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RESEARCH PAPER

Evaluating the Effect of Fleet Management on the Performance of Mining Operations Using Integer Linear Programming Approach and Two Different Strategies

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Abstract
This paper presents an integer linear programming (ILP) model for allocating trucks according to their operating performances in a truck-shovel system of an open-pit mine, so as to minimize the total operating cost of trucks. To evaluate the performance of the proposed model, the model was applied with two different strategies, namely independent fleet management and integrated fleet management. The results of the research in a copper mine case study showed that the developed strategies were capable of handling the operation with a fewer number of trucks than the actual mine strategy. In addition, integrated fleet management indicated 2% and 3% cost-savings over the shift compared to strategy 1 and the mine allocation schedule, respectively.

Keywords: optimization of truck-shovel allocation, fleet management, integer linear programming model, minimizing operating costs, open-pit mines.

Introduction

Mining is a high-risk industry, and the fundamental goal of a mining operation is to provide raw materials for the community at the lowest possible cost throughout the life of mine. To achieve the desired production rate at the least expense, the mining operations must be managed in the most optimal manner. In open-pit mines, the material haulage is a challenging task, because its cost accounts for more than half of the total operational costs (Alarie & Gamache, 2002). The truck-shovel mining system is a flexible mining method commonly used throughout the world since the 1930s (Govinda et al., 2009). Therefore, haul trucks and loading shovels perform a vital role in transporting materials and have great potential to generate savings. Optimal decisions regarding the material haulage result in economic and operational gains. An inappropriate truck allocation planning and the absence of integrated activities of equipment in mines with several transportation companies can increase hauling, operating, and maintenance costs, and consequently reduce fleet utilization. Hence, efficient truck scheduling is well recognized as a crucial problem that requires substantial attention from both industry and research. Over the last few decades, extensive efforts have been made to achieve high levels of effectiveness and efficiency in the fleet management process, which result in profitability and, therefore, in an overall productivity improvement of the fleet. Various researchers have implemented distinct mathematical models based on the optimization of differently defined objective functions to evaluate, optimize, and control the

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fleet allocation schedule in open-pit mines. In other words, all the previous studies examine only the role of a mathematical model on equipment assignments without considering the impact of independent or integrated fleet management strategies on the transportation system. In fact, the models are solved based on the existing conditions at mines. However, in the real world, the mining transportation system is complex and is performed by numerous independent companies. Better management of the fleet would integrate the activity of all the mining companies in the optimization model. Nevertheless, integrated management to optimize fleet operation has not been reported earlier.

In this view, this paper studies the fleet management problem using an optimization model based on two different strategies, namely independent fleet management and integrated fleet management. The objective function of the model is to minimize the total truck operating costs, subject to a set of technical and operational constraints. The cost of operation is directly related to the traveling distance of trucks in the mine transportation network, which on the other hand, tend to correlate with the productivity of the mine. This leads to effective utilization of the equipment in mining operations.

The primary aim of this study is to present and test the proposed mathematical model for short-term mine production planning with a focus on different fleet management strategies. To illustrate the proposed procedure, the structure of this paper is as follows. A review of related work is presented in Section 2, and the research methodology is explained in Section 3. Section 4 describes the parameters and mathematical formulations that have been used to develop the mathematical optimization model. A case study based on the Sungun mining companies' data is then presented, and the implementation results are discussed to validate the developed model. Finally, the conclusions and suggestions for future research are presented.

