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Drill bit monitoring and replacement optimization in open-pit mines

Açık ocak madenlerinde delme operasyonunda kullanılan delici uçların optimum değiştirme zamanının tayini

Ömer Faruk UĞURLU[a,*]

[a] *Istanbul University - Cerrahpaşa, Faculty of Engineering, Mining Engineering Department, Istanbul, TURKEY*

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A B S T R A C T

Since 2012, low commodity prices have forced many mining companies to suspend or cease operations. To remain in business, some mine managers are exploring strategies to reduce operational costs. Given its importance as a cost element, increasing bench drilling efficiency and performance in open-pit mines has the potential to generate considerable savings. Efficiency and performance gains can be realized by monitoring the drilling operation, analyzing monitoring data with statistical tools and optimizing operational variables. Finding the best configuration of controllable drilling parameters would help to increase penetration rate and optimize drill bit replacement time so that fewer drill bits are consumed. In this paper, the optimal replacement time of a tricone drill bit is formulated as a cost minimization problem and solved by a genetic algorithm (GA). To demonstrate the proposed approach, the effects of controllable variables on drilling performance are experimentally quantified by statistical methods and used for optimization. Results show that the proposed approach can be used to determine the optimal replacement time for drill bits in open-pit mines.

Keywords: Open-pit mining, Drilling operation, Design of experiment, Genetic algorithm, Optimization.

Introduction

Rotary drilling is the most extensively used technique for drilling operations, ranging from surface blast hole mining to deep drilling. The rotary drilling technique is based on two distinct motions-axial thrust and rotational torque-provided by a hydraulic or electric rotary head. Axial thrust is needed to push the bit into the rock to break one unit volume of rock. Rotational torque is a force acting on a drill rig to rotate a drill bit through the rock formation. The tricone bits use the thrust and torque to spall the rock (Ghosh et al. 2016). Sufficient weight on the drill bit is necessary to accomplish the drilling operation. Weight on the bit includes the dead weight of the drilling rig (i.e., the rotary head, drill rods and cables) and the pulldown force. A feed system that generates adequate pulldown force is used to move the rotary head up and down (Atlas Copco, 2012).

Drill holes must also be cleaned during drilling by removing cuttings between the wall of the hole and drill rod with compressed air (Ghosh et al., 2016). The air is also used for cooling to protect the bearings. Insufficient air pressure is among the primary reasons for drill bit wear and shorter bearing life. On the other hand, excessive air causes dust and noise problems, shortens bit life and increases operational costs (Fiscor, 2011). Therefore, the operational parameters of a drilling machine such as rotation speed, pulldown force and bailing air pressure have a profound effect on rock fragmentation success.

Rate of Penetration (ROP) is assumed as an effective way to measure drilling operation because it directly shows the capacity of the production (Kricak et al., 2015). Even though ROP is directly affected by the properties of rock formation, it is difficult to model the precise association between them in relation to non-linearity, complexity and deviousness (Taheri et al., 2016). Furthermore, operational parameters are adjusted for rock characteristics. The investigators showed, depending upon the hardness of the rock, that increasing weight on the bit helps to increase ROP. For the soft type of formations, bit weight can cause a slight rise in ROP because the teeth of the bit will bury into the formation and increased torque can hardly change ROP. Moreover, rotation speed must be chosen carefully to achieve the desired ROP. High rotation speed increases ROP when the bit is new. However, the bit is worn the effect of rotation speed is decreasing dramatically. For hard rock formations, weight on the bit is crucial to increase ROP until a certain point because it reduces the life of the bit which affects the drilling rate (Irawan et al., 2012).

*Corresponding author/Sorumlu yazar: ofugurlu@istanbul.edu.tr • https://orcid.org/0000-0002-5817-3268

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It is important to note that before having a high rotation speed in order to achieve the desired ROP, the drill bit should be allowed to move into the rock with a slow rotation speed. As a result, it is not only difficult but also infeasible to develop a model that take into account all parameters which have a direct impact on ROP (Taheri et al., 2016). The complexity of drilling operation increases particularly by geological condition (Hatherly et al., 2015). Hence, the drilling environment is generally assumed to be homogenous.

