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PERFORMANCE EVALUATION OF BUCKET BASED EXCAVATING, LOADING AND TRANSPORT (BELT) EQUIPMENT – AN OEE APPROACH

OCENA DZIAŁANIA SYSTEMU ZŁOŻONEGO Z URZĄDZEŃ DO URABIANIA, ZAŁADUNKU ORAZ TRANSPORTU – PODEJŚCIE OPARTE O CAŁOŚCIOWĄ OCENĘ EFEKTYWNOŚCI

Overall Equipment Effectiveness (OEE) has been used since last over two decades as a measure of performance in manufacturing industries. Unfortunately, enough, application of OEE in mining and excavation industry has not been duly adopted. In this paper an effort has been made to identify the OEE for performance evaluation of Bucket based Excavating, Loading and Transport (BELT) equipment. The conceptual model of OEE, as used in the manufacturing industries, has been revised to adapt to the BELT equipment. The revised and adapted model considered the operational time, speed and bucket capacity utilization losses as the key OEE components for evaluating the performance of BELT equipment. To illustrate the efficacy of the devised model on real-time basis, a case study was undertaken on the biggest single bucket excavating equipment – the dragline, in a large surface coal mine. One-year data was collected in order to evaluate the proposed OEE model.

Keywords: OEE, Performance Measurement, Availability, Utilization, Speed Factor, Bucket Capacity, Mining Equipment

Podejście oparte o całościową ocenę efektywności używane jest od ponad dwóch dekad w analizach skuteczności działania urządzeń w przemyśle wytwórczym. Niestety podejście to nie zostało szeroko przyjęte w przemyśle górniczym. W pracy tej podjęto próbę dokonania całościowej oceny efektywności pracy układu złożonego ze sprzętu do urabiania, załadunku (koparki) oraz transportu. Model koncepcyjny podejścia całościowej oceny stosowany dotychczas w przemyśle wytwórczym został zaadaptowany by uwzględniać specyfikę systemów urabiania, ładowania i transportu. Odpowiednio zmodyfikowany model uwzględnia czas pracy układu, tempo pracy, spadek ładowności koparki i spowodowane w ten sposób straty, umożliwiając dokonanie całościowej oceny wydajności pracy systemu. Poprawność opracowanego modelu działającego w czasie rzeczywistym zbadano na przykładzie systemu do urabiania, załadunku

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i transportu wykorzystywanego w dużej kopalni odkrywkowej węgla. Do oceny poprawności modelu wykorzystano zebrane dane obejmujące cały rok pracy urządzeń.

Słowa kluczowe: całościowa ocena efektywności, pomiar wydajności, wykorzystanie sprzętu, tempo prac, ładowność, sprzęt górniczy

1. Introduction

The ever increasing demand for minerals has forced the surface mines to consistently upgrade the mechanization, for extracting minerals and removing overburden (OB), as well. As such, a large number of Bucket based Excavating, Loading and Transport (BELT) equipment such as dragline, shovel, Load-Haul-Dump (LHD) and truck are deployed to meet the demand. 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).

The BELT equipment are highly capital intensive to procure, operate and maintain in any surface mining operation. Notwithstanding, the loading, hauling and transport operations are widely recognized as the backbone of the surface mining industry, as these activities comprise up to 50% of the total mining costs (Oraee et al., 2009; Rodigo et al., 2013). Hence, improving the overall effectiveness and performance of BELT equipment (which depends on, how effectively all its resources are utilized) is absolutely important.

Scrutiny of literature in performance measurement of BELT equipment shows that prevailing methods for performance evaluation of BELT equipment are primarily based on the concepts of measurement of availability and utilization. Besides, other indices such as bucket fill factor, material swell factor, cycle time and production index etc. have been used since long in evaluation of equipment's performance in order to improve the same. Although, many improvements have been reported by using these indices, 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. The OEE concept can bring together all the aforesaid indices under the domain of a comprehensive index.

Since last over two decades, OEE has been aptly used as a good performance indicator to assess, how effectively manufacturing industries utilize all the resources. OEE concept as used by the manufacturing industry, takes into account all types of losses in time, speed and quality of product, which appears to provide a reasonably comprehensive solution to the performance evaluation. A host of publications dealing with the various applications of OEE show its popularity in manufacturing industries (see for example Jonsson & Lesshammar, 1999; Dal et al., 2000; Jeong & Phillips, 2001; De Ron & Rooda, 2005; Anvari et al., 2010; Zandieh et al., 2012; Wibowo, 2012; Tsarouhas, 2013).

