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An Integer Programming Approach for Truck-Shovel Dispatching Problem in Open-Pit Mines

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Abstract

The truck dispatching problem in open-pit mines is formulated into an integer programming problem in order to optimally determine the trip numbers of trucks from a shovel (dump site) to a dump site (shovel). The dispatching result aims to answer the question of where should a truck go so that the production target is achieved with minimum operating cost. An analytic method to determine the optimal fleet size taking advantage of the dispatching result is also presented. It is shown by experiments that the proposed integer programming approach is capable of saving 15.65% truck operating cost than fixed truck assignment policy in the studied homogeneous fleet case. It is also shown that the truck operating cost can be further reduced by proper use of a heterogeneous fleet.

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Keywords: truck dispatching; open-pit mine; integer programming.

1. Introduction

Material transportation represents 50%-60% of operating costs in open-pit mines [1-2]. Reducing these costs by a few percent will result in significant savings. The truck-shovel system, which transports materials from mining sites to dump sites for further processing, plays an essential role in an open-pit mine's operation. As stated in [1], the truck dispatching problem in open-pit mines answers the question each time a truck leaves a site in the mine: “Where should this truck go now?” Hence, the fleet dispatcher has to find the best destination to send the truck to satisfy the production requirements and to minimize truck operating costs.

The most recent literature review in this field was published in 2002 [1]. It is shown that majority of the truck shove dispatching approaches can be classified into single stage and the multistage methods. It is then concluded that multistage approach is superior to the single stage one because it takes into the

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production target into consideration. The multistage system usually divides the dispatching problem into two sub-problems including setting the production target in an upper stage and truck assignment for shovels in a lower stage with the objective of achieving the production targets set by the upper stage. The focus of this study is to address the lower stage of this problem.

Various heuristic methods are used to solve the lower stage problem [3-5]. However, they tend to give suboptimal solution of the dispatching problem because the criteria used are either to maximize the tonnage production or to minimize equipment inactivity (truck waiting and/or shovel idle time). While it is intuitive to do so, the optimality of the solution is not guaranteed because they are rules-based approaches. It is also noted that the most successful mine truck dispatching system is claimed to be the one using dynamic programming method [6]. But little detail of that approach is known since it is developed for the commercial software DISPATCH™.

In this study, the truck dispatching problem is modeled as an integer programming problem with the goal to meet production target with minimum operating cost. It is noticed that, instead of solving a real-time vehicle routing problem, this study focuses on solving the truck dispatching problem at a higher level that determines the numbers of trips to and from a dump site (shovel) in a complete shift. Result of this study can be used as input for a vehicle routing algorithm that solves the timetabling problem for each truck in real-time environment. A formula to analytically determine the optimal fleet size making use of the dispatching result is also presented. In comparison to the fixed truck assignment method, the proposed approach can achieve 15.65% reduction of operating cost savings.

The integer programming model of the truck dispatching problem is described in Section 2 followed by the optimal fleet size determination criterion presented in Section 3. Experiments are given in Section 4 to validate the efficiency and effectiveness of the approach. Lastly, conclusion is drawn in Section 5.

Nomenclature

T	shift duration (h)
n	number of shovels
H	total types of trucks in use
m	number of dump sites, of which the first m_r are waste sites and the others are ore sites
O_j	available ore at shovel j (kt)
W_j	available waste at shovel j (kt)
b_j	percentage of valued content (such as Fe, Coal, etc.) in the ore (%)
K_i	production requirement of the dump site i (kt)
d_{ij}	distance from shovel j to dump site i (km)
$\overline{v}_s^j$, $\overline{v}_d^h$	average loading speed of shovel j and average dumping speed of truck of type h (kt/h)
c^h	capacity of tuck of type h (t)
x_{ij}^h	total trip numbers of trucks of type h from shovel j to dump site i

y_{ij}^h	total trip numbers of trucks of type h from dump site i to shovel j

2. Modeling Of The Truck Dispatching Problem

To model the truck-shovel dispatching problem and solve it in a mathematical way, an integer programming model is presented for heterogeneous fleets which contain different types of trucks and shovels in this section. Homogeneous fleets can be described by a simplified version of this model.

