Open-Pit Mine Production Operation Optimization

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Abstract

Decision making in mining is a challenging task. Optimal decisions regarding shovel and truck allocations, 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 to optimize the operations based on four desired goals of the company: a) maximize production, b) minimize deviations in head grade, c) minimize deviations in tonnage feed to the processing plants from the desired feed, and d) minimize operating cost. The model provides shovel assignments and the target productions; as an input to the dispatching system while meeting the desired goals and constraints of the mining operation. The model implementation with an iron ore mine case study provided average plant utilization above 99%, average truck utilization above 92% and average shovel utilization above 95%.

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 mine-life (Askari-Nasab et al., 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 uncertain uptime 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 showed that though sufficient attention has been given to optimization of the operations, very few try to link the production operations with the mine strategic plans by providing optimal shovel allocations, which often lead to deviations from the short-term and in-turn long-term production targets. The problem

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of shovel assignments to mining faces has not received sufficient attention in the literature. Optimal shovel assignment to available mining-faces over the shift-by-shift operations can act as a link between the production operations and the mine strategic plans.

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:

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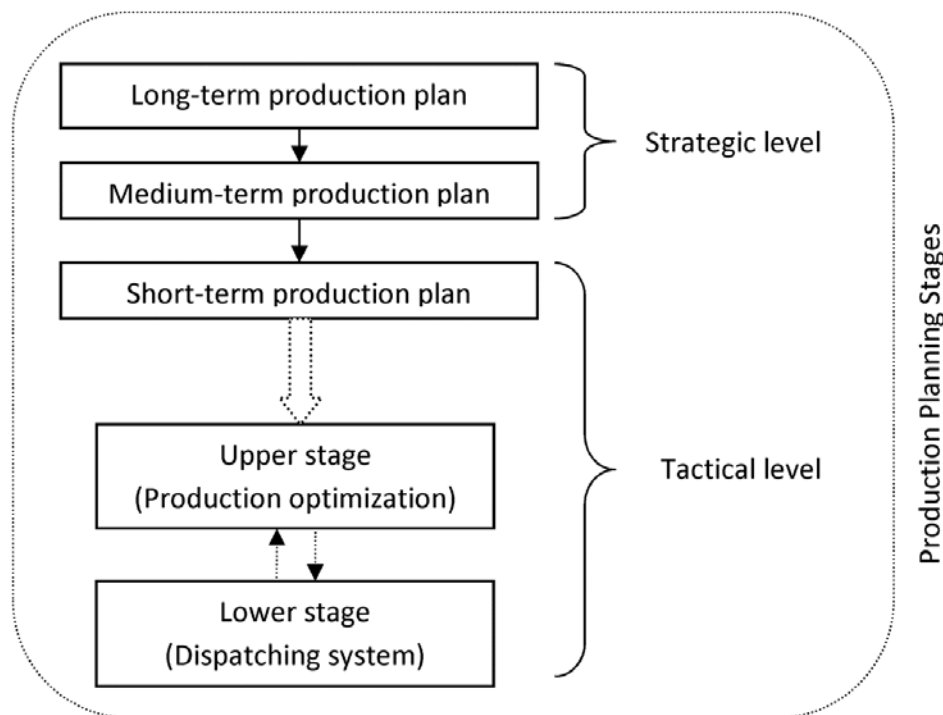- Operational cost escalation due to improper resource allocation.

Fig. 1. Mine production planning stages

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, truck-shovel allocation at the operational level.

We present 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 available faces 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 is proposed to act as the upper stage in a two stage dispatching system, where upper stage provides the shovel assignments and target productions over a fixed time horizon, and lower stage (dispatching algorithm) achieves those targets in real time.

This paper is structured as follows; a review of research on production scheduling with emphasis on operations is presented in literature review section. Model development section describes the parameters and mathematical formulations that have been used to develop the MILGP model. Subsequently, a case study is presented and the results of application of the model 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 for decision making purposes 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 purposes. 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. 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 and 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.

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. Discrete 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 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); where 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.* (1989) 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.

White and Olson (1986) describe the need of a model which could concurrently maximize the production, minimize the re-handle, meet blending limits and feed the plant. The major limitation of their model is the weak link between the two LP segments proposed. As transportation, in truck-shovel based mining system, occurs as discrete function of number of truck trips and their capacities, modeling it as continuous flow rate is inappropriate, which is another major limitation of their model. Not accounting for mixed fleet poses another limitation on its applicability in mixed fleet mining systems. The MILGP model proposed in this paper is similar in its applicability to the

LP segments proposed by White and Olson (1986) which is solved every time the system state changes.

Soumis *et al.* (1989) proposed a three stage model, which also included shovel assignments. The mixed integer programming model in the first stage, through man-machine interaction, provides 10 best alternatives for the shovel assignments to choose from in the reasonable time. The increased human intervention at this stage poses a limitation on the optimality of the decisions regarding shovel assignments. The second stage determines the production rates of the shovels and truck assignments using non-linear programming with three objectives: maximize shovel productions, minimize the squared difference between computed and available truck hours and minimize the grade deviations (blending). One unique characteristic of the proposition is the use of queuing theory to calculate the truck waiting time so as to compute the truck hours.

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. 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.

Gurgur *et al.* (2011) proposes an LP model for the shovel and truck allocations with an objective to minimize the deviation of the mine progress from the target provided by the MIP model. Although the model provides shovel assignments, it does so solely on strategic considerations (MIP model). The economic feasibility related to shovel movement cost and production lost during movement is not included in the model, which makes the shovel assignments not optimal. The continuous variables also pose a limitation on modeling the discrete nature of the production. Another model proposed by Subtil *et al.* (2011) does not consider objectives such as grade blending, constant desired feed to plants etc. and do not provide shovel assignments as well.

With the exception of Gurgur *et al.* (2011), 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 by optimal shovel assignments. 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 production operations and the strategic schedules.
5. Modeling of truck-shovel production operation, in terms of flow rate, seams inappropriate.