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 (see Emery 1998, Samanta and Banerjee 2004, Dhillon 2008, Elevli and Elevli 2010). These studies 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 aim of this research is, to suitably translate the concept of OEE for BELT equipment by evolving appropriate methodologies and tools for measurement of OEE in large-scale surface mining operations.

2. Basic Concept of OEE

Nakajima (1988) 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 1.

$$OEE = Availability\,rate \times Performance\,rate \times Quality\,rate \tag{1}$$

This concept accounted "Six big losses" for computing availability; performance and quality rates which is illustrated in Figure 1.

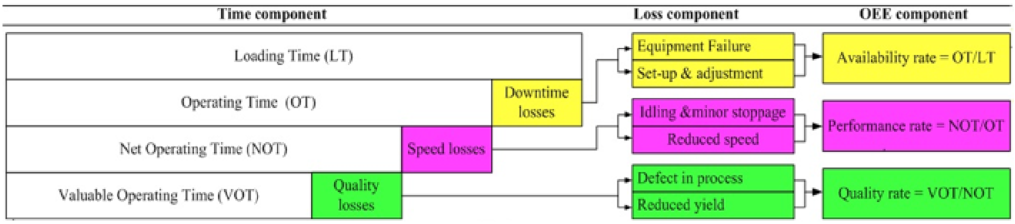

Fig. 1. OEE components based on Nakajima's concept (After Nakajima, 1988)

From the Figure 1, 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. From Figure 1 and equation 1 it is also revealed that OEE can be computed as the following equation.

$$OEE = \frac{Valuable\,operating\,time}{Loading\,time} \tag{2}$$

Jeong and Phillips (2001) considered that the equipment should work for full calendar time i.e. 8760 hours per year. Various components of OEE and calculation procedure based on Jeong and Phillips' concept are illustrated in Figure 2.

From Figure 2 and equation 1 it is also revealed that OEE can be computed as the following equation.

$$OEE = \frac{Valuable\,production\,time}{Total\,calendar\,time} \tag{3}$$

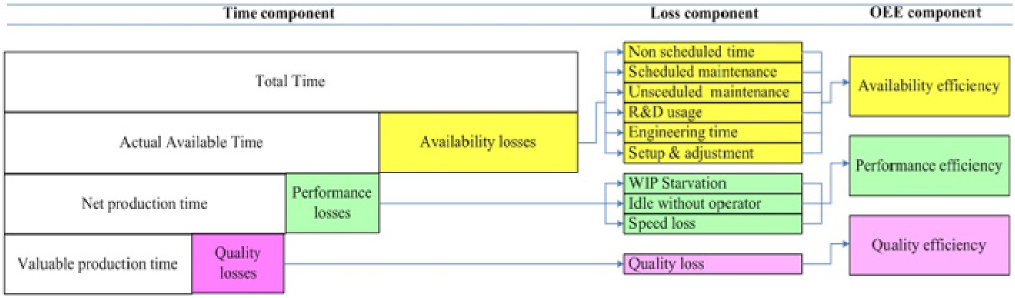

Fig. 2. OEE components based on Jeong and Phillips' concept (Jeong & Phillips, 2001)

The main difference between these two approaches lies in the consideration of total accountable time for evaluating the OEE. In other words, Jeong and Phillips' approach is based on calendar time, whereas; Nakajima's approach is based on loading time. Loading time based approach provides higher OEE values than calendar time based approach. Therefore, it is important to be very clear about the selection and application of approach before proceeding for evaluation of any productive system.

3. Methodology for translating OEE of BELT equipment

To translate OEE concept for BELT equipment, following methodology has been proposed and discussed step by step:

- Review the literature of performance measurement indicators for BELT equipment in mining industry,
- Review the literature of OEE approach in manufacturing industry,
- Field visits in the study mines to investigate BELT equipment operational and performance details, so as to identify the events and losses in detail,
- Categorical scrutiny of the field study data in order to formulate a frame work for recording, collecting and classifying the data for BELT equipment.
- Identification and clear definition of OEE components for designing a suitable OEE model and then evaluating the performance of BELT equipment vis-à-vis the designed model, and
- Implementation of devised OEE model on real-time basis to evaluate the BELT equipment performance.

