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A Goal Programming Model for Dispatching Trucks in an Underground Gold Mine

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Abstract

The cost of transporting mined materials in an underground mine is major. This cost typically represents between 50 to 60 percent of a mine's total operating costs. The problem of dispatching trucks in an underground gold mine is of major economic importance and warrants the use of a decision support model. The developments of a realistic decision-support model for the dispatching problem in an underground gold mine were addressed in this paper. The problem must address multiple conflicting objectives, and therefore, a goal programming model was formulated. The model was applied to a case study, the Red Lake underground gold mine, in Ontario, Canada. The results showed major improvements in meeting the multiple objectives of this problem versus a single objective model. The results also illustrate the flexibility that the dispatching problem (in underground gold mines) yields when solved for multiple objectives using a goal programming model.

Keywords: Truck Dispatching Problem, Underground Mine, Goal Programming

Introduction

The movement of mined ore in an underground mine typically represents between 50 to 60 percent of a mine's total operating costs (Newman et al., 2010; Fadin et al., 2017). Therefore, the dispatching of trucks in an

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underground mine is a daily decision of major economic consequence and warrants the use of a decision support model. In dispatching problem addressed in this paper, a set of trucks must be assigned to a set of trips and to a set of mining levels with each containing different grades of ore. The assignment of trucks must be made in such a way that four objectives are met. They are; transportation costs are minimized, the ounces of gold retrieved are maximized, the number of shovels used is minimized, and the total number of trucks required is minimized for a given shift. Given that this problem has multiple conflicting objectives, a goal programming model is developed and tested in this paper. The objective of this paper is therefore to formulate and evaluate a goal programming model of the truck-dispatching problem for underground gold mines.

The paper is structured as follows: first, a review of the literature relating to this dispatching problem is given. Second, the problem modeled is defined (with a conceptual figure). Third, the mathematical formulation of the model is presented. Fourth, a description of the case study on which the model is to be evaluated, the Red Lake gold mine in Ontario, Canada, is presented. Finally, the results of the model are presented, and the merits of the model are observed and evaluated in the discussion.

Previous Studies

The truck dispatching problem in the mining industry has received minor but consistent attention by researchers who specializes in optimization models. The problem has received wider attention for above-ground mines than for below-ground mines. Indeed, there are few studies that have been made for truck-dispatching in underground ground mines (Mahdi et al., 2014). Newman et al. (2010), in their review paper on operations research models used in mining, observed that rather than one universal dispatching model for the mining industry, there exists a great diversity of models for this problem. This is because the different types of mine structures require different objective functions and different constraints. Hence, there is no universal model of the truck dispatching problem (in either above- or below-ground mining) given the great diversity of mines structures (Newman et al., 2010). In this review, we will examine the diversity of optimization models that have been recently formulated for the truck dispatching problem in both above-ground and underground mines.

Ercelebi et al. (2009) used a linear programming model to improve the truck-to-shovel dispatching system and established a method of accurately determining the optimal number of trucks. They also applied the single objective model to an open-pit coal mine in Turkey. Nehring et al. (2010) formulated a mixed integer programming model and applied it to a transportation system that used trucks and shovels in an underground mine in order to maximize net revenue within a shift. Song et al. (2013) formulated a linear programming model to solve the truck and shovel dispatch problem in an open-pit mine. This paper focuses on maximizing the total transportation (in tonnes) of ore and waste material in a given shift. Zhang et al. (2015) presented a new model of the truck dispatching problem in an open-pit iron mine by using integer programming to represent the optimal number of discrete trips for trucks to make between loading sites and dumping sites in one shift. However, their results showed reduced transportation operating costs of 15%. Schulze and Zimmerman (2017) used a mixed integer programming model to optimize the objective function of maximizing the total material moved by a set of loader-trucks in an underground potash mine.

Simulation-based optimization was recently used by Ozdemir et al. (2019) to optimize a truck/shovel dispatching problem in an open-pit mine. The objective function of the optimization model was to maximize the total material moved in a shift. Wang et al. (2020) recently used a Genetic Algorithms Model (GAM) to solve the truck dispatching problem for an underground mine in China. In addition, their model had the objective to maximize production at the shift level (tonnes moved per shift) as it is subject to constraints on the number of loading locations available, the capacity of the trucks, the material quantities available in each level, and the distance between loading levels. The results showed that the optimization model improved operational productivity by 8%.