Literature Review

There are plenty of studies published on the truck-scheduling problem in open-pit mines. Operation research techniques have evolved and applied for better decision-making in the truck allocation process since the 1970s. These techniques include queuing theory, nonlinear programming (NLP), linear programming (LP), mixed-integer linear programming (MILP), stochastic programming (SP), goal programming (GP), etc. Some studies have employed the queuing theory approach to analyze the truck allocation problem. The first application of the queuing theory in the open-pit mining operation was carried out by Koenigsberg (1958). Afterward, this approach has been implemented in the truck and shovel surface mining operation, as discussed in Barnes et al. (1978), Dallaire et al. (1978), Carmichael (1987), Kappas and Yegulalp (1991), and Xi and Yegulalp (1993). LP and (especially) MILP methods have been applied in fleet management optimization more than any other approach. Zhang et al. (1990) proposed an LP model that minimized the number of trucks required to meet mine production in the short-term horizon. Although the model provided a set of constraints, including the flow conservation, loaders capacity, a minimum level of production, blending constraints, ore and waste ratio, and minimum and maximum capacities of the dumping sites, it ignored the capacity of trucks in mining operations. Li (1990) used a transportation approach based on an LP model to assign trucks to loading units in open-pit mines. The model tried to optimize haulage planning by minimizing the total transportation work per time unit along with the available paths in truck-shovel haulage systems. The model was developed based on a homogeneous truck fleet and could not be applied to real projects where the fleet is heterogeneous. Moreover, it did not guarantee some constraints such as the minimum amount of ore and waste production, truck availability, and equipment breakdowns. Mirzaei-Nasirabad et al. (2019) developed a new version of Li's model, in which some mentioned drawbacks of the model were incorporated for better decision making in mine haulage planning. Gamache et al. (2009) developed a generic LP model to optimize the truck allocation schedule over a work shift resolution considering the long-term mine production planning. The set of constraints was broad and included stripping ratio, the amount of available material in front of each mining face, the capacity of equipment, blending constraint, etc. The drawback of this research was ignoring the waiting time at service points. De Melo (2021) proposed an LP model for the truck allocations with an objective to maximize the mine's production. One of the major drawbacks of the model was that it did not consider the stripping ratio requirement. Chang et al. (2015) applied a MILP model to optimally solve the truck fleet management problem by maximizing the total transport revenue of all trucks in the scheduling horizon and considering the idle probability of shovel. The model did not consider a heterogeneous fleet, plant capacity, feed head grade, and the stripping ratio requirement, which caused the results to be far from reality. Torkamani and Askari-Nasab (2015) developed a MILP model to deal with shovel and truck allocation decisions in open-pit mines. The objective of the model was to minimize the costs linked to the trips that trucks took from a loading point to different destinations. The model was not able to account for more than one crusher and waste dump within a specific mine. Shah and Rehman (2020) modified and implemented the model through a case study considering the two types of rock materials (low- and high-grade). Bajany et al. (2017) formulated an LP model to minimize the fuel consumption of dump trucks and shovels to generate short-term production schedules. Accordingly, the number of trips that each truck realized on each route of the pit was optimized by estimating the idle time of equipment in the transportation network. A major shortcoming of this work was ignoring the limitations of the operation, such as stripping ratio and required feed grade in open-pit mines. Manríquez et al. (2019) formulated a fleet allocation using a deterministic MILP optimization approach that accommodated mining sequencing constraints and time and cost of movement between phases of each shovel. This model generated a short-term open-pit mine production schedule optimizing multiple hierarchical objectives to make the vital decisions for the allocation of trucks and shovels to mining faces. However, the main weakness of the study was the failure to address the uncertainties in the optimization process of the model. Liu and Chai (2019) described a new MILP model based on the minimization of time-varying transport energy consumption. Soumis et al. (1989) used an NLP model to solve the truck travel plan between shovels and dumping points. The objective function of the model consisted of three components: (1) shovels' production, (2) available truck hours, and (3) blending requirements. The model accounted for a homogenous truck fleet and ignored the stochastic nature of the ore material quality. In the literature, only a few studies have attempted to consider the SP approach in evaluating the mining fleet management systems. Ta et al. (2005) implemented a chance-constrained programming model, as a branch of SP, for defining the number of trucks on each path of the mine transportation network to keep the ore grade control at the crusher within the blending requirement. In other words, the aim of the model was to minimize truck resources required to satisfy production constraints. The model addressed only the truckload and cycle time of trucks as uncertain parameters. Another problem with this study was that the model was not formulated in a general way that could enable a flexible definition of other mining systems. Bakhtavar and Mahmoudi (2020) described a scenario-based robust optimization model to solve the fleet allocation problem. The study consisted of two steps. The first step determined the optimal production plan from the loading points to destinations considering the output of the shovel and crusher capacity as the uncertain parameters. The second step calculated the number of trucks by considering the production plan defined in the first stage. The model was applied to trucks with various capacities and different routes between loading and dumping areas. However, the major drawback of the research was that it did not consider the uncertainty associated with equipment availability. Several studies have examined the GP approach in the fleet decision-making problem. Goodfellow and Dimitrakopoulos (2016) rendered an operational plan using a two-stage stochastic global optimization model for the production scheduling of open-pit mining complexes under uncertainty. In the first stage, the long-term extraction sequence and destination policies were defined as decision variables. In the second stage, recourse variables (the processing stream variables and penalties for ignoring the desired targets) were used to adapt to the first-stage decisions. The primary objective of this research was to maximize the net present value (NPV) of mining complexes. The study would have been more useful if they had considered uncertainties related to plant throughput, the density of mined material, and metal recovery in different processing facilities. This model was extended by Both and Dimitrakopoulos (2020) for the joint optimization of a short-term production schedule and fleet management in a mining complex. Mohtasham, Mirzaei-Nasirabad, , Askari-Nasab, and Alizadeh (2021) introduced a GP model to maximize production, meet the desired head grade and tonnage at the ore destinations, and minimize fuel consumption of trucks for making operational decisions in truck-shovel systems. This model provided optimal decisions for shovel assignments and truck allocation in the mining transportation system. Upadhyay and Askari-Nasab (2016) proposed a GP model for the truck-shovel allocation problem by identifying four the desired goals of the mining industry, including fleet utilization, operational cost, head grade deviations, and deviations in tonnage of processing feed. This research did not consider equipment breakdowns in the mining transportation systems. Temeng et al. (1998) formulated a GP model to maximize production and maintain ore quality characteristics within prescribed limits such as ore grade, shovel dig rate, dumping capacity, and stripping ratio requirements. One of the criticisms in literature against this model is that it does not take into account all the goals supposed to be met in an open-pit mine operation and does not consider the waiting time of trucks during the operation. Micholopulos and Panagiotou (2001) developed Temeng's model using SP, which paid attention to random parameters on shovel output. However, the model assumed that all trucks in the fleet had the same capacity. In the same vein, Mohtasham et al. (2017) modified Temeng's model for solving the truck allocation problem based on four important goals, namely the requirement of the production, head grade, tonnage of processing plants, and operating cost by incorporating the mentioned limitations of the model. Four years later, a stochastic extension of the model was introduced to estimate the impacts of the uncertainty on the efficiency of truck-shovel systems (Mohtasham, Mirzaei-Nasirabad, and Alizadeh, 2021). More related works on the fleet allocation problem can also be found in the literature (e.g., Eivazy & Askari-Nasab, 2012; Ercelebi & Bascetin, 2009; L'Heureux et al., 2013; Matamoros & Dimitrakopoulos, 2016; Rubito, 2007; Topal & Ramazan, 2010; White & Olson, 1986). As it is evident, all the models mentioned above suffer from limitations. Thus, a more comprehensive model would cover all the serious weaknesses of the previous literature.

