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UNCERTAINTY ANALYSIS OF PRODUCTION IN OPEN PIT MINES – OPERATIONAL PARAMETER REGRESSION ANALYSIS OF MINING MACHINERY

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Abstract: In mining uncertainties related to equipment and operation are major reasons for loss of production. In order to address this issue, a wide literature review was done in this study. It showed that reliability of equipment, spare part availability, automation of equipment are researched areas focused. However, a methodology which relates operational issues directly to production levels has been not studied with detailed analysis. In order to overcome this issue and propose, a method to achieve production assurance is the objective of this study. A case study with 2.5 years of data from a large open pit mine is carried out. Following the statistical principles, multiple regressions modeling with details analysis, optimization of payload and interpretation of analysis are used. It showed that at system level availability, utilization and maximum capacities are important criteria for finding root cause in loss of production. Model for shovel fleet showed that availability is the most important characteristics hindering it to achieve a higher level of production. It was also seen that 3 to 4 number of shovels are optimal for achieving current level of production. For truck fleet model represented that capacities involved are less important factor as compared to the utilization of the fleet.

Keywords*: *mine production, availability, utilization, regression

INTRODUCTION AND BACKGROUND

In order to increase the output and satisfy increasing market demand, mining research is focused on optimization which is branched off in many areas, such as automa-

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tion, uncertainty analysis, equipment design and implementation (Gustafson, 2011; Ramazan and Dimitrakopoulos, 2013; Samanta et al., 2002).

In mining where production of ore is most important outcome, knowledge of operations is essential for the management of risk, maintenance of low costs, and increasing of the output. In broad sense uncertainty may be defined as being any deviation from the unachievable ideal of completely deterministic knowledge of a relevant system (Walker et al., 2003). Uncertainties are inherent in the circumstances in which mines are planned, developed and operated. The uncertainties related to mining project are represented in Figure 1. Larger the degree of uncertainty, more valuable it becomes to know effect of internal and external factors causing uncertainty. The sources of mining uncertainties could either be planned or unplanned and due to internal or external events.

Equipment production is affected by the factors causing uncertainties. These factors broadly can be divided in; mechanical properties of equipment such as design, shovel bucket size, operational and working plan for equipment, environmental factors such as temperature, rain, ice etc., human factors such as skill, competency, fatigue experienced by operator etc.

Focus of current study relies in area of increasing the production based on available equipment. To increase the production by equipment in mining, most of research in mining is related to increase the reliability of equipment. Mining equipment output is mainly based on availability, utilization and its rated capacity (Lanke et al., 2016). Temperature and effect of precipitation can also associated with this variation of output.

It may be advantageous to acquire additional information about the relationship between these factors for mining production increase. The important information or knowledge here is the relation between the internal and external factors which govern the equipment output uncertainty.

A methodical approach, based on analysis could be beneficial to determine the uncertainties and affecting the equipment operation and their relationship with total output. In this paper it is tried to develop a general uncertainty analysis model of mining machinery production in open pit mines.

Cause/s of origin of uncertainties in mining are sometimes difficult to determine, they may be specific to environment as explained by Barabadi (2011), or system (Abdel Sabour et al., 2008) and context under study (Dimitrakopoulos and Sabour, 2007). One of earliest study which related external uncertainties and their cause-effect is presented in a study by Vernon (1984). This study states prominent reasons explained for uncertainty are external causes such as supply and demand fluctuations, political instability and lack of vertical integration in process.

Economic uncertainties are another area studied and improved in mining research. Economic uncertainties include market volatility, demand and price fluctuations uncertainty has been addressed with real options approach in many studies (Dehghani and Ataee-pour, 2012; Dimitrakopoulos and Sabour, 2007).