Based on our literature review, we can identify the following trends: a) many researchers have shown that the use of a truck dispatching optimization model has improved the shift-level productivity in their mines; b) no researchers have (to our knowledge) formulated a goal programming model for this problem in underground gold mines. Hence, the research presented in this paper is an innovation on a problem of major economic consequence in underground gold mines.

Methods

The description of the methods used in this research has three parts. First, the problem modeled is defined and illustrated with a conceptual figure. Second, the new mathematical formulation of the goal programming model for dispatching trucks in an underground gold mine is presented. Third, the data acquired from the case study, Red Lake's underground gold mine in Ontario, Canada, are described.

Definition of the Problem Modeled

A conceptual figure (of a small problem instance) of the dispatching problem modeled in this paper is presented in Figure 1 below. In Figure 1, first observe that there are 6 levels in the problem instance. These represent

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

different levels in the underground gold mine, and each level supplies gold ore of a different grade (in grams per tonne) and a fixed number of tonnes of ore are available per shift. Second, observe the elevator. The elevator is the point of demand for gold ore. It carries gold ore to the surface where there is a target-demand in ounces of gold per day. The elevator also has a capacity constraint on the number of tonnes of gold ore it can move in one shift. Third, observe the distances between the 6 levels and the elevator. The distance and the slope of the path between each supply point and the elevator determines the transportation cost, of which all are different for each level. Fourth, observe that level 1 and 3 have a shovel assigned. This means that, in the particular solution illustrated in Figure 1, level 1 and 3 have been selected as supply points to meet the shift's demand. If a level has been selected, then it is assigned a shovel. There is a constraint on and cost for the number of shovels that can be used for any given shift. Finally, observe that, for each level selected, there is also a truck assigned. Trucks assigned can be of different sizes and each size can move a fixed number of tonnes per trip.

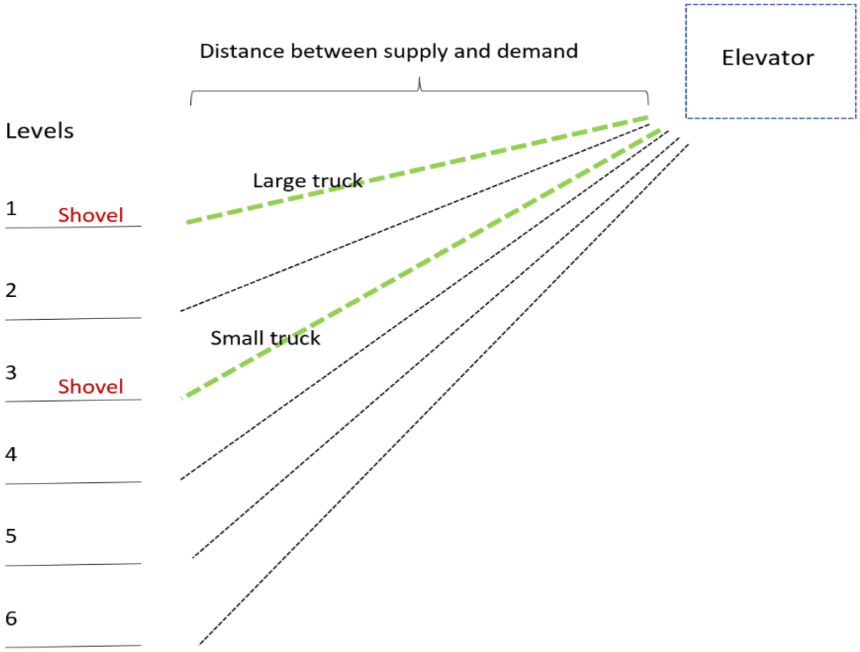

Figure 1. Conceptual Figure of the Problem Modeled

The problem to be solved is assigned a number of truck-trips (for each truck size) such that the following four goals can be met in a shift:

1. the gold goal (ounces per shift);
2. the goal for transportation cost ($);
3. the goal for the number of shovels; and
4. the goal for the number of trucks and truck sizes used.

