

Shovel Allocation Optimization: A Goal Programming Approach

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Abstract

Decision making in mining is a challenging task. Decisions regarding faces to be mined, in consideration to the short-term production schedule, are very important to keep the operations in line with the planned objectives of the company in long-term. This paper presents a mixed integer linear goal programming (MILGP) model that acts as an upper stage in a two-stage dispatching system and optimizes the operations based on desired goals of the company. The model assigns the shovels to mining-faces and determines the target production as an input to the dispatching system while meeting the desired goals and constraints of the system. The paper discusses the benefits of using this model by presenting the impact on head grade, feed to processing plants, production and economics of an iron ore mine.

1. Introduction

Mining is a highly capital intensive operation and the major objective of any mining company remains to maximize the profit by extracting the material at lowest possible cost over the life of the mine (Askari-Nasab, Frimpong, & Szymanski, 2007). Since truck and shovel operations account for approximately 60% of total operating costs in open-pit mines, optimal use of these equipment is essential for the profitability of the mine. It is also important that operations achieve the production targets set by the long-term mine plans. As mining operations are highly stochastic, it is practically impossible to accurately predict the production figures and deliver on them. Amongst many, the main reason of such variability is due to the unavailability of truck-and-shovel fleet in surface mines. The variability of truck-and-shovel availability and utilization may become a cause of deviation from the short-term and in-turn long-term production plans. The operational production plans, therefore, must incorporate two objectives, optimize the usage of mobile assets and meet the strategic production schedule.

Fig.1 presents various mine production planning stages. Tactical plans are linked with strategic plans through short-term production schedules. The literature reviewed in this paper show that though sufficient attention has been given to optimization of the operations, none try to link the production operations with the strategic plans of the mine which often lead to deviations from the short-term and in-turn long term production targets. The problem of shovel assignments to mining-faces has not received sufficient attention in the literature. Optimal shovel assignment to available mining-faces over a shift-by-shift time horizon can act as a link between the production operations and the strategic plans of the mine.

Hence, two major problems have been identified for this study: 1) the production optimization problem and, 2) the link between operations and the strategic production schedule. Production operations can have a number of problems, out of which four major problems have been identified in this paper:

1. Underutilization of shovels due to in-efficient operational plans,
2. Deviation of quantity of processing plant feed with respect to desired feed,
3. Deviation of quality of material feed to the processing plants and stock-piles compared to the desired quality, and
4. Operational cost escalation due to improper resource allocation.

These four problems can be optimized by combining them into a single objective function and formulating a mixed integer linear goal programming (MILGP) model. To link the production operations with the strategic schedule, shovel assignments can be incorporated into the MILGP model.

The objective of this study is to formulate, implement and verify a mixed integer linear goal programming (MILGP) model for optimal production and shovel allocation at the operational level.

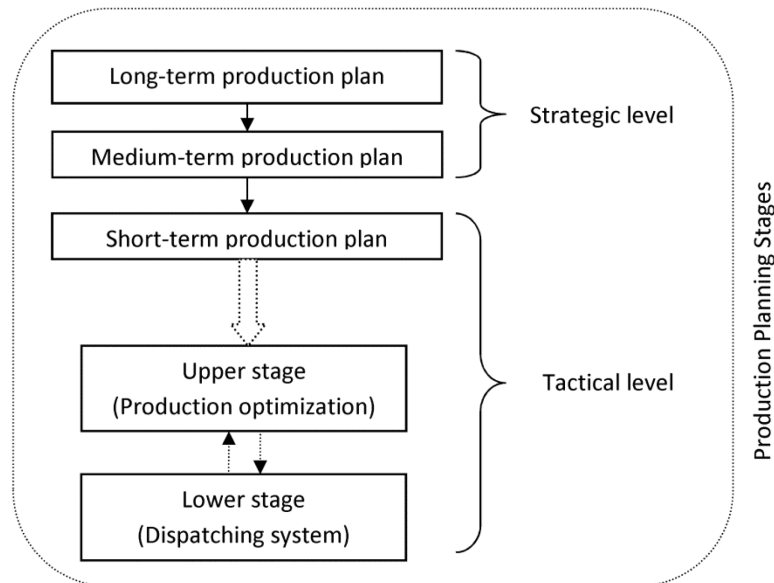


Fig.1. Mine production planning stages

This paper presents a MILGP model, as an upper stage in a two stage dispatching system, to overcome the limitations of the models described in the literature review section. Taking into account the short-term production plan of the mine, this model assigns the shovels to the faces available and determines their production by maximizing shovel utilization, minimizing the deviation of quality and quantity of the processing plants' feed from the set targets, and minimizing the operational cost.

The model presented in this paper can help improve the automation in operations by removing the need for manual assignment of shovels, to meet the long term production schedule. The MILGP model can act as the upper stage in a two stage dispatching system, where upper stage provides the shovel assignments and target productions, and lower stage (dispatching algorithm) implements the production strategy into the operations.

The rest of the paper is structured as follows. A detailed review of research on production scheduling with emphasis on operations is presented in literature review section. Model development section introduces the problem in detail and describes the parameters that have been

used to develop the MILGP model. Model formulation section presents the modeling equations with brief description on their functions, the solution strategy and the inputs required by the model. Subsequently, the results of a case study is presented and discussed. Finally the conclusion and future scope of research are presented.

2. Literature review

Over the years operations research techniques have evolved and found applicability in decision making processes in mining. Topuz & Duan (1989) mention some of the potential areas in mining such as equipment selection, production planning, maintenance, mineral processing and ventilation, where operations research techniques can act as a helping tool for decision making processes. Newman et al. (2010) provides a comprehensive review of the application of operations research in mining.

Production scheduling in mining has seen a good development over the years. With evolution in computing power and operations research techniques, this problem can now be modeled and solved. But it is still computationally not possible to solve the entire problem by scheduling each block in the block model. So, the problem is generally solved in stages (Hustrulid & Kuchta, 2006). Based on the period and planning horizon production scheduling can be achieved in three stages i.e. long-term, medium-term and short-term (Osanloo, Gholamnejad, & Karimi, 2008). Long-term production scheduling has seen considerable improvement over the years by formulating the problem using mixed integer programming, dynamic programming and solving using meta-heuristic techniques such as Lagrangian Relaxation (Osanloo, et al., 2008). For a detailed review of the researches in the field of long-term production scheduling using operations research techniques, see Osanloo et al. (2008) and Newman et al. (2010). Most of the research in mine production scheduling has remained confined to long-term; and short-term production scheduling has seen very little development in this area (Eivazy & Askari-Nasab, 2012). Eivazy and Askari-Nasab (2012) provides a mixed integer linear programming model to generate short-term open pit mine production schedule over monthly resolution. The schedule provided by Eivazy and Askari-Nasab (2012) has been used as an input into the model described in this paper to link the daily production operations with strategic production plans of the mine.

Long-term strategic plans can only be realized with efficient operational production planning. Literature provides broadly two approaches for the optimization of shovel – truck systems at the operational level. Early researches were mostly using queuing theory for studying and optimizing the shovel – truck systems. Koenigsberg (1958) can be considered as the first person who applied queuing theory in mining. With the evolution in computing capability and optimization techniques, mathematical optimization models started to gain more attention.

Simulation is another technique which has evolved over time and is now frequently being used for understanding the behavior of the systems and for decision making purposes.

