Short-term Production Planning in Open Pit Mines using Dynamic Shovel Allocations

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Abstract

The complexity and uncertainties associated with mining operations often lead to deviations from strategic plans, forcing a reactive planning approach. This paper presents a simulation optimization approach for uncertainty based short term planning and proactive decision making, which provides substantial economic and operational gains. An optimization tool is presented in this paper to achieve uniform desired grade and tonnage feed to processing plants, and maximum production to comply with medium to long term production schedule with minimal shovel movement within a simulation model. A verification of the model is presented in this paper using an iron ore mine case study.

1. Introduction

In mine planning context, long term and medium term plans are generally referred to as strategic plans, whereas short term and operational plans constitute tactical plans. Short term and operational plans are developed considering the detailed operations to ultimately comply with the medium and long term plans and also achieve operational objectives on a day-to-day basis. Detailed short term plans are desired to provide equipment planning and sequence of extraction of mining faces over short time horizons such as months or weeks. The prime objective of a short term mine plan is to provide sequential shovel placements and truck allocation such that quantitative and qualitative operational targets are met while there is a high level of compliance with strategic mine plans.

A main problem of concern in any mining operation is a short-term planning framework/tool that generates near-optimal production schedules in the presence of uncertainty that satisfies the operational objectives. These objectives are predominantly maximizing the utilization of shovels and crushers at the processing plants, and also meeting the grade blending requirements at the processing plants. This framework/tool must also comply with strategic schedules and capable of assisting in proactive short term decision making to realize strategic objectives. The proactive planning minimizes the deviations from the strategic mine plans and will assist in minimizing substantial losses in revenue that mining organizations incur every year due to opportunity loss.

Newman *et al.* (2010) provides a comprehensive review of the application of operations research in mine planning. Mine planning and scheduling has received sufficient attention of the researchers, but has remained limited to long term planning or truck dispatching. Short term mine planning and scheduling problem is addressed by very few researchers. Modeling the detailed mining operations over multiple periods incorporating all the faces, shovel movements between faces, truck allocations and plants, increases the problem size and poses the limitation on the solvability of the model as observed by L'Heureux, *et al.* (2013). Bjørndal, *et al.* (2012) observes that even state of the art hardware and software cannot handle the size and complexity of such detailed scheduling models.

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L'Heureux*, et al.* (2013) presents a detailed model for short term planning for a period of up to three months, where they consider precedence among blocks, precedence among operational activities, drilling, blasting, transportation, processing, movement of shovels, drills and more in detail as operating constraints. Gurgur*, et al.* (2011) proposed a LP model for short term planning, but do not consider mine operations in details. Fioroni *et al.* (2008) proposed a simulation optimization model to generate short term mine plans over monthly resolution. Their model does not consider any mining precedence constraints limiting it to run over shorter time horizons. Eivazy & Askari-Nasab (2012) proposed a multi-destination mixed integer linear programming model to minimize the overall operating cost to generate short term production schedules. One major limitation of the existing approaches is that grade blending objectives optimized at short term planning stage are hard to achieve at operational stage, due to mismatch between planned and operating ore faces, and realized mainly through truck dispatching logic. Another major drawback of existing models is that they fail to consider the dynamic nature of mining operations leading to frequent updates of operational plans as well as short term plans. The dynamic components of the system which must be accounted at this stage include equipment availabilities due to failures, changing rates of production from shovels based on their location, haulage capacities, and unavailability of faces due to precedence requirements. The capturing of dynamic nature of the mining systems provides an opportunity to develop more robust mine plans and thus supports an opportunistic proactive planning framework by determining the bottlenecks of the operation.

To capture the operational uncertainty, a bottom up approach is proposed in this paper, where production operations within a simulation model are optimized iteratively to develop short term production plans constrained by the strategic mine plans. The operational optimization tool here works as an upper stage of a multi-stage dispatching system proposed by Elbrond and Soumis (1987), White and Olson (1986) and Soumis, *et al.* (1989). The operational optimization tool at this stage is required to optimize the operational objectives by providing optimal shovel placements and target productions. The scope of the existing multi-stage dispatching models (Elbrond & Soumis, 1987; Li, 1990; Soumis*, et al.*, 1989; Subtil*, et al.*, 2011; Temeng*, et al.*, 1997, 1998; White & Olson, 1986) in the literature has remained limited to truck allocations for better operational results. The multi-stage model proposed by Soumis *et al.* (Soumis*, et al.*, 1989) provides shovel allocation decisions using man machine interaction, which render it unusable for a dynamic tool. In a similar approach, Lestage*, et al.* (1993) proposed a computerized tool for daily operational decision making by optimizing the system over a given time horizon.

The approach proposed in this paper is an iterative simulation optimization approach which breaks the problem into smaller number of periods and simulates the operations over longer time horizons. This approach considerably reduces the problem size and captures the operational uncertainty at the same time. This bottom-up approach addresses the solvability issue to a great extent. Using the dynamic decision making tool at the operational decision making stage, grade blending can also be achieved better by first optimally placing the shovels and then using truck dispatching.

The proposed framework/tool in this paper solves the short term mine planning problem using a simulation-optimization approach. A dynamic decision making tool, Mixed Integer Linear Goal Programming (MILGP) model, is proposed for dynamic operational decision making within a simulation model of the mining operations to generate short term plans capturing the operational uncertainty with a reduced run time. The dynamic tool provides shovel allocation and target productions for the current state of the system by optimizing the operations for a predetermined number of periods of time in future. The MILGP model provides shovel allocation decisions based on the available mining faces in the strategic schedule, thus linking the operational decisions with the strategic plans. The MILGP model can also be used standalone for short term production planning as a traditional approach which is not considered in this paper.

The MILGP model presented here is an improvement to the previously published model (Upadhyay & Askari-Nasab, 2016), where the current model provides allocation decisions considering near future allocation requirements as well. The foresight was observed to be an essential characteristic requirement of the model, because allocations made solely on current state do not take into account future allocation requirements and thus the decisions may not be optimal on an aggregated basis for the entire planning period.

The objective of this paper is to present and test the simulation optimization approach for short term mine production planning and scheduling, with a focus on the MILGP optimization model. To illustrate the proposed model, the paper is structured as follows: the objectives, definitions and scope and limitations of the model are presented in problem definition section. The proposed MILGP model is then described detailing the objectives and constraints of the mining operation. A case study is then presented and the implementation results are discussed. Finally, the conclusion and future scope of the research are presented.

2. Problem definition

2.1. System

The system considered in this model is an open pit mine with truck-shovel operations. The system includes trucks, shovels, plant crushers, waste dumps, haul road network and mining faces (scheduling polygons) with different material types based on the medium to long term production schedule.

2.2. Objective

The objective of the MILGP model is to provide near optimal shovel allocations and target productions at a system state to achieve operational objectives of:

1. Maximum production
2. Meeting the desired feed to processing plants
3. Meeting the grade blending requirements of the processing plants
4. Minimize shovel movements

The goal of the paper is to develop, implement, and verify the simulation optimization framework for generating efficient and practical short term mine production schedule.

2.3. Definitions

2.3.1. Faces

Faces in the model refers to the clusters of the blocks grouped together based on similarity in material content and rock types, also known as scheduling polygons. The basic mining unit considered in the model is a face which reduces the problem size considerably compared to small blocks as mining units. This assumption limits the model to capture the grade variability among blocks clustered together, which can be minimized while developing clusters. Other block aggregation techniques may also be used to generate bigger blocks as mining units. As blasting and excavation operations are carried out over wider areas consisting of a group of blocks, this assumption of considering clusters as basic mining unit is practically more representative of the mining operations comparing to the blocks level.

