Age-based maintenance for a fleet of haul trucks

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Abstract

Purpose – The most costly part in an open-pit mine is the transportation of material out of the mine. The efficiency of the truck-and-shovel fleet plays a major role in cost control. The paper aims to discuss these issues.

Design/methodology/approach – The truck dispatching simulation model with consideration of age-based maintenance is proposed.

Findings – This paper underlines an impact of truck dispatching decisions and reveals remarkable differences in the total production under different approaches of operational availability. Additionally, the simulated results introduce an effective scheduled maintenance for different truck age levels.

Originality/value – The approach is based on a case study taking into account the stochastic equipment behavior and environment in a real open-pit mine. This approach can be used more generally in situations in which truck fleets are used to transport material.

Keywords Availability, Productivity, Simulation, Maintenance, Mining equipment

Paper type Research paper

1. Introduction

In coal open pits, a large amount of coal and overburden must be transported in the pit on a daily basis. The main methods for moving these materials are belt conveyor, train track railway, truck, or intermodal transport. Truck–shovel systems are the most commonly used because they offer many advantages: flexibility, high mobility, climbing ability, small turning radius, short time investment, and low infrastructure cost (He *et al.*, 2010; Mena *et al.*, 2013). However, the operating cost of truck–shovel systems is the most expensive part of the process in the mining activity (Aksoy and Yalcin, 2000; Alarie and Gamache, 2002; Niemann-Delius and Fedurek, 2004; Ta *et al.*, 2005; He *et al.*, 2010). It is widely recognized that the maintenance cost of trucks and shovels can constitute around 30–50 percent of the overall haulage costs (Topal and Ramazan, 2010). Reduction in the operating costs can be effectively achieved by increasing mining equipment productivity.

Previous research has presented solutions to improve equipment productivity using an optimal number of truck–shovel combinations in the fleet, haulage network planning, truck allocation methods, and dispatching strategy (Morgan and Peterson, 1968; Ta *et al.*, 2005; Burt and Caccetta, 2007; Krause and Musingwini, 2007; Fioroni *et al.*, 2008; Guilherme Sousa Bastos, 2010; He *et al.*, 2010; Montiel and Dimitrakopoulos, 2015; Chaowasakoo *et al.*, 2017a; Chaowasakoo *et al.*, 2017b). The proposed solutions are based on the optimization of differently defined objective functions that affect a number of main problems, such as minimizing the transportation and maintenance costs, minimizing the truck–shovel waiting and cycle times, as well as maximizing the amount of transported material. In general, these

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objective functions assume that all trucks and shovels have the same operating performance, while in reality each machine has its own reliability, availability, and maintainability.

One of the prior research studies presents an improved simulation and optimization model, in which equipment availability is one of the variables in the expected productivity function. The objective function is to maximize the overall productivity of the fleet by allocating the most performing trucks on the more productive routes (Mena *et al.*, 2013). Scheduled maintenance plays a crucial role in the operations as they directly influence the equipment availability and reliability. Effective maintenance offers sustaining the long-term profitability (Crespo Marquez and Sánchez Heguedas, 2002; Marquez, 2005; Lhorente *et al.*, 2004; Silva *et al.*, 2016). Therefore, finding a close to optimal scheduled maintenance in a truck–shovel fleet is extremely important. Only few research papers on truck–shovel fleet systems consider these characteristics to improve equipment productivity. Moreover, using age-based maintenance in a truck dispatching simulation model based on actual filed data has not been reported earlier.

This paper presents a novel truck dispatching simulation model based on availability and maintainability characteristics for each truck age level. The proposed model considers the maintenance cost variation with truck age while maximizing the production. This approach is based on a case study taking into account the stochastic equipment behavior and environmental changes in an actual open-pit mine. The findings underline the impact of chosen truck dispatching decisions and reveal remarkable differences in the production under different approaches of operational availability. Moreover, the simulated results introduce an effective scheduled maintenance for different truck age levels.

2. Process properties of truck dispatching in an open-pit mine

It is common for many open-pit mines to have fleets containing trucks of different age levels. The operating hours of all trucks are not expected to stay the same throughout the shift. Some trucks may need to be temporarily stopped for preventive or corrective maintenance, which influence their availability to operate. Based on these considerations, the objective of this study is to improve the simulation modeling framework for allocating trucks in the fleet by maximizing the productivity, in which reliability, availability, and maintainability characteristics of each truck age level are taken into account.

2.1 Truck dispatching strategies

For several years, a major focus of truck allocation has revolved around the dispatching system. This system assigns trucks to a shovel and manages the truck destinations based on two main approaches: a single-stage or multi-stage. In the single-stage approach, the trucks are dispatched to shovels consistent with one or several criteria without considering any production targets and constraints. On the other hand, in the multi-stage approach, the dispatching problem is divided into sub-problems or stages. These stages are the upper stage and the lower stage. The upper stage contains the setting of the production target for every shovel. Moreover, the lower stage assigns trucks to a shovel to minimize the deviation from the production targets, which is suggested by the upper stage. The two main approaches are used in the concept of truck dispatching strategies described below (for further details see Alarie and Gamache, 2002; Ta *et al.*, 2005; Guilherme Sousa Bastos, 2010; Topal and Ramazan, 2010; Chaowasakoo *et al.*, 2017a, b):

(1) The 1-truck-for-*n*-shovels is based on a single-stage approach, illustrated in Figure 1. Truck dispatching decisions are made by taking into account only one truck to dispatch, but considering *n* possible shovels. A truck is assigned for the highest potential shovel. Typically, the choice of shovels in which the truck is assigned for depends on one of the heuristic truck dispatching methods.

(2) The m-trucks-for-1-shovel is based on a multi-stage approach, illustrated in the middle panel of Figure 1. Truck dispatching decisions consider m trucks and one shovel at a time. More specifically, the shovels are sorted according to the production priority scheme. Afterwards, the decision is made by assigning the best truck to the shovel, in which is the first on the priority list.

