Short-term Planning of Open Pit Mines with Semi-Mobile In-Pit Crusher

Nasib Al Habib[1*], Eugene Ben-Awuah[2] and Hooman Askari-Nasab[3]
[1] Graduate Research Assistant, University of Alberta, Edmonton, Canada
[2]Associate Professor, Laurentian University, Sudbury, Canada
[3] Professor, University of Alberta, Edmonton, Canada
* Corresponding author email: nasib@ualberta.ca*

ABSTRACT

Open pit mines are getting deeper with time and transportation expenses are increasing because of the increasing haulage distance. In-pit crushing and conveying (IPCC) is getting popular in deeper open pit mines as a suitable alternative because it offers a lower operating cost due to shorter haulage distance and less truck requirement. Semi-mobile in-pit crusher, currently the most popular IPCC system, is relocated every two to five years and the short-term plan needs to be updated accordingly. To the best of our knowledge, short-term planning with IPCC is an area of research that has not been explored extensively yet and hardly any model can generate short-term extraction sequence considering an IPCC in place. This research work proposes a mixed integer programming model to generate short-term production plan within a time horizon of 12 months. The objective of the model is to optimally allocate shovels to minimize cost of material handling and maximize revenue subject to meeting plant requirement, maximum allowable tonnage variation and IPCC location constraints to achieve production and NPV targets set by strategic plan. The proposed model will be implemented in a hypothetical case study for validation. The model will be developed and solved using MATLAB. The comparison of results between scenarios with and without IPCC is expected to justify the use of IPCC in large open pit mines from a short to medium term perspective. The project on completion will be a pioneering work in the arena of short-term mine planning. A *semi-mobile IPCC system with one relocation will be considered in the case study.*

1. Introduction

Mining is a highly capital-intensive operation and proper production planning is required to keep the overall setup, including all the equipment, from performing sub-optimally. The primary objective of any mining project is to maximize the profit by keeping the cost at minimum. Mine planning can be divided into long-term and short-term planning based on the planning time-horizon and objectives being optimized. While the long-term plan is created at the management level to maximize the net present value (NPV) throughout the life of mine, the short-term planning aims at optimizing the operational activities like shovel allocation, grade blending, truck requirement etc. to help achieve the ultimate long-term schedule. The time horizon of short-term planning can be monthly, weekly or even daily. The several stages of mine planning are delineated in Figure 1.

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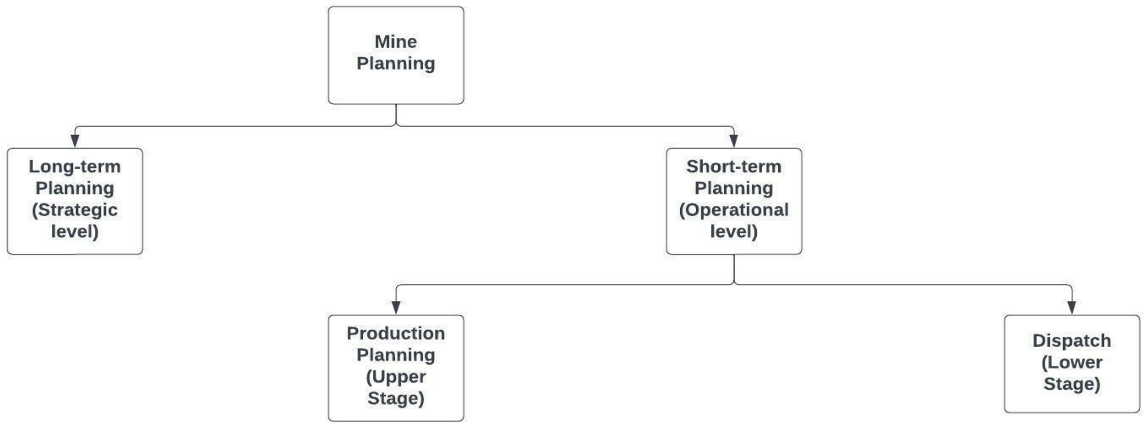

Figure 1. Mine planning stages.

Optimal utilization of the equipment used in mining is of vital importance because the truck-shovel operation may account for over 50% of the total operating cost (Moradi Afrapoli and Askari-Nasab 2017). This optimality can only be realized with efficient utilization of all the assets involved, to achieve the production targets set by the long-term production plans. Therefore, short-term scheduling by optimal allocation of assets (shovels and trucks) is of utmost importance.

Mixed integer programming (MIP) models have been used extensively to generate short-term schedules of open pit mines. Most of the modern short-term planning models are MIP based with explicit precedence constraints applied. (Smith 1998), was the first to use the precedence constraints in mine planning and scheduling. The model uses an MIP for constructing short-term schedules with explicit accessibility constraints, requiring the nine blocks above a block to be mined before that block can be accessed. (Gholamnejad 2008) proposed a binary integer programming model to solve the short-term mine scheduling problem to decide which blocks of ore and waste must be mined in which period (shift, days, weeks or months) by satisfying several operational and geometrical constraints simultaneously. (Eivazy and Askari-Nasab 2012) solved a short-term planning MIP model under several different scenarios, in which the direction of mining varies with different mining precedence constraints. The objective is to minimize the overall cost of mining operations including mining, processing, haulage, re-handling and rehabilitation costs.

(L'Heureux, et al. 2013) proposed a detailed mathematical optimization model for short-term planning, with operational details for a period of up to three months. The objective is to minimize operational costs of trucks' and shovels' activity, drilling and blasting. The authors solved the problem for up to 5 shovels, 90 periods and 132 faces. (Kozan, et al. 2013) modelled drilling, blasting and mining of blocks, and allocation of equipment to these activities with an objective of minimizing the make-span (elapsed time between the start and end of a schedule). Later (Kozan and Liu 2016) formulated another short-term planning model to maximize the throughput and minimize the total idle times of equipment at each stage of drilling, blasting and excavation subject to equipment capacity, speed, read times and activity precedence constraints. The latest contribution of (Liu and Kozan 2017) is an is an innovative mine management system. The proposed methodology integrates a series of mathematical models for ultimate pit limit determination in long-term, medium-term block sequencing over quarterly, half-yearly or yearly time periods, and operational level planning of equipment with a job-shop scheduling model to achieve an overall mining efficiency improvement.

(Blom, et al. 2017) presented a rolling planning horizon-based MIP model to generate multiple short-term production schedules to optimize equipment use and shovel movement constrained by precedence relationships, blending requirements, equipment availabilities and trucking hours considering multiple processing paths.

Integration of simulation with MIP is a tool that has been used by some researchers to account for the uncertainty that exists in mining operations such as, equipment failure, haulage etc. (Upadhyay and Askari-Nasab 2016), and (Upadhyay and Askari-Nasab 2017) integrated simulation with an MIP based short-term planning model, to illustrate how proactive decisions can be made in dynamic environment of mining and operational plans can be synced with long-term planning to reduce opportunity cost, maximize production and equipment utilization. The authors solved the MIP model to optimally allocate shovels to meet production and grade requirement and minimize shovel movement time. (Manríquez, et al. 2020) proposed a similar simulation optimization framework to increase the adherence of short-term mining schedules to execution for underground mining operation. The model generates an initial schedule based on an MILP model embedded in UDESS and then simulated in any data encryption standard (DES) software to replicate the schedule and estimate equipment utilization. The authors claim the model to be general one that is applicable to open pit mining.

The short-term planning models discussed so far are all designed to generate schedules assuming truck-shovel haulage system. While there are studies, such as, (Paricheh and Osanloo 2019), (Samavati, et al. 2020), (Shamsi, et al. 2022), (Liu and Pourrahimian 2021) etc., that justify the use of in-pit crushing in long-term, to the best of our knowledge, there is hardly any research work that do the same in operational level. Several key decisions regarding IPCC, such as, optimum location, relocation time, conveyor design and length etc., are made in the strategic level of mine planning. Therefore, short-term planning needs to investigate the changes in schedules (extraction sequence) that occur because of housing and moving a crusher inside the pit over time. It is also important to verify if the operational plans can sync with the long-term plan to deliver the desired NPV of mine with IPCC.

This research formulates a short-term planning methodology to generate monthly production schedules by optimum shovel allocation. This is a general shovel allocation model that can generate short-term schedule for both truck-shovel haulage and IPCC systems. The model will be used to compare scenarios with IPCC and traditional truck shovel haulage system to determine which one provides more cost saving and generates higher revenue from a short-term perspective with a time horizon of 1 year.

