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Development of a goal programming model for optimization of truck allocation in open pit mines

M. Mohtasham[1], H. Mirzaei Nasirabad[1*] and A. Mahmoodi Markid[2]

1. Department of Mining Engineering, Sahand University of Technology, Tabriz, Iran
2. Department of Electrical Engineering, Sahand University of Technology, Tabriz, Iran

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**Corresponding author: hmirzaei@sut.ac.ir (H. Mirzaei Nasirabad).*

Abstract
Truck and shovel operations comprise approximately 60% of the total operating costs in open pit mines. In order to increase productivity and reduce the cost of mining operations, it is essential to manage the equipment used with high efficiency. In this work, the chance-constrained goal programing (CCGP) model presented by Michalakopoulos and Panagiotou is developed to determine an optimal truck allocation plan in open pit mines and reduce the waiting times of trucks and shovels. The developed goal programming (GP) model is established considering four desired goals: “maximizing shovel production”, “minimizing deviations in head grade”, “minimizing deviations in tonnage feed to the processing plants from the desired feed” and “minimizing truck operating costs”. To employ the developed model, a software is prepared in Visual Studio with C# programming language. In this computer program, the CPLEX optimizer software is incorporated for solving the developed goal programing model. The case study of Sungun copper mine is also considered to evaluate the presented GP model and prepared software. The results obtained indicate that the developed model increases the mine production above 20.6% with respect to the traditional truck allocation plan, while meeting the desired grade and the stripping ratio constraints.

Keywords: *Transportation, Production Optimization, Truck Allocation, Goal Programming, Truck Allocation Software.*

1. Introduction

Material transportation is one of the most important tasks in open pit mine operations. The truck-shovel system is the major form of material handling operations in open pit mines. This process includes 50% of the operating costs, and it may reach 60% in some mines [1]. Reduction of operating costs and improvement of productivity can be achieved by the optimum control of the truck-shovel system.

In truck-shovel operated open pit mines, after the drilling and blasting activities, the ore and waste materials are loaded with shovels onto trucks and transported to proper discharge points (ore crushers or waste dumps). Figure 1 shows a schematic view of the network of transport routes in an open pit mine consisting of n number of loading points and m number of dump points. During the mine product operations, once a truck is discharged in a destination (dump point), it should be sent to an appropriate loading point such that the productivity of the truck-shovel system is maximized while meeting the desired production objectives included. The decision about which loading point the empty truck should be allocated to, is the truck dispatching problem (Figure 1).

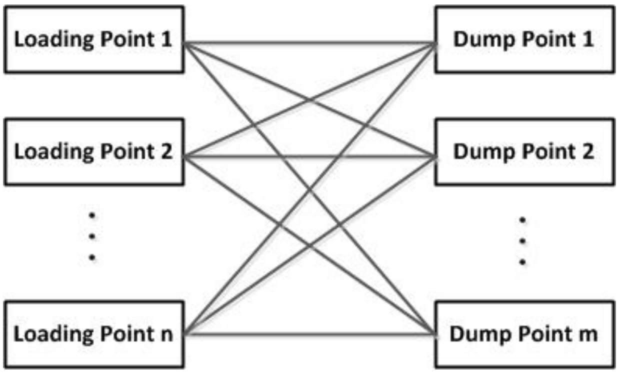

Figure1. Network of transport routes of an open pit mine.

The efficiency of the truck-shovel system depends on the capability of the real-time dispatching algorithm to be used for the efficient assignment of trucks to shovels according to a given mine configuration. Optimal fleet size is another factor affecting the efficiency of the truck-shovel system; an insufficient number of trucks lead to a shovel idle time, and too many trucks lead to the queues at shovels and truck waiting drawback. To avoid the waste times, setting the optimal size of the fleet is necessary. Analytical methods generally over-estimate the truck number since they often assume the same pick-up and delivery points for trucks [1]. Hence, simulation is required to determine the optimal fleet size, although a way to dispatch the trucks or a dispatching plan is required.

The objective of dispatching models is to achieve the one or several criteria such as maximizing the total tonnage production, minimizing the costs or minimizing the equipment inactivity such as the shovel idle time and the truck waiting time for a given set of practical constraints including the blending requirements at crushers and stockpiles, stripping ratios, minimum and maximum digging rate at each shovel, and other operational considerations according to the need of the mine managers [2].

Due to the combinatorial form of dispatching problem and the stochastic nature of individual elements such as work cycle components, unpredicted grade variation, and general changes in digging and haulage conditions, and the short time available to take a decision, in real time, even with powerful computers, a true optimization of this problem may be impossible [3]. This complexity has inspired the operational research scientists to employ the mathematical methods and heuristics to solve the dispatching problem in the last decades.

The goal programming (GP) method comprises a powerful framework for a selective arrangement of the optimization criteria based on the requirements of an open pit mine to solve the first stage (truck allocation problem) of the dispatching problem. In this work, a goal programming (GP) model is formulated considering four goals (maximizing shovel utilization, minimizing the grade deviations, minimizing the deviation in tonnage supplied to the processing plants, and minimizing the truck operating costs) to solve the truck allocation problem in open pit mines.

The rest of this paper is organized as what follows. Section 2 explains the literature review for the dispatching problem. Section 3 describes the developed goal programming model to solve the truck allocation problem. Section 4 introduces the prepared truck allocation software based on the developed GP model. Sections 5 and 6 illustrate the results of the developed model in Sungun copper mine.