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

3. Problem Statement

Fig. 2 shows a schematic view of an open-pit mining system, modeled in this paper, consisting of $\hat{F}$ number of available faces to be mined within a predefined time period 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. 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*.
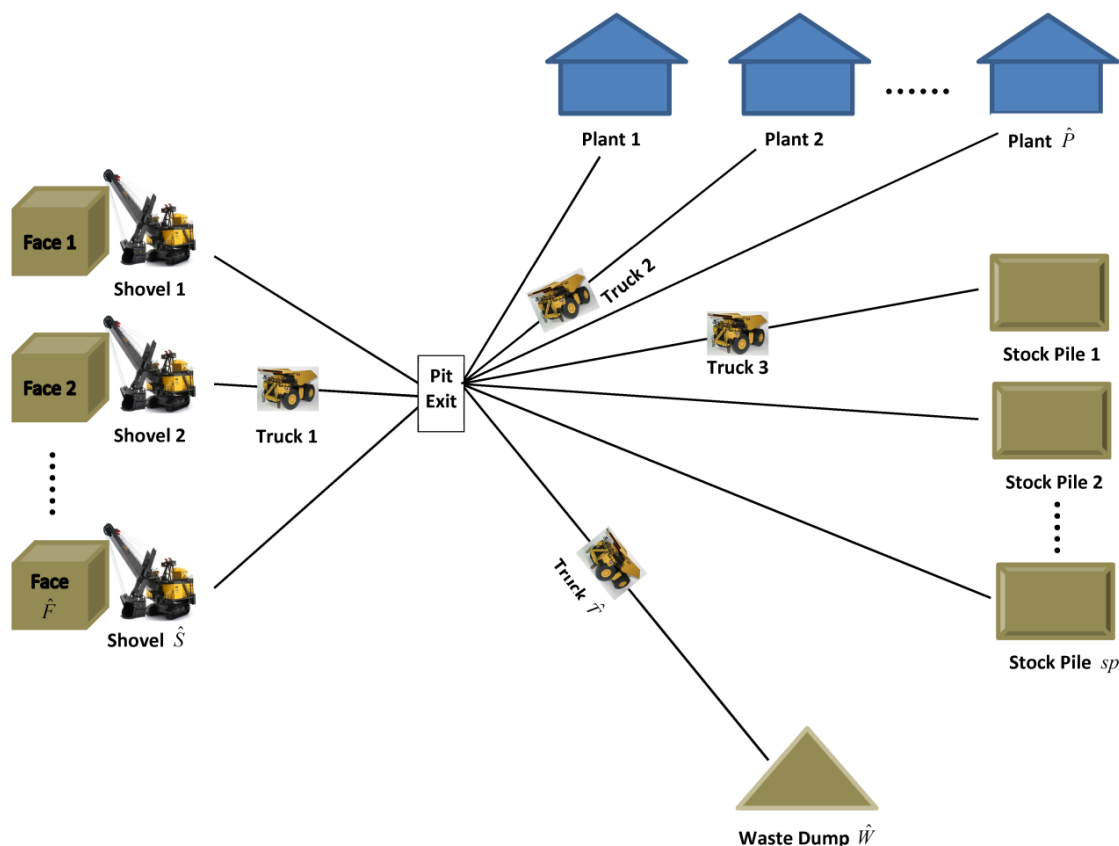

Fig. 2. A typical layout of an open-pit mining system

There is cost associated with truck and shovel operation: shovel movement cost as $ per meter of shovel movement, including additional man hours, when reassigned to a different face; and truck operating costs as $/Km while empty and loaded.

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 coming from different ore faces.
- Grade range requirements could be applied to multiple elements present in the ore.
- Processing plants are desired to have supply of material at a steady feed but cannot receive material at a rate above the specified limits.

This MILGP model optimizes the multi-destination open-pit mine production and shovel allocation problem subject to available shift time, truck and shovel availability, processing capacity and stripping ratio constraints. The four goals, considered, are to:

1. Maximize the shovel utilization (maximize production),
2. Minimize the grade deviations at ore destinations compared to desired grade,
3. Minimize the deviation in tonnage supplied to the processing plants compared to desired tonnage feed, and
4. Minimize the operating cost of the mine (truck and shovel movement 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 minimizes the truck and shovel movement cost. It should be noted that, including operating cost as a goal in this model becomes necessary to keep a check on abnormal shovel movement to very far off faces and to achieve the production targets with minimum truck and shovel movement. A flow chart representing the applicability of the proposed MILGP model in dynamic decision making for optimal production operations is given in Fig. 3.

4. Model development

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

4.1. Parameter calculations

Some of the parameters, described as calculated parameters in Appendix, are determined using Eq. (1) to Eq.(6), which are not provided directly as an input to the model. Eq. (1) calculates the distance between available faces, which is primarily used for predicting the shovel movement time and cost in the model. The distance between faces is calculated as straight line distance using the coordinates of the faces.