2. Problem Definition

The goal of this research study is to demonstrate the effects of IPCC installation on short-term planning by generating near optimal schedules. The proposed model is intended as a tool to compare IPCC and truck haulage system from the operational perspective of mine planning.

The proposed short-term planning methodology optimally allocates shovels to the mining faces (aggregated blocks into a single entity to reduce the number of variables) to meet production requirements, reduce the cost of haulage and maximize the revenue. The model will generate monthly schedules for a 12-month planning time horizon. The idea is to present two scenarios, one with IPCC and the other one with traditional truck haulage and compare the results to find out the overall revenue generated and cost incurred in each of the scenarios. The difference in scheduling or extraction sequence based on shovel allocation will also be highlighted to demonstrate how IPCC installation affects mine plan from an operational viewpoint. The comparison of results should enable mine planners to decide on the better haulage option for a specific year of mine life.

2.1. Objectives

The operational objectives of the study are:

1. Maximize revenue
2. Meet production requirement to feed the mill to its capacity
3. Minimize haulage cost

The paper develops, implements and verifies the model to compare schedules with semi-mobile IPCC and traditional truck-shovel haulage system.

2.2. Scope and Assumptions of the Study

The proposed model provides a tool to generate and compare short-term schedules for open pit mines.

The MILP is a general shovel allocation model. It can generate schedules for both truck-shovel haulage and IPCC systems.

The model allocates shovels considering both cost minimization and revenue maximization unlike the previous models of (Upadhyay and Askari-Nasab 2016),(Upadhyay and Askari-Nasab 2017) and (Manríquez, et al. 2020), where revenue maximization was not considered.

The model can be integrated with haulage simulation models to account for operational uncertainty.

The model can be extended to find the optimal number of trucks required in a specific period of mine life.

The model is based on the following assumptions.

1. The IPCC system is semi-mobile
2. The optimum locations and relocation time of the crusher is known throughout the life of mine from strategic planning.
3. There is no waste crusher. Waste material goes directly to external waste dumps.
4. The ore and waste faces are labeled. Hence, ore material will go to mill or crusher and waste material will go to waste dump.
5. There is no stockpiling.
6. The model does not consider ore blending in its current state.
7. The model does not consider multiple processing destinations.
8. Production loss due to shovel movement time is not considered.
9. Production loss due to equipment failure and maintenance is not considered.
10. The model is strictly deterministic.
11. The mill requirement is constant throughout the planning horizon.

3. Model Formulation

The objective function, variables, parameters and the constraints of the MILP model are described in the section below.

3.1. Objective Function

The objective function consists of three components. The first two components calculate the cost of hauling ore material to crusher or mill and waste material to waste dumps respectively, using regular diesel trucks. The third part calculates the cost of conveying ore material from crusher to processing plant. The last component calculates the revenues earned from ore production. The flow of ore and waste material from source to destination is displayed in Figure 2.

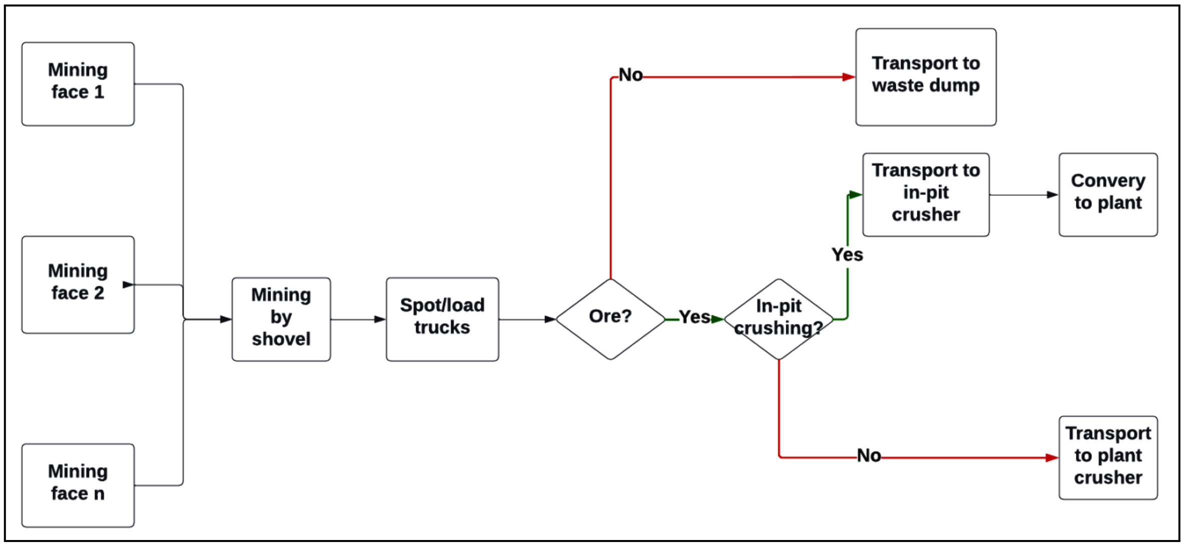

Figure 2. Flow of material from mine to crusher, plant and waste dump.

Objective function, minimize f = cost of transporting material to crusher or waste dump from mine by trucks + cost of conveying ore material from crusher to processing plant – revenue earned from selling ore.

Mathematically, the objective function can be represented as:

$$\text{Min, f} = \sum_{p\in P\in T, f\in F_{ore}} x_{p,f,t} \times RM_{p,f} \times TT \times D_{f,r} \times H_t +$$

$$\sum_{p\in P\in T, f\in F_{waste}} x_{p,f,t} \times RM_{p,f} . TT \times D_{f,w} \times H_t +$$

$$\sum_{p\in P,\in T, f\in F_{ore}} x_{p,f,t} \times RM_{p,f} \times TT \times C \times H_c -$$

$$\sum_{p\in P\in T, f\in F_{ore}} x_{p,f,t} \times RM_{p,f} \times TT \times p_k$$

3.2. Variables, Parameters and Indexes Explanations

Variable	Description
$x_{p,f,t} \in [0, 1]$	Time percentage of period $t\in T$ where shovel $p\in P$ is active in face $f\in F$, 0 otherwise

$s_{p,f,t} \in \{0, 1\}$	Shovel allocation variable. Equal to 1 if shovel $p \in P$is allocated to face$f \in F$ in period$t \in T$, 0 otherwise
$m_{f,t} \in \{0, 1\}$	Equal to 1 if face $f \in F$ is mined out in period$t \in T$, 0 otherwise
$l_{f,t} \in R^{+}$	Tonnage of face f in period the beginning of period t

Parameter	Unit	Description
TT	H	Total time per period
$AV_{p,t}$	%	Availability of shovel p in period t
$RM_{p,f}$	t/h	Material throughput of shovel p in face f
TM_{f}	Tonnes	Total material in face f
$D_{f,w}$	km	Distance to waste dump from face f
TC	Tonnes	Mill capacity per period
C	Km	Conveyor length
$D_{f,r}$	Km	Distance to crusher/mill from face f
H_{t}	\$/tonneKm	Transportation cost per unit
H_{c}	\$/tonneKm	Conveying cost per unit
M		A big number
p_{k}	\$/ton	Iron ore price
N^{f}		Number of precedences for face f
$c_{f,t} \in \{0, 1\}$		Equal to 1 if crusher is located on face $f \in F$ in period $t \in T$, 0 otherwise