2. Literature review

Two different approaches are used in the literature to develop a real-time dispatching strategy to optimize the productivity of the truck-shovel system; the single-stage approach and the multi-stage approach. Single-stage models are heuristic methods that simply assign trucks to shovels based on one or several criteria without considering any production targets or constraints [1].

Multi-stage dispatching models include two main parts. The first part is commonly a linear or non-linear programming model, used to determine the production rate on the basis of short range planning goals. The second part that employs the heuristics or mathematical methods, is used for the real-time assignment of trucks to shovels based on the optimal solutions of the first part [4].

The dispatching models developed by Li [5], Xi and Yegulalp [6], White and Olson [7], Elbrond and Soumis [8], and Temeng et al. [4] are based on a multi-stage strategy.

In the recent years, different attempts have been made to improve the efficiency of the truck dispatching systems to achieve the desired targets and constraints of the mining operations related to the requirements of real case studies.

Zhang et al. have developed a linear programming model to optimize the truck allocation process in open pit mines. The objective function is to minimize the number of trucks required to meet mine production in a short-term horizon of time. Although a broad set of constraints including shovels capacity, a minimum level of production, blending constraints, ore and waste ratio, and minimum and maximum capacities of the dumping sites are considered, some constraints such as those with the capacity of the truck fleet are ignored [9].

Burt et al. have presented a linear programming model to minimize the operation cost of the truck-shovel system. They used the match factor to evaluate the productivity of the fleet. This model employs the average equipment cost that does not coincide with the real conditions of the mine transportation system [10].

Rubito has proposed a truck allocation procedure using the linear programming method to optimize the productivity of the transportation system. The presented model is very simple, and only considers the shovels capacity constraint [11].

Ta et al. have presented a linear integer programming model using the queuing theory to minimize the number of trucks assigned to a set of shovels, subject to throughput and ore grade constraints [12].

Topal and Ramazan have developed a new approach based on the mixed integer programming (MIP) techniques for annually scheduling a fixed fleet of mining trucks in a given operation, over a multi-year time horizon to minimize the maintenance cost. The model uses the truck age, maintenance cost, and required operating hours to achieve the annual production targets to produce an optimum truck schedule [13].

Souza et al. have proposed a hybrid heuristic algorithm to optimize the mineral extraction in the mines by minimizing the number of mining trucks used to meet the production goals and quality requirements [14].

He et al. have employed genetic algorithm to solve the established linear programing model to minimize the transportation and maintenance costs in open pit mines. This model only considers the homogeneous fleet size [15].

Gurgur et al. have implemented a linear programing and a mixed integer programming model for truck allocation to overcome the shortcomings of the existing models by taking into account the economic parameters, multi-time periods, and uncertainty in load, travel times, and ore grades [16].

Subtil et al. have proposed a multi-stage approach for dynamic truck dispatching to maximize the tonnage production [17]; the first stage defines the optimal number of trucks by means of a robust linear programming model, and the second stage uses a dynamic dispatching heuristic for decision-making for truck dispatching.

Ahangran et al. have developed a real-time dispatching model to minimize five cost components using the two techniques of flow networks and integer programming [18].

Rodrigo et al. have established a binary integer linear programming model to maximize the overall productivity of the fleet by taking into account the truck and shovel RAM aspects [19].

Faraji has developed the linear programming model presented by Gamache et al., disregarding the truck waiting times [20].

Kaboli and Carmichael have established a linear programming model presented by White et al. to investigate the effect of truck allocation on unit emissions and unit costs [21].

Fu et al. have developed the Topal-Ramazan MIP model to incorporate the new truck-purchase option to the truck allocation problem [22].

Alexandre et al. have presented a linear goal programming model for optimal allocation of trucks based on maximizing production and minimizing truck numbers [23].

Chang et al. have formulated a mixed integer programming model to maximize the overall transport revenue in which some properties and two upper bounds of the problem are proposed [24]; a heuristic solution approach with two improvement strategies is proposed to resolve the problem.

Upadhyay and Askari-Nasab have developed a mixed integer linear goal programming (MILGP) model, considering four goals to optimize the truck-shovel operation in open pit mines [25].

3. Developed goal programming model

In this work, a goal programming model was developed to solve the truck allocation problem in open pit mines. The framework of this model is inferred from the model presented by Michalakopoulos and Panagiotou in 2001 [26]. The deficiencies of the Michalakopoulos and

Panagiotou model are as what follow: The model is not properly equipped to handle mixed fleet systems; it does not consider the average waiting times; it does not consider the minimum amount of ore production during the shift based on the requirement of the processing plants; only one processing plant is considered for a mine, and the truck-shovel production operation is defined in terms of a flow-rate that seems unsuitable.

To remove the above-mentioned shortcomings, a new goal programming model was developed. In the established model, n_s number of loaders is considered to load rock materials into *h* number of trucks, which transport the material to n_d destinations through the mine road network. The destination points include n_c crushers, n_{xd} oxide stockpiles, n_{ld} low grade ore stockpiles, and waste dumps. The presented model optimizes the truck allocation problem, considering four goals: "maximizing the shovel utilization", "minimizing the grade deviations", "minimizing the deviation in tonnage supplied to the processing plants", and "minimizing the truck operating costs" to determine the optimal production rates.