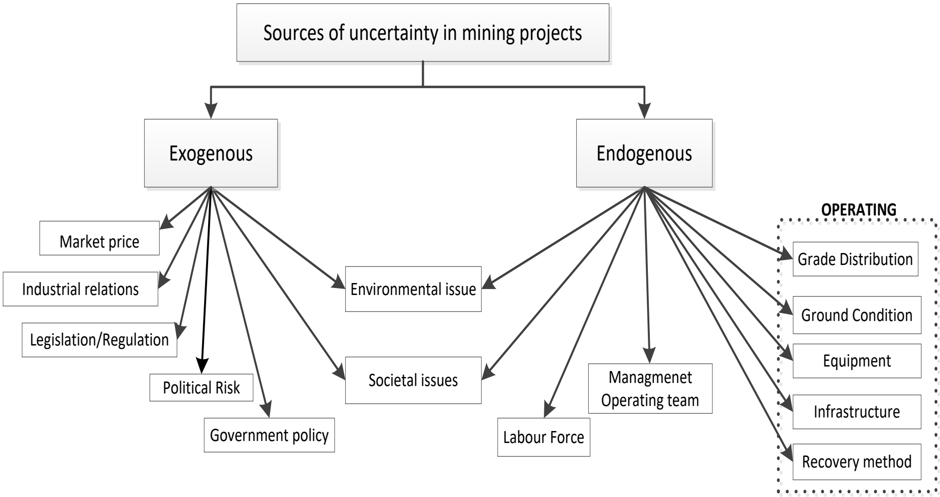


Fig. 1. Sources of uncertainty in mining (Kazakidis, 2001)

Equipment and their operation are one of the uncertainty that is shown in figure 1. In a study by Samanta et al. (2002) author mentions various internal and external factors which could help the optimal production by equipment. It is seen that effects of operational factors on equipment output has been addressed by most equipment selection studies in mining research for example (Haidar et al., 1999; Ekipman et al., 2003; Samanta et al., 2004). The factors or scenarios related to equipment and its output are focused with optimal mine conditions and stabilizing the reliability of equipment. These research topics explain and propose methods and tools to increase the reliability and life of equipment and specify criteria required for high output.

An effect of environmental factors specifically in area with extreme temperature and weather on mining equipment has also been studied. Availability of spare parts and its effect of equipment production have been shown in (Ghodrati, 2005). Throughput capacity and environmental effects using covariate analysis have been explored (Barabadi et al., 2011).

These studies however, do not specifically target factors which cause loss of production due to uncertainties related to equipment operation. Studies which specifically address operational parameters related to equipment operation and its effect on production are limited. Considering such limitation an extensive literature review led to conclusion that availability, utilization and performance of mining equipment are key parameters along with environmental factors (Lanke et al., 2016). As lack of knowledge i.e. contribution and effect of operational factors on equipment production is important uncertainty, solution to reduce the uncertainty is quantification of such uncertainty. This would lead to achievement of planned production beneficial for mining organization.

METHODOLOGY

Based on literature review in uncertainty reduction for mining, it can be seen that analytical methods are pervasive and applicable for mining research and application. Many of these analytical methods are based on statistical analysis. Using statistical analysis provides principles and methods for collecting, summarizing, and analyzing data, and for interpreting the results. Applied statistical methods are useful for describing the data and proposing inferences based on analysis. Collection of data for the factors which are relevant for analysis based on requirements and finalizing the analytical method and tools are two main steps that must be followed. Initial step will help in carrying out statistical analysis.

It has been established that operation factors affecting the equipment output are divided into three main components; equipment availability, utilization and their performance (Lanke et al., 2016). These factors are dependent upon downtime, standby time, and rated capacities. These factors can, in turn, represent as the function of involved parameters' (Lanke et al., 2016; Dhillon, 2008). They are represented as following equations ((1) to (3)):

$$A = f\,(TH, DT) \tag{1}$$

$$U = f\,(TH, DT, SH) \tag{2}$$

$$P = f\,(RC, AC) \tag{3}$$

where: A – availability, U – utilization, P – performance, TH – total hours, DT – downtime, SH – standby hours, RC – rated capacity and AC – actual capacity.

