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A Comparison between Various Dispatching Strategies for Truck-Shovel Productivity Optimization in Open Pit Mines

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ABSTRACT

In order to improve the efficiency of truck-shovel transportation systems and to decrease the relevant operational cost, an appropriate truck dispatching strategy should be utilized. In this paper, a modified Li model is used to cover heterogeneous fleet size. An extra goal of "minimizing the truck operating cost" was appended to the objective function of the modified Temeng model. Sungun Copper Mine transportation system was considered as a case study to evaluate the performance of three dispatching models: Extended Li model, Temeng model, and Developed Temeng model. In the different routes of mine transportation network, using these models the truck flow rates and the number of truck trips were determined. In order to implement these models, the CPLEX software was utilized. The results indicated that Extended Li model, Temeng model, and Developed Temeng model all improve the total production above 38%, 25%, and 25% respectively compared to the current mine production plan. Each of three dispatching models satisfies various operational constraints such as ore grade quality and stripping ratio.

Keywords : *CPLEX, Li Model, Open pit mine transportation, Temeng Model, Truck dispatching*

1. Introduction

Ore and waste material transportation is one of the major activities in open pit mining operations. The truck-shovel system is the most common method of material handling in open pit mines due to their inherent flexibility. The truck-shovel operations are highly expensive and comprise 50-60% of the total direct operational cost of open pit mines [1]. Hence, optimal control and management of truck fleet is an essential task in order to reduce the operational cost and to improve the total productivity of the mine.

A typical transportation network in an open pit mine is schematically illustrated in Fig 1. Several trucks are loaded by several operational shovels at different production places in the pit. The trucks travel across many feasible routes toward different dumping points (crusher, low-grade stockpiles, or waste dumping points), and they return empty to loading points to complete a haulage cycle.

The dispatching problem is the dynamic allocation of empty trucks throughout the operating shift. In order to reduce the operational cost and to improve the efficiency of the truck-shovel system, the dispatching problem should be solved considering various criteria such as maximization of total production, minimization of re-handling cost, meeting of the blending requirements, minimization of the grade deviation and finally the minimization of the trucks operation cost. Therefore, a dispatching algorithm will be required to achieve the mentioned objectives [2].

During the last decades, different authors have presented various mathematical methods to solve the dispatching problem. The various dispatching models are grouped into two categories: single-stage and multi-stage approaches.

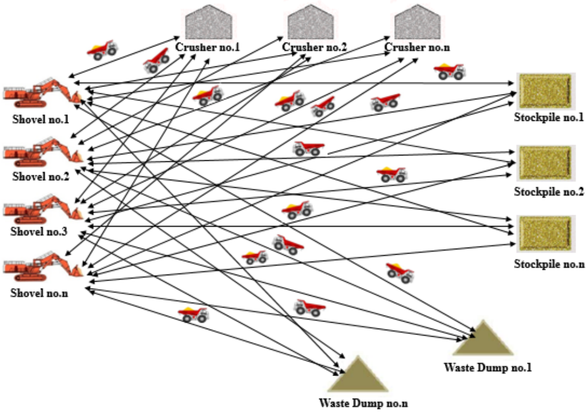

Fig 1. Schematic representation of a transportation system in an open pit mine

Single stage approaches are heuristic models which simply allocate the trucks to the shovels considering one or some objectives without any production targets or constraints [3]. For example, the dispatching models developed by Lizotte and Bonates (1987) [4], Forsman et al. (1993) [5], Ataeepour and Baafi (1999) [6], Panagiotou and Michalakopoulos (2001) [7], Bissiri (2002) [8], He (2010) [9], Souza (2010) [10], Arelovich (2010) [11], and Bastos (2013) [12], are all based on single stage strategy.

Multi-stage approaches include two main parts: first, the production rates of routes are determined based on short-range planning goals using a linear or nonlinear programming model. At the second stage, the trucks are allocated to the shovels based on the optimal solutions of the first part using heuristics or mathematical methods [3]. The dispatching

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models developed by White and Olson (1986) [13], Soumis and Elbrond (1987) [14], Lizotte and Bonates (1987) [4], Soumis et al. (1989) [15]. Li (1990) [16], Xi and Yegulalp (1993) [17], Temeng (1997) [18], Subtil et al (2011) [19], and Ahangaran et al (2012) [20] are all based on multistage strategy.

When compared with the results of single stage algorithms, the multistage dispatching algorithms produce more desirable results. Nevertheless, they also have some shortcomings. The mine configuration and the goals of mine managers restrict the efficiency of these strategies in some cases. For example, the well-known Li model is only practical when the truck fleet is homogeneous, and it does not consider some operational constraints [16]. Temeng model only considers two goals among different technical and operational criteria and it overlooks some operational constraints [18]. Therefore, considering the configurations and the requirements of an open pit mine, the mentioned shortcomings should be handeled and the models should become more generalized. Furthermore, in order to assess the efficiency of different models, it is necessary to compare the outcomes of models in the transportation system of a large-scale open pit mine.

In this paper, first the Li methodology was extended to include the different size of trucks in the fleet and subsequently, the Temeng model was modified to integrate one additional goal in the objective function of the prepared goal programming framework. Finally, the efficiency of the dispatching models including Extended Li model, Temeng model - by Oraee and Asi (2004) [21], and Developed Temeng model were assessed in the transportation network of Sungun Copper Mine. The studies indicated that the extended models improve the total production of mine substantially while they satisfy the governing operational and technical constraints.