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

Since these four goals can conflict with one another, the problem is modeled as a goal programming model. The model is to be used not only to find the optimally satisfying solution for the decision-maker, but also to explore and quantify trade-offs to support the decision made.

Mathematical Formulation of the Model

The mathematical formulation of the goal programming model for dispatching trucks in an underground gold mine is presented below.

Indices and Sets

i, I = *index and set of levels within the mine.*
j, J = *index and set of truck-types, by capacity.*

Parameters

a_{ij} = *fraction of total shift time (C) required for one complete truck-trip assigned to level i using truck type j.*
b_j = *number of minutes required to load truck type j.*
C = *total number minutes in a shift.*
M = *arbitrarily large number.*
e_j = *capacity of truck type j (tonnes).*
D = *total demand for gold ore per shift at the elevator (tonnes).*
S_i = *supply of gold ore at level i, during the shift (tonnes).*
c_{ij} = *cost of trip needed for transporting one truckload of gold ore from level i using truck j.*
q_i = *grams per tonne of gold ore at level i.*
G_ta = *goal value for transportation cost ($)*
G_tk = *goal value for number of trucks required.*
G_s = *goal value for number of shovels required.*
G_g = *goal value for mass of gold removed (grams)*
p_ta = *percent deviation factor for transportation goal variable = 1/ G_ta.*
p_tk = *percent deviation factor for truck goal variable = 1/ G_tk.*
p_s = *percent deviation factor for shovel goal variable = 1/ G_s.*
p_g = *percent deviation factor for transportation goal variable = 1/ G_g.*
w_ta = *penalty weight for transportation goal variable.*
w_tk = *penalty weight for truck goal variable.*
w_s = *penalty weight for shovel goal variable.*
w_g = *penalty weight for gold goal variable.*

Decision Variables

x_{ij} = *number of trips assigned to level i using truck type j.*
y_j = *total number of trucks of type j required.*
z_i = *1 if shovel at level i is used, 0 otherwise.*

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

Accounting Variables

s = *total number of shovels required in a shift.*
t = *total number of trucks required in a shift.*

Goal Variables

g_ta^+, g_ta^- = *positive and negative deviations, respectively, from transportation goal ($).*
g_tk^+, g_tk^- = *positive and negative deviations, respectively, from truck goal (number).*
g_g^+, g_g^- = *positive and negative deviations, respectively, from gold goal (grams).*
g_s^+, g_s^- = *positive and negative deviations, respectively, from shovel goal (number).*

Objective Function

Minimize the total weighted percent deviations from all four goals.

$$(w\_ta * p\_ta * g\_ta^+) + (w\_tk * p\_tk * g\_tk^+) + (w\_s * p\_s * g\_s^+) + (w\_g * p\_g * g\_g^-) \quad [1]$$

Subject to

The total number of trucks required, of each type, is a function of the trucks assigned to all levels.

$$\sum_{i \in I} a_{ij} x_{ij} = y_j \quad \text{for each } j \in J \quad [2]$$

$$\sum_{j \in J} y_j = t \quad [3]$$

If a level is assigned a truck, then it is also assigned a shovel.

$$\sum_{j \in J} x_{ij} \leq M z_i \quad \text{for each } i \in I \quad [4]$$

The total number of shovels required in a shift is the sum of all shovels assigned to all levels.

$$\sum_{i \in I} z_i \leq s \quad [5]$$

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There is a limit on the number of trucks that can be assigned to each level and this is based on the total time required to load all assigned trucks within the period of one shift.

$$\sum_{j \in J} b_j x_{ij} \leq C \quad \text{for each } i \in I \qquad [6]$$

The total number of truck-trips is limited by the total demand per shift, in tonnes, at the elevator.

$$\sum_{i \in I} \sum_{j \in J} e_j x_{ij} \leq D \qquad [7]$$

The total number of truck-trips, assigned to each level, is limited by the total gold ore available at each level.

$$\sum_{j \in J} e_j x_{ij} \leq S_i \quad \text{for each } i \in I \qquad [8]$$

The deviation from the goal in transportation-cost is a function of the total number of truck-trips assigned, the cost of each trip, and the chosen goal for transportation cost.

$$\sum_{i \in I} \sum_{j \in J} c_{ij} x_{ij} + g\_ta^- - g\_ta^+ = G\_ta \qquad [9]$$