4. Loss component of BELT equipment

By closely scrutinizing the pertinent literature (e.g. Misra, 1979, 2006; Sarnathan, 1979; Nakajima, 1988; Kumar, 1988, 1989, 1990, 1998; Osanloo, 1995; Rai, 1992, 2004, 2007; Rai et al., 2000, 2011; Mirabediney, 1998; Zoltan, 1999; Doktan, 2001; Jeong & Phillips, 2001; Erdem & Baskan, 2005; Osanloo & Hekmat, 2005; Barabady, 2007; Dhillon, 2008; Oraee et al., 2009; Elevli & Elevli, 2010; Gupta & Bhattacharaya, 2012; Erdem & Korkmaz, 2012; Mena et al., 2013), field visits and investigations in the case study mines, various events and losses in the BELT equipment operation were identified, defined and classified, while keeping in mind, the aim of translating OEE concept of performance evaluation on the BELT equipment.

The suggested framework takes into account all loss components of BELT equipment and is illustrated in Figure 3.

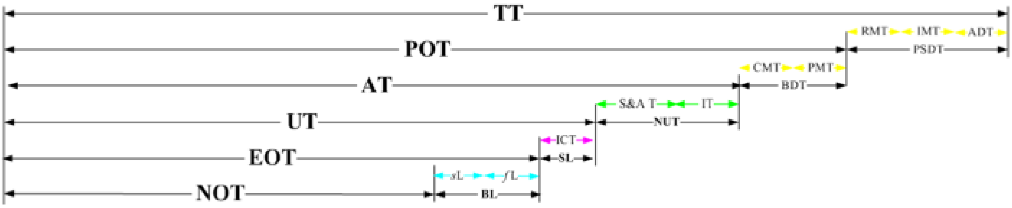

Fig. 3. Break-up of total calendar time and loss components of BELT equipment

The unit of all the time element data is in h. These time elements are briefly described as:

4.1. Total calendar time (TT)

It is the actual no. of hours in a given period of observation. For instance, an equipment operating 8 hours per shift on 3-shift basis will have 8760 hours per year as total calendar time.

4.2. Planned shutdown time (PSDT)

It is the time during which equipment is planned for not to operate owing to following:

Administrative time (ADT): It includes all planned shutdown related to administrative/ management, such as, statutory holidays, major weather related shutdown, acts of nature, shift changeovers, refuelling, administratively permissible personal needs of an operator etc.

Improvement time (IMT): It is the time spent on research and development (R&D), and activities for upgrading equipment, which need no operation of machines.

Routine maintenance time (RMT): It is an essential part to take care of routine service and unreported minor repairs, if at all needed. RMT is done as per the recommendation of manufacturers. The aim of this type of maintenance is sustaining or extending the useful life of the equipment.

4.3. Planned operating time (POT)

Planned Operating Time (POT) is the time during which, the machine is scheduled to operate. It is also known as loading time.

4.4. Breakdown time (BDT)

It is the period of time that a piece of machinery or equipment is non-operational as a result of maintenance due to a malfunction or breakdown. BDT includes not only repair time, but also other shutdown activities such as delay time in repair. Maintenance program consists of planned maintenance (PM) and corrective maintenance (CM).

PM is performed to pre-empt the chance of occurrence of breakdown by finding the fault and evaluating the reason (detecting) before occurrence of failure. To this end, there are two maintenance strategies, which are prevalent, namely time based and condition based. Time based maintenance (TBM) is performed at scheduled intervals and is named as preventive maintenance. Whereas, the condition based maintenance (CBM) is named as predictive maintenance and performed after one or more indicators show that condition falls below acceptable thresholds.

CM is basically the “run-to-failure” maintenance mode. It is always done after the occurrence of failure in order to correct and restore failed equipment by following an established repair/replacement procedure. It is also termed as unplanned maintenance. It is done when failure of component is not predictable or controllable.

4.5. Available time (AT)

It can be represented by the total number of hours within a period that machinery is fit for work. In other words, AT represents the working time available for operation. Available time reveals the breakdown time losses in POT.