2.3.2. Decision and optimization time frames

For optimal short term production scheduling, following a simulation optimization approach, it is considered essential for the model to make decisions for the current state considering future decision requirements at the same time. The time frame for which the decision is required in the simulation model is called the decision time frame in this paper, which is the first period. The optimization time frame includes the total time for all the periods (Fig. 1). So if simulation is desired to have decisions for a shift of 12 hours (1 shift per day) with 30 periods, the decision time frame is a shift of 12 hours and optimization time is a month, i.e. allocation decisions will be provided to the simulation model for one shift, but the model optimizes the operations for an entire month. This helps the simulation optimization approach to foresee the unavailability of faces and provide shovel allocations to minimize face unavailability.

Optimization Time Frame					
Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
Decision Time Frame (T)					

Fig. 1. Decision and optimization time frame of the model

2.4. Scope and limitations

The MILGP model is a dynamic decision making tool for shovel allocation optimization.

- It can be used stand alone to generate short term production schedules.
- It can be used in combination with a deterministic mine discrete event simulation model for a deterministic short-term production schedule.
- It can be used in conjunction with a stochastic discrete event simulation model for scenario analysis and developing uncertainty based short term production schedules and opportunistic proactive planning.
- The model is developed as part of a multi-stage dispatching system and it can be implemented in conjunction with a real-time dispatching system in an operating mine for operational decision making.

The combined simulation optimization model is used in this paper to generate deterministic short-term production schedule.

The model although considers the most critical operational objectives and constraints for shovel allocations, there are always other considerations in place which are taken into account for shovel allocations by the planners at site. The problem, as can be perceived, requires human intervention to account for some other considerations such as haul road development or drilling, blasting and face development activities in specific parts of the pit. Thus the implementation of the model as part of a multi-stage dispatching for real time decision making may not be possible in its current form. As the main goal of this model is to work in conjunction with a simulation model for operational planning purposes, the extent of modeling is reasonable for practical short term mine scheduling.

3. MILGP model formulation

The mixed integer linear goal programming (MILGP) model is a shovel-truck allocation optimization model. The objective of this model is to provide shovel allocations and target productions; and to concurrently maximize the production, optimize ore tonnage received at processing plants and minimize the deviations in grade requirements at various ore destinations. To achieve these objectives, a non preemptive goal programming approach is adopted for the model. The constraints and the formulation of the objective function are described in this section (see Appendix for details on the indices, variables and parameters used in this model).

3.1. Variables

The constraints have been formulated to account for shovel assignments using a binary variable $a_{s,f,p}$ which becomes true if shovel 's' is assigned to face 'f' in period 'p'. To control the number of binary variables, shovel movements are also controlled using the same assignment variables in conjunction with another binary variable $m_{f,p}$ to keep track of mined out faces. Another binary variable $y_{s,p}$ is used, for an if-else constraint, to model the continuous nature of shovel movements. Integer variable $n_{t,f,d}$ is used to formulate number of required truck trips between faces and destinations in the decision time frame. Number of truck trips is derived only for the decision time frame, i.e. the first period of optimization, and thus $n_{t,f,d}$ variable is not indexed over 'p'. Other real value variables include: $x_{s,f,d,p}$ as fraction of tonnage at face, to model production by shovels from faces to destinations in each period, $x^-_{s,p}$ as fraction of capacity of shovels, to model negative deviation in production by shovels compared to their capacity, $\delta^-_{d^c,p}, \delta^+_{d^c,p}$ as fraction of target capacity of processing plants, to model negative and positive deviation in production received at processing plants compared to target, $g^-_{k,d^o,p}, g^+_{k,d^o,p}$ as negative and positive deviation in grades received at ore destinations, $l_{f,p}$ as tonnage of material available at faces in each period, $r_{s,p}$ as movement time for shovel relocations in each period and, $r^{rem}_{s,p}$ and $r^{act}_{s,p}$ as remaining movement time for shovels to be covered in next period and actual movement time for relocation in each period.

3.2. Goals

Four operational objectives have been considered here as goals:

1. Maximum production objective is formulated as minimizing the negative deviation in production by shovels compared to their maximum capacity.

$$\Psi_1 = \sum_p \sum_s \left(\frac{1}{p}\right) \times x^-_{s,p} \tag{1}$$

2. Objective to meet the desired tonnage feed to processing plants is formulated as minimizing the negative and positive deviation in production received at processing plants.

$$\Psi_2 = \sum_{d^c} \sum_p \left(\frac{1}{p}\right) \times (\delta^-_{d^c,p} + \delta^+_{d^c,p}) \tag{2}$$

3. Objective to meet grade blend requirements at processing plants is formulated as minimizing the negative and positive deviation in grades received at processing plants.

$$\Psi_3 = \sum_p \sum_{d^o} \sum_k \left(\frac{1}{p}\right) \times (g^-_{k,d^o,p} + g^+_{k,d^o,p}) \tag{3}$$

4. Shovel movement objective is formulated as minimizing the total movement time of shovels over all periods.

$$\Psi_4 = \sum_s \sum_p r_{s,p} \tag{4}$$

A weight, as inverse of period, is multiplied to the first three objectives to prioritize the first period, which is the decision time frame. As shovel movement objective requires seeing future movements, no priority is assigned to it based on period. It is desired here that shovel allocations are made such that first three objectives are achieved better for the decision time frame but shovel movements are minimized over the whole optimization time frame.

3.3. Objective function

The problem is optimized following a non-preemptive weighted sum approach as described by Grodzevich & Romanko (2006). Before optimizing the goal individual objectives are optimized to determine their respective values in pareto optimal space. Individual objectives are then normalized and combined to generate the goal given in eq. (5).

$$\Psi = W_1 \times \overline{\Psi}_1 + W_2 \times \overline{\Psi}_2 + W_3 \times \overline{\Psi}_3 + W_4 \times \overline{\Psi}_4 \tag{5}$$

3.4. Constraints

Constraints have been formulated to model a mining operation where shovels are assigned to their initial faces where they were working at the start of optimization. Shovels are not allowed to leave a face un-mined, i.e. shovels won't be reassigned to a new face unless they have mined out their current working face completely. If a shovel is re-assigned to a new face it will take some movement time to reach the new face leading to some production loss. Shovel movement time is based on the defined speed of shovel and location of the new face, following the ramp if on a different bench, or a straight line distance if on the same bench.

Constraint eq. (6) to (12) control the shovel allocation to faces in each period. As the optimization time frame of the model is divided into multiple periods, an assignment variable, indexed over multiple periods, is used for shovel assignment in each period. Constraint eq. (6) does not let multiple shovels to be assigned to any one face, which means any face can be mined by only one shovel. Eq. (7) assigns shovels in the first period to their initial faces where shovels were working at the start of optimization. Constraint eq. (8) allows any shovel to be assigned to at maximum two faces in any period. This constraint allows the shovels move to their new faces when their working face is mined out.

$$\sum_s a_{s,f,p} \le 1 \qquad \forall f \;\&\; \forall p \tag{6}$$

$$a_{s,Fi_s,p} = 1 \qquad \forall s \;\&\; p = 1 \tag{7}$$

$$\sum_f a_{s,f,p} \le 2 \qquad \forall s \;\&\; \forall p \tag{8}$$

Eq. (9) models the same constraint as eq. (8), but also controls *when* a shovel can work at two faces. Left hand side of the constraint is the maximum number of faces a shovel is assigned to in any period. The right hand side of the constraint (9) looks over all the faces and takes a very large value if shovel 's' is not assigned to the face in that period. For the faces shovel is assigned to, last part of the constraint will become zero and remaining portion may take a value of 1 or 2. If the shovel was working on the face in the previous period and still hasn't finished mining it, maximum number of faces that shovel can work on can be 1, but if the face is mined out completely, $m_{f,p}$ will become 1 and thus the shovel will be allowed to be assigned to another face. For the new face $a_{s,f,p-1}$ and $m_{f,p}$ will be zero and thus the constraint will still hold true and allow the shovel to be assigned to two faces in that period. Constraint (10) force a shovel to remain assigned to a face in the next period, if it is not mined out in that period, i.e. a shovel will continue working on a face until it is completely mined.

$$\sum_f a_{s,f,p} \le a_{s,f,p} + m_{f,p} + (1 - a_{s,f,p-1}) + (1 - a_{s,f,p}) \times BM \qquad \forall s, f, p \tag{9}$$

$$a_{s,f,p+1} \ge a_{s,f,p} - m_{f,p} \qquad \forall s, f, p = 1 \ldots P-1 \tag{10}$$

Constraint (11) ensures that shovels cannot be assigned to a face which is already mined, except if face was mined by itself and shovel is sitting idle. Constraint (12) ensures that if shovel 's' was assigned to face 'f' and to only one face in period 'p', it will continue to be assigned to face 'f' in the next period.