The next step was to identify the suitable approach for data analysis and estimation of components characteristics such as availability, utilization, performance, downtime, standby hours, idle times, and their effect on production. In order to propose a formal presentation of theory in terms of the equation; a method must be determined. The chosen method should reply two questions for the study. How much variance in the equipment output is accounted for by the combination of the considered factors? How to represent effect of factor in terms of change in equipment production? In statistical modeling, estimation of the relationship among variables is done with help of regression analysis method. The result obtained in a process is denoted by the dependent variable, whereas factors leading to result are termed as predictor variables. In mine production, output in terms of tonnage by each equipment can be termed as result or dependent variable. Availability, performance, utilization and their factors can be considered as predictor variables. Effect of each factor on the dependable variable can be evaluated through the regression model. However, the equipment output is affected by all the factors simultaneously. The multiple regressions will yield results of comparing all factors effect on the dependable variable.

The methodology is represented in flow chart in Figure 2.

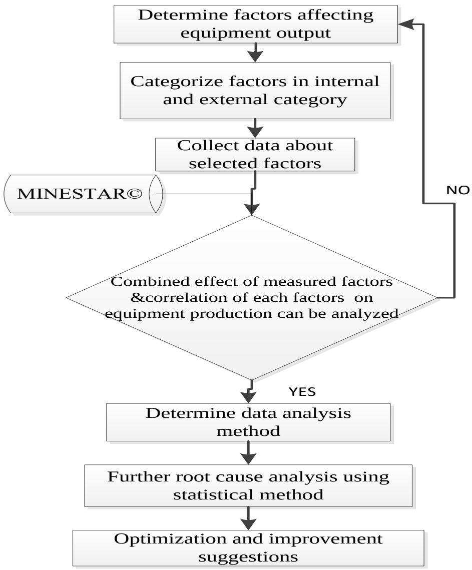


Fig. 2. Methodology followed for data collection and analysis

CASE STUDY

DATA COLLECTION

For developing a new production uncertainty model, a case study was conducted in a large Swedish open pit mine. The data was collected for 30 months from January 2013 to June 2015. Mine operates with temperatures varying from minus 30°C to 25°C. During the period of peak winter the snowfall reached 1.21 meters, varying within the range of 0.5 to 1 meter during the whole winter season. These conditions cause harsh effects not only on ore but also on equipment operation and operators skills. Haulage system in this mine composed of 31 trucks with two different capacities and six shovels. The mine is operated for 24 hours with 7 days per week. The applied data for modeling was extracted from "Minestar©" software. The data is recorded output from sensors installed on equipment. For trucks data related to its destination (a specific crusher or dump site), assigned shovel and its rated capacities acts as an input and are recorded for each loading and unloading cycle. This data is complicated since trucks are assigned to different areas in the mine in real-time and keep changing their destination. The shovel input includes its identity, its source destination (extraction site in mine) and assigned crusher. A common output recorded for both equipment is production in terms of tonnage. Shovel data includes sensor data for each of its activity, which include its availability time (working duration, standby duration) and utilization (idle time, queuing time etc.). Similarly, for trucks data which is useful for evaluating availability and utilization is recorded. The collected data was in a big size which was a mixture of automatic and manual entries. Data related to factors such as availability, utilization and performance were calculated for each day based on available raw data. Within 21 working hours, data for trucks fleet and shovel fleet is consolidated. Rated capacity of a single shovel is 3840 tons per hour, with six shovels; and nominal 21 hours non-stop operation, the maximum rated capacity is 483840 tons/day. This is considered as theoretical maximum rated capacity for a shovel. In similar manner maximum rated capacity for trucks is calculated. Based on these calculation optimization report and interpretation of results can be drawn.

Conversion from raw information, application of consistency and frequency matching was done by developing and applying for a specific computer program with spreadsheet software. Internal factors which affect the output by equipment are represented with by data. Completing these stages will lead to the formulation of a model which can represent the uncertainty.

