As such, it should be taken care of during design and user should put reliability as a criterion in the selection and evaluation of surface mining equipment.

Grujic et al. [29] pointed that operating environment has a significant role on the system’s reliability and efficiency. Observing the dynamic nature of the operating environment and quality of repair, a genetic algorithm based reliability assessment has been proposed by Nuziale and Vagenas [30] for mining equipment. Hall and Daneshmand [31] used Pareto analysis to identify the principle subsystems of haul trucks, responsible for high maintenance and downtime cost. They performed a comparative study of the MTTF and MTTR of hydraulic and electrical shovels deployed in surface mines.

Gupta et al. [32] discussed the methodologies to evaluate the effectiveness of the active maintenance polices to frame an importance measure based maintenance and replacement schedule for availability improvement of long-wall shearer.

Marquez [33] studied the critical failures of heavy duty earth moving machines to design maintenance policy. Barabady [2] analyzed TTF and TTR data for studying the reliability of crushing plant at Jajarm Bauxite mine. Elevli et al. [34] analyzed the maintainability of mechanical systems of electric cable shovel.

On the basis of all these studies it may be appropriate to state that RAM approach has been effectively used for identifying the A_i of various equipment since last 40 years in mining industry. The idea has evolved over these years to improve the equipment performance by the proper investigation of reliability and maintainability aspects.

C. Utilization

Utilization signifies the productive use of available hours. A machine may be available but still may not be working during the available hours due to inordinate and idling conditions. Thus, utilization represents a loss in available hours [3,9,10,35]. Utilization of available hours can be expressed as the ratio of UT & AT. Mathematically, it can be expressed in equation 6.

$$ U = \frac{UT}{AT} \quad (6) $$

It is also revealed by the review of literature [5,6,9,11,16,36] that there are some inconsistencies in the definition and classification of events that affect the value of utilization and ability to compare results.

It is worthy to note that, the low utilization of excavating, loading and transport equipment operation in surface mines, is largely due to the problem in their control or management. This is particularly pronounced in large and deep open pits with large fleet of trucks and many dump points. Different methods of truck control and truck allocation have been classified as non-dispatching (locked-out or fixed-assignment mode) and dispatching mode by Pfleider [37] and Burton [38]. To optimize utilization of shovel and truck operation, dispatching system (manual, Semi-automatic and Automatic) is being effectively applied in mining industry [39,40,41,42,43,44].

Trivedi et al. [45] in their study used the approach of queuing model to optimize the shovel truck operation. They critically analyzed the relation between the length of queues, waiting time in queue, utilization of shovel, approximate output from the shovel-truck combination and the cost involved in the system with respect to variation in the number of trucks.

Rai et al. [46] evaluated Computerized Truck Dispatch System (CTDS) in order to improve utilization and performance of shovel-truck combination.
Benjamin et al. [47] conducted an investigation to improve the utilization time of trucks based on an operating mine in South-east Queensland using a commercially available GPS collision avoidance system. The approach was to use the GPS collision avoidance system to collect the truck positioning, speed, and timing data, which gets automatically recorded as part of its normal function in order to translate this information in a conventional time and motion study.

Operation Research (O.R.) is another popular technique used widely in mining industry since 1960s in the areas of mine planning, design, production scheduling, equipment selection, and dispatching, etc. O.R. helps us in making a correct decision where a number of alternative solutions are available and is thus helpful in choosing the optimum policy. It is the application of mathematical methods for obtaining optimum and/or exact solution for the problems of economic, planning and management [48]. Burt and Caccetta [49] discussed the use of operational research to solve equipment selection problem in the context of surface mining. Fitspatrik [50] cited methods used by mining industry in the evaluation and selection of new haulage equipment and in increasing the utilization of existing fleet. White et al. [51] suggested an operational truck-dispatching system based on network models, linear programming, and dynamic programming. Dash [52] discussed a linear programming model for energy optimization. Brahma [53] studied application of operational research techniques in an open cast mining. Martinez and Newman [54] proposed a mixed-integer program to schedule long- and short-term production at LKAB's Kiruna mine, an underground sublevel caving mine. The proposed model minimizes deviations from monthly pre-planned production quantities while adhering to operational constraints.

Rai et al. [57] reported the cycle and idle time analysis for draglines operation in field. On the basis of image analysis, Osanloo and Hekmat [58] reported the influence of degree of fragmentation on the dig-ability of excavators.

Influence of geometry and dimension of excavation face on the digging time of excavators operating in surface mines has been reported by Rai [16], Erdem and Pasamehmetoglu [59], Erdem and Baskan [60], Patnayak et al. [61], Erdem and korkmaz [62], Mohammadi et.al. [63]. Benjamin et al. [47] did investigation to optimize truck-shovel fleet cycle using GPS collision avoidance system focused on the speed and timing data of a selected fleet of coal trucks at an open cast mine.