Constraint (12) works in conjunction with constraint (10) to eliminate any scenario where a face is mined out in a period and shovel movement cannot be finished in that period, model tries to assign the shovel to the new face in the next period without modeling the movement time and the loss in production.

$$a_{s,f,p+1} \le 1 + a_{s,f,p} - m_{f,p} \qquad \forall s, f, p = 1...P-1 \qquad (11)$$

$$a_{s,f,p+1} \ge 2 \times a_{s,f,p} - \sum_{f} a_{s,f,p} \qquad \forall s, f, p = 1...P-1 \qquad (12)$$

Constraints eq. (13) to eq. (18) control the travel time of shovels from one face to the next one. Eq. (13) determines the travel time of shovels in a period. As travel time variable is indexed over shovel and period only, it is not possible to formulate as equality constraint. Thus travel time is formulated as greater than or equal to the required travel time between faces. As travel time will incur loss in production, model will make travel time variable equal to the required travel time. Constraint (13) is formulated for all the faces and to determine the travel time between the assigned faces. For the face, shovel is not assigned to, last part of the constraint makes the right hand side negative and thus does not affect the value of the travel time variable. For the faces shovel is assigned to, it calculates the distance as the sum of distance from that face to all other assigned faces, which includes the same face itself and the second face. As the distance between the same face is zero, constraint (13) makes the travel time variable $r_{s,p}$ greater than or equal to the required travel time between the assigned faces.

$$r_{s,p} \ge \sum_{f^1} a_{s,f^1,p} \times \Gamma^F_{f^1,f} \big/ S_s - (1 - a_{s,f,p}) \times BM \qquad \forall s, \forall f \ \& \ p \qquad (13)$$

Constraint (14) is included to model the continuous nature of shovel movement. If a shovel starts traveling towards the end of a period, it may finish the travel in the next period. $r^{act}_{s,p}$ and $r^{rem}_{s,p}$ variables divide the required travel time into actual travel time in that period and the remaining travel time for the next period. Constraint (15) is included to make sure travel time is zero, if shovel is assigned to only one face in a period.

$$r_{s,p} = r^{act}_{s,p} + r^{rem}_{s,p} \qquad \forall s \ \& \ \forall p \qquad (14)$$

$$r_{s,p} \le \left(\sum_{f} a_{s,f,p} - 1 \right) \times BM \qquad \forall s \ \& \ \forall p \qquad (15)$$

Constraints (16), (17) and (18) are formulated to ensure that no production is possible from the newly assigned face in a period if shovel hasn't finished traveling in that period. Constraints (17) and (18) make sure that binary variable $y_{s,p}$ becomes true if remaining travel time is zero and false if greater than zero. Then this binary variable $y_{s,p}$ is used in constraint (16) to control production from the newly assigned face. Constraint (16) is formulated for all the faces and right hand side takes a very large value for all other faces where shovel is not working and thus do not put any constraint on the production from those faces. For the face where shovel was initially working, first part of the right hand side takes a very large value, thus do not affect the production from that face as well. For the newly assigned face, first part of the right hand side of constraint (16) becomes zero and production from the new face is controlled by the binary variable $y_{s,p}$, which ensures that if remaining travel time is greater than zero, ($y_{s,p}$=0), no production is possible from the newly assigned face in that period.

$$\sum_{d} x_{s,f,d,p} \le \left(1 - a_{s,f,p} + a_{s,f,p-1}\right) \times BM + y_{s,p} \times BM \qquad \forall s, \forall f \ \& \ \forall p \qquad (16)$$

$$r^{rem}_{s,p} \ge \left(1 - y_{s,p}\right) \times \left(2 \times \varepsilon\right) \qquad \forall s \ \& \ \forall p \qquad (17)$$

$$r_{s,p}^{rem} \le y_{s,p} \times \varepsilon + \left(1 - y_{s,p}\right) \times BM \qquad \forall s \,\&\, \forall p \tag{18}$$

Constraint (19) controls the total production possible by the shovels in any period, which has to be less than the maximum production capacity of the shovels in any period. First part of the constraint (19) is the total production by the shovel from all the faces in that period and the second part is the production lost due to the travel in that period, which includes remaining travel time from the last period and the new travel time, if any, in the current period.

$$\sum_{f}\sum_{d} x_{s,f,d,p} \times O_f + \left(r_{s,p-1}^{rem} + r_{s,p}^{act}\right) \times 60 \times X_s \big/ L_s \le T \times 3600 \times X_s \times \alpha_s^S \big/ L_s \qquad \forall s \,\&\, \forall p \tag{19}$$

Constraints (20) to (24) determine mined out faces and the material available at faces. Eq. (20) is the equality constraint to read the material available at the faces initially and eq. (21) determines the material available at the faces in the subsequent periods based on the production by shovels. Eq. (22) and (23) determines if a face is mined out completely during a period. Eq. (22) is a strict in-equality constraint and thus is modelled using a very small decimal value 'epsilon', which converts it to a general in-quality constraint in the model to be solved directly using CPLEX solver (CPLEX, 2014). Eq. (24) ensures that if a face is mined out during a period, it will remain mined out in the subsequent periods.

$$l_{f,p} = O_f \qquad \forall f \,\&\, p = 1 \tag{20}$$

$$l_{f,p+1} = l_{f,p} - \sum_{s}\sum_{d} x_{s,f,d,p} \times O_f \qquad \forall f \,\&\, p = 1 \ldots P-1 \tag{21}$$

$$l_{f,p} - \sum_{s}\sum_{d} x_{s,f,d,p} \times O_f \ge \left(1 - m_{f,p}\right) \times \left(O_{\min} + \varepsilon\right) \qquad \forall f \,\&\, \forall p \tag{22}$$

$$l_{f,p} - \sum_{s}\sum_{d} x_{s,f,d,p} \times O_f \le m_{f,p} \times O_{\min} + \left(1 - m_{f,p}\right) \times BM \qquad \forall f \,\&\, \forall p \tag{23}$$

$$m_{f,p+1} \ge m_{f,p} \qquad \forall f \,\&\, p = 1 \ldots P-1 \tag{24}$$

Eq. (25) is an equality constraint on the production to capture the negative deviation in production by a shovel compared to its maximum capacity. Eq. (26) ensures that there is no production possible from a face by a shovel if the shovel is not assigned to that face in that period. Eq. (27) and (28) limit the total production from a face to ore or waste destinations based on the amount of material available at the face and whether it is ore or waste.

$$\sum_{d}\sum_{f} x_{s,f,d,p} \times O_f \big/ X_s^{+} + x_{s,p}^{-} = 1 \qquad \forall s \,\&\, \forall p \tag{25}$$

$$\sum_{d} x_{s,f,d,p} \le a_{s,f,p} \qquad \forall s, \forall f \,\&\, \forall p \tag{26}$$

$$\sum_{s}\sum_{d^o} x_{s,f,d^o,p} \times O_f \le l_{f,p} \times Q_f \qquad \forall f \,\&\, \forall p \tag{27}$$

$$\sum_{s}\sum_{d^w} x_{s,f,d^w,p} \times O_f \le l_{f,p} \times (1 - Q_f) \qquad \forall f \,\&\, \forall p \tag{28}$$

One major requirement of the model is to provide realistic shovel allocations. Thus it is necessary to include precedence requirements within the model. To ensure that a shovel is assigned to a face only if the face is available for mining, eq. (29) is included in this model. Eq. (29) specifies that assignment variable for a face cannot take a value of one unless all the faces in its precedence set are mined out completely.