4.6. Non Utilization time (NUT)

A machine may be available but still may not be working during the available hours due to inordinate and idling conditions. NUT accommodates Idle Time (IT) and set-up & adjustment time (S&A T). IT is the time losses by expected stoppages or unexpected events that make the equipment non-operating. Idle time is considered the time which, the equipment is available and ready to operate but not involved in production. These stoppages are not due to malfunctions or failures. Inordinate dozing, non-availability of power, extended tiffin time or extended shift change-over time are some of the reasons for equipment idling.

Setup is the time spent in organizing the infrastructure for preparation of the machine to perform. Adjustment time is the time consumed to adjust the machine and operator for producing an assigned task. Cable and field switch shifting is an example of set-up time of dragline. While marching of dragline between two sitting positions and relocating itself at the second sitting positions is an example of adjustment time.

4.7. Utilization Time (UT)

It is the time when the equipment is running and performing its designated function(s).

4.8. Speed Loss (SL)

Speed loss for BELT equipment can be defined as the Increase in Cycle Time (ICT) of operation (Mohammadi and Rai 2015). In other words, it is discrepancy between actual and planned cycle time. Cycle time of dragline and other excavators can be distinctly split into four discrete segments namely: digging/scooping, swing-to, unloading and swing-back. Similarly, time segments in cyclic operation of trucks could be split as spotting time, loading time, travel-to (loaded), spotting at unloading site (if needed), unloading time and travel-back (empty).

Speed loss lead to reduction in utilization time, which in turn, evolves the concept of Effective Operating Time (EOT). The EOT, being less than the utilization time, indicates reduction in output.

4.9. Bucket capacity utilization loss (BL)

In place of quality loss in manufacturer industry, BL may be introduced to represent decrease in quantity of loaded material in the bucket of BELT equipment. BL are responsible for creating a discrepancy between the planned and actual output per cycle.

Planned output per cycle (O_{pc}) represents the theoretical volume of material that can be moved by the bucket of BELT equipment in one full pass. It is obtained by adjusting the bucket volume by incorporating the material swell and bucket-fill-factors as given in equation 4.

$$O_{pc} = BC \times f_P \times s_P \tag{4}$$

Where, O_{pc} is planned output per cycle (m^3), BC is bucket capacity (m^3), f_P is planned bucket-fill factor, and s_P is planned swell factor.

These factors have been defined as follows:

Bucket capacity (BC): The bucket capacity can be expressed as struck and heaped. The struck capacity of a bucket is rated on the inside physical dimensions of the bucket only. In other words, the struck capacity is based on an envelope covered by the dump body. The heaped capacity is the amount of material inside the bucket plus the amount piled on top. The amount of material piled on top of the bucket (heap) is determined by the angle of repose of the material being handled.

Bucket-fill factor (f): This 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:

$$Bucket\ fill\ factor = \frac{volume\ of\ material\ in\ the\ bucket}{bucket\ capacity} \tag{5}$$

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 bucket, operator skills, etc. (Mirabediney, 1998; Doktan, 2001; Osanloo & Hekmat, 2005). Also the decrease in bucket-fill factor may be attributed to sticking of material inside the bucket (rework) and material spillage during loading.

Swell factor (s): Material once excavated becomes loose and its original volume increases. The swell factor is defined as the ratio of volume (m^3) of equal weight of material before and after blasting/excavation as:

$$s = \frac{volume\ of\ material\ before\ blasting\ (bank\ volume)}{volume\ of\ equal\ weight\ of\ material\ after\ blasting\ (loose\ volume)} \tag{6}$$

The swell factor depends on the nature of material (stickiness, moisture content), fragmentation (shape, size and distribution of material), etc.

Actual output per cycle (O_{ac}): The losses in the planned output per cycle (BL) may be summarized as:

- Equipment operates at lower bucket-fill factor than planned (Bucket-fill factor loss – fL),
- Variation (mostly reduction) in swell factor (swell factor loss – sL).

Actual output per cycle (O_{ac}) can be compute as:

$$O_{ac} = BC \times f_a \times s_a \tag{7}$$

Where, f_a is actual bucket-fill factor, and s_a is actual swell factor.

