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An Optimization Approach for Shovel Allocation to Minimize Fuel Consumption in Open-pit Mines: Case of Heterogeneous Fleet of Shovels.

D.M. Bajany L. Zhang X. Xia

* *Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria 0002, South Africa*

Abstract:
This paper presents a realistic model that can be used to minimize fuel consumption in surface mining operations. The developed model dispatches trucks to destinations by optimally determine the paths that can lead to the minimum fuel consumption per truck and shovel cycle while the handling demands of each dumping site are met. This model is applicable to all types of open-pit mines, including over and under-trucked mines. The formulation takes into account the waiting time of trucks at dumping and loading sites and the idle times of shovels. The effectiveness of the proposed model in the determination of the best shovel allocation in the case of a heterogeneous fleet of shovels is also demonstrated in this study.

Keywords:
Truck-shovel dispatch, fuel minimisation, shovel allocation

1. INTRODUCTION

Shovels and dump trucks are commonly used in open-pit mines for ore loading and transportation because of their flexibility and ability to transport material over long distances (Bajany et al. (2017b)). It has been shown in the literature that excavating the material and transporting excavated material represent a large part of the operational costs in surface mining (Da Cunha Rodovalho et al. (2016)). The haulage cost can be approximately 50% of the entire operational cost or 60% of the total operational cost in large surface minings (Bajany et al. (2017a); Alarie and Gamache (2002); Zhang and Xia (2015)). The large contributor to the transportation cost in open-pit mining operations is the fuel consumption of the haul trucks and shovels. Sahoo et al. (2014) pointed out that this represents 32% of the total energy input in mines.

In most of the surface mining, diesel is the main fuel used by trucks and shovels. However, diesel engines used in a lot of equipment have a noxious impact on the environment because of their greenhouse gas emissions (Rahman et al. (2013); Bagheri et al. (2015)). Lashgari et al. (2014) has indicated in their research conducted on a coal open-mine in West Virgina that 44.7% of the total nitrogen oxides (NOx) emission is produced in the haulage transportation.

Therefore, reducing the fuel consumptions of the haulage operation provides a good opportunity to reduce operational costs and environmental impacts of open pit mines (Jochens (1980); Abdelaziz et al. (2011)). In the literature optimum truck dispatch models do exist, only Bajany et al. (2017b) has developed an optimal dispatch model that minimizes simultaneously the fuel consumption of trucks and shovels. However, the model was specifically dedicated to under-trucked mines as it does not consider in its formulation the waiting time of trucks at loading and dumping sites, which situation can happen in practice.

The contribution of this study is the development of an optimal truck-shovel dispatch strategy for existing mines to minimize fuel consumption of both trucks and shovels considering their technical specifications. Moreover, this model can also be used by decision-makers as a planning tool to identify the best allocation of shovels that will result in the minimum fuel consumption for the haulage operations during the planning phase of a new open-pit mine or during the re-allocation planning of shovels in existing mines. In addition, the developed model can assist project managers to estimate the expected fuel consumption per tonne for a given production target and justify the budget allocated to the haulage operations. The model presented in this work is build based on the *m-trucks-for-n* strategy and is capable of solving the dispatching problem for heterogeneous fleets of equipment, including trucks and shovels. This model is applicable to under and over-trucked mines as the waiting time at both loading and unloading sites are taken into account in its formulation.

In this study, we use empirical values of waiting time in the simulations to show the effectiveness of the developed dispatch model in optimizing the route choices of dump trucks and minimizing the fuel consumption of both trucks and shovels. However, waiting time values can be determined approximately from the database history of the haulage operations using queuing theories (May (2013)).

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2. FUEL CONSUMPTION OF TRUCKS AND SHOVELS

Fuel consumption and emissions of diesel trucks and shovels depend on a variety of factors such as the efficiency of the diesel engine, the operating conditions of the trucks/shovels, and drivers' behavior, ignition timing, to name a few (Suzdaleva and Nagy (2014)). For estimation purposes as suggested in Peralta et al. (2016), the rate of fuel consumption by trucks can be determined by equation (1).

$$f^y = 0.3 \times P^y \times LF, \tag{1}$$

where P^y, 0.3 and LF represent the maximal engine power (kW), the unit conversion factor (L/kW/h) and the engine load factor respectively. The load factor is the portion of the full power required by the truck. Common load factors for dump trucks are given in the manufacturer's catalogue. In this study, to determine the fuel consumption of dump trucks, the following values of load factors are considered: 45% for a loaded truck (high load), 20% for an empty truck and 10% for an idling truck (Kecojevic and Komljenovic (2010)).