2. Multistage Solution Strategies for Truck-Shovel System

The dispatching problem of open pit mines is a complicated process. Ensuring the optimality of several economic and technical criteria and simultaneously considering various technical and operational constraints are essential in this process. Therefore, in the last decades, a considerable amount of research has been carried out to solve this complex problem.

White and Olson (1986) have developed a multistage dispatching algorithm to optimize truck-shovel productivity by minimizing the operational cost and considering the mine production capacity, blending quality, and processing plant feed rate. The first stage of this algorithm is a linear programming model, and the second stage is a dynamic programming model which utilizes the solution of the first part to assign the best truck to the shovel most urgently in need [13]. Alarei (2002) argued that the second stage is not a dynamic programming model [1].

Lizotte and Bonates (1988) proposed an algorithm which in its first stage is a linear programming model, and the second stage takes advantage of heuristic procedures to assign the trucks on the basis of the solution of the first stage [22].

Soumis and Elbrond (1987) suggested a multistage truck dispatching method as well. First, a nonlinear programming model is used to determine the optimal truck flow rate (in terms of trucks per unit of time) from each shovel to each dumping point. In the second stage, an assignment problem is solved to assign trucks by minimizing the deviation of the truck waiting time values from the expected value [14].

In the multistage dispatching algorithm presented by Soumis el al (1989), the first stage itself consists of two sub-stages. In the first sub-stage, a MILP (Mixed-Integer Linear Programming) model maximizes mine production with consideration of different constraints. Then, an NLP model is used to solve the truck travel plan between loading and dumping points. Three objective functions are considered in the NLP model which are the minimization of the deviations in head grade, shovel production, and available truck hours. In the second stage, an algorithm is solved to assign trucks by minimizing the deviation of the truck waiting times from the expected value based on the assignment problem [15].

Li (1990) presented a methodology for the optimum control of shovel and truck operations in open pit mines. The first part of his model applied a linear programming technique to optimize the haulage planning by minimizing the total transportation work. The second part employed a heuristic dispatching rule, called maximum inter-truck time deviation, to assign the trucks based on the flow rate determined in the previous stage [16]. This algorithm involves a homogeneous truck fleet and will be discussed in more details in the next part.

Temeng et al. (1997) developed a multistage dispatching algorithm to maximize tonnage production and to satisfy the blending requirements. In the first stage, the goal programming model is employed to evaluate the optimal production rate from each shovel to each dumping point. In the second part, an assignment technique is used to select the shovels, most urgently in need of service by trucks. The technique minimizes the deviation of the cumulative tonnage of each shovel route from the target as obtained in the first part. Trucks are assigned to needy shovels in order to minimize the total waiting time of both shovels and trucks and to maximize the total production of mine [18]. Alarie (2002) argued that the dispatching decisions of Temeng model underestimate waiting times because the waiting time of a truck at a shovel depends on the assignment of other trucks to this shovel [1].

Subtil et al. (2011) have developed a multistage dispatching algorithm which its upper stage uses LP (Linear Programming) model to determine the maximum production capacity of mines. In the second part, a dispatching strategy of assigning M trucks for N shovels was employed based on Alarie and Gamacheis (2002) [19].

In the multistage dispatching algorithm presented by Ahangaran et al. (2012), the first stage uses a network analysis technique to determine the optimal routes between loading and dumping points. The second part employs a MILP model to dynamic truck assignments by minimizing the total cost of loading and transportation [20].

Upadhyay and Askari-Nasab (2015) presented a Mixed Integer Linear Goal Programming (MILGP) model to optimize the production and truck-shovel allocation based on four goals at the operational level. This model assigns the shovels to the available faces and allocates the trucks to the best shovels based on four goals: to maximize production, to minimize deviations in head grade, to minimize deviations in tonnage fed to the processing plants, and to minimize operating costs [23].

3. Development of Models

The aim of this paper is to generalize the well-known Li and Temeng models and evaluate their results. So, the Li model is extended to include the different size of trucks in the fleet, and the Temeng model is modified to integrate one additional goal in its objective function.

The following section explains the details of the preliminary equations and the formulation of the developed models along with the required inputs of the models. The parameters and variables considered in the models are described in the Appendix.

3.1. Development of Li Methodology

As mentioned before, Li (1990) proposed a combinatorial technique for systematic and dynamic management of the haulage planning, truck dispatching, and equipment matching problems. The first part of the algorithm is a linear programming model with the objective of minimizing the total transportation work (W) per time unit which is defined as the product of transported weight and hauled distance.

Since most of the open pit mines use heterogeneous fleets, the dispatching algorithm should be capable of considering this heterogeneity. The model presented by Li is based on homogeneous fleet size, and it does not guarantee the optimality of shovels production. Moreover, this model does not consider some of the other constraints such as maximum and minimum rate of productivity of shovels, the available number of trucks and shovels, minimum amount of ore and waste production, average waiting times and queue at servers, and upper and lower limits of material grades during the shift.