4.10. Net operating time (NOT)

It refers to the time in which the materials are carried in the full capacity of bucket. It is noteworthy to mention that BL can be converted into the time losses which, in turn, can be converted into equivalent production losses. Therefore, the term NOT may hence be conceived to describe the reduction in equipment output due to bucket losses.

5. Translate OEE for BELT equipment

In line with Nakajima's concept, the overall equipment effectiveness of BELT equipment has been configured and defined as the product of availability, utilization, speed and bucket factors. Figure 4 reveals OEE components and all the losses related to time, speed and bucket-capacity utilization for BELT equipment deployed in excavating industry.

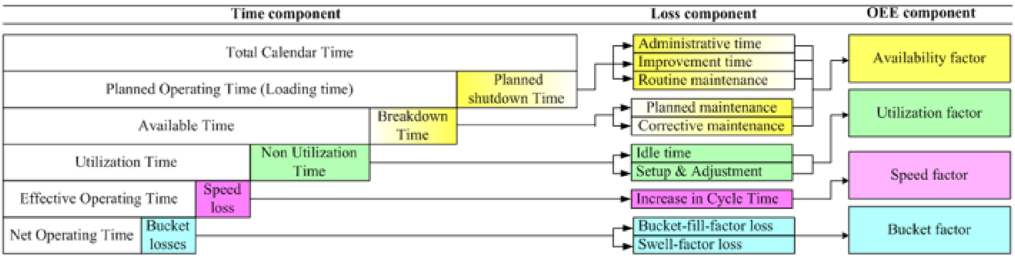

Fig. 4. OEE components of BELT equipment

Giving due consideration to different losses, the corresponding OEE components have been identified and assigned. These factors are briefly described as:

5.1. Availability factor (A)

Availability is associated with the operation of an equipment or system. Mathematically, it can be expressed as:

$$A = \frac{AT}{TT} \tag{8}$$

5.2. Utilization factor (U)

Utilization signifies the productive use of available hours. Utilization of available hours can be expressed as:

$$U = \frac{UT}{AT} \tag{9}$$

5.3. Speed factor (S)

Speed factor is the ratio of the planned cycle time of the equipment to the actual cycle time. Mathematically, it can be expressed as:

$$S = \frac{CT_p}{CT_a} \tag{10}$$

Where, CT_p is planned cycle time (s), and CT_a is actual cycle time (s).

5.4. Bucket factor (B)

This factor signifies the productive use of bucket capacity. 'B' expresses the ratio of actual quantity of material loaded by bucket (bucket payload) with respect to the planned output per cycle. Accordingly, it can be computed by equation (11).

$$B = \frac{O_{ac}}{O_{pc}} \tag{11}$$

5.5. OEE of BELT equipment

OEE of BELT equipment is obtained by incorporating the availability, utilization, speed and bucket factors. Consequentially, a mathematical relationship is presented in equation (12) for OEE as given:

$$OEE = A \times U \times S \times B \tag{12}$$

From figure 4 and equation 14 it is revealed that the OEE of BELT equipment also can be expresses as:

$$OEE = \frac{AT}{TT} \times \frac{UT}{AT} \times \frac{EOT}{UT} \times \frac{NOT}{EOT} = \frac{NOT}{TT} \tag{13}$$

6. Output computation vis-à-vis OEE concept

For incorporating the OEE concept in projecting the real-time output, equation (14) has been developed as:

$$O = O_{pc} \times \frac{TT \times 3600}{CT_P} \times OEE \tag{14}$$

Where, O is output (production) in a period of time (m^3).

7. Implementation of the devised model

To illustrate the efficacy of the devised model on real-time basis, a case study was undertaken on the biggest single-bucket equipment (the dragline) in a large opencast coal mine. Dragline

(DL) works as an excavator, digging the overburden (OB) cover the coal seam and side casting it directly into the de-coaled area. This operation, in turn, exposes the underlying coal seam. Figure 5 shows the draglines operating in horizontal tandem mode, being seated at top of the overburden bench and exposing the coal seam underneath. It is observed in the figure 5 that the dragline (A) is in the process of filling the bucket and dragline (B) is in the process of discharging the filled material.

Fig. 5. Draglines in operation sitting at the top of the blasted overburden bench

On the field scale, one-year data with respect to one dragline for operation time, time losses, actual cycle time, bucket-fill factor and swell factor was collected to compute the A, U, S and B (the four important OEE components of BELT equipment- as already established in the preceding section) in order to implement and evaluate the OEE model.