Truck and shovel operations, now a days, are primarily optimized by employing truck dispatching algorithms. Munirathinam and Yingling (1994) provide a review of truck dispatching in mining. Elbrond and Soumis (1987) emphasize on a two-step optimization proposed by White and Olson (1986). The first stage chooses the shovels, the sites and the production rates. The second stage also determines the rates of the shovels but this time it considers the operation in more detail. Soumis et al. (1990) proposed a three stage dispatching procedure, namely equipment plan, operational plan and dispatching plan. Based on the overall approach, similar procedures have evolved as multi-stage dispatching systems. Bonates and Lizotte (1988) emphasizes on the accuracy of the model in the upper stage in terms of the true representation of the mining system, so that realistic targets could be fed to the dispatching model in the lower stage.

Li (1990) proposed a three stage methodology for automated truck dispatching system, by determining the target tonnage to be produced along a path in the network using linear

programming as haulage planning stage, truck dispatching based on maximum inter-truck-time deviation, and equipment matching using a least square criterion. Temeng et al. (1998) developed a goal programming formulation as an upper stage of a two-stage dispatching system and implemented it with a dispatching system developed by Temeng, Otuonye, & Frendewey (1997). Their paper describes goal programming to be better compared to linear programming using the results obtained. The major limitation of the models in both papers is that they do not take into account the short term production schedule and do not provide any information regarding shovel assignments (which face to be mined?). Shovel assignment is an important decision making problem which has a direct impact on achieving the production targets and thus need to be accounted by the upper stage of the dispatching system. Although the model developed by Temeng et al. (1998) account for mixed fleet, it does so by taking the average payload of trucks, which would not be a realistic way of modeling this system. A better approach would be to optimize the operation by considering the actual capacities of every truck in the system and their respective payload.

To the best of the author's knowledge, no literature in the multi-stage dispatching discussed try to link the operational plans with the strategic plans of the mine. All those models try to improve the efficiency of the mining operations but miss to incorporate an important objective of production operations i.e. to meet the long term strategic schedule. None discusses in detail the shovel assignments to faces which still remain a manual task of a planner. Most of the published work focuses on developing mathematical models for maximizing production or minimizing the grade deviation or both. But there can be a number of conflicting objectives of any mining operation, such as steady and desired feed of ore to the processing plants, minimizing the operating costs etc.

The review of literature in the area of multi-stage dispatching at the operational level revealed that:

1. The shovel allocation problem did not receive sufficient attention,
2. Existing models are not equipped sufficiently to handle mixed fleet systems,
3. Optimization models do not incorporate all the major objectives of a production operation,
4. Models do not bridge the existing gap between the operational planning and the strategic long-term planning.

The proposed MILGP model provides significant improvement over the existing mathematical optimization models for production operations by incorporating the four major limitations identified above.

3. Statement of the problem

Fig.2 shows an open pit mining system, modeled in this paper, consisting of \hat{F} number of available faces to be mined within a month and \hat{S} number of shovels to be assigned to the available faces. The excavated material is transported from the face to its respective destination, through the pit exit, using \hat{T} haul trucks. A typical open pit mine can have \hat{K} different elements, consisting of one major element and by-products. Finding the optimal shovel allocations to mining-faces to meet the targets of an optimal monthly production schedule is the main purpose of this paper. The destinations consist of \hat{O} ore destinations and \hat{W} waste destinations. Ore destinations consist of \hat{P} processing plants and rest as stockpiles sp .

There is cost associated with every operation: shovel operating cost as \$ per tonne of material produced; shovel movement cost as \$ per meter of shovel movement when reassigned to a different face; truck operating costs as \$/Km; processing cost as \$ per tonne of ore processed. Revenue is generated by selling the recovered final product out of the processing plants.

The assumptions and characteristics of the developed MILGP model for shovel allocation and optimal production are:

- Each ore destination can receive material with a specific grade range. The desired grade can be achieved by blending the ore from different ore faces.
- Grade range requirements could be applied to multiple elements present in the ore.
- There is no limit on the amount of material stockpiles can receive.
- Processing plants are desired to have supply of material at a steady feed but cannot receive material at a rate above or below the specified limits.
- A shovel can be reassigned only if the face that it is currently operating on is completely excavated.

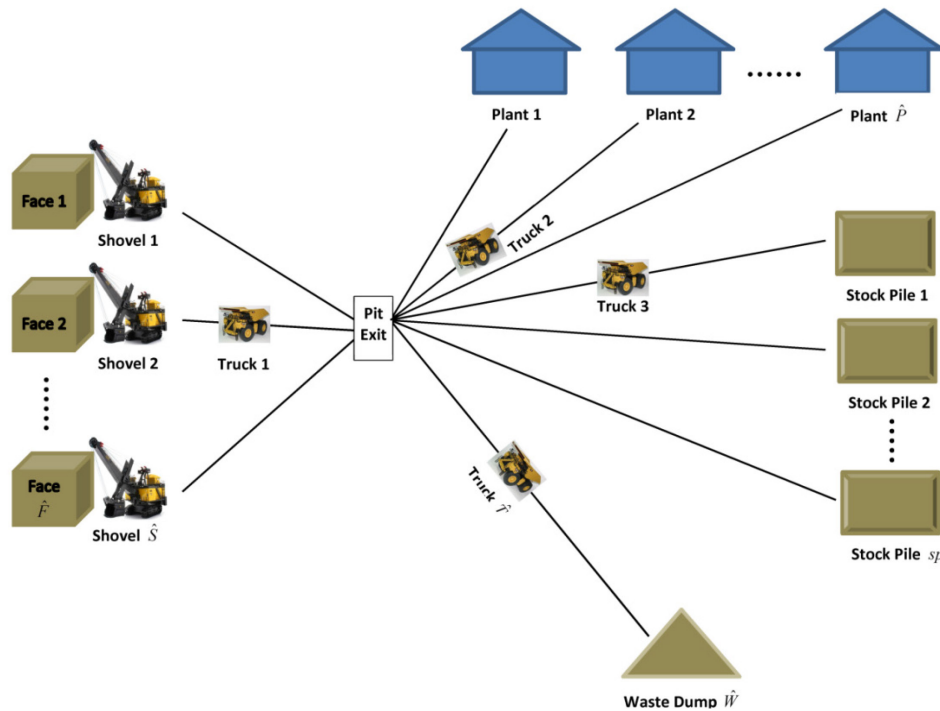


Fig.2. A typical layout of an open pit mining system

This paper presents a mixed-integer linear goal programming (MILGP) model to optimize the multi-destination open pit mine production and shovel allocation problems subject to available shift time, truck and shovel availability, processing capacity and stripping ratio constraints. The four goals, considered in this paper, are to:

1. Maximize the shovel utilization (maximize production)
2. Minimize the grade deviations at ore destinations compared to desired grade ranges.
3. Minimize the deviation in tonnage supplied to the processing plants compared to desired tonnage feed
4. Maximize the profit of the mine (revenue - processing cost - mining cost)

First goal is to maximize the shovel utilization, which is achieved by minimizing the negative deviation in the production of each shovel compared to its maximum production capacity in a shift. The second goal is to minimize the deviation in grade of each material type compared to the desired grades at the ore destinations. These two goals are similar to those presented by Temeng et al. (1998).

The third goal optimizes the utilization of processing plants by minimizing the positive and negative deviation in total tonnage supplied, compared to desired, to the processing plants. The fourth goal maximizes the profit and hence tries to maximize the production of high grade ore.

It should be noted here that, including profit as a goal in this model becomes necessary to make sure it does not treat ore to be sent at processing plants and ore at stockpiles equally. Unlike to the model by Temeng et al. (1998), we can control the ore to be sent to stockpiles or processing plants by controlling the weights, which are discussed later.