In order to overcome the mentioned shortcomings of Li model, the model was generalized with the same methodology by considering the heterogeneous fleet size and additional practical constraints. So, the new modified objective function and relevant subjected constraints for the improved model are set as follows:

$$\begin{aligned} Min\ W = &\sum_{i=1}^{n_{os}}\sum_{j=1}^{n_c}\sum_{h=1}^{n_h} X_{ijh}(Z_{1h}+Z_{2h})\sum_{k=1}^{k_{ij}} D_{ij}^{(k)} \\ &+ \sum_{i=1+n_{os}}^{n_{os}+n_{xs}}\sum_{j=1+n_c}^{n_c+n_{xd}}\sum_{h=1}^{n_h} X_{ijh}(Z_{1h}+Z_{3h})\sum_{k=1}^{k_{ij}} D_{ij}^{(k)} \\ &+ \sum_{i=1+n_{os}+n_{xs}}^{n_{os}+n_{xs}+n_{ls}}\sum_{j=1+n_c+n_{xd}}^{n_c+n_{xd}+n_{ld}}\sum_{h=1}^{n_h} X_{ijh}(Z_{1h}+Z_{4h})\sum_{k=1}^{k_{ij}} D_{ij}^{(k)} \\ &+ \sum_{i=1+n_{os}+n_{Xs}+n_{ls}}^{n_s}\sum_{j=1+n_c+n_{xd}+n_{ld}}^{n_d}\sum_{h=1}^{n_h} X_{ijh}(Z_{1h}+Z_{5h})\sum_{k=1}^{k_{ij}} D_{ij}^{(k)} + \sum_{j=1}^{n_d}\sum_{i=1}^{n_s}\sum_{h=1}^{n_h} Y_{jih}(Z_{1h})\sum_{k=1}^{k_{ij}} D_{ji}^{(k)} \end{aligned} \tag{1}$$

Subject to:

$$W_t\sum_{i=1}^{n_{os}}\sum_{j=1}^{n_c}\sum_{h=1}^{n_h} X_{ijh}z_{2h} \geq \mathrm{F}_o \tag{2}$$

$$W_t\sum_{i=1+n_{os}}^{n_s}\sum_{j=1+n_c}^{n_d}\sum_{h=1}^{n_h} X_{ijh}z_{5p} \geq F_w \tag{3}$$

$$W_t\sum_{j=1}^{n_c}\sum_{h=1}^{n_h} X_{ijh}z_{2h} \leq \mathrm{P}_{u_i} \qquad \forall i = 1,\dots,n_{os} \tag{4}$$

$$W_t\sum_{j=1+n_c}^{n_c+n_{xd}}\sum_{h=1}^{n_h} X_{ijh}z_{3h} \leq P_{u_i} \qquad \forall i = 1+n_{os},\dots,n_{os}+n_{xs} \tag{5}$$

$$W_t\sum_{j=1+n_c+n_{xd}}^{n_c+n_{xd}+n_{ld}}\sum_{h=1}^{n_h} X_{ijh}z_{4h} \leq P_{u_i} \qquad \forall i = 1+n_{os}+n_{xs},\dots,n_{os}+n_{xs}+n_{ls} \tag{6}$$

$$W_t\sum_{j=1+n_c+n_{xd}+n_{ld}}^{n_d}\sum_{h=1}^{n_h} X_{ijh}z_{5h} \leq P_{u_i} \qquad \forall\ i = 1+n_{os}+n_{xs}+n_{ls},\dots,n_s \tag{7}$$

$$W_t\sum_{j=1}^{n_c}\sum_{h=1}^{n_h} X_{ijh}z_{2h} \geq P_{l_i} \qquad \forall i = 1,\dots,n_{os} \tag{8}$$

$$W_t\sum_{j=1+n_c}^{n_c+n_{xd}}\sum_{h=1}^{n_h} X_{ijh}z_{3h} \geq P_{l_i} \qquad \forall i = 1+n_{os},\dots,n_{os}+n_{xs} \tag{9}$$

$$W_t\sum_{j=1+n_c+n_{xd}}^{n_c+n_{xd}+n_{ld}}\sum_{h=1}^{n_h} X_{ijh}z_{4h} \geq P_{l_i} \qquad \forall i = 1+n_{os}+n_{xs},\dots,n_{os}+n_{xs}+n_{ls} \tag{10}$$

$$W_t\sum_{j=1+n_c+n_{xd}+n_{ld}}^{n_d}\sum_{h=1}^{n_h} X_{ijh}z_{5h} \geq P_{l_i} \qquad \forall i = 1+n_{os}+n_{xs}+n_{ls},\dots,n_s \tag{11}$$

$$W_t\sum_{i=1}^{n_{os}}\sum_{h=1}^{\mathrm{n_h}} X_{ijh}z_{2h} \leq C_j \qquad \forall j = 1,\dots,n_c \tag{12}$$

$$W_t\sum_{i=1+n_{os}}^{n_{os}+n_{xs}}\sum_{h=1}^{\mathrm{n_h}} X_{ijp}z_{3h} \leq C_j \qquad \forall j = 1+n_c,\dots,n_c+n_{xd} \tag{13}$$

$$W_t\sum_{i=1+n_{os}+n_{xs}}^{n_{os}+n_{xs}+n_{ls}}\sum_{h=1}^{\mathrm{n_h}} X_{ijp}z_{4h} \leq C_j \qquad \forall j = 1+n_c+n_{xd},\dots,n_c+n_{xd}+n_{ld} \tag{14}$$

