Short-term Planning of Open Pit Mines with Semi-Mobile IPCC: A Shovel Allocation Model[1]

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ABSTRACT

In-pit crushing and conveying (IPCC) is considered a suitable alternative to truck haulage in open pit mines because it offers a lower operating cost than a truck-shovel system. It also reduces truck haulage distance and truck requirements. One of the IPCC variations is the semi-mobile system, which is relocated every two to five years. The short-term plan needs to be updated accordingly, based on the crusher's optimal location and relocation time. 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 schedules considering an IPCC in place. This research work proposes a mixed integer programming model to generate short-term production plans and near-optimal shovel allocation to mining faces, within a time horizon of 12 months. The objective of the model is to minimize the cost of material handling and maximize revenue, with respect to plant requirement, maximum allowable tonnage variation and IPCC location constraints, and the production and NPV targets set by the strategic plan. An iron ore mine case including a semi-mobile IPCC system with one relocation is used as the case study to verify the proposed model. The comparison of results between scenarios with and without IPCC justifies the use of IPCC in the iron ore mine from a short to medium-term perspective. The project can be considered a pioneering work in the arena of short-term mine planning with the IPCC.

Keywords: IPCC, optimization, haulage

1. Introduction

This paper proposes a short-term planning methodology by near-optimal shovel allocation in the presence of IPCC or traditional truck-shovel haulage. It is a general short-term planning model that is applicable to all types of open pit mines. The most significant contribution of this research is the generation of short-term mining sequences with IPCC as the major means of transportation. The model takes into account the revenue earned from selling ore along with the cost of production and haulage from a short to medium-term perspective. Most of the existing short-term planning models focus on cost minimization without focusing on profit maximization. The biggest challenge to optimizing shovel allocation by profit maximization is the contradictory nature of the objective

[1] This paper is under review for publication in the International Journal of Mining, Environment and Reclamation

ISBN: 978-1-55195-503-2

function, which requires simultaneous maximization of revenue and minimization of cost by meeting production targets. The number of variables increases exponentially with an increase in the number of benches and mining faces. Solving the model to develop short-term mining sequences within a reasonable time has also been a substantial challenge in this research.

Mining is a highly capital-intensive operation and proper production planning is required to avoid the sub-optimality of the overall setup, including all the equipment utilization. The primary objective of any mining project is to maximize the net present value (NPV) by keeping the cost at a minimum. Mine planning can be divided into long-term and short-term planning based on the planning time horizon and the objectives being optimized. While the long-term plan is created at the strategic level to maximize the NPV throughout the life of mine, the short-term planning aims at optimizing the operational activities like shovel allocation, grade blending to meet head grade requirements at the plant, 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.

Optimal utilization of the equipment used in mining operations is of vital importance because the haulage costs may account for over 50% of the total operating cost in a truck-shovel operation (Moradi Afrapoli and Askari-Nasab 2017). The optimal utilization of the equipment can only be achieved by efficient utilization of all the assets involved, to meet the production targets set by the long-term production plan. Therefore, optimal allocation of assets such as shovels and trucks as part of the short-term production scheduling is of utmost importance.

Mied 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 popularize the use of 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 (shifts, 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) was an is an innovative mine management system. The suggested approach combines various mathematical models to determine the ultimate pit limit in the long-term and medium-term block sequencing, while also optimizing equipment planning with a job-shop scheduling model to enhance mining efficiency. Overall, this methodology aims to improve mining efficiency by integrating various planning and scheduling models. Blom, et al. (2017) proposed a MIP model for generating multiple short-term production schedules that optimize equipment and shovel use while taking into account constraints such as blending requirements, equipment availability, trucking hours, and precedence relationships among tasks. The model uses a rolling planning horizon approach and considers 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) developed an MIP-based short-term planning model that incorporates simulation to enable proactive decision-making in the dynamic mining environment. The model synchronizes operational plans with long-term planning to minimize opportunity costs, optimize production, and enhance 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 actual execution for underground mining operation. The framework generates an initial schedule using a MILP model embedded in UDESS, a software implemented via Python and can be used through scripts or graphical interface. The model is then simulated using any discrete event simulation (DES) software to replicate the schedule and estimate equipment utilization. . The authors claim the model to be general and applicable to open pit mining as well. Gong, et al. (2023a) formulated an integrated simulation-optimization approach for short-term planning with a new conceptual mining method called the near-face stockpile (NFS), which combines the in-pit crushing and conveying IPCC system with a pre-crusher stockpile. The simulation results revealed a 5% improvement in overall production for an oil sands mine case study.

The short-term planning models discussed so far are all designed to generate schedules assuming truck-shovel haulage system. A close look at the IPCC literature shows that many of the research works focus on optimizing the crusher location. Examples are Konak, et al. (2007), Taheri, et al. (2009), Rahmanpour, et al. (2013), Paricheh, et al. (2016), Paricheh (2017), Paricheh and Osanloo (2019b) etc. All these studies present methodologies to find the optimum crusher location, candidate crusher locations and/or optimum relocation time of crusher, assuming that the long-term plan was generated considering IPCC.

The life cycle assessment studies like Norgate and Haque (2013), Awuah-Offei and Askari-Nasab (2009), Erkayaoğlu and Demirel (2016), Fuming, et al. (2015) present comparisons between IPCC and truck haulage system or among different IPCC systems in terms of environmental sustainability. The results of these studies are highly case specific and varies substantially based on the geological location of the mine and types of trucks and IPCC systems used. However, most of these life cycle assessment studies identify IPCC as the more environmentally sustainable haulage option over trucks.

While there are studies, such as, Paricheh and Osanloo (2019a), Samavati, et al. (2020), Shamsi, et al. (2022), Liu and Pourrahimian (2021), Gong, et al. (2023b) etc., that justify the use of in-pit crushing in long-term by simultaneous optimization of IPCC location and long-term plan, to the best of our knowledge, except there is hardly any research work that does the same in operational or short-term level. Haulage is one of the largest sources of expense in any open pit mining operation. Several fleet optimization models, such as, (Mirzaei-Nasirabad, et al. 2023; Moradi Afrapoli, et al. 2019a; Moradi Afrapoli and Askari Nasab 2020; Moradi Afrapoli, et al. 2019b; Moradi Afrapoli, et al. 2022) have been formulated to minimize the cost of the truck fleet in open-pit mining operations. IPCC has the potential to reduce this cost and in turn maximize the profit. Hence it is crucial to explore the effects of IPCC on short-term planning of open pit mines. 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 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 be synced with the long-term plan to deliver the desired NPV of the mine in presence of 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 has been 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 within a time horizon of one year. This research can be marked as one of the pioneering works on short-term planning of open pit mines with IPCC.

2. Problem Definition

This research study aims to demonstrate the effects of IPCC installation on short-term planning by generating near-optimal schedules. The proposed model is intended to be used as a tool to compare IPCC and truck haulage systems to identify the better haulage options for a specific year of mine life.

The proposed short-term planning methodology optimally allocates shovels to the mining faces, which are an aggregation of blocks to reduce the number of variables, meet production requirements, reduce the cost of haulage and maximize the revenue per period. 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 with traditional truck haulage, and compare the results to find out the overall revenue generated and haulage cost incurred in each scenario. The difference in scheduling or extraction sequence based on shovel allocation will also be highlighted to demonstrate how IPCC installation affects the mine plan from an operational viewpoint. Comparing results should enable mine planners to decide on the better option haulage for cost saving and higher revenues earned for a specific year of mine life.

The model's objectives include:

1. Maximizing revenue earned by ore material per period.
2. Meeting production requirements to feed the mill to its capacity.
3. Minimizing ore haulage cost.

The model's development, implementation and verification to compare schedules with semi-mobile IPCC and traditional truck-shovel haulage systems will be shown in section 3.

2.1. Scope and Assumptions of the Model

The proposed model provides a tool to generate and compare short-term schedules for open pit mines. The developed MILP is a general allocation model that can generate schedules for truck-shovel haulage and IPCC systems. For shovel allocation, the model considers both haulage cost minimization and revenue maximization per period, unlike the models proposed by Upadhyay and Askari-Nasab (2016), Upadhyay and Askari-Nasab (2017) and Manríquez, et al. (2020), where the revenue component was missed. The proposed model can be integrated with haulage simulation models to account for operational uncertainty and can be extended to find the optimal number of trucks required in a specific period of mine life. The model is developed based on the following assumptions:

1. The IPCC system is semi-mobile and only used for ore crushing and conveying.
2. The optimum locations and relocation time of the crusher are known throughout the life of mine from the strategic mine plan.
3. The ore and waste faces are known from long-term plans. Hence, ore material will go to the mill or crusher, and waste material will go to the waste dump.
4. Ore shovels are locked to ore faces, and waste shovels are locked to waste faces.
5. There is no stockpiling.
6. The model does not consider ore blending in its current state of the art.

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 this section.

3.1. Objective Function

The objective of the model is to maximize the total profit generated by the mined material. The objective function consists of five components. The first component calculates the mining cost of the material. The second and third components calculate the cost of hauling ore material to the crusher or mill and the waste material to the waste dumps using diesel trucks. The fourth part calculates the cost of conveying ore material from the crusher to the processing plant. The last component calculates the difference between the revenues earned from and the processing cost of ore. The flow of ore and waste material from source to destination is displayed in Figure 1. The materials are mined from the mining faces by shovels and then loaded onto trucks. The waste material is transported to the waste dumps by the waste trucks. The ore material will be hauled by the ore trucks to the in-pit crusher from mining faces, then conveyed to the plant in the scenario with IPCC. In the scenario without IPCC, the ore material will be hauled by trucks from the pit to the plant crusher.

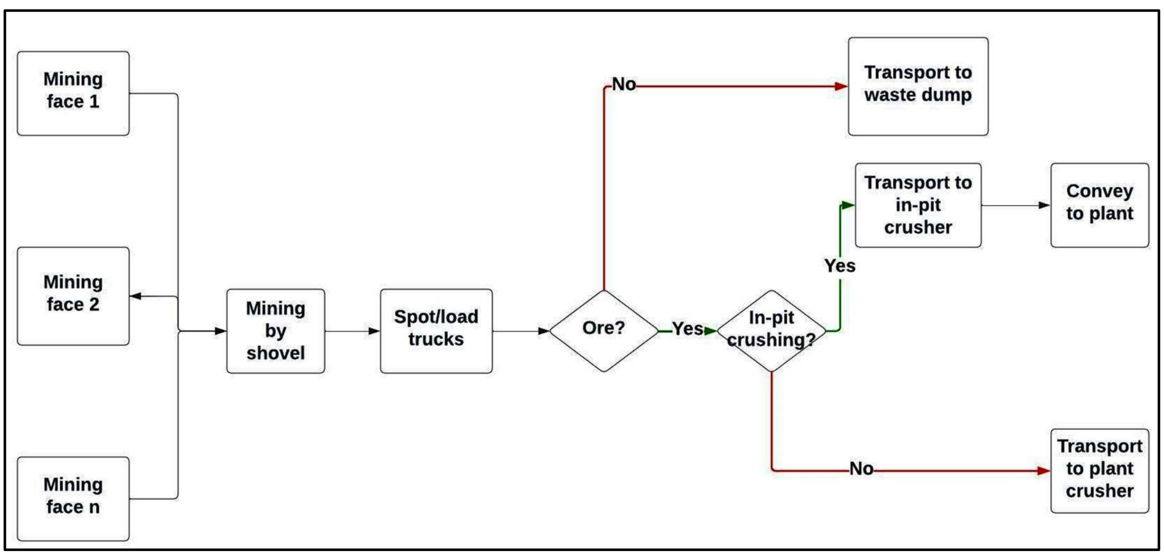

Figure 1: Flow of material from mine to crusher, plant and waste dump.