The model is built in such a way that the integer numbers of trips from a shovel to a dump site and from a dump site to a shovel is determined for the considered shift duration so that the production target is reached and truck operating cost is minimized. In such a way, a truck's route for the complete shift is determined explicitly. Approximation of the optimized result, as done by linear or nonlinear programming approaches, is not required. The objective of the model presented is to minimize total truck operating costs, which is related to the truck's traveling distance when both loaded and empty, and is calculated by

$$J = \sum_{h=1}^{H}\sum_{i=1}^{m}\sum_{j=1}^{n}(\alpha^h x_{ij}^h d_{ij} + \beta^h y_{ij}^h d_{ij}). \tag{1}$$

Operational constraints are given as

$$\sum_{h=1}^{H}\sum_{j=1}^{n} c^h x_{ij}^h \geq K_i,\ i = 1,\ldots,m; \tag{2}$$

$$\sum_{h=1}^{H}\sum_{i=m_r+1}^{m} c^h x_{ij}^h \leq O_j\ \ j = 1,\ldots,n; \tag{3}$$

$$\sum_{h=1}^{H}\sum_{i=1}^{m_r} c^h x_{ij}^h \leq W_j\ \ j = 1,\ldots,n; \tag{4}$$

$$\sum_{h=1}^{H}\sum_{j=1}^{n} b_j x_{ij}^h c^h \Big/ \sum_{h}\sum_{j} x_{ij}^h c^h \in [p_l, p_u], i = m_r + 1,\ldots,m; \tag{5}$$

$$\sum_{h=1}^{H}\sum_{i=1}^{m} x_{ij}^h \frac{c^h}{\overline{v}_s^j} \leq T\ \ j = 1,\ldots,n; \tag{6}$$

$$\sum_{h=1}^{H}\sum_{j=1}^{n} x_{ij}^h \frac{c^h}{\overline{v}_d^h} \leq T\ \ i = 1,\ldots,m; \tag{7}$$

$$\sum_{j=1}^{n} x_{ij}^h = \sum_{j=1}^{n} y_{ij}^h,\ i = 1,\ldots,m, h = 1,\ldots H; \tag{8}$$

$$\sum_{i=1}^{m} x_{ij}^h = \sum_{i=1}^{m} y_{ij}^h,\ \mathrm{j} = 1,\ldots,n, h = 1,\ldots H; \tag{9}$$

$$x_{ij}^h \in N^+,\ y_{ij}^h \in N^+\ , i = 1,\ldots,m,\ j = 1,\ldots,n, h = 1,\ldots,H; \tag{10}$$

where α^h and β^h are per kilometer cost of trucks of type h when loaded and empty, respectively. The variables p_l and p_u are the lower and upper limit of the quality indicator in the ore dump sites (resemble to the Fe% content in ore used in [7]). The symbol N^+ stands for integers no less than zero.

The objective function represents truck operating cost that should be minimized during the shift considered. The constraint (2) ensures that all demands of each dump sites are met. Constraints (3) and (4) prescribe that the ore and waste transported must be no more than their available quantity at each shovel. Constraint (5) stands for the ore quality constraint. The maximum number of trucks a shovel can serve in a shift are represented by constraint (6) and the maximum number of trucks a dump site can serve in a shift is constrained by(7). Constraints (8) and (9) ensure that the number of trucks at each dump sites and loading areas remain unchanged after the shift. The last constraint (10) ensures that the solution is physically meaningful, that is, the trip number of trucks from or to a shovel is an integer.

3. Determining the optimal fleet size

As the truck operating cost is directly related to the number of trucks used, it is always desirable to use the least number of trucks to finish the required transportation work.