$$W_t\sum_{i=1+n_{os}+n_{xs}+n_{ls}}^{n_s}\sum_{h=1}^{\mathrm{n_h}} X_{ijp}z_{5h} \leq C_j \qquad \forall j = 1+n_c+n_{xd}+n_{ld},\dots,n_d \tag{15}$$

$$\sum_{j=1}^{n_d} Y_{jih} = \sum_{j=1}^{n_d} X_{ijh} \qquad \begin{aligned}&\forall i = 1,\dots,n_s\\ &\forall h = 1,\dots,\mathrm{n_h}\end{aligned} \tag{16}$$

$$\sum_{\mathrm{i}=1}^{\mathrm{n_s}} X_{ijh} = \sum_{\mathrm{i}=1}^{\mathrm{n_s}} Y_{jih} \qquad \begin{aligned}&\forall j = 1,\dots,n_d\\ &\forall h = 1,\dots,\mathrm{n_h}\end{aligned} \tag{17}$$

$$\sum_{i=1}^{n_{os}}\sum_{h=1}^{n_h} X_{ijh}z_{2h}\,Q_{kj} \leq U_{Kj}\sum_{i=1}^{n_{os}}\sum_{h=1}^{n_h} X_{ijh}z_{2h} \qquad \begin{aligned}&\forall j = 1,\dots,n_c\\ &\forall k = 1,\dots,n_q\end{aligned} \tag{18}$$

$$\sum_{i=1}^{n_{os}}\sum_{h=1}^{\mathrm{n_h}} X_{ijh}z_{2p}\,Q_{kj} \geq L_{kj}\sum_{i=1}^{n_{os}}\sum_{h=1}^{n_h} X_{ijh}z_{2p} \qquad \begin{aligned}&\forall j = 1,\dots,n_c\\ &\forall k = 1,\dots,n_q\end{aligned} \tag{19}$$

$$\sum_{i=1}^{n_s}\sum_{j=1}^{n_d} X_{ijh}(H_{ijh}+D_{jh}+SD_{jh}) + \sum_{j=1}^{n_d}\sum_{i=1}^{n_s} Y_{jih}(R_{jih}+S_{ih}+SS_{ih}) \le N_h \qquad \forall h = 1, \dots, n_h \qquad (20)$$

$$X_{ijh}, Y_{jih} \ge 0 \qquad (21)$$

The constraints of (2) and (3) fulfill the minimum required production amount of ore and waste per shift, respectively. The constraints of (4), (5), (6), and (7) satisfy the minimum expected production of shovels for ore, oxide, low grade, and waste material, respectively. The maximum expected production of shovels for ore, oxide, low grade, and waste material is satisfied with the constraints (8), (9), (10), and (11), respectively. The constraints of (12), (13), (14), and (15) ensure that the capacities of dumping points for ore, oxide, low grade, and waste materials are considered, respectively. Constraints (16) and (17) assure that the number of incoming empty trucks is equal to the number of outgoing loaded trucks for each loading point. Equations (18) and (19) are blending constraints which guarantee the suitable ore grade fed to the crushers. Constraint (20) ensures that the total production of shovels does not exceed the available trucks or the production target. Finally, constraint (21) guarantees positive values for variables.

3.2. The Developed Temeng Model

As explained above, Temeng et al. (1997) established a goal programming model for truck allocation system in order to maximize production and to minimize the total waiting time of shovels and trucks. The objective function of the goal programming model includes production rate and ore grade. This model optimizes the total production by minimizing the cumulative deviations of the optimal production target.

The Temeng Model suffers from some drawbacks including the homogeneity of fleet size, overlooking the minimum amount of ore and waste production, and disregarding of the waiting time and queue at servers.

To overcome these shortcomings, Oraee and Asi (2004) improved the Temeng model. The objective function of this model remained the same as the original Temeng model. However, the governing constraints were rearranged to generalize the Temeng model.

3.3. Development of Temeng Model for Optimization of Truck-Shovel System

In the transportation systems of open pit mines, the truck operating cost is one of the most important issues which affect the total operational cost. So, considering this factor in dispatching problems is essential. Consequently, an additional goal of “minimizing the truck operating cost” was added to the objective function of the modified Temeng model (by Oraee & Asi). The final objective function of the developed model is given by equation (22). The modified constraints are set as equations (23) to (40):

$$Min\ Z = W_1 \sum_{i=1}^{n_s} \frac{d_i^-}{\| d_i \|} + W_2 \sum_{j=1}^{n_c}\sum_{k=1}^{n_q} \frac{(C_{kj}^- + C_{kj}^+)}{\| C_{kj} \|} + W_3 \frac{\sum_{i=1}^{n_s}\sum_{j=1}^{n_d}\sum_{h=1}^{n_h} X_{ijh} \times d_{ij} \times Cf_h}{\| \psi \|} \qquad (22)$$

$$\psi = \sum_{i=1}^{n_s}\sum_{j=1}^{n_d}\sum_{h=1}^{n_h} X_{ijh} \times d_{ij} \times Cf_h \qquad (23)$$