Cutting tools are considered the most expensive tools during a drilling operation (Plinninger et al., 2002), accounting for an estimated 21% of total drilling costs (Tail et al., 2010). The main reason for tool consumption is bit deterioration associated with the interaction between the rock and the bit. As the worn bit penetrates into the ground, ROP decreases. On the other hand, if the bit is changed before its beneficial life, the cost of drilling increases unnecessarily (Tail et al., 2010). As a result, a trade-off can be seen between drill bit wear and drilling cost (Ugurlu and Kumral, 2020a).

The mechanism of drill bit wear depends on rock characteristics and equipment reliability (Ugurlu and Kumral, 2020b). Moreover, operational parameters also have a huge impact on drill bit wear. Immoderate pull down force can cause over stress on drill bits and it might even break the teeth of the bits. Besides, both an immoderate rotation speed and a lack of bailing pressure are two of the main reasons for bit wear. Optimization of operational parameters minimizes operational costs while maximizing the sustainability of drill bits (Eren and Ozbayoglu, 2010).

Drill bit manufacturers and testing laboratories can provide predicted drill bit replacement times. However, the manufacturer's recommendations are general and do not consider mine- and equipment-specific characteristics (Motahhari et al., 2009). During field operations, drill bits are changed when the drilling operator detects comparatively high vibration (Ghosh et al., 2016). An alternative to both approaches is to use drill bit monitoring and optimize drilling parameters to calculate drill bit replacement time. Statistical methods can be used to find optimum parameters such that longer drill bit life and higher ROPs will be attained. Accordingly, the operational cost of drilling can be minimized.

Operational cost in drilling consists of two elements; cost of assets and energy consumption. The concept of specific energy, the energy required to drill a unit volume of rock, is the way to calculate the energy consumption of drilling activity (Teale, 1965). The operational parameters, such as rotation speed, pull down force, rotation torque, ROP and the area of the hole are needed to calculate specific energy (Ghosh et al., 2015).

In this research, optimum replacement times for drill bits are determined for a given drilling operation. First, prior to data gathering in the mine field, a full factorial design model was developed on the basis of the specified variables and levels. Based on this design, the testing procedure was conducted on an open-pit iron mine, analyzed and evaluated by statistical tools to quantify the relationship between operational parameters and ROP. Finally, a genetic algorithm (GA) was applied to determine optimum drill bit replacement time while minimizing operational costs, calculated from the specific energy. Field data were chosen over laboratory data because they were considered to be most representative of operational conditions (Ghosh et al., 2016). The originality of the paper rests on modeling parameters affecting bench drilling, formulating the problem through mathematical programming and solving the problem with a GA.

1. Model development

Model development phases are summarized in Figure 1.