Eq. (2) calculates the total haul distance between a face and the destinations by summing up the distance to the pit exit from the face and distance of the destination from the pit exit. Eq. (3) determines the shovel movement time based on the distance between faces and the average travel speed of the shovel. Eq. (4) and (5) determines the maximum and minimum production limits for the shovels based on the maximum and minimum desired utilizations, shovel capacities, availabilities and the shift time.
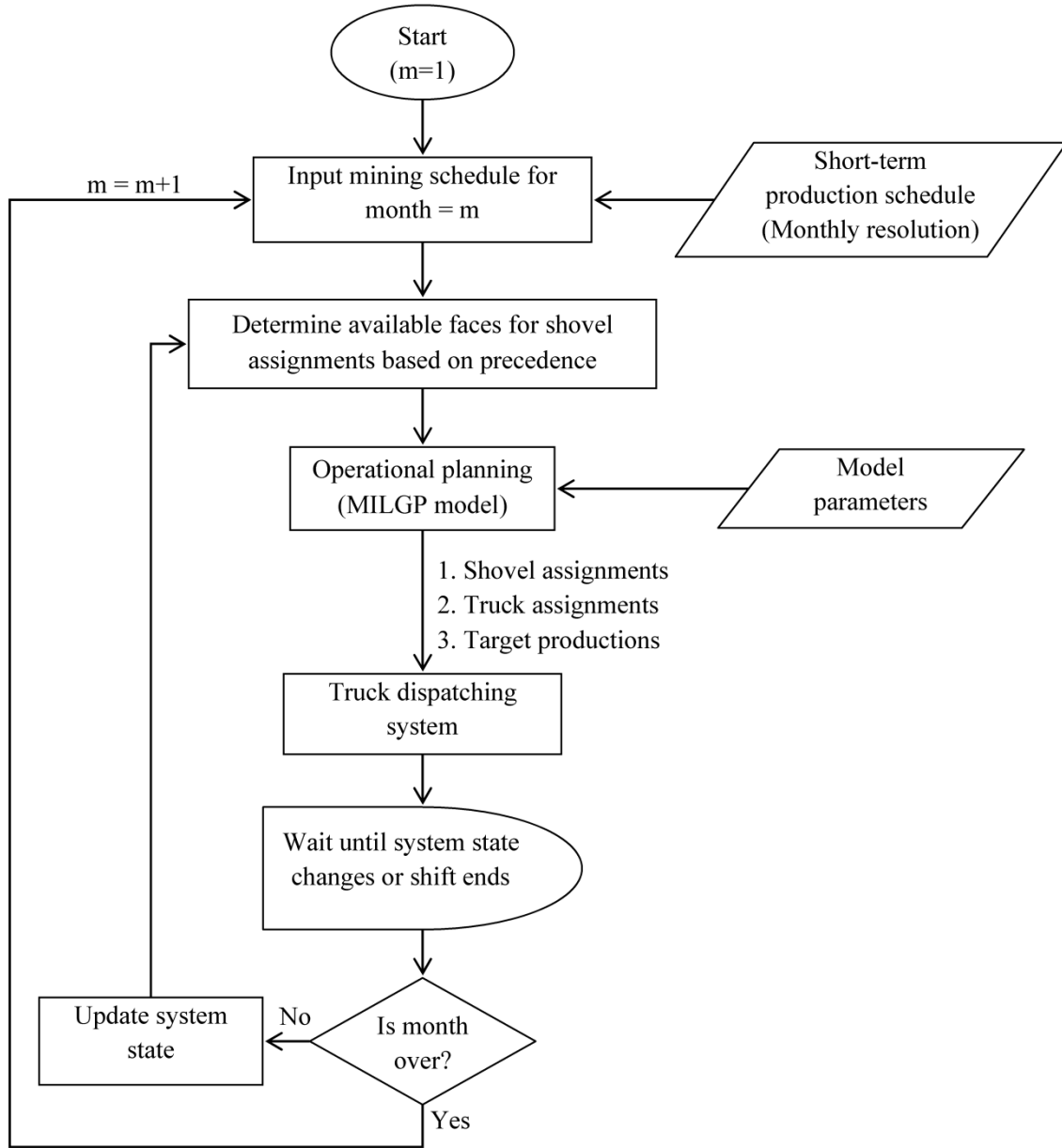
Fig. 3. Flow chart representing the dynamic decision making process for optimal production operations

Eq. (6) calculates the cycle time of trucks of each type between the faces and the destinations by adding the travel time, dumping time, spotting time and the loading time. To keep the model linear and to limit the number of integer variables ($n_{t,f,d}$), cycle time calculation only involves the truck type, the face and the destination. It does not include the shovel working on the face, posing a limitation onto the calculation of truck loading time based on shovel characteristics. Thus an average loading time of all the shovels is used for calculating the total cycle time of trucks.

$$\Gamma^{F}_{f^{1},f^{2}} = \sqrt{\left(F^{x}_{f^{2}} - F^{x}_{f^{1}}\right)^{2} + \left(F^{y}_{f^{2}} - F^{y}_{f^{1}}\right)^{2} + \left(F^{z}_{f^{2}} - F^{z}_{f^{1}}\right)^{2}} \tag{1}$$

$$\Gamma^{D}_{f,d} = D^{FE}_{f} + D^{ED}_{d} \tag{2}$$

$$\tau_{s,f} = \Gamma^{F}_{F_{s},f} \Big/ S_{s} \tag{3}$$

$$X_s^+ = U_s^+ \times \alpha_s^S \times X_s \times T \times 36/L_s \tag{4}$$

$$X_s^- = U_s^- \times \alpha_s^S \times X_s \times T \times 36/L_s \tag{5}$$

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

4.2. MILGP formulation

The mixed integer linear goal programming model has been formulated to optimize the goals represented by Eqs. (7), (8), (9) and (10).

4.2.1. Goals

$$\Psi_1 = \sum_s x_s^- \tag{7}$$

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

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

$$\Psi_4 = \sum_s \sum_f \Gamma_{F_s,f}^F \times A_s \times a_{s,f} + \sum_t \sum_f \sum_d n_{t,f,d} \times \Gamma_{f,d}^D \times (C_t + \overline{C}_t) \tag{10}$$

Eq. (7) represents the difference between the maximum target production and production achieved by the shovels over a shift. Eq. (8) represents the difference between the material content received at the ore destinations and the material content based on desired grade. Eq. (9) represents the difference between the quantities of ore supplied to the processing plants compared to the target quantities desired over the optimization period. Eq. (10) represents the total cost of shovel movement (if any shovel is reassigned to a new face) and truck operating cost.