The MILGP model proposed in this paper is based on a short term production schedule at the block aggregate level, where mining cuts (faces) are provided to be excavated within a given period of one month. The short-term schedule generated by the model of Eivazy and Askari-Nasab (2012) includes cut precedence, i.e. the schedule provides cuts to be mined prior to mining any face. Incorporating mining cuts directly from the short term schedule help to remove the block precedence constraints from the current optimization problem. This schedule also provides the shortest distance from the mining cuts to the pit exit, which is directly used for calculating truck haul distances in the model. The most significant contribution that the short-term schedule provides is a link between the tactical and the strategic plan, by providing the available faces for shovel assignment in the given period of one month.

4. Model development

In this section, all the parameters and variables used in MILGP formulation are presented. First all the variables and input parameters are defined and then the calculated parameters and their equations are presented.

4.1. Index for variables and parameters

s	index for set of <i>shovels</i> ($s = 1, \dots, \hat{S}$)
f	index for set of <i>faces</i> ($f = 1, \dots, \hat{F}$)
t	index for set of truck types <i>trucks</i> ($t = 1, \dots, \hat{T}$)
k	index for set of material types <i>MatType</i> ($k = 1, \dots, \hat{K}$)
d	index for set of <i>destinations</i> (processing plants, stockpiles, waste dumps)
d^p	index for set of <i>processing plants</i> ($d^p = 1, \dots, \hat{P}$)
d^o	index for ore destinations (processing plants and stockpiles)
d^w	index for waste dumps ($d^w = 1, \dots, \hat{W}$)

4.2. Decision variables

To formulate all the system constraints and to represent the system as precisely as possible, while keeping the model linear, following decision variables have been considered.

$a_{s,f}$	Assignment of shovel s to face f (binary)
$n_{t,f,d}$	Number of trips made by truck type t , from face f , to destination d (integer)
$x_{s,f,d}$	Tonnage production sent by shovel s , from face f , to destination d
x_s^-	Negative deviation of shovel production from the maximum capacity in a shift
$\delta_{d^p}^-, \delta_{d^p}^+$	Negative and positive deviation of production received at the processing plants d^p
$g_{kd^o}^-, g_{k,d^o}^+$	Negative and positive deviation of tonnage content of material type k compared to tonnage content desired, based on desired grade at the ore destinations d^o

4.3. Parameters

D_t	Dumping time of truck type t (minutes)
E_t	Spotting time of truck type t (minutes)
N_t	Number of trucks of type t
H_t	Tonnage capacity of truck type t
J	Flexibility in tonnage produced, to allow it not to be an integral multiple of truck capacity (tonne)
V_t	Average speed of truck type t when empty (Km/hr)
\bar{V}_t	Average speed of truck type t when loaded (Km/hr)
C_t	Cost of empty truck movement (\$/Km)
\bar{C}_t	Cost of loaded truck movement (\$/Km)
$\bar{A}_{t,s}$	Binary parameter, if truck type t can be assigned to shovel s
X_s	Shovel bucket capacity (tonne)
L_s	Shovel loading cycle time (seconds)
U_s^+	Maximum desired shovel utilization (%)
U_s^-	Minimum desired shovel utilization (%)
B_s	Cost of shovel per tonne production (\$/tonne)
A_s	Cost of shovel movement (\$/meter)
S_s	Movement speed of shovel (meter/minute)
α_t^T	Truck availability (fraction)
α_s^S	Shovel availability (fraction)
F_s	Face where shovel is initially located (start of the shift)
D_f^{FE}	Distance to exit from face f
D_d^{ED}	Distance to destination d from the pit exit
Z_{d^p}	Maximum capacity of the processing plants (tonne/hr)
Λ_{d^p}	Maximum acceptable deviation in tonnage received at processing plants (tonne/hr)
M_{d^p}	Processing cost at the processing plants (\$/tonne)
R_{k,d^p}	Recovery of material type k at the processing plants
G_{k,d^p}	Desired grade of material types at the processing plants

$G_{k,d}^-$	Lower limit on grade of material type k at processing plants
$G_{k,d}^+$	Upper limit on grade of material type k at processing plants
F_f^x, F_f^y, F_f^z	x, y, z coordinates of the faces available for shovel assignment (meters)
$\bar{G}_{f,k}$	Grade of material type k at face f
O_f	Tonnage available at face f (tonne)
Q_f	1 if material at face is ore, 0 if it is waste (binary parameter)
T	Shift duration (hr)
Π^-	Lower limit on desired stripping ratio
Π^+	Upper limit on desired stripping ratio
P_k	Price of recovered material k in the market
W_i	Normalized weights of individual goals ($i = 1, 2, 3, 4$) based on priority

4.4. Calculated Parameters

Γ_{f^1, f^2}^F	Distance between available faces (meters)
$\Gamma_{f,d}^D$	Distance of destinations from faces, based on the haulage profile in short-term schedule (meters)
$\tau_{s,f}$	Movement time of shovel s from initial face to face f (minutes)
X_s^+	Maximum shovel production calculated using availability and maximum desired utilization (tonne)
X_s^-	Minimum shovel production calculated using availability and minimum desired utilization (tonne).
$\bar{T}_{t,f,d}$	Cycle time of truck type t from face f to destination d (minutes)

4.5. Calculations

$$\Gamma_{f^1, f^2}^F = \sqrt{(F_{f^2}^x - F_{f^1}^x)^2 + (F_{f^2}^y - F_{f^1}^y)^2 + (F_{f^2}^z - F_{f^1}^z)^2} \quad (1)$$

$$\Gamma_{f,d}^D = D_f^{FE} + D_d^{ED} \quad (2)$$

$$\tau_{s,f} = \Gamma_{F_s, f}^F / S_s \quad (3)$$

$$X_s^+ = U_s^+ \times \alpha_s^S \times X_s \times T \times 36 / L_s \quad (4)$$

$$X_s^- = U_s^- \times \alpha_s^S \times X_s \times T \times 36 / L_s \quad (5)$$

$$\bar{T}_{t,f,d} = 0.06 \times \Gamma_{f,d}^d \times \left(\frac{1}{V_t} + \frac{1}{\hat{V}_t} \right) + \left(\frac{D_t + E_t}{60} \right) + \frac{H_t}{\hat{S} \times 60} \times \sum_s \left(\frac{L_s}{X_s} \right) \quad (6)$$

5. MILGP formulation

A mixed integer linear goal programming model has been formulated to optimize the goals represented by equations (7), (8), (9) and (10) in the order of their priority considered in this paper.

5.1. Goals

$$\Psi_1 = \sum_s x_s^- \quad (7)$$

$$\Psi_2 = \sum_{d^p} \sum_k (g_{k,d^p}^- + g_{k,d^p}^+) \quad (8)$$

$$\Psi_3 = \sum_{d^p} (\delta_{d^p}^- + \delta_{d^p}^+) \quad (9)$$

$$\begin{aligned} \Psi_4 = & \sum_s \sum_f (\Gamma_{F_s,f}^F \times A_s \times a_{s,f} + \sum_d B_s \times x_{s,f,d}) + \sum_t \sum_f \sum_d n_{t,f,d} \times \Gamma_{f,d}^D \times (C_t + \bar{C}_t) + \\ & \sum_s \sum_f \sum_{d^p} x_{s,f,d^p} \times M_{d^p} - \sum_s \sum_f \sum_{d^p} \sum_k P_k \times R_{k,d^p} \times x_{s,f,d^p} \times \bar{G}_{f,k} \end{aligned} \quad (10)$$

Equation (7) represents the difference between the maximum target production and production achieved by the shovels over a shift. Equation (8) represents the difference between the material content received at the ore destinations and the desired material content based on desired grade. Equation (9) represents the difference between the amounts of ore supplied to the processing plants compared to the amount of processing desired over a shift. And equation (10) represents the total cost of the operation, incorporating shovel movement cost (if any shovel is reassigned to a new face), shovel operating cost, truck operating cost, processing cost and revenue generated by the recovered metal of interest in the milling process.

