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Evaluation of rope shovel operators in surface coal mining using a Multi-Attribute Decision-Making model

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ABSTRACT

Rope shovels are used to dig and load materials in surface mines. One of the main factors that influence the production rate and energy consumption of rope shovels is the performance of the operator. This paper presents a method for evaluating rope shovel operators using the Multi-Attribute Decision-Making (MADM) model. Data used in this research were collected from an operating surface coal mine in the southern United States. The MADM model consists of attributes, their weights of importance, and alternatives. Shovel operators are considered the alternatives. The energy consumption model was developed with multiple regression analysis, and its variables were included in the MADM model as attributes. Preferences with respect to min/max of the defined attributes were obtained with multi-objective optimization. Multi-objective optimization was conducted with the overall goal of minimizing energy consumption and maximizing production rate. Weights of importance of the attributes were determined by the Analytical Hierarchy Process (AHP). The overall evaluation of operators was performed by one of the MADM models, i.e., PROMETHEE II. The research results presented here may be used by mining professionals to help evaluate the performance of rope shovel operators in surface mining.

1. Introduction

Rope shovels are used in large surface mining operations for the digging and loading of materials. Shovel productivity is highly influenced by the skill and working practices of operators. Caterpillar indicates that one of the major factors for obtaining maximum productivity is a well-trained operator [1]. According to Fiscor, better operator training and a consistent clean-up process around the loading area and face could save 20 min of cycle time per day [2]. Several research studies have shown that mine operating conditions and operators' practices significantly affect energy consumption [3–7].

The most influential factors related to the overall working cycle of the shovel that impact its productivity are cycle time and fillability of the bucket. The basic rope shovel motions involve hoist, crowd, swing, and propel. The shovel operating cycle consists of digging, swinging, dumping, returning, and positioning. Even though these parts of the operation are operationally independent, the skill and coordination of an operator is required for a smooth cycle.

The digging phase involves crowd motion of the bucket into the bank, hoist motion to fill the bucket, and drawing from the bank [8]. When the bucket is hoisted to the bank, crowd and retract motion are used to control the depth of the bucket penetration. Penetration that is too shallow will lead to longer hoist travel distance needed to fill the bucket, which will increase the fill time and decrease the fill factor. However, applying excessive crowd motion will make the hoist motion slower. The whole cycle time increases up to 50%, or even more, when the bucket is stalled in the bank [8]. Therefore, to achieve an effective digging process, it is mandatory for an operator to establish balance between the hoist and crowd motion. In addition, unbalanced crowd and hoist forces lead to jacking of the boom, which can cause serious damage to the shovel.

The swinging phase begins when the bucket is full of material, and in this phase, the operator controls the movement of the bucket though a defined swing path and dump height toward the haul truck. An experienced operator can achieve smooth and continuous acceleration, maximum speed, and deceleration. Motion that is not smooth can result in the increase of time and spillage, which can further damage the body of the truck. In addition, the operator influences the propel function, or positioning of the shovel in order to get the highest number of filled buckets before moving again. Locating the shovel too far from the bank can decrease available digging power. Also, inappropriate shovel location leads to an increase in cycle time. Maximum efficiency is achieved when it is positioned close to the toe of the bank. According to P&H Mine Pro Services, by saving 2 min per operating hour on propelling, a 23 m^3 shovel could load one additional 154-tonne truck per hour [8].

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Since operator performance significantly affects performance of the shovel, it is important to analyze parts of the cycle that can be improved. The evaluation of shovel operators will help mining professionals develop strategies for improving productivity and energy efficiency, and reducing the operating cost.

There is a lack of quantitative models to evaluate shovel operator performance. Particularly, there is a lack of models that consider the relationship between production of the shovel and energy consumption, and the relationship between shovel operator performance and the elements of cycle time, production rate, and energy consumption. The objective of this research was to develop a methodology to evaluate rope shovel operators with the goal of maximizing production rate and minimizing energy consumption.

2. Literature review

Sage indicates that a skilled performer is one who produces a fast and accurate output with a high consistency [7]. However, according to Bernold, this approach, which is based on behavioral observation, has two main shortcomings [3]. One of them is that performance is not clearly related to skill since other aspects such as fatigue, motivation, boredom, temperature, and noise can also affect the performance. The second shortcoming is that this approach is qualitative in nature. Bernold suggests that motor skills of the operator are essential component for everyday operations [3]. Robbins also states that the aim is to understand how people differ in abilities and use that information to improve their performance [10].

Well-trained operator contributes to increased productivity. Automated equipment involves electronically sophisticated commands and accessories that ease the operation tremendously. Therefore, introducing controls that require minimal effort has changed the training requirements for operators. Work experience is also positively correlated with skill. According to Harrel and Daim, motivation is particularly important for good performance; in fact, unmotivated employee contributes to decreased productivity and quality [11]. Likewise, according to Peterson et al., good attitudes are important for high productivity [12].