4.2.2. Objective

The objective of the model 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 (2006). Normalized goals are then multiplied with weights to achieve the desired priority. The final objective function, thus obtained, is given by Eq. (11).

$$\Psi = W_1 \times \overline{\Psi}_1 + W_2 \times \overline{\Psi}_2 + W_3 \times \overline{\Psi}_3 + W_4 \times \overline{\Psi}_4 \tag{11}$$

Where

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

4.2.3. Constraints

$$\sum_s a_{s,f} \leq 1 \qquad\qquad \forall f \tag{13}$$

$$\sum_f a_{s,f} \leq 1 \qquad\qquad \forall s \tag{14}$$

$$\sum_d \sum_f x_{s,f,d} + x_s^- = X_s^+ \qquad\qquad \forall s \tag{15}$$

$$\sum_d \sum_f x_{s,f,d} \geq X_s^- \qquad\qquad \forall s \tag{16}$$

$$\sum_s x_{s,f,d} \leq \sum_t n_{t,f,d} \times H_t \qquad\qquad \forall d\ \&\ \forall f \tag{17}$$

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

$$\sum_{d^o} x_{s,f,d^o} \leq a_{s,f} \times O_f \times Q_f \qquad\qquad \forall s\ \&\ \forall f \tag{19}$$

$$\sum_{d^w} x_{s,f,d^w} \leq a_{s,f} \times O_f \times (1 - Q_f) \qquad\qquad \forall s\ \&\ \forall f \tag{20}$$

$$\sum_d n_{t,f,d} \times H_t \leq \sum_s \left(\sum_d x_{s,f,d} + a_{s,f} \times J \right) \times \overline{A}_{t,s} \qquad\qquad \forall t\ \&\ \forall f \tag{21}$$

$$\sum_f \sum_d n_{t,f,d} \times \overline{T}_{t,f,d} \leq T \times 60 \times N_t \times \alpha_t^T \qquad\qquad \forall t \tag{22}$$

$$\sum_d x_{s,f,d} \leq \left(T \times 60 - \tau_{s,f} \right) \times 60 \times X_s \times \alpha_s^S \times a_{s,f} \Big/ L_s \qquad\qquad \forall s\ \&\ \forall f \tag{23}$$

$$\sum_s \sum_f x_{s,f,d^p} + \delta_{d^p}^- - \delta_{d^p}^+ = Z_{d^p} \times T \qquad\qquad \forall d^p \tag{24}$$

$$\delta_{d^p}^- \leq \Lambda_{d^p} \times T \qquad\qquad \forall d^p \tag{25}$$

$$\delta_{d^p}^+ \leq \Lambda_{d^p} \times T \qquad\qquad \forall d^p \tag{26}$$

$$\sum_f \sum_s x_{s,f,d^o} \times \overline{G}_{f,k} + g_{k,d^o}^- - g_{k,d^o}^+ = \sum_s \sum_f x_{s,f,d^o} \times G_{k,d^o} \qquad\qquad \forall k\ \&\ \forall d^o \tag{27}$$

Constraints (13) and (14) assure 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 less 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 objective function, 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) and (20) 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 (21) 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 (22) limits the maximum possible trips by any truck type considering the truck availability and optimization time. Constraint (23) 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 from where it initially was). Constraints (24), (25) and (26) are the processing constraints on the desired tonnage feed to the processing plants and maximum allowable deviation in tonnage accepted at the plants. Constraint (27) tries that the average grade sent to the processing plants is of the desired grade and deviation is within the upper and lower acceptable limits.

4.3. 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 and Romanko (2006) provides different normalization strategies that can be adopted for optimization of similar models. Normalization 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 and 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 Eq. (28) (Grodzevich and Romanko, 2006).

$$z_i^N = \max_{1 \le j \le K}(f_i(x^{[j]})) \qquad\qquad \forall i \in goals \qquad\qquad (28)$$

Once the Nadir and Utopia points have been determined, goals can be normalized using Eq. (29) (Grodzevich and Romanko, 2006) to range between 0 and 1, and multiplied with respective weights to give priority to desired goals over others.

$$\overline{f_i}(x) = \frac{f_i(x) - z_i^U}{z_i^N - z_i^U} \qquad\qquad \forall i \in goals \qquad\qquad (29)$$

Weighted sum method, given by Eq. (30), has been used to assign the priority weights to be multiplied to goals.

$$\sum_i w_i = 1 \qquad\qquad i \in goals \qquad\qquad (30)$$

4.4. Model inputs

The MILGP model presented is proposed to work with 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 production schedule is generated using the clustering and scheduling algorithm proposed by Tabesh et al.(Tabesh et al., 2014). Incorporating mining cuts directly from the short-term schedule, with precedence mining cuts, help to remove the block precedence constraints from the current optimization problem. 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 a month.

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.

Other inputs include:

1. Shovel: shovel ID's, bucket capacities, loading cycle time, availability, cost of shovel movement as per meter moved, movement velocity of shovel and the face where the shovel is initially located.
2. 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.
3. Destinations: maximum rate of processing at processing plants (tonne/hr), maximum allowed deviation in tonnage supplied to the processing plants per hour, desired grade of each material type at processing plants
4. Optimization duration (hours), 0 or 1 parameter inputs to match trucks with shovels and weights for different goals in the objective function.

5. 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 sulphur as contaminants or secondary elements.