Indexes	Description
p	Index for shovels
f	Index for faces
t	Index for periods

3.3. Constraints

$$\sum_{p\in P} s_{p,f,t} \le 1;\ \forall f \in F,\ \forall t \in T \tag{1}$$

$$\sum_{f\in F} s_{p,f,t} \le 2;\ \forall p \in P,\ \forall t \in T \tag{2}$$

$$\sum_{p\in P, f\in F_{ore}} x_{p,f,t} \times RM_{p,f} \times TT <= TC;\ \forall t \in T \tag{3}$$

$$\sum_{p\in P, f\in F_{waste}} x_{p,f,t} \times RM_{p,f} \times TT >= TC;\ \forall t \in T \tag{4}$$

$$l_{f,t} = TM_f;\ \forall f \in F \,\&\, t = 1 \tag{5}$$

$$l_{f,t+1} = l_{f,t} - \sum_{p\in P} x_{p,f,t} \times RM_{p,f} \times TT;\ \forall f \in F \,\&\, t = 1 \ldots T - 1 \tag{6}$$

$$M \times m_{f,t} <= \text{epsilon} - l_{f,t} \quad ; \forall f \in F,\ t \in T \tag{7}$$

$$M \times (1 - m_{f,t}) >= -\text{epsilon} + l_{f,t}\ ;\ ; \forall f \in F,\ t \in T \tag{8}$$

$$m_{f,t+1} \ge m_{f,t}\ ;\ ; \forall f \in F,\ t \in 1 \ldots T - 1 \tag{9}$$

$$\sum_{f\in F} s_{p,f,t} \le s_{p,f,t} + m_{f,t} + \left(1 - s_{p,f,t-1}\right) + \left(1 - s_{p,f,t}\right) \times BM; \forall f \in F, t \in T, p \in P \tag{10}$$

$$s_{p,f,t+1} \ge s_{p,f,t} - m_{f,t};\ ; \forall f \in F,\ p \in P,\ t \in 1 \ldots T - 1 \tag{11}$$

$$s_{p,f,t} \ge c_{f,t} \times BM\ ;\ ; \forall f \in F,\ p \in P,\ t \in T \tag{12}$$

$$\sum_{p\in P, t\in T} x_{p,f,t} \times RM_{p,f} \times TT \le TM_f; \forall f \in F \tag{13}$$

$$N^f \times \sum_p s_{p,f,t} - \sum_{f'} m_{f',t} \le 0;\ ; \forall f \in F,\ p \in P,\ f' \in \textit{precednece set} \tag{14}$$

$$\sum_{f \in F} x_{p,f,t} \leq AV_{p,t};\ p \in P,\ t \in T \quad (15)$$

Where,

Equation 1: Only 1 shovel can be assigned to a face in a specific period.

Equation 2: One shovel cannot be assigned to more than 2 faces in a period. This constraint allows the shovels to move to a new face when the working face is mined out.

Equation 3: Total material extracted in a period must not exceed the destination/mill capacity.

Equation 4: Total waste material to be mined each period. The model tries to minimize waste mining as waste material increases haulage cost and does not contribute to revenue. Therefore, this constraint makes sure that the tonnage of waste mined in a period is such that the total waste material is mined out at the end of 12 periods.

Equation 5: Initial tonnage of the faces. The total tonnage of each face TM_f is assigned to the $l_{f,t}$ variable in the initial period.

Equation 6: Remaining tonnage of a face after a period of extraction. This equation keeps track of the remaining tonnage of each face at the end of a period.

Equations 7 and 8: Makes sure that when $l_{f,t}$<= epsilon (a small number), $m_{f,t}$= 1. The $m_{f,t}$ is used to keep track of faces that have been mined out.

Equation 9: If a face is mined out, it stays mined out in the next periods.

Equation 10: It strengthens equation 2. This equation controls when a shovel can be assigned to more than one faces in a 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, $m_{f,t}$ will become 1 and thus the shovel will be allowed to be assigned to another face. For the new face as $s_{p,f,t-1}$ and $m_{f,t}$ will be zero and thus the constraint will still hold true and allow the shovel to be assigned to two faces in that period.

Equation 11: Forces a shovel to stay in the same face unless it is mined out.

Equation 12: A shovel cannot be assigned to a face in a period if the crusher is located on that face during that period. This constraint controls if in-pit crusher is present or not in the mine.

Equation 13: The total material mined by all the shovels from all the faces must not exceed the total material available in this face.

Equation 14: Face f cannot be mined before the precedence faces (f') have been mined out.

Equation 15: The fraction of time a shovel works in several faces must not exceed the shovel availability.

The model will be solved using rolling-planning horizon technic to reduce the runtime. The model will look into 3 months ahead while assigning shovels to faces. It assigns shovels to faces for the first three periods at first. Then it looks into the next three periods, assigns shovels to the available faces and so on. The periods are denoted by P in the following Figure 3 that demonstrates the rolling-planning horizon time frame used in the model.

Optimization Time frame											
P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
Decision Time Frame(T)											

Figure 3. Optimization and decision time frame of the model.

4. Case Study

The case study will present two scenarios in an iron mine with IPCC and traditional truck-shovel mining method to verify the model. The short-term schedule will be generated for the 11th year of mine life. Two benches with elevations 1595 and 1610m are available to be mined and the total available material to be mined is 16MT of ore and 16.5MT of waste. There is only one mill to process material. The crusher requirement (in-pit or plant) is 2700 tons per hour. Assuming 16 hours of operation in a day with 2 eight-hour shifts, the monthly crusher requirement is 1.33MT. The mine layout is shown in Figure 4 for year 11. Figure 5 and Figure 6 show the pit layout at the elevations of the two benches to be mined in year 11. The distances from each face to the waste dump, crusher and plant are calculated using the nodes in the road network. The grade of the designed ramps is 8%. The length of the conveyor belt for the IPCC scenario is 2550 m, which comes from the strategic plan.

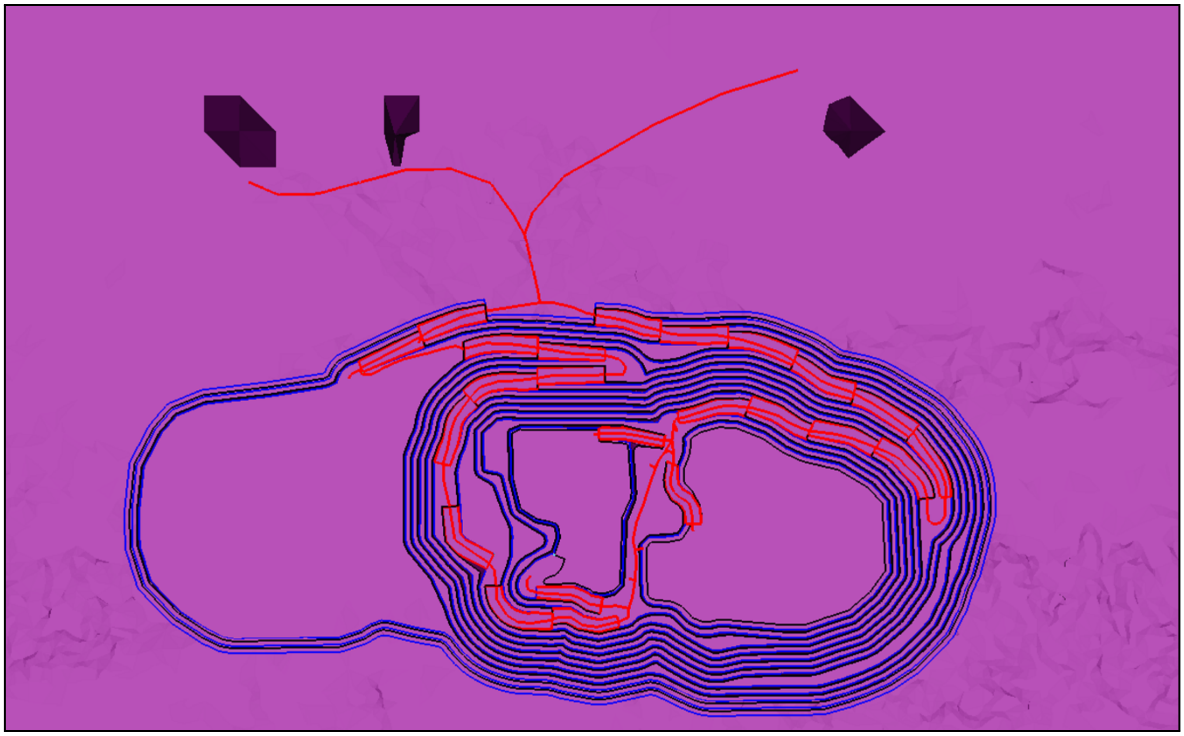

Figure 4. Pit layout with roads and ramps in year 11.