(3) The m-trucks-for-n-shovels is based on a multi-stage approach. Truck dispatching decision is made by considering the assignment of m forthcoming trucks to n shovels (m should be greater than or equal to n), which is illustrated in the rightmost panel of Figure 1. The assignment is based on different objectives in the upper and lower stage.

2.2 Heuristic truck dispatching methods

The basic heuristic truck dispatching methods in this study are explained next (Alarie and Gamache, 2002; Cetin, 2004; Guilherme Sousa Bastos, 2010; Chaowasakoo *et al.*, 2017a, b):

(1) Minimizing shovel waiting time (MSWT): an empty truck is assigned to the shovel with the longest idle time or to the shovel that is expected to be idle first. The aim of this method is to maximize the utilization of both trucks and shovels.

(2) Minimizing truck cycle time (MTCT): an empty truck is assigned to the shovel that allows the shortest cycle time, with the aim to maximize the total productivity.

(3) Minimizing truck waiting time (MTWT): an empty truck is assigned to the shovel that the loading operation starts first. The purpose of this method is to maximize the utilization of the shovel and minimize the truck waiting time.

(4) Minimizing shovel saturation and coverage (MSC): an empty truck is assigned to the shovel at equal time intervals to keep shovels busy. This method aims to minimize the shovel waiting time.

2.3 Reliability, availability, and maintainability characteristics

Katukoori (1995) defines reliability as the probability that the equipment will not break down or fail. Moreover, maintainability is the probability that the equipment is successfully repaired or restored. Availability is a metric performance parameter that takes both reliability and maintainability of a component or system into account, considering the probability that the component or system operates at a given time.

The level of availability affects directly the production since it is a measure of time in which the equipment is available to operate. To ensure a minimal probability of equipment failures, it routinely needs monitor equipment condition. Moreover, it requires the predictions on the basis of current conditions based on historical equipment maintenance and operations (Kothamasu *et al.*, 2006). As a result, the level of availability can be predicted and controlled (Katukoori, 1995; Silva *et al.*, 2016). Some useful definitions relating to

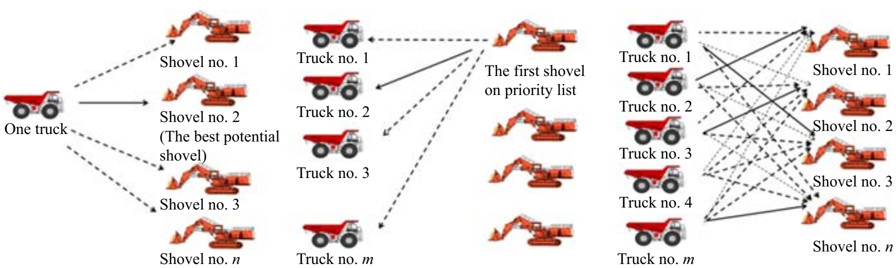

Figure 1. Truck dispatching strategies

different classifications of availability are given below (for further details, see Katukoori, 1995; Silva *et al.*, 2016):

(1) Inherent availability (A_i) refers to the expected level of availability, which considers only the performance of corrective maintenance. It excludes administrative inherent time delays, logistics time, and preventive maintenance downtime. Inherent availability can be computed by using estimated values of *MTBF* and *MTTR*, as shown in the following equation:

$$A_i = \frac{MTBF}{MTBF+MTTR}, \tag{1}$$

where *MTBF* is mean time between failure and *MTTR* is mean time to recovery.

(2) Achievable availability (A_a) refers to the expected level of availability, which considers the performance of corrective and preventive maintenance. It assumes that all necessary spare parts, support tools, and manpower are available without delay. Achievable availability is defined by the following equation:

$$A_a = \frac{OT}{OT+MCT+MPT}, \tag{2}$$

where *OT* is the operational time period, *MCT* is the required time for corrective maintenance, which excludes inspection time, administrative time, or logistical delay time, and *MPT* is the required time for preventive maintenance.

(3) Operational availability (A_o) refers to a realistic level of availability, which considers all required times for corrective and preventive maintenance, administrative functions, and logistical delays. Operational availability is defined by the following equation:

$$A_o = \frac{CH-MH}{CH}, \tag{3}$$

where *CH* is the total time based on calendar hours and *MH* is the required time in hours in which the equipment is in the maintenance process.

2.4 System characteristic

The present case study is carried out at a real open-pit mine, located in East Kalimantan, Indonesia. The amount of coal and overburden to be daily hauled within and from the site is massive. The overall volume of transported coal is 3m tons per annum with a total movement of overburden of 50m bank cubic meter (bcm). The fleet contains 115 machines. The actual production of the mine varies significantly from month to month, which is relatively low compared to the equipment capacity. It is of great interest to find the reasons behind this, which would allow decision makers to plan better the production process and decide any possible improvements.

The extraction and transportation overburden system is composed of 32 small trucks (23 bcm), 36 large trucks (41.5 bcm), 16 small shovels (7 m^3), and 4 large shovels (14 m^3). The truck fleet contains trucks of different age levels, and the maintenance costs increase as the age of the truck increases. In the case study presented in this paper, a 50,000 h range is used. This means when a truck age is between 50,000 and 90,000 h, it is allocated to Level 1, and when it is less than 50,000 h, it is allocated to Level 2. There are 18 small and 16 large trucks at Level 1, and 14 small and 20 large trucks at Level 2. Table I presents the maintenance, breakdown, and operating costs as dollars per hour for different truck age levels. In the considered open-pit mine operation, it is assumed that the unit operating cost of trucks and shovels is a measure of time in which the equipment will be available for production operations.

In the case study, the dispatching method currently used by the mine is the simplex algorithm, which computes a set of optimal paths between shovels and the dump point. The actual strategy not only tries to satisfy the linear programming requirement to minimize the total cost but also actively minimizes the shovel idle time. Operationally, a truck receives a dispatching order and then travels to the assigned shovel. Subsequently, the shovel loads the overburden on the truck, which drives it to the dump point. After that, the truck waits for another dispatching order. This sequence is repeated until the end of the eight-hour shift. Generally, a cyclic operating event of truck consists of eight sequence activities, such as traveling, waiting, spotting, loading, hauling, queuing, backing, and tipping, lasting 12–16 min, which is really short compared to the length of the shift. Moreover, the time between truck assignment requests at each loading point is frequently high, on average 2–3 min. As a result, the extraction and transportation processes of overburden are emulated in a stochastic environment. More details about the cyclic operating time in each type of truck and shovel are presented in Tables AII–AV.