A life of mine extraction schedule, presented in Fig. 4, is obtained using Whittle software. Year six was selected to run a clustering algorithm and generate a short term production schedule over monthly resolution using the model of Tabesh et al. (Tabesh et al., 2014).
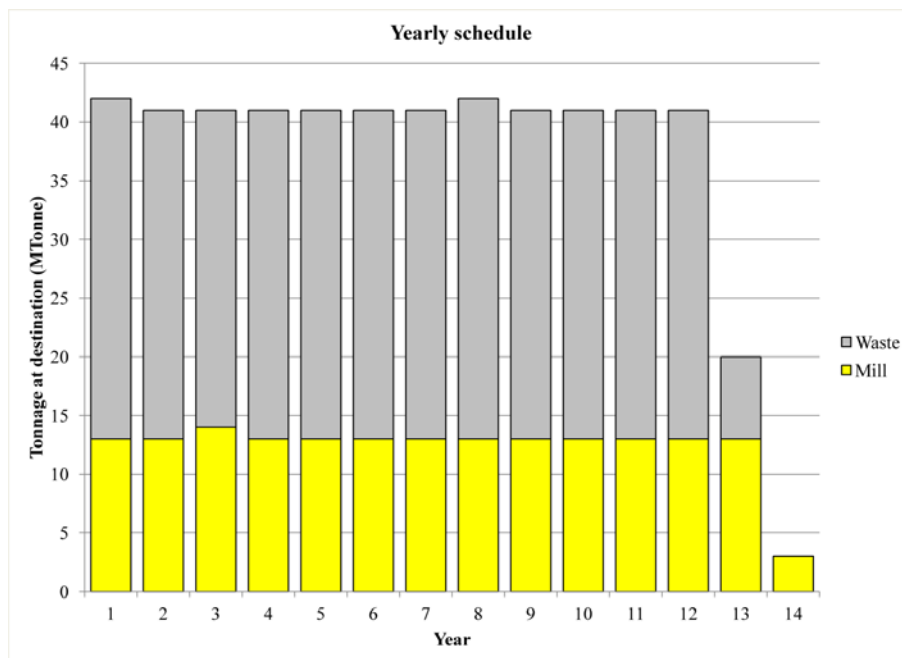

Fig. 4. Life of mine schedule for Gol-E-Gohar mine obtained through Whittle

We have used scheduled fractions of 2904 blocks, located over 3 benches, to be mined in the fourth month to run the optimization model. The schedule requires 1,023 ktonnes of Ore and 2,373 ktonnes of waste to be mined, working a 12 hour shift daily over 30 days. The grade distribution, over several mining cuts scheduled in the fourth month, is presented in Fig. 5.
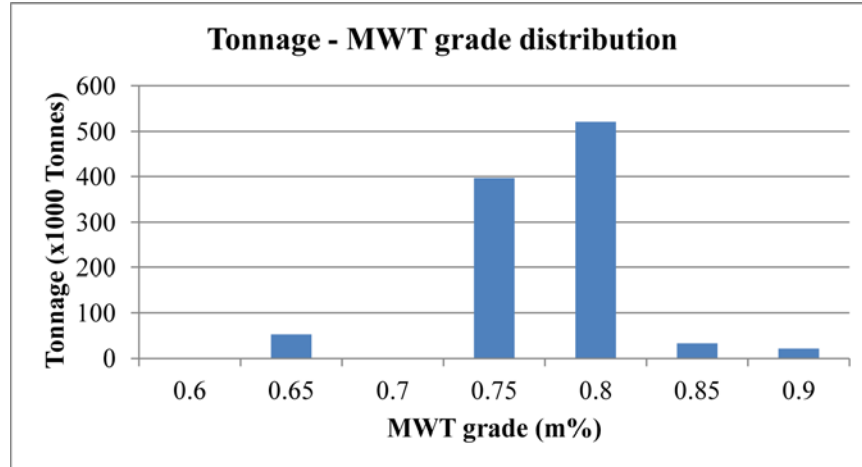

Fig. 5. Graph of grade distribution of MWT (magnetic weight recovery) in the scheduled cuts for month four.

The open-pit is designed to have only one exit. The distance from pit exit to dump destinations are given in Table 1. The distance from pit exit to mining faces (mining cuts) are calculated as distance from pit exit to bench following the gradient of the ramps, and a straight line distance from the ramp access point to mining face.

Table 1. Desired grades, targets, limits and distances to pit exit for the dump destinations

Destinations	Desired MWT grades (m%)	Processing target (t/h)	Processing limit (t/h)	Distance to pit exit (m)
Plant 1	72	1500	1700	1000
Plant 2	78	1500	1700	750
Waste Dump	-	-	No limit	1000

This scenario considers two processing plants and a waste dump as dump destinations in the mine. Table 1 provides the desired grades of MWT, target and maximum processing limits for processing plants and corresponding distances from the pit exit.

The mine employs two Hitachi ZAXIS-650H and two Hitachi Ex 1900-6 hydraulic excavators. ZAXIS-650H excavators work mostly with ore with an average shovel availability of 0.68, and they load on an average 15 tonne per bucket with 24 second bucket cycle time. The two Hitachi Ex 1900-6 excavators load on an average 30 tonne per bucket with 25 second bucket cycle time and an average shovel availability of 0.78. Cost of shovel movements from one face to other is considered to be $1 per meter with an average speed of 50m/min considering all required manpower and moving related equipment. Mine employs 15 Hitachi EH1100-5 haul trucks, with nominal capacity of 90 tonne, and 19 Hitachi EH1700-3 trucks with nominal capacity of 120 tonnes. The 90 tonne nominal capacity trucks are compatible to work only with 15 tonne bucket capacity shovels and move at an average speed of 36 Km/h when empty and 18 km/h when loaded. 120 tonne nominal capacity trucks are compatible to work only with 30 tonne bucket capacity shovels and move at an average speed of 34 Km/h when empty and 17 km/h when loaded. The empty and loaded movement cost for EH1700-3 trucks is considered to be $ 0.22 and $ 0.32 per Km and for EH1100-5 trucks is $ 0.2 and $ 0.3 per Km respectively.