The assumptions and characteristics of the developed GP model are as follow:

- Each ore destination can receive material with a specific grade range
- The desired grade can be achieved by blending the ore coming from different ore faces
- Grade range requirements could be applied to multiple elements present in the ore
- Processing plants are desired to have supply of material at a steady feed but cannot receive material at a rate out of the specified limits
- Ability to optimize a system with the four types of rock materials high-grade ore, low grade ore, oxide, and waste
- Usability in mines with multiple processing plants, where each processing plant has several production lines and each production line accepts certain quality mineral.

The following section elaborates the preliminary equations and the developed GP model formulation along with the required inputs for the model. The parameters and variables considered in the model are described in the Appendix.

3.1. Goals of model

As mentioned earlier, four desired goals of this model are as follow: maximize shovel production, control ore quality, optimize efficiency of processing plants, and minimize truck operating costs. These goals are represented by equations (1)-(4), respectively.

$$\sum_{i=1}^{n_s} d_i^- \qquad \forall \mathrm{i} = 1, \dots, \mathrm{n_s} \tag{1}$$

$$\sum_{j=1}^{n_c} \sum_{k=1}^{n_q} \left(C_{kj}^- + C_{kj}^+\right) \tag{2}$$

$$\sum_{p=1}^{d_p} \left(\delta_p^+ + \delta_p^-\right) \tag{3}$$

$$\sum_{i=1}^{n_s} \sum_{j=1}^{n_d} \sum_{h=1}^{n_h} X_{ijh} \times d_{ij} \times Cf_h = \psi_4 \tag{4}$$

Since the positive deviation from the shovel target production is not undesirable, in first goal, only negative deviations of shovel production are minimized. In the second goal, in order to achieve the desired grade at crushers, the total positive and negative deviations must be minimized. In the third goal, in order to achieve the desired tonnage in each processing plant, the total of positive and negative deviations must be minimized. Finally, by the fourth goal, the cost required to transport a certain amount of material will be minimized.

3.2. Objective function

The objective function of the model is formulated by combining all the goals. Since the goals of objective function have different dimensions, combining them is not meaningful. Therefore, it is necessary to normalize them into dimensionless objectives before combining. The utility function is used to normalize the objective function; different objective functions are normalized by dividing each one of them to their norms. Each objective function norm is calculated as the square of the sum of the coefficients of the decision variables. The normalized goals are then multiplied with proper weights to achieve the desired priority. The final objective function is given by equation (5).

$$Min \quad Z = W_1 \sum_{i=1}^{n_s} \frac{d_i^-}{\| d_i \|} + W_2 \sum_{j=1}^{n_c} \sum_{k=1}^{n_q} \frac{\left(C_{kj}^- + C_{kj}^+\right)}{\| C_{kj} \|} + W_3 \sum_{p=1}^{d_p} \frac{\left(\delta_p^+ + \delta_p^-\right)}{\| \delta_p \|} + \mathrm{W}_4 \left(\frac{\psi}{\| \psi \|}\right) \tag{5}$$

3.3. Goal constraints

The first goal of the model is to maximize the system production. Since the shovel production bounds the overall system production, in order to maximize production, the demand of haulage capacity from the shovels should be covered. This constraint is shown in equation (6).

Goal constraint (7) denotes the production maximization goal by minimizing the negative deviation of each shovel in the objective function over a shift.

Equations (8), (9), (10), and (11) represent goal constraints associated to shovels that load ore, oxide, low grade ore, and waste, respectively.

Goal constraint (12) tries that the average grade sent to the processing plants is of the desired grade and deviation is within the upper and lower acceptable limits.

Constraints (13) and (14) limit the quality deviations in a prescribed range of acceptable values.

Constraint (15) is the processing constraint on the desired tonnage feed to the processing plants and maximum allowable deviation in tonnage accepted at the plants.

Constraints (16) and (17) limit the negative and positive deviations of production received at the processing plants in a prescribed range of acceptable values.

$$\sum_{j=1}^{n_d}\sum_{h=1}^{n_h} X_{ijh} \geq Q_i \qquad \forall \mathrm{i} = 1, \dots, \mathrm{n_s} \tag{6}$$

$$\sum_{j=1}^{n_d}\sum_{h=1}^{n_h} X_{ijh} + d_i^- = Q_i \qquad \forall \mathrm{i} = 1, \dots, \mathrm{n_s} \tag{7}$$

$$\sum_{j=1}^{n_c}\sum_{h=1}^{n_h} X_{ijh} + d_i^- = Q_i \qquad \forall \mathrm{i} = 1, \dots, \mathrm{n}_{os} \tag{8}$$

$$\sum_{h=1}^{n_h}\sum_{j=n_c+1}^{n_c+n_{xd}} X_{ijh} + d_i^- = Q_i \qquad \forall \mathrm{i} = \mathrm{n}_{os} + 1, \dots, \mathrm{n_{os}} + \mathrm{n_{xs}} \tag{9}$$

$$\sum_{h=1}^{n_h}\sum_{j=n_c+n_{xd}+1}^{n_c+n_{xd}+n_{ld}} X_{ijh} + d_i^- = Q_i \qquad \forall \mathrm{i} = \mathrm{n_{os}} + \mathrm{n_{xs}} + 1, \dots, \mathrm{n_{os}} + \mathrm{n_{xs}} + n_{ls} \tag{10}$$