Similarly, the fuel consumption of shovels can be estimated knowing their operating conditions. Indeed, the engine fuel is controlled by the engine load factor, which depends on the application of the shovel. In this study, the hourly fuel consumption rate f_j of shovels during working times will be estimated by assuming that shovels are working with high load factors. The hourly fuel consumption $f_{j,idle}$ of shovels during idle times will be assumed to be 10% of the hourly fuel consumption of those shovels when they are working with low load factors.

3. TRUCK-SHOVEL DISPATCHING PROBLEM

In the case of a heterogeneous fleet of shovels, during the planning phase of a new open-pit or during a short- and medium-term planning of existing mines where it is needed to reallocate the shovels, one question arises: "what is the best allocation of shovels that can result in the minimum liters of fuel consumed per tonne moved for the entire haulage operations?" An illustration of this problem is shown on Fig. 1. This figure displays, for a mixed fleet of shovel made up of shovels of two different capacities, all the possible allocations of shovels in different pits of a generic open-mine constituted of two unloading points and three loading points.

To answer this question, given a fleet of trucks, the model developed in this study is used to determine the expected liters of fuel consumed per tonne of material moved for all the possible shovel allocations in different pits. The obtained results are then compared to find the allocation that results in the minimum liters of fuel consumed per tonne of material moved.

For this purpose, the total number of possible shovel allocations in different pits for a mixed fleet of shovels, P_j, is determined by the following equation:

$$P_j = \frac{S!}{S_{C_1}! \times S_{C_2}! \times ... \times S_{C_{j=k}}!}, \tag{2}$$

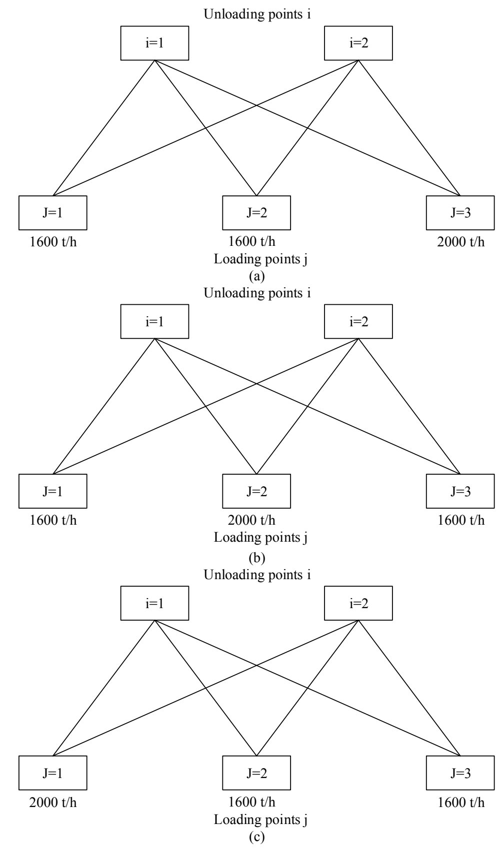

Fig. 1. (a) j_3 = shovel 2000 t/h, (b) j_2 = shovel 2000 t/h; (c) j_1 = shovel 2000 t/h

where S is the number of shovels, S_{C_1}, S_{C_2}...$S_{C_{j=k}}$ are the numbers of shovels of capacity C_j and k is the number of types of shovels.

4. MATHEMATICAL FORMULATION

In the haulage operations, the fuel consumption of each equipment (truck and shovel) depends on its size, type, operating time, operating conditions and technical specifications, etc. Trucks consume fuel during loading, unloading and travel periods, whereas shovels consume fuel during their working and idling periods.