3. Modeling

The specific simulation modeling framework presented in this paper aims to allocate available trucks for maximizing the overburden production. It is measured by the total number of trips that each truck can perform under the ideal operation and breakdown event. The proposed conceptual model is presented in Figure 2. The starting point is the analysis of collected data, which is the historical data of truck–shovel activity times from January to December, 2014. The collected data are rich enough for the statistical analysis, which are

The comparison cost of truck age levels (USD/h)	Truck age level 1		Truck age level 2	
A number of trucks/truck types	18/small	16/large	14/small	20/large
Average maintenance cost	24	38	20	20
Average breakdown cost	40	80	40	80
Operating cost	90	130	90	130

Table I. The comparison cost of truck age levels

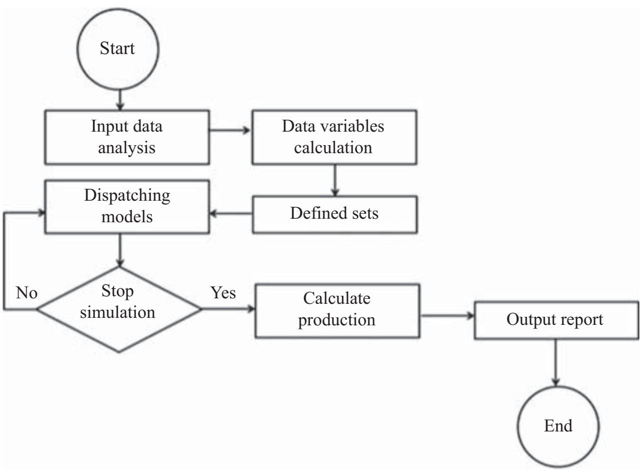

Figure 2. The conceptual simulation model for truck dispatching strategies

provided by the global positioning system (GPS). The distributions of truck–shovel activity times are analyzed to find a suitable parametric model. A log-normal distribution is chosen because it fits sufficiently well to the empirical distribution of activity times. The fitting is based on the sample mean and the standard deviation, (for further details see Appendix).

All data variables are calculated and converted into input data sets for the dispatching simulation models, which seek to find the total production based on different truck dispatching strategies and operational availability. The simulation models in this study are run for 1,000 replications to calculate the lower bound for the production, which is exceeded with 95 percent probability under the assumption that the model is correctly specified.

3.1 The proposed truck dispatching model

The objective function of each proposed truck dispatching model is to maximize the production for the fleet in the mining operation (Cetin, 2004; Mena *et al.*, 2013; Chaowasakoo *et al.*, 2017b), where $VT_{[i,j]}$ is the volume of truck i ($i \in X$, X is the set of all truck types) on the selected shovel j ($j \in Y$, Y is the set of all shovel types) in bcm; $R_{[i,j]}$ is a binary variable which indicates the possible shovels j where the truck i could be sent; VS_j is the total volume of shovel j when it has completed loading of the assigned truck over the shift in bcm; O_i is the total number of trips of each type of trucks in one month, $r \in O_i$; T^r is cycle traveling time of each truck per trip in hour; L is a measure of time in which the truck is available to operate in one month; and P is the production requirement per month in bcm. The implementation of the proposed model was carried out using MATLAB®:

$$\text{Max} \sum_{i \in X} \sum_{j \in Y} VT_{[i,j]} R_{[i,j]}, \tag{4}$$

with the constraint conditions:

$$\sum_{i \in X} \sum_{j \in Y} VT_{[i,j]} R_{[i,j]} \leqslant VS_j \quad \forall j \in Y, \tag{5}$$

$$\sum_{i \in X} \sum_{j \in Y} VT_{[i,j]} O_i \geqslant P \quad \forall i \in X, \tag{6}$$

$$\sum_{r \in O_i} T^r = L \quad \forall r \in O_i, \tag{7}$$

$$\sum_{i \in X} \sum_{j \in Y} R_{[i,j]} \leqslant 1, \tag{8}$$

$$\sum_{i \in X} \sum_{j \in Y} R_{[i,j]} = 0 \quad \text{if } i = i' \text{ with } i' \in X, \tag{9}$$

$$\sum_{i \in X} \sum_{j \in Y} R_{[i,j]} = 0 \quad \text{if } j = j' \text{ with } j' \in Y, \tag{10}$$

$$R_{[i,j]} = \begin{cases} 1 \text{ if truck is assigned to shovel } j \\ 0 \text{ otherwise} \end{cases}. \tag{11}$$

Constraint (5) ensures that the production of truck associated to the shovel j should not exceed the total volume of the shovel when the loading is completed. Constraint (6) enforces the total production to be equal or greater than the production requirement. Constraint (7) ensures that the total operating times of truck should be equal to the level of operational availability. Constraint (8) avoids the duplications, once truck i is assigned to shovel j, it cannot be assigned to another shovel. Constraint (9) is activated when truck i' is temporarily inactive, and it is deactivated when truck returns to operation. Constraint (10) is activated when shovel j' fails, and it is deactivated when shovel j' returns to operation. Constraint (11) is a binary decision variable representing assignment of truck i to shovel j based on truck selection criteria. The truck selection criteria rely on the choice of truck dispatching strategies and heuristic truck dispatching methods. These criteria are the 1-truck-for-n-shovels with MSWT, the m-trucks-for-1-shovel, and the m-trucks-for-n-shovels with MTCT.