6. Model implementation and results

The MILGP model is used to carry out the case study, optimizing the system over half hour durations up to 12 hours daily, and recording the daily production indices for one month. At the beginning of the month ore shovels 1 and 2 are scheduled to be working on bench 1, shovel 3 on bench 2, and shovel 4 on bench 3. Bench 1 contains mostly ore whereas bench 2 and 3 contains waste scheduled for the month. Fig. 6 represents part of the second bench scheduled and worked upon during the month. Fig. 6 presents the start of working day for every face in numerals, working shovels in color and mining cuts (faces) by solid boundaries.
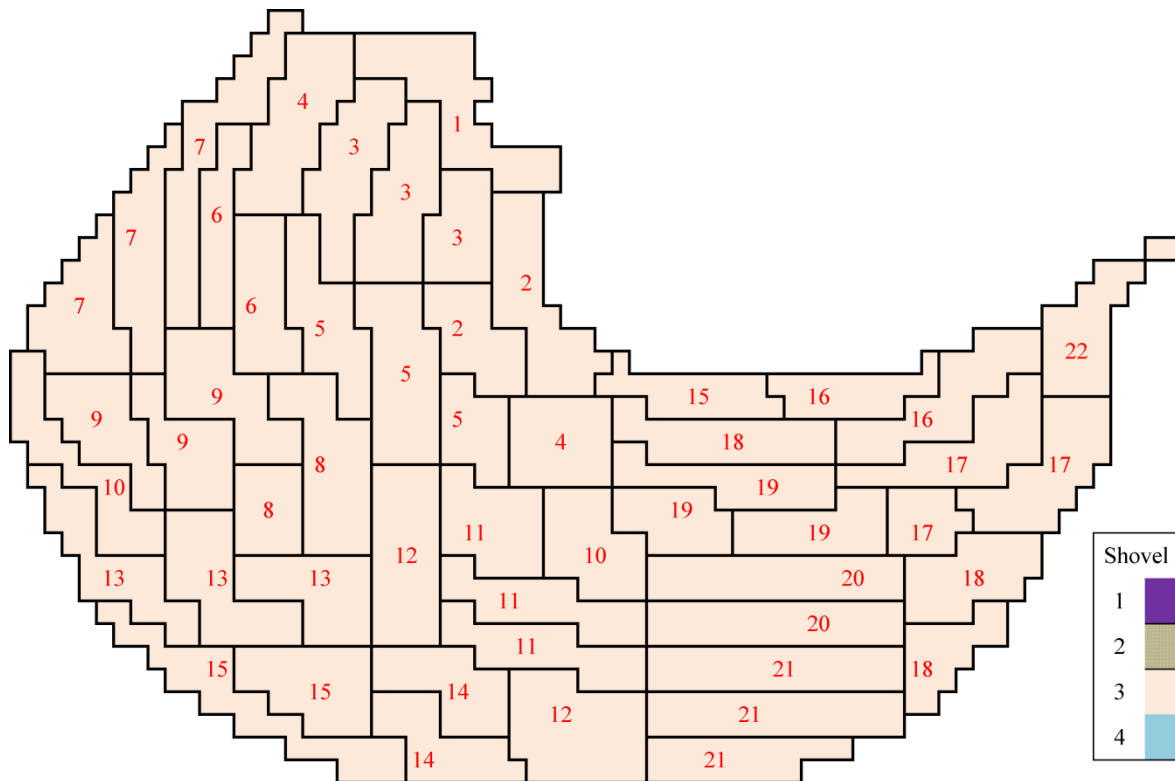

Fig. 6. Start day of working (represented by numerals) of mining blocks forming mining cuts (represented by solid boundaries) by shovels (represented by color) for part of bench 2 at elevation 1655

Shovel 1 and 2 were observed to be mining ore on bench 1 throughout the month. Shovel 3 mines out the scheduled faces on bench 2 and move to bench 3 at the end of the month, whereas shovel 4 remains on bench 3 throughout the month.

Fig. 7 presents the daily production received at processing plants and the waste dump for 20 days. Very small variations observed are attributed to the loss in production due to shovel movements from face to face, or from bench to bench. Capacity utilization curve presents the variation in percentage of production capacity utilization of the mine, including all four shovels.

Fig. 8 and Fig. 9 show the performance of the operational objectives included in the MILGP model for minimizing the deviations in feed and grade to processing plants compared to desired feed and grade. Referring to Table 1, daily desired feed to processing plants is 18,000 tonne and desired grade is 72 and 78 m% at plant 1 and 2 respectively. Fig. 8 shows that daily tonnage fed to processing plants is almost constant at 18,000 tonnes as desired. The small variation in tonnage fed to plants is attributed to the movement time of shovels between faces causing loss in ore production coupled with other optimization objectives of desired feed and grade at the plants. Comparing to available grades distribution in mining faces scheduled (Fig. 5), the obtained results of average

grade fed to processing plants shown in Fig. 9 is satisfactory. It should be noted that exact grade requirements are met at the plants from day 16 to 20, where shovel 1 and 2 mine out faces with grades 70 and 80 m% respectively.
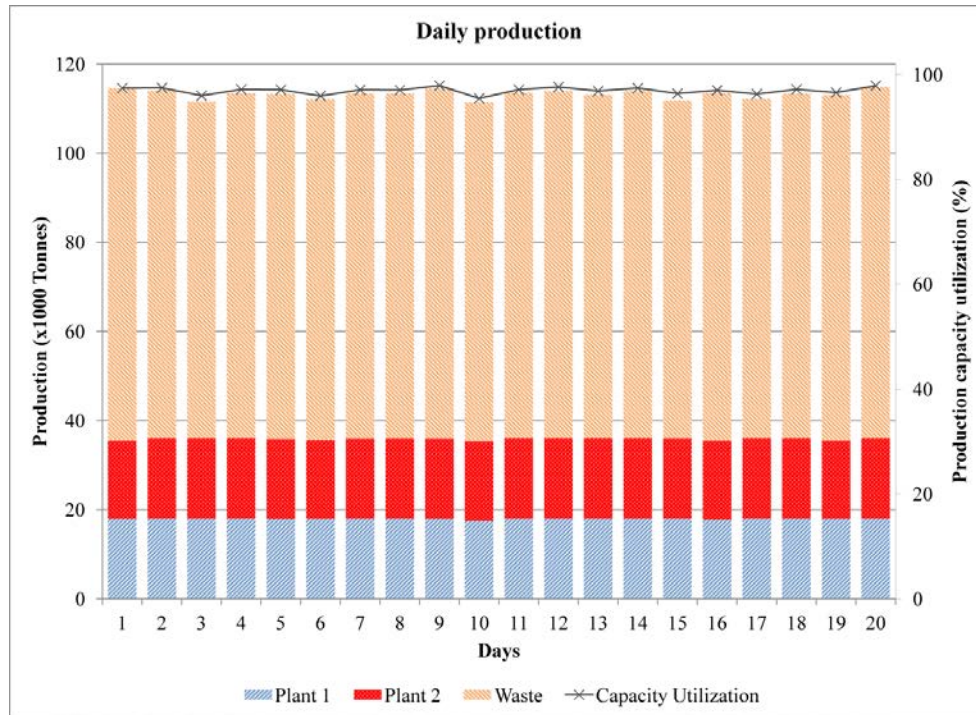