IV. BUCKET-FILL FACTOR

Bucket-fill factor indicates how well the available room in the bucket is used. This is the percentage of the bucket capacity that is actually filled with material.

Mathematically, it is expressed as:

\[
\text{Bucket fill factor} = \frac{\text{volume of material in the bucket}}{\text{bucket capacity}}
\]

The bucket-fill factor depends on bucket size & shape, dig-ability of material (dragging and filling the bucket), fragmentation (particle size, shape and distribution of material in the bucket), the angle of repose of the material on top of the bucket, operator skills, etc. [5,58,64].

Misra [65] stated that the Bucket-fill factor for dragline operation is 0.95-1.10 for easy digging conditions, 0.80-0.90 for medium digging conditions, 0.65-0.75 for medium-hard digging conditions and 0.40-0.65 for very hard digging conditions. Mirabediny [5] pointed out that bucket-fill factor may vary from 0.4-1.2 in practice

V. MATERIAL-SWELL FACTOR

Material once excavated becomes loose and its original volume increases. The material-swell factor is defined as the ratio of volume (m³) of equal weight of material before and after blasting/excavation as:

\[
s = \frac{\text{volume of material before blasting (bank volume)}}{\text{volume of equal weight of material after blasting (loose volume)}}
\]

The swell factor may vary between 0.6-0.9, depending on the nature of material (stickiness, moisture content), fragmentation (shape, size and distribution of material), etc. [5,64].
VI. PRODUCTION INDEX

Production index (PI) is another indicator in mining industry which serves to control day-to-day and shift-to-shift operations. Rai [16] termed it, as Production Efficiency in respect of the studies performed by him on shovel-truck and dragline operations in surface mines.

Production Index for any earthmoving equipment may be understood as the ratio between the actual production (output) and its potential production (rated output) of the equipment during the period of its operation [3,65]. However, PI does not indicate the reasons for low production. Mathematically, it can be expressed as:

\[ PI = \frac{\text{Actual Production (Output)}}{\text{Potential Production (Rated Output)}} \]  

(9)

Misra [67] stated that production efficiency of any excavator has two components: machine operating efficiency and the job management efficiency. Operating efficiency of a machine depends on the condition of operation, environmental conditions, experience and ability of the operator, and the state of maintenance of the machine itself. But usually such machines operate in conjunction with other equipment. In such cases the output also depends on the job management efficiency that controls the extent of utilization of the machine in the system.

Chironis [68] suggests that the efficiency of shovels should lie in the range of 85 to 90 percent. Misra [67] found that power shovels have a utilization of 31 to 77 percent with a production efficiency of 25-60 percent in Indian mines. Carter [69] pointed that the shovels in Lee Ranch mines, are operating at efficiencies of 80-85 percent. Rai [16] reported production efficiency of shovel in large surface mines, in the range of 58 and 66 percent.

To compute potential production, CMPDI [11] proposed equation 10 for BELT equipment.

\[ O = \frac{BC \times f \times s \times TT \times A \times U \times 3600}{CT \times m} \]  

(10)

Where,

- \( O \) is potential production per period (m³),
- \( BC \) is bucket capacity (m³),
- \( f \) is bucket-fill factor,
- \( s \) is material-swell factor,
- \( TT \) is total calendar time (h),
- \( A \) is operational availability,
- \( U \) is utilization,
- \( CT \) is cycle time (s), and
- \( m \) is factor to be allowed for travelling, positioning, etc. (\( m = 0.8 \) for dragline operation at Northern Coalfield Limited, India.)

Pundari [66] pointed that potential production per hour can be computed by equation 11 as:

\[ O' = \frac{BC \times f \times s \times d \times a \times 3600}{r \times CT} \]  

(11)

Where,

- \( O' \) is rated output per hour (m³),
- \( d \) is depth of cut (m),
- \( a \) is factor of swing angle, and
- \( r \) is stripping ratio.

Misra [67] proposed that output of shovel and dragline (m³) can be obtained from the equation 13.

\[ O' = \frac{BC \times f \times s \times \alpha \times D \times 3600}{CT} \]  

(13)

Where,

- \( \alpha \) is angle of swing factor, and
- \( D \) is depth of cut factor.

VII. PROBLEMS OF STATED INDICES AND SUGGESTED SOLUTION

Although, many improvements have been reported by using these indices, but these concepts are capable of providing 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 light, the concept of Overall Equipment Effectiveness (OEE) seems to be contemporary and truly relevant to address the growing demands on production and productivity. In other words, the OEE concept can bring together all the aforesaid indices under the domain of a comprehensive index. Managers appreciate such an aggregated metric instead of many detailed indices [70].