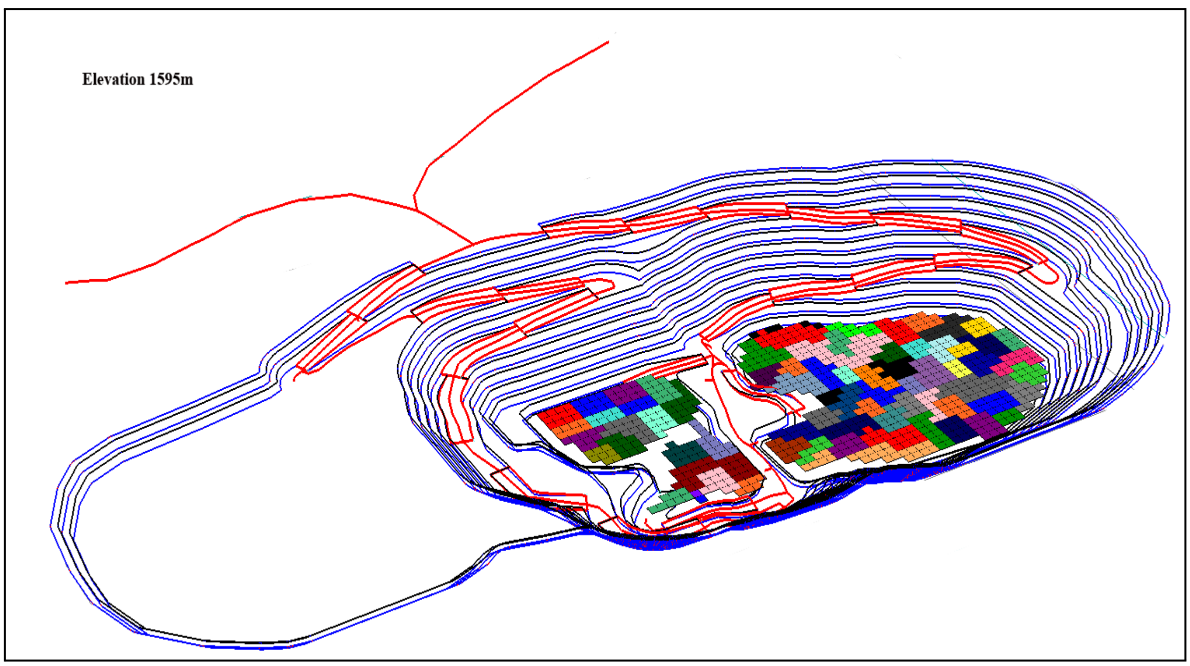

Figure 5. Layout of the pit at elevation 1595m.

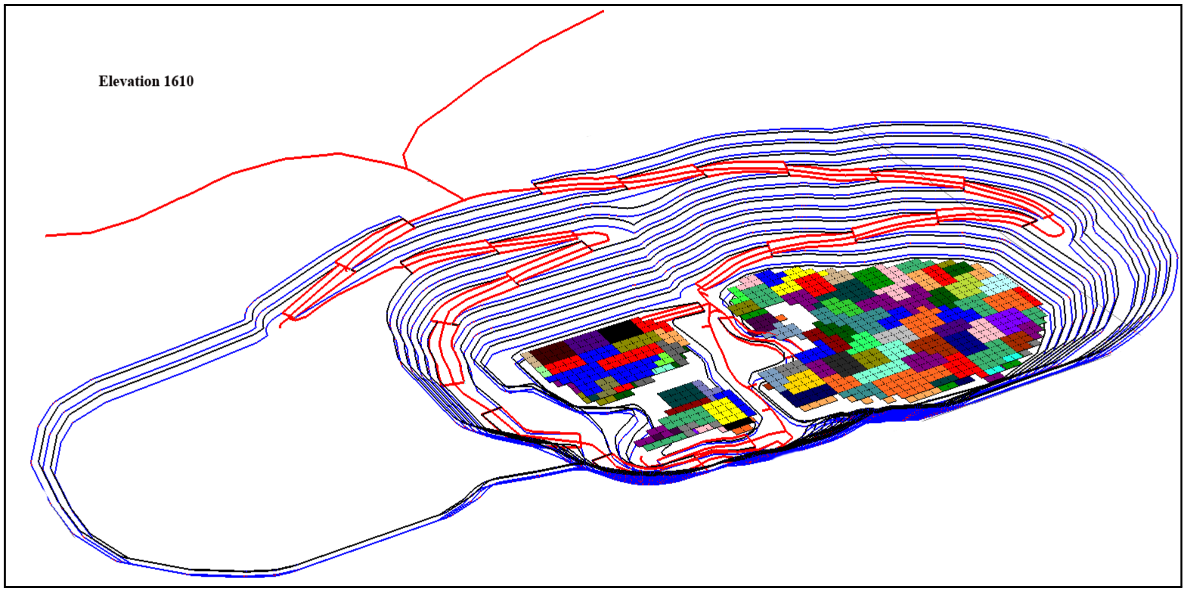

Figure 6. Layout of the pit at elevation 1610m.

The element of interest in the mine is magnetic weight recovery of iron (MWT). The grade and tonnage distribution of MWT in year 11 is presented in Figure 7.

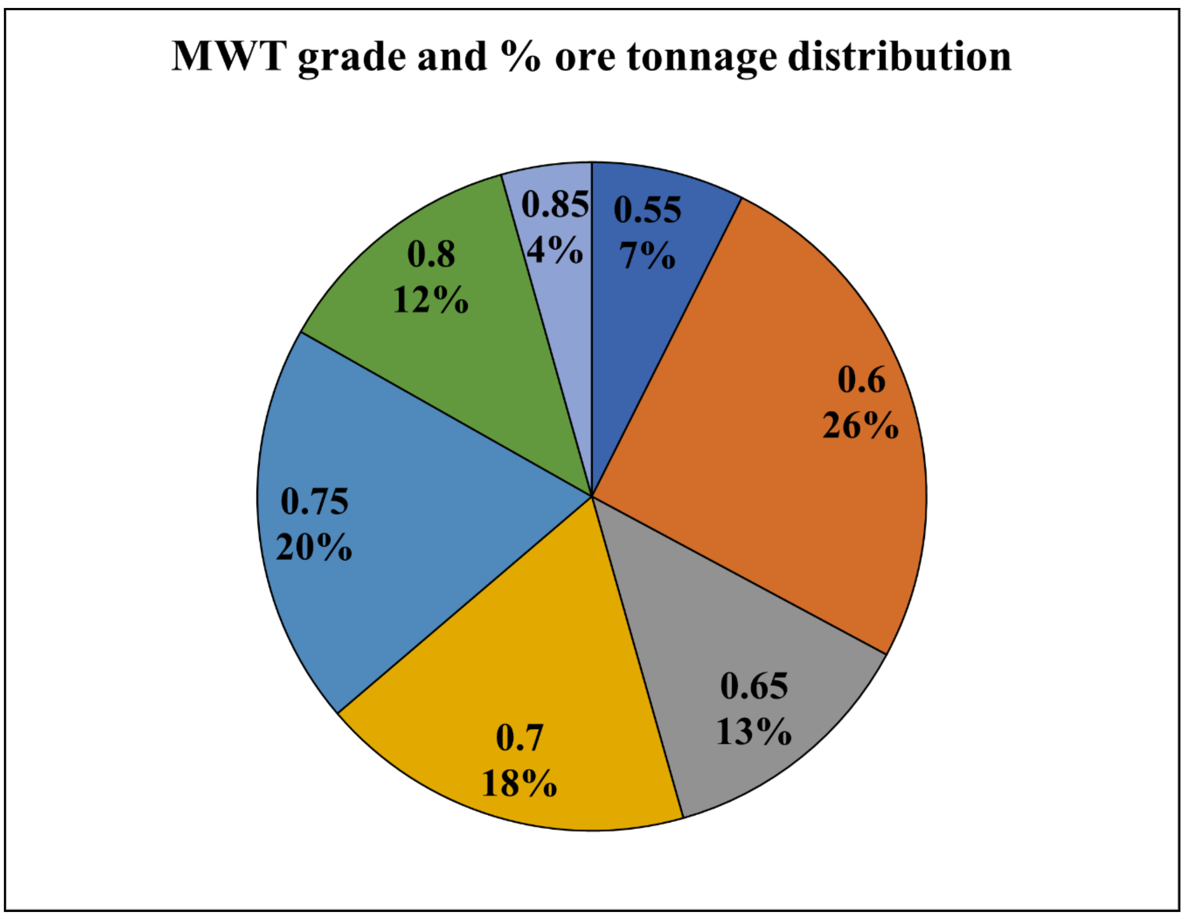

Figure 7. Grade and tonnage distribution of MWT.