Subject to:

$$\sum_{j=1}^{n_c}\sum_{h=1}^{n_h} X_{ijh} + d_i^- = Q_i \qquad \forall i = 1, \dots, n_{os} \qquad (24)$$

$$\sum_{h=1}^{n_h}\sum_{j=n_c+1}^{n_c+n_{xd}} X_{ijh} + d_i^- = Q_i \qquad \forall i = n_{os}+1, \dots, n_{os}+n_{xs} \qquad (25)$$

$$\sum_{h=1}^{n_h}\sum_{j=n_c+n_{xd}+1}^{n_c+n_{xd}+n_{ld}} X_{ijh} + d_i^- = Q_i \qquad \forall i = n_{os}+n_{xs}+1, \dots, n_{os}+n_{xs}+n_{ls} \qquad (26)$$

$$\sum_{h=1}^{n_h}\sum_{j=n_c+n_{xd}+n_{ld}+1}^{n_d} X_{ijh} + d_i^- = Q_i \qquad \forall i = n_{os}+n_{xs}+n_{ls}+1, \dots, n_s \qquad (27)$$

$$\sum_{i=1}^{n_{os}}\sum_{h=1}^{n_h} X_{ijh} * G_{ik} + C_{kj}^- - C_{kj}^+ = Q_{kj} \sum_{i=1}^{n_{os}}\sum_{h=1}^{n_h} X_{ijh} \qquad \begin{array}{l} \forall\, k = 1, \dots., n_q \\ \forall j = 1, \dots., n_c \end{array} \qquad (28)$$

$$C_{kj}^- \le (Q_{kj} - L_{kj}) \sum_{i=1}^{n_{os}}\sum_{h=1}^{n_h} X_{ijh} \qquad \begin{array}{l} \forall k = 1, \dots, n_q \\ \forall j = 1, \dots, n_c \end{array} \qquad (29)$$

$$C_{kj}^+ \le (U_{kj} - Q_{kj}) \sum_{i=1}^{n_{os}}\sum_{h=1}^{n_h} X_{ijh} \qquad \begin{array}{l} \forall k = 1, \dots, n_q \\ \forall j = 1, \dots, n_c \end{array} \qquad (30)$$

$$\sum_{j=1}^{n_d}\sum_{h=1}^{n_h} X_{ijh} \le P_{u_i} \qquad \forall i = 1, \dots, n_s \qquad (31)$$

$$\sum_{i=1}^{n_{os}}\sum_{j=1}^{n_c}\sum_{h=1}^{n_h} X_{ijh} \ge F_o \qquad (32)$$

$$\sum_{i=1+n_{os}}^{n_s}\sum_{j=1+n_c}^{n_d}\sum_{h=1}^{n_h} X_{ijh} \geq F_w \tag{33}$$

$$\sum_{i=1}^{n_s}\sum_{h=1}^{n_h} X_{ijh} \leq C_j \qquad \forall j = 1, \dots, n_d \tag{34}$$

$$\sum_{j=1}^{n_d} X_{ijh} = \sum_{j=1}^{n_d} Y_{jih} \qquad \begin{matrix}\forall i = 1, \dots, n_s \\ \forall h = 1, \dots, n_h\end{matrix} \tag{35}$$

$$\sum_{i=1}^{n_s} X_{ijh} = \sum_{i=1}^{n_s} Y_{hji} \qquad \begin{matrix}\forall j = 1, \dots, n_d \\ \forall h = 1, \dots, n_h\end{matrix} \tag{36}$$

$$\frac{\sum_{i=1+n_{os}}^{n_s}\sum_{j=1+n_c}^{n_d}\sum_{h=1}^{n_h} X_{ijh}}{\sum_{i=1}^{n_{os}}\sum_{j=1}^{n_c}\sum_{h=1}^{n_h} X_{ijh}} \geq R_l \tag{37}$$

$$\frac{\sum_{i=1+n_{os}}^{n_s}\sum_{j=1+n_c}^{n_d}\sum_{h=1}^{n_h} X_{ijh}}{\sum_{i=1}^{n_{os}}\sum_{j=1}^{n_c}\sum_{h=1}^{n_h} X_{ijh}} \leq R_u \tag{38}$$

$$\begin{aligned}&\sum_{i=1}^{n_s}\sum_{j=1}^{n_d} H_{ijh}X_{ijh} + \sum_{j=1}^{n_d}\sum_{i=1}^{n_s} R_{jih}Y_{jih} + \sum_{i=1}^{n_s}\sum_{j=1}^{n_d} D_{jh}X_{ijh} + \sum_{i=1}^{n_s}\sum_{j=1}^{n_d} SD_{jh}X_{ijh} + \\ &\quad \sum_{j=1}^{n_d}\sum_{i=1}^{n_s} S_{ih}Y_{jih} + \sum_{j=1}^{n_d}\sum_{i=1}^{n_s} SS_{ih}Y_{jih} \leq W_t \times N_h \times T_h \qquad \forall h = 1, \dots, n_h\end{aligned} \tag{39}$$

$$X_{ijh}, Y_{jih}, \delta_p^-, \delta_p^+, C_{kj}^-, C_{kj}^+, d_i^- \geq 0 \tag{40}$$

The constraints (24), (25), (26), and (27) maximize the production by means of minimizing the negative deviations of each shovel production for ore, oxide, low grade, and waste materials, respectively. Equation (28) ensures that the average grade of ore fed to the processing plant has the desired grade and its deviation is within the given acceptable range. Constraints (29) and (30) limit the deviations of ore quality between the upper and lower acceptable limits. Constraint (31) is applied to reach the maximum loading capacity of shovels. Equations (32) and (33) are used to achieve the desired production of ore and waste materials. Constraint (34) satisfies the maximum capacity of dumping points. Constraints (35) and (36) are used to balance the material flows in different loading and unloading points. Constraints (37) and (38) limit the stripping ratio in the given range. Constraint (39) guarantees that the total production of shovels does not exceed the production target (with respect to the fleet capacity). Finally, constraint (40) ensures the positive value for model variables.