The objective function is defined as the minimization of the cost of transporting material to the crusher or waste dump from the mine by trucks, plus the cost of conveying ore material from the crusher to the processing plant, minus the profit earned from selling ore. Mathematically, the objective function can be represented as Equation:

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

$$RM_{p,f} \times TT \times C \times H_c - \sum_{p\in P,t\in T,f\in F_{ore}} x_{p,f,t} \times RM_{p,f} \times TT \times (R_k - PR_c) \tag{1}$$

Where the variables, parameters and indexes are,

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

Parameter	**Unit**	**Description**
TT	hr	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
SR	-	Stripping ratio
$D_{f,r}$	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
R_k	\$/tonne	Iron ore price

M_c	\$/tonne	Mining cost per unit
PR_c	\$/tonne	Processing cost per unit
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

4. Constraints

$$\sum_{p \in P} s_{p,f,t} \leq 1; \forall f \in F, \forall t \in T \tag{2}$$

$$\sum_{f \in F} s_{p,f,t} \leq 2; \forall p \in P, \forall t \in T \tag{3}$$

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

$$\sum_{p \in P, f \epsilon F_{waste}} x_{p,f,t} \times RM_{p,f} \times TT >= SR \times TC; \forall t \in T \tag{5}$$

$$l_{f,t} = TM_f;\ \forall f \in F \ \&\ t = 1 \tag{6}$$

$$l_{f,t+1} = l_{f,t} - \sum_{p \in P} x_{p,f,t} \times RM_{p,f} \times TT;\ \forall f \in F \ \&\ t = 1 \ldots T-1 \tag{7}$$

$$\mathrm{M} \times m_{f,t} <= \text{epsilon} - l_{f,t} \quad ; \forall f \in F, t \in T \tag{8}$$

$$\mathrm{M} \times (1 - m_{f,t}) >= -\text{epsilon} + l_{f,t}\ ;\ ; \forall f \in F, t \in T \tag{9}$$

$$m_{f,t+1} \geq m_{f,t}\ ;\ ; \forall f \in F, t \in 1 \ldots T-1 \tag{10}$$

$$\sum_{f \in F} s_{p,f,t} \leq s_{p,f,t} + m_{f,t} + \left(1 - s_{p,f,t-1}\right) + \left(1 - s_{p,f,t}\right) \times \mathrm{BM}\ ; \forall f \in F, p \in P, t \in T \tag{11}$$

$$s_{p,f,t+1} \geq s_{p,f,t} - m_{f,t};\ ; \forall f \in F, p \in P, t \in 1 \ldots T-1 \tag{12}$$

$$s_{p,f,t} \geq c_{f,t} \times BM\ ;\ ; \forall f \in F, p \in P, t \in T \tag{13}$$

$$\sum_{p \in P, t \epsilon T} x_{p,f,t} \times RM_{p,f} \times TT \leq TM_f; \forall f \in F \tag{14}$$

$$N^f \times \sum_p s_{p,f,t} - \sum_{f'} m_{f',t} \leq 0; \;\forall f \in F, p \in P, f' \in precednece\ set \quad (15)$$

$$\sum_{f \in F} x_{p,f,t} \leq AV_{p,t}; p \in P, t \in T \quad (16)$$

Equation 2 ensures that only one shovel can be assigned to a face in a specific period. Every shovel is allowed to be allocated to 2 faces at any given time of a period by equation 2. This constraint enables the shovels to move to a new face whenever the working face is mined out. Equation 3, combined with Equation 10, ensures that a shovel can always move to the next face in a period if a face is mined out.

Equation 4 puts an upper limit on ore material extraction in a period. It guarantees that the ore extraction does not exceed the mill capacity in a period. The model naturally tries to maximize ore production as it aims to maximize revenues earned per period. Hence, the upper limit is set on ore production so it does not overproduce, as we are not considering stockpiling now. Equation 5, however, sets a lower limit on the total waste material to be mined in each period. The model tries to minimize waste mining as waste material increases haulage costs and does not contribute to revenue. Therefore, this constraint ensures that the tonnage of waste mined in a period is at least such that the total available waste material is mined out at the end of the 12 periods. Changing the value of the stripping ratio will increase or decrease the tonnage of waste mined. Hence, this constraint guarantees that the model applies to other case studies with more benches and available material to be mined.

The total tonnage of each face TM_f is assigned to the $l_{f,t}$variable in the initial period by equation 6. Equation 7 keeps track of the remaining tonnage of each face at the end of a period. This constraint lets the model know when a face is mined out so that it can update the variable $m_{f,t}$, which is controlled by Equations 8 and 9 and becomes 1 when $l_{f,t}$becomes very small. Therefore, the $m_{f,t}$ variable is used to keep track of the mined-out faces.

Equation 10 takes care of the fact that if a face has been mined out, it stays mined out in the next periods so that the model does not allocate any shovels to that face in future. Equation 11 strengthens equation 2 by controlling when a shovel can be assigned to more than one face in a period. The right-hand side of this constraint 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 allocated 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 the 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, the constraint will still hold true and allow the shovel to be assigned to two more faces in that period.

Equation 12 forces a shovel to stay in the same face unless it is mined out so that the shovels do not make unnecessary movements from the working faces. Equation 13 is the IPCC location constraint. It does not let a shovel to be assigned to a face in a period if the crusher is located on that face during that period. The right-hand side of the constraint becomes zero for the scenario without IPCC in the mine and the model behaves like a traditional shovel allocation model for truck haulage.

Equation 14 ensures that the total material mined by all the shovels from a face across all the periods does not exceed the total material available in that face. Equation 15 is the precedence constraint. The precedence among faces are known from the long-term plan. This constraint ensures that a face f cannot be mined before the precedence faces (f’) are completely mined out. Equation 16 is the shovel availability constraint, which guarantees that the fraction of time a shovel works in several faces in a period does not exceed the shovel availability.

The model has been solved using a rolling-planning horizon technic to reduce the runtime. The model looks 3 months ahead while assigning the shovels to the faces. It assigns shovels to faces for the first three periods at first. Then it investigates the next three periods, assigns shovels to the available faces and so on. The periods are denoted by P in Figure 2 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 2. Optimization and decision time frame of the model.

5. Case Study

The case study presents two scenarios in an iron mine with IPCC and a traditional truck-shovel mining method to verify the model. The short-term schedule will be generated for the 11th year of mine life. Four benches at elevations 1595m, 1610m, 1730m and 1745m are available to be mined with a total 16MT (mega tonnes) of ore and 35MT of waste. There is only one mill to process the ore material. The in-pit or plant crusher requirement is 2700 tons per hour. The monthly crusher requirement is 1.33MT assuming 16 hours of operation in a day with 2 eight-hour shifts. The mine layout for the eleventh year is shown in Figure 3. 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.

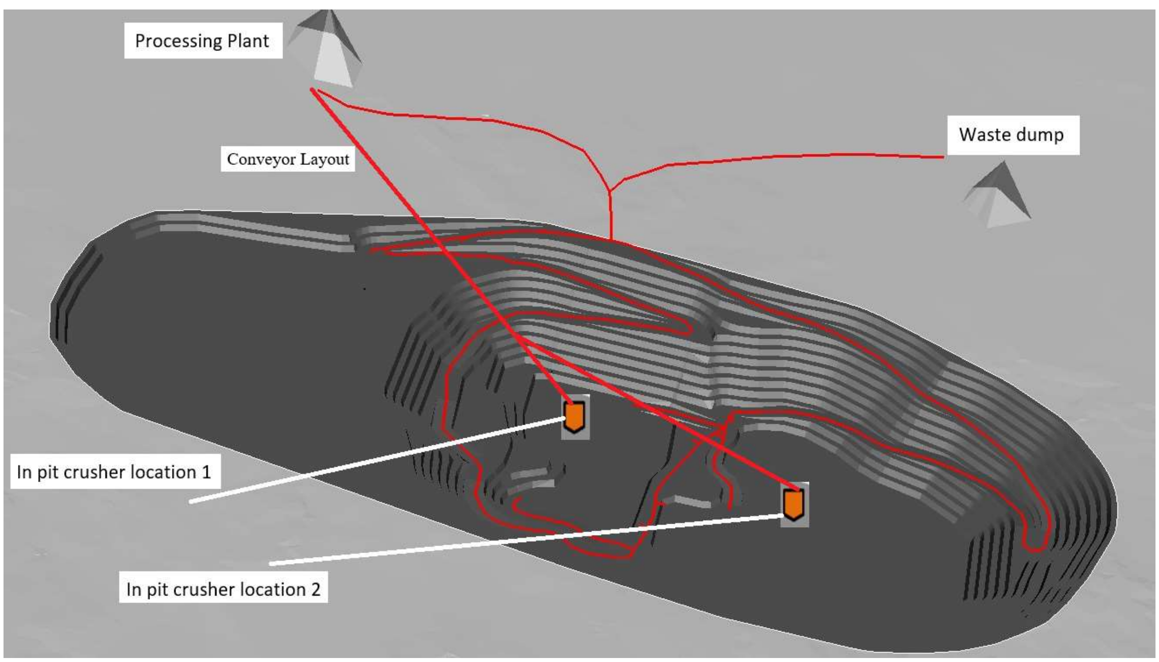

Figure 3. Pit layout with roads and ramps in year 11.

The element of interest in the mine is the magnetic weight recovery of iron (MWT). The grade and tonnage distribution of MWT in year 11 is presented in Figure 4.

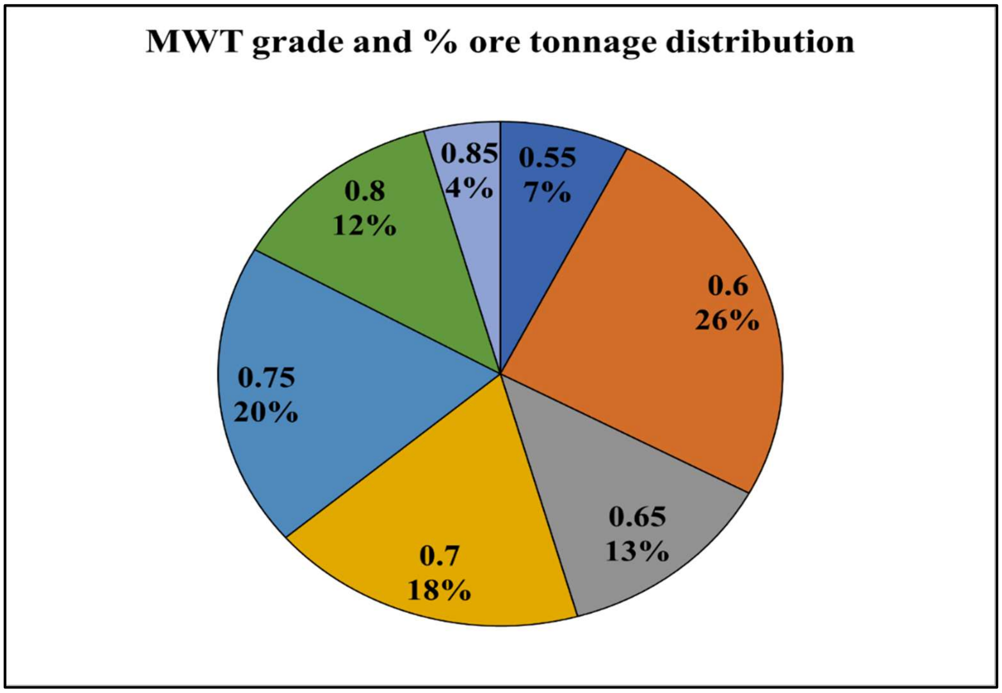

Figure 4. Grade and tonnage distribution of MWT.