DATA ANALYSIS

Variation or uncertainty in output is caused by three main factors availability, utilization and capacities of equipment involved. In order to determine the uncertainty in production and its correlation with these factors, multiple regression analysis was carried out. From the raw data preliminary analysis shows that the availability of whole mine fleet varies from 1 hour to 277 hours (Fig. 3). The mean available hours are 117 hours with standard deviation of 80 hours. The mean time for the utilization of the whole fleet is 114 hours per day (Fig. 4). The utilization time varies between 1 hour to a maximum of 245 hours. This is associated with standard deviation of 66 hours. The performance graph shows that payload achieved has been 167000 tons per day at its maximum value (Fig.5). Mean production per day is 97000 tons with standard deviation of 30000 tones.

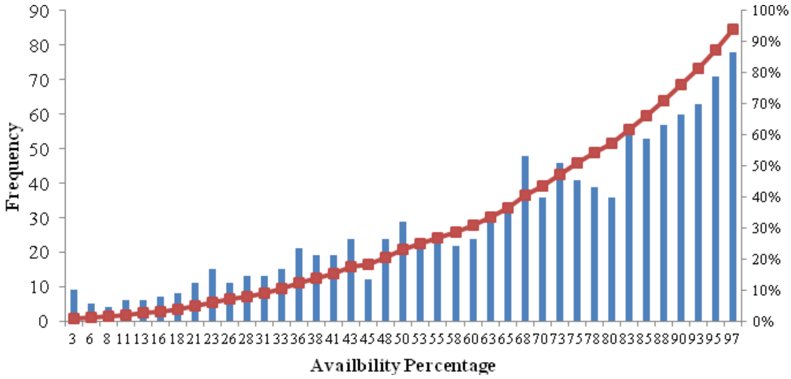


Fig. 3. Overall fleet availability with frequency and cumulative %

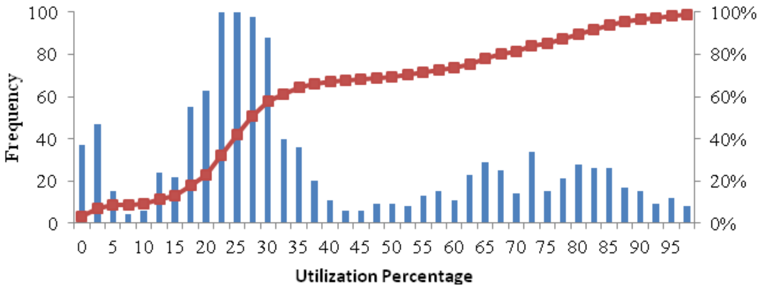


Fig. 4 . Overall fleet utilization percentage and cumulative %

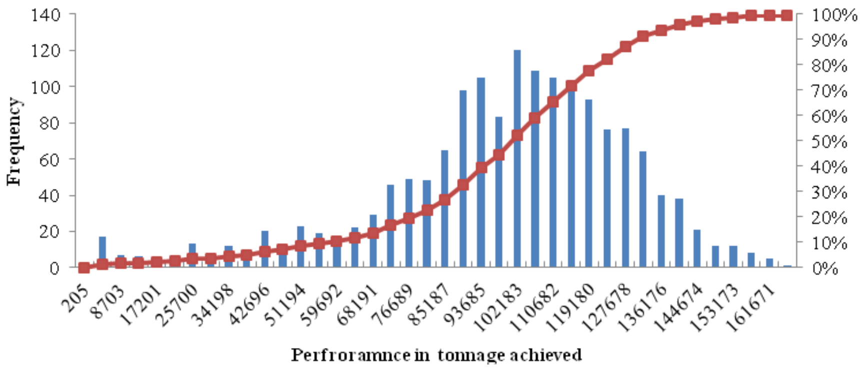


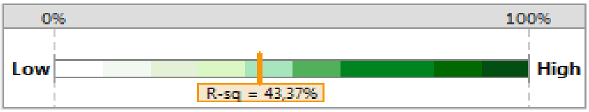
Fig. 5. Overall system payload achievement