7.1. Analysis of A and U from the field data

Field studies provided the monthly data on total calendar time (TT), Planned Shutdown Time (PSDT), Breakdown Time (BDT), Non-utilization time (NUT) of DL over a period of year 2012. Table 1 presents the classified data and calculated values of A and U by using equations 8 and 9.

The results of table 1 show that 'A' for the month of March was 0.9226 and declined to as low as 0.0420 in the month of May. The sharp downfall in availability clearly indicates problems in health and upkeep of the dragline. Additionally, it can also be observed from the table 1 that the dragline faced large number of breakdowns during the stated period of lean availability. Furthermore, the corresponding 'U' value was also very low (0.5488).

TABLE 1

Month-wise operational time (h), availability & utilization of DL under study

Month	TT	PSDT (h)			BDT (h)		NUT (h)		A	U
		ADT	IMT	RMT	CMT	PMT	S&AT	IT		
Jan.	744	12.45	0	24	10.5	300	11.3	41	0.5337	0.8683
Feb.	696	0.45	0	44.5	33	73.8	15.4	34.8	0.782	0.9078
Mar.	744	0.45	0	42.3	8.8	6	18.2	45.5	0.9226	0.9072
Apr.	720	0.45	0	39	25.8	50	17.6	54.5	0.8399	0.8808
May	744	0.45	0	1.8	702.5	8	0.8	13.3	0.042	0.5488
June	720	12.45	0	38	9	120.3	50.9	122.8	0.7503	0.6785
July	744	12.45	0	40.5	15.8	42.8	10.2	32.5	0.8501	0.9325
Aug.	744	12.45	0	58.5	18	3	0	59.3	0.8764	0.9091
Sept.	720	12.45	0	39.3	70	8	11.3	43.0	0.8198	0.908
Oct.	744	0.45	0	24.3	27.8	33.3	19.1	50.3	0.8846	0.8946
Nov.	720	4.45	0	48.8	11.5	20	17.5	34.3	0.8823	0.9185
Dec.	744	0.45	0	33.8	4.8	37	21.6	36.5	0.8978	0.913
Ann.	8784	69.4	0	434.5	937.3	702	193.9	567.5	0.756	0.8853

7.2. Analysis of Speed factor (S)

For the purpose of systematic investigation, one complete cycle of operation of dragline was split into four 'time segments', namely digging time (T_1), Swing-to time (T_2), Unloading time (T_3) and swing-back time (T_4). Individual time for each of these segments was carried out in the field at various cut depths, cut geometry and swing angles as given in table 2. Mathematically, the actual cycle time (CT_a) can be simply represented as the sum of the segmental times:

$$CT_a = T_1 + T_2 + T_3 + T_4 \tag{15}$$

TABLE 2

Segmental and actual cycle time results

Actual cycle time and its segments (s)				
T_1	T_2	T_3	T_4	CT_a
23.91	30.97	4.39	30.61	89.88

Central Mine Planning & Design Institute Limited (CMPDI, 2000) has stipulated the dragline under study CT_p as 74 s. Therefore, the speed factor by using equation (10) is computed as:

$$S = \frac{CT_p}{CT_a} = \frac{74}{89.88} = 0.8233$$

An important feature, which is noteworthy from the cycle time and speed factor results, is the increase of CT_a (89.88 s) in comparison of CT_p (74 s) for the dragline under study. Discrepancy of over 16s per cycle is the cycle time loss (CTL). Correspondingly, there exists a speed loss of 17.7% and the dragline operates only at speed of 82.33%.

Table 3 presents the month-wise variations of average of actual cycle time and speed factor for the dragline under study.

