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Overall equipment effectiveness of shovel-dumper operation in opencast mining – a review

One of the principal costs in opencast mine is related to application of loading and haulage equipment. The real challenge of mine management of an opencast mines is to select the proper fleet size of dumpers and shovels and to utilize them effectively; it secures the production needs of a mine as well as minimizes costs of production. Overall equipment effectiveness can be used as a tool to measure the performance and utilization of shovel-dumper operation in opencast mines. Authors of the paper have discussed on the cycle time of shovel and dumper, their dispatching and allocation problem and proper combination in opencast mining operation to optimize the productivity and to reduce the operational cost after reviewing several research artcles.

Keywords: *Dumper, shovel, productivity, operational cost, OEE,*

1. Introduction

In the current competitive global economic scenarios, effective equipment utilization in opencast mines is an important aspect; since industry wants to utilize their equipment as effectively as possible to reduce the total production cost and get an early return on the investments. Loading and haulage operation involve high costs and contributes as the largest cost component in the total operating cost, constituting 50-60% of the total mine operating cost (Alarie and Gamache, 2002) (Ercelbi and Basçetin, 2009). Dumpers and shovel are considered to be one of the key resources in loading and haulage operation and their productivity largely depends on their cycle time, allocation and combination for every operation. Lots of effort has been directed to cost saving by improving efficiency and effectiveness in shovel-dumper haulage operation and the same over the time has also proven to be improving in terms of reliability. The research on efficiency of shovel and dumper focuses on estimating and optimizing the productivity of a fleet of hauling and loading equipment. This is based on the intuitive notion that improving productivity will translate into cost reductions (Schexnayder et al. 1999). Productivity is a function of a number of factors, the major influences being: dumper size selection, blasting proficiency, average swing angle, dumper presentation, dumper spotting time, operator's efficiency (Paterson and Özdoga, 2001). Using discrete event simulation to analyse earthmoving operation, various authors observed that the most important factors affecting rate of production were in order: the number of dumpers, haul return time, the number of passes per load and then the loading rate (Douglas 1964, Morgan 1994). Smith et al. (1995) indicated that the importance of the factors, affecting the production rate, varied along with the change in haul distances. Optimization of a dumper-shovel operation might appear straight forward in theory; however it is quite complex due to the interdependent nature of the system.

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2. Overall effectiveness of shovel-dumper operation

Overall effectiveness of equipment (OEE) comprises three elements, namely availability, utilization and performance (Paraszczak, 2005). OEE can be used applied with other parameters for improvement of mining performance. It has been used by Akande et. al. to determine the loaders and dumpers performance in Namibian mines with results of suggestions to improve the availability of the equipment. Elevli and Elevli (2010) have applied OEE as benchmark formation for improvement of shovel and dumpers performance and described it as follows:

OEE = Availability × Performance × Quality

OEE takes the most common and important six sources of productivity loss, which are given in Table 1 (Elevli and Elevi, 2010) (Nakajima, 1998)

TABLE 1: THE MOST COMMON AND SIX SOURCES OF PRODUCTIVITY LOSS

Big losses	Category of OEE loss	OEE factor
Equipment failure Set up and adjustment	Downtime loss	Availability (A)
Idling and minor stoppages Reduced speed	Speed loss	Performance (P)
Reduced sield Quality defects	Defect loss	Quality (Q)

3. Cycle time of shovel

Production from a shovel is expressed in bank cubic meter per unit time. The production cycle of shovel consists of four elements; load the bucket, swing with the load, dump the load and return swing for next load. Actual production per cycle is always less than the rated capacity of the equipment. Major factors those affect the shovel performance are swell factor, fill factor, bench height, swing factor, quality of rock fragmentation. The Technical Capacity Q_t, makes allowance for operating conditions of a shovel and is maximum possible for a given model operation in the continuous mode under specific mining-technical conditions (Molotilov et.l. 2008). Qt of a shovel can be calculated from the Equation 1 (Molotilov et.l. 2008).

$$Q = 3600EK/t_c \quad \text{... (1)}$$

Where,

$$K_s = \frac{K_{nk}}{K_{rk}}$$

K_s is the excavation factor; K_{nk} is bucket fill factor; K_{rk} is the rock fragmentation degree in the bucket; t_c is minimal technical duration of the machine running cycle, t_c can be calculated from the Equation 2.

$$t_c = t_w + t_{pm} + t_r \quad \text{... (2)}$$

where, t_w is digging time; t pm is total turning time of a shovel in the face; t_r is the shovel bucket dump time.