Although the development of methods and strategies to help tackle the truck allocation problem is significant, no studies have been found on evaluating the effect of the integrated fleet management on the productivity of an open-pit mine with numerous transportation companies. The main contribution of this research is to evaluate the effect of integrated fleet management on the performance of mining operations using a mathematical optimization model. In other words, the principal purpose of this study is not to develop a complete optimization model for decision-making of operational planning, but rather to demonstrate the efficiency of the integrated management system in the overall productivity of the mine using a common mathematical model. The truck scheduling (fleet management) problem is solved by diverse operations research techniques. Thus, an integer linear programming (ILP) model is proposed for truck allocation planning over a given time horizon to obtain minimum truck operating costs. The model provides truck allocation decisions considering independent and integrated fleet management in the mining operation.

Methodology

The objective of the truck allocation is to improve the overall performance of the equipment while reducing the cost of mine operations over a certain period. Accordingly, the proposed methodology consists of optimizing the truck fleet allocation to minimize the overall operating costs of trucks while meeting production, quality, and stripping ratio requirements. This is done by modeling the problem as an integer linear programming (ILP) model over a shift, explained in detail in the next section. There are two main reasons for choosing this technique: (1) the ILP-based models are mathematically strong and widely used in mining optimization problems, and (2) the truck allocation problem also can be easily formulated using an ILP model under the specified objective function and constraints. In the final step, the model is tested on a real open-pit mine and the performance of the methodology is evaluated extensively.

The model is based on the following assumptions: the average waiting time of trucks at service points (shovels and destinations) is accounted for, no queuing of trucks can happen at waste dumps, the model is established on the number and type of equipment used in the actual mine, a heterogeneous fleet of trucks can be applied in the haulage system, a specific range of grade can be defined for each ore destination, multiple elements with different grade ranges could be applied in the model, only one shovel can operate at each mining face in all the time periods, each shovel can operate at only one mining face in all the time periods, the material extracted by the shovel must be moved to a specific dump site depending on the material type during the shift, and there is a maximum and minimum limit on the capacity of shovels and ore destinations. The mathematical model generates new truck allocation planning per shift in the mine or during the shift when there is a change in the operational conditions.

In some open-pit mines, there are several mining companies that independently carry out the loading and hauling operation. To consider the impact of integrated fleet management on the operating performance of the fleet, the model is applied with two different strategies. In the first strategy, the model is performed individually for the mining operation of each company, which is the same method used in the case study. In the second strategy, all the loading and hauling units of the mine are considered simultaneously in the model. In other words, it is assumed that only one mining company executes the material handling process. In summary, this methodology addresses the following research questions:

1. How much ore and waste material should be traveled during a particular shift?
2. What is the required number of loaded and empty truck trips for each route of the mine transportation network?
3. What effect does the integrated fleet management have on the total efficiency of the mine?

These kinds of models are easily solvable with existing optimization software. The software used for solving the proposed ILP model was IBM ILOG CPLEX Optimization version 12.6 in a laptop computer with an Intel i7 CPU and 12GB of RAM. The computation time for CPLEX to solve the model was less than 60 seconds, with a zero percent gap from the optimal solution. In this study, the solution of an operating shift required 280 decision variables and 89 constraints.

Optimization Model

This section presents an ILP model for optimal decision-making on the truck allocation problem to determine the required number of truck trips on each route of the mine transportation network. To define and formulate the problem explicitly, the following notations need to be introduced to represent all sets, indices, parameters, and decision variables.

Sets:

$I = \{1, \dots, I\}$	Set of shovels
$I^o = \{1, \dots, I^o\}$	Set of shovels that operate only at ore areas
$I^w = \{1, \dots, I^w\}$	Set of shovels that operate only at waste areas
$J = \{1, \dots, J\}$	Set of unloading points
$J^o = \{1, \dots, J^o\}$	Set of ore unloading points
$J^w = \{1, \dots, J^w\}$	Set of waste unloading points
$H = \{1, \dots, H\}$	Set of types of trucks
$K = \{1, \dots, K\}$	Set of material types

Indices:

$i \in I$	Index for shovels
$i^o \in I^o$	Index for shovels that operate only at ore areas
$i^w \in I^w$	Index for shovels that operate only at waste areas
$j \in J$	Index for unloading points
$j^o \in J^o$	Index for ore unloading points
$j^w \in J^w$	Index for waste unloading points
$h \in H$	Index for types of trucks
$k \in K$	Index for material types

Parameters:

d_{ij}	Distance between shovel i and unloading point j (km)
C_h	Transport cost of the loaded truck type h per kilometer
$\overline{C_h}$	Transport cost of the empty truck type h per kilometer
CA_h	Capacity of truck type h
C_j^{max}	Maximum capacity of unloading point j per shift (tones)
C_j^{min}	Minimum capacity of unloading point j per shift (tones)
O_i	Tonnage available at shovel i (tones)
Q_i	1 if the material at shovel i is ore, 0 if it is waste (binary parameter)
G_{ik}	Average grade of ore material type k at shovel i (%)
GU_{jk}	Upper grade of ore material type k at shovel i (%)
GL_{jk}	Lower grade of ore material type k at shovel i (%)
P_i^{max}	Maximum production possible for shovel i per shift (tones)
P_i^{min}	Minimum production possible for shovel i per shift (tones)
R_{max}	Upper limit of stripping ratio according to production schedule
R_{min}	Lower limit of stripping ratio according to production schedule
TF_{ijh}	Average haul time from shovel i to unloading point j by truck type h (s)
TW_{jh}	Average waiting time at unloading point j by truck type h (s)
TSD_{jh}	Average spotting time at unloading point j by truck type h (s)
TD_{jh}	Average dumping time at unloading point j by truck type h (s)
TE_{jih}	Average traveling time from unloading point j to shovel i by truck type h (s)
TI_{ih}	Average idle time at shovel i by truck type h (s)
TSL_{ih}	Average spotting time at shovel i by truck type h (s)
TL_{ih}	Average loading time at shovel i by truck type h (s)
T	Shift duration (h)
N_h	Number of trucks type h