TABLE 3

Month-wise variations of actual cycle time (s) and speed factor for DL

Month	CT_a (s)	CT_p (s)	S
Jan.	89.92		0.8230
Feb.	90.91		0.8140
Mar.	91.08		0.8125
Apr.	90.11		0.8212
May	89.48		0.8270
June	88.76		0.8337
July	90.75	74	0.8154
Aug.	89.99		0.8223
Sept.	88.75		0.8338
Oct.	89.52		0.8266
Nov.	89.98		0.8224
Dec.	88.53		0.8359
Ann.	89.88		0.8233

7.3. Analysis of bucket factor (B)

The mine deployed 24 m^3 bucket capacity draglines for the removal of overburden (OB) muck for exposing the underlying coal seam. OB of dragline bench mainly comprised of fined grained sandstone with sandy and gray shale. The planned values, (stipulated by CMPDI) for bucket-fill and swell factors (f_p & s_p) for digging the given OB were 0.951 and 0.732 respectively. Planned output per cycle (O_{pc}) for the case study dragline was computed by using equation 4 as:

$$O_{pc} = BC \times f_p \times s_p = 24 \times 0.951 \times 0.732 = 16.71 \text{ m}^3$$

The computation of O_{ac} was done by using equation 7. The month-wise variations of O_{ac} (m^3) and 'B' for the dragline under study over a year are given in Table 4.

The actual swell factor of material (s_a) has been estimated by thoroughly surveying the volume of dragline bench before blasting (bank volume) and after blasting (loose volume). The actual bucket-fill factor (f_a) has also been estimated by thoroughly surveying the dragline bench before and after handling of the blasted OB to obtain the loose volume of removed OB (V_l). The number of cycles (NC) required to handle this volume of OB was adopted from the field logs. By substituting the value for bucket capacity as 24 m^3, the loose volume of OB and the number of buckets in equation 16 the f_a is estimated.

$$f_a = \frac{V_l}{NC \times BC} \tag{16}$$

The results of table 4 show that 'B' in the month of May was 0.9759 and declined to as low as 0.6445 in the month of March. Notwithstanding, the variation in 'B' for the present case can be attributed to loss in bucket-fill and swell factors. In other words, the reduction in bucket-fill and swell factors exert tremendous impact on the bucket capacity utilization.

During the field-work, it was observed that dig-ability of material (dragging and filling the bucket), particle size, sticking of material inside the bucket (rework), material spillage during loading, and operator's skill affected the bucket losses.

TABLE 4

Month-wise variations of O_{ac} (m^3) and 'B' for DL under study

Month	BC (m^3)	s_a	f_a	O_{ac} (m^3)	O_{pc} (m^3)	B
Jan.		0.723	0.901	15.63		0.9354
Feb.		0.725	0.848	14.75		0.8831
Mar.		0.732	0.613	10.77		0.6445
Apr.		0.729	0.867	15.18		0.9084
May		0.722	0.941	16.30		0.9759
June		0.727	0.856	14.94		0.8941
July	24	0.732	0.873	15.34	16.71	0.9180
Aug.		0.730	0.821	14.38		0.8604
Sept.		0.728	0.860	15.02		0.8991
Oct.		0.725	0.857	14.90		0.8921
Nov.		0.727	0.872	15.22		0.9108
Dec.		0.728	0.859	15.01		0.8986
Ann.		0.728	0.834	14.58		0.8724

7.4. Analysis of OEE

The computation of OEE for the study dragline was done by using equation 12 and tabulated in Table 5.

TABLE 5

Month-wise variations of OEE and its component for DL under study

Month	A	U	S	B	OEE
Jan.	0.5337	0.8683	0.8230	0.9354	0.3568
Feb.	0.782	0.9078	0.814	0.8831	0.5103
Mar.	0.9226	0.9072	0.8125	0.6445	0.4383
Apr.	0.8399	0.8808	0.8212	0.9084	0.5519
May	0.042	0.5488	0.827	0.9759	0.0186
June	0.7503	0.6785	0.8337	0.8941	0.3795
July	0.8501	0.9325	0.8154	0.9180	0.5934
Aug.	0.8764	0.9091	0.8223	0.8604	0.5637
Sept.	0.8198	0.908	0.8338	0.8991	0.5580
Oct.	0.8846	0.8946	0.8266	0.8921	0.5836
Nov.	0.8823	0.9185	0.8224	0.9108	0.6070
Dec.	0.8978	0.913	0.8359	0.8986	0.6157
Ann.	0.756	0.8853	0.8233	0.8724	0.4807

A scrutiny of OEE results from table 5 clearly indicates that the range of OEE varies from 0.0186-0.6157. For an idealized situation, the OEE should be equal to 1. The low range of OEE values is indicative of the high losses in availability, utilization, speed, and bucket-capacity utilization as detailed in Figure 6.