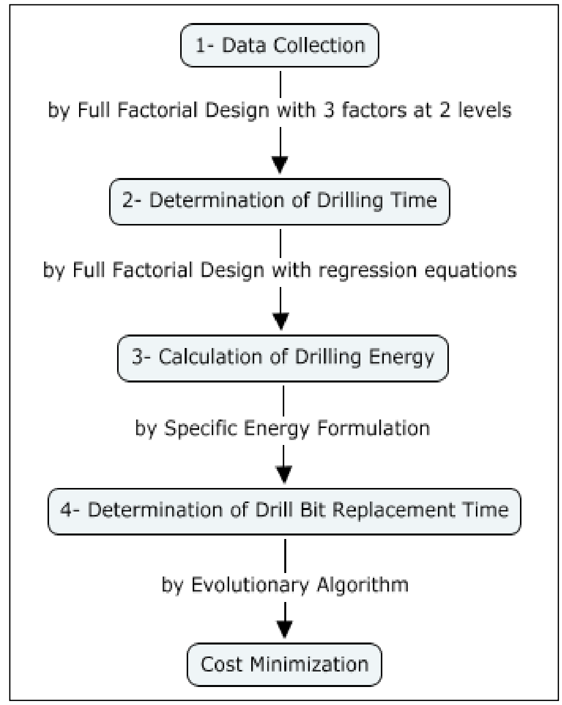

Figure 1: *Model development steps*

1.1. Data Collection

Data collection is the first step to develop an appropriate cost minimization model. In engineering research, the dataset should be large enough to represent the entire population; on the other hand, data collection should be cost effective (Myers et al., 2009). Therefore, experimental design methods should be used to create data collection patterns. They allow the researcher to plan experiments so as to generate quantitative data. Moreover, they help to minimize the cost of data collection (Montgomery, 2009).

Full factorial design includes all possible combinations for all factors. In full factorial design, X^k shows the number of trials that are needed to collect data, where X and k represent levels and factors, respectively. The three controllable factors (rotation speed, pull down force and bailing air pressure) were analyzed at two levels. A 2^3 full factorial design is displayed graphically in Figure 2 as a cube showing eight combinations.

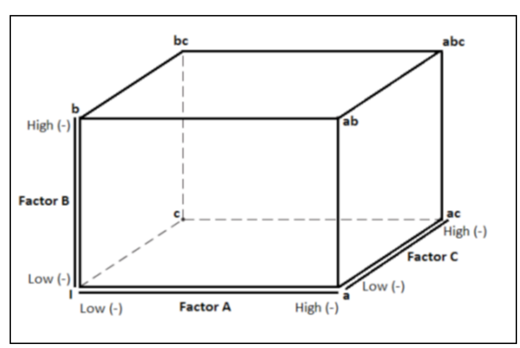

Figure 2: *2^3 full factorial design*

The operational parameters and their levels were selected by considering the real drilling operational conditions at mine site. Table 1 shows the required combinations (C.). (More details about the mine cannot be provided to protect the confidentiality of the company).

***Table1.** Full factorial design with three factors at two levels*

C.	Rotation Speed, (rev/min)	Pulldown Force, (kN)	Bailing Air Pressure, (MPa)
1	40	100	1.0
2	40	100	1.6
3	40	150	1.0
4	40	150	1.6
5	80	100	1.0
6	80	100	1.6
7	80	150	1.0
8	80	150	1.6

1.2 Determination of Drilling Time

Full factorial experiments can be used to detect interactions between dependent and independent (predictor) variables Equation (1) is the model of linear regression formula with three independent variables; a, b and c which are affecting dependent variable Y. α is the intercept and β denotes the partial regression coefficient that is the change in the dependent variable corresponding to a unit change of an independent variable when other variables are constant (Montgomery, 2009). In other words, β allows the dependent variable to be predicted from changes to the independent variable. The most influential independent variable can be determined. The equation is used to determine drilling time for each drill holes according to the level of operational parameters – independent variables.

$$Y = \alpha + \beta_1 a + \beta_2 b + \beta_3 c + \beta_{12} ab + \beta_{13} ac + \beta_{23} bc + \beta_{123} abc \qquad (1)$$

1.3 Calculation of Drilling Energy

The calculation of energy consumption is required in different combinations of drilling parameters. The concept of specific energy is one of the best ways to measure sufficient energy in order to drill a unit volume of rock for rotary drilling which is a combination of axial thrust and rotational torque. Axial thrust is a force which is needed to push the bit into the rock so as to break one unit volume of rock. Rotational torque is a force acting on a drill rig to rotate a drill bit through rock formation. Specific energy shows the total work per unit time which is done by summation of axial feed force and rotational torque (Ghosh et al., 2016). It is also introduced as an indicator of the mechanical efficiency of a drilling process. Equation (2) which is formulated by Teale (1965) shows specific energy calculation.

$$e_s = \left(\frac{F}{A}\right) + \left(\frac{2\pi}{A}\right)\left(\frac{NT}{ROP}\right) in - lb/in^3 \qquad (2)$$

where e_s is the Specific Energy (in-lb/in^3), F is the Axial Feed Force (lb), A is the area of the borehole (in^2), N is the Rotation Speed (rpm), T is the Rotary Torque (lb-in), and P is the ROP (in/min). Variables were converted from imperial units to SI units for this research.