$$\sum_{h=1}^{n_h}\sum_{j=n_c+n_{xd}+n_{ld}+1}^{n_d} X_{ijh} + d_i^- = Q_i \qquad \forall \mathrm{i} = \mathrm{n_{os}} + \mathrm{n_{xs}} + n_{ls} + 1, \dots, \mathrm{n_s} \tag{11}$$

$$\sum_{i=1}^{n_{os}}\sum_{h=1}^{n_h} X_{ijh} * G_{ik} + C_{kj}^- - C_{kj}^+ = Q_{kj} \sum_{i=1}^{n_{os}}\sum_{h=1}^{n_h} X_{ijh} \qquad \forall\, k = 1, \dots., n_q \quad \forall j = 1, \dots., n_c \tag{12}$$

$$\mathrm{C}_{kj}^- \leq (\mathrm{Q_{kj}} - \mathrm{L_{kj}}) \sum_{\mathrm{i}=1}^{\mathrm{n_{os}}}\sum_{h=1}^{n_h} X_{ijh} \qquad \forall \mathrm{k} = 1, \dots, \mathrm{n_q} \quad \forall \mathrm{j} = 1, \dots, \mathrm{n_c} \tag{13}$$

$$\mathrm{C_{kj}^+} \leq (\mathrm{U_{kj}} - \mathrm{Q_{kj}}) \sum_{\mathrm{i}=1}^{\mathrm{n_{os}}}\sum_{h=1}^{n_h} X_{ijh} \qquad \forall \mathrm{k} = 1, \dots, \mathrm{n_q} \quad \forall \mathrm{j} = 1, \dots, \mathrm{n_c} \tag{14}$$

$$\sum_{i=1}^{n_{os}} \sum_{j=1}^{n_c} \sum_{h=1}^{n_h} X_{ijh} + \delta_p^- - \delta_p^+ = PU_{kp} \qquad \forall\, k = 1, \dots, n_q \quad \forall p = 1, \dots, d_p \tag{15}$$

$$\delta_p^- \le (PU_{kp} - PL_{kp}) \times W_t \qquad \forall \mathrm{k} = 1, \dots, \mathrm{n_q} \quad \forall \mathrm{P} = 1, \dots, \mathrm{d_p} \tag{16}$$

$$\delta_p^+ \le (PU_{kp} - PL_{kp}) \times W_t \qquad \forall \mathrm{k} = 1, \dots, \mathrm{n_q} \quad \forall \mathrm{P} = 1, \dots, \mathrm{d_p} \tag{17}$$

3.4. Typical constraints

The haulage capacity allocated to each shovel should be less than the shovel's maximum capacity of production. This is fulfilled by the following deterministic constraint (equation 18).

Constraint (18) is a constraint that puts a lower limit on the production by each shovel.

The constraint for crusher capacity or limited dump capacity is given in equation 19.

The constraints for balancing material flow at sources and destinations are given in equations (20) and (21), respectively.

Minimum and maximum stripping ratio constraints are given in equations (22) and (23), respectively.

The capacity of the truck is defined as the total available time of all trucks during the duration of the shift. This capacity must not be exceeded by the time of use of trucks. Constraint in equation (24) ensures that the total production of shovels does not exceed the available trucks or the production target.

Finally, constraint (25) guarantees the integrality and non-negativity of variables in the model.

$$\sum_{j=1}^{n_d} \sum_{h=1}^{n_h} X_{ijh} \le P_{u_i} \qquad \forall \mathrm{i} = 1, \dots, \mathrm{n_s} \tag{18}$$

$$\sum_{i=1}^{n_s} \sum_{h=1}^{n_h} X_{ijh} \le C_j \qquad \forall j = 1, \dots, n_d \tag{19}$$

$$\sum_{\mathrm{j=1}}^{\mathrm{n_d}} \mathrm{X_{ijh}} = \sum_{\mathrm{j=1}}^{\mathrm{n_d}} \mathrm{Y_{jih}} \qquad \forall \mathrm{i} = 1, \dots, \mathrm{n_s} \quad \forall \mathrm{h} = 1, \dots, \mathrm{n_h} \tag{20}$$

$$\sum_{\mathrm{i=1}}^{\mathrm{n_s}} \mathrm{X_{ijh}} = \sum_{\mathrm{i=1}}^{\mathrm{n_s}} \mathrm{Y_{hji}} \qquad \forall \mathrm{j} = 1, \dots, \mathrm{n_d} \quad \forall \mathrm{h} = 1, \dots, \mathrm{n_h} \tag{21}$$

$$\frac{\sum_{i=1+n_{os}}^{n_s} \sum_{j=1+n_c}^{n_d} \sum_{h=1}^{n_h} X_{ijh}}{\sum_{i=1}^{n_{os}} \sum_{j=1}^{n_c} \sum_{h=1}^{n_h} X_{ijh}} \ge R_l \tag{22}$$

$$\frac{\sum_{i=1+n_{os}}^{n_s} \sum_{j=1+n_c}^{n_d} \sum_{h=1}^{n_h} X_{ijh}}{\sum_{i=1}^{n_{os}} \sum_{j=1}^{n_c} \sum_{h=1}^{n_h} X_{ijh}} \le R_u \tag{23}$$