4. Case Study

The transportation system of Sungun Copper Mine was used to evaluate the efficiency of the three mentioned dispatching models. Sungun Copper Mine is located in the northwest of Iran. It has the maximum capacity of 20,000 tons per shift ore which is fed to the crusher and 800,000 tons per shift waste which is sent to three different waste dumping points. The minimum and maximum values of stripping ratio are 2.5 and 5, respectively. According to the mine production plan, the grade of ore material fed to the processing plant should be kept in the range of 0.68 to 0.78 percent, while, the optimum grade is 0.73 percent.

In the considered 8-hour shift of mining operations, nine loading points including four ore material extraction faces and five waste removal faces were active. The production rate of operating loaders was monitored during various shifts. The maximum and average production rate of these loaders were determined. Table 1 lists the operational characteristics of various loading points. The distance between different loading points and dumping points are listed in Table 2.

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)	Minimum production rate (ton/shift)	Average production rate (ton/shift)	Average grade (%)
1	1912.5	ore	Komatsu-600A	4800	300	3600	1.42
2	1950	ore	Komatsu-600A	4800	300	3600	0.74
3	1962.5	ore	NEWHOLLAND- 270	4000	250	3000	0.92
4	2100	ore	Komatsu-600A, Komatsu PC-800	8000	500	6000	0.39
5	1937.5	ore	Komatsu PC-800	6000	750	5000	-
6	2237.5	waste	CAT-988B	5600	700	4600	-
7	2262.5	waste	CAT-988B	5600	700	4600	-
8	2287.5	waste	CAT-988B	5600	700	4600	-
9	2312.5	waste	CAT-988B Komatsu PC-1250	13600	17000	10800	-

Table 2. Distance of loading points from dumping points in target shift (km)

Loading points	Dumping 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

The mine employs 25 Komatsu HD-325 haul trucks with a nominal capacity of 32 t and 10 Komatsu HD-785 trucks with a nominal capacity of 100 t. The practical capacity of HD-785 trucks is almost 72 t due to their depreciation. Average waiting and loading time for two types of trucks at different loading points as well as average waiting and dumping time of trucks at different dumping points are recorded.

The average travel time of loaded trucks (from loading points to dumping points) and the average travel time of empty trucks (from dumping points to production points) are summarized in Tables 3 and 4, respectively.

Table 3. Average travel time of loaded trucks in target shift (s).

Loading points	Unloading points							
	crusher		Dump 1950		Dump 2250		Dump 2275	
	32	72	32	72	32	72	32	72
1	442	506	-	-	-	-	-	-
2	323	363	-	-	-	-	-	-
3	362	408	-	-	-	-	-	-
4	378	396	-	-	-	-	-	-
5	-	-	225	268	1686	1417	1986	2356
6	-	-	1024	1154	368	504	993	1164
7	-	-	1108	171	362	378	540	638
8	-	-	1269	1382	503	541	244	284
9	-	-	1386	1537	611	668	336	346

For three established goals of Developed Temeng model, the weight of each goal should be determined based on the technical conditions and production schedule of the mine. In this work, the weights of three goals are assumed to be identical and equal to 0.33.

5. Results and Discussion

In order to implement the developed dispatching models and to solve the truck allocation problem in a target shift of Sungun Copper Mine, CPLEX software code was utilized. The required parameters of the three models were derived from the data presented in Table 1 to 4. The determined decision variables of three models include loaded and empty truck rates in the different routes of the mine transportation network.

Table 4. Average travel time of empty trucks in target shift (s).

Loading points	crusher		Dump 1950		Dump 2250		Dump 2275	
	32	72	32	72	32	72	32	72
1	284	327	193	223	1088	1259	1362	1496
2	221	253	124	143	1096	1158	1296	1421
3	247	241	263	204	1082	1213	1323	1449
4	378	396	635	269	742	814	744	821
5	275	273	162	183	1083	1204	1351	1440
6	803	895	1024	1154	283	326	665	726
7	843	973	1108	1211	362	378	387	403
8	1050	1144	1269	1400	503	541	244	284
9	1166	1278	1386	1537	611	668	336	346

The results of three models for truck rates (per min) and the number of trips among each route for loaded and empty trucks are presented in Table 5 and 6, respectively.

Based on the results of Tables 5 and 6, three models determine different truck flow rates for the transportation network. Consequently, three models indicate that the different configuration of trip numbers satisfy the desired objectives under the same constraints. These differences are due to the various nature of models which have different objective functions. The Li methodology tries to minimize the total transportation work, while the Temeng model (by Oraee and Asi) attempts to maximize shovel production and to minimize deviations values in grade; and the developed Temeng model includes three goals: maximizing shovel production, minimization of deviations in grade, and the minimization of the truck operating costs. Despite the significant differences in the results of models, each model seeks to determine the optimal distribution of truck flow rates in order to increase the performance of the transportation system.