Decision variables:

X_{ijh} Number of loaded trips made by truck type h from shovel i to unloading point j per shift

Y_{jih} Number of unloaded trips made by truck type h from unloading point j to shovel i per shift

Based on the above notations, the problem can be formulated as follows:

$$Min \quad \sum_i \sum_j \sum_h d_{ij} \times \left(C_h X_{ijh} + \overline{C_h} Y_{jih} \right) \tag{1}$$

Subject to:

$$\sum_i \sum_h CA_h X_{ijh} \le C_j^{max} \qquad \forall j \in J \tag{2}$$

$$\sum_i \sum_h CA_h X_{ijh} \ge C_j^{min} \qquad \forall j \in J \tag{3}$$

$$\sum_i \sum_h CA_h X_{ijh} \ge C_j^{min} \qquad \forall i \in I \tag{4}$$

$$\sum_{j^w} \sum_h CA_h X_{ijh} \le O_i \times (1 - Q_i) \qquad \forall i \in I \tag{5}$$

$$\sum_{j^w} \sum_h CA_h X_{ijh} \le O_i \times (1 - Q_i) \qquad \forall j^o \in J^o, \forall k \in K \tag{6}$$

$$\sum_i \sum_h \left(G_{ik} - GL_{jk} \right) \times CA_h X_{ijh} \ge 0 \qquad \forall j^o \in J^o, \forall k \in K \tag{7}$$

$$\sum_j \sum_h CA_h X_{ijh} \le P_i^{max} \qquad \forall i \in I \tag{8}$$

$$\sum_j \sum_h CA_h X_{ijh} \ge P_i^{min} \qquad \forall i \in I \tag{9}$$

$$\sum_{i^w} \sum_{j^w} \sum_h CA_h X_{ijh} - R_{min} \times \sum_{i^o} \sum_{j^o} \sum_h CA_h X_{ijh} \ge 0 \tag{10}$$

$$\sum_{i^w} \sum_{j^w} \sum_h CA_h X_{ijh} - R_{max} \times \sum_{i^o} \sum_{j^o} \sum_h CA_h X_{ijh} \le 0 \tag{11}$$

$$\sum_i \sum_j X_{ijh} \times \left(TF_{ijh} + TW_{jh} + TSD_{jh} + TD_{jh} \right) + Y_{jih} \times \left(TE_{jih} + TI_{ih} + TSL_{ih} + TL_{ih} \right) \le 3600 \times T \times N_h \qquad \forall h \in H \tag{12}$$

$$\sum_i X_{ijh} = \sum_i Y_{jih} \qquad \forall j \in J, \forall h \in H \tag{13}$$

$$\sum_j X_{ijh} = \sum_j Y_{jih} \qquad \forall i \in I, \forall h \in H \tag{14}$$

$$X_{ijh}, Y_{jih} \in N^+ \tag{15}$$

The objective function (1) corresponds to minimizing the total truck operating costs, which is associated with the traveling distance of trucks from the shovel to the unloading point and that of the return trip. Constraints (2) and (3) ensure the maximum and minimum capacity of each dumpsite, respectively. Constraints (4) and (5) state that the material transported from each shovel is smaller or equal to the total available material at that shovel. Constraints (6) and (7) guarantee that the suitable ore grade is fed to each ore destination. Constraints (8) and (9) prescribe that the ore and waste transported from each loading point is less than or equal to the shovel's capacity allocated to that loading point. Constraints (10) and (11) relate to the stripping ratio requirement. Constraint (12) assures that the number of truck trips in a shift does not exceed the capacity of available trucks. Constraints (13) and (14) maintain the continuity of loading and transportation flow in the mine. The last constraint (15) ensures that the trip number of trucks from or to a shovel is positive and integer.

Results and Discussions

A Real Case Study

The open-pit mine under study is a large-scale copper ore mine in the northwest part of Iran. Copper is the main element of interest in the deposit of the Sungun mine. In this mine, loading and hauling operations are performed by three independent companies, namely, AhanAjin, Mobin, and Noavaran. Figure 1 shows the schematic view of the mine transportation system. The work is carried out considering 14 mining faces on several benches. AhanAjin company operates in mining face 1 to mining face 4, Mobin company operates in mining face 5 to mining face 10, and Noavarans company operates in mining face 11 to mining face 14. Based on the scheduled target and working on 14 benches, the mine employs five types of loaders to carry out mining activity in the pit. The detailed information about the loading equipment in each mining face is provided in Table 1. Loaders 3, 4, 8, 9, and 10 are located in the valuable mineral (ore) area and the rest in the waste area. The grade characteristics, about mining faces scheduled in the given shift, are presented in Table 2. The desired grade of copper in the ore destination is 0.61%, with a range between 0.60% and 0.62% throughout the shift. Five types of trucks with different capacities are used in haulage operations. Specification of the hauling equipment applied by each company is summarized in Table 3, indicating the number of equipment of each type, and the nominal capacity. There are two destinations in the mine: one crusher and one waste dump. Haul trucks transport waste rock to the waste dump and ore material to the crusher from the benches. The minimum and maximum capacities of the crusher to feed the processing plant are 12500 and 14000 tons per shift, respectively.