$$N_f^F \times \sum_s a_{s,f,p} - \sum_{f'} m_{f',p} \le 0 \qquad \forall f, \forall p \;\&\; f' \in PrecedenceSet_f \tag{29}$$

The tonnage of ore delivered at the processing plants is controlled using eq. (30) to (32). Eq. (30) is a soft constraint which determines positive or negative deviation in production received at processing plants and eq. (31) and eq. (32) puts a limit on the allowed deviation from the capacity. Eq. (33) is an equality constraint which determines the positive or negative deviation in tonnage content of material types received at ore destinations which is minimized in the objective function.

$$\sum_s \sum_f x_{s,f,d^c,p} \times O_f \Big/ \left(Z_{d^c} \times T \right) + \delta^-_{d^c,p} - \delta^+_{d^c,p} = 1 \qquad \forall d^c \;\&\; \forall p \tag{30}$$

$$\delta^-_{d^c,p} \le \Lambda^-_{d^c} \Big/ Z_{d^c} \qquad \forall d^c \;\&\; \forall p \tag{31}$$

$$\delta^+_{d^c,p} \le \Lambda^+_{d^c} \Big/ Z_{d^c} \qquad \forall d^c \;\&\; \forall p \tag{32}$$

$$\sum_s \sum_f x_{s,f,d^o,p} \times O_f \times \bar{G}_{f,k} + g^-_{k,d^o,p} - g^+_{k,d^o,p} = \sum_s \sum_f x_{s,f,d^o,p} \times O_f \times G_{k,d^o} \qquad \forall k, \forall d^o \;\&\; \forall p \tag{33}$$

Constraint eq. (34) to (37) provide truck allocations to shovels. As only first period in the optimization time corresponds to decision time frame and truck allocation decisions do not significantly affect the objectives of the model (if sufficient haulage capacity is available), truck allocations are made only for the first period. Eq. (34) specifies that total number of truck trips from a face to a destination should be sufficient to transport the material produced by the shovel in the first period. Eq. (35) puts an upper limit on the total number of truck trips specifying that even if some over-loading or under-loading of trucks takes place, total tonnage haul capacity by the number of truck trips should be less than the specified deviation, which is considered as one truck load in this model. Eq. (36) controls the total number of truck trips based on the truck type. Eq. (36) specifies that if a truck type is not desired to work with a shovel, number of truck trips from the corresponding face has to be zero. Eq. (36) also specifies that number of truck trips from a face with no shovel assigned to it, has to be zero. Eq. (37) puts a limit on the possible number of truck trips based on the available time and number of trucks of each type available.

$$\sum_s x_{s,f,d,p} \times O_f \le \sum_t n_{t,f,d} \times H_t \qquad \forall d, \forall f \;\&\; p = 1 \tag{34}$$

$$\sum_s x_{s,f,d,p} \times O_f + J \ge \sum_t n_{t,f,d} \times H_t \qquad \forall d, \forall f \;\&\; p = 1 \tag{35}$$

$$\sum_d n_{t,f,d} \times H_t \le \sum_s \left(\sum_d x_{s,f,d,p} \times O_f + a_{s,f,p} \times J \right) \times M^t_{t,s} \qquad \forall t, \forall f \;\&\; p = 1 \tag{36}$$

$$\sum_f \sum_d n_{t,f,d} \times \bar{T}_{t,f,d} \le T \times 60 \times N^T_t \times \alpha^T_t \qquad \forall t \tag{37}$$

To run the model in a dynamic environment in conjunction with a simulation model eq. (38) is added to model the shovel failures. Eq. (38) specifies that no production is possible by a failed shovel although it will remain assigned to its current face. Shovels are locked to material types (ore or waste) using eq. (39)

$$\sum_f \sum_d \sum_p x_{s,f,d,p} \le \left(1 - \phi_s \right) \times BM \qquad \forall s \tag{38}$$

$$a_{s,f,p} \le 1 - abs\left(M^{ore}_s - Q_f \right) \qquad \forall s, \forall f \;\&\; \forall p \tag{39}$$

4. Case study

A case study of an iron ore open pit mine is considered to verify the model. Based on the drillhole prospecting data, mine planning activities have been carried out and a long term production schedule is generated. Year 11 was selected as the strategic plan for the case study. The schedule requires 16.42 MT of ore and 39.11 MT of waste to be mined in year 11 with four benches 1745, 1730, 1610 and 1595. A clustering algorithm (Tabesh & Askari-Nasab, 2013) is run to cluster similar blocks together to generate 174 mining faces (polygons) out of 4227 blocks to be mined in year 11 with four benches. Fig. 2 presents the clustered mining blocks as faces on the bottom bench 1595 scheduled in year 11.

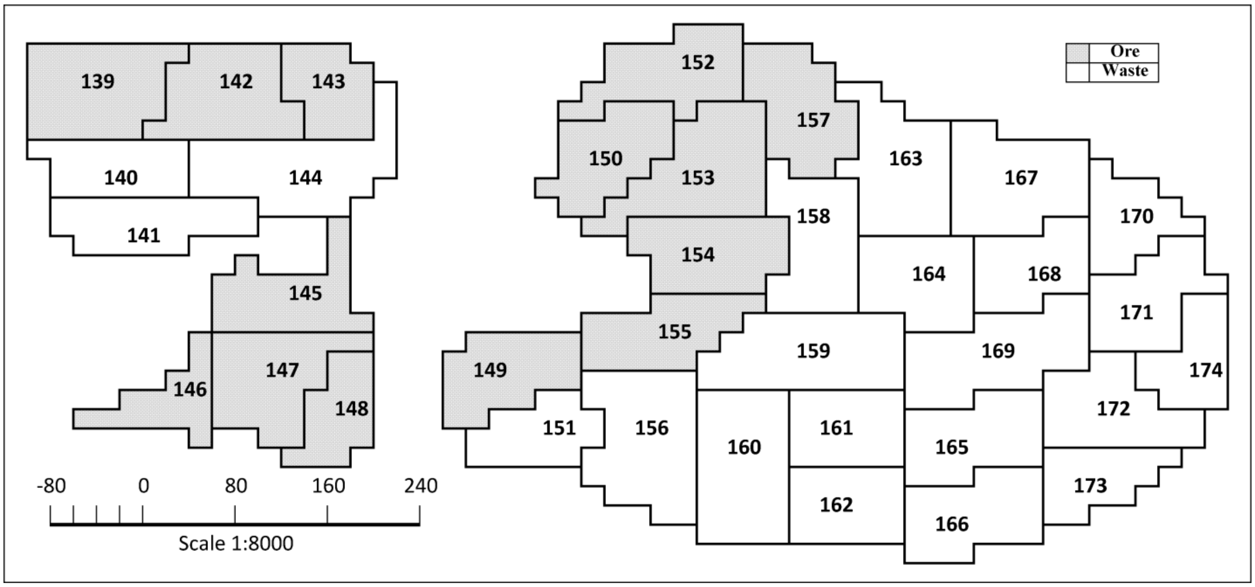

Fig. 2. Clustered mining blocks as faces (numbered) in the bench 1595 scheduled in Year 11