Evaluating the efficiency of three models, based on truck flow rates and the number of trips is not reasonable. Therefore, the ore and waste production values resulting from each model was calculated. Considering the capacity of different truck models, the flow rates shown in Table 5 were converted to production rates. Subsequently, the production values of ore and waste materials which are transported in various routes between loading and dumping points were determined. The expected production improvement of each model based on the resultant production quantities of each loading point and the relevant stripping ratios are calculated and summarized in Table 7.

According to Table 7, the modified Li model provides a total production of 43700 t including 12100 t ore and 31600 t waste materials. Temeng model (by Oraee and Asi) predicts the transportation of 39466 t rocks including 9866 t ore and 29600 t waste materials. Finally, the developed Temeng model produces 39466 t including 9866 t ore and 29600 t waste materials for the considered shift. In this shift, the short-term production strategy of mine plans the total production of 31500 t including 7000 t ore and 24500 t waste materials. Hence, models 1, 2, and 3 improve the total ore production about 38%, 25%, and 25%, respectively. It is important that the truck rate distributions provided by models 2 and 3 shows significant differences. However, the final total production of these models is the same.

For three dispatching models, the average grade of ore materials fed to the processing plant was calculated based on the average grade of ore materials in four loading points (see Table 1) and the expected production of these loading points (see Table 7). For models 1, 2, and 3 the average grades of total ore production were 0.75, 0.73 and 0.73, respectively. As discussed earlier, in Sungun Copper Mine, the grade of ore material fed to the processing plant should be kept in the range of 0.68 to 0.78 percent, and the desired grade is 0.73 percent. Therefore, each of the three models satisfies the grade quality constraint while model 2 and 3 exactly provide the desired grade for the processing plant.

As mentioned earlier, the stripping ratios of three dispatching models are calculated and listed in Table 7 for the considered shift. The resulting stripping ratio of model 1 is 2.6 while models 2 and 3 both give the stripping ratio of 3. The prevailing constraints of mine restrict the stripping ratio between 2.5 and 5. Therefore, the investigated models all satisfy this constraint as well.

According to the discussed results, each of the three dispatching models leads to significant improvements in the total ore production of mine. Concurrently, they meet the various operational and technical constraints of mine. It is noticeable that the modified Li model shows better performance among the three models examined.

Table 5. Results of models: truck rates (rate) and the number of trips (num.) for loaded trucks (from loading points to dumping points) in target shift.

Loading points	Unloading points	32 tons truck						72 tons truck					
		Model 1*		Model 2**		Model 3***		Model 1*		Model 2**		Model 3***	
		rate	Num.	rate	Num.	rate	Num.	rate	Num.	rate	Num.	rate	Num.
1	crusher	0.15	72	0.05	22	-	-	-	-	-	-	0.02	10
2	crusher	0.19	91	0.2	94	-	-	-	-	-	-	0.09	42
3	crusher	0.16	77	-	-	-	-	-	-	0.09	42	0.09	42
4	crusher	-	-	0.21	99	0.21	99	0.15	72	-	-	-	-
5	Dump 1950	0.59	283	0.33	156	-	-	-	-	-	-	0.14	69
6	Dump 1950	-	-	0.28	135	-	-	-	-	0.005	3	-	-
6	Dump 2250	0.55	264	0.004	2	0.25	118	-	-	-	-	0.02	11
7	Dump 2250	-	-	-	-	0.3	144	0.11	53	0.31	64	-	-
8	Dump 2275	0.2	96	0.3	144	0.3	144	0.13	62	-	-	-	-
9	Dump 2275	-	-	-	-	0.7	338	0.27	130	0.31	150	-	-

* Modified Li model
** Temeng model by Oraee and Asi
*** Developed Temeng model

Table 6. Results of models: truck rates (rate) and the number of trips (num.) for empty trucks (from dumping points to loading points) in target shift.

Destination	source	32 tons truck						72 tons truck					
		Model 1*		Model 2**		Model 3***		Model 1*		Model 2**		Model 3***	
		rate	Num.	rate	Num.	rate	Num.	rate	Num.	rate	Num.	rate	Num.
crusher	1	-	-	-	-	-	-	0.01	5	-	-	-	-
Crusher	2	-	-	-	-	-	-	-	-	-	-	0.03	14
Crusher	3	0.16	77	-	-	-	-	-	-	-	-	-	-
crusher	4	-	-	-	-	0.21	99	0.15	72	-	-	-	-
crusher	5	0.34	163	0.33	156	-	-	-	-	-	-	0.14	69
crusher	6	0.12	58	-	-	-	-	-	-	-	-	0.02	10
crusher	-		-	-	-	-	-	-	-	0.09	42	-	-
Dump 1950	1	0.15	72	0.05	22	-	-	-	-	-	-	-	-
Dump 1950	2	0.19	91	0.2	94	-	-	-	-	-	-	0.06	29
Dump 1950	3	-	-	-	-	-	-	-	-	0.09	42	0.09	42
Dump 1950	4	-	-	0.21	99	-	-	-	-	-	-	-	-
Dump 1950	5	0.25	-	-	-	-	-	-	-	-	-	-	-
Dump 1950	6	-	-	0.16	77	-	-	-	-	0.005	3	-	-
Dump 1950	7	-	-	-	-	-	-	-	-	0.05	24	-	-
Dump 2250	1	-	-	-	-	-	-	-	-	-	-	0.02	10
Dump 2250	2	-	-	-	-	-	-	-	-	-	-	-	-
Dump 2250	6	0.55	264	0.004	2	0.25	118	-	-	-	-	-	-
Dump 2250	7	-	-	-	-	0.3	144	0.11	53	-	-	-	-
Dump 2275	8	0.2	96	0.3	144	0.3	144	0.13	62	-	-	-	-
Dump 2275	9	0.26	125	-	-	0.7	338	0.27	130	0.31	150	-	-

* Modified Li Model
** Temeng model by Oraee and Asi
*** Developed Temeng model

Table 7. Expected production of different loading points based on calculated truck rates and corresponding stripping ratios of three models.