5.2. Objective

The objective of the problem is formulated by combining all the goals and applying a non-preemptive goal programming approach. It should be noted here that, as the goals have different dimensions, it is necessary to normalize them into dimensionless objectives before combining them together. Normalization is carried out by determining the Utopia and Nadir values for individual goals Grodzevich et al. (2006). Normalized goals are then multiplied with weights to achieve the desired priority. The final objective function, thus obtained, is given by equation (11).

$$\Psi = W_1 \times \bar{\Psi}_1 + W_2 \times \bar{\Psi}_2 + W_3 \times \bar{\Psi}_3 + W_4 \times \bar{\Psi}_4 \quad (11)$$

Where

$$\bar{\Psi}_i = (\Psi_i - Utopia_i) / (Nadir_i - Utopia_i) \quad i \in 1, 2, 3 \& 4 \quad (12)$$

5.3. Constraints

$$\sum_s a_{s,f} \leq 1 \quad \forall f \quad (13)$$

$$\sum_f a_{s,f} \leq 1 \quad \forall s \quad (14)$$

$$\sum_d \sum_f x_{s,f,d} + x_s^- = X_s^+ \quad \forall s \quad (15)$$

$$\sum_d x_{s,f,d} \geq a_{s,f} \times X_s^- \quad \forall s \& \forall f \quad (16)$$

$$\sum_s x_{s,f,d} \leq \sum_t n_{t,f,d} \times H_t \quad \forall d \ \& \ \forall f \quad (17)$$

$$\sum_s x_{s,f,d} + J \geq \sum_t n_{t,f,d} \times H_t \quad \forall d \ \& \ \forall f \quad (18)$$

$$\sum_d x_{s,f,d} \leq a_{s,f} \times O_f \quad \forall s \ \& \ \forall f \quad (19)$$

$$\sum_{d^o} x_{s,f,d^o} \leq a_{s,f} \times O_f \times Q_f \quad \forall s \ \& \ \forall f \quad (20)$$

$$\sum_{d^w} x_{s,f,d^w} \leq a_{s,f} \times O_f \times (1 - Q_f) \quad \forall s \ \& \ \forall f \quad (21)$$

$$\sum_d n_{t,f,d} \times H_t \leq \sum_s \left(\sum_d x_{s,f,d} + a_{s,f} \times J \right) \times \bar{A}_{t,s} \quad \forall t \ \& \ \forall f \quad (22)$$

$$\sum_f \sum_d n_{t,f,d} \times \bar{T}_{t,f,d} \leq T \times 60 \times N_t \times \alpha_t^T \quad \forall t \quad (23)$$

$$\sum_d x_{s,f,d} \leq (T \times 60 - \tau_{s,f}) \times 60 \times X_s \times \alpha_s^S \times a_{s,f} / L_s \quad \forall s \ \& \ \forall f \quad (24)$$

$$\sum_s \sum_f x_{s,f,d^p} + \delta_{d^p}^- - \delta_{d^p}^+ = Z_{d^p} \times T \quad \forall d^p \quad (25)$$

$$\delta_{d^p}^- \leq \Lambda_{d^p} \times T \quad \forall d^p \quad (26)$$

$$\delta_{d^p}^+ \leq \Lambda_{d^p} \times T \quad \forall d^p \quad (27)$$

$$\sum_f \sum_s x_{s,f,d^p} \times \bar{G}_{f,k} + g_{k,d^p}^- - g_{k,d^p}^+ = \sum_s \sum_f x_{s,f,d^p} \times G_{k,d^p} \quad \forall k \ \& \ \forall d^p \quad (28)$$

$$g_{k,d^p}^- \leq (G_{k,d^p} - G_{k,d^p}^-) \times \sum_s \sum_f x_{s,f,d^p} \quad \forall k \ \& \ \forall d^p \quad (29)$$

$$g_{k,d^p}^+ \leq (G_{k,d^p}^+ - G_{k,d^p}^-) \times \sum_s \sum_f x_{s,f,d^p} \quad \forall k \ \& \ \forall d^p \quad (30)$$

$$\Pi^- \times \sum_s \sum_f \sum_{d^o} x_{s,f,d^o} \leq \sum_s \sum_f \sum_{d^w} x_{s,f,d^w} \quad (31)$$

$$\Pi^+ \times \sum_s \sum_f \sum_{d^o} x_{s,f,d^o} \geq \sum_s \sum_f \sum_{d^w} x_{s,f,d^w} \quad (32)$$

Constraints (13) and (14) assures that only one shovel is assigned to any face and also that any shovel is assigned to only one face. Constraint (15) is a soft constraint on the production by any shovel with a deviational variable that is minimized in the objective function. Constraint (16) is a hard constraint that puts a lower limit on the production by any shovel. Constraint (17) assures that total production by any shovel from its face to a destination is less than or equal to the total material hauled by trucks between the face and the destination, which in turn is equal to the product of number of trips between the face and destination, and the truck capacity. The inequality constraint makes sure that total material hauled may not be an integer multiple of truck capacity and so some trips may have slightly lesser load hauled. This constraint enables the model to excavate the faces completely and reduces infeasibility of the model to a great extent due to the tight equality constraint. To counter the effect caused by the inequality, constraint (18) has been

included which puts a lower limit on production deviation as equal to a predefined value J . To optimize the case considered in this paper, J is considered as the minimum of the truck capacities in the truck fleet. It means, at the end of the shift, the maximum allowed difference between the shovel production from a face to a destination and the material hauled based on number of truck trips is J . In other words, constraints (17) and (18) allow the shovels to load the trucks slightly less than the capacity of the trucks if required. Constraints (19), (20) and (21) make sure that total ore or waste production by any shovel from its assigned face cannot exceed the total available ore or waste material at that face. This constraint also makes sure that no production is possible by the shovel from the face it is not assigned to. Constraint (22) assures that a particular truck type will have zero trips from any non-matching shovel. Part of the right hand side of the inequality is included to incorporate what is modeled in constraint (18). Constraint (23) limits the maximum possible trips by any truck type in a shift considering the truck availability and available shift time. Constraint (24) limits the total production possible by a shovel taking into account its availability and the movement time to the face (if assigned to a different face where it initially was). Constraints (25), (26) and (27) are the processing constraints on the desired tonnage feed to the processing plants and maximum allowable deviation in tonnage accepted at the plants. Constraints (28), (29) and (30) are the grade constraints, which make sure that the average grade sent to the processing plant is of desired grade and deviation is within the upper and lower acceptable limits. Constraints (31) and (32) keep the stripping ratio within defined limits.

Constraints (29) and (30) put hard constraints on the lower and upper limits of the grade deviation, which make the problem infeasible in case the limit range is tight and blending using the available faces and shovels is unable to provide the head grade in the desired range. Considering the applicability of the model as to bring automation at the tactical stage, these constraints are removed for the case study presented. Instead of using these constraints, a high preference is given to the grade deviation goal in the objective function.

5.4. Normalization of goals

The goals considered in this model are conflicting and incomparable in dimensions. Also a non-preemptive approach is adopted for the optimization. Such type of goal programming models need normalization of the goals before the optimization process. Grodzevich et al. (2006) provides different normalization strategies that can be adopted for optimization of similar models. Normalization, in this paper, has been carried out by determining the Nadir and Utopia points for individual goals. The goals are then normalized by the differences of optimal function values in the Nadir and Utopia points. This difference is the length of the interval where the optimal objective function vary within the pareto optimal set (Grodzevich & Romanko, 2006).