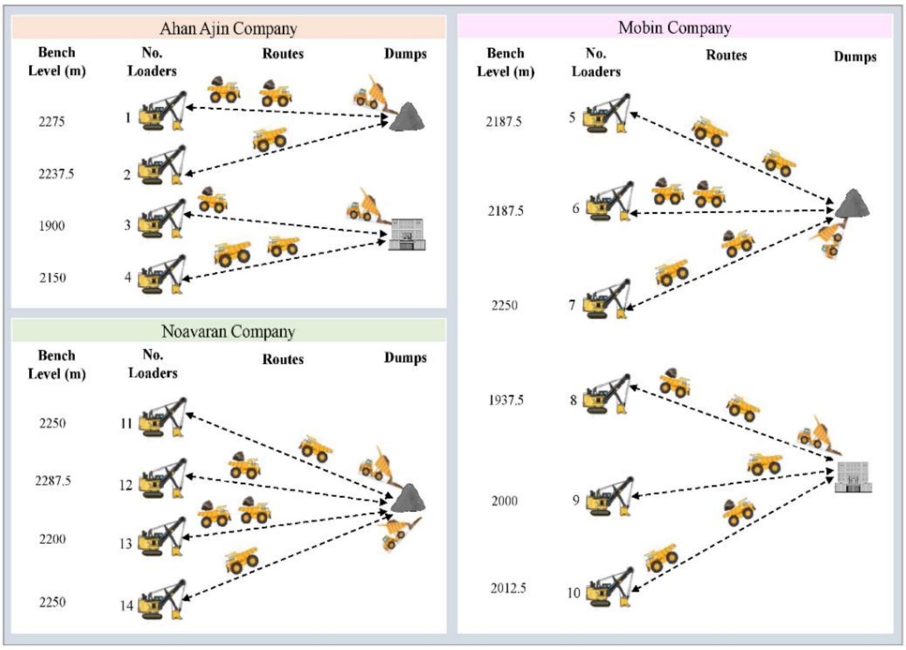

Figure 1. A Schematic View of the Sungun Copper Mine Transportation System

The number of possible transport routes is 28. The distance between loaders and destinations in the transportation network is given in Table 4. The time horizon of the collected data is 7 hours. The current mine policy used to address the truck allocation schedule is the fixed allocation strategy. The number of truck trips performed by mine's strategy for each company during the given shift has been shown in Table 5. The actual production obtained by companies for the target shift using the mine allocation strategy is listed in Table 6. The required stripping ratio to handle the extraction lies in the 2.5–3.5 range during the target shift. The mine production operations are executed in three 7-hour shifts every day of the week. We cannot present the truck operating cost data because of the confidentiality of the provided information by each company.

Table 1. Specification of the Loading Equipment Applied in the Mine

Loader	Model	Maximum production capacity (t/shift)	Minimum production capacity (t/shift)
1	Komatsu-PC2000	10000	5000
2	Komatsu-PC1250	7700	3800
3	Komatsu-PC1250	7700	2800
4	Komatsu-PC1250	7700	1350
5	Komatsu-PC850	7000	3500
6	Komatsu-PC850	6600	3300
7	Komatsu-PC800	3000	1500
8	Komatsu-PC850	7000	2700
9	Komatsu-PC850	7000	2300
10	Komatsu-PC800	7000	3600
11	Komatsu-WA800	8400	4200
12	Komatsu-PC850	7000	3500
13	Komatsu-WA700	7700	3800
14	Komatsu-PC1250	7700	3800

Table 2. Grade Characteristics in Different Mining Faces

Mining face	Loader	Average grade	Desired grade	
			Minimum	Maximum
1	1	-	-	-
2	2	-	-	-
3	3	0.75	0.62	0.64
4	4	0.42		
5	5	-	-	-
6	6	-	-	-
7	7	-	-	-
8	8	0.9	0.59	0.60
9	9	0.51		
10	10	0.42		
11	11	-	-	-
12	12	-	-	-
13	13	-	-	-
14	14	-	-	-

Table 3. Specification of the Hauling Equipment Applied in the Mine

Company	Trucks' model	Truck type	Number of trucks	Nominal payload capacity
Ahan Ajin	Komatsu-HD325	1	4	24
	Komatsu-HD758	2	15	80
Mobin	Komatsu-HD325	1	2	24
	Komatsu-HD605	2	9	48
	Komatsu-HD785	3	11	80
Noavaran	BELAZ-7555B	1	6	44
	Komatsu-HD605	2	2	48
	Komatsu-HD785	3	6	80
	BELAZ-75131	4	2	105

Table 4. Distance Between Shovels and Unloading Points (km)

Loader	Dump	Crusher
1	2.5	6
2	3.65	7.4
3	6.5	2.1
4	4.1	3.15
5	4.4	6.8
6	4.4	6.8
7	3.65	7.4
8	6.1	1.75
9	5.85	1.5
10	5.5	1.2
11	2.9	8.3
12	2.8	9
13	3.7	7.45
14	2.9	7

Table 5. The Number of Loaded and Empty Truck Trips Generated by the Mine's Strategy

Company	Unloading point	truck type	Mining face													
			1	2	3	4	5	6	7	8	9	10	11	12	13	14
Ahan Ajin	Dump	1	70	84	-	-	-	-	-	-	-	-	-	-	-	-
		2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Crusher	1	-	-	35	-	-	-	-	-	-	-	-	-	-	-
		2	-	-	-	63	-	-	-	-	-	-	-	-	-	-
Mobin	Dump	1	-	-	-	-	55	-	-	-	-	-	-	-	-	-
		2	-	-	-	-	-	52	28	-	-	-	-	-	-	-
		3	-	-	-	-	-	-	-	1	-	-	-	-	-	-
	Crusher	1	-	-	-	-	-	-	-	11	29	45	-	-	-	-
		2	-	-	-	-	-	-	-	33	-	-	-	-	-	-
		3	-	-	-	-	-	-	-	11	-	-	-	-	-	-
Noavaran	Dump	1	-	-	-	-	-	-	-	-	-	-	16	12	-	-
		2	-	-	-	-	-	-	-	-	-	-	-	-	48	30
		3	-	-	-	-	-	-	-	-	-	-	-	-	13	17
		4	-	-	-	-	-	-	-	-	-	-	63	28	-	18