$$\sum_{\mathrm{i=1}}^{\mathrm{n_s}} \sum_{\mathrm{j=1}}^{\mathrm{n_d}} H_{ijh} X_{ijh} + \sum_{\mathrm{j=1}}^{\mathrm{n_d}} \sum_{\mathrm{i=1}}^{\mathrm{n_s}} \mathrm{R_{jih} Y_{jih}} + \sum_{\mathrm{i=1}}^{\mathrm{n_s}} \sum_{\mathrm{j=1}}^{\mathrm{n_d}} \mathrm{D_{jh} X_{ijh}} + \sum_{\mathrm{i=1}}^{\mathrm{n_s}} \sum_{\mathrm{j=1}}^{\mathrm{n_d}} \mathrm{SD_{jh} X_{ijh}} + \sum_{\mathrm{j=1}}^{\mathrm{n_d}} \sum_{\mathrm{i=1}}^{\mathrm{n_s}} \mathrm{S_{ih} Y_{jih}} + \sum_{\mathrm{j=1}}^{\mathrm{n_d}} \sum_{\mathrm{i=1}}^{\mathrm{n_s}} \mathrm{SS_{ih} Y_{jih}} \le 3600 \times W_t \times N_h \times T_h \qquad \forall h = 1, \dots, n_h \tag{24}$$

$$X_{ijh}, Y_{jih}, \delta_p^-, \delta_p^+, C_{kj}^-, C_{kj}^+, d_i^- \geq 0 \quad (25)$$

4. Truck allocation Software based on developed GP model

To employ the developed GP model, a software was prepared in Visual Studio with C# programming language. In this computer program, the CPLEX optimizer software is incorporated for solving the developed goal programing model.

The main form of the prepared software is shown in Figure 2. This form contains different parts: "Input Parameters" to insert the required information of the GP model; "Goal Weights" to arrange the weight of different goals in the model; "Results" and "Data Grid View" to present the results of the GP model by clicking on "Solve Optimization Model" button.

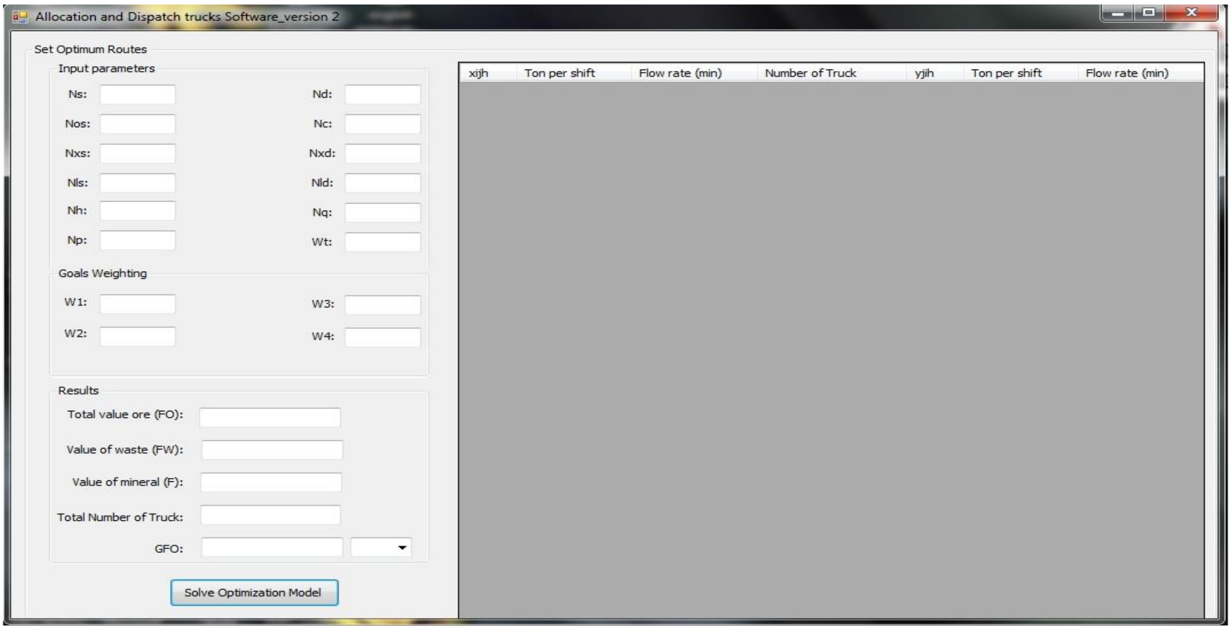

Figure 2. Main form of prepared truck allocation software.

5. Case study

The case study of Sungun copper mine, located in the NW of Iran, was considered to evaluate the presented model and prepared software. Thus an 8-hour shift of mine transport operations was selected to verify the results of the GP model in comparison with the traditional truck allocation procedure.

In this mine, the maximum capacity of the crusher was 20000 tons per shift, and the total capacity of three waste dumps was limited to 800000 tons per shift. The upper and lower limits of stripping ratio were 5 and 3, respectively. The grade of ore material feed to processing plant had to be kept in the range of 0.68-0.78%; the desired grade for processing plant was 0.73%. The minimum and maximum allowable tonnages for processing plant were 600 and 1050 tons, respectively.