The deviation from the goal for the number of trucks assigned is based on the total trucks assigned (t).

$$t + g\_tk^- - g\_tk^+ = G\_tk \qquad [10]$$

The deviation from the goal for the number of shovels assigned is based on the total shovels assigned (s).

$$s + g\_s^- - g\_s^+ = G\_s \qquad [11]$$

The deviation from the goal for total gold removed is a function of the truck-trips assigned to each level and the grade at each level.

$$\sum_{i \in I} \sum_{j \in J} q_j x_{ij} + g\_g^- - g\_g^+ = G\_g \qquad [12]$$

Constraints on Decision Variables

$x_{ij} \geq 0$ and integer [13]

$y_i \geq 0$ [14]

$z_i \in \{0, 1\}$ [15]

The objective function [1] is used to minimize the total weighted percent deviation from all goal variables. By default, all weights are valued at 1 unless otherwise stated. Equation [2] defines the number of trucks, t, required per shift for each truck-type. The total number of trucks required is defined in Equation [3]. Equation [4] defines whether or not a shovel is used at a given level. Since the use of a shovel (z_i) is triggered by the dispatching of a truck to that level (x_{ij}), the variable representing the use of a shovel (z_i) must be binary for this equation to work (see Equation 15). Equation [5] defines the total number of shovels used in a shift. Equation [6] limits the maximum number of shovels required at each level to be 1. This constraint is based on the reasoning that the total number of minutes that a shovel may be used in loading trucks may not be more than the number of minutes in a shift. Equation [7] limits the total ore removed during the shift from exceeding the total demand for the shift. Equation [8] limits the ore removed by dispatched trucks, of varying capacities, from exceeding the supply of ore at each level. Equation [9] defines the goal variables for transportation. Each trip dispatched is a round-trip from the demand point (the elevator) to the supply-point at a given level of the shovel. The key importance here is the parameter c_{ij}, which varies for each level, depending on the distance travelled and slope at which a truck is required to travel, both empty and full. Equations [10] and [11] define the goal variables for trucks and shovels. Equation [12] defines the goal variables for gold. It should be noted that the goal for gold (by historical convention) is in ounces, and that this goal is based on the estimated grams of gold per tonne of gold ore, which varies from level to level. Equation [13] ensures that the number of trips dispatched to each level is integer. Equation [14] constrains the number of each truck type required to be non-negative. This variable, for the work in this paper, was not constrained to be integer. This is because an integer constraint requires excessive computing time, and the variable only needed to be rounded up in order to interpret the number of trucks of each type required by the dispatching solution. Equation [15] ensures that the variable representing whether a shovel is used at a given level or not is binary.

Case Study Definition

The underground gold mine in Red Lake, Ontario (Canada), has been in operation for more than 50 years. This history has resulted in 52 levels reaching a depth below surface of 2.4 km. Figure 2 (below) illustrates that the first 38 levels are connected to a main shaft into which mined material is dumped. However, at the bottom of level 38 is an elevator which carries the mined material to the surface. Figure 2 also illustrates that, below level 38,

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

there are 14 levels which are not connected to the main shaft. Material mined from these levels (levels 39 to 52) must be transported by trucks to the elevator at level 38. In general, the deeper the location of each level, the more costly is the transportation required to service it. The problem in this case study is the dispatching of trucks, per shift, to these 14 levels (levels 39-52) such that the multiple objectives (described above) are optimally satisfied.