OVERALL ANALYSIS OF DAILY PRODUCTION OF MINE

Fleet analysis was started with considering the effect of shovel and trucks' fleet together along with the actual payload. For selecting the significant factors and the acceptable relationship between the studied parameters, two metrics were chosen: 1) percentage of variation explained by parameters and 2) P-value. At the system level, regression analysis reveals that 43.4% variation in achieved payload is explained with three variables namely available time, operating time and maximum theoretical capacity for the overall system. P-value (<0.001) also suggests that there is a strong correlation between these factors and the payload achieved as shown in Figure 6(a). Based on analysis, presented model in Equation (4) presents the daily production in overall system level:

$$Daily\ Production = 231.2 - 4A - 1.1U - 6.7Ca._{max} \tag{4}$$

This equation suggests that achieved payload for the entire fleet of trucks and shovels is dependent upon availability, utilization, and maximum theoretical capacities. Achieved payload is more sensitive to changes in maximum capacity followed by availability.

a) 

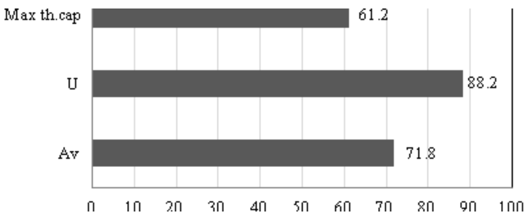
b) 

Fig. 6. Statistical analysis of important factors: a) variation percentage explained by model presented; b) bach factor regressed over the other variables

The interaction between factors shows that with increasing of mean availability and utilization mean, mean of daily production will increase. As shown in Figure 7, interaction plot between the maximum capacity of both trucks and shovels show that mean daily production will increase with increasing of availability. The analysis shows that at a certain point, an increase of available capacity will not help to increase the daily production. Considering the effects of entire equipment parameters on achieved production, uncertainties are caused by changes in overall availability.

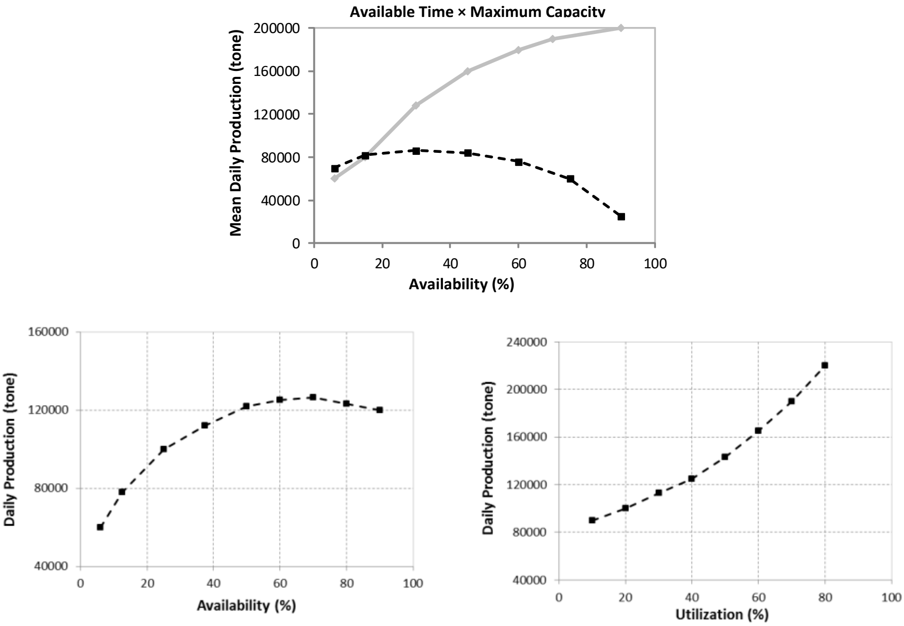


Fig. 7. Analysis of daily production (change in payload when availability, utilization and capacity changes)

This means that it is essential to delve into system at component level. In current scenario trucks and shovel fleet are components. With further analysis with trucks and shovel separately, it will be clear to see which elements affect their output most. This will also give insight into what changes in availability and utilization should be done to achieve maximum possible daily production.