The travel time from the i-th unloading point to the j-th shovel, $t^y_{e,ij}$, and the travel time from the j-th shovel to the β-th unloading point, $t^y_{lo,j\beta}$, are calculated by equations (3) and (4) respectively:

$$t^y_{e,ij} = \frac{d_{ij}}{v^y_{e,ij}} \quad (i = 1, 2, ..., U; \quad j = 1, 2, ..., S), \tag{3}$$

$$t^y_{lo,j\beta} = \frac{d_{j\beta}}{v^y_{lo,j\beta}} \quad (\beta = 1, 2, ..., U; \quad j = 1, 2, ..., S), \tag{4}$$

where the subscripts e denotes an empty truck, lo denotes a loaded truck; y is the truck index, d_{ij} is the distance between the unloading point i to the shovel j, $d_{j\beta}$ is the distance between the shovel j to the unloading point β, $v^y_{e,ij}$ is the speed at which the empty truck y travels from an unloading point i to a shovel j, $v^y_{lo,j\beta}$ is the speed at which the loaded truck y travels from the shovel j to an unloading point β, U is the number of unloading points and S is the number of shovels.

The loading time $t^y_{l,j}$ of a truck y with the j-th shovel is determined by:

$$t^y_{l,j} = \frac{C_y}{C_j}, \tag{5}$$

where C_y is the loading capacity of the truck y and C_j is the capacity of the shovel j.

The fuel consumption of a dump truck y per single cycle is given as:

$$F^y_{ij\beta} = f^y_{e,ij} t^y_{e,ij} + f^y_{lo,j\beta} t^y_{lo,j\beta} + f^y_{idle}(t^y_{l,j} + t^y_u + t^y_{w,j} + t^y_{w,\beta}), \tag{6}$$

where $f^y_{e,ij}$ is the fuel consumption of the empty truck y moving from the unloading point i to the shovel j, $f^y_{lo,j\beta}$ is the fuel consumption of the loaded truck y moving from the shovel j to the unloading point β, f^y_{idle} is the fuel consumption of the truck y during engine idling time, t^y_u is the unloading time of the truck y, $t^y_{w,j}$ is the waiting time of the truck y at the shovel j, $t^y_{w,\beta}$ is the waiting time of the truck y at the dumping point β. Note that $i = \beta$ implies that the truck returns to the original unloading point where it started its cycle.

The number of times x^y_j a y truck is loaded by the j-th shovel during a shift and the number of times a y truck has dumped his load at the dumping β during a shift are calculated by equations (7) and (8) respectively:

$$x^y_j = \sum_{i=1}^{U} Z^y_{e,ij} \quad or \quad x^y_j = \sum_{\beta=1}^{U} Z^y_{lo,j\beta}, \tag{7}$$

$$x^y_\beta = \sum_{j=1}^{S} Z^y_{e,ij} \quad or \quad x^y_\beta = \sum_{j=1}^{S} Z^y_{lo,j\beta}, \tag{8}$$

with U, the number of unloading points, and S, the number total of shovels.

For x^y_j cycles that a y truck has accomplished to the j-th shovel during a shift, the fuel consumption Ft^y_j of that truck is calculated as:

$$Ft^y_j = \sum_{i=1}^{U} Z^y_{e,ij} f^y_{e,ij} t^y_{e,ij} + \sum_{\beta=1}^{U} Z^y_{lo,j\beta} f^y_{lo,j\beta} t^y_{lo,j\beta} + \sum_{\beta=1}^{U} Z^y_{lo,j\beta} f^y_{idle}\left(t^y_{l,j} + t^y_u + t^y_{w,j} + t^y_{w,\beta}\right), \tag{9}$$

where $Z^y_{e,ij}$ is the number of journeys that the truck y has travelled from the i-th unloading point to the j-th shovel during a shift and $Z^y_{lo,j\beta}$ is the number of journeys that the truck y has travelled from the j-th shovel to the β-th unloading point during a shift.

From the above equation, for a given shift, the total amount of fuel Ft consumed by all trucks is calculated as:

$$Ft = \sum_{j=1}^{S}\sum_{y=1}^{N} Ft^y_j, \tag{10}$$

with N, the number of trucks used in the haulage operations.