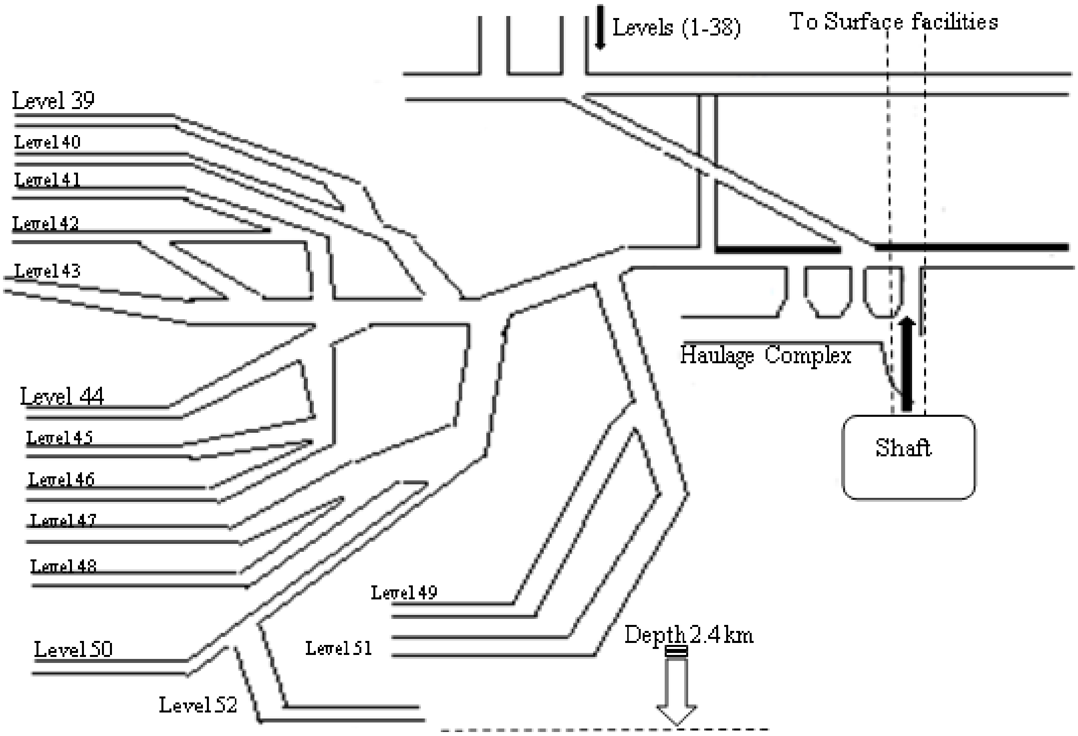

Figure 2. Underground Transportation Network for Trucks at Red Lake Mine

At present, there is no optimization model used for dispatching trucks at the Red Lake mine. Dispatching decisions, made at the beginning of each shift, are supported using analysis of data on spreadsheets. The managers of Red Lake mine expressed interest in the development of an optimal dispatching model because the cost of trucking materials in the underground mine is a major one. The mine's managers wanted a model that addresses several objectives as follows: optimize gold production, transportation costs, shovels required, and the number of truck types and sizes required. Given these four objectives, the analysts and decision-makers at Red Lake wanted a model that could support decisions on the trade-offs involved between competing objectives. For these reasons, a goal programming model was formulated and evaluated.

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

Transportation, shovel, and trucking data were provided by the managers at Red Lake mine for parameters in the goal programming model. There were only two truck sizes used. Data on the gold grades in the mine were not provided. Our industrial partner, understandably, wished to keep these values on grade private. The parameters for the grade of ore were therefore generated using a random number generator such that each level was randomly assigned (with equal probability) a grade between 5 and 15 grams of gold per tonne of ore. This range of grades is realistic for a typical gold mine, and the fact that the values assigned are not real does not compromise the evaluation of our optimization model.

Results

Since the decision-makers at the Red Lake mine were interested in quantifying the trade-offs among the competing objectives in this problem, a pre-emptive method was used in applying the goal programming model. In the pre-emptive method of goal programming (Eschenbach et al., 2001), goals are ordered according to priorities, and the values assigned to each goal are determined by executing a sequence of scenarios. For example, in the results shown in Table 1 (below), the first scenario was run with gold as the top priority. Therefore, gold was the *only goal* used in the model's objective function in scenario 1. The achieved value for gold, in scenario 1, was then used as the gold goal's value in scenario 2. This sequential method was used for directing the assignment of all goal values.

The priorities underlying the pre-emptive method were selected in consultation with the decision-makers at Red-Lake. The priorities of the objectives were ranked as follows:

1. Gold removed
2. Transport cost
3. Shovels used
4. Trucks used

The results of the four scenarios are shown in Table 3.1 (Note: the values in square brackets are *achieved* values of goals that were not optimized in the objective function but resulted from the optimal solution).