In the considered shift, nine loading points were operating including four ore material extraction faces and five waste removal faces. The daily production of operating loaders was monitored during various shifts, and the maximum production rate and average production rate of these loaders were determined. The operational characteristics of loaders and average grade of loaded ore materials for target shift are reported in Table 1.

The mine uses 25 Komatsu HD-325 haul trucks; with nominal capacity of 32 t, and 10 Komatsu HD-785 trucks with nominal capacity of 100 t. The HD-785 trucks were not able to operate with their full capacity due to their depreciation. Practically, the maximum payload on these trucks was almost 72 t. Therefore, the practical capacity (72 t) was considered to adapt with real conditions. The distance between loading points and destinations for target shift are listed in Table 2.

The average waiting and loading time for two types of trucks at different loading points and average waiting and dumping time of trucks at different dump points are presented in Tables 3 and 4, respectively.

For two types of trucks, the average traveling time of loaded trucks from different loading points to

dump points are listed in Tables 5 and 6, and the average traveling time of empty trucks from different dump points to production points are shown in Tables 7 and 8.
As mentioned earlier, the weight of each established goal must be determined based on the technical conditions and production schedule of the open pit mine. For this case study, the weight of the four goals is considered to be the same and equal to 0.25.

Table 1. Operating characteristics of different loading points in target shift.

Loading points	Bench level (m)	Type of material	Loading device model	Maximum production rate (ton/shift)	Average production rate (ton/shift)	Average grade (%)
1	1912.5	ore	Komatsu-600A	4800	3600	1.42
2	1950	ore	Komatsu-600A	4800	3600	0.74
3	1962.5	ore	NEWHOLLAND-270	4000	3000	0.92
4	2100	ore	Komatsu- 600A, Komatsu PC-800	8000	6000	0.39
5	1937.5	ore	Komatsu PC-800	6000	5000	-
6	2237.5	waste	CAT-988B	5600	4600	-
7	2262.5	waste	CAT-988B	5600	4600	-
8	2287.5	waste	CAT-988B	5600	4600	-
9	2312.5	waste	CAT-988B, Komatsu PC-1250	13600	10800	-

Table 2. Distance between loading points and dump points in target shift (km).

Loading points	Dump points			
	Crusher	Dump 1950	Dump 2250	Dump 2275
1	1.7	1.2	7.2	8.5
2	1.3	1	6.8	8.1
3	1.4	1	6.9	8.2
4	2.1	3.6	4.5	4.6
5	1.5	1	7	8.4
6	4.8	6.2	1.7	4
7	5.2	6.7	2	2.2
8	6.3	7.7	2.8	1.4
9	7	8.4	3.5	1.8

Table 3. Average waiting and loading time of trucks in loading points (s).

Loading points	Average loading time of 32 tons trucks (s)	Average loading time of 72 tons trucks (s)	Average waiting time of trucks (s)
1	120	265	35
2	120	265	63
3	135	335	7
4	60	121	-
5	69	263	60
6	121	300	-
7	121	300	60
8	121	300	-
9	81	68	-

Table 4. Average waiting and dumping times of trucks in dump points in target shift (s).

Dump points	Average dumping time of 32 tons trucks (s)	Average dumping time of 72 tons trucks (s)	Average waiting time of trucks (s)
Crusher	68	93	60
Dump 1950	85	92	-
Dump 2250	85	92	-
Dump 2275	85	90	-

Table 5. Average travel time of loaded 32 t trucks in target shift (s).

Loading points	Unloading points			
	Crusher	Dump 1950	Dump 2250	Dump 2275
1	442	-	-	-
2	323	-	-	-
3	362	-	-	-
4	378	-	-	-
5	-	225	1686	1986
6	-	1024	368	993
7	-	1108	362	540
8	-	1269	503	244
9	-	1386	611	336

Table 6. Average travel time of loaded 72 t trucks in target shift (s).

Loading points	Unloading points			
	Crusher	Dump 1950	Dump 2250	Dump 2275
1	506	-	-	-
2	363	-	-	-
3	408	-	-	-
4	396	-	-	-
5	-	268	1417	2356
6	-	1154	504	1164
7	-	171	378	638
8	-	1382	541	284
9	-	1537	668	346

Table 7. Average travel time of empty 32 t trucks in target shift (s).

Loading points	Unloading points			
	Crusher	Dump 1950	Dump 2250	Dump 2275
1	284	193	1088	1362
2	221	124	1096	1296
3	247	263	1082	1323
4	378	635	742	744
5	275	162	1083	1351
6	803	1024	283	665
7	843	1108	362	387
8	1050	1269	503	244
9	1166	1386	611	336

Table 8. Average travel time of empty 72 t trucks in target shifts (s).

Loading points	Unloading points			
	Crusher	Dump 1950	Dump 2250	Dump 2275
1	327	223	1259	1496
2	253	143	1158	1421
3	241	204	1213	1449
4	396	269	814	821
5	273	183	1204	1440
6	895	1154	326	726
7	973	1211	378	403
8	1144	1400	541	284
9	1278	1537	668	346

6. Results and discussion

The developed GP model was used to solve the truck allocation problem in the target shift of Sungun copper mine. The prepared code that employs CPLEX Version 12.6 optimizer software is used to solve the model. The input parameters of the GP model were derived from the data presented in the previous section (Tables 1-8). As discussed earlier, the output decision variables of the GP model were loaded truck rates, travelling from loading points to dump points and empty truck rates, returning from dump points to loading points for both truck types. Tables 9 and 10 present the indicated truck rates for the loaded and unloaded trucks along various routes of the transportation network, respectively.