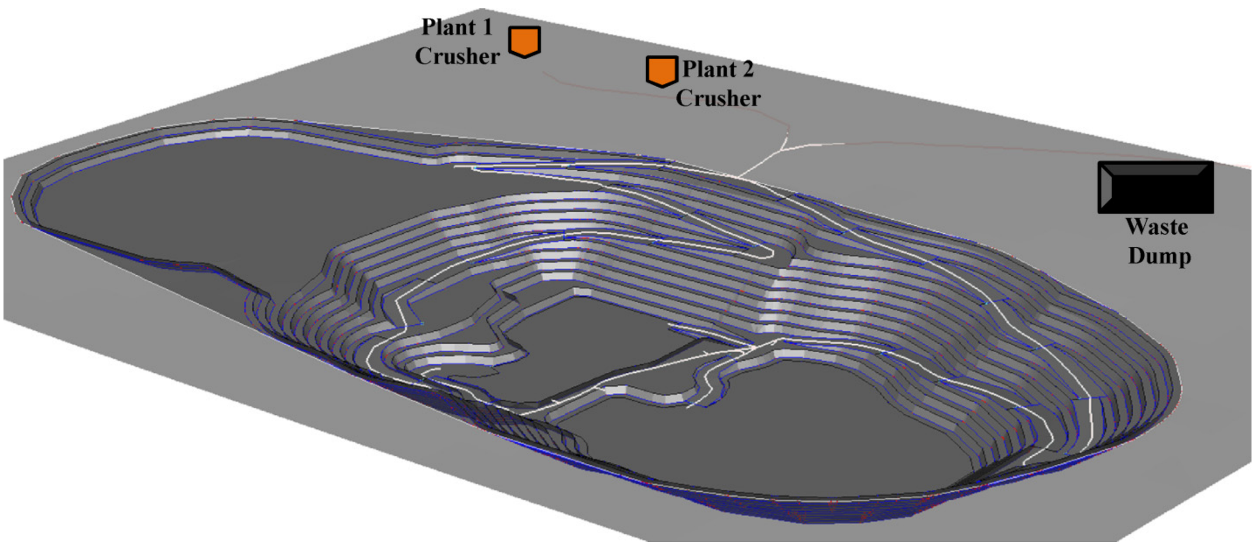

Fig. 3. Mine layout with ramps and road network in year 11

Fig. 3 depicts the mine layout in year 11 of the production with the road network, two plant crushers and a waste dump. The plant crushers require 2000 ton per hour of ore with each having a hopper capacity of 500 ton. Plant 1 and plant 2 crushers are desired to have ore with magnetic weight recovery (MWT) grade of 65% and 75% respectively. Plant 2 is required to get higher priority in meeting the desired grade compared to plant 1. Fig. 4 shows the grade distribution of ore scheduled for year 11 out of which blending objectives need to be achieved.

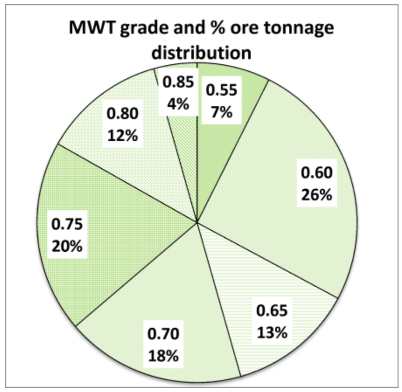

Fig. 4. Percent ore tonnage of MWT grades scheduled in year 11

Mine production operations are carried out in one 12 hour shift daily and 7 days a week. The mine employs a total of 5 shovels with 2 Hit 2500 shovels specifically for ore and 3 Hit 5500Ex shovels only for waste mining. The Hit 2500 shovels have a bucket capacity of approximately 12 ton and a bucket cycle time of about 22 seconds; whereas Hit 5500Ex shovels have a bucket capacity of approximately 22 ton and a bucket cycle time of about 23 seconds.

To haul the material from the faces mine employs 15 Cat 785C and 18 Cat793C trucks with nominal capacities of 140 ton and 240 tons respectively. Cat 785C trucks are locked to ore shovels and thus they may be loaded only by Hit 2500 shovels, and Cat 793C trucks can only be loaded by Hit 5500Ex shovels.

5. Results

The MILGP model is a dynamic decision making tool and is implemented with a simulation model providing it decisions as system state changes and shovel relocations are desired. At this stage, to verify the behavior of the MILGP model correctly, equipment failures and other uncertainties are not included in the simulation model. Also, a higher weight of one is given to plant 2 compared to 0.5 to plant 1 in the MILGP model to meet grade blending requirements as required by the case. The MILGP model is solved using CPLEX (CPLEX, 2014) and discrete event simulation model is developed in Arena simulation package (Arena, 2013).

Dynamic decisions provided by MILGP model were analyzed by examining the simulation results and KPIs related to the objectives considered in the model. Realistic shovel allocation was the prime requirement of the model and its performance greatly rely on it. Shovel positions and the working months were plotted to analyze the allocation decisions made by the model. Fig. 5, Fig. 6, Fig. 7 and Fig. 8 shows the shovels in shaded color, polygon boundaries by solid edges and working (starting) month in numerals for the four benches 1745, 1730, 1610 and 1595 respectively scheduled in the year. Benches 1745 and 1610 overlap over benches 1730 and 1595 respectively, leaving no available faces in the beginning on benches 1730 and 1595 due to vertical dependencies. In the beginning ore shovels 1, 2 and waste shovel 5 are assigned on bench 1610, and waste shovels 3 and 4 start on bench 1745. Ore shovels 1 and 2 remain only on benches 1610 and 1595 as other two benches contain only waste. Also ore on bench 1595 becomes available only after vertical dependencies on bench 1610 are mined.

It can be observed that ore shovels 1 and 2 start from bench 1610, waste mining shovel 3 and 4 start from top bench 1745 and waste mining shovel 5 starts from bench 1610. Bench 1745 and 1730 is mined by shovel 3 and 4, and waste on bench 1610 is mined by shovel 5. A small portion of bench 1610 is mined by shovel 4 in month 10 when it moves down to lower benches. Due to slower mining rate of ore shovels and only one waste shovel on bench 1610, faces were not readily available on bench 1510, causing it to be mined towards the end of the year when all other waste shovels move to it. This cluttering of shovels happen due to lesser number of faces available for shovel allocations towards the end of year, and will be mitigated by bringing in next year's schedule early.

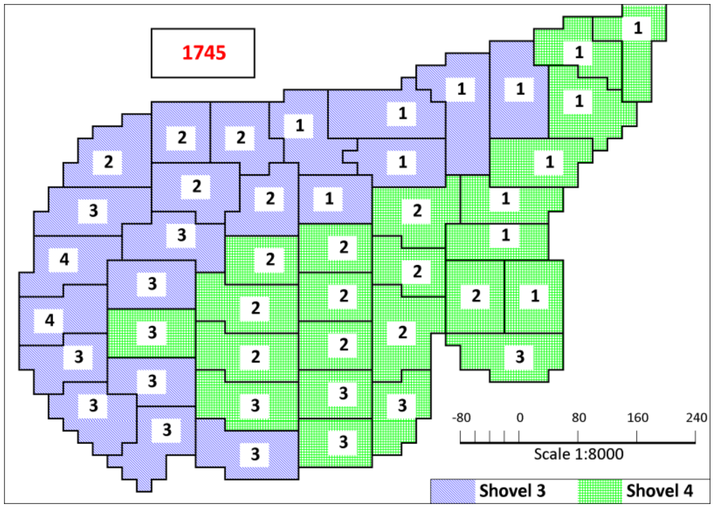

Fig. 5. Shovel positions and corresponding starting month of mining for bench 1745

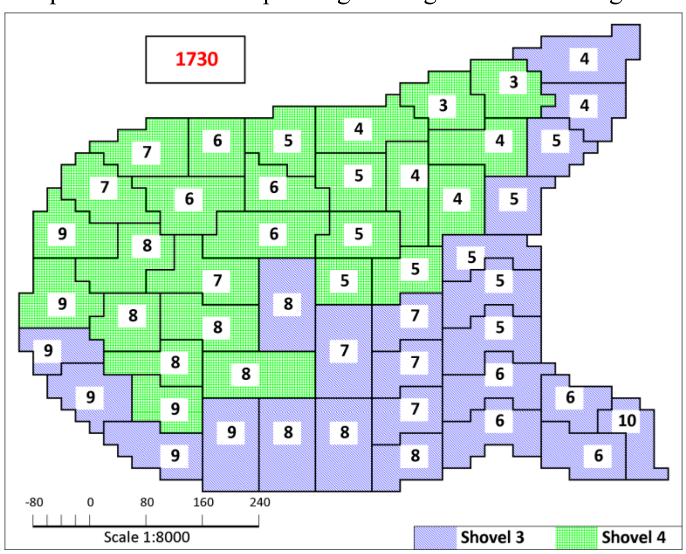

Fig. 6. Shovel positions and corresponding starting month of mining for bench 1730

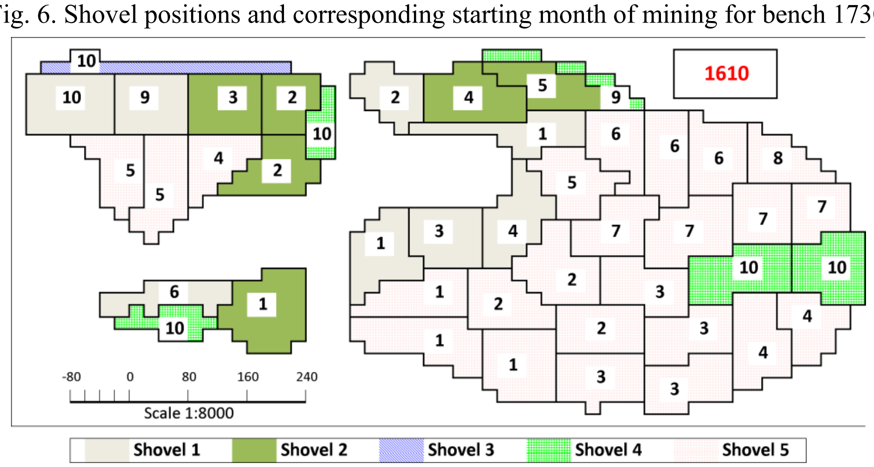

Fig. 7. Shovel positions and corresponding starting month of mining for bench 1610

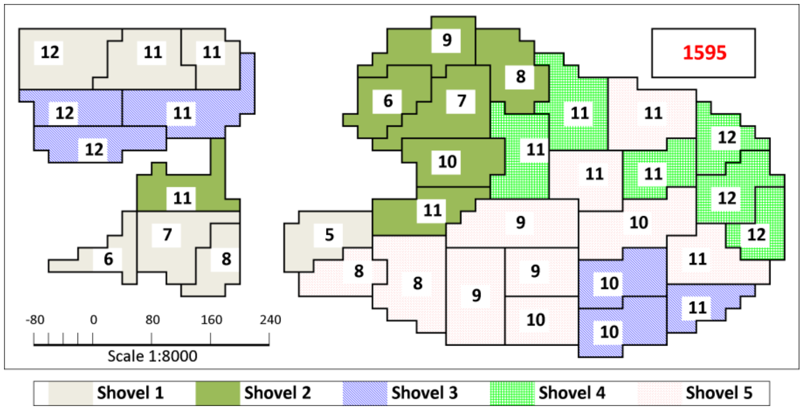

Fig. 8. Shovel positions and corresponding starting month of mining for bench 1595

It can be observed that waste shovels move mostly to the nearest faces, but it is not the case for ore shovels 1 and 2. This happens because of the ore blending objective in the objective function, which gives higher preference on achieving grade blending requirements for plants. An overall analysis of the shovel positions show reasonable and realistic shovel allocations made by the MILGP model.

Considering the tight precedence requirements and very limited available faces, the MILGP model could assign shovels to the faces and at the same time minimize the shovel idle times due to unavailability of faces. The foresightedness in the model let the model foresee the unavailability of faces and allocate the shovels so that other shovels do not encounter idling due to unavailability of faces in the future.

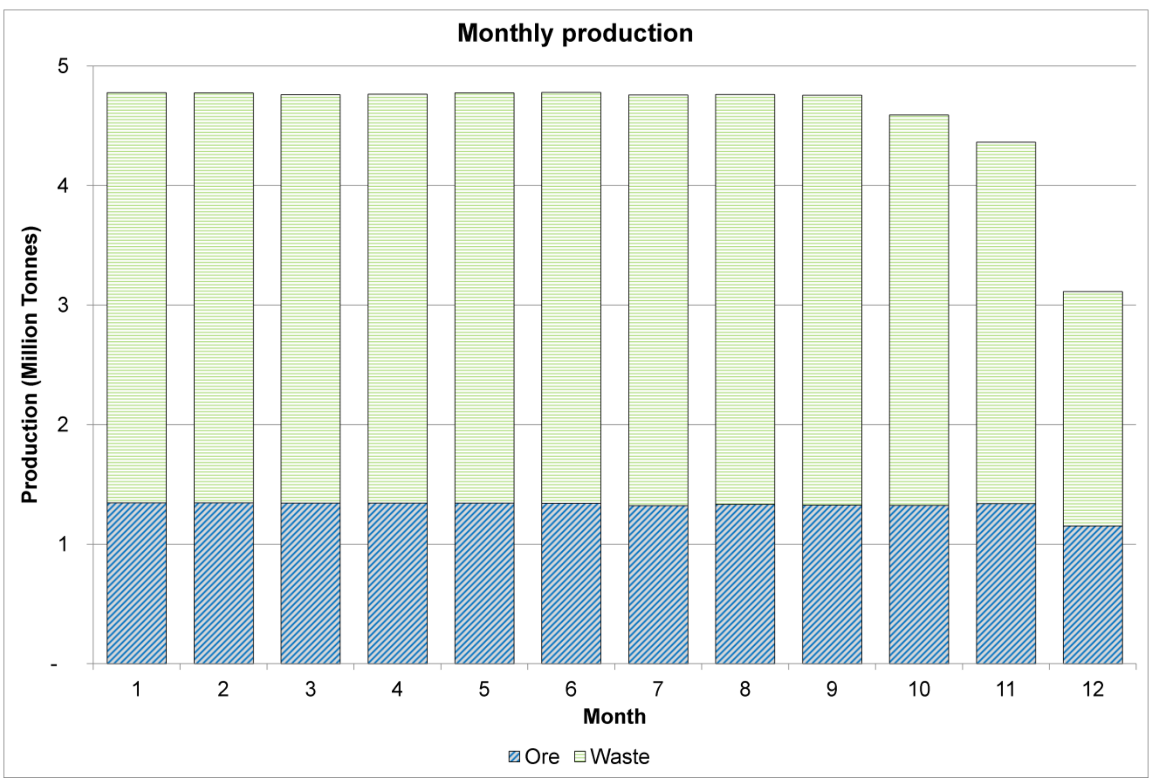

Fig. 9. Monthly ore and waste mining production obtained

Fig. 9 presents the monthly production of the mine, accounting for the production lost due to shovel movements and idle times due to unavailability of the faces. It clearly verifies that the model was capable of achieving its objective of maximum production. Deviation in production towards the end is mostly caused due to unavailability of faces, which would not happen if next year's schedule is brought in early and more faces are available.

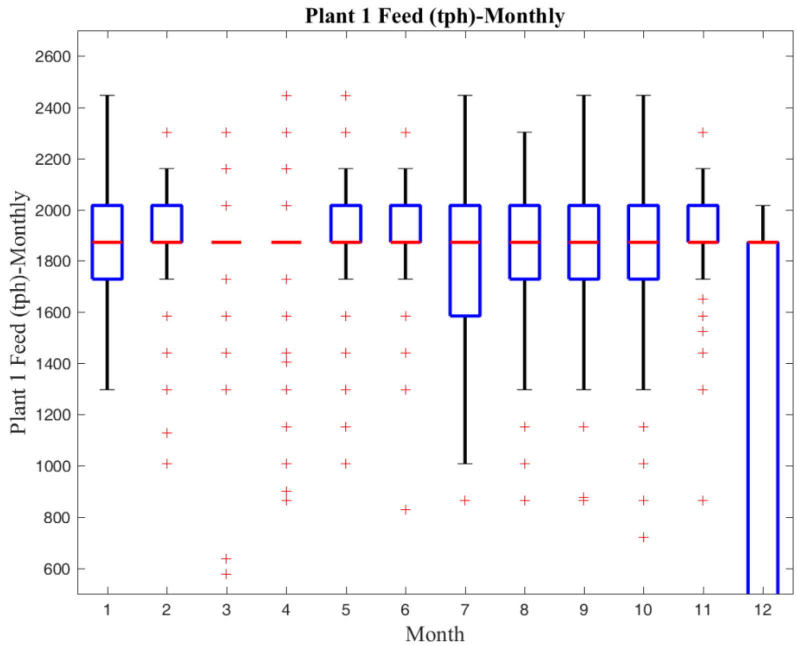

Fig. 10. Box plot showing hourly recorded tonnage (TPH) distribution delivered to plant 1

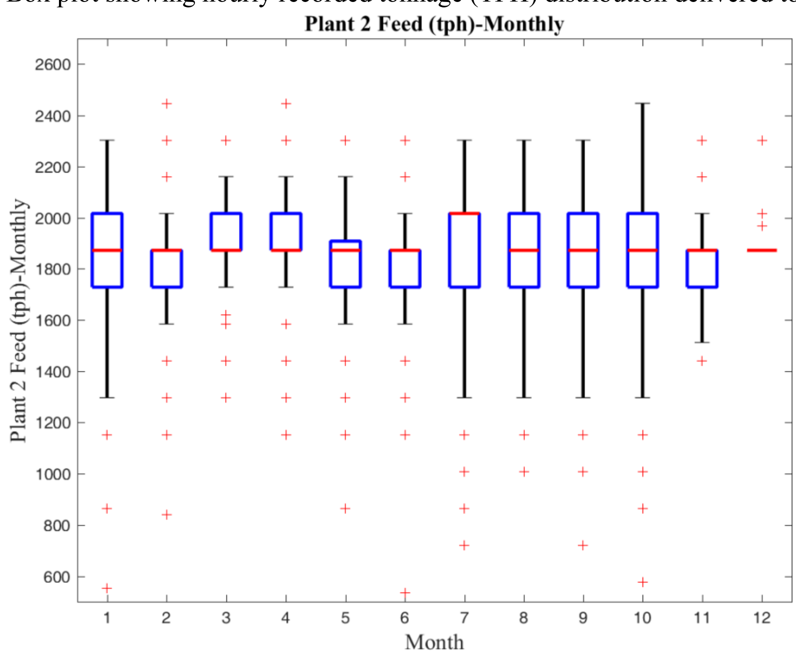

Fig. 11. Box plot showing hourly recorded tonnage (TPH) distribution delivered to plant 2

The simulation model incorporates a truck dispatching system which tries to achieve the flow of trucks to shovels and their respective destinations, as targeted by the MILGP model for desired blending and feed to plants. Fig. 10 and Fig. 11 shows the box plots for ton per hour (TPH) delivered to plants every month. Greater variability is observed at month 12 due to unavailability of ore faces. Analyzing the average TPH delivered to plants, it was verified that the MILGP model could attain the second objective which tries to minimize the deviation in production received at processing plants compared to target.

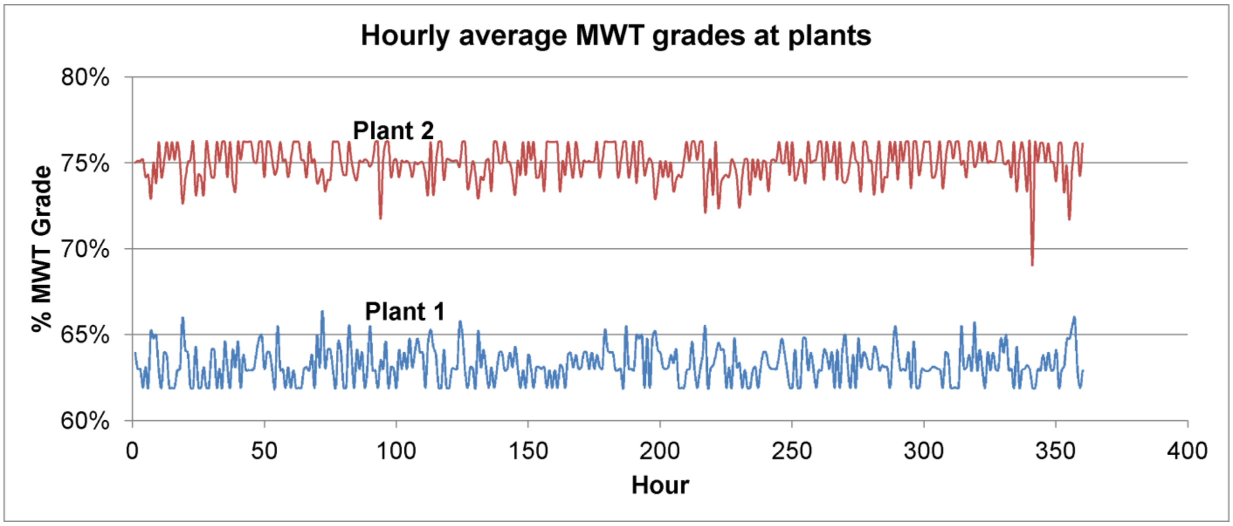

Fig. 12. Average hourly grades at plants for the first month

The most difficult objective of the MILGP model was to deliver the desired grades to the plants, which can only be achieved if suitable combinations of ore faces are mined together in the course of time. Fig. 12 shows the hourly average grades delivered to the plants in the first month and Fig. 13 shows weekly average of grades delivered to the plants for the year. The model results presented here are with higher weight to minimize the grade deviation at plant 2 as desired by the case. Fig. 12 shows that simulation could achieve the truck allocations provided by the MILGP model and average grades delivered were very close to desired grades at the hourly resolution in first month. Average weekly grades in Fig. 13 show that plant 2 received grades as desired except for few weeks in the middle and towards the end. As higher weight was given to grade blending requirements at plant 2, better results are obtained for plant 2, and plant 1 show higher deviations compared to desired grade. Grade blending was also affected by the availability of the suitable faces. It can be observed from Fig. 5 to Fig. 8 that model assigned ore shovels to suitable faces with less priority to movement and higher priority for grade blending as desired. This causes more movement for ore shovels affecting hourly TPH to plants (Fig. 10 and Fig. 11) during movements. As given in Fig. 4, 33% of scheduled ore tonnage was below 65% MWT grade and 36% of scheduled ore tonnage was above 75% MWT grade, which was blended reasonably to achieve the target grades. Compared to grade distribution of scheduled faces (Fig. 4), it can be verified that model could achieve the grade blending objective to a reasonable extent.

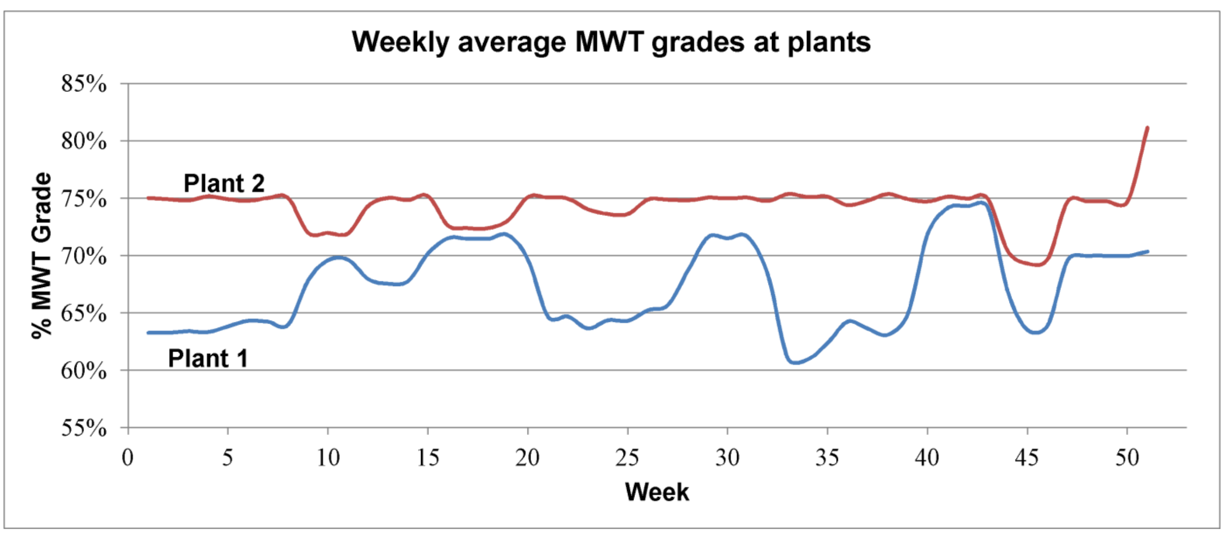

Fig. 13. Average weekly grades delivered to plants for the year

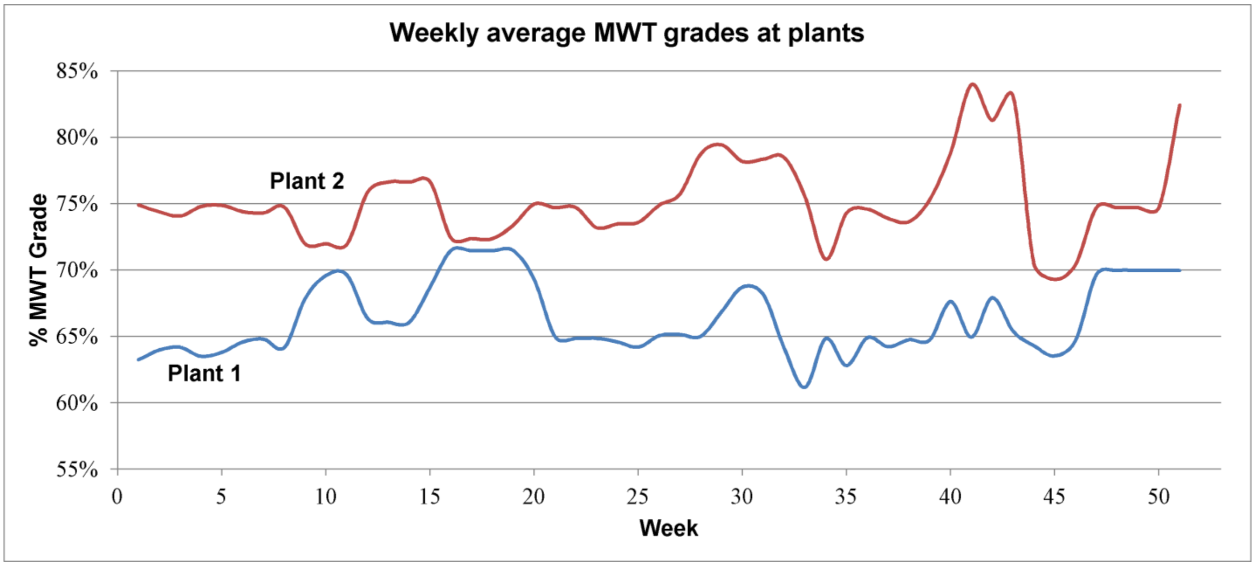

Fig. 14. Average weekly grades delivered to plants with equal grade blending priority to both plants

A second scenario is also run to further analyze the strength of the MILGP model if equal priority is given to both plants to achieve grade blending requirement. Fig. 14 shows the average weekly grades delivered to plants in this scenario. Although grade deviations for plant 1 are less in this scenario, grades at plant 2 becomes poor compared to original scenario. The results obtained in this scenario are not as promising as in original scenario and thus original scenario should be adopted in the operations.

Other KPIs of the system were also analyzed for the year, except month 12 which performed poor due to unavailability of faces and higher idle times. Ore and waste shovels were observed to have an average utilization of 99% and 98% respectively, with average truck utilization being 72%. As no equipment failures were considered for the verification, equipments were available all the time. The use of availability of shovels in this scenario was observed to be 99% due to about 150 hours of shovel idle times in month 10 and 11. This occurs due to the cluttering of all three waste shovels on last bench towards the end of year. The total time spent in movement by all the shovels was obtained to be 78 hrs with an average movement time of 16 hrs per shovel for the whole year.

6. Conclusion and future work

The MILGP model presented in this paper is a unique approach towards short term production planning and scheduling. The bottom-up approach, to generate short term plans by simulating production operations, makes it more practical and provides opportunities for proactive planning by scenario analysis.

The results presented in this paper verify the MILGP model and illustrates the capabilities of the approach in attaining short term and operational objectives. As a future work the model is proposed to implement with a stochastic simulation model incorporating all the uncertainties including equipment failures to verify the model behavior. It is proposed to be made more flexible and user friendly to develop as a tool for short term production planning and analysis purposes.

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8. Appendix

8.1. Notations

Index for variables, parameters and sets

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

8.2. 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.

$a_{s,f,p}$	Assignment of shovel s to face f in period p (binary)
$m_{f,p}$	0 or 1 binary variable if face f is mined out in period p
$y_{s,p}$	0 if $r_{s,p}^{rem}$ is greater than 0, else 1
$n_{t,f,d}$	Number of trips made by truck type t, from face f, to destination d (integer) in first period
$x_{s,f,d,p}$	Fraction of tonnage at face f sent by shovel s, to destination d in period p
$x_{s,p}^{-}$	Fraction of maximum capacity of shovel s less produced in period p
$\delta_{d^c,p}^{-}, \delta_{d^c,p}^{+}$	Negative and positive deviation in production received at processing plants d^c in period p, as fraction of processing plant capacities
$g_{k,d^o,p}^{-}, g_{k,d^o,p}^{+}$	Negative and positive deviation in tonnage content of material type k compared to tonnage content desired, as per desired grade, at ore destinations d^o in period p
$l_{f,p}$	Tonnage of material available at face f at the start of period p
$r_{s,p}$	Movement time (minutes) for shovel 's' in period 'p' to go to next assigned face
$r_{s,p}^{rem}$	Remaining movement time (minutes) to be covered in next period

$r_{s,p}^{act}$ Actual movement time (minutes) covered in period 'p'

8.3. Parameters

T Decision time frame (hr)

Fi_s Face where shovel 's' is initially located (start of the optimization)

X_s Shovel bucket capacity (ton)

X_s^+ Maximum possible shovel production in decision time frame 'T' (ton)

L_s Shovel loading cycle time (seconds)

S_s Movement speed of shovel (meter/minute)

α_s^S Shovel availability (fraction)

Γ_{f^1,f^2}^F Distance between faces (meters), calculated as linear distance between faces on the same bench, and following the haul road and ramps between faces on different benches.

N_f^F Number of precedence faces required to be mined before mining face f

Z_{d^c} Maximum capacity of the crushers/processing plants (ton/hr)

$\Lambda_{d^c}^+$ Maximum positive deviation in tonnage acceptable at crushers/processing plants (ton/hr)

$\Lambda_{d^c}^-$ Maximum negative deviation in tonnage acceptable at crushers/processing plants (ton/hr)

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

$\bar{G}_{f,k}$ Grade of material type 'k' at face 'f'

O_f Tonnage available at face f at the beginning of optimization (ton)

$O_{\min}$ Minimum material at face below which a face is considered mined

Q_f 1 if material at face is ore, 0 if it is waste (binary parameter)

H_t Tonnage capacity of truck type t

J Flexibility in tonnage produced, to allow fractional overloading of trucks (ton)

$M_{t,s}^t$ Binary parameter, if truck type t can be assigned to shovel s

N_t^T Number of trucks of type t

α_t^T Truck availability (fraction)

$\bar{T}_{t,f,d}$ Cycle time of truck type 't' from face 'f' to destination 'd', averaged over all working shovels and following the haul road network (minutes)

ϕ_s 0 or 1 binary variable if shovel s is working or failed

M_s^{ore} Binary parameter, if shovel s is locked to an ore face

W_i	Normalized weights of individual goals (i = 1, 2, 3, 4) based on priority
ε	A very small decimal value to formulate strict in-equality (depending on constraint)
BM	A very large number (depending on constraint)