3.2 The 1-truck-for-n-shovels with MSWT

The current time of all trucks and shovels are assigned to be 0 at the beginning of the simulation. The first truck has its current time updated with the simulated sequence activity (traveling, spotting, loading, hauling, backing, and tipping). After that the trucks are sorted in ascending order by their current time. The trucks and shovels are matched based on the chosen heuristic truck dispatching method, which is MSWT. The simulation continuously iterates until the simulation time reaches a limit. The selected truck is assigned to shovel d, that is expected to have the longest idle time, that is:

$$d = \arg\max_j\{\max_j\{tt_j - ts_j\}, 0\},$$

where d is the shovel for which the truck is assigned, tt_j is the expected time of assigned truck from the dispatching point to the shovel, and ts_j is the expected time of the shovel to complete loading all the trucks in the queue, including the one being loaded and those that are en route to this shovel, but have not yet reached it. This model aims to maximize the utilization of both trucks and shovels.

3.3 The m-trucks-for-1-shovel

The time of all trucks and shovels are assigned to be 0 in the beginning of the simulation. The m trucks have updated their current times based on the simulated sequence activity times. After that, the m trucks are sorted in ascending order. The selected truck is chosen based on the lowest cycle time operation. Moreover, the shovels are sorted according to the loading time priority. The shortest loading time is the expected shovel, in which is assigned to the selected truck in order to achieve the production target. It is generally defined by the following:

$$d = \arg\min_j\{tl_j\},$$

where tl_j is the simulated loading time of the assigned truck to shovel j. The main focus of this model is to maximize the production. The simulation loop is run until the simulation time reaches a limit.

3.4 The m-trucks-for-n-shovels with MTCT

In the beginning of the simulation, the times of all trucks and shovels are assigned to be 0. The m forthcoming trucks are assigned to the most suitable n shovels, in which m is greater than n. The trucks and shovels are matched based on one of the heuristic truck dispatching methods (MTCT), which aims to maximize the total productivity. The selected truck is assigned to the shovel d that allows the shortest truck cycle time. The decision-making criteria for assigning a truck is:

$$d = \arg\min_j\{tc_j\},$$

where tc_j is defined as the truck cycle time for shovel j, which is a sum of the expected arrival time of the truck from the dispatching point to the loading point area, the simulated loading time required by the shovel, and the expected time when the assigned truck hauls it load to the waste dump and tipping.

4. Results

4.1 Truck dispatching models

The simulated results of overburden production are obtained using two models based on three unique truck selection criteria, including the 1-truck-for-n-shovels with MSWT, the m-trucks-for-1-shovel, and the m-trucks-for-n-shovels with MTCT. The first model (hereafter named Model I) represents the ideal operation, which does not account for breakdowns of different truck and shovel types. The second model (hereafter named Model II) takes these breakdowns into account. Figures 3 and 4 illustrate the total production values under the ideal operation and breakdown event.

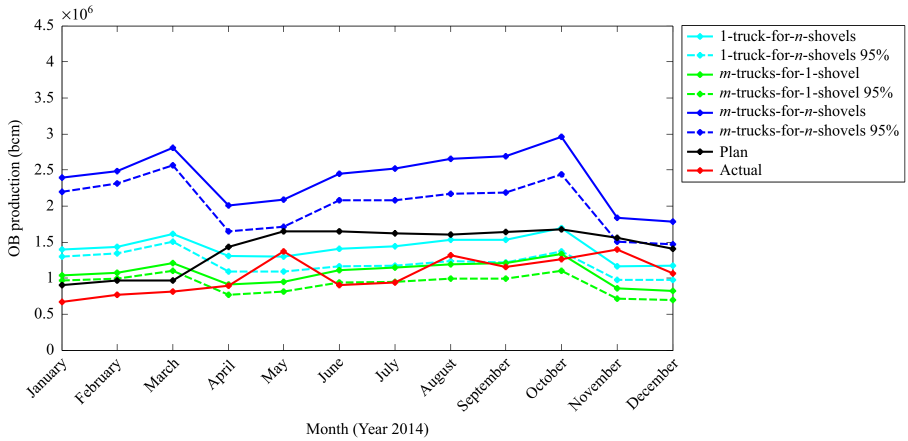

Figure 3.
The simulated results of overburden production under the ideal operation (Model I)

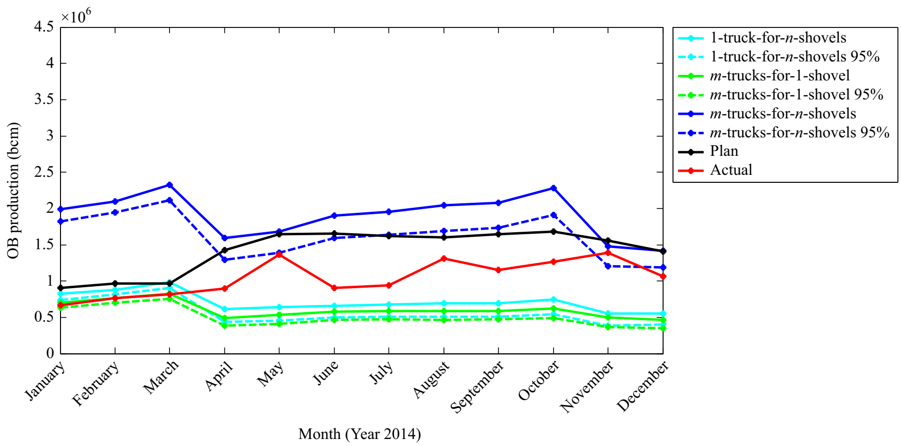

Figure 4.
The simulated results of overburden production under random failure events (Model II)

Figure 3 presents the ideal operation assuming that all trucks and shovels, irrespective of age, have identical performance levels and 100 percent availability. The simulated result of the *m*-trucks-for-1-shovel yields a similar result as the actual production, while the 1-truck-for-*n*-shovels with MSWT appear to be 25 percent higher than the actual production. However, the *m*-trucks-for-*n*-shovels with MTCT yields the highest production, which is 55 percent higher compared to the actual production. The figure also shows the level, above which 95 percent of the simulated production results, that is, the production is more than this with 95 percent probability.