The required numbers of trips for each route of transportation network were calculated based on the expected values for the truck rates (Tables 9 and 10) and reported, respectively, in Tables 11 and 12 for both truck types.

Table 9. Truck rates for loaded trucks (from loading points to dump points) in target shift.

Loading point	Destination	Truck rates for 32 t truck type (truck per minutes)	Truck rates for 72 t truck type (truck per minutes)
1	Crusher	0.01	-
2	Crusher	-	0.09
3	Crusher	0.001	0.09
4	Crusher	0.14	-
5	Dump 1950	-	0.14
6	Dump 2250	0.30	-
7	Dump 2250	0.30	-
8	Dump 2275	0.30	-
9	Dump 2275	0.70	-

Table 10. Truck rates for empty trucks (from dump points to loading points) in target shift.

Destination	Loading point	Truck rates for 32 t truck type (truck per minutes)	Truck rates for 72 t truck type (truck per minutes)
Crusher	1	0.01	-
	2	-	0.03
	3	0.001	-
	4	0.14	-
	5	-	0.14
Dump 1950	2	-	0.06
	3	-	0.09
Dump 2250	6	0.30	-
	7	0.30	-
Dump 2275	8	0.30	-
	9	0.70	-

Table 11. Number of trips from loading points to dump points for both truck types.

Loading points	Dump points	The number of trips for 32 t trucks (per shift)	The number of trips for 72 t trucks (per shift)
1	crusher	7	-
2	Crusher	-	42
3	Crusher	1	42
4	crusher	68	-
5	Dump 1950	-	69
6	Dump 2250	144	-
7	Dump 2250	144	-
8	Dump 2275	144	-
9	Dump 2275	338	-

Table 12. Number of trips from dump points to loading points for both truck types.

Dump points	Loading Points	The number of trips for 32 t trucks (per shift)	The number of trips for 72 t trucks (per shift)
Crusher	1	7	-
	2	-	14
	3	1	-
	4	68	-
	5	-	69
Dump 1950	2	-	28
	3	-	42
Dump 2250	6	144	-
	7	144	-
Dump 2275	8	144	-
	9	338	-

The results of truck rates presented in Table 9 were translated to production tons in order to determine the expected production of ore materials or waste rocks transported from different loading points to specified dump points throughout target working shift, considering the load capacity of truck types. The obtained production rates of loaders are summarized in Table 13.

Referring to Table 13, the GP model provides a total production of 38000 t (8400 t ore materials and 29600 t waste rocks) in considered working shift of 8 h. According to the Sungun copper mine short-term production plan, the total production of 31500 t (7000 t ore materials and 24500 t waste rocks) was scheduled in this shift. Comparison of the results obtained from the GP model with the current truck allocation policy of mine indicates that the proposed GP model increases 6500 t of the total production (1400 t ores and 5100 t waste rocks) in the target shift. In other words, utilization of the new developed GP model generates a suitable truck allocation plan that increases above 20.6% in mine total production with respect to the current policy:

$$\frac{38000-31500}{31500}\times 100 \cong 20.6\ \%$$

This improvement demonstrates that the proposed model provides more effective and efficient usage of the loader-truck resources.

Considering the average grade of ore materials in four loading points (see Table 1) and expected production of these loading points (Table 13), the average grade of ore materials feed to processing plant was 0.73%. As mentioned earlier, in Sungun copper mine, the desired grade of ore materials feed to processing plant was 0.73%. It means that the truck allocation plan obtained by the developed GP model exactly satisfies the grade requirements of mine. Moreover, according to Table 13, stripping ratio is 29600/8400 ≅ 3.52, demonstrating that the generated truck allocation plan satisfies the stripping ratio constraint as well.

From the above discussed results, it is evident that the developed goal programming model provides an effective truck allocation plan that meets the desired production goals and operational constraints.

Table 13. Expected production of different loading points based on desired truck rates.

Loading points	Production (tons per shift)	
	Ore materials	Waste rocks
1	210	-
2	3000	-
3	3000	-
4	2190	-
5	-	5000
6	-	4600
7	-	4600
8	-	4600
9	-	10800
Total	**8400**	**29600**

7. Conclusions

In this work, a goal programming model was developed to provide a truck allocation plan in open pit mines considering four desired goals: "maximizing shovel production", "minimizing deviations in head grade", "minimizing deviations in tonnage feed to the processing plants", and "minimizing truck operating costs". To run the developed model, a computer program was prepared in Visual Studio with C# programming language, in which the CPLEX optimizer software was incorporated for solving the developed model. The case study of Sungun copper mine was selected to evaluate the efficiency of the presented model. The results obtained showed that the developed GP model improved the mine production rate above 20.6% in comparison with the traditional truck allocation policy, and satisfied the stripping ratio constraint with respect to the considered upper and lower stripping limits. Additionally, the GP model exactly satisfied the desired grade of the processing plant.

The results obtained demonstrated that the developed model provided a more effective usage of the loader-truck resources and proved the efficiency of the model to work as the upper stage of a multi-stage truck dispatching system.