A hierarchical clustering algorithm has been used (Tabesh and Askari-Nasab 2013) to aggregate similar blocks together to generate 170 mining faces (polygons) out of 4200 blocks to be mined in year 11 within the four available benches. A more advanced clustering algorithm by Tabesh and Askari-Nasab (2019) has not been used in this paper as geological uncertainty of the material is not part of this model in its current state of the art.The clustered ore and waste faces on 1595 and 1610 benches are shown in the Figure 5 and Figure 6 for illustration purposes. The other two benches contain waste faces only. The numbers in the figures represent the face IDs on the benches.

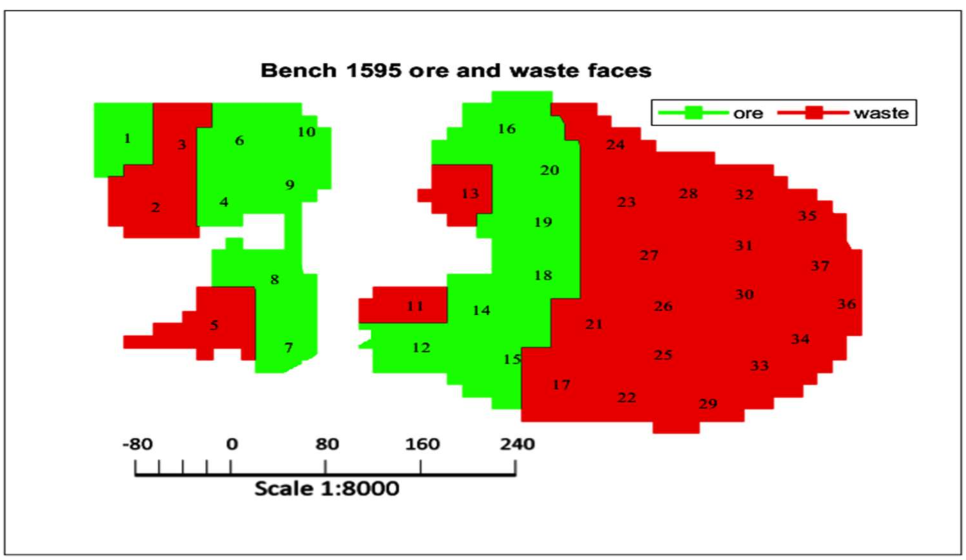

Figure 5. Clustered faces on bench 1595.

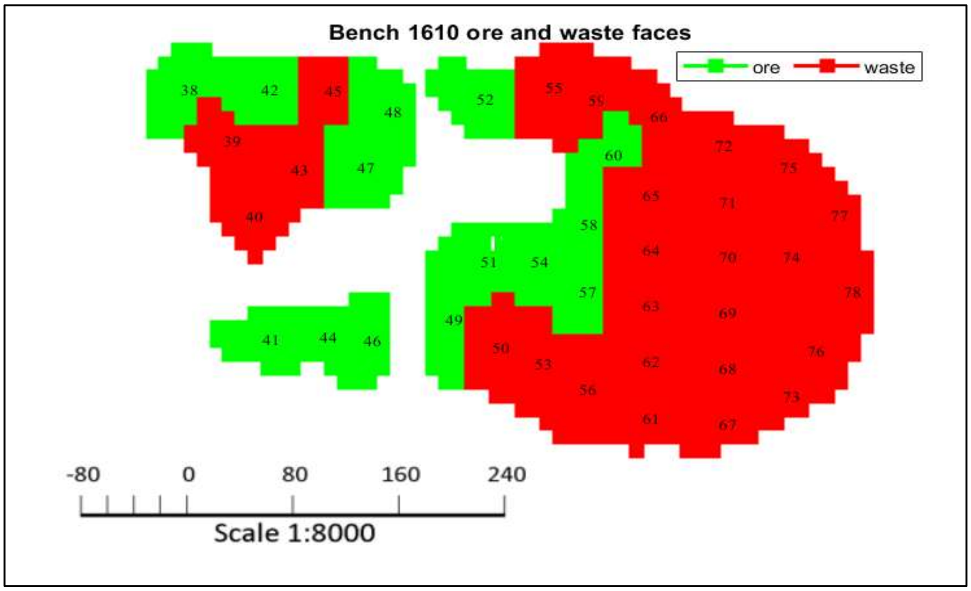

Figure 6. Clustered faces on bench 1610.

The mine employs five shovels, including two Hit 2500 shovels (shovel indexes 1 and 2) specifically for ore and three Hit 5500Ex shovels (shovel indexes 3, 4 and 5) only for waste mining. The Hit 2500 shovels have a bucket capacity of approximately 12 tons and a bucket cycle time of about 22 seconds, whereas Hit 5500Ex shovels have a bucket capacity of roughly 22 tons and a bucket cycle time of about 23 seconds.

The mine employs Cat 785C and Cat793C trucks with nominal capacities of 140 tons and 240 tons, respectively, to haul the material mined from the faces. Cat 785C trucks are locked to ore shovels, and thus, they may be loaded only by Hit 2500 shovels, whereas Hit 5500Ex shovels can only load Cat 793C trucks. The truck requirement for both scenarios are calculated and compared to investigate the change in fleet size requirement.

6. 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. The model runs for twelve months in four steps where it allocates shovels to faces for three months, saves the results and then looks 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 219 seconds to run, and the IPCC scenario (scenario 2) took 237 seconds in a Dell XPS machine with 16 GB RAM. The optimality gaps in both cases are less than 0.5%. The problem has 24,480 variables, and the rolling planning horizon reduced the computational expense substantially. A comparison of the solution quality and computation time among the global solution approach and several rolling planning time horizon solution technics used is shown in Table 1.

Table 1: Comparison of solution quality and computation time.

Solution Approach	Scenario 1		Scenario 2	
	Solution time	Optimality gap	Solution time	Optimality gap (per rolling horizon)
Global Solution	20 hours	8.35%	20 hours	7%

approach				
Rolling time horizon of 6 months	700 sec	3%	759 sec	2.8%
Rolling time horizon of 4 months	319 sec	1.1%	350 sec	1.05%
Rolling time horizon of 3 months	219 sec	0.44%	237 sec	0.5%

The computational time to find an optimal or near-optimal schedule is crucial for short-term mine planning as it is dynamic. The reduction of computing time from 20 hours to only 240 seconds makes the model usable for an actual mining operation. The optimality gap also reduces significantly when each scenario's solution space is compressed. A comparison of the optimal results and generated schedules are presented in the following sections.

7. Scenario 1 (No IPCC)

This scenario represents a conventional truck-shovel (TS) mining operation where trucks haul the mined material to the plant crusher and waste dump. Pragmatic and near-optimal shovel assignment to the faces is the model's primary goal. Shovel positions and the working periods 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 and maintenance. The optimal objective function value for this scenario is \$1957M. Figure 7, Figure 8, Figure 9 and Figure 10 display the mining periods for bench 1595, 1610, 1730 and 1745 respectively. Here p1 to p12 denote the twelve periods in the time horizon.

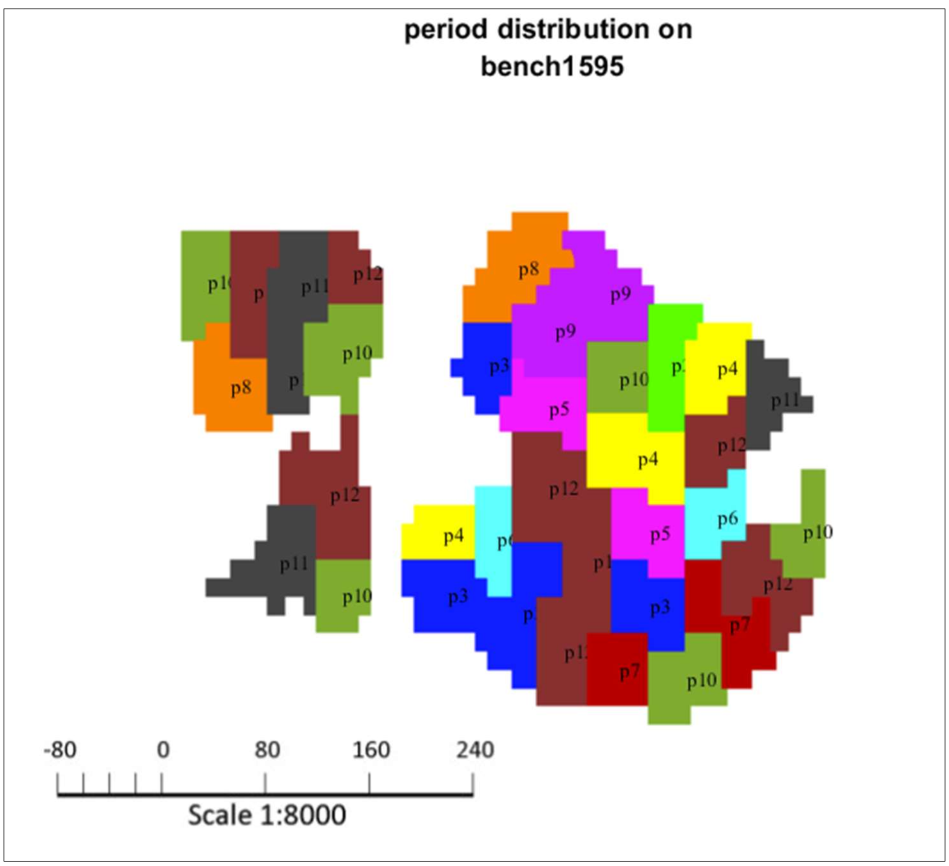

Figure 7. Mining periods of faces on bench 1595.