A hierarchical clustering algorithm has been used (Tabesh and Askari Nasab 2013) to aggregate similar blocks together to generate 78 mining faces (polygons) out of 1900 blocks to be mined in year 11 within two benches. The face 37 on bench 1595 has a very low waste tonnage of less than 60000 tons. Hence, this face has been omitted in the data input to the model. The clustered faces in the benches are shown in the Figure 6 and Figure 7.

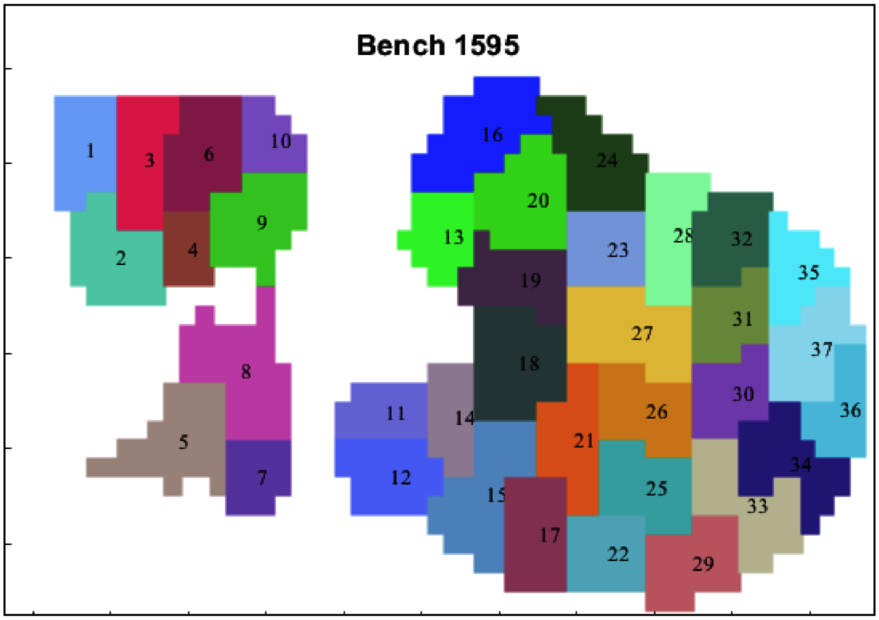

Figure 8. Clustered faces on bench 1595.

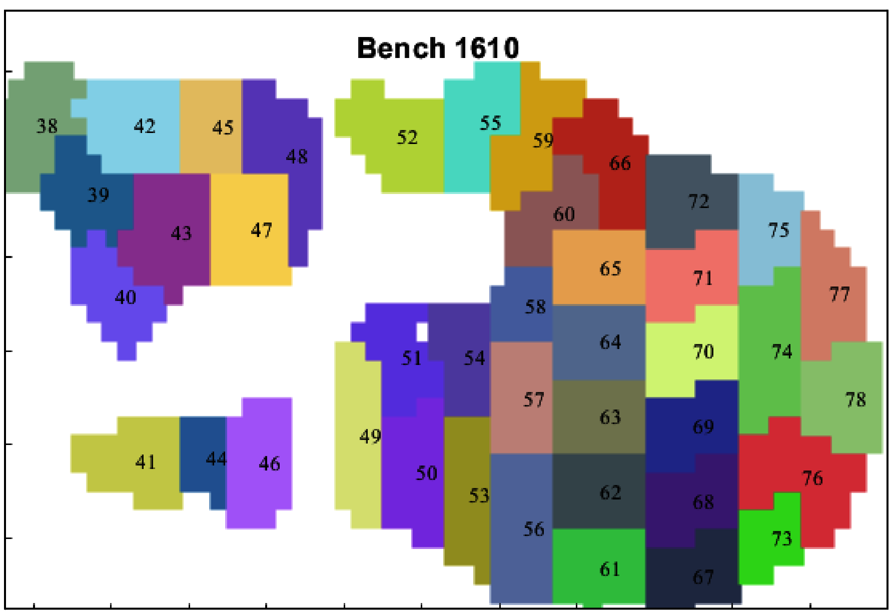

Figure 9. Clustered faces on bench 1610.

The mine employs a total of 4 shovels including 2 Hit 2500 shovels specifically for ore and 2 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 Cat 785C and 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. The truck requirement for both the scenarios are calculated and compared based on the truck cycle time, shovel capacity and production requirement.

5. Results

The MIP model is solved for two scenarios: one with semi-mobile IPCC and one with Truck-shovel only. The two scenarios are differentiated by Equation 12, which controls whether the mine has an in-pit crusher or not. The model runs for 12 months in four steps where it allocates shovels to faces for three months, saves the results and then look for available faces for the coming three months. The model is formulated and solved in MATLAB 2021(B). The scenario without IPCC (scenario 1) took 192 seconds to run and the IPCC scenario (scenario 2) took 204 seconds. The optimality gaps in both cases are less than 0.5%. A comparison of the optimal results and generated schedules are presented in the following sections.

5.1. Scenario 1 (No IPCC):

This scenario represents a traditional truck-shovel (TS) mining operation where the mined material is hauled to the plant crusher and waste dump by trucks. Pragmatic shovel assignment to the faces is the primary goal of the model. Shovel positions and the working months are summarized to analyze the allocation decisions made by the model. The model does not take shovel movement time into account. A shovel availability of 80% is assumed to account for the lost time for movement among faces. The optimal objective function value for this scenario is **$2138M**. Figure 10 and Figure 11 show the ore and waste faces in shaded color for bench 1610 and 1595 respectively. Figure 12 and Figure 13 show the shovels in shaded color, polygon boundaries by edges and working (starting) month in numerals for bench 1610 and 1595.

1610	38	39	40	41	42	43
	44	45	46	47	48	49
	50	51	52	53	54	55
	56	57	58	59	60	61
	62	63	64	65	66	67
	68	69	70	71	72	73
	74	75	76	77	78	
			ore	waste		

Figure 10. Ore and waste faces on bench 1610.

1595	1	2	3	4	5	6
	7	8	9	10	11	12
	13	14	15	16	17	18
	19	20	21	22	23	24
	25	26	27	28	29	30
	31	32	33	34	35	36
			ore	waste		

Figure 11. Ore and waste faces on bench 1595.

1610	9	6	3	6	8	11
	7	9	5	4	6,7	1
	2	3	1	5	2	11
	11	2	7	2	4	4
	6	8	6	8	2	3
	1	1	1	5	7	8
	9	5	12	7	9	
	Sh1	Sh2	Sh3	Sh4		

Figure 12. Shovel assignment to faces and corresponding mining period in bench 1610.

1595	10	8	12	11	11	11
	10	12	10	12	4	3
	3	6	3	8	12	12
	5	9	12	7	10	9
	3	5	4	2	10	6
	12	4	7	12	11	10
	Sh1	Sh2	Sh3	Sh4		

Figure 13. Shovel assignment to faces and corresponding mining period in bench 1595.

The model assigns shovels to bench 1610 from period 1 and mining starts at bench 1595 from period 2 because of the vertical precedences that exist between the two benches. Generally, the waste faces are mined in the earlier than ore faces for both the faces because the waste faces precede the ore faces in many of the cases. The shovels do not look for the nearest faces for next assignment after a face is mined out because the model does not consider shovel movement costs. The allocations demonstrate that the model is capable of assigning shovels to faces respecting the precedence relationships and the production requirements. All the faces are mined within the 12 months optimization time frame making sure that the production requirement of the strategic plan is satisfied.