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Appendix

Notations

Index for variables parameters and sets

i index for set of $n_s$shovels (Include: number of n_{os}ore shovels, number of n_{xs} oxide shovels, number of n_{ls} low grade ore shovels)

j index for set of n_d destinations (number of $n_c$crusher, number of n_{xd} oxide dumps, number of n_{ld} low grade ore dumps)

k index for set of n_q material types

h index for set of n_d truck types trucks

P index for set of d_p processing plants

Decision variables

X_{ijh} Production to assign from source i (shovel) to destination j (crusher/dumps) per shift by truck h

Auxiliary variables

Y_{jih} Empty truck capacity to assign from destination j to source i per shift by truck h

d_i^- Negative deviational variable for shovel i's production

C_{kj}^+ Positive deviational variable of ore quality k at crusher j

C_{kj}^- Negative deviational variable of ore quality k at crusher j

δ_p^+ Positive deviation of tonnage content of material type k compared to tonnage content desired, based on desired grade at the ore destinations

δ_p^- Negative deviation of tonnage content of material type k compared to tonnage content desired, based on desired grade at the ore destinations

Complementary Parameters

W_1 priority factor for shovel production goal

W_2 priority factor for ore quality goal

W_3 priority factor for tonnage supplied to processing plants goal

W_4 priority factor for the operating truck costs goal

Parameters

d_{ij} Distance from source i to destination j (km)

T_h weighted average payload of a truck h

N_h Number of truck h

W_t Hours per shift

P_{u_i} Maximum production of source i per shift (ton)

Q_i Average production of source i per shift (ton)

C_j Maximum available capacity of destination j per shift

R_l Prescribed lower limit of stripping ratio

R_u Prescribed upper limit of stripping ratio

H_{ijh} Average travel time of shovel i to destination j by truck h (s)

D_{jh} Average dumping time at destination j by truck h (s)

SD_{jh} Average spotting time at destination j by truck h (s)

R_{jih} Average traveling time from destination j to shovel i by truck h (s)

S_{ih} Average loading time at source i by truck h (s)

SS_{ih} Average spotting time at source i by truck h (s)

Cf_h Cost of loaded truck h movement ($/km)

G_{ik} Value of ore quality k at source i (percent)

Q_{kj} Target value of ore quality k at crusher j (percent)

L_{kj} Prescribed lower limit of ore quality k at crusher j (percent)

U_{kj} Prescribed upper limit of ore quality k at crusher j (percent)

PL_{kp} Minimum acceptable tonnage received of ore quality k at processing plants p
(tonne/h)

PU_{kp} Maximum acceptable tonnage received of ore quality k at processing plants p
(tonne/h)

توسعه یک مدل برنامه‌ریزی آرمانی برای بهینه‌سازی تخصیص کامیون در معادن روباز

مهرناز محتشم[1]، حسین میرزائی نصیرآباد[1]* و عباس محمودی مرکید[2]

۱- دانشکده مهندسی معدن، دانشگاه صنعتی سهند تبریز، ایران

۲- دانشکده مهندسی برق، دانشگاه صنعتی سهند تبریز، ایران

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* نویسنده مسئول مکاتبات: hmirzaei@sut.ac.ir

چکیده:

عملیات کامیون- شاول تقریباً ۶۰ درصد از کل هزینه‌های عملیات استخراج را در معادن روباز شامل می‌شود. برای افزایش کارایی عملیات و کاهش هزینه‌های عملیات معدنکاری، لازم است تجهیزات به طور مؤثر مدیریت شوند. در این مطالعه مدل برنامه‌ریزی آرمانی ارائه شده توسط میکولاپولوس و پاناگیوتو، برای تعیین طرح بهینه تخصیص کامیون در معادن روباز و کاهش زمان‌های انتظار کامیون‌ها و شاول‌ها، توسعه داده شده است. مدل برنامه‌ریزی آرمانی توسعه داده شده با در نظر گرفتن چهار هدف: «افزایش تولید شاول»، «کاهش انحرافات در عیار»، «کاهش انحرافات در خوراک کارخانه فرآوری نسبت به مقدار مطلوب» و «کاهش هزینه‌های عملیاتی کامیون» ساخته شده است. برای به کارگیری مدل توسعه داده شده، یک نرم‌افزار کامپیوتری به زبان سی شارپ در محیط ویژوال استودیو تهیه شده است. در این برنامه کامپیوتری، برای حل مدل برنامه‌ریزی آرمانی توسعه داده شده، نرم‌افزار CPLEX به کار گرفته شده است. برای ارزیابی مدل برنامه‌ریزی آرمانی ارائه شده و نرم‌افزار تهیه شده، معدن مس سونگون به عنوان مورد مطالعاتی در نظر گرفته شده است. نتایج به دست آمده بیانگر این است که مدل توسعه داده شده مقدار تولید معدن را در مقایسه با طرح رایج تخصیص کامیون، به اندازه ۲۰/۶ درصد افزایش می‌دهد در حالی که محدودیت‌های عیار و نسبت باطله برداری به طور مطلوب تأمین می‌شوند.

کلمات کلیدی: ترابری، بهینه‌سازی تولید، تخصیص کامیون، برنامه‌ریزی آرمانی، نرم‌افزار تخصیص کامیون.