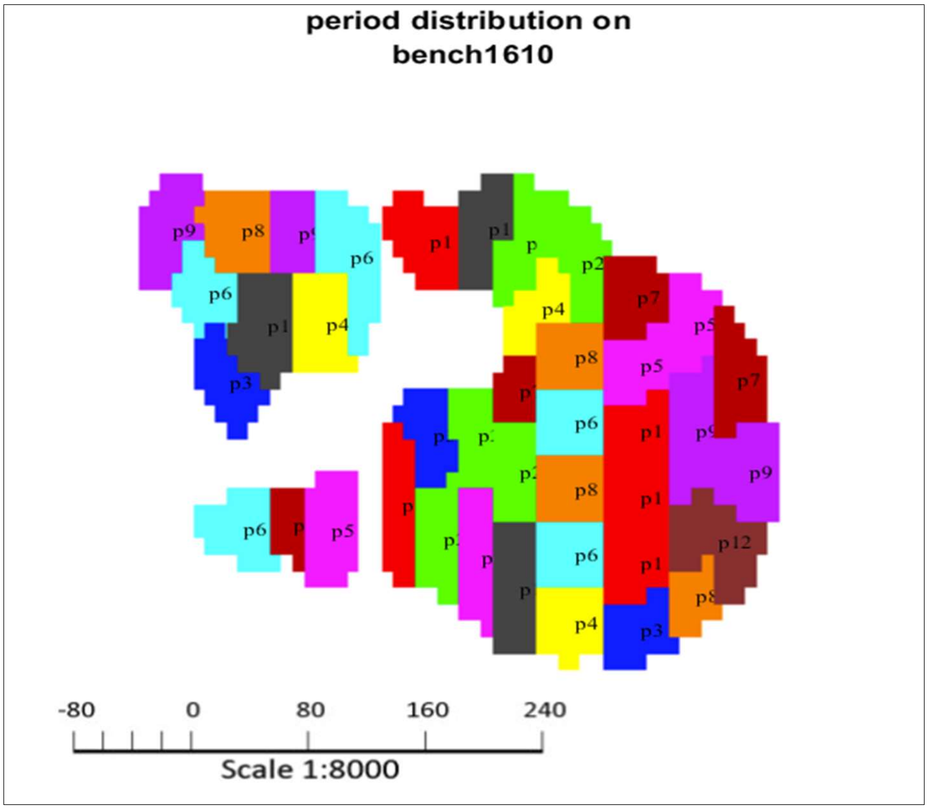

Figure 8. Mining period of faces on bench 1610.

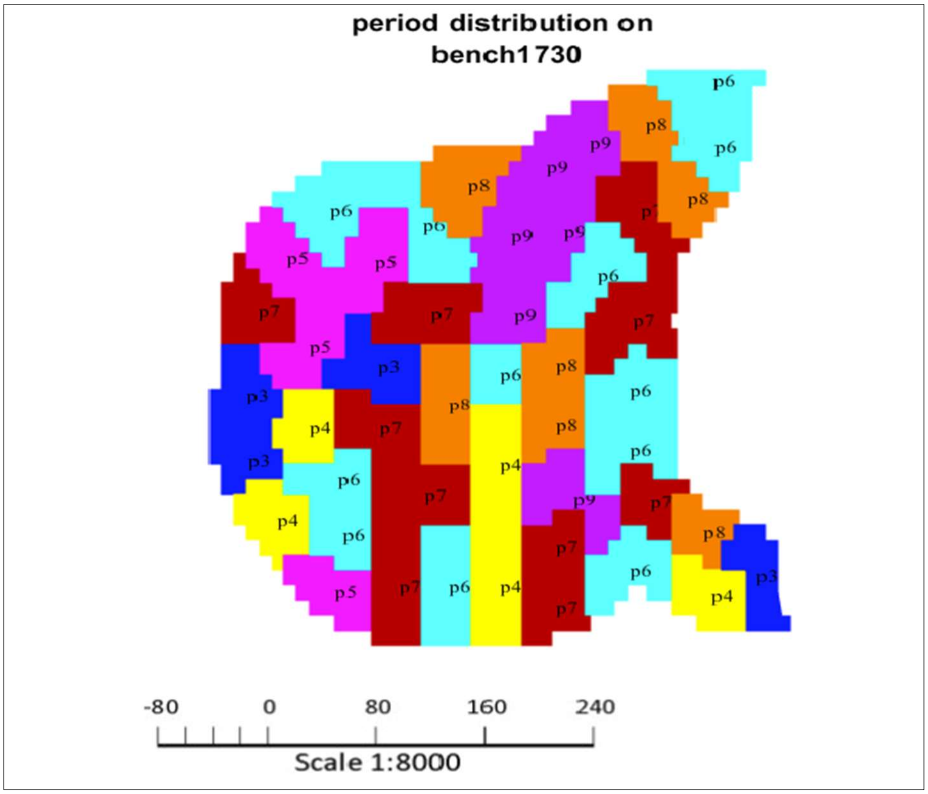

Figure 9. Mining period of faces on bench 1730.

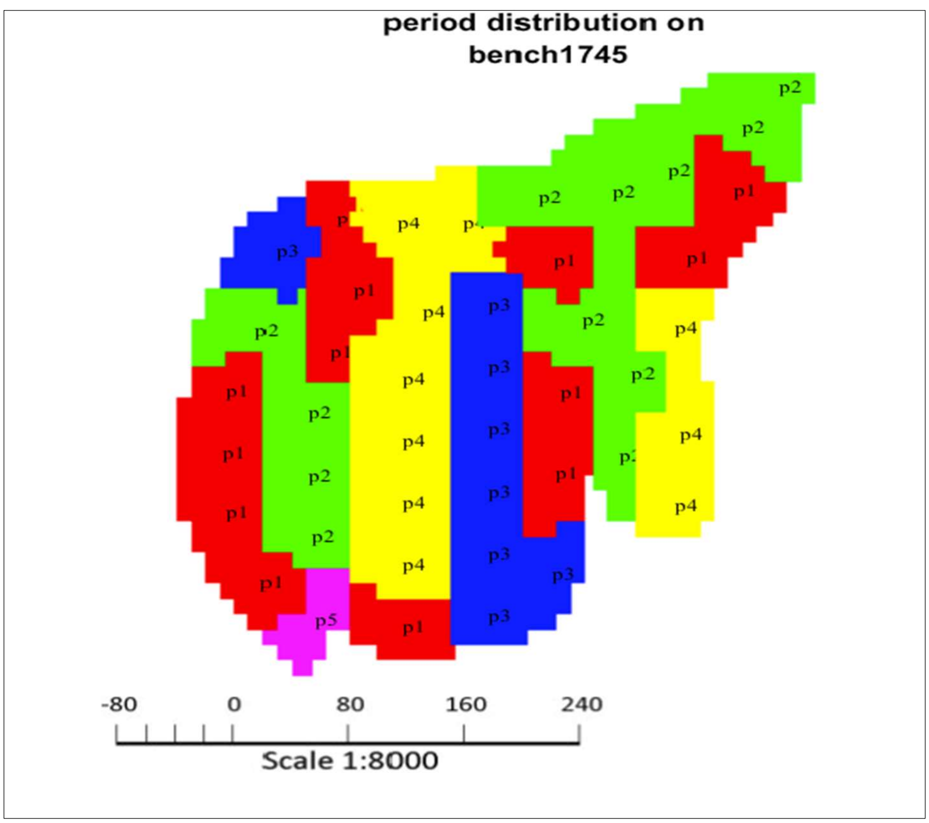

Figure 10. Mining period of faces on bench 1745.

The top bench on 1745 m is mined within the first five periods. The next bench on 1730m elevation is being mined within period 3 and period 9. Both these benches are waste benches and mining on bench 1730 starts from a later period than bench 1745 because of the precedence relationships that exist among several faces of these two benches. The model assigns shovels to ore bench 1610 from period 1 but mining starts at bench 1595 from period 2 because of the vertical precedences that exist between these two benches. Generally, the waste faces are mined in the earlier periods than ore faces for both benches at 1595m and 1610m elevation because the waste faces precede the ore faces in many of the cases.

The following Figure 11, Figure 12, Figure 13, and Figure 14 demonstrate the shovel assignment to the four benches at 1595m, 1610m, 1730m and 1745m respectively. The five shovels are indicated by s1 to s5 in the figures.

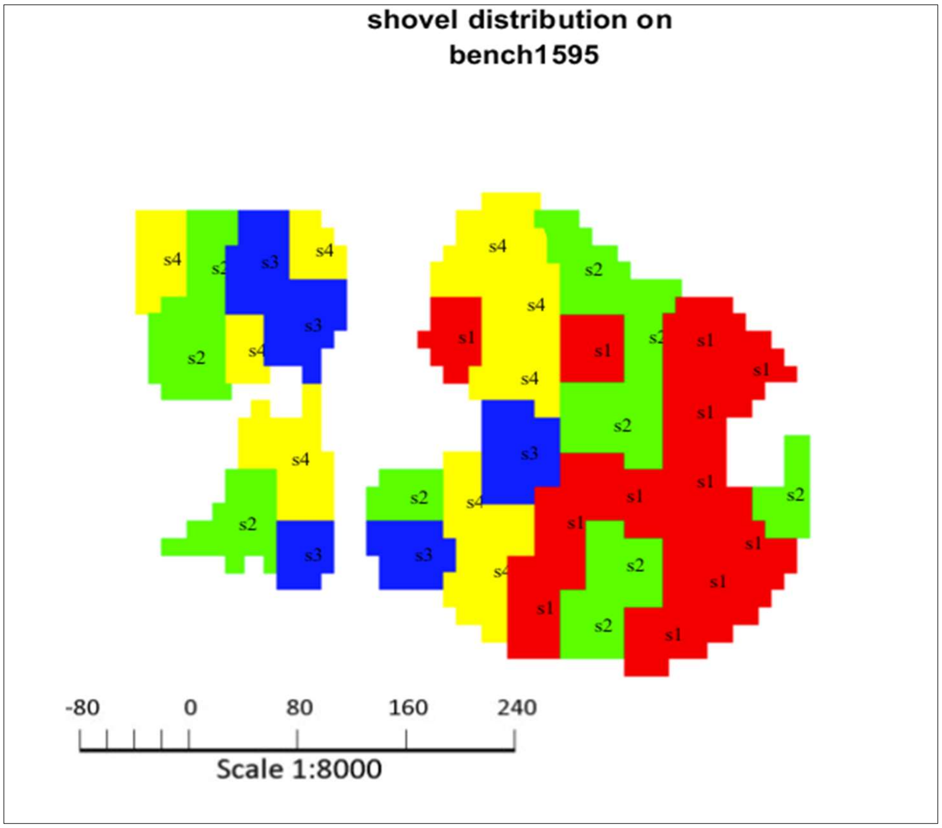

Figure 11. Shovel allocation on bench 1595.

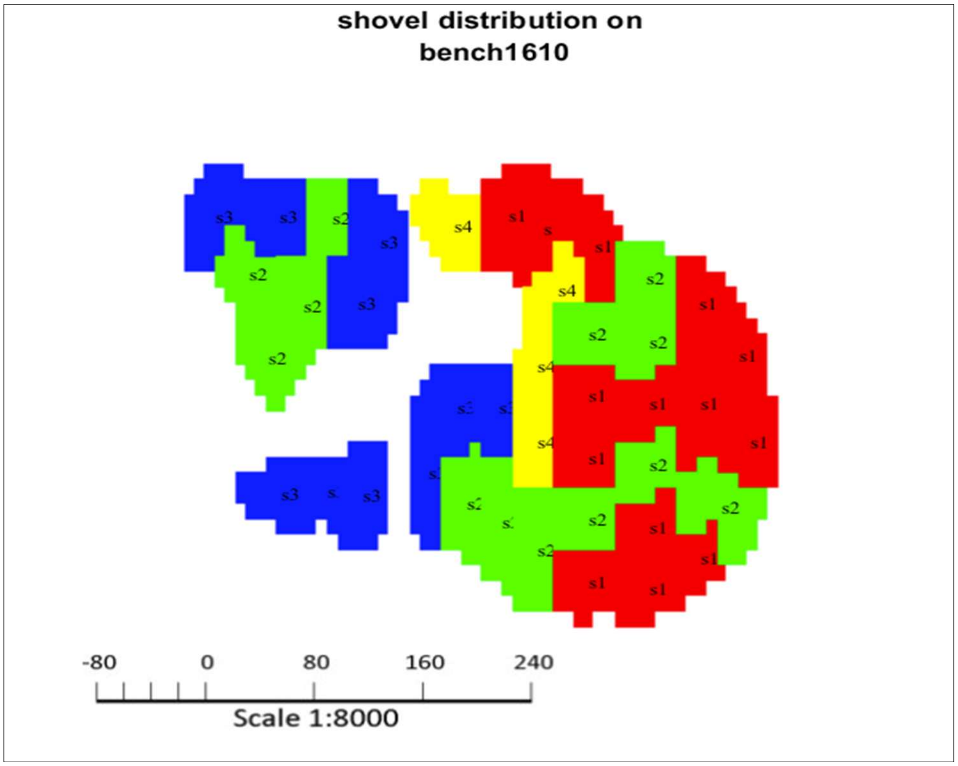

Figure 12. Shovel allocation on bench 1610.

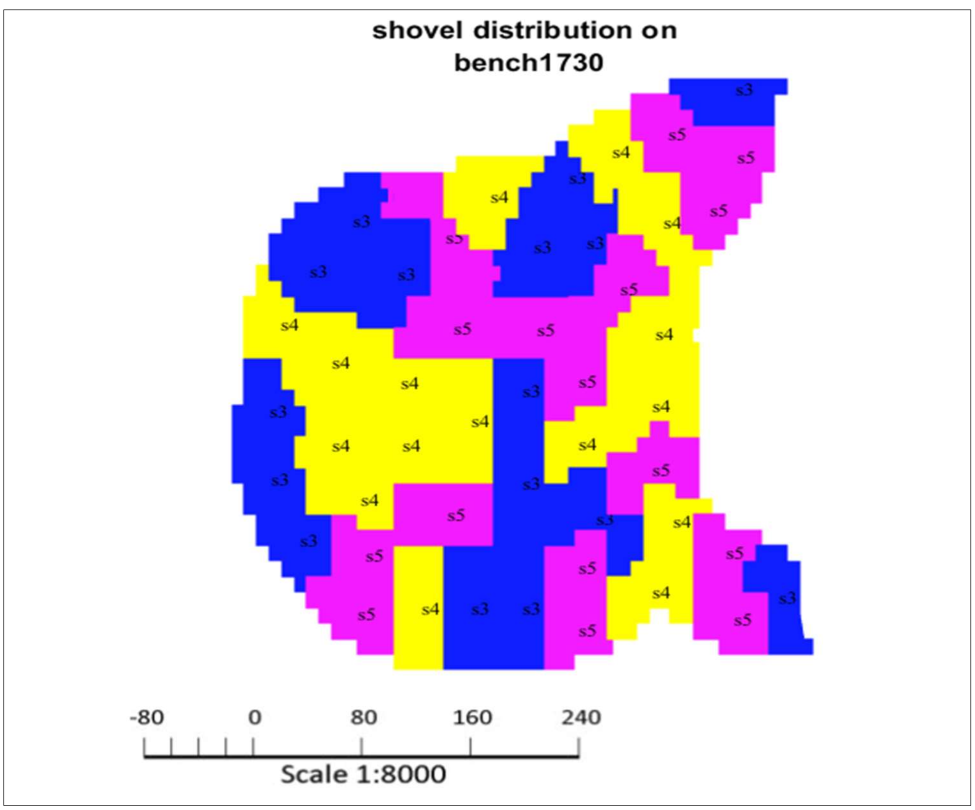

Figure 13. Shovel allocation on bench 1730.

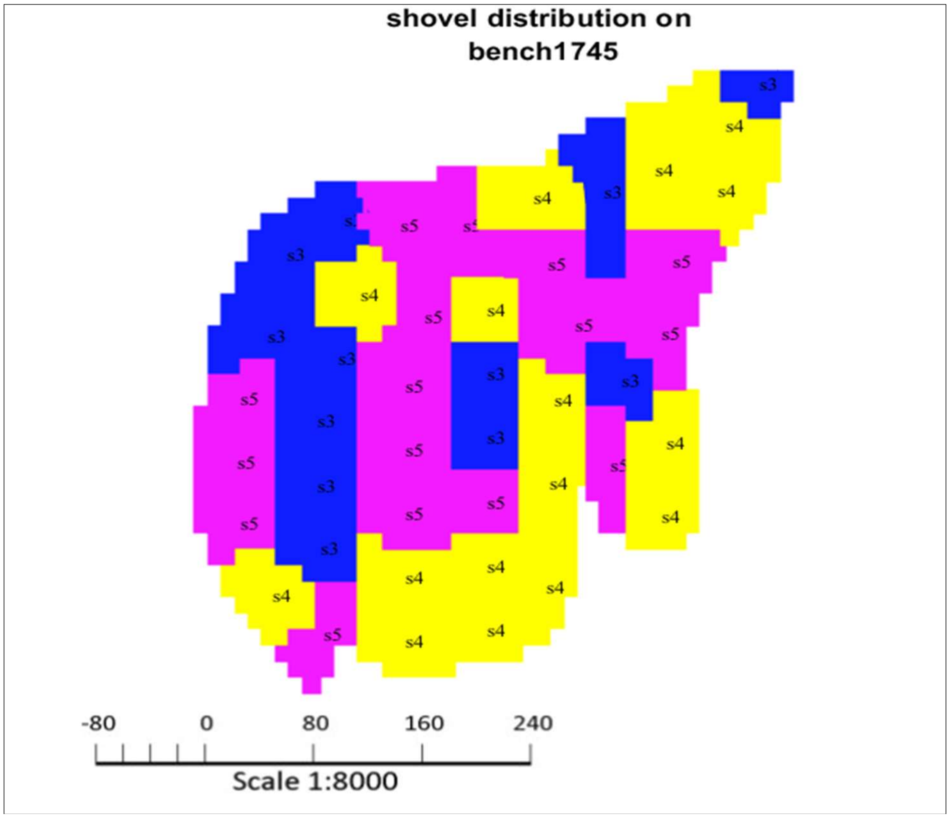

Figure 14. Shovel allocation on bench 1745.

Shovel 5 works solely on the two waste benches at 1730m and 1745m along with shovel 3 and shovel 4. Shovel 3 and shovel 4 also mine the waste faces on the bottom two benches at 1610m and 1595m elevation. Shovel 1 and shovel 2 are ore shovels. Hence these two shovels work only on the bottom two ore benches at elevations 1610m and 1595m. The shovels do not look for the nearest faces for next assignment after a face is mined out because the model does not minimize shovel movement costs or movement time in its current state. 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 target of the strategic plan is met.

Figure 15 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 slight variation of less than 1.5% across the planning horizon.

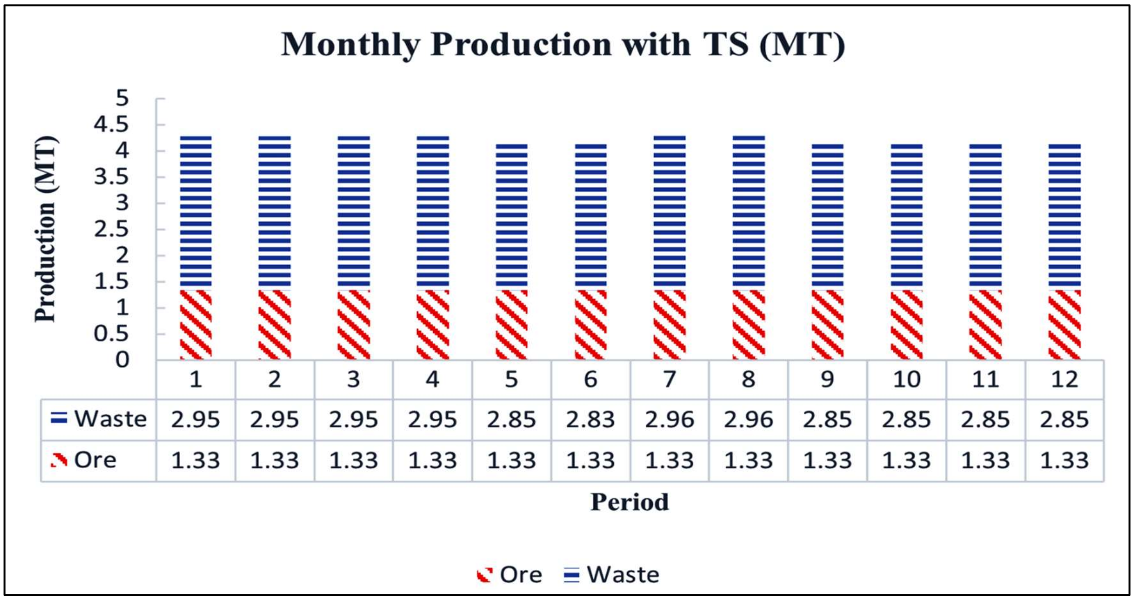

Figure 15. Monthly ore and waste production for scenario 1.

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,

$$N_h = \frac{P_h \times TC_{ch}}{60 \times L_h \times E} \tag{17}$$

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 11 respectively assuming a 65% efficiency.

8. Scenario 2 (IPCC)

This scenario assumes an 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 crusher is located on face 3 over the first six months and face 18 for the rest of the periods. Equation 12 prevents mining of the faces that house the crusher for the IPCC scenario. The optimal objective value is $1969M. Figure 16, **Error! Reference source not found.**, Figure 18 and Figure 19 display the resulting mining periods of the faces for bench 1595, 1610, 1730 and 1745 respectively.

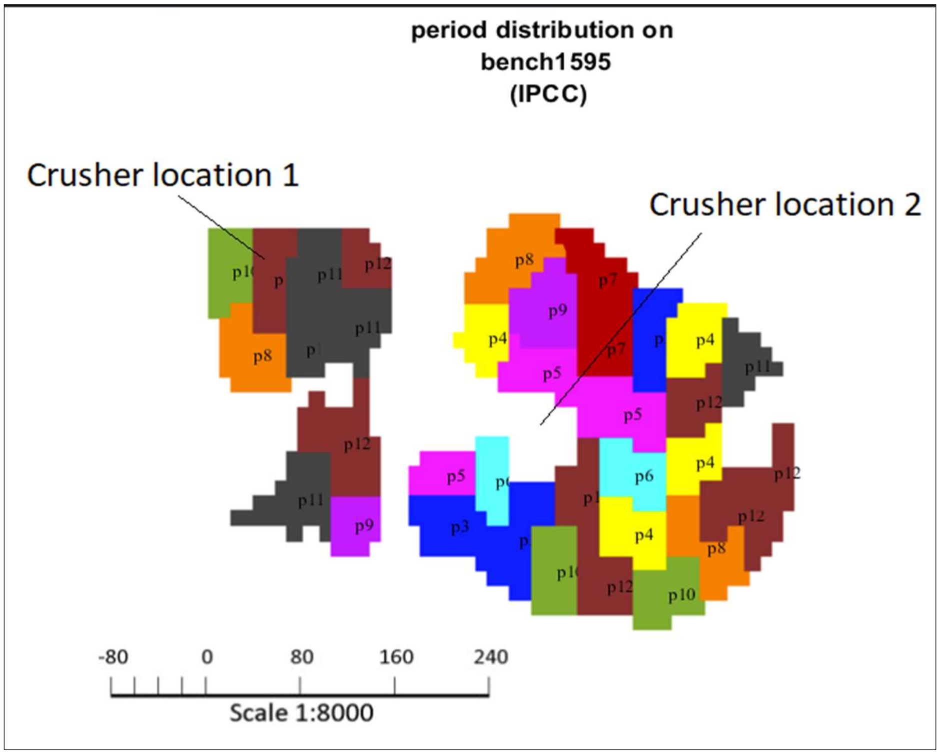

Figure 16: Mining period of faces on bench 1595

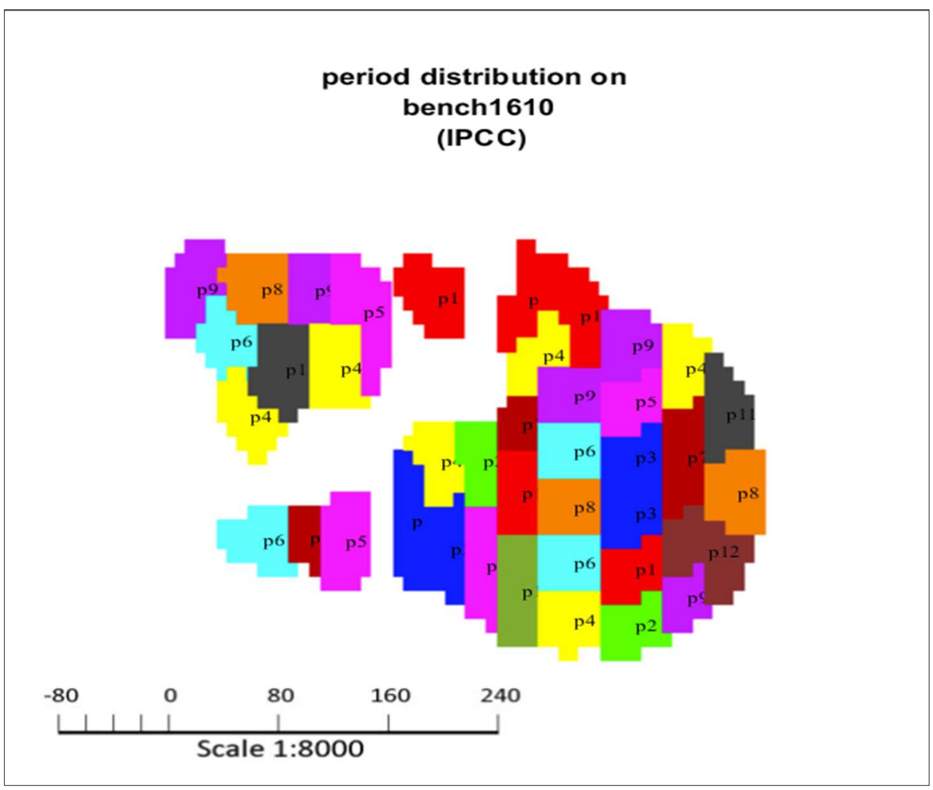

Figure 17. Mining period of faces on bench 1730.

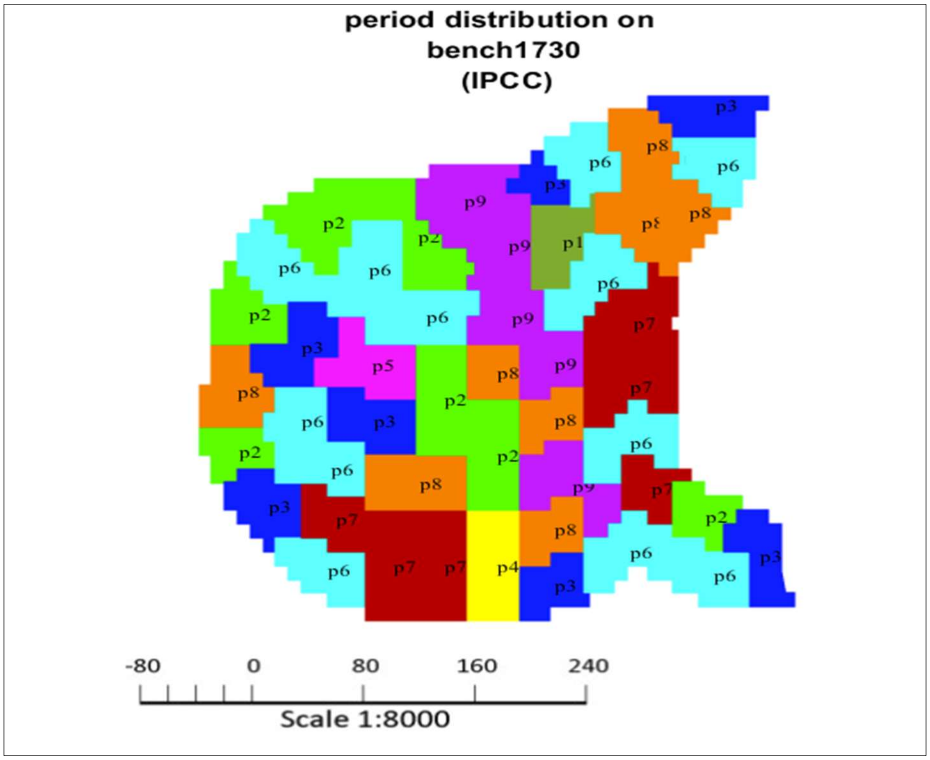

Figure 18. Mining period of faces on bench 1730.

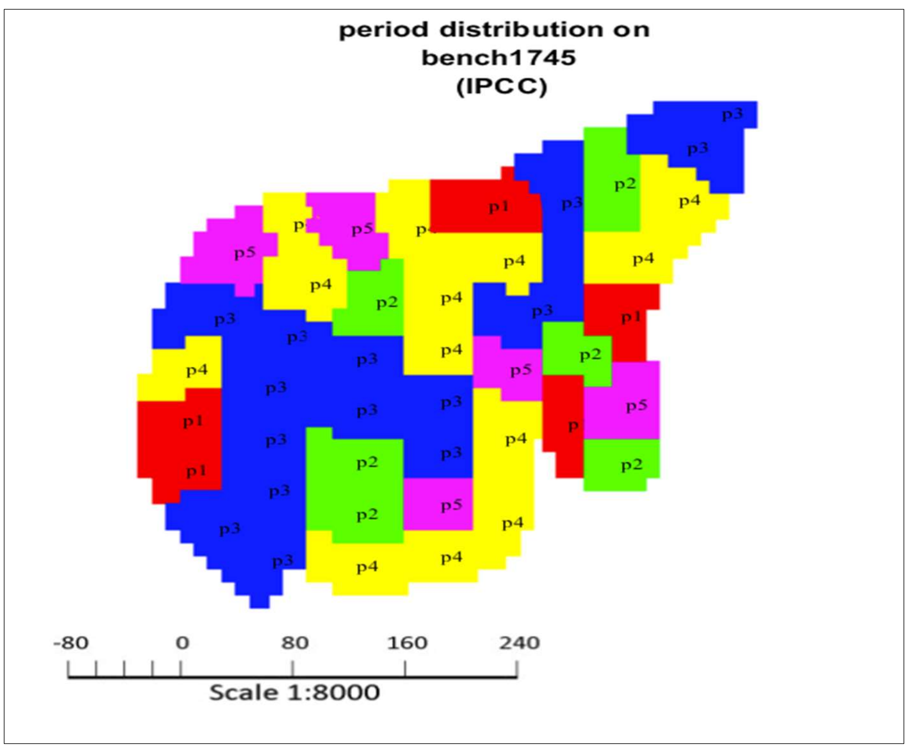

Figure 19. Mining period of faces on bench 1745.

The faces of bench 1595 starts from period 3 while mining in bench 1610 starts from the first period. The waste faces are generally mined in earlier months compared to ore faces just like the previous scenario. This proves that the shovel assignments are made respecting the precedence relations. The crusher was located on face 3 of bench 1595 from period 1 to 6 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. This face has to be mined when the crusher is relocated in a next period. Face 3 on bench 1595 has been mined on the twelfth period. These results confirm that the model is well capable of providing schedules respecting the locations of the IPCC. The two waste benches at 1730m and 1745m are being mined out in a similar manner to scenario 1. These two benches do not have the IPCC on them at any given time of the planning horizon, which justifies the similar mining sequence of these benches between the scenarios in consideration.

Shovel allocation to the benches are delineated in Figure 20, Figure 21, Figure 22, and Figure 23 for bench 1595m, 1610m, 1735m and 1745m respectively.

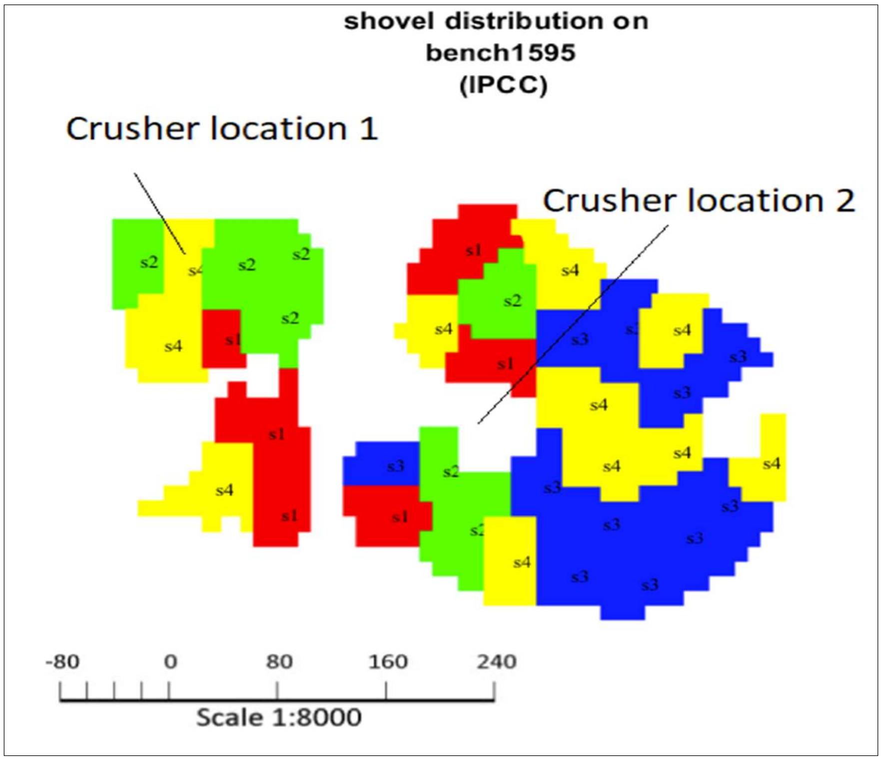

Figure 20. Shovel allocation on bench 1595.

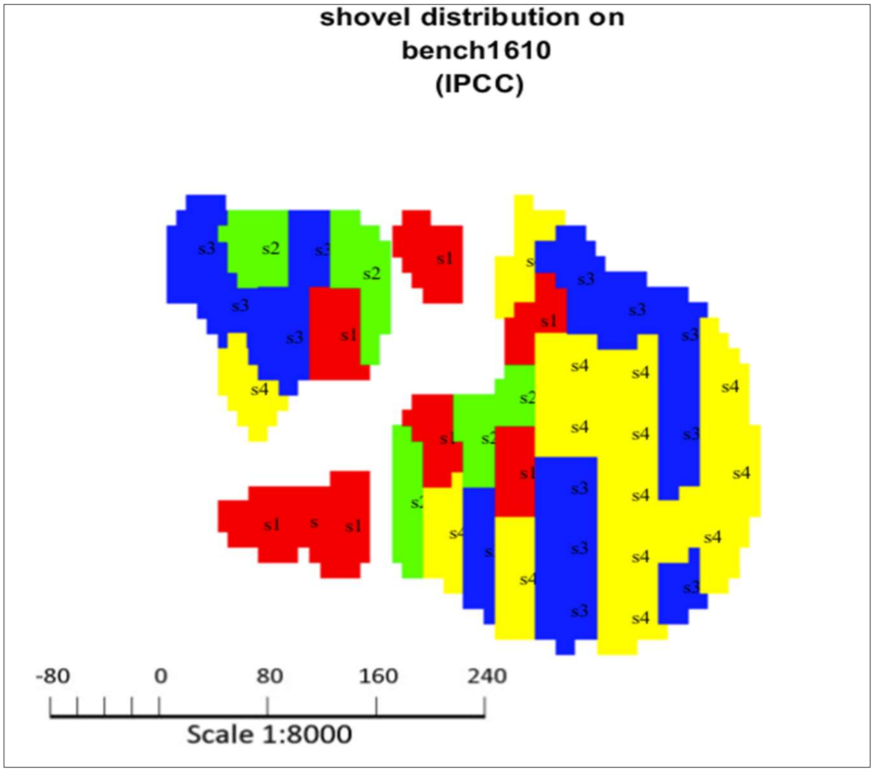

Figure 21. Shovel allocation on bench 1610.

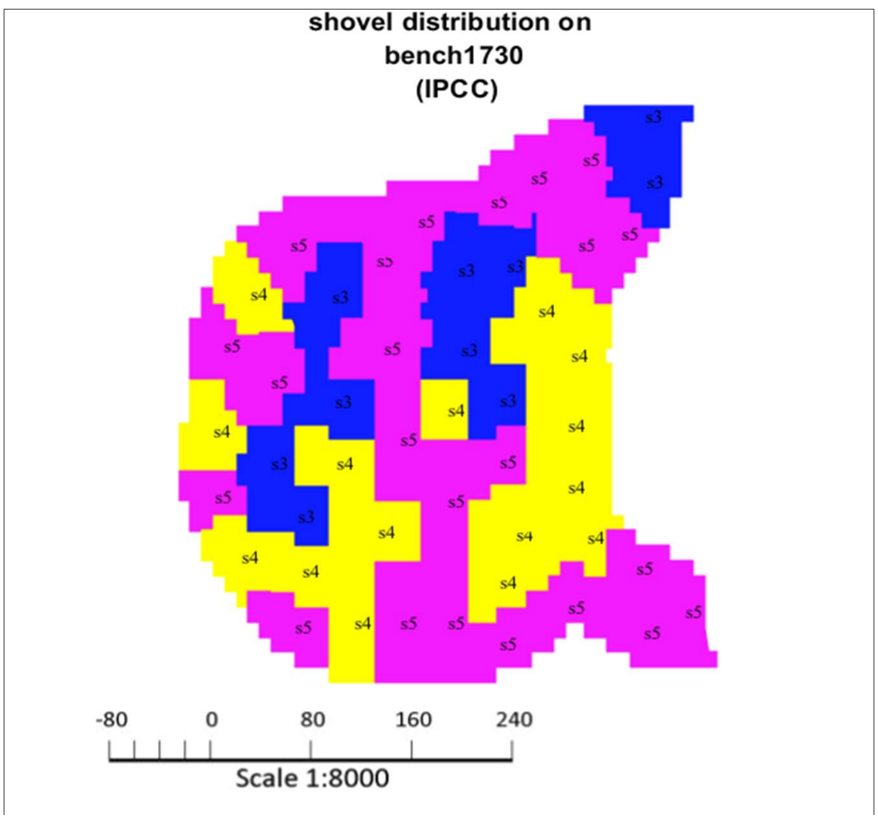

Figure 22. Shovel allocation on bench 1730.

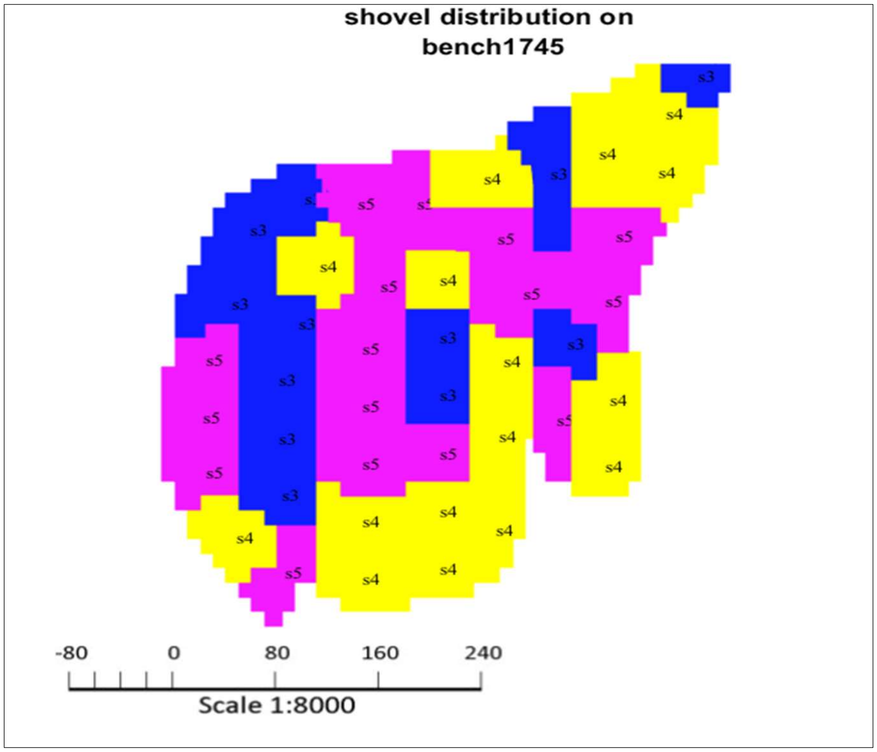

Figure 23. Shovel allocation on bench 1745.

The only face that is left unmined is face 18 on bench 1595, as shown in Figure 20, because this face is housing the IPCC from period 6 onwards. Shovel 5 dedicatedly works on the top two waste benches like the previous scenario. Shovel 1 and 2 mines the ore faces from the bottom two benches at 1595m and 1610m elevation. The assignment of shovels also verifies the model's capacity to provide short-term planning schedules with semi-mobile IPCC.

Figure 24 shows the production of ore and waste for this scenario. The ore production is low in the last period because of unavailability of enough ore faces on this period. The production of ore and waste otherwise is steady and meets the crusher requirements and the long-term production target for the rest of the periods.

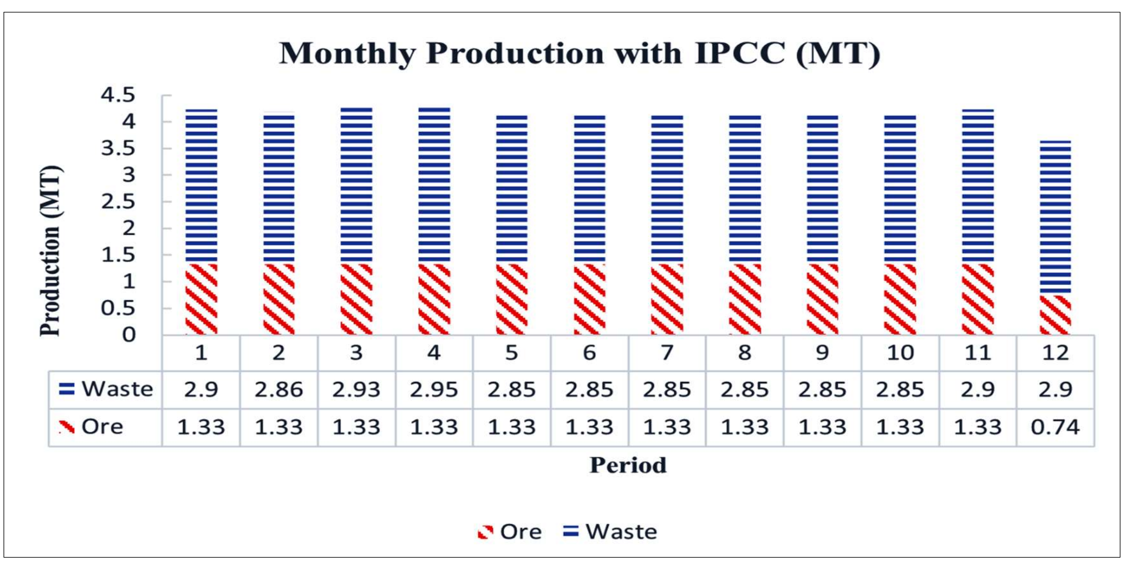

Figure 24. Monthly ore and waste production for scenario 2.

The required number of ore and waste trucks for this scenario is 9 and 11 respectively with a 65% efficiency.

9. Discussion of Results

The purpose of introducing IPCC systems to open pit mines is to reduce the number of trucks required, truck haulage cost and distance. Figure 25 shows that the truck requirement for scenario 2 with IPCC is 35% lower than scenario 1 with no IPCC. The waste truck requirement does not change as the waste transportation method does not change across the scenarios. This outcome proves the hypothesis that the introduction of IPCC reduces the required number of trucks.

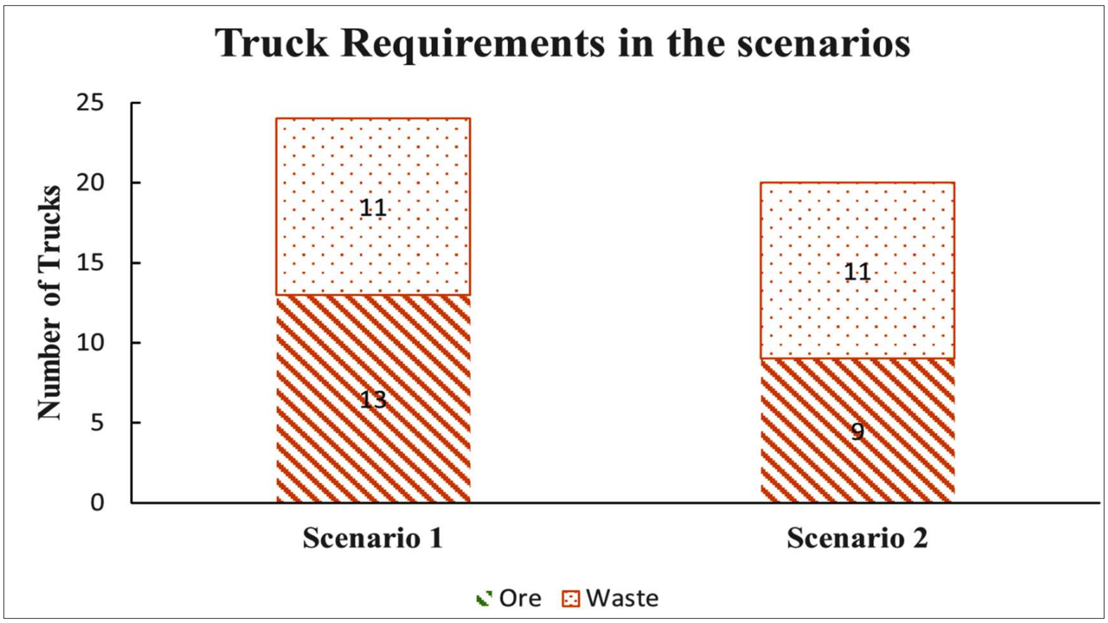

Figure 25. Ore truck requirement for scenarios without IPCC and with IPCC.

Now we will investigate the impact of IPCC on ore haulage cost. Table 2 summarizes the total ore haulage cost over the planning horizon, the mean and standard deviation of ore haulage cost per period for both the scenarios. The annual ore haulage cost is $37M lower with IPCC in scenario 2 compared to scenario 1 with only truck haulage. The mean haulage cost per period for scenario 1 and scenario 2 is $6.87M and $3.78M respectively. The standard deviation of haulage cost is higher in the scenario with IPCC compared to the scenario with no IPCC. The reason of the higher standard deviation in scenario 2 is the lower ore haulage cost ($2M) in the last period compared to the other periods due to the lower production of ore. The lower production of ore in the last period occurred due to the unavailability of ore faces.

Table 2: Summary of ore haulage cost for two scenarios.

Cost Summary	Scenario 1	Scenario 2
Total Haulage Cost (M$)	82.45	45.32
Mean Haulage Cost Per Period (M$)	6.87	3.78
Standard Deviation of Haulage Cost Per Period (%)	41.97	55.70

Figure 26 shows the ore haulage cost comparison between scenarios across all periods within the time horizon. The ore haulage cost hovers around $4.5 to $5.5 per kilometer per period for scenario 1 with truck haulage and it is between $2.5 to $3.5 per kilometer per period for the scenario with IPCC. The sharp dip in haulage cost in the last period of scenario 2 represents the lower ore production in that period.

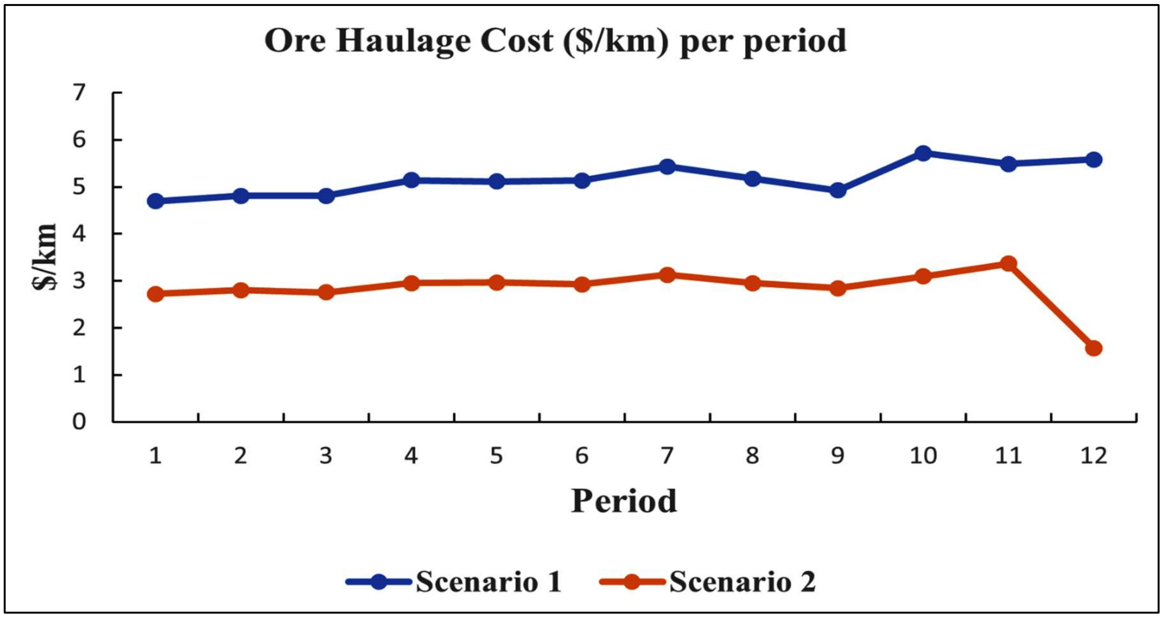

Figure 26. Comparison of ore haulage cost per period between scenarios.

The impact of increasing truck operating cost has been checked for both scenarios. Figure 27 shows the impact of increasing truck operating cost on ore haulage for both the scenarios.

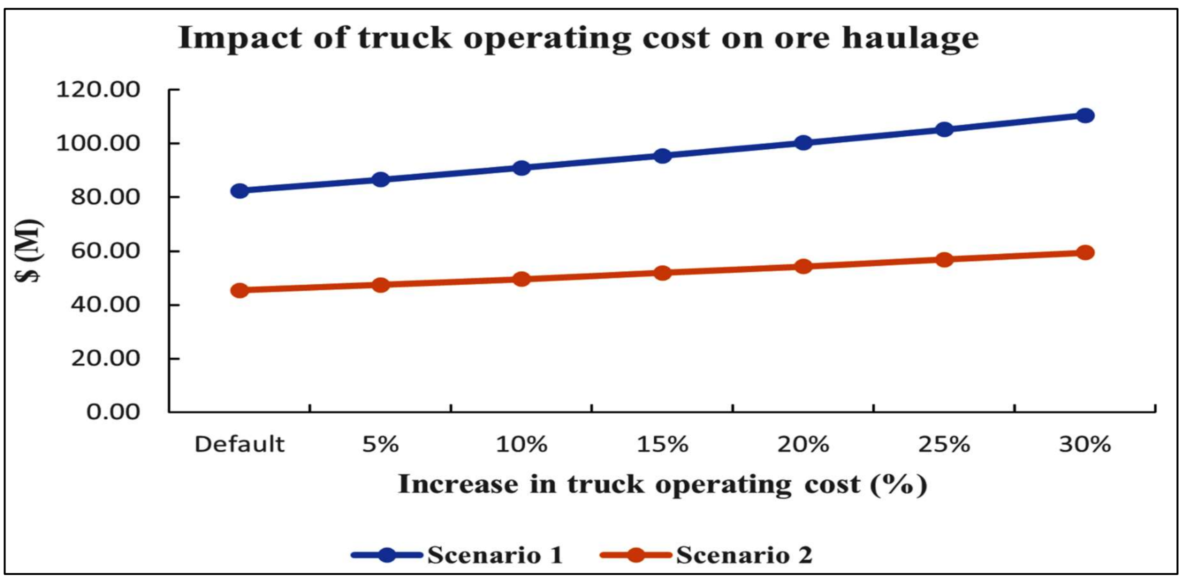

Figure 27. Sensitivity of ore transport cost to increasing truck operating cost.

The percent change in ore haulage cost is slightly sharper in scenario 1 with truck haulage compared to scenario 2. Superimposing the curves of Figure 27 shows that a 30% increase in truck operating cost increases ore haulage cost by 34% and 31% for scenario 1 and scenario 2 respectively, as shown in Figure 28.

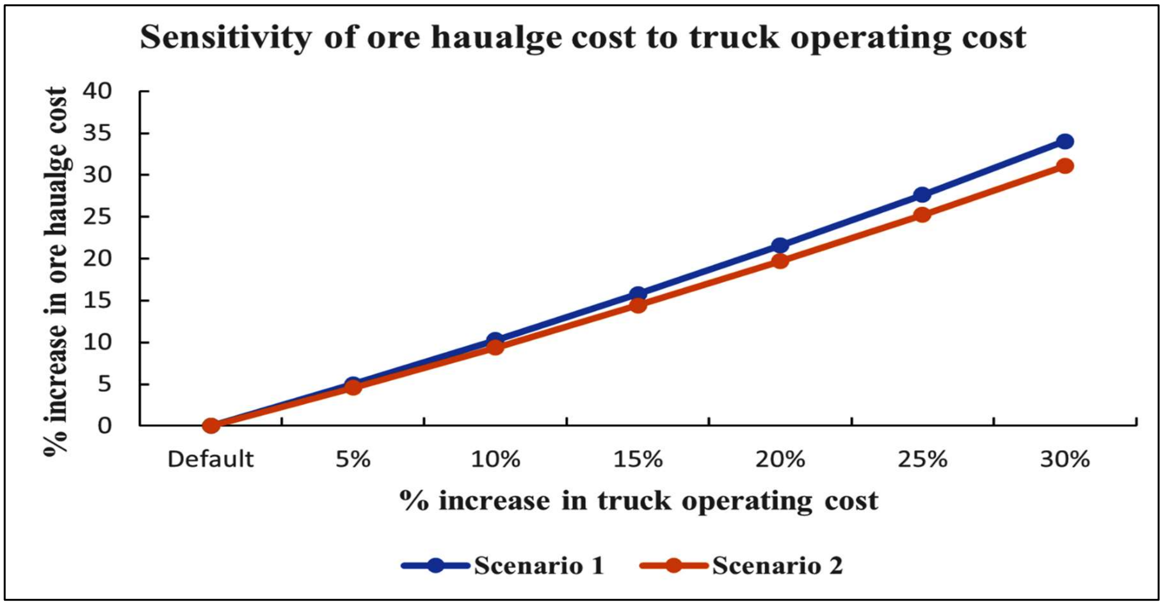

Figure 28. Truck operating cost vs haulage cost.

The analysis presented in Table 2 and Figure 25, Figure 26, Figure 27 and Figure 28 substantiates the fact that the installation of IPCC reduces haulage cost, truck requirements and delineates the impact of increasing truck operating cost on haulage from an operational perspective.

We have calculated the shovel efficiency for all five shovels over the 12 periods. Equation 18 shows the shovel efficiency formulation.

$$\textbf{Shovel efficiency}, \boldsymbol{\vartheta} \;=\; \boldsymbol{availability} \times \boldsymbol{utilization} \tag{18}$$