For a complete shift, the idle time I_j of the j-th shovel is calculated as:

$$I_j = sh - \sum_{y=1}^{N}\sum_{\beta=1}^{U} Z^y_{lo,j\beta} t^y_{l,j}, \tag{11}$$

where sh is the shift duration, and, the fuel $F_{idle,j}$ consumed by the j-th shovel during its idling period is given as:

$$F_{idle,j} = I_j f_{j,idle}, \tag{12}$$

with $f_{j,idle}$, the fuel consumption rate of shovel j during idling time. For a complete shift, the fuel $F_{u,j}$ consumed by the j-th shovel during periods when it was used to load trucks is calculated as:

$$F_{u,j} = f_j \sum_{y=1}^{N}\sum_{\beta=1}^{U} Z^y_{lo,j\beta} t^y_{l,j}, \tag{13}$$

where f_j is the fuel consumption of shovel j during the time it is used to load a truck.

The total fuel F_j consumed by the j-th shovel during a shift is determined by:

$$F_j = F_{idle,j} + F_{u,j}. \tag{14}$$

The total fuel Fs consumed by all the shovels for the whole shift duration is given as:

$$Fs = \sum_{j=1}^{S} F_j. \tag{15}$$

The total fuel F consumed for whole haulage operations during a shift is calculated as:

$$F = Ft + Fs. \tag{16}$$

There are many variables that can be used to evaluate the haul truck energy efficiency (Krzyzanowska (2007)). In this study, the liters of fuel per tonne moved is adopted as a performance indicator for the truck-shovel dispatching system. The liters of fuel per tonne moved at the end of a shift is evaluated by:

$$LTts = \frac{F}{\sum_{y=1}^{N}\sum_{\beta=1}^{U}\sum_{j=1}^{S} Z^y_{lo,j\beta} C_y}. \tag{17}$$

As previously mentioned, the objective of this study is to minimize the fuel consumption of both trucks and shovels. The model is built in such a way that all the requirements of dump sites are met and the optimal number of trips of each truck on each route of the pit is determined. The technical specifications, such as payload of trucks, loaded capacity of shovels, and fuel consumption in function of the operating conditions of equipment are directly considered in the mathematical model. The objective function is given in the following:

$$\min F. \tag{18}$$

The operating constraints of the problem include the following:

- The material transported from all shovels should be greater than the handling demand of each unloading point (of ore and waste). This constraint ensures that trucks are dispatched so that the production target at the mine is satisfied. The way this requirement is taken into account is shown in equation (19):

$$\sum_{y=1}^{N}\sum_{j=1}^{S} Z^y_{lo,j\beta} C_y \geq D_\beta sh, \quad \forall \beta \in \{i, w\}, \tag{19}$$

with D_β, the handling demand per hour of the unloading point i and sh, the shift duration.

- Material transported by trucks during the shift duration from each loading point is less than the shovel capacity allocated to that pit.

$$\sum_{y=1}^{N}\sum_{\beta=1}^{U} Z^y_{lo,j\beta} C_y \le C_j sh, \quad \forall j. \tag{20}$$

- The ore transported by trucks during the shift duration from a loading point j to the unloading points of ore is less or equal to their available quantity at the considered loading point.

$$\sum_{y=1}^{N} Z^y_{lo,j\beta} C_y \le O_j, \tag{21}$$

$\forall j,\ \forall sh,\ \beta \in i \ with \ i = \{i_1,\ i_2,\ ...,\ i_q\}$, with O_j, the available quantity of ore at the loading point j and q, the total number of ore unloading points.

- The waste transported by trucks during the shift duration from a loading point j to the unloading points of waste is less or equal to their available quantity at the considered loading point.

$$\sum_{y=1}^{N} Z^y_{lo,j\beta} C_y \le W_j, \tag{22}$$

$\forall j,\ \forall sh,\ \beta \in w \ with \ w = \{w_1,\ w_2,\ ...,\ w_r\}$, with W_j, the available quantity of waste at the loading point j and r, the total number of waste unloading points.