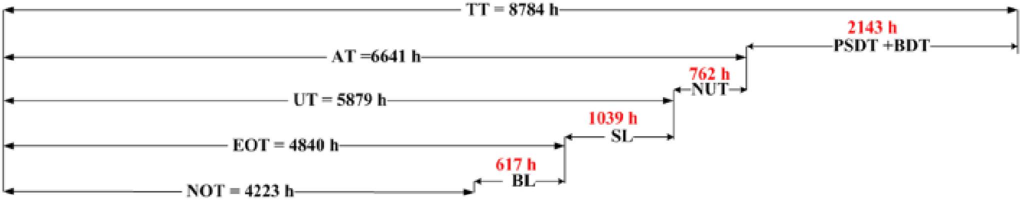

Fig. 6. Year-wise variations in time and losses (h) for the dragline under study

As mentioned earlier, the speed loss (SL) and bucket-capacity utilization loss (BL) can be converted into the time losses which, in turn, can be converted into equivalent production (output) loss. Considering PSDT+BDT, NUT, SL, BL, CT_p and O_{pc} as 2143 h, 762 h, 1039 h, 617 h, 74 s and 16.71 m^3 the equivalent loss in output, has been computed and shown in figure 7.

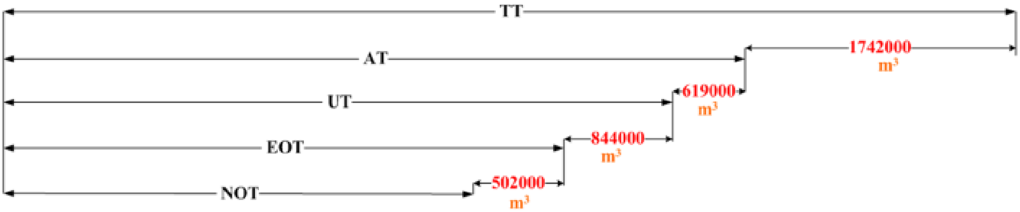

Fig. 7. Equivalent production (output) loss of DL under study (m^3)

The ranking of these losses was done on the basis of respective loss hours and loss outputs. The ranking reveals that availability losses (almost 47%) stood at the top, followed by speed losses (almost 23%), utilization losses (almost 17%) and bucket loss (almost 13%).

The value of OEE reflects the equipment's performance vis-à-vis the problem areas for further improvements. The area of problem, the bottlenecks and areas need attention and improvement, which mostly related to equipment failure and cycle time of operation. Given this, it is suggestive from the present study that there is sufficient scope to improve the system by addressing to maintenance and repair issues, overall system organization, planning and design issues.

8. Output (production) of the dragline under study

Using the OEE approach the annual output of DL under study, is computed, by substituting the obtained values for O_{pc}, TT, CT_p and OEE as 16.71 m^3, 8784 h, 74 s and 0.4807 respectively in the equation 14 as:

$$O = O_{pc} \times \frac{TT \times 3600}{CT_P} \times OEE = 3{,}431{,}910 \ \text{m}^3$$

By comparing the obtained value of this computation, it has been revealed that output projected on the basis of OEE studies, represents very close to the actual output (3,432,285 m^3) reported by the surveying department of the study mine.

The result reveals that production of BELT equipment is highly depend on OEE, because it accounts all sources of losses in production and higher level of output can be obtained by improving the OEE components.

9. Conclusions

Following conclusions may be drawn from the present study:

- Adoption of OEE concept from manufacturing industry and its adaptation for the BELT equipment, operating in real-time, has yielded useful insights in terms of losses related to operational time, speed and bucket capacity utilization.
- The study suggests that OEE for the BELT equipment is a function of its availability, utilization, speed and bucket factors.
- The value of OEE reflects the equipment's performance vis-à-vis the problem areas for further improvements.
- OEE analysis of the case study system shows that low availability and speed factor are the mainly responsible for low OEE figures.
- The reduction in bucket-fill and swell factors exert tremendous impact on the bucket capacity utilization.
- From the actual field measurements and related computations, it has been revealed that the bucket-fill factor, as stipulated in the production computation norms, needs to be critically re-looked.

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