It is fair to assume that all the trucks in use are working all times, which implies that a truck is either loading, traveling between shovel j and dump site i, or unloading, if one tries to use as less truck as possible to complete the transporting target. In this way, the optimal number of trucks of type h should be used can be determined by the following formula

$$N^h = \left\lceil \frac{1}{T}\sum_{i=1}^{m}\sum_{j=1}^{n}[x_{ij}^h(\frac{c^h}{\overline{v}_s^j} + \frac{d_{ij}}{\overline{v}_l^h} + \frac{c^h}{\overline{v}_d^h}) + y_{ij}^h\frac{d_{ij}}{\overline{v}_e^h}] \right\rceil, \tag{11}$$

where the $\lceil x \rceil$ operation gives the smallest integer no less than x. The variable $\overline{v}_l^h$ is the average speed of truck of type h when loaded, $\overline{v}_e^h$ is the average speed of truck of type h when empty and N^h is the calculated optimal number for trucks of type h.

Results of the above formula can be used in two ways. One is to use the above formula after the dispatching problem is solved (x_{ij}^h and y_{ij}^h determined). The other is to use the above formula as another objective function in the problem formulated in the preceding section and solve the new problem as a whole. In this study, the formula (11) is used directly after the dispatching problem is solved to calculate the optimal truck number.

4. Experiments

Experiments are carried out to verify effectiveness of the proposed approach. The fixed truck assignment strategy which assigns trucks to a fixed route between a shovel and a dump site during a shift is used in experiments as a comparing reference of the proposed integer programming approach because it is accepted by most researchers that the fixed truck assignment approach is still in practice and can serve as a reference truck dispatching policy [4].

The truck operating costs used in experiments are the overall cost including fuel cost, tyre cost, maintenance cost, etc. As the operational data from mine sites are confidential, there is little mine truck operating cost data available. In this study, the target is to reduce truck operating cost, so it is assumed that truck operating cost is proportional to its capacity when empty and there exist a scale factor that can be used to determine the truck’s cost when loaded [8].

To be specific, the truck operating cost per kilometer when traveling empty is used as a unit of the operating cost and a factor 1.283 is used to calculate the same truck's traveling cost when loaded [8]. That is $\alpha = 1.283$ and $\beta = 1$. For instance, when the truck traveled 1.5 km empty and 2 km loaded, the operating cost would be $1.5 + 1.283 \times 2 = 4.066$, which implies that the total cost is 4.066 times of the 1 km traveling cost for an empty truck. Although this kind of measure seems does not contain direct truck cost information, it can be used to compare the cost using different dispatching strategies without losing generality because comparisons are always determined as the percentage reduction/increase of the cost.

The studied mine is an iron mine with ten shovels working at ten loading areas and five dump sites (three of them are ore dump sites and the other two are waste dump sites). The distance between each shovel and dump site are given by Table 1, in which S1-S10 denotes the shovels, O1-O3 denote ore dump sites, and W1-W2 denote waste dump sites. The available ore/waste and the percentage of iron in the ore at each loading area is shown in Table 2, in which O stands for ore, W stands for waste and b is the percentage iron content in the ore. The quality constraints on the ore at each ore dump sites are the same and are fixed at $29.5\%\pm1\%$. The production target for ore dump site 1, 2 and 3 are 12, 13 and 13 kilotons. Production goals at waste dump site 1 and 2 are 12 kilotons each. The shift duration is 8 hours.