PRODUCTION ANALYSIS OF SHOVEL FLEET

As discussed earlier, overall daily production of any open pit mine is resulted by interaction and combination of shovel fleet and truck fleet production. In shovel fleet perspective, number of available shovels and their nominal capacity are dynamic and uncertain parameters which deeply affect the daily production of the whole mine.

Based on the available data, regression analysis of shovel fleet production reveals that all variables (availability, utilization and maximum capacity) have a significant effect on fleet production with P-value less than 0.1. Equation (5) shows the relationship between all mentioned factors and shovel fleet production.

$$Shovel\ fleet\ production = -4.58 + 5.2A_{shovel} + 0.14U_{Shovel} + 0.05Ca._{ideal.actual} \qquad (5)$$

This model states that availability is the most correlated factor for shovels to achieve production. It also represents that once the ideal actual capacities are considered, utilization of shovels becomes a more impactful factor in achieving production goal. Figure 8 shows that available time causes more impact, followed by the ideal actual capacities and then the utilization time. However, when operating time is regressed over other factors involved, it reaches R^2 value of 95% as compared to 93% of R^2 value for availability. The significance of availability i.e. reliability of equipment is the key factors that must be focused.

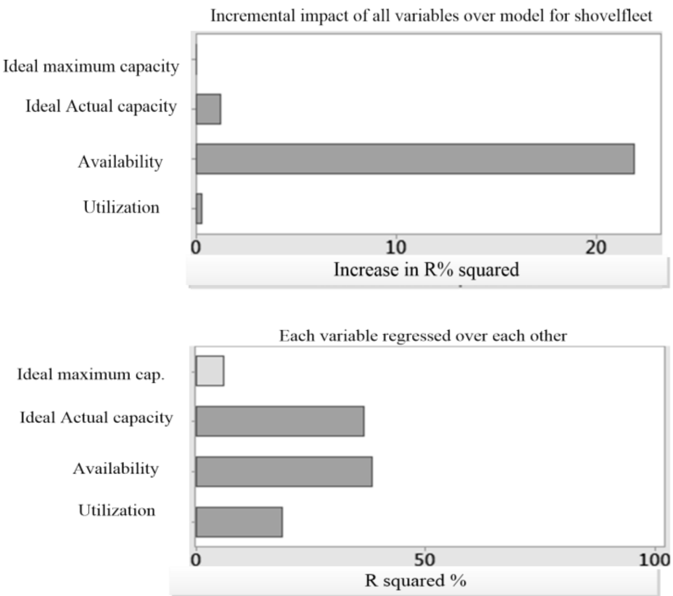


Fig. 8. Impact of factors on shovel fleet output when regressed individually and when regressed over all other parameters

Number of working shovels per day is another important factor for achieving higher availability. Considering the availability and actual maximum capacities, this gives us insight into the optimal number of shovels that can be used for the operation. When the model is analyzed for current condition with objective of maximizing the payload, it is seen that use of 4 to 5 shovels daily would be ideal as seen in Figure 9. This would not only impact shovel capacities but also increases the overall or production of the shovel fleet.

To see how utilization affects production levels by shovel fleet, correlations between reasons which could lead to loss of utilization are evaluated. For this analysis idle time, delay time and downtime were considered. Analysis of the components reveals that shovel fleet is more sensitive to idle time compared to delay and downtime. In order to increase the production by a reduction in shovel idle time, one of the prominent area of research is related to trucks and shovel system. Requirement of optimum number of trucks or match factor has potential to save cost for the system (Ercelebi and Bascetin, 2009; Alarie and Gamache, 2002). A comprehensive strategy which reduces the shovel idle times based on increasing utilization of truck has been discussed by Alarie and Gamache (2002). Operational planning, efficiency of blasting operation, impact of ageing machinery, optimum truck dispatching time are important reasons for idle time for shovel operation (Mohammadi et al., 2013; Rai et al., 2000; Mohammadi et al., 2016; Patnayak et al., 2008).