- For the sh-th shift, the utilization time of each shovel is less or equal to the shift duration. This constraint is written as follows:

$$\sum_{y=1}^{N} x^y_j t^y_{l,j} \le \ sh, \quad \forall j. \tag{23}$$

From equation (7), the constraint (23) can also be written as:

$$\sum_{y=1}^{N}\sum_{\beta=1}^{U} Z^y_{lo,j\beta} t^y_{l,j} \le sh, \quad \forall j. \tag{24}$$

- The sum of cycle times of all cycles performed by a truck y during the shift is less or equal to the shift duration.

$$Ft^y_j = \sum_{j=1}^{S}\sum_{i=1}^{U} Z^y_{e,ij} f^y_{e,ij} t^y_{e,ij} + \sum_{j=1}^{S}\sum_{\beta=1}^{U} Z^y_{lo,j\beta} f^y_{lo,j\beta} t^y_{lo,j\beta} + \sum_{j=1}^{S}\sum_{\beta=1}^{U} Z^y_{lo,j\beta} f^y_{idle}\left(t^y_{l,j} + t^y_u + t^y_{w,j} + t^y_{w,\beta}\right) \le sh, \quad \forall y. \tag{25}$$

- The number of trips that a truck y makes to a shovel equals to the number of trips that the same truck leaves that shovel. Equation (26) shows how this requirement is considered:

$$\sum_{i=1}^{U} Z^y_{e,ij} = \sum_{\beta=1}^{U} Z^y_{lo,j\beta}, \quad \forall j,\ \forall y. \tag{26}$$

- The difference between the number of times a truck y dumps its load at an unloading point i and the number of times that a truck travels empty from that unloading point to different shovels can not exceed one. This constraint is written as follows:

$$\sum_{j=1}^{S} Z^y_{e,ij} - \sum_{j=1}^{S} Z^y_{lo,j\beta} \le 1 \quad for \quad i = \beta, \quad \forall j,\ \forall y. \tag{27}$$

- The difference between the number of times an empty truck y travels from an unloading point i to different shovels and the number of time this truck dumps its load at that unloading point can not exceed one. This constraint is written as follows:

$$\sum_{j=1}^{S} Z^y_{lo,j\beta} - \sum_{j=1}^{S} Z^y_{e,ij} \le 1 \quad for \quad i = \beta, \quad \forall j,\ \forall y. \tag{28}$$

- The last constraint (29) ensures that the number of trips of trucks are positive and integer.

$$Z^y_{e,ij} \in N^+;\ Z^y_{lo,j\beta} \in N^+;\ i = 1,2,...,U;\ \beta = 1,2,...,U;\ j = 1,2,...,S;\ y = 1,2,...,N. \tag{29}$$

Constraints (26), (27) and (28) ensure that the continuity of loading and transportation is maintained.

5. SIMULATIONS

A case study of a hypothetical downgrade open-pit mine with two unloading points (one for waste materials and one for ores) and three shovels located at three pits is considered for optimization and simulation of the model. Among these shovels, two have a capacity of 1600 t/h and one, a capacity of 2000 t/h. The length of each road in the haulage network is given in Table 1. The total resistance of the haul road is assumed to be equal to 4%. Operating speeds of loaded trucks are estimated using the Rimpull-Speed-Grade curves given in Caterpillar.Inc (2007) [1] . The mine topography and operating parameters of the loading and haulage equipment used as input parameters of the model are shown in Table 1. The three possible shovel allocations in different pits are determined by equation (2) as $P_j = \frac{3!}{2!1!} = 3$, they are displayed on Fig. 1.

6. SIMULATION RESULT

In order to show the effectiveness of the developed method and the impact of the waiting time on the fuel consumed in the haulage operations, three dispatch scenarios with different waiting time at loading and unloading points have been considered in the simulations. The waiting times considered at loading and dumping points were as follows: 0.30 min for the first scenario, 0.48 min for the second scenario and 0.78 min for the third scenario. The shift duration of each scenario was 8 hours. Solving the developed model with a mixed integer nonlinear programming algorithm for the three scenarios, the following results were found. For the same amount of material transported (37248 t), the first scenario, with the shovels allocate following the allocation (a), results in 130.99 milliliters per tonne and 4879.80 liters of fuel consumed for the whole haulage operation; with the allocation (b), it results in 136,90 milliliters per tonne and 5099.30 liters of fuel consumed for the whole haulage operation and with the allocation (c), its results in 132,92 milliliters per tonne and 4851,12 liters

[1] Caterpilar. Inc, 777D Off-Highway Truck, USA.2007.