Utopia point (z^U) for individual goals is obtained by considering only one goal in the objective and optimizing the system (minimization). This provides the lower bound on the values of individual goals in the Pareto optimal space.

Nadir point sets an upper bound on individual goals. This is the maximum possible value of any goal in the objective space. So, if $z_i^U = f_i(x^{[i]})$ represents Utopia point for goal i with solution vector $x^{[i]}$, Nadir point can be obtained for K number of goals using equation (33) (Grodzevich & Romanko, 2006).

$$z_i^N = \max_{1 \leq j \leq K} (f_i(x^{[j]})) \quad \forall i \in \text{goals} \quad (33)$$

Once the Nadir and Utopia points have been determined, goals can be normalized using equation (34) (Grodzevich & Romanko, 2006) to range between 0 and 1, and multiplied with respective weights to give priority to desired goals over others.

$$\bar{f}_i(x) = \frac{f_i(x) - z_i^U}{z_i^N - z_i^U} \quad \forall i \in \text{goals} \quad (34)$$

Weighted sum method, given by equation (35), has been used to calculate the priority weights to be multiplied to goals.

$$\sum_i w_i = 1 \quad i \in \text{goals} \quad (35)$$

5.5. Model inputs

Model takes two types of input. All the face characteristics are obtained using the short-term mine production schedule. Information received includes mining cuts (face) IDs, coordinates of faces (for approximating the shovel movement distances from face to face), tonnage of material, fraction to be mined in the given period, minimum haul road distance from the face to the mine exit, precedence cut's IDs and average grades of different material. All of these information is retrieved from the model given by Eivazy and Askari-Nasab (2012).

Other inputs include:

- i. Shovel: shovel ID's, bucket capacities, loading cycle time, availability, minimum and maximum desired utilization, cost of shovel operation as per tonne of material mined, cost of shovel movement as per meter moved, movement velocity of shovel and the face where the shovel is initially located.
- ii. Trucks: truck types ID's, number of trucks of each type, capacities, dump time, spot time, availability, average speed of trucks when empty and when loaded, cost of truck operation per meter moved when empty and when loaded.
- iii. Destinations: maximum rate of processing at processing plants (tonne/hr), maximum allowed deviation in tonnage supplied to the processing plants per hour, cost of processing per tonne of ore processed, recovery fraction at the plants, desired grade of each material type at processing plants and stockpiles
- iv. Shift duration (hours), lower and upper limit on stripping ratio, selling price of material recovered at the processing plants, 0 or 1 parameter to match trucks with shovels and weights for different goals in the objective function.

6. Model implementation and results

To verify the MILGP model, it has been encoded using AMPL (a modeling language for mathematical programming) (Fourer, Gay, & Kernighan, 2002) and solved using CPLEX optimizer for an iron ore mine, short-term schedule for which is generated by the model provided by Eivazy and Askari-Nasab (2012).

6.1. Case study

The case study of Gol-E-Gohar iron ore complex, located in south of Iran, has been considered to verify the model presented in this paper. Iron is the main element of interest in the deposit. As the mine employs magnetic separators for recovering the iron, magnetic weight recovery (percent MWT) is the main criterion for selecting the ore to be sent to the processing plants. The ore contains phosphor and sulfur as contaminants or secondary elements to be controlled. Eivazy and Askari-Nasab (2012) used 3089 blocks from the long-term plan allocated in the benches 14, 15, 16 and 17, out of 20 benches of the open pit mine, for the purpose of short-term planning over 12 months, with a monthly resolution. See Eivazy and Askari-Nasab (2012) for detailed information of the model used for generating the short-term production schedule.

The open pit is designed to have only one exit. The distance from the face to the pit exit is provided in the short-term production schedule. For the model implementation five destinations are considered. The distances from the pit exit to various destinations are provided in Table 1.

Table 1. Distance between pit exit and various truck destinations in the mine

Destination	Distance (meter)
Processing plant 1	1500
Processing plant 2	750
Stock-pile 1	1500
Stock-pile 2	750
Waste dump	1000

It should be noted that, only one waste dump is considered here though more than one are possible. It is because model does not consider any constraints associated with the waste dumps. If multiple sites are available, having no constraints associated with them, model will send all the material to the nearest waste dump, by minimizing the hauler travel times and costs. If some specific constraints, such as maximum daily dumping rate, for waste dumps are available, multiple dump sites can be included with the inclusion of dump characteristic constraints.

Table 2 provides the desired grades of material types at ore destinations and processing plant characteristics considered.

Table 2. Desired grades of various elements at the destinations and the target

	Desired grades (%)			Target production (t/h)	Processing limits (t/h)	
	MWT	S	P		Lower	Upper
Processing plant 1	77	1	0.15	650	600	700
Processing plant 2	80	1	0.15	650	600	700
Stock pile 1	77	1	0.15	No limit	-	-
Stock pile 2	80	1	0.15	No limit	-	-

The mine operates for two 12 hour shifts in a day and 6 days in a week. For the verification, the model is made to run on the available faces in the 1st month, provided by the short-term production schedule. As this model requires a real-time monitoring system, so that system is optimized whenever system state changes, running the model standalone for full shifts would be inappropriate. To overcome this problem, model is run to optimize the system for a time frame of 30 minutes, repeating up to 12 hour shift. Data is recorded after every shift. Model runs for 26 working days in a month or until all the faces are depleted (whichever is less). It should be kept in mind that due to the stripping ratio constraint, at any time, mine must have at least one ore and one waste face available for mining, to get a feasible solution. Therefore model would become infeasible if no ore face is available or no waste face is available or only one face is available.

6.2. Scenario Analysis

The MILGP model proposed is implemented on the case study with two scenarios.

6.2.1. Scenario 1

First scenario is considered where mine employs two hydraulic shovels of 40 tonne bucket capacity. Six trucks of 150 tonne capacity and 8 trucks of 120 tonne capacity are available to haul the material. Both types of trucks can be assigned to any of the two shovels. Table 3 shows the operational costs assumed in this case study. The costs are assumed to be same for all types of shovels and all types of trucks. The selling price of recovered Iron is \$130 per tonne.

Table 3. Mine operational costs

Operation	Cost
Cost of shovel operation	0.12 \$/t
Cost of shovel movement	1.00 \$/m
Cost of empty truck movement	0.20 \$/Km
Cost of loaded truck movement	0.30 \$/Km
Processing cost	5.00\$/t

Fig.3 to Fig.8 show the results obtained by implementing the proposed model on the case study under scenario 1. The results describe the key performance indices included as goals in the model.

Fig.3 shows the tonnage of material sent to the processing plants, directly from the faces; and the desired feed with lower and upper permissible limits of the processing plants. It can be noted that plants are mostly under-fed, but the deviations are not substantial and well within limits. The under feeding, observed in this case can be attributed to the conflicting grade deviation goal, which performs poorly under this scenario and impacts other goals. Daily feed to processing plants is very much sensitive to economic goal. A higher preference weight to minimize cost may result in a positive shift in the graph given by Fig.3.