The production of each unique truck selection criteria decreases gradually by 38 percent when the breakdowns are included into the simulation model (Model II), as illustrated in Figure 4. It results from the different downtimes of each truck and shovel type, which are modeled by the log-normal distribution, whose parameters are calibrated using the collected data from the GPS (Tables AII-AV, Appendix). The simulated result of the 1-truck-for-*n*-shovels with MSWT appears to be 37 percent lower than the actual production, while the *m*-trucks-for-1-shovel is 39 percent. However, the *m*-trucks-for-*n*-shovels with MTCT yield a significantly higher production even though unpredictable events are included in the model. The index production comparison of Models I and II is provided in Table II.

4.2 Forecasting operational availability

Since, the main focus of this study is in the actual field operation then operational availability (A_o) is more realistic to implement than inherent availability (A_i) and achievable availability (A_a). In general in open-pit mine operations, the expected level of operational availability for trucks is around 85–90 percent (Silva *et al.*, 2016). In this case, 85 and 90 percent are selected and applied to truck age levels 1 and 2. Therefore, the total maintenance time per month of truck age levels 1 and 2 is 108 and 72 hours. All these parameters are given as an input to Model I, only the *m*-trucks-for-*n*-shovels with MTCT is applied because it yields more improvement in the total production than others. The simulated result of this traditional approach with the yellow line is presented in Figure 5. The average production is higher than the average plan by 34.68 percent.

With regards to the cyan line in Figure 5, it is the original case. This approach is evaluated in Model I, specifically the *m*-trucks-for-*n*-shovels with MTCT. Two additional input parameters are given to the simulation model: breakdowns of different truck and shovel types (Tables AII–AV, Appendix) and the required times for corrective and preventive maintenance of each truck age level (Table AVI). The average production yields 16.25 percent higher than the average plan.

	The 1-truck-for-*n*-shovels		The *m*-trucks-for-1-shovel		The *m*-trucks-for-*n*-shovels			
Month	Model I	Model II	Model I	Model II	Model I	Model II	Plan	Actual
January	155	91	115	77	265	220	100	74
February	148	91	111	79	257	217	100	79
March	166	102	124	86	290	240	100	84
April	92	43	64	34	140	111	100	63
May	79	39	58	32	127	102	100	83
June	85	40	67	35	148	115	100	55
July	89	41	71	36	156	121	100	58
August	95	43	75	37	166	128	100	82
September	94	42	74	36	164	127	100	70
October	101	44	79	37	176	136	100	75
November	75	35	55	32	118	95	100	90
December	83	39	58	33	126	101	100	75

Table II. The comparison of Model I and Model II based on the index production (percent)

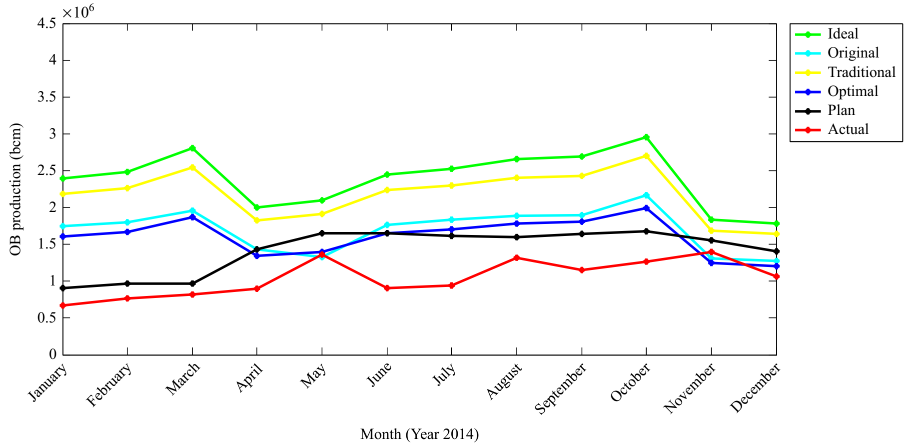

Figure 5.
The simulated results of overburden production under the operational availability

Finally, the optimal approach is evaluated in Model I based on the *m*-trucks-for-*n*-shovels with MTCT by fixing the monthly production to 10 percent above the average plan production (defined in Table III). The simulated result yields an effective scheduled maintenance for different truck age levels as the optimal scheduled maintenance for the truck age levels 1 and 2 are 216 and 252 h per month. The operational availability of truck age level 1 and 2 is 65 and 70 percent. Figure 5 presents the simulated result of this approach based on the blue line. The total expense of each truck type in different age levels is calculated using the unit cost of maintenance, breakdown, and operating as dollars per hour provided in Table I. The simulated result of the optimal approach provides the unit cost saving for individual truck age levels, which is presented in Table III.

4.3 Discussion

Typically, the number, size, and age of the equipment in large open-pit mines are often high as well as their operating costs. The ability to reduce overall costs can be effectively achieved by increasing mining equipment productivity. The methods for improving equipment productivity are discussed extensively in the literature. However, the use of the truck dispatching model with age-based maintenance in the actual field data has not been reported earlier. This study addresses the problem within three different truck dispatching simulation

Table III.
The comparison cost of the simulated approaches

Description		Ideal operation	Original case	Traditional approach	Optimal approach
Maintenance cost of truck age level (USD/year)	Large 1		890,256	984,960	2,298,240
	Small 1		247,512	276,480	829,440
	Large 2		377,617	435,456	1,016,064
	Small 2		454,908	311,040	933,120
Breakdown cost (USD/year)			46,355	–	–
Total maintenance and breakdown costs (USD/year)			2,016,648	2,007,936	5,076,854
Total operating cost (USD/year)		65,318,400	49,256,208	48,988,800	22,861,440
Average cost of the fleet (USD/month)		5,443,200	4,272,738	4,249,728	2,328,192
Average production[a] (bcm/month)		2,389,461	1,698,486	2,177,649	1,606,201
Average productivity		0.439	0.398	0.512	0.690

Note: [a]Average plan production is 1,422,548 bcm; average actual production is 1,044,509 bcm models, including the 1-truck-for-n-shovels with MSWT, the m-trucks-for-1-shovel, and the m-trucks-for-n-shovels with MTCT. The findings provide evidence that that the choice of truck dispatching strategies, e.g., the m-trucks-for-n-shovels with MTCT reveals remarkable differences in the production under the ideal operation and breakdown event.