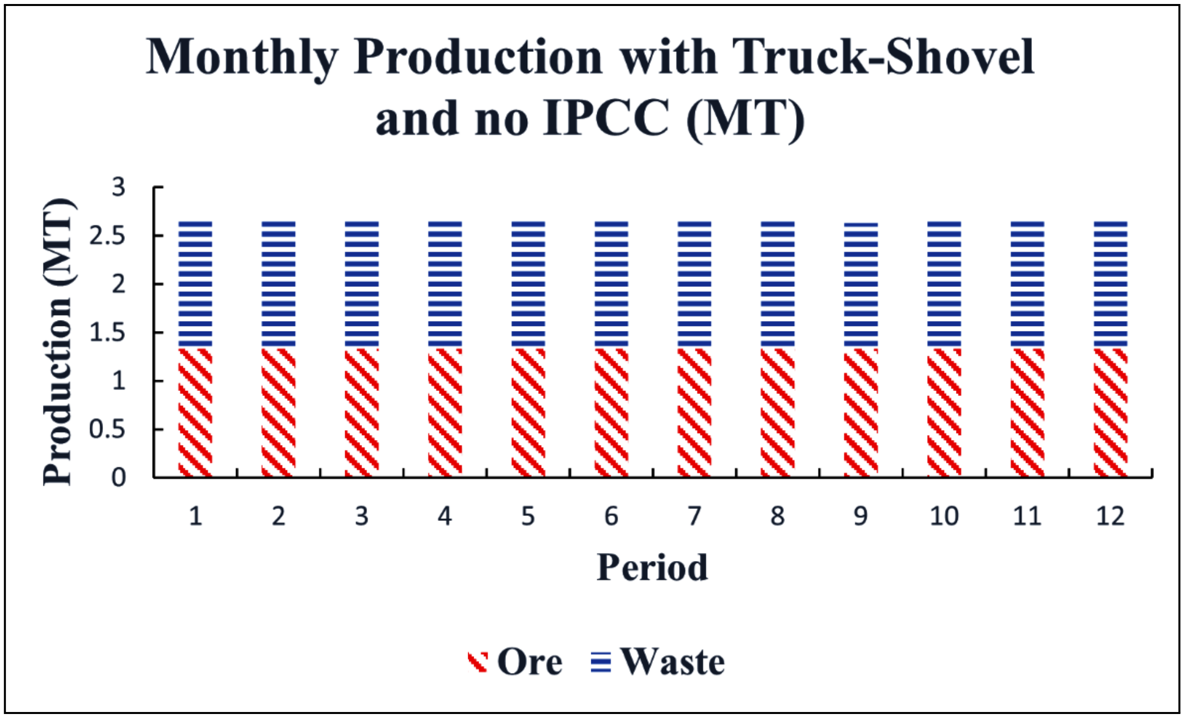

Figure 14. Monthly ore and waste production for scenario 1.

Figure 14 shows the monthly production of ore and waste. The production of ore is uniform throughout the 12 periods which ensures that the mill is fed to its capacity. The waste production is also fairly uniform too with a variation of less than 1.5% in period 9.

Figure 15 demonstrates average shovel efficiency for all four shovels over the 12 periods. The equation used to calculate shovel efficiency is displayed below.

$$Shovel\,efficiency, \vartheta \; = \; availability \times utilization \qquad (16)$$

Utilization is being defined as the percent of time a shovel is busy working in a face in a period in this equation.

It is evident from Figure 15 that the ore shovels have higher efficiency compared to the waste shovels. Waste shovels have higher bucket capacity compared to the ore shovels. While the number of waste faces is significantly higher than the number of available ore faces, the tonnage of ore and waste to be mined is similar. This justifies the lower efficiency of the waste shovels. The efficiency of the waste shovels is around 50% and the ore shovels is between 70 to 75%.

The ore and waste truck requirement has been calculated based on the production requirement, truck cycle time and shovel capacity. The average one-way distance from all the faces to the plant crusher is 5km and the one-way distance to the waste dump is 3.2kms. The loaded and empty haul speed are estimated from the rimpull characteristics curve for CAT 785C and CAT 793C trucks. The equation used to calculate the truck requirement is,

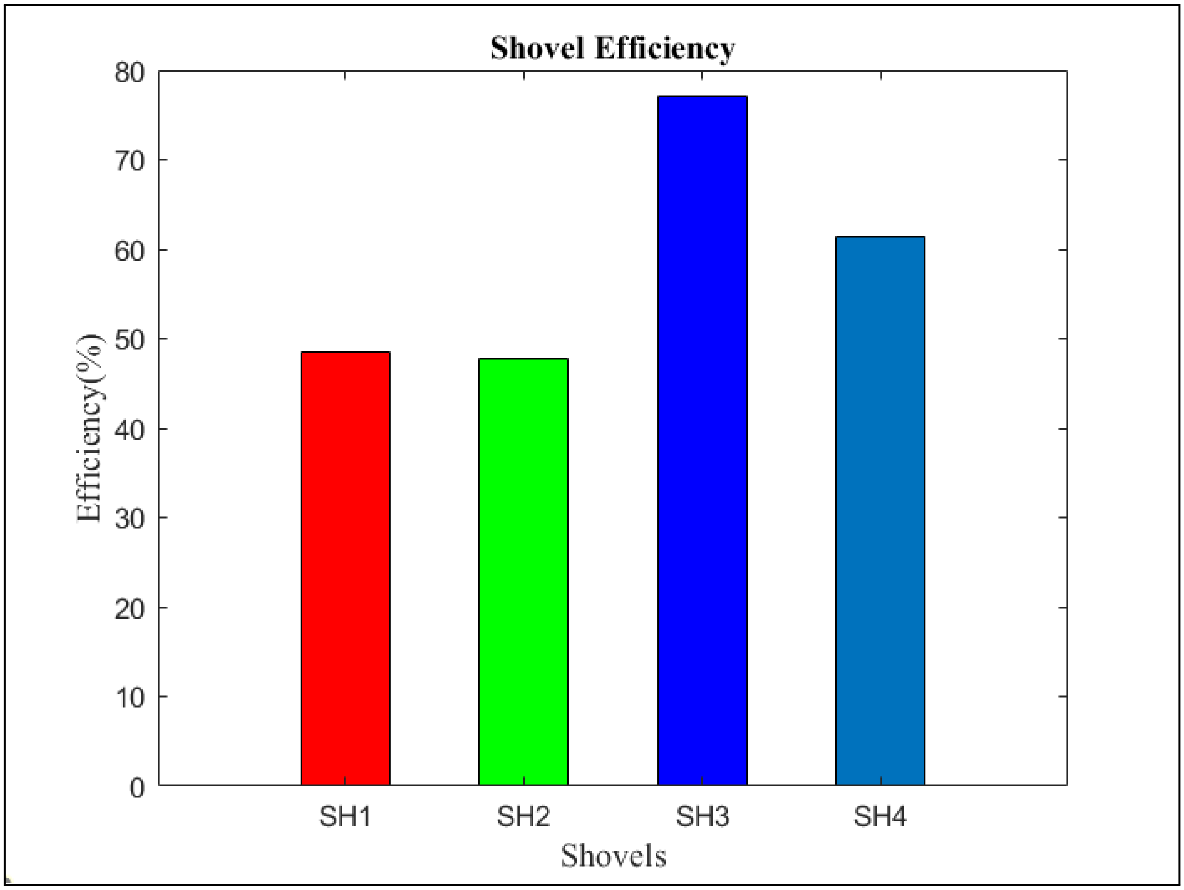

Figure 15. Average shovel efficiency.

$$N_h = \frac{P_h \times TC_{ch}}{60 \times L_h \times E} \quad (17)$$

Where, N_h = Number of trucks required

P_h = Production rate per hour

TC_{ch} = Truck cycle time

L_h = Nominal truck load

E = Operating efficiency

The required number of ore and waste trucks for this scenario is 13 and 6 respectively assuming a 65% efficiency.

5.2. Scenario 2 (IPCC):

This scenario assumes one in-pit crusher for ore crushing. The trucks haul the mined material to the crusher. The crushed material is conveyed to the processing plant by a 2.5km long conveyor belt. The location of the crusher is face 3 for the first six months and face 18 for the rest of the periods. The constraint shown in Equation 12 for IPCC prevents mining of the face that houses the crusher. The optimal objective value is **$2152M**. Figure 16 and Figure 17 display the shovel assignment and corresponding mining periods for bench 1610 and 1595 respectively.

1610	9	6	2	6	8	11
	7	9	5	4	5	1
	1	50	51	5	2	
	10	1	7	1	4	4
	6	8	6	9	1	2
	1	3	3	5	9	9,10
	7	4	12	11	8	
	Sh1	Sh2	Sh3	Sh4		

Figure 16. Shovel assignment to faces and corresponding mining period in bench 1610.

1595	10	8	12	11	11	11
	9	12	11	12	5	3
	4	6	3	8	10	
	5	9	12	12	7	7
	2	6	5	3	10	4
	12	4	8	12	11	12
	Sh1	Sh2	Sh3	Sh4		

Figure 17. Shovel assignment to faces and corresponding mining period in bench 1595.