VIII. BASIC CONCEPT OF OEE

OEE is one of the most widely used performance indicator in production industries to assess how effectively the manufacturing operations utilize the facilities, time and material. It is a good indicator and compares the status of the performance with the designed capacity and the best practices in the industry. OEE analysis distinctly highlights the areas which need improvement, to optimize the manufacturing process.

Nakajima [12] introduced the concept of OEE to measure the performance of machine/equipment in manufacturing industries which considers the various sources of production losses.
He expressed OEE as a function of availability, performance and quality rates as given in equation 14.

\[
OEE = \text{Availability rate} \times \text{Performance rate} \times \text{Quality rate}
\]  

(14)

This concept accounted ‘Six big losses’ for computing availability, performance and quality rates which is illustrated in figure 2.

![OEE components based on Nakajima’s concept](image)

FIGURE 2: OEE components based on Nakajima’s concept [12].

From the figure 2, it is evident that the time component of any operating system suffers from three losses namely, downtime, speed and quality losses, which have been further divided on the basis of ascribing the reasons. Given this, ‘six big losses’ are clearly described as:

1. Equipment failure losses refer to the breakdown of equipment.
2. Set-up and adjustment time losses, occur when the production of one item ends and the equipment needs to be adjusted to meet the requirements to produce another item.
3. Idling and minor stoppage losses occur when the production is interrupted by a temporary malfunction or when a machine is idle.
4. Reduced speed losses refer to the difference between the speed for which the equipment is designed (standard speed) and the actual operating speed.
5. Defect in process and rework are considered as losses in quality which are caused by the malfunction of production equipment.
6. Reduced yield occurs during the early stages of production as the machine takes time to stabilize after its start up.

By closely scrutinizing in literature [7,14,15,17,71,72], it is clear that OEE has been used by various industries to provide meaningful solutions to real-time problems since 1988.

**IX. Concept of State of Art ‘OEE’ in Mining Industry**

Unfortunately, the excavation and mining industry in general has lagged behind other industries in the adoption of OEE as a good performance measurement and only a few studies [3,73,74,75,76] have been reported.

Emery [73] described the application of the Total Productive Management (TPM) technique, to improve OEE for a coal mining operation through loss analysis.

Samanta and Banerjee [75] investigated the improvement in productivity of mining machinery through TPM and OEE. Based on Nakajima’s concept, they proposed OEE as a function of availability (A), performance (P) and utilization (U) for mining equipment. They stated that Nakajima’s concept have given equal weights to A, P and U for calculating OEE, whereas it is not applicable in mining industry. So they assume some weight for A, P and U as 0.3, 0.5 and 0.2 respectively, for computing the OEE of mining equipment as given in equation 15.

\[
OEE = A^{0.3} \times P^{0.5} \times U^{0.2}
\]  

(15)

Dhillon [3] proposed that OEE is a function of availability, utilization and production index as equation 16.

\[
OEE = A \times U \times PI
\]  

(16)

Elevli and Elevli [76] reported that, there was no study in literature regarding how to use OEE metric for mining equipment. They tried to identify causes of time losses for shovel and truck operations, and classified these losses into three categories i.e. availability, performance, and quality losses.

**X. Critical Evaluation of the Literature and Research Issues**

Scrutiny of literature in performance evaluation of BELT equipment shows that all the indices (availability, utilization, cycle time, bucket-fill-factor, material-swell-factor, production index) have been in vogue since long in evaluation of equipment’s performance in order to improve the same.
Although, many improvements have been reported by using these indices, but traditional indices for measuring performance of BELT equipment are capable of providing a tunnel view to the scope of the problem by considering the equipment in isolation from the system.

However, the concept of OEE holds promise in bringing together the aforesaid indices in a comprehensive index for its evaluation and further improvement. In other words, OEE is a simple and clear overall indicator, which managers appreciate such an aggregated metric instead of many detailed indices.

Unfortunately, the excavation, construction and mining industry in general has lagged behind other industries in the adoption of OEE as a good performance measurement and only a few studies have been reported. Although, these studies are suggestive of improvement to the adoption of OEE’s concept in performance evaluation of mining equipment, they do not address the need to standardize the concept of OEE and its applicability to the BELT equipment to indicate how well the equipment was run in a holistic manner. In other words, the true benefit of OEE concept and its application has not been fully realized in BELT equipment because of the absence of a standard methodology to estimate OEE for BELT equipment.

Given the reasonably comprehensive (holistic) approach of the OEE and also keeping in mind its successful application in the manufacturing industry, the path forward is, to suitably translate the concept of OEE for BELT equipment by evolving appropriate methodologies and tools for the measurement of OEE in mining operations.

REFERENCES