Table 1. Mine topography and resources

Parameters	Specifications
Model	777D
Rated payload	96 t
Gross vehicle weight	161 030 kg
Speed of empty truks	50 km/h
Speed of loaded trucks	36 km/h
Fuel consumption (idle time)	22.38 L/h
Fuel consumption empty truck	44.76 L/h
Fuel consumption loaded truck	78.33 L/h
Shovel capacity	1600 t/h 2000 t/h
Fuel consumption of shovel	
- during idle time	1600 t/h - 6.6 L/h 2000 t/h -9.5 L/h
- during working time	1600 t/h - 117 L/h 2000 t/h -130 L/h
Mine topography	Downgrade mine
Fuel consumption loaded truck	78.33 L/h
Gradient	1:14 4^0
Distance between dumping and loading point	$i_1 - j_1$ 1.5 km $i_1 - j_2$ 2.5 km $i_1 - j_3$ 3 km $i_2 - j_1$ 3.5 km $i_2 - j_2$ 2.5 km $i_2 - j_3$ 1.5 km
Demand of ore at unloading point i_1	2375 t/h

of fuel consumed for the whole haulage operation. The second scenario, with the allocation (a), results in 133,08 milliliters per tonne and 4956 liters of fuel consumed for the whole haulage operation; with the allocation (b), it results in 139,69 milliliters per tonne and 5203,37 liters of fuel consumed for the whole haulage operation and with the allocation (c), it results in 135.53 milliliters per tonne and 5052,16 liters of fuel consumed for the whole haulage. The last scenario, with the allocation (a), results in 141,19 milliliters per tonne and 5259,14 liters of fuel consumed for the whole haulage operation; with the allocation (b), it results in 148,21 milliliters per tonne and 5520.50 liters of fuel consumed for the whole haulage operation and with the allocation (c), it results in 143.32 milliliters and 5338,45 liters of fuel consumed for the whole haulage operation. The fuel consumed in the haulage by trucks and shovels and by trucks itself per scenario are displayed in Fig. 2 and Fig. 3 respectively. The contribution of each shovel to the total handling demand per scenario is shown in Fig. 4, Fig. 5 and Fig. 6 respectively. Comparing the obtained results, the following observations were made. The first scenario with small waiting time at loading and dumping sides is the most efficient scenario as it results in less fuel consumed in the haulage and small liters per tonne.

The applicability of the developed model to determine the best shovel allocation was also demonstrated in this study. Indeed, from the obtained results it is clear that the second allocation is the least efficient one compared to the other two. Indeed, for the first scenario, by allocating the shovel with the highest capacity at the second loading point and for the same amount of material transported, roughly 242.5 liters and 148.18 liters of fuel are additionally consumed in the haulage operations compared to the allocations (a) and (c) respectively . The explanation

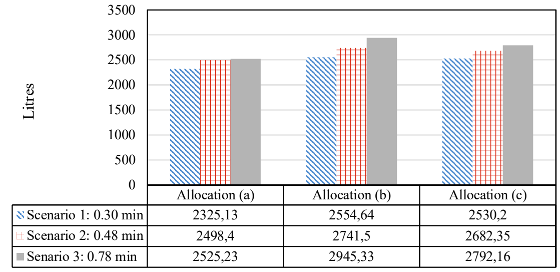

Fig. 2. Fuel consumed in the haulage by trucks and shovels per scenario

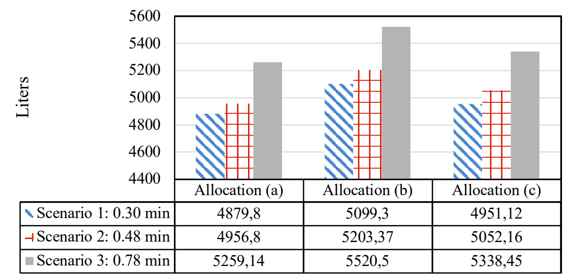

Fig. 3. Fuel consumed by trucks

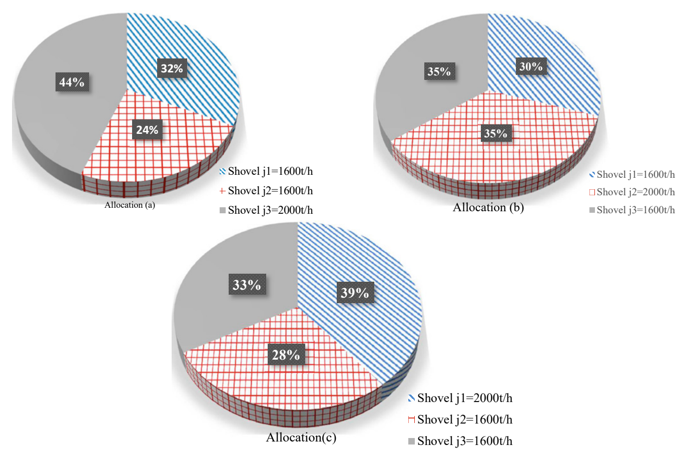

Fig. 4. Contribution of each shovel to the total handling demand (Waiting time: 0.30 min))