The precedence relationships still hold for this scenario. The faces of bench 1595 starts from period 2 while mining in bench 1610 starts from the first period. The waste faces are generally mined in earlier months compared to ore faces. The crusher was located on face 3 of bench 1595 and it has been mined on period 12. Face 18 has been left unmined as the crusher has been located here from period 6 onwards. One of the waste faces (face 55) remains unmined on bench 1610.

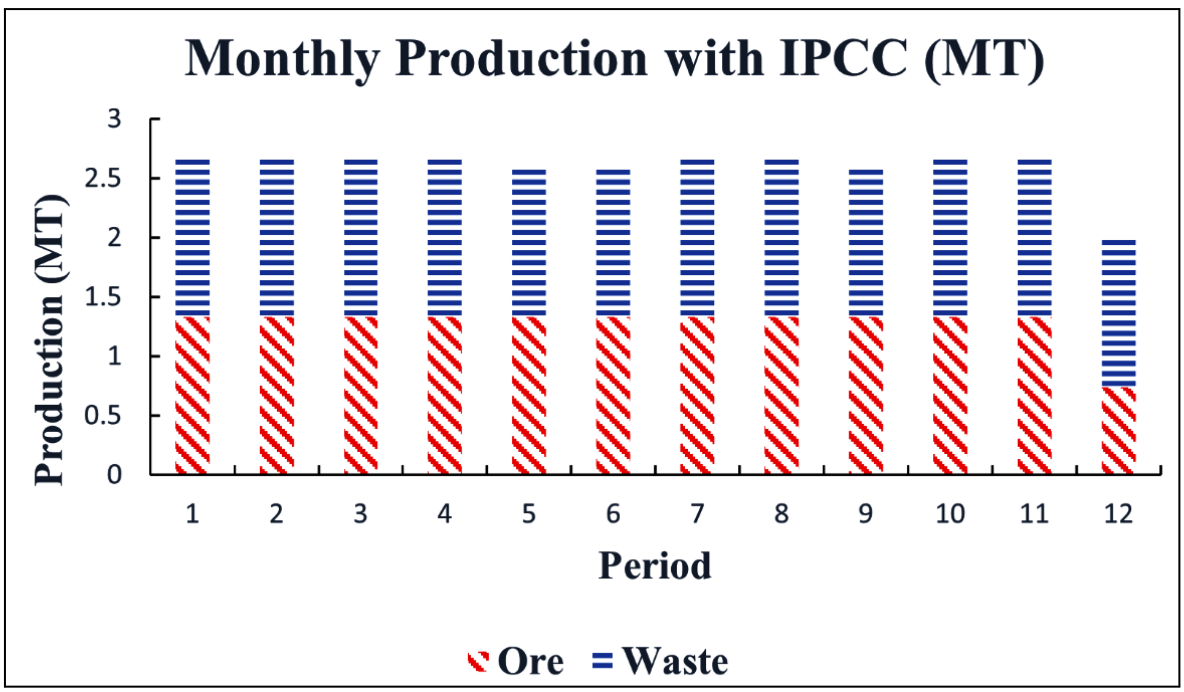

Figure 18. Monthly ore and waste production for scenario 2.

Figure 18 shows the production of ore and waste for this scenario. The ore production is low in the last period because of unavailability of faces. The overall waste production is 0.4MT less than scenario 1 because face 54 is left unmined. This face has to be mined in the next year. The tonnage of the face is negligible and does not really affect the overall production substantially.

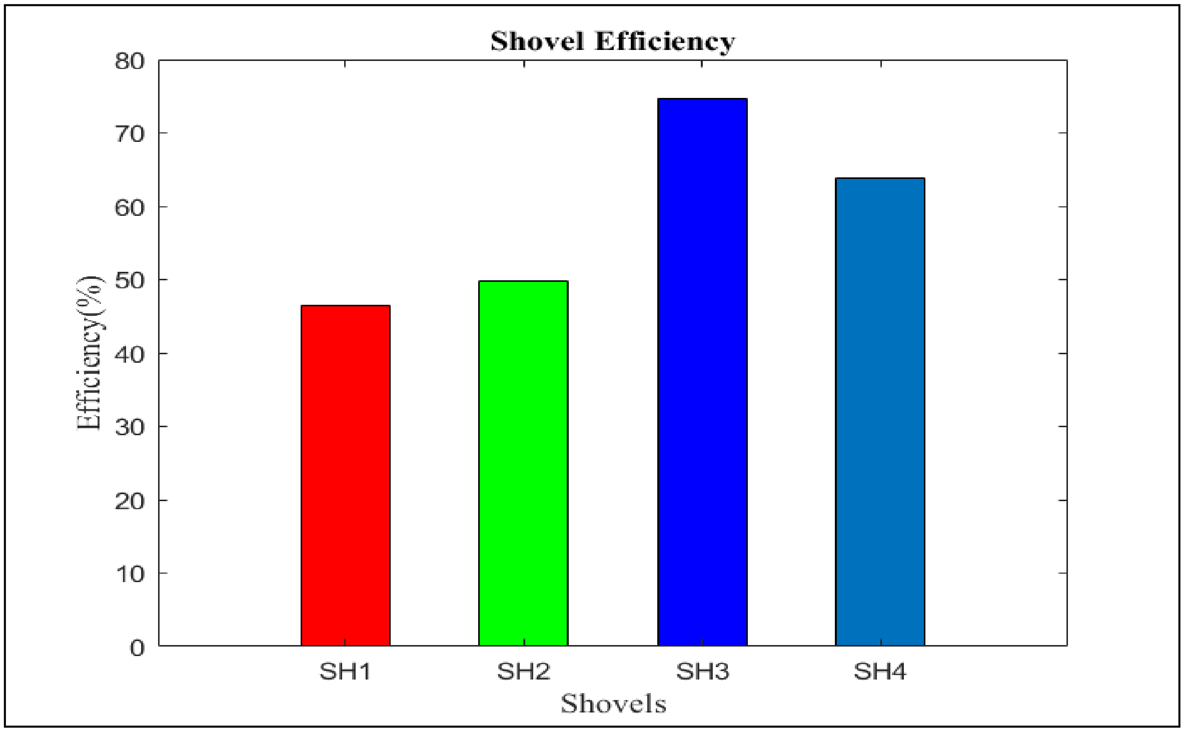

Figure 19. Average shovel efficiency across all periods.

The shovel efficiencies are displayed in Figure 19. The waste shovel efficiency is low compared to ore shovels for the same reason explained in scenario 1. A comparison of shovel efficiencies between the scenarios is shown in Figure 20. The difference in shovel efficiency between scenarios is negligible. Shovels 2 and 4 exhibit slightly higher (3%) efficiency in scenario 2. But shovels 1 and 3 display lower efficiency (2%) in scenario 2 than scenario 1.

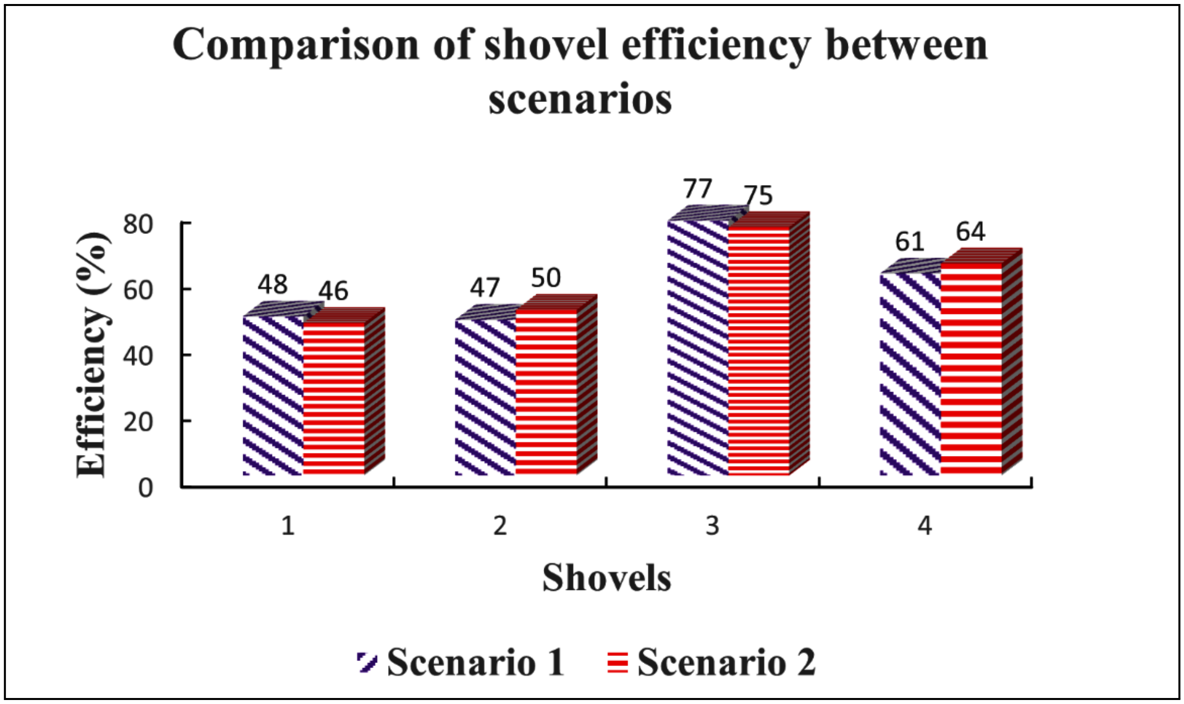

Figure 20. Shovel efficiency comparison between scenarios.