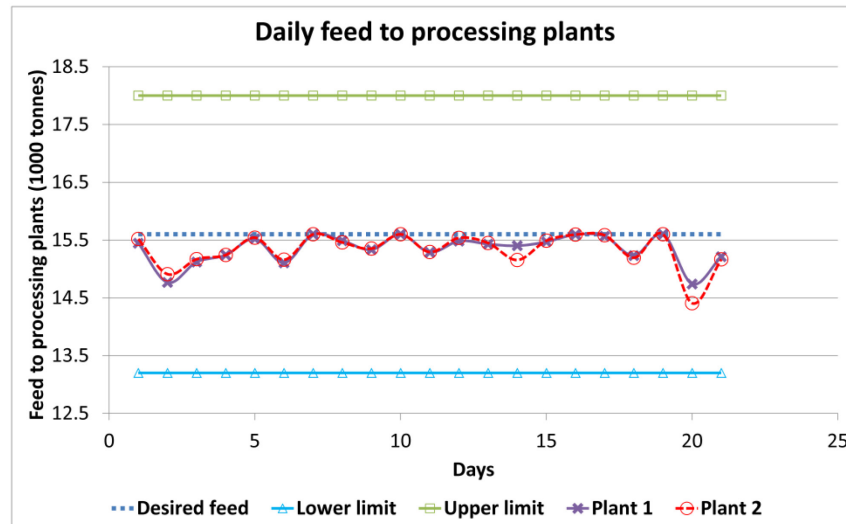


Fig.3. Daily supply of ore from faces to the processing plants for scenario 1

Fig.4 provides a daily production chart over the 22 days of production. In the first shift of 22nd day, only one face remains as un-mined. Fig.4 shows that no material is sent to the stockpiles over the month, because ore sent to stockpiles does not generate revenue and only increases cost in the model. If a higher preference is provided to the production goal in the objective function, some amount will be observed to be sent to the stockpiles as well. It should be noted here that, this model does not associate any revenue with the ore sent to the stockpiles as it does not incorporate re-handling.

The observed deviations in the total production can be attributed to the fact that no real time monitoring is considered here. This results in nonproductive time for shovels which finish mining the available material at the face well before the time frame of 30 minutes. In such a case the shovel produces less material compared to its capacity. It also affects the other shovels production due to the stripping ratio constraint. These limitations are not the limitations of the model, but the process adopted here for verification. These limitations can be removed if the model is run in association with a real-time monitoring system, such as simulation.

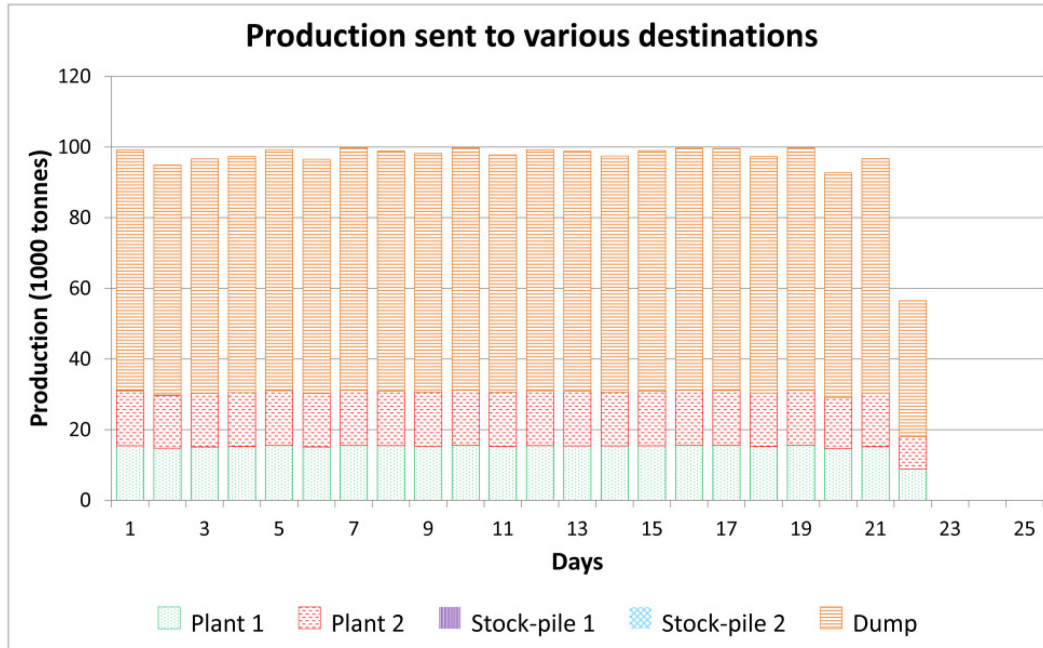


Fig.4. Daily production sent at various destinations for scenario 1

Fig.5, Fig.6 and Fig.7 presents the average MWT, Sulfur and Phosphor head grade respectively compared to the desired grades at the two processing plants. The head grades at both plants are observed to be the same throughout the month. This is because no blending is possible in this scenario. With only two shovels in the system, following the stripping ratio constraints, only one shovel can produce ore. Hence the resulting ore production will follow the grade of the ore face, being mined, at both of the processing plants.

A schedule obtained by the model, describing the faces being mined and the shovels assigned to them in each shifts is presented in Fig.8. The schedule shows that all faces are excavated by the 1st shift of 22nd working day of the month except face number 34. The multiple faces, shown to be mined by one shovel over one shift, is because of face having small tonnages (small cuts). Shovel shifts to a different face, within a shift, once the assigned face is completely depleted. This is one of the reasons which make it necessary to time windows of 30 minutes to optimize the operations over a shift and in turn over a month. A production output of the model for the first shift of the first day is also presented in Fig.12 for a better understanding of the implementation of the model for the case study presented.