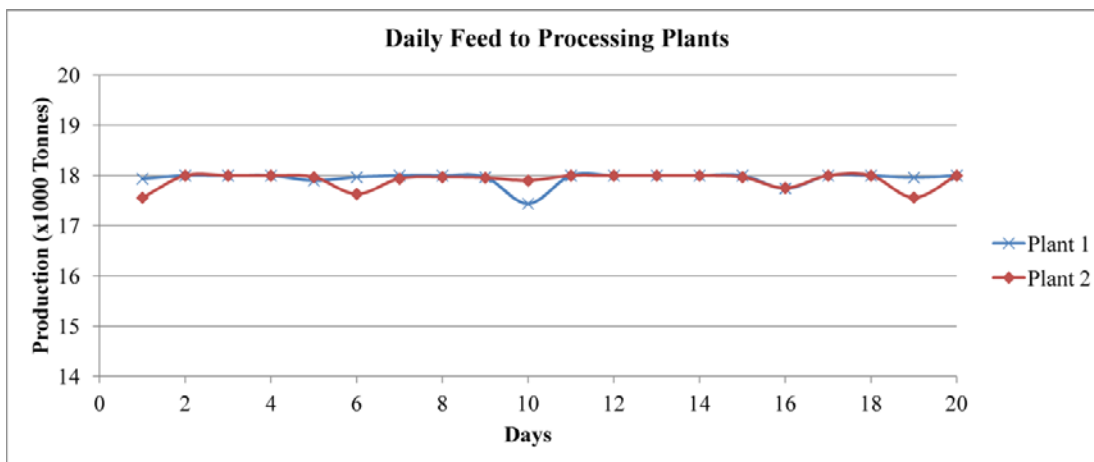Fig. 7. Daily production sent to processing plants and waste dump

Fig. 8. Daily feed to processing plants

Truck fleet utilizations are presented in Fig. 10, where truck type 2 (EH1100-5) works only with ore shovels 1 and 2, and truck type 1 (EH1700-3) works only with shovels 3 and 4. Truck utilizations are obtained to be above 90% with the variations accounted towards the varying distances of shovels from destinations.
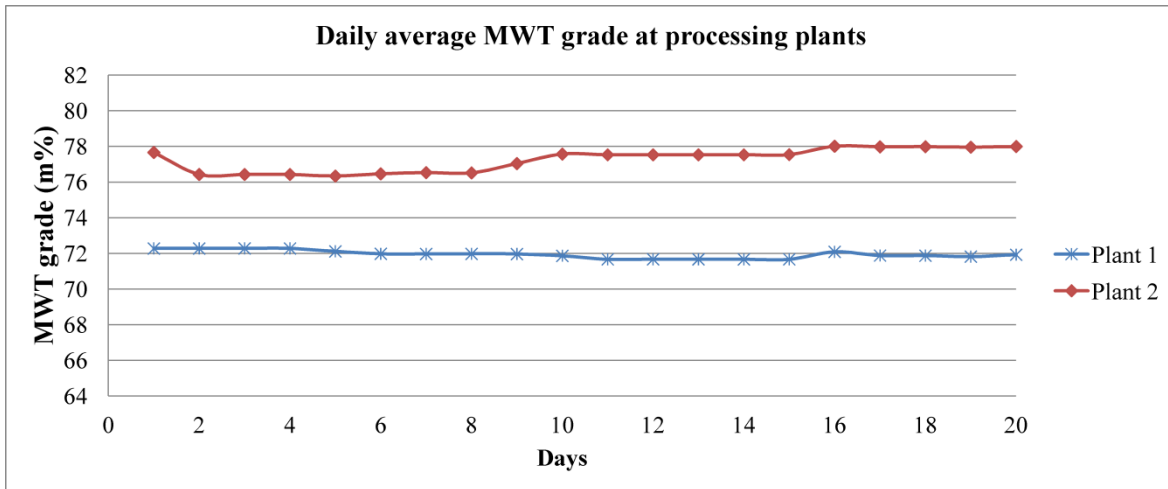
Fig. 9. Average MWT grade received at processing plants
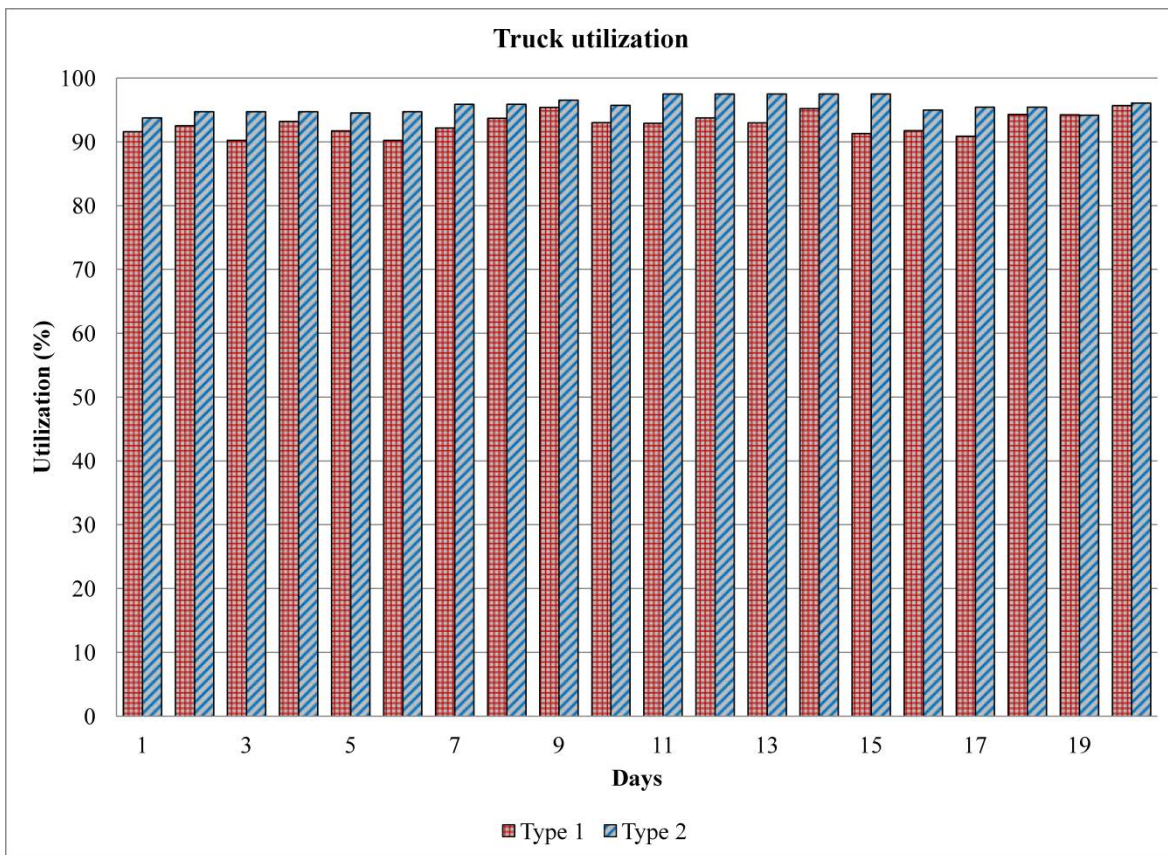