Sayadi et al. (2012) developed models using Uni-variable Exponential Regression (UVER) and Multi Variable Linear Regression (MVLR) for the cost estimation of Backhoe Shovels considering the variables like bucket size of shovel, digging depth, dump height, weight and power of the machine. Evaluation models show that the functions of the models are the credible tool for cost estimation during prefeasibility and feasibility study of mining projects. The paper compared actual costs with the estimated cost and it was concluded that these models are quick, easy and accurate tools and can be useful for making accurate decisions about the size of the loading equipment fleet in mining projects.

4. Cycle time of dumper

The typical haulage operation in any opencast mines is cyclic in nature, Fig.1 (Stahl et. al., 2011) shows a typical haulage cycle of opencast mines.

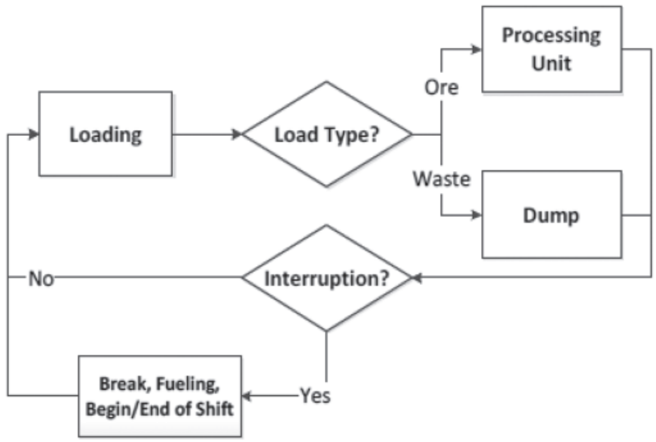

Fig.1 Ttypical haulage operation in any opencast mines

In ideal cases total cycle time (T) for any haulage operation comprises travel time of empty dumper (t_{te}), maneuvering or spotting time beside a shovel (t_{ml}), loading time (t_l), travel time of a loaded dumper (t_{tl}), maneuvering time or spotting time for dumping material (t_{md}), time for dumping of material (t_d) and waiting and delay time (t_{wd}) . Waiting time of dumper includes the time beside a shovel at loading point and waiting time of dumper at dump point. Total cycle time of haulage operation can be calculated using Equation 3 (Choi et. al.)

$$T = t_{te} + t_{wl} + t_{ml} + t_l + t_{tl} + t_{wd} + t_d \quad \text{... (3)}$$

There are various methods, utilize the combination of empirical and calculated data, currently available for the prediction of dumper cycle times. All of these methods appear to provide results that are acceptable within industry standards. The methods, which have already presented, can be divided into three subgroups dependant on the level of manual input required, historical data and degree of automation. The three subgroups include the following (Patrick and Kizil, 2013):

- Talpac, aren and FPC;
- Multiple regression and artificial neural networks; and
- Deswik and mineSched TM.

The dumper cycle time directly depends upon few parameters like rimpull, haul grade and haul distance, condition of the dumper, operator's efficiency etc. but the level of queuing that occurs in a dumper feet depends upon the number of dumpers operating against each shovel. The speed of the dumper mentioned in manufacturer performance guidelines is used to estimate the dumper cycle time in industry and it is the most common method (Smith et al. 2000). These guidelines are generated through simulation considering engine power, engine transmission efficiency, dumper weight, capacity, rimpull, and road gradients and conditions (Blackwell 1999). These guidelines along with the topographical information help an engineer in mining industry for proper estimation of the hauling route. Celebi (1998) also calculated dumper cycle time using regression models, whereas Blackwell (1999) developed a multiple linear regression model by using the parameters like dumper cycle time, tire consumption, fuel consumption and dumper operating hours, which are having a great influence in actual practice. The author communicated that estimation with the help of simulation due to variation in engine power can be effectively used to determine an appropriate fleet of dumpers and loaders with the help of match factor.