According to Ghosh et al., (2016), there is a missing part to calculate specific energy correctly. Cleaning the boreholes by bailing air pressure has a crucial impact to drilling activity. It is as important as other two operational parameters. Hence, bailing air pressure is the missing part to fill the gap due to determine reliable specific energy calculation. After calculating specific energy for all combinations, results were converted as kWh. It helps us to determine the cost of unit energy (c_e) which is the multiplication of specific energy (e_s) and the unit price of energy consumption (P_u).

1.4 Determining Drill Bit Replacement Time

The optimal time of the drill bit replacement under the constraint of completing bench drilling in a given time was determined in this research. The aim is to minimize the operational cost. All variables needed to develop the optimization model were calculated from Equation (1) to Equation (3). The model is given below (Ugurlu and Kumral, 2020a).

- *Decision variables*

x_n represents the number of bits.

t_t represents the total time required to complete drilling on the bench which is calculated at the second step of model development.

- *Model parameters*

c_b is the cost of a bit.

c_e is the energy cost.

$\mathbf{t}_{\mathbf{max}}$ is the maximum allowable time to complete the task.

b_t is the total number of available bits.

- *Objective Function*

Minimize $x_n c_b + c_e t_t$ (3)

Subject to;

$t_t \le t_{max}$ and $t_t > 0$ (4)

$x_n \le b_t$ (5)

$x_n > 0$ and $x_n \in N^+$ (6)

1.5 Genetic Algorithm (GA)

The GA optimization technique provided in the Solver MS Office tool was used to determine the replacement time of drill bits. Meta-heuristics have been widely used to solve various mining problems (Kumral, 2013; Kumral and Ozer, 2013; Shishvan and Sattarvand, 2015).

In the GA optimization technique, several initial solutions (chromosomes) are randomly produced. A set of chromosomes is generated at random to create a population. The number of chromosomes in the population is the population size. A new population is created by the selection process using various sampling mechanisms. The production of a new solution through an iteration is called a generation. All chromosomes are updated by the reproduction, crossover and mutation operators in each new generation. The revised chromosomes are termed offspring.

Although a binary vector is generally used, integer or floating vectors can also be used as the representation structure in GA-based meta-heuristics. A chromosome is represented as $Y = (y_1 (l_1), y_2 (l_2), \ldots, y_m(l_m))$, where m is the population size. Since the problem is a cost minimization problem, the randomly generated chromosomes are ranked in ascending order. The selected chromosome is perturbed through crossover and mutation operators. It is important to note that good solutions always have less chance to be perturbed. This mechanism keeps good solutions with higher probability. Thus, as the process advances, low-cost solutions survive. If the procedure is continued for sufficient iterations, it converges in optimality or near-optimality.

2. Case study

A case study was carried out in a bench at an iron-ore mine that has an abrasive geological condition to evaluate the performance of the proposed approach. Data sets were collected by full factorial design of experiment model in two levels which consists of all possible combinations for all factors. Drill bits were selected as 7 7/8 inches (200 mm) tungsten carbide – tricone – drill bits. Bit replacement time was determined for eight combinations of operational parameters. Eight field tests were carried out under the operation condition to estimate the mean operational life time of drill bits. The tests were replicated five times and the means were used. The ROP was recorded from an iron mine every hour for all combinations until it reached the fifth hour. To quantify the relationship between operational parameters and ROP for all combinations, operational characteristics were regressed. Interaction effects were ignored because their p-values were higher (p= 0.1-0.4) than alpha (p=0.05). Therefore, interaction effects were extracted from the equations. Parameter estimation results which were obtained from full factorial design by JMP Software can be seen at Table 2. The most influential parameter for rotary drilling operation is rotation speed when the bit is new. Over time, because of bit wear, the effect of rotation speed and the ROP decrease dramatically.