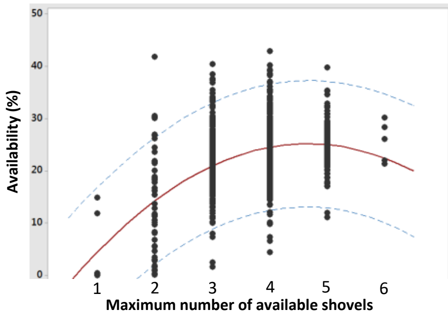


Fig. 9. Optimal number of shovels required for the current level of production

TRUCK FLEET ANALYSIS

In initial truck evolution, P-value indicates a significant relation between utilization, availability, performance and achieved payload. The analysis shows that 47.6% of the variation in carried payload by trucks is explained by the regression model. The regression model for truck fleet productions is presented by Equation (6).

$$Overall\ payload\ of\ truck\ fleet = 36.35 + 1.24U_{truck} + 0.7A_{truck} \tag{6}$$

The achieved model shows that availability and utilization of trucks are significantly important in reaching the production goal. As shown in the model increase in 1% utilization will increase the payload by 1.24%. This leads to attention for analysis of utilization and its elements. As lower truck utilization translates to higher idle times for shovels and overall delay in production process causing loss of ore tonnage. The analysis shows that it is possible to achieve 50% utilization with 25 hours of idle time for the whole fleet per day. The mean of utilization varies with changes in idle and delay time. Based on the data analysis, with an increase in idle times and decrease in delay times to minimum hours it is possible to achieve 70% mean utilization.

To pinpoint the reason for uncertainty in production through the availability of trucks, further analysis is carried out. During this model building between payloads achieved and trucks downtime, and total operating hours are evaluated. Uncertainty or variation of achieved payload is explained 40% by downtime and total operating hours.

DISCUSSION

In open pit mining, uncertainties related to equipment and operations are prime reason for loss of production. In mining literature there is lack of method for directly relating uncertainty with production by equipment. With this research attempt had been made to fill such a gap. The aim of study was to exemplify quantification of uncertainties with production output by fleet of mining equipment. Root cause analysis for production loss through this quantification was another objective of this study. To demonstrate this method, 2 years and 6 months of data was obtained from mining organization and analyzed. Based on requirement of study and statistical principle it was observed that multi-regression analysis modeling is suitable methodology. Using this methods analysis was carried out considering two equipment fleet together (system) and further for fleet of shovel and truck separately.

CONCLUSION

During the period of observation it was seen that daily production is sensitive to availability more than current maximum theoretical capacities at overall system level. With detailed analysis of shovel fleet it was seen that number of shovels and their idle time are dominant factors to achieve target production. With shovels' analysis it is observed that 4 to 5 number of shovels is optimal size of fleet to achieve current level of production and operating of less than full number of shovels for operation could be potentially economical. This will reduce the downtime for fleet of shovel thus causing increase in utilization of shovels leading to further increase in output.

Model for truck fleet showed that utilization followed by availability is main important criteria that must be focused on increase of production. The model for truck fleet lacks ideal actual or ideal maximum capacities. When truck fleets utilization was analyzed it was seen that combined standby time is limiting factor compared to downtime. Truck fleet idle time i.e. waiting for the ore or waiting at crusher is one of root causes that cause hindrance to increased production level. To increase the in mine output from current levels, capacities of trucks and shovels can be exploited further. The analysis shows that current configuration of both equipment fleets is able to respond to higher demand of production. It is possible to achieve current level of production of ore with 4 to 5 shovels instead of 6 shovels. The truck fleet capacities are more than adequate for achieving required performance. Economical optimization thus can be achieved by reduction in number of equipment.

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REFERENCES

ABDEL SABOUR S., DIMITRAKOPOULOS R., KUMRAL M., 2008. *Mine design selection under uncertainty*, Mining Technology 117,2, 53–64.

ALARIE S., GAMACHE M., 2002. *Overview of solution strategies used in truck dispatching systems for open pit mines*, International Journal of Surface Mining, Reclamation and Environment 16,1, 59–76.

BARABADI A. (2011), *Production performance analysis: Reliability, maintainability and operational conditions*. University of Stavanger,Norway, Phd. Thesis .