In reality each truck has it owns reliability, availability, and maintainability, in which these characteristics play a crucial role in the production and operating costs. Therefore, the extension of the simulation models is derived by taking operational availability into account. The models are used to predict the number of total maintenance hours for different truck age levels. The optimal approach yields a good result, in which the production is above the average target plan by 10 percent and the substantial operating cost reduction is 40 percent. In the open-pit mine operation under consideration, the ratio of preventive and corrective maintenance is 7:3. The forecast of preventive and corrective maintenance schedules for the truck age level 1 is 151.2 and 64.8 h per month, while the truck age level 2 is 176.4 and 75.6 h per month.

Naturally, each mine is unique in its topography and operations. The input data for the simulation models were collected from only one mine. However, the collected data over a one-year period are sufficient to produce significant results and provide information for the decision maker to know where improvement is needed in the operation process. Moreover, the time period allows a significant observation that heavy rainfall has an impact on the operation by making trucks travel more difficult and leading to more equipment breakdowns than during the dry season, as presented in Table II. The actual production in June and July is 43 percent lower compared to the plan production, in which it falls in the period of heavy rains with an average rainfall of 200 mm on 14 days totaling 49 h per month. On the other hand, in August, September, and October fall in moderate rains with an average rainfall of 113 mm on 10 days totals 25 hours per month, the average actual production of these months is 24 percent lower than the plan production.

5. Conclusions

One significant factor in a profitable open-pit mine is an efficient overburden transport system. For this reason, the ability to improve the equipment productivity has been achieved directly by allocating trucks and shovels in an efficient manner with consideration of age-based maintenance. The simulation study conducted in this paper provides new guidelines of the volumes of improvement, which is applicable for other industries, such as shipping, taxis, and package delivery. Obviously it is likely that in practice one faces problems that are not included in the simulation models, but the improvement is so pronounced that it is likely that the use of this more sophisticated approach would yield more significant improvements in the mine production than one would expect.

The following recommendations are addressed for further study. First, the dispatching simulation models in this paper focus on the overburden fleet allocation. To deal with the problem comprehensively, the simulation models should be covered to quantity and quality of coal by considering several options for loading and dumping points, including stockpiles and crushers. Second, the considered open-pit mine operation uses only two truck age levels, which are classified by the operating hour range. To deal with this limitation and make the results more accurate, it needs to consider more age levels, age levels of the shovels, and other splitting criteria like number of overhauls, unexpected breakdowns, accidents, etc. Third, one can write an automatic program that makes the real-time optimal decision in the actual operation, where the times distributions are in the beginning of each shift and update the distributions when more data are gathered. Finally, the total expense of the fleet in each forecasting operational availability approach is calculated using the maintenance, breakdown, and operating costs. These costs are collected based on the historical information in the actual mine operation, but in reality there are indirect costs of not operating certain equipment. To make the cost model more precise, one needs to consider the cost model in the open-pit mine in more detail.

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Appendix

1. Fitting probabilities

The probability distribution used for the simulation models is the log-normal distribution because it fits to the data better than many other parametric distributions, such as the exponential distribution or Weibull distribution. The fit of the log-normal distribution to the empirical distribution calculated from the GPS data, is illustrated in Figure A1.

With regards to the maintenance activity time of different truck age levels, these parameters are calibrated under the assumption of a log-normal distribution based on the historical data, see Figure A2. Only, the results for June/large truck combination are shown, because the different activities and also figures for other months and other types look almost identical.

2. Model fit

Figure A3 and Table AI illustrate the comparison of simulation models by re-sampling from the real activity time data and the fitted log-normal distributions, using “the *m*-trucks-for-1-shovel” strategy. The results obtained from the re-sampling are almost identical to the results obtained from the log-normal distribution, which confirm that the log-normal distribution is sufficiently accurate for modeling activity times, in order to get realistic results for simulated production (Chaowasakoo *et al.*, 2017a, b).

3. The cyclic operating time of each truck type

The operating times in each cyclic activity of trucks and shovels are traveling, waiting, spotting, loading, hauling, queuing, backing, tipping, and inactive, which are presented in Tables AII–AV. Only five months are shown as an example (Chaowasakoo *et al.*, 2017b).

4. The required times for preventive and corrective maintenance of each truck age level are inferred from the historical data of the equipment, which are presented as an example in Table AVI.