Table 2. *Parameter estimation results*

H	Int.	Rotation Speed, (rev/min)	Pulldown Force, (kN)	Bailing Air Pressure, (MPa)
1	156.16	31.11	5.26	6.64
2	148.74	31.11	5.54	6.19
3	108.04	14.79	3.49	3.74
4	47.54	3.14	2.51	0.76
5	11.36	0.14	2.09	0.49

Regression equations showing the exponential relationship between ROP and drilling length are presented in Table 3, where *y* is the penetration time (min) and *x* is the drilling length (m).

Table 3. *Regression equations of the combinations*

1	$y=7.2471e^{0.0019x}$	$R^2 = 0.7434$	p = 0.014
2	$y=7.0330e^{0.0016x}$	$R^2 = 0.7923$	p = 0.013
3	$y=6.9579e^{0.0016x}$	$R^2 = 0.7602$	p = 0.015
4	$y=6.6386e^{0.0015x}$	$R^2 = 0.7746$	p = 0.015
5	$y=5.9572e^{0.0014x}$	$R^2 = 0.8268$	p = 0.011
6	$y=5.7342e^{0.0013x}$	$R^2 = 0.7893$	p = 0.015
7	$y=5.4655e^{0.0013x}$	$R^2 = 0.7853$	p = 0.014
8	$y=5.2764e^{0.0011x}$	$R^2 = 0.7403$	p = 0.017

The underlying reason to have relatively low R^2 results is the approximation of multiple linear regression method. In addition, the mining site is assumed as homogeneous; however, rock formation has many fractures and different minerals. It also directly affects the ROP. It can be easily seen from Table 3 that the differences between the intercepts of combinations 2 and 4 and between the intercepts of combinations 6 and 7 are relatively small. Therefore, the significance of the rotation speed for drilling activity is higher than other controllable parameters.

Table 4 presents the parameters of the simulation. The length of boreholes was selected as 20 m based on the drill holes in the field where the data were collected. The cost of the bit was provided by the mining company.

Table 4. *Parameters of the simulation*

Total Length (m)	8400
Maximum Time (h)	96
Total Number of Bits	20
Total Bit Cost (C$)	5000
Drill Length per Hole (m)	20

Total operational cost of eight combinations were calculated by specific energy formula and the penetration time calculated by multiple regression equations. The unit price of the energy consumption (P_u) was C$0.05/kWh. The results of the simulations are summarized for all combinations in Table 5.

Table 5. *Results of the simulation for all combinations*

C.	Drill Length per Bit, (m)	Drilling Time per Bit, (h)	Total Drilling Time, (h)	Number of Bits
1	560	6.15	92.22	15
2	646	7.26	94.40	13
3	700	7.60	91.24	12
4	764	8.72	95.97	11
5	933	9.81	88.30	9
6	1050	11.05	88.39	8
7	1200	13.34	93.39	7
8	1400	14.81	88.86	6

As can be seen from Table 5, the first four combinations consumed more drill bits compared to the last four combinations, because of the time constraint and the effect of rotation speed. The ROP is strongly affected by rotation speed, thus the lower level of rotation speed causes a lower ROP and it also affects drilling time directly. Therefore, drill bits must be changed to keep ROP high when rotation speed is low. Pulldown force is slightly significant compared to bailing air pressure. According to the optimization results, combination 8 is the most effective: cost minimization is taken into consideration due to the required number of bits and operating time which is needed to have a desired drilling operation.

Conclusion

This paper proposes a statistical analysis and model to optimize replacement time of drill bits in open pit mines. First, data interpretation and statistical testing were implemented to analyze controllable drilling parameters that affect drilling activity directly. A full factorial design at two levels was used. A drilling operation was investigated as a case study for a specific geological condition. The parameters affecting ROP and their relative importance were determined. Furthermore, the association between operational parameters and ROP was quantified for eight combinations. Rotation speed was the most influential operational parameter particularly when the drill bit was new. The specific energy formulation was used to precisely determine operation cost. The GA approach was developed to optimize drill bit replacement time with a mathematical approach. The results of the study showed that the proposed approach can be used as a tool for drill bit management in open pit mining operations.

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