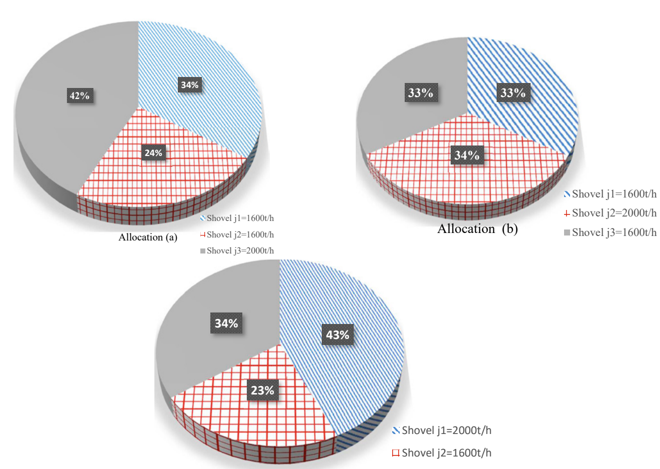

Fig. 5. Contribution of each shovel to the total handling demand (Waiting time: 0.48 min)

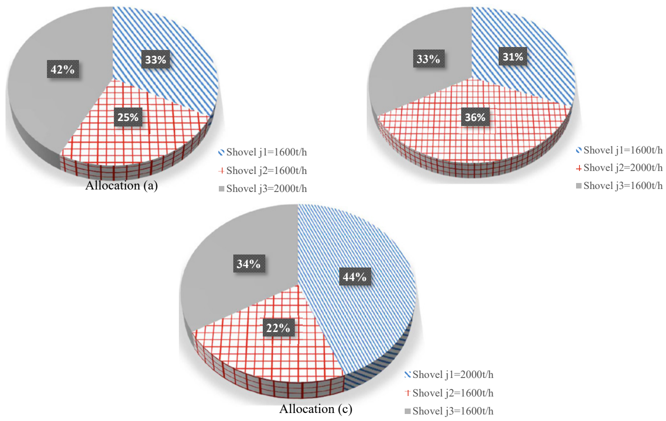

Fig. 6. Contribution of each shovel to the total handling demand (Waiting time: 0.78 min)

of this observation is that, with the allocation (b), the total travel distances of loaded and empty trucks are much longer than those obtained with the other two allocations. Hence, trucks consume more fuel with the allocation (b). This is shown in the Fig. 3. Another explanation of this observation is that the shovel of capacity 2000 t/h is not properly utilized with the allocation (b). This can be seen by comparing the contributions of this shovel to the total handling demand displayed in Fig. 4, Fig. 5 and Fig. 6. To be specific, only 35% of materials moved in the haulage are loaded by the shovel of capacity 2000 t/h; whereas for the two other allocations, 44% (allocation (a)) and 39% (allocation (c)) of materials are loaded by this shovel. With the 2000 t/h shovel being the most fuel efficient, less utilization of it resulted in more fuel consumption for the allocation (b).

The results of this work are important as the proposed method considers the waiting time of trucks at shovels and dumping points and the specific characteristic of each truck and shovel used in the haulage, unlike previously reported optimization work.

7. CONCLUSION

A model for minimization of fuel consumption of dump trucks and shovels in open-pit mine was developed. To evaluate the developed model, a case study of an open-pit mine with two unloading points and three shovels was considered. In the case of a mixed fleet of shovels, for each possible shovel allocation, the optimal number of trips that each truck should make on each route of the mine during a shift was realized. It was possible to determine the best shovel allocation which is the allocation with the lowest fuel consumption in the haulage operation and therefore with the lower diesel emission. The results of this work serve the foundation for future research that could include the fact that, in practice, the waiting time varies stochastically.

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