Loading points	Model 1* Production (tons per shift) Ore materials	 Waste rocks	Model 2** Production (tons per shift) Ore materials	 Waste rocks	Model 3*** Production (tons per shift) Ore materials	 Waste rocks
1	2400	-	694	-	694	-
2	2400	-	3000	-	3000	-
3	2000	-	3000	-	300	-
4	5300	-	3172	-	3172	-
5	-	6800	-	5000	-	5000
6	-	6400	-	4600	-	4600
7	-	3520	-	4600	-	4600
8	-	6400	-	4600	-	4600
9	-	8480	-	10800	-	10800
Total	12100	31600	9866	29600	9866	29600
stripping ratio	$31600/12100 \cong 2.6$		$29600/9866 \cong 3$		$29600/9866 \cong 3$	
production improvement	$\frac{(43700-31500)}{31500} \times 100 \cong 38\%$		$\frac{(39466-31500)}{31500} \times 100 \cong 25\%$		$\frac{(39466-31500)}{31500} \times 100 \cong 25\%$	

* Modified Li model

** Temeng model by Oraee and Asi

*** Developed Temeng model

6. Conclusion

Optimal management of truck-shovel transportation system in open pit mines demands for an efficient truck allocation plan in order to reduce the cost and to improve productivity. In this research, the dispatching model presented by Li was extended to consider the different size of trucks in the fleet. Subsequently, Temeng model was modified to add an extra goal of "minimizing the operational cost" to the objective function in Goal Programming framework. Three dispatching models i.e. Modified Li methodology, Temeng Model (proposed by Oraee & Asi), and Developed Temeng Model were implemented for determination of the truck allocation plan for a work shift in Sungun Copper Mine, Northwestern Iran. In order to solve the established mathematical dispatching models, CPLEX software was employed. Output decision variables of these models include truck flow rates in different routes of the mine transportation network. These models resulted in significantly different truck rate distributions. Considering the capacities of allocated trucks on each route, the required numbers of trips for both types of trucks were calculated. The expected production of ore and waste materials were determined based on the truck rates for each of the three models. Moreover, the corresponding average grade of transported ore materials and stripping ratios were determined. The results indicate that the modified Li model, Temeng Model (by Oraee & Asi), and developed Temeng model all improve the total mine production by 38%, 25%, and 25% respectively for the target shift of mine, when compared to the current mine production plan. All the implemented models satisfy the various governing operational and technical constraints. It is remarkable that the efficiency of any truck dispatching strategy is related to the mine configuration and the needs of mine managers.

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Appendix

The notation of decision variables, parameters, sets, and constraints are as follows:

Table 1. List of parameters.

Symbol	Name/Description
n_s	Number of sources (shovels)
n_{os}	Number of ore shovels
n_{xs}	Number of oxide shovels
n_{ls}	Number of low grade ore shovels
n_d	Number of destinations
n_c	Number of crushers
n_{xd}	Number of oxide dumps
n_{ld}	Number of low-grade ore dumps
n_q	Number of ore qualities
n_h	Number of truck types
Z_{1h}	Net truck weight
Z_{2h}	Ore payload truck weight
Z_{3h}	Oxide payload truck weight
Z_{4h}	Low-grade ore payload truck weight
Z_{5h}	Waste payload truck weight
$D_{ij}^{(k)}$	Length factor of road segments k on path i to j
d_{ij}	Distance from source i to destination j
T_h	Weighted average payload of a truck
N_h	Number of truck h

W_t	Hours per shift
P_{u_i}	Maximum production of source i per shift
P_{l_i}	Minimum production of source i per shift
Q_i	Average production of source i per shift
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
F_o	Least required ore production
F_w	Least required waste production
H_{ijh}	Average travel time of shovel i to destination j by truck
D_{jh}	Average dumping time at destination j by truck h
SD_{jh}	Average spotting time at destination j by truck h
S_{ih}	Average loading time at source i by truck h
SS_{ih}	Average spotting time at source i by truck h
G_{ik}	Value of ore quality k at source i
Q_{kj}	Target value of ore quality k at crusher j
L_{kj}	Prescribed lower limit of ore quality k at crusher j
U_{kj}	Prescribed upper limit of ore quality k at crusher j
W_1	Priority factor for shovel production goal
W_2	Priority factor for ore quality goal
W_3	Priority factor for the operating truck costs goal
cf_h	Cost of loaded truck h movement ($/km)
$\lVert d_i \rVert$	Norm for ore quality goal
$\lVert C_{kj} \rVert$	Norm for ore quality goal
$\lVert \psi \rVert$	Norm for the operating truck costs goal

Table 2. List of variables.

Symbol	Name/Description
X_{ijh}	Truck flow rate along path i to j by truck h (model 1) Production to assign from source i to destination j by truck h (model 2 and 3)
Y_{jih}	Empty truck capacity to assign from destination j to source i 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