Table 1. Distance between shovels and dump sites (km)

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
O1	5.26	5.19	4.21	4.00	2.95	2.74	2.46	1.90	0.64	1.27
O2	1.90	0.99	1.90	1.13	1.27	2.25	1.48	2.04	3.09	3.51
W1	5.89	5.61	5.61	4.56	3.51	3.65	2.46	2.46	1.06	0.57
W2	0.64	1.76	1.27	1.83	2.74	2.60	4.21	3.72	5.05	6.10
O3	4.42	3.86	3.72	3.16	2.25	2.81	0.78	1.62	1.27	0.50

Table 2. Available ore/waste (kt) and iron ratio (%)

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
O	9.5	10.5	10	10.5	11	12.5	10.5	13	13.5	12.5
W	12.5	11	13.5	10.5	11.5	13.5	10.5	11.5	13.5	12.5
b	30	28	29	32	31	33	32	31	33	31

First of all, results for a homogenous fleet obtained. Trucks used in this case have a capacity of 154 ton and an average speed of 28km/h (the average speed when loaded and empty are assumed to be the same). Shovels' loading rates are assumed to 1.848kt/h and trucks' dumping rates are 3.078kt/h.

Solving the dispatch problem formulated in Section 2 with the operational data yields the following result:

$$X=\begin{bmatrix}0&13&0&0&0&0&0&20&0&45\\0&32&0&17&0&0&36&0&0&0\\0&0&0&0&0&0&0&70&15\\81&0&43&0&0&0&0&0&0&0\\0&23&0&0&0&0&26&0&0&36\end{bmatrix},\quad Y=\begin{bmatrix}0&0&0&0&0&0&0&8&70&0\\0&68&0&17&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0&85\\81&0&43&0&0&0&0&0&0&0\\0&0&0&0&0&0&62&12&0&11\end{bmatrix},$$

where X is a matrix with entries x_{ij} and Y is a matrix with elements y_{ij}.

According to the solution X and Y, no truck was dispatched to shovel 5 and 6. The quality indicator (iron ratio in the ore at ore dump sites) is maintained in specified range: 30.50\%, 30.49\% and 30.49\% for ore dump site 1, 2 and 3 to be exact. Also, the prescribed transportation targets are met in the shift, which can be verified by the quantity of ore/waste transported to each dump sites. Moreover, the minimum truck number that should be used can be determined by (11) as [11.89]=12. The truck operating cost using this dispatching result is 1122.80 units and the truck use rate (traveling distance when loaded over traveling distance when empty) is 60.88%.

For comparison purpose, the same data set is used to solve the dispatch problem using fixed truck assignment policy. The resulted truck operating cost is 1331.10 units and truck use rate is 50.00\% since the trucks are assigned to fixed pairs of shovels and dump sites. Besides, using this fixed assignment requires 13 trucks while only 12 trucks are necessary for the dispatching result using the integer programming method. This further implies that the proposed truck dispatch approach results in a 15.65% reduction of truck operating cost and a 21.76% improvement in truck use rate. This infers that the trucks' traveling distance when empty is reduced as well as the overall operational cost.

Application to a heterogeneous fleet is also investigated. Two types of trucks, type 1 is the same as the ones used in the homogeneous fleet experiment and the type 2 has a 192t capacity and an average speed of 35km/h when loaded and 50km/h when empty. The average dumping speed of the latter is 2.4kt/h. Results of the heterogeneous fleet dispatching shows that a further 19.56% reduction of operating cost can be achieved in the case studied.

5. Conclusion

The truck-shovel dispatching problem is formulated as an integer programming problem in this study to determine the best truck assignment to shovels. The optimal number of truck that should be used during a shift is obtained analytically taking advantage of the dispatching result. With the goal of meeting production target with minimum truck operating cost, the dispatching result using the proposed method is compared with that from fixed truck assignment policy. The results show that a 15.65% reduction of truck operating cost is achieved in the studied case. Further analysis reveals that this cost decrease is mainly resulted from reduction in distance travelled by empty trucks. In addition, the experiments of heterogeneous fleet indicate that properly mixed fleets can leads to further operating cost reductions.

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Biography

Mr. Lijun Zhang obtained his B.Eng and M.Eng from School of Power and Mechanical Engineering, Wuhan University, China, in 2010 and 2012, respectively. He is currently a Ph.D candidate at the University of Pretoria, South Africa. His research interests include modeling, optimal operation, control and monitoring of power and industrial systems.