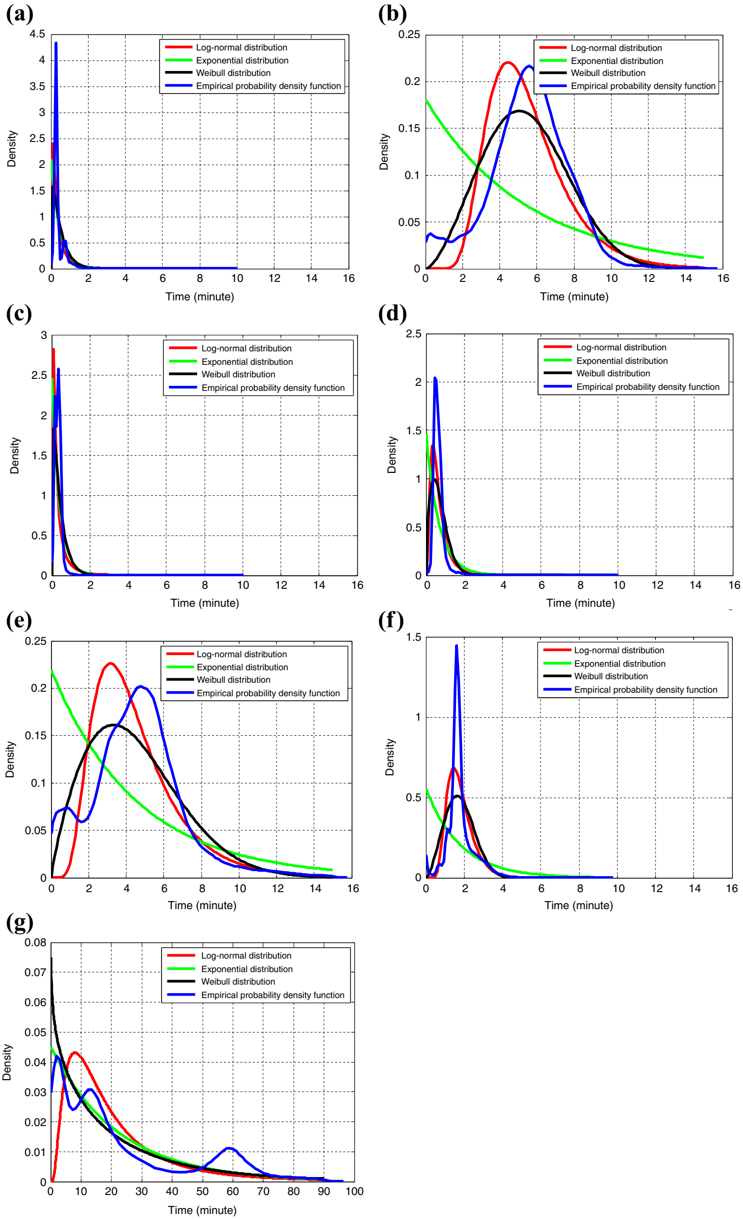
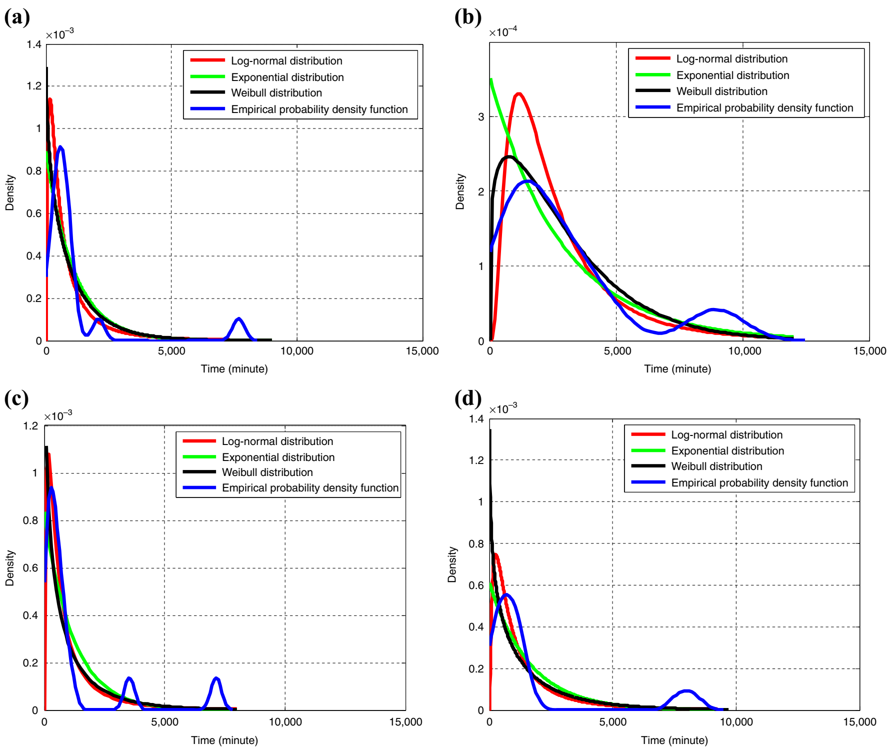


Figure A1.
The distribution of a cyclic operating time of large trucks

Notes: (a) Spotting; (b) hauling; (c) backing; (d) tipping; (e) traveling; (f) loading; (g) inactive



Notes: (a) Preventive maintenance of large truck level 1; (b) corrective maintenance of large truck age level 1; (c) preventive maintenance of large truck age level 2; (d) corrective maintenance of large truck age level 2

Figure A2. The distribution of preventive and collective maintenance time of large truck age levels

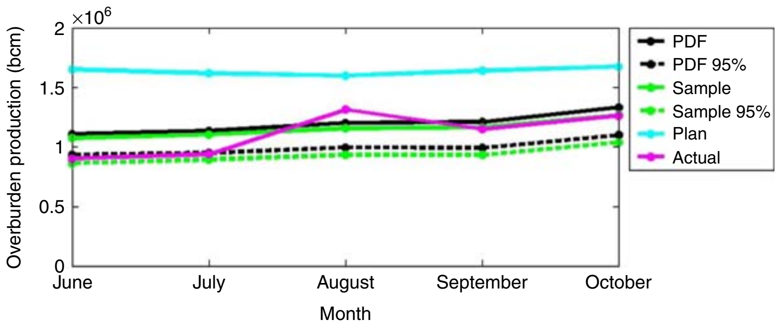


Figure A3. The production of the m-trucks-for-1-shovel

Month/methods	June	July	August	September	October
PDF: the *m*-trucks-for-1-shovel	67	70	75	74	79
Sample: the *m*-trucks-for-1-shovel	65	68	72	71	76
Plan	100	100	100	100	100
Actual	55	58	82	70	75

Table AI. The index production of the *m*-truck-for-1-shovel (percent)