Table 6. Delivered Material Tonnage Following the Mine's Strategy

Company	Material type		Total
	Ore	Waste	
Ahan Ajin	4312	12320	16632
Mobin	8648	8696	17344
Noavaran	-	15500	15500
Mine's production	12960	36516	49476

Model Implementation

The proposed mathematical model was implemented with two different strategies to determine the truck schedule in the mine. The primary purpose of creating two strategies is to investigate the performance of different fleet management in the truck allocation problem and subsequently in the productivity of the mine. Strategy 1 is developed based on independent fleet management where each company operates separately in the mine. In this strategy, the model is solved n times based on the mining data of each company. However, strategy 2 considers one company for material handling processed to implement the integrated fleet management in the mining operation. Regarding this method, the model is solved concurrently for all operational data of the mine. In these two strategies, the optimal trip schedule of trucks is determined under the framework of the proposed models considering imposed constraints such as stripping ratio, ore grade, etc.

To implement the developed strategies, the model in Section 3 was used to solve the truck allocation problem in the target shift of the Sungun copper mine. In the following, the results obtained from the developed strategies are presented.

Strategy 1: Independent Fleet Management

The results obtained from strategy 1 are presented in Figure 2 and Tables 7 and 8. To clarify the results of this strategy, at the first step of analyzing the results, the optimum number of truck trips was evaluated. The optimal number of truck trips refers to the number of loaded and empty trucks that should pass through each route per unit of time to meet the production requirements. Table 7 displays the number of loaded and empty truck trips along various routes of the mine transportation network by taking different types of trucks. It is clear in this table how the optimizer assigns loaded and empty trucks to the proper destinations of the operation to move scheduled material (response to question 2 in the Methodology section). By comparing Tables 5 and 7, it can be found that the total number of truck trips using strategy 1 is less than the mine allocation policy. It means that the model attempts to decrease the required number of truck trips for each route of the transportation network to reduce the truck operating costs while considering production requirements. Table 8 compares the total number of trucks required in the mine based on the mine's strategy (MS) and strategy 1 (S1) to meet the mining operation targets. The major difference between the two strategies is highlighted in Table 8. As it is observed in strategy 1, each company operates with a fewer number of trucks compared to the mine allocation plan strategy. This depicts how the operation requirements were met at lower operating costs using strategy 1.

Table 7. The Number of Loaded and Empty Truck Trips Generated by Strategy 1

Company	**Unloading point**	**Truck type**	**Mining face**													
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Ahan Ajin	Dump	1	104	46	-	-	-	-	-	-	-	-	-	-	-	-
		2	8	5	-	-	-	-	-	-	-	-	-	-	-	-
	Crusher	1	-	-	35	17	-	-	-	-	-	-	-	-	-	-
		2	-	-	-	6	-	-	-	-	-	-	-	-	-	-
Mobin	Dump	1	-	-	-	-	42	41	17	-	-	-	-	-	-	-
		2	-	-	-	-	3	-	0	-	-	-	-	-	-	-
		3	-	-	-	-	-	1	18	-	-	-	-	-	-	-
	Crusher	1	-	-	-	-	-	-	-	29	-	-	-	-	-	-
		2	-	-	-	-	-	-	-	8	48	73	-	-	-	-
		3	-	-	-	-	-	-	-	-	-	4	-	-	-	-
Noavaran	Dump	1	-	-	-	-	-	-	-	-	-	-	-	30	1	5
		2	-	-	-	-	-	-	-	-	-	-	-	1	45	41
		3	-	-	-	-	-	-	-	-	-	-	16	3	2	-
		4	-	-	-	-	-	-	-	-	-	-	78	5	-	-

Table 8. The Total Number of Trucks Used in the Mine for Each Company Considering Two Different Strategies

Company	**Allocation method**	**Truck**				
		Komatsu-HD325	**Komatsu-HD758**	**Komatsu-HD605**	**BELAZ-7555B**	**BELAZ-75131**
Ahan Ajin	MS	4	15	-	-	-
	S1	1	15	-	-	-
Mobin	MS	2	11	9	-	-
	S1	2	11	7	-	-
Noavaran	MS	-	6	2	6	2
	S1	-	6	2	6	2

Figure 2 illustrates the total material (ore and waste) produced in the shift using MS and S1 strategies (response to question 1 in the Methodology section). As depicted in Figure 2, strategy 1 approach yields a good result, in which the production is about the same as the actual mine plan, and the operating cost reduction for Ahan Ajin, Mobin, and Noavaran companies is 7%, 1%, and 1.4%, respectively. This is because fewer truck trips are required in this strategy to deliver the extracted material. Moreover, the total production obtained for each company satisfies the stripping ratio constraint with respect to the considered upper and lower stripping limits. The same figure also shows that the performance of the mathematical model is optimal against the mine's strategy. As shown in these results, changing the fleet management policy has a significant impact on the results of empty and loaded truck trips as well as the production rates of the companies. Therefore, fleet management optimization must be implemented to reach the high performance of the mining equipment.