Fig. 10. Daily average truck utilizations for truck type 1 (EH1700-3) and truck type 2 (EH1100-5)

Table 2 presents the key performance indices (KPIs) recorded over 20 days to demonstrate the applicability of the MILGP model while meeting the desired production goals included.

Table 2. Observed production KPIs over 20 days

		Min	Max	Average	Summation
Plant Utilization (%)	Plant 1	96.9	100.0	99.7	-
	Plant 2	97.6	100.0	99.5	-
Truck Utilization (%)	Type 1	90.2	95.7	92.9	-
	Type 2	93.8	97.5	95.8	-
Shovel Utilization (%)	Shovel 1	93.4	98.2	96.7	-
	Shovel 2	95.6	100.0	98.7	-
	Shovel 3	90.7	98.8	95.4	-
	Shovel 4	93.0	99.0	97.0	-
Shovel Movement time (min)	Shovel 1	0.0	6.6	0.0	10.8
	Shovel 2	0.0	4.0	0.0	12.3
	Shovel 3	0.0	7.5	0.2	89.6
	Shovel 4	0.0	6.1	0.1	46.9

7. Conclusion

The solution of the MILGP model for the iron ore mine case study provided average plant utilizations above 99%, average truck utilizations above 92% and average shovel utilizations above 95%. The operational objectives of minimizing the deviations in feed and grade to processing plants compared to desired feed and grade are also met satisfactorily. Also because model provides shovel assignments based on short-term production schedule, it helps realize the strategic production schedule. The results obtained prove the applicability of the model for providing shovel and truck allocations in open-pit mine operations and work as upper stage in a two stage dispatching system.

The MILGP model also provides a scope to work with simulation models for analyzing the operations over longer time horizons. An integrated system with simulation will provide better opportunities for efficient equipment planning and strategic decision making towards achieving long term mining objectives. The future research in this area includes developing an integrated simulation optimization model for understanding the production operations and thus aligning the system towards achieving better compliance with strategic plans.

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9. Appendix

9.1. Notations

Index for variables, parameters and sets

s index for set of *shovels*($s = 1, \dots \hat{S}$)

f index for set of *faces*($f = 1, \dots \hat{F}$)

t index for set of truck types *trucks* ($t = 1, \dots \hat{T}$)

k index for set of material types *MatType* ($k = 1, \dots \hat{K}$)

d index for set of *destinations* (processing plants, stockpiles, waste dumps)

d^p index for set of *processing plants* ($d^p = 1, \dots \hat{P}$)

d^o index for ore destinations (processing plants and stockpiles)

d^w index for waste dumps ($d^w = 1, \dots \hat{W}$)

9.2. 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_{k,d^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

9.3. 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)

$\overline{V}_t$ Average speed of truck type t when loaded (Km/hr)

C_t Cost of empty truck movement ($/Km)

$\overline{C}_t$ Cost of loaded truck movement ($/Km)

$\overline{A}_{t,s}$ 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 (%)

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)

G_{k,d^o}　　　Desired grade of material types at the ore destinations

G_{k,d^o}^-　　　Lower limit on grade of material type k at ore destinations

G_{k,d^o}^+　　　Upper limit on grade of material type k at ore destinations

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

W_i　　　Normalized weights of individual goals (i = 1, 2, 3, 4) based on priority

9.4. 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)