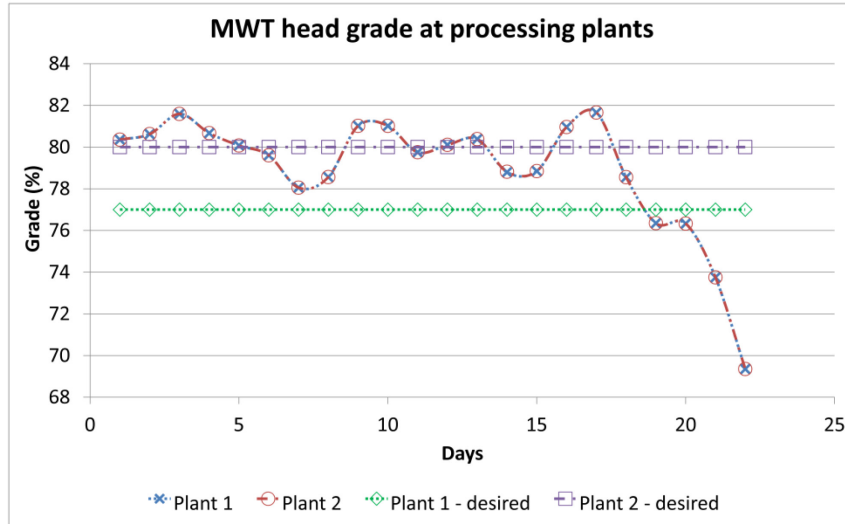


Fig.5.MWT head grade at processing plants for scenario 1

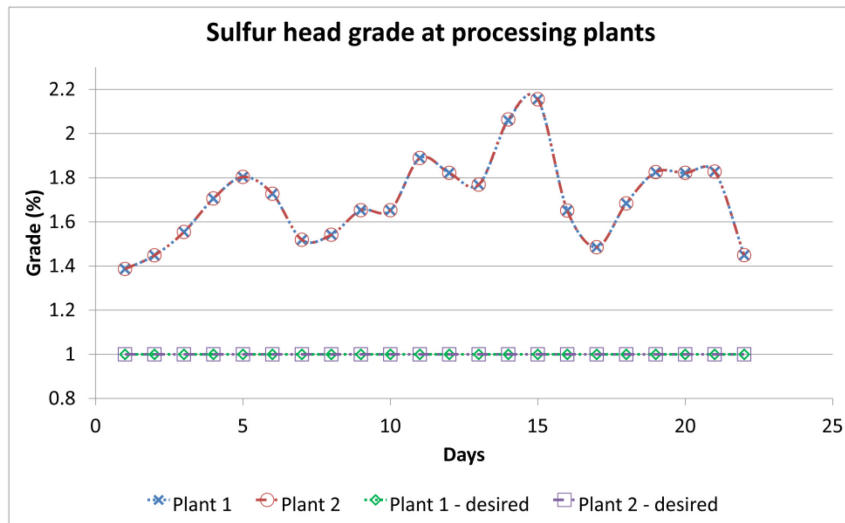


Fig.6. Sulfur head grade at processing plants for scenario 1

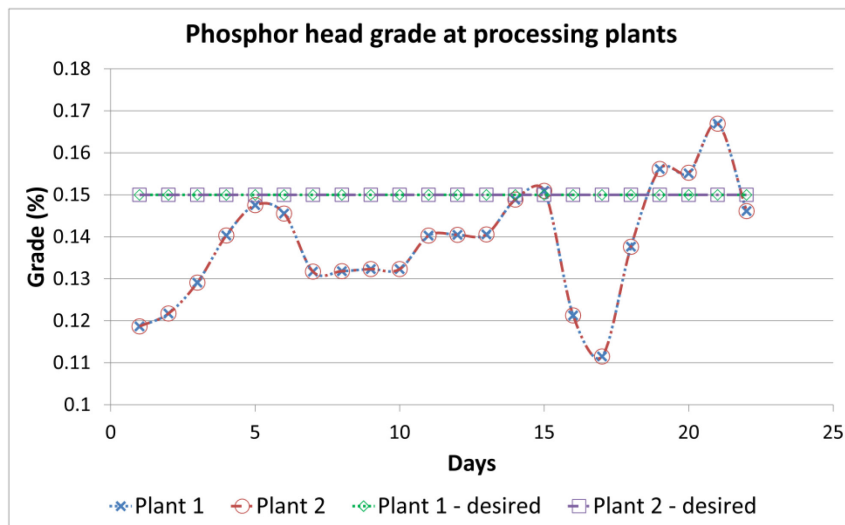


Fig.7. Phosphor head grade at processing plants for scenario 1



Fig.8. Mining schedule obtained in scenario 1

6.2.2. Scenario 2

To justify the grade blending problem associated with scenario one, a second scenario is considered having three 40 tonne bucket capacity hydraulic shovels in the system. All other parameters are considered to be exactly same as scenario 1. It should be noted here that this scenario is considered only to verify the working of the model. It is not realistic to have incomparable production and

processing capacity in a mining system. Due to increase in number of shovels in the system production capacity increases, but the processing capacity remains the same. This may result in mining out all the faces early, which were otherwise scheduled for the whole month, by sending extra ore to the stock-piles. Fig.9, Fig.10 and Fig.11 show much better results compared to scenario one in terms of head grades. This is because of possible blending of high grade and low grade ore in this scenario. It can be observed in Fig.9 that, though head grade at processing plant 2 is quite stable at the desired grade, head grade at processing plant 1 rises over days. This happens because of reduced selectivity for shovels amongst available faces. As the mining progresses in a month, available faces to be mined decreases, resulting in better performance of the model initially and a deteriorating performance towards the end.

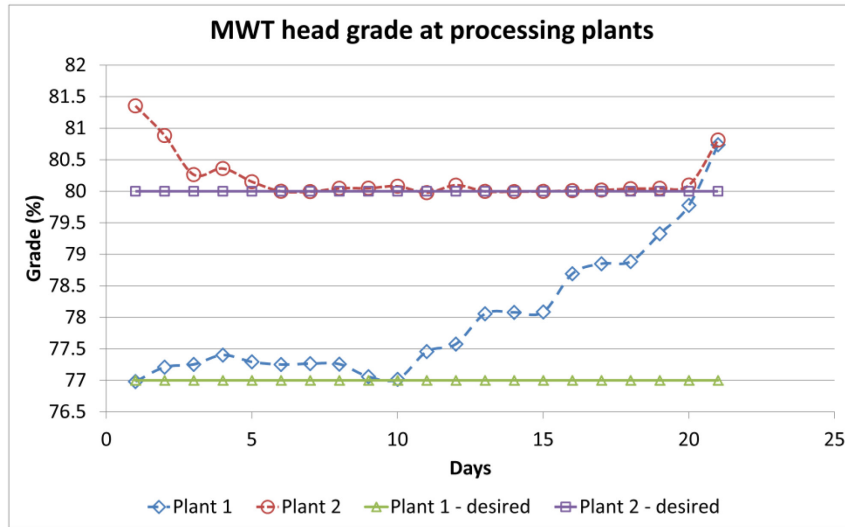


Fig.9. MWT head grade at processing plants for scenario 2

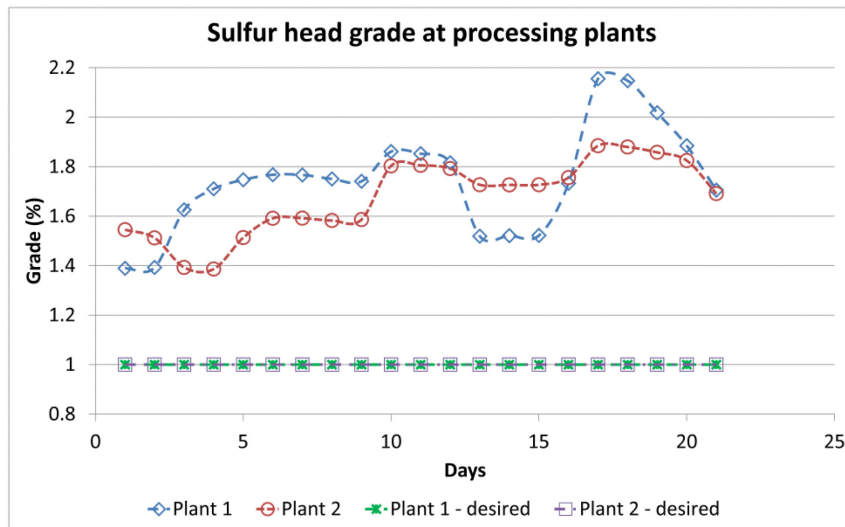


Fig.10. Sulfur head grade at processing plants for scenario 2

Fig.10 shows no significant improvement in Sulfur head grade compared to scenario 1. This poor performance can be attributed to the sulfur grade distribution of various faces available for mining. As no face contains a sulfur grade, that is less than the desired grade, blending to reduce the positive deviation is impossible, resulting in a poor performance. Fig.11 shows an improved and stable result for phosphor grade in comparison to scenario 1.