Table 1. Results for Four Scenarios using Pre-emptive Method

Scenari	**Goals in Objective Function**	**Goal Values**				**Achieved Values**			
		Gold (g.)	**Transport ($)**	**#Shovels**	**#Trucks**	**Gold (g.)**	**Trans port ($)**	**#Shovels**	**#Trucks**
1	Gold	**10,000**				7,570	[5,848]	[10]	[11]
2	Gold + Transportation	**7,570**	**5,000**			7,553	4,984	[11]	[8]

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

3	Gold + Transportation + Shovels	**7,570**	**5,000**	**9**		7,509	5,007	9	[6]
4	Gold + Transportation + Shovels + Trucks	**7,570**	**5,000**	**9**	**4**	7,425	5,024	9	4

The results in Table 1 yield several observations. First, in scenario 2, one can observe the trade-off between gold removed and transportation costs by comparing the achieved values for these goals in scenarios 1 and 2. Here, we observe that by adding transportation cost as a goal in scenario 2, transportation costs were reduced from $5,848 per shift to $4,984. Furthermore, a reduction of 14.8% was achieved by lowering the total gold removed by less than 1% (from 7,563 g to 7,553 g). The improved solution of scenario 2 shows the benefit of dispatching trucks for both gold and transportation costs simultaneously using this model.

Second, scenario 2 also shows that the reduction in transportation costs resulted in an increase in the number of shovels used (from 10 to 11). Why did this happen? By comparing the solution of scenario 1 with scenario 2 (see Table 2, below), we observe two things. First, that when the goal was only for gold, the solution was easy to form by simply sending the smaller trucks to the levels with the richest deposits, regardless of cost. Smaller trucks were sent because carrying smaller discrete volumes of ore makes it easier to remove, as closely as possible, the total discrete volume of ore supplied at the ore-rich levels than if one dispatched a discrete set of larger trucks. Second, Table 2 also shows that different levels (in scenario 1 versus 2) were accessed in order to reduce transportation costs. However, recalling that the depth of a level influences its transportation cost, we can observe that scenario 2 added the less costly levels (44 and 46) and removed the more costly level (50). Hence, scenario 2 showed an unintended consequence of adding the objective to reduce transportation costs. Furthermore, in order to reduce transportation costs and to meet the gold goal, an extra level was added to the solution requiring an extra shovel. This unintended consequence shows the need for adding shovels as an objective in a goal programming model of this dispatching problem.

Third, scenario 3 (in Table 1, above) shows that by adding a goal of 9 shovels to the model's objective function, we were able to meet this objective and improve upon the solution in scenario 2, which entailed 11 shovels and a reduction in shovel cost of 18.2%. This improvement came with a small trade-off, i.e., a reduction in gold removed in scenario 3 versus scenario 2 (less than 0.1%) and a slight increase in transportation cost (less than 0.1%). Table 2 also shows that the solution for scenario 3 is radically different from that of

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

scenario 2. These results show that, with a slight trade-off for two objectives, it is possible to achieve a major improvement in the third objective. Hence, the solution to scenario 3 illustrates how well the dispatching problem in an underground gold mine is flexible and suitable for multiple objective optimization through goal programming.

Table 2. Solutions for Four Scenarios (Note: the values in the scenario columns represent the number of trips dispatched to each level, for each truck type)

Level	Truck Capacity (tons)	Scenario			
		1	2	3	4
39	17	5	5	5	1
40	17	5	1	5	1
41	17	6	1	5	1
42	17	4	0	2	0
43	17	4	1	1	0
44	17	0	1	0	3
45	17	5	0	2	2
46	17	0	1	0	0
47	17	4	0	0	3
48	17	0	0	0	0
49	17	0	0	0	0
50	17	1	0	0	0
51	17	3	1	0	0
52	17	4	0	0	0
39	30	0	0	0	2
40	30	0	2	0	2
41	30	0	3	0	3
42	30	0	2	1	0
43	30	0	1	1	2
44	30	0	0	2	1
45	30	0	3	2	2
46	30	0	0	1	0
47	30	0	2	2	1
48	30	0	0	0	0
49	30	0	0	0	0
50	30	0	0	0	0
51	30	0	2	1	2
52	30	0	2	2	2

Finally, scenario 4 (see Table 1) shows that by adding a fourth objective (i.e., the number of trucks required), the overall solution was further refined. Comparing scenarios 3 and 4, we observe that the number of trucks was reduced from 6 to 4 (33.3% reduction). This came with a trade-off of reducing the gold removed by less than 1% and of increasing the transportation cost by less than 1%. The number of shovels used remained the same. Table 2 also shows that the solutions of scenarios 3 and 4 differ in a predictable manner. Furthermore, the number of trips assigned to the larger capacity

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

trucks was greatly increased in scenarios 4 in order to meet the targets with fewer trucks. Therefore, scenario 4 illustrates the model's ability to engage in the exploration of meaningful trade-offs given trucks and truck-sizes as an objective in the problem.