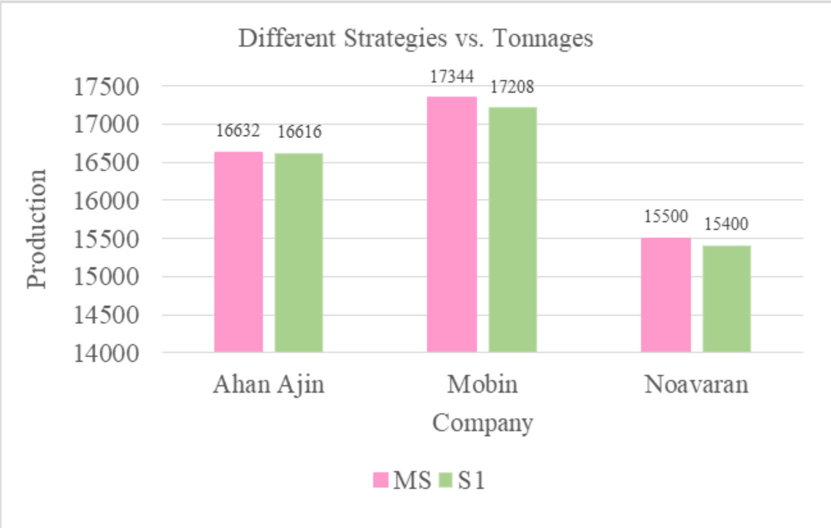

Figure 2. Delivered Material Tonnage by Each Company Resulting From Two Strategies

Strategy 2: Integrated Fleet Management

Similar to the previous strategy, the results of the proposed model considering strategy 2 are compared to the actual mine strategy to assess the performance of the integrated fleet management in the mining operation. The different allocations of trucks to various loading points and destinations were assigned for strategy 2 based on the quality and quantity requirements. Table 9 shows the performance of the operational objective included in the ILP model for the results of the problems, including the production schedule of each route (response to question 1 in the Methodology section) and the number of truck trips (response to question 2 in the Methodology section). Decisions provided by this strategy were analyzed by comparing the results related to the mine allocation policy. According to Tables 5 and 9, the required number of truck trips employing strategy 2 decreases compared to the current mine allocation plan strategy. Therefore, the model yields good results, where the truck trips with the low operational cost are more optimal than the mine's strategy. Table 10 shows a clear trend of decreasing the total number of trucks with decreasing numbers of truck trips in the mining operation. Additionally, the total number of trucks required in the mining operation is lower in strategy 2 than in the mine's strategy, demonstrating that the integrated fleet management describes an optimal usage of the fleet.

Figure 3 represents the amount of material (ore and waste) produced through the implementation of strategy 2 and the mine allocation strategy in the given shift. The ore and waste material produced for both strategies are almost the same, while the truck operating costs for strategy 2 are 3% below the mine's strategy. A comparison of the two strategies (MS and S2) reveals that the performance of strategy 2 is optimal against the mine allocation strategy. Thus, the effectiveness of strategy 2 is verified by comparing the results of the two strategies. This means that replacing the current fleet management strategy of the mine with strategy 2 helps meet the scheduled production requirements with a high production rate. Moreover, according to Figure 3, the stripping ratio is 36304/13006 = 2.8, demonstrating that the proposed strategy satisfies the stripping ratio constraint as well. In the following, the results of the strategies (MS, S1, and S2) are compared to provide insights into the impact of fleet management on the performance of the mining operation.

Table 9. The Number of Loaded and Empty Truck Trips Generated by Strategy 2

Unloading point	Truck type	Mining face													
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Dump	1	110	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	-	46	-	-	30	41	17	-	-	-	3	24	46	46
	3	2	-	-	-	-	-	-	-	-	-	-	33	-	-
	4	-	-	-	-	25	-	-	-	-	-	90	-	-	-
	5	-	5	-	-	-	1	6	-	-	-	-	-	5	5
Crusher	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	-	-	-	35	17	-	-	-	2	3	-	-	-	-	-
	-	-	-	-	-	-	-	-	53	-	59	-	-	-	-
	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	2	-	-	-	-	86	36	-	-	-	-

Table 10. Comparison of the Total Number of Trucks Required in the Mining Operation Following Strategy 2 and Mine's Strategy

Allocation method	Truck				
	Komatsu-HD325	**Komatsu-HD758**	**Komatsu-HD605**	**BELAZ-7555B**	**BELAZ-75131**
MS	6	32	11	6	2
S2	2	32	10	4	2