Operators are usually evaluated by being observed in the performance of equipment-related tasks [13,14,15]. Evaluations are performed by observation of operators engaging in duties such as equipment inspection prior to operation, excavating operations, safety practices, etc. Also, operators usually have to pass not only practical exams but also written exams. The evaluator's judgment is based on how often the task is performed and how critical it is when it is irregularly performed. Both of these criteria are qualitative in nature and dependent on subjective judgment by the evaluator.

There are various simulators that are used to train operators [16–21]. These simulators expose operators to a virtual rope shovel working in the common mining site with trucks. Through each simulation module, productivity and quality of work are measured. Also, while using simulators, operators learn from their mistakes, as the simulators identify the least effective parts of their performance.

Bernold used a backhoe shovel simulator for analyzing the motor skills of operators [3]. Another example of simulating operations of a rope shovel was carried out by Awuah-Offei and Frimpong [4]. The task was carried out with the purpose of finding hoist rope and crowd arm speeds for optimal performance of the shovel. The authors pointed out that hoist rope and crowd arm speeds present fundamental actions for assessing of operator practices. Patnayak used the average hoist and crowd power consumption of different teams of operators as a parameter for assessing the effect of operator practice on the performance of the shovel [22]. According to Widzyk-Capehart and Lever, operator digging technique has the direct influence on the stalling of the hoist during dig and slacking of the hoist ropes [5]. The performance was examined by analyzing productivity, operator cycle time, and techniques that operators practiced during the digging part of the cycle with respect to hoist/crowd utilization. Widzyk-Capehart and Lever pointed out that the individual styles of operators have a significant impact on shovel productivity, and the operator behavior was examined through a real-time feedback system [5]. Weiss and Shanteau indicated that application of measurement instruments eliminates inconsistencies related to fatigue and bias associated with human operation [23]. One of such examples would be using radar/ultrasound system as a position control system that would bring the bucket into the right position [2].

Various systems have been developed to provide feedback about different shovel parameters. One of the most advanced shovel monitoring systems is Tritronics ShovelPro Monitor, developed by Thunderbird Mining Systems, and it is being used worldwide [24]. This real-time monitoring system measures different shovel parameters such as bucket payload, coordinates of each bucket engaged and disengaged, and dump point. The system gives the operator feedback about delays, positioning, and digging time, along with total production information (cycles, tonnes) in chronological order. The Accuweight by Drivers & Control Services, Inc. is a similar system that measures these parameters [25].

3. Methodology

In order to achieve the objective of this research, a Multi-Attribute Decision-Making (MADM) model was used. The MADM model consists of attributes (criteria), their weights of importance (if necessary), and alternatives. The first step was to derive energy consumption and production rate models. The energy consumption model was derived using a multiple regression tool. Production rate has an established method of formulation, based on the volume of material in the bucket and number of cycles. After defining these models, multi-objective optimization was performed using an evolutionary algorithm. Optimization was performed with respect to the minimization of energy consumption and maximization of the production rate, using measured data on four rope shovel operators with arbitrary names (Operators A, B, C, and D). In the next phase, the significant variables and their values obtained from the previous analyses were used for establishing the criteria for the MADM. The alternatives of the MADM were the rope shovel operators, while weights of the criteria were obtained from the Analytical Hierarchy Process (AHP). Finally, the overall ranking of rope shovel operators was performed using one of the MADM models from the outranking family – the Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) II. An outline of the methodology is presented in Fig. 1.

Data used in this research were collected in a surface coal mine located in the southern part of United States. The mine uses a truck and shovel fleet composed of a P&H 2800 XPB (30.6 m^3 bucket) rope shovel and Caterpillar 789 dump trucks (payload of 163 t). Usually, the shovel removes up to 15 m of overburden before reaching the coal. Caterpillar 789 trucks transport overburden to spoil dump areas.

The shovel has an integrated AccuWeight real-time information monitoring system, from which data were retrieved. The system contains sets of programmable logic controllers (PLCs) that monitor shovel parameters such as cycle time, fill time, payload, energy to load a bucket, etc. This system simultaneously samples 20–50 times per second and stores in database average values of 20 parameters per shovel cycle. Data flow involves cycle detection, payload weight, and input in a database. Measuring and recording events for a new cycle begins at the moment when the material in the bucket is dumped. Shovel parameters analyzed in this research are: cycle time, fill time, payload, and energy to load a bucket. Energy to load a bucket is recorded in a unit-less number format, which must be adjusted to obtain energy consumption in kWh.