5. Dispatching and allocation problem of shovel – dumper operation

Dispatching and allocation of dumpers against loading equipment (shovel) is a major factor, which affects the productivity of shovel-dumper network system in opencast mines. The basic challenge lies on proper dumper allocation for an excavation equipment and the efficiency of dispatching system in opencast mines depends on the procedures of the system; those are used to implement it. Mathematical programming based procedures were introduced in the early 1970's as alternatives to heuristic based procedures that usually lead to shortsighted decision making (Munirathian and Yingling, 1994). The literature on allocation mainly focuses on the satisfaction of productivity requirements, often with complex features such as bottleneck prevention; the dispatch optimization literature seeks to maximize the efficiency of the fleet (Newman et al. 2010).

Mueller, 1977 described dumpers and shovels as blocks and he presented a dispatch board, which helps to track the position of the loading and hauling equipment with proper communication with the operators. This process helps to make the decision about the loading–hauling system. Hodson and Barker,1985 developed a computer based semi automated dispatching system and used match factor for the proper allocation of dumpers against loading equipment. In his model track allocation is in two stage process and the controlling is done by the computer. Automated dispatching systems have been discussed by Lizotte and Bonates (1987) and they presented the automated dispatching system to optimize the dumper requirement. Bonates (1988) used computer simulation model for dispatching system and the system is grouped into manual dispatching, semi-automated dispatching and automated dispatching system. FORTAN was used to develop the computer model, the objective function of the model was to optimize the utilization of the dumpers and shovels. Himebaugh, 1980 developed system "DISPATCH" to maximize productivity by optimum utilization of available equipment. Tu and Hucka, 1985 developed a stochastic simulation model for the measurement of performance of a dumper and shovel. They also discussed about the effect of maximizing shovel utilization and maximizing dumper utilization on productivity and it is revealed from their study that; the computerized dispatching system will be more useful in case of shovels are under trucked rather than shovels are over trucked. White and Olson (1989) developed linear programming model for dispatching problems. There are two stages in the model. The first stage was to minimize the cost, which is associated with operating cost of shovels, processing rate and penalties for quality requirement. Three constrains were considered in first stage; those are digging rate of shovel will not be above the maximum possible digging rate, total material feed will not cross the plant's capacity and quality of plant feed is within acceptable bound. The second stage was for shortest route for the vehicle. Z. Li (1989) developed a methodology for optimum control of shovel and dumper operation with three basic information, the optimum haul route and the maximum to be handle in each route, how trucks will be assigned to the shovels and the optimum number of trucks to be assigned to achieve the production target.

In 1993, Forsman et al. developed a computer simulation model for Aitik open pit mine using microcomputer METAFORA to satisfy the target production through optimum haulage network and number of trucks. In other attempt in 1999, A.J. Basu designed a simulation model for Kalgoorlie Consolidated Gold Mines (KCGM) using GPSS/H to assign a truck to a shovel with least queue length.

Queuing theory is applied by different researchers to minimize the waiting times of dumper shovel in connection with shovel-dumper productivity. Huang and Kumar (1994) developed below mentioned fleet size selection model applying queuing theory to minimise the cost of idle machinery.

$$M\backslash M_2\backslash N\backslash FIFO\backslash n_1\backslash n_2$$

Where, M_1 and M_2 are customer arrival rate and service rate which are exponentially distributed, N parallel servers are there, n_1 is the upper bound of customers allowed in the system, n_2 is the maximum number of potential customers and the service discipline is First-In-First-Out.

6. Matching of shovel and dumper in mining operation

Dumper shovel matching can be defined as how well dumpers are suited to a particular shovel and it depends upon the factor like dumper height, bucket capacity of shovel, shovel reach etc. The selected loaders are necessary to be compatible with the selected dumper fleets and conversely, loaders should be compatible to dumper capacity. Tan and Ramani (1992), Kesimal (1998) and Blackwell (1999) describe this approach in combination with match factor (described in modelling and solution approaches), a product of shovel-dumper productivity research, to select equipment.

Kirmanli and Ercelebi (2009) developed an expert system to select the excavator dumper combination that minimizes production cost while satisfying the technical constraints. It must be noted, that with this approach, the excavator is selected before the haul units, in order to address production requirements. This implies that the number of haul units selected must be excessive in order to enable the excavator to be the limiting resource. The dumper type is again based on being able to be filled within three to seven passes of the excavator. As did Karshenas (1989), Kirmanli and Ercelebi (2009), made the excavator the limiting resource in all cases. This approach may miss the true optimal dumper excavator combination which minimizes unit cost.