BARABADI A., BARABADY, J. MARKESET T., 2011. *A methodology for through- put capacity analysis of a production facility considering environment condition*, Reliability Engineering & System Safety 96,12, 1637–1646.

DEHGHANI H., ATAEE-POUR M., 2012. *Determination of the effect of operating cost uncertainty on mining project evaluation*, Resources Policy 37,1, 109–117.

DHILLON B. S. (2008), *Mining equipment reliability, maintainability safety*, Springer Science & Business Media.

DIMITRAKOPOULOS R.G., SABOUR S.A.A., 2007. *Evaluating mine plans un- der uncertainty: Can the real options make a difference?* Resources Policy 32,3, 116–125.

EKIPMAN A., BİR S.İ., SİSTEMİ K.D., PROSESİ A.H., 2003. *A decision support system for optimal equipment selection in open pit mining: analytical hierarchy process*. Istanbul University, Mining Engineering Department, 16(2), 1-11.

ERCELEBI S., BASCETIN A., 2009. *Optimization of shovel-truck system for surface mining*, Journal of The Southern African Institute of Mining and Metallurgy 109,7, 433–439.

GHODRATI B., 2005. *Reliability and operating environment based spare parts planning*, Lulea, University of Technology, Ph.D Thesis.

GUSTAFSON A., 2011. *Automation of load haul dump machines*, Lulea University of Technology, Ph.D.Thesis.

HAIDAR A., NAOUM S., HOWES R., TAH J., 1999. *Genetic algorithms application and testing for equipment selection*, Journal of Construction Engineering and Management 125,1, 32–38.

KAZAKIDIS V.N. (2001), *Operating risk: Planning for flexible mining systems*, University of British Columbia, PhD thesis.

LANKE A.A., HOSEINIE S.H., GHODRATI B., 2016. *Mine production index (MPI)-extension of OEE for bottleneck detection in mining.* International Journal of Mining Science and Technology, 26,5, 753-760.

MOHAMMADI M., RAI P., ORAEE K. KUMAR M., 2013. *Analysis of availability and utilization of dragline for enhancement of productivity in surface mines-a case study*, in: Proceedings of the 23rd World Mining Congress, Montreal.

MOHAMMADI M., RAI P., SINGH U., SINGH S., 2016. *Investigation of cycle time segments of dragline operation in surface coal mine: A statistical approach*, Geotechnical and Geological Engineering. 1–10.

PATNAYAK S., TANNANT D., PARSONS I., DEL VALLE V., WONG J., 2008. *Operator and dipper tooth influence on electric shovel performance during oil sands mining*, International Journal of Mining, Reclamation and Environment 22,2, 120– 145.

RAI P., TRIVEDI R., NATH R., 2000. *Cycle time and idle time analysis of draglines for increased productivity-a case study*, Indian Journal of Engineering and Materials Sciences 7,2, 77–81.

RAMAZAN S., DIMITRAKOPOULOS R., 2013. *Production scheduling with uncertain supply: a new solution to the open pit mining problem*, Optimization and Engineering 14,2, 361–380.

SAMANTA B., SARKAR B., MUKHERJEE S., 2002. *Selection of opencast mining equipment by a multi-criteria decision-making process*, Mining Technology 111,2, 136–142.

SAMANTA B., SARKAR B., MUKHERJEE S., 2004. *Reliability modelling and performance analyses of an LHD system in mining*, Journal of the South African Institute of Mining and Metallurgy 104,1, 1–8.

VERNON R., 1984. *Uncertainty in the resource industries: the special role of state- owned enterprises*, in: *Risk and the Political Economy of Resource Development*, Springer, 207–223.

WALKER W.E., HARREMOËS P., ROTMANS J., VAN DER SLUIJS J. P., VAN ASSELT M. B., JANSSEN, P., KRAYER VON KRAUSS M. P., 2003. *Defining uncertainty: a conceptual basis for uncertainty management in model-based decision support*. Integrated assessment, 4(1), 5-17.