Table AII.
A cyclic operating time (in minute) of small trucks

Cyclic activity/month	Value	Waiting	Spotting	Loading	Hauling	Queuing	Backing	Tipping	Traveling	Inactive
June	Data points	38,466	23,591	40,997	41,492	28,334	27,948	36,499	45,048	9,772
	Mean	1.899	0.629	1.602	5.435	0.225	0.285	0.803	4.750	49.502
	SD	2.061	0.802	0.648	2.430	0.636	0.621	0.705	2.714	129.263
July	Data points	30,112	18,629	33,837	33,945	24,064	23,591	30,576	38,358	8,884
	Mean	2.031	0.646	1.638	5.349	0.256	0.297	0.829	4.705	57.097
	SD	2.146	0.739	0.704	2.761	0.711	0.655	0.787	2.930	159.043
August	Data points	31,039	18,831	33,960	34,640	26,564	24,884	30,779	37,308	8,619
	Mean	1.954	0.617	1.673	4.937	0.308	0.295	0.844	4.786	64.283
	SD	2.022	0.746	0.708	2.818	0.894	0.660	0.768	2.962	172.572
September	Data points	32,053	19,884	35,365	36,021	27,611	25,209	31,196	38,482	8,607
	Mean	1.974	0.621	1.762	4.974	0.357	0.281	0.873	4.907	53.449
	SD	2.087	0.771	0.846	2.808	1.015	0.645	0.844	3.078	156.718
October	Data points	33,312	21,611	35,754	36,162	27,414	25,150	31,889	38,151	7,559
	Mean	1.837	0.619	1.722	4.611	0.252	0.331	0.828	4.350	65.434
	SD	1.923	0.645	0.684	2.620	0.745	0.801	0.737	2.799	194.224

Cyclic activity/month	Value	Waiting	Spotting	Loading	Hauling	Queuing	Backing	Tipping	Traveling	Inactive
June	Data points	37,222	22,553	40,784	41,254	32,101	29,923	38,116	45,418	9,382
	Mean	1.832	0.499	1.913	5.518	0.260	0.406	0.681	4.554	56.878
	SD	1.901	0.709	0.775	2.166	0.665	0.686	0.504	2.397	151.331
July	Data points	41,738	26,075	45,483	46,127	35,297	33,249	42,511	50,780	10,372
	Mean	1.911	0.497	1.780	5.438	0.276	0.422	0.664	4.264	51.999
	SD	1.919	0.743	0.689	2.152	0.715	0.708	0.479	2.309	138.568
August	Data points	43,640	26,976	45,787	46,379	37,530	33,875	43,384	50,852	9,662
	Mean	1.649	0.464	1.759	4.793	0.284	0.380	0.657	4.101	53.920
	SD	1.702	0.687	0.657	2.158	0.690	0.528	0.453	2.300	134.245
September	Data points	38,858	25,041	40,659	41,093	34,044	29,374	38,923	44,893	7,831
	Mean	1.777	0.470	1.819	4.349	0.247	0.349	0.702	4.071	60.635
	SD	1.772	0.618	0.709	1.937	0.546	0.448	0.585	2.327	190.130
October	Data points	33,945	21,904	35,649	36,095	29,542	27,301	33,613	38,439	6,426
	Mean	1.693	0.446	1.708	3.894	0.203	0.421	0.687	3.609	71.807
	SD	1.655	0.605	0.621	1.607	0.504	0.752	0.528	2.077	204.946

Table AIII. A cyclic operating time (in minute) of large trucks

Table AIV.
A cyclic operating time (in minute) of shovels

Cyclic activity/month	Value	Small shovel Loading	Small shovel Waiting	Small shovel Inactive	Large shovel Loading	Large shovel Waiting	Large shovel Inactive
June	Data points	49,462	52,436	941	27,597	28,660	235
	Mean	1.930	2.831	185.330	1.698	1.978	195.797
	SD	0.999	6.582	313.398	0.616	5.683	309.424
July	Data points	41,585	43,970	746	34,726	35,969	238
	Mean	1.920	3.063	201.747	1.648	1.897	157.927
	SD	0.956	7.266	342.239	0.525	5.770	257.238
August	Data points	39,025	41,259	786	38,056	39,508	337
	Mean	1.925	3.122	176.650	1.650	1.878	115.453
	SD	0.972	7.311	316.457	0.556	5.500	167.519
September	Data points	41,398	43,568	733	31,804	32,810	186
	Mean	2.033	3.198	156.364	1.648	1.789	135.325
	SD	1.087	7.583	293.255	0.453	5.784	271.105
October	Data points	38,788	40,661	624	30,630	31,594	218
	Mean	1.927	2.965	214.551	1.621	1.787	137.961
	SD	0.942	7.542	384.843	0.508	5.734	261.823

Table AV.
Service loading time (in minute) of trucks and shovels

Cyclic activity/month	Truck size	Small shovel Mean	Small shovel SD	Large shovel Mean	Large shovel SD
June	Small	1.828	0.842	1.663	0.619
	Large	1.911	0.834	1.825	0.705
July	Small	1.807	0.809	1.650	0.606
	Large	1.827	0.759	1.722	0.622
August	Small	1.786	0.784	1.661	0.593
	Large	1.817	0.745	1.708	0.598
September	Small	1.875	0.876	1.677	0.525
	Large	1.896	0.807	1.733	0.602
October	Small	1.811	0.731	1.641	0.481
	Large	1.802	0.703	1.661	0.538

Table AVI.
The required times for preventive and corrective maintenance (in minute) based on equipment age levels

Month	Value	Preventive maintenance Small truck Age level 1	Preventive maintenance Small truck Age level 2	Preventive maintenance Large truck Age level 1	Preventive maintenance Large truck Age level 2	Corrective maintenance Small truck Age level 1	Corrective maintenance Small truck Age level 2	Corrective maintenance Large truck Age level 1	Corrective maintenance Large truck Age level 2
June	Mean	525	3,108	1,117	1,195	2,438	1,146	2,841	1,631
	SD	281	3,141	1,810	2,000	2,663	1,048	2,614	2,513
July	Mean	724	1,133	1,298	1,890	932	1,620	1,778	997
	SD	1,199	2,031	2,333	2,623	690	1,814	929	1,087
August	Mean	732	2,030	2,890	1,110	640	1,676	1,940	2,220
	SD	888	3,152	3,476	2,432	650	1,387	1,638	3,160
September	Mean	572	1,300	1,370	1,795	1,043	2,311	3,400	1,588
	SD	1,295	1,911	2,598	2,757	771	2,369	3,759	1,908
October	Mean	1,125	1,460	1,190	849	1,830	1,623	765	996
	SD	2,219	2,285	2,053	1,212	1,963	1,122	799	1,367

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