Limsiri (2011) applied genetic algorithms, performing a similar operation to lower total equipment cost as Marzouk and Mosehli (2002), but allowed for a multiple dumper and loader types to be considered and a heterogeneous fleet to be outputted.

Gransberg (1996) identified that the loading units' ability to load the haul units would determine the maximum productivity of the system and acknowledged that most approaches do not consider that the haul unit capacity, which is often not an even multiple of that of the loader bucket, and that a partial bucket takes approximately the same time to load as a full bucket. Considering these factors, Gransberg (1996) produced load growth curves for various loading facilities. A model was developed to determined the number of dumpers required by dividing the dumper cycle time by the dumper loading time. The model remained deterministic and shared all limitations of deterministic models. Haul unit size was selected by looking at direct cost per tonne relating to the loading unit only and did not consider the entire earthmoving system.

Komljenovic et al. (2003) established a comparative coefficient for different mining dumpers, and established that motor power depends strongly on gross vehicle weight, payload and heaped capacity. Their selection methodology considered only technical parameters and ratios and again was useful for narrowing the field of possibilities to be considered but did not guarantee an optimal pairing of hauler and loading unit.

Speed of all the dumpers in the fleet may not be same. It is observed faster dumper in the fleet sometimes bunch behind the slower dumper if overtaking is not permitted therefore the actual average cycle time of dumpers may be lower than the estimated. Bunching reduces the ability of dumper fleet to utilize maximum capacity of fleet. Smith et al., 2000 suggested that the bunching effect of a dumper fleet can be minimized or restricted by estimating accurate equipment speeds at the time of selecting haulage equipment and fleet sizes.

Shovel and dumper become idle in the field because of many reasons like unavailability of operators, break of operators, shift change of operators, blasting for production in mines but the major reason behind the idling of shovel and dumper is lack of planning to improve the match factor of shovel and dumper. The match factor is the ratio of dumper arrival rate to loader service time. The match factor can be deduced from the Equation 4 (Hanby, 1991) (Kesimal, 1998)

$$\text{Match Factor (MF)} = \frac{\text{No of dumper} \times \text{shovel cycle time}}{\text{No of shovel} \times \text{dumper cycle time}} \quad ...(4)$$

Morgan and Peterson (1968) described Equation 5, where, $MF_{i,i'}$ match factor of dumper type i working with loader type i'

$$MF_{i,i'} = \frac{t_{i,i'} X_i}{t_X \, y_{i'}} \quad ... (5)$$

x_i is the number of dumpers of type i; $y_{i'}$ is the number of loaders of type i'; $t_{i,i'}$ is the time taken to load dumper type i with loader type i'; and t_X is the average cycle time of the dumpers excluding waiting times.

Above two equations of match factor ratio relies on the assumption that hauling and loading equipment are homogeneous. Burt (2008) described Equation 6 in his thesis for heterogeneous loading as well as hauling equipment.

$$MF = \frac{\Pi_{i,i'} \, t_{i,i'} x_i}{\Pi_{h \neq i}(t_{i,h} \; x_i) \; \Sigma_{i'} x_{i'} \, t_X} \quad ... (6)$$

Where, t_X is the average cycle time of all type of dumpers; x_i is the number of i type of dumper; $x_{i'}$ is i' type of loader; $t_{i,i'}$ is time taken to serve the dumper type i by the loader type i'; $t_{i,h}$ is the cycle time of dumper type i on haul route h.

7. Conclusion

Different techniques have been used to optimize the productivity of dumper and shovel operation in opencast mines to achieve target production with minimum cost. A number of real-time approaches and developed strategies or methods had been in operation at different mine sites all over the world. Most of the conclusions, which are drawn from these studies, have already been proven effective and generally applicable. It has also been revealed that the selection of best strategy for the effective utilization of shovel and dumper in opencast mines is a site specific problem. Different modelling approaches used in the study depend upon purpose of the study, available data and simulation language used. Parameters, which affect the operational strategies of dumper and shovel as well as performance of the mine, change with the progress of the mine. Therefore selection of best fit strategy at design stage may not be realistic and real time study of dumper-shovel operation could help the mine management to take the optimum decision in the advance stages of mines. The decision-maker should consider all the alternatives and economic issues, in order to choose the most appropriate shovel and dumper fleet and it has a significant impact on the productivity and operation cost of mines.

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