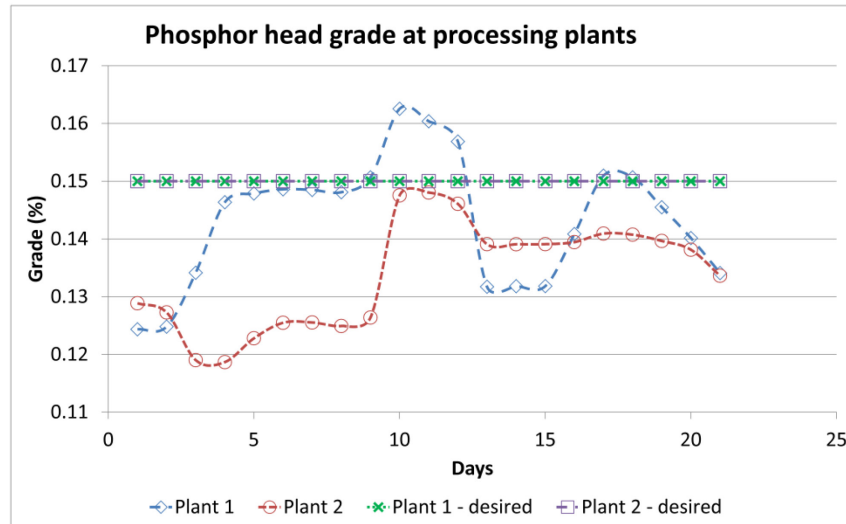


Fig.11. Phosphor head grade at processing plants for scenario 2

7. Conclusion

Decision making in mining operations is a challenging task. Competitive market and increasing demands have made it imperative for mining companies to improve upon their productivity and efficiency. Automation is the solution everyone is looking for. Increased computation power and technology have already created grounds for system automation. Truck dispatching systems are an attempt towards automation which is in place at most of the highly productive mines nowadays. But these systems lack a connection between the strategic and tactical plans. This paper attempts to create a bridge between the short-term production plan and tactical plan by acting as the upper stage in a two-stage dispatching algorithm. The proposed MILGP model assigns the shovels to the available faces, provided by the short-term production plan, and set their target production. The target is then fed into the truck dispatching system to be achieved in real time operations.

The main contribution of this paper is a MILGP model that acts as an upper stage in a two-stage dispatching algorithm. The improvements over previous research in this area using operations research techniques include: connecting short-term production plan with operations (tactical plans), incorporating shovel assignments and considering multiple destination mining systems.

Future research in the area includes assessing the optimization model with simulation over a larger time period (about a year). The integration with a simulation model will provide a real time monitoring of the system that will watch and optimize the system whenever its state changes.

8. References

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9. Appendix

A report of the production in the first shift of first day is presented in Fig.12 for scenario 1. Optimization sequence is the sequence of 30 minute time windows over which optimization takes place. Fig.12 shows the faces assigned to shovel 1 and 2 by the model; and the material available at those faces in the beginning of the optimization. Production section shows the tonnage of material sent from the faces to different destinations. The last section shows the total number of truck trips from the faces to different destinations by each truck type; i.e. it includes the trips made by each

truck of a type T1 or T2. T1 and T2 in Fig.12 refer to 150 tonne and 120 tonne capacity trucks respectively.

Optimization sequence	Shovel ID	Face assignment	Tonnage available at face	Production (tons)					Total number of trips by all trucks of each type (to – truck type)									
				Plant 1	Plant 2	Stock Pile 1	Stock Pile 2	Dump	Plant 1 - T1	Plant 1 - T2	Plant 2 - T1	Plant 2 - T2	Stock Pile 1 - T1	Stock Pile 1 - T2	Stock Pile 2 - T1	Stock Pile 2 - T2	Dump - T1	Dump - T2
1	1	25	50484	325	325	0	119	0	0	3	0	3	0	0	0	1	0	0
1	2	56	2874	0	0	0	0	1615	0	0	0	0	0	0	0	0	11	0
2	1	25	49715	300	300	0	0	0	2	0	2	0	0	0	0	0	0	0
2	2	56	1259	0	0	0	0	1259	0	0	0	0	0	0	0	0	5	5
3	1	25	49116	332	350	0	0	0	1	2	0	3	0	0	0	0	0	0
3	2	57	2874	0	0	0	0	1500	0	0	0	0	0	0	0	0	10	0
4	1	25	48434	325	329	0	0	0	1	2	0	3	0	0	0	0	0	0
4	2	57	1374	0	0	0	0	1374	0	0	0	0	0	0	0	0	10	0
5	1	25	47779	332	350	0	0	0	0	3	1	2	0	0	0	0	0	0
5	2	58	4311	0	0	0	0	1500	0	0	0	0	0	0	0	0	10	0
6	1	25	47098	325	325	0	0	0	1	2	0	3	0	0	0	0	0	0
6	2	58	2811	0	0	0	0	1430	0	0	0	0	0	0	0	0	9	1
7	1	25	46448	325	333	0	0	0	0	3	0	3	0	0	0	0	0	0
7	2	58	1381	0	0	0	0	1381	0	0	0	0	0	0	0	0	10	0
8	1	25	45790	318	325	0	0	0	0	3	0	3	0	0	0	0	0	0
8	2	59	4311	0	0	0	0	1350	0	0	0	0	0	0	0	0	9	0
9	1	25	45147	325	325	0	0	0	1	2	0	3	0	0	0	0	0	0
9	2	59	2961	0	0	0	0	1430	0	0	0	0	0	0	0	0	9	1
10	1	25	44497	325	325	0	64	0	0	3	0	3	0	0	1	0	0	0
10	2	59	1531	0	0	0	0	1500	0	0	0	0	0	0	0	0	10	0
11	1	25	43783	332	350	0	0	0	0	3	0	3	0	0	0	0	0	0
11	2	60	3593	0	0	0	0	1500	0	0	0	0	0	0	0	0	10	0
12	1	25	43101	325	325	0	0	0	1	2	0	3	0	0	0	0	0	0
12	2	60	2093	0	0	0	0	1430	0	0	0	0	0	0	0	0	9	1
13	1	25	42451	158	158	0	0	0	2	0	1	1	0	0	0	0	0	0
13	2	60	663	0	0	0	0	663	0	0	0	0	0	0	0	0	5	0
14	1	25	42135	325	325	0	0	0	0	3	0	3	0	0	0	0	0	0
14	2	61	2982	0	0	0	0	1413	0	0	0	0	0	0	0	0	10	0
15	1	25	41485	325	325	0	0	0	0	3	0	3	0	0	0	0	0	0
15	2	61	1569	0	0	0	0	1430	0	0	0	0	0	0	0	0	10	0
16	1	25	40835	350	350	0	0	0	0	3	0	3	0	0	0	0	0	0
16	2	62	59649	0	0	0	0	1500	0	0	0	0	0	0	0	0	10	0
17	1	25	40135	325	325	0	0	0	0	3	0	3	0	0	0	0	0	0
17	2	62	58149	0	0	0	0	1430	0	0	0	0	0	0	0	0	10	0
18	1	25	39485	325	325	0	0	0	0	3	0	3	0	0	0	0	0	0
18	2	62	56719	0	0	0	0	1430	0	0	0	0	0	0	0	0	10	0
19	1	25	38835	325	325	0	0	0	0	3	0	3	0	0	0	0	0	0
19	2	62	55289	0	0	0	0	1430	0	0	0	0	0	0	0	0	10	0
20	1	25	38185	325	325	0	0	0	0	3	0	3	0	0	0	0	0	0
20	2	62	53859	0	0	0	0	1430	0	0	0	0	0	0	0	0	10	0
21	1	25	37535	325	325	0	0	0	0	3	0	3	0	0	0	0	0	0
21	2	62	52429	0	0	0	0	1430	0	0	0	0	0	0	0	0	10	0
22	1	25	36885	325	325	0	0	0	0	3	0	3	0	0	0	0	0	0
22	2	62	50999	0	0	0	0	1430	0	0	0	0	0	0	0	0	10	0
23	1	25	36235	325	325	0	0	0	0	3	0	3	0	0	0	0	0	0
23	2	62	49569	0	0	0	0	1430	0	0	0	0	0	0	0	0	10	0
24	1	25	35585	325	325	0	0	0	0	3	0	3	0	0	0	0	0	0
24	2	62	48139	0	0	0	0	1430	0	0	0	0	0	0	0	0	10	0

Fig.12. A production report of the first shift of the first day for scenario 1