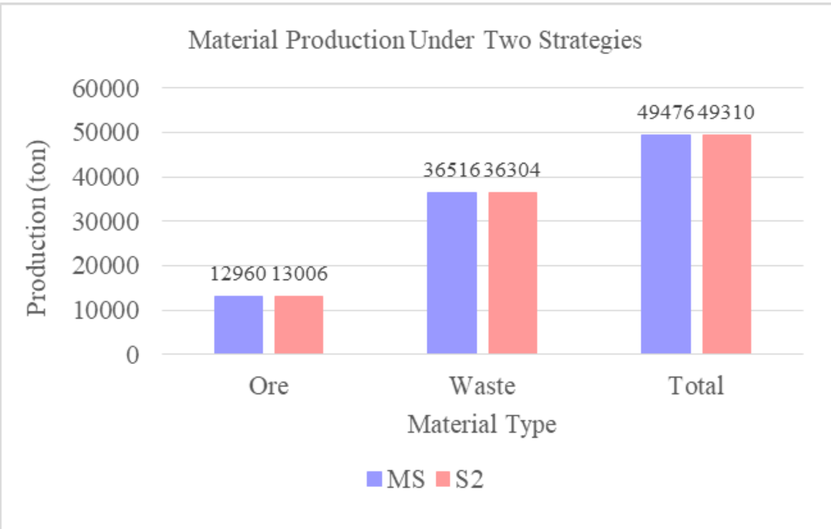

Figure 3. Results of the Delivered Material Tonnage in Two Different Strategies

Comparison of Results From Different Strategies

Figure 4 describes the delivered material to destinations and the number of truck trips determined by the mine's strategy (fixed allocation), strategy 1, and strategy 2 in the target shift (response to question 3 in the Methodology section). As shown in the figure, changing the truck allocation strategy has a significant impact on the results of truck trips, material production, and total truck operating costs. Referring to Tables 7 and 9, the presented model uses different numbers of truck trips for each strategy to meet the mining operation targets. In other words, the different allocation strategies indicate that the different numbers of truck trips satisfy the desired strategy under the same model. Regarding the total number of trucks allocated to the operation, the mine operates with 57 trucks while strategy 1 and strategy 2 are optimized with 52 and 50 trucks, respectively. As it can be seen in this figure, the total number of truck trips for strategy 2 is less than the other two. It means that this strategy attempts to decrease the required number of truck trips for each route of the transportation network to optimally manage the performance of the fleet. As the mine's strategy does not apply an appropriate fleet management policy, the number of trucks needed to meet the production goals is overestimated and consequently, the truck operating costs are above the optimal level. What is interesting in this figure is that the results of strategies 1 and 2 yield a similar result as the actual mine production though they suggest using a fewer number of trucks than the actual case. It follows from the figure that both strategies can reduce the truck operating costs compared to the mine's strategy. Nevertheless, the truck operating cost in strategy 2 is 2% less than that of strategy 1. Therefore, strategy 2 with the integrated fleet management policy reaches the optimal production level with the lowest operating cost and fewest truck trips compared to the other strategies. In summary, these results indicate a linear relationship between the optimal number of truck trips and operating costs in the proposed strategies. That is, the total production and operating costs decrease with the decrease of the number of truck trips and vice versa. The main results of this research can be summarized as follows:

- The stripping ratio requirement can be met with a fewer number of trucks if the developed strategies in this paper are used to make truck allocation decisions.
- As mentioned before, the material delivered to the ore destination must have a grade between 0.60% and 0.62%. The results show that during the given shift, the material delivered to the crusher using both strategies falls into the acceptable range and follows the crusher's head grade requirement. This is due to the ore grade constraints considered in the programming model.
- The truck allocation using the proposed strategies is more efficient and effective than the actual strategy in mine.
- By replacing the mine's strategy with strategy 2, the truck decisions are made in a way that the optimal production with minimum operating costs is obtained.

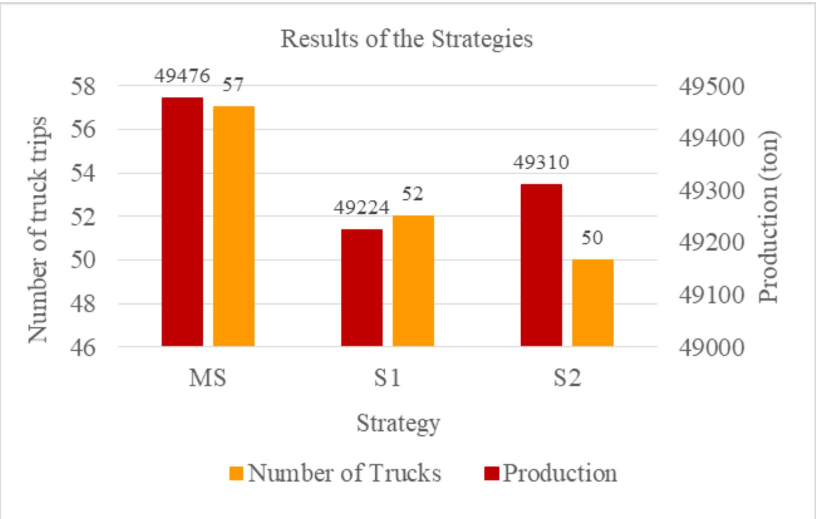

Figure 4. Comparison of the Results Obtained From the Different Strategies

Conclusions and Future Research

The truck allocation problem is one issue that has become the focus in mining operations for efficiency improvement and cost reduction purposes. This paper defines a methodology for making operational decisions in truck-shovel systems of open-pit mining operations. The proposed methodology is based on the integer linear programming (ILP) model to determine the optimal allocation of trucks and achieve the required production in a given time period. The modeling framework devised allows the total truck operating costs to be minimized for decision-making of operational planning. The model takes into account the attributes of different types of equipment, open-pit mine haul road network, and operational constraints. To evaluate the transportation system performance, the mathematical model was implemented with two different strategies through a case study. In the case study, three mining and road construction companies carry out separately the loading and hauling operations. For this reason, in the first proposed strategy, the model is performed individually for the mining operation of each company. To consider the impact of the integrated fleet management on the operating performance of the fleet, in the second proposed strategy, all the loading and hauling units of the mine are considered simultaneously in the model. Solutions found by the developed strategies were compared with each other and with the mine allocation policy. The results obtained from the strategies proved the applicability of the model for providing the truck allocation schedule in an open-pit mining operation. Strategy 2 was able to generate the best results that met the production objectives (stripping ratio, feed grade, etc.) and reduced the truck operating costs.

The main scientific contribution of this study on the body of knowledge is the development and implementation of a mathematical optimization model by considering two different strategies.

One of the potential directions for future research is to extend the ILP model to capture the variant goals of mining operations.

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