Discussion

The results illustrate how the goal programming model presented in this paper may be useful to decision-makers for the problem of dispatching trucks in an underground gold mine. We now discuss several reasons for this conclusion.

First, the nature of the problem is such that it is flexible enough to be solved effectively for multiple objectives simultaneously. For example, the solution in scenario 2 lowered transportation costs by 14.8%, while also lowering gold achievement by less than 1%. This was clearly a favourable trade-off made possible by some flexibility (i.e., multiple means) in solving the problem, but what do the results in Table 1 really imply about the flexibility of this problem? Three observations are required before we can answer this question. First, given the great economic importance of mining levels with the highest grade of gold, it might appear that a greedy solution, in which levels with the highest grades of gold are mined first, would be the most valuable. This is true in terms of the gold objective. The results show (see Table 1) that the highest possible number of gold ounces that can be mined in a shift occur in scenario 1, which has only one objective: gold. Second, the solution to scenario 2 (see Figure 2) in which both gold and transportations goals are optimized simultaneously shows that the set of levels selected in scenario 2 differs greatly from the set of levels selected in scenariuo 1. Third, even though the set of levels selected in scenario 2 are radically different from those selected in scenario 1, the number of gold ounces mined in these two scenarios differs by less than 1%. These three observations imply that the variation in gold grade between levels (described in Methods) is such that there are multiple near-optimal solutions with regard to the gold objective. This is an important implication, for it means that, although maximizing gold production is the first objective in this problem, there are multiple ways to achieve this, in practice, since there are multiple near-optimal solutions. This flexibility in planning, shown in the results, also illustrates the great value of using an optimization model with multiple objectives when planning for a dispatching problem in an underground gold mine.

A second reason for the usefulness of this model is illustrated in the results on optimizing the number of shovels and trucks used. The results in Table 1 show that when shovels and trucks are included as objectives in the model, a redution in shovel costs by 18.2% and a reduction in trucks used by 33.3% is possible. This reduction has two important implications for

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

operations. First, a reduction in the number of trucks used implies that the operational problem of live dispatchers avoiding wait-times at loading or unloading points is reduced in difficulty. Second, a reduction in the number of shovels used implies less idle-time for shovels, which is an unproductive cost. Once again, the results on the objectives for shovels and trucks shows the surprising and valuable flexibility that this problem offers when solved for multiple objectives.

A third reason for the usefulness of this model is that it allocates trucks and shovels to multiple levels at the beginning of the shift. Some truck-dispatching models are "live" and are concerned with the scheduling of truck movements in order to optimize shovel productivity and minimize wait-times at loading and unloading points (Newman et al., 2010). Such models are valuable, but they assume that optimal mining levels and truck-trips and numbers and sizes have already been selected. Hence, this model is useful in that it addresses a valuable planning problem that should be solved before the problem of "live" dispatching is solved.

Conclusion

In this chapter, we have presented a new formulation of the truck dispatching model for an underground gold mine. The model was formulated as a goal programming model and applied to Red Lake's gold mine in Ontario, Canada. The results showed that major reductions in transportation costs, shovels used, and trucks required can be achieved with a minimal decrease (less than 1%) in the maximum quantity of gold that can be removed in a shift. The results illustrate the valuable flexibility that this problem offers when solved for multiple objectives. Given the scale of these reduced costs, this model will be a valuable addition to the decision-makers seeking to increase the efficiency of their dispatching decisions both before and during operations in an underground gold mine.

Future research on the problem of modeling this dispatching problem would be in exploring the applicability of a goal programming as a useful approach for modeling the dispatching problem in different types of underground mines, i.e., to determine whether its benefits can be expanded to mines other than gold mines.

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