The truck requirement for ore (CAT 785C) and waste (CAT 793C) transportation for this scenario are 9 and 6 respectively for 65% efficiency. The waste truck requirement does not change as the waste transportation method does not change across the scenarios. A comparison of the required number of ore trucks between the scenarios is shown in Figure 21.

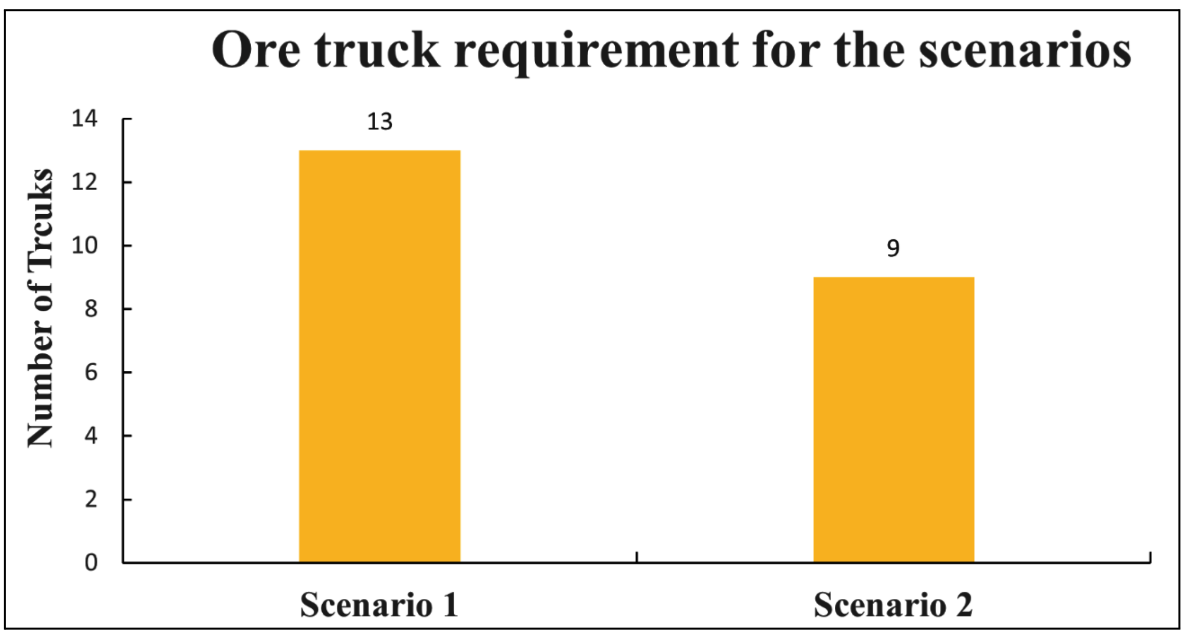

Figure 21. Ore truck requirement for scenarios without IPCC and with IPCC.

Figure 22 shows the optimal objective function values for both the scenarios. The objective function value is $14M higher for scenario 2 with IPCC, which justifies the use of IPCC in the mine in year 11. Although the total production is slightly lower for scenario 2, the mill requirement is fulfilled and the difference in production compared to scenario 1 is insignificant.

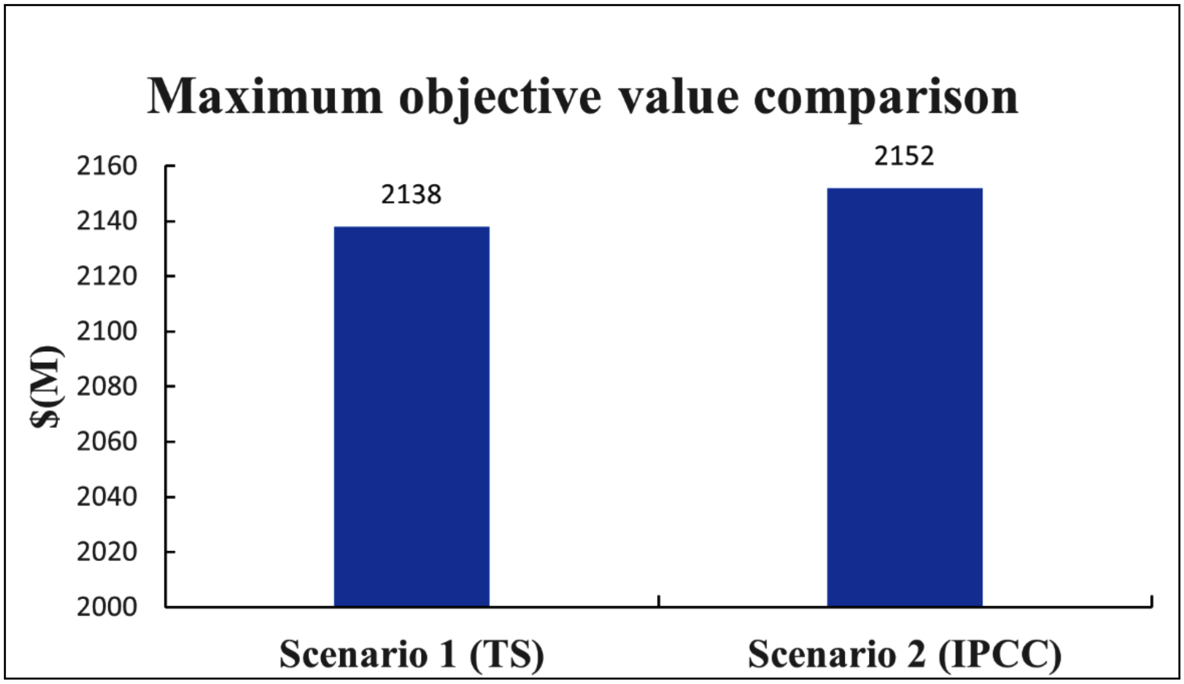

Figure 22. Comparison of (revenue - cost) between scenario 1 and scenario 2.

6. Conclusions and Future Work

The proposed shovel allocation model shows an approach to select a better haulage option for mines and a unique approach towards short-term planning with IPCC. The results show that the scenario with IPCC, scenario 2, generates 0.66% higher profit compared to the scenario with no IPCC, scenario 1. The truck requirement in scenario 2 is also 30% lower than scenario 1. Since both scenarios have been able to meet the long-term production target for year 11, introduction of IPCC in year 11 is justified in the mine in terms of haulage cost saving and revenue generation.

While the model performs well in the case study shown, the model has the following discrepancies.

The model allocates shovels without considering ore blending requirements.

The model does not consider shovel movement cost and constraint shovel movements between benches. This is the reason why in several periods, shovels move to a new face in a different bench after mining a face. This is acceptable in this scenario with two consecutive benches. But for cases with more than two non-consecutive benches, this issue needs to be addressed.

The model does not consider the capital investment required for IPCC installation.

The model cannot consider any operational uncertainty in its current state.

Constraining the model with blending requirements and shovel movement between benches by minimizing shovel movement costs will generate more realistic shovel allocations. Combining the model with a haulage simulation model will enable it to capture uncertainties associated with haulage operations. These modifications in future will make the model more pragmatic and provide a more comprehensive tool for short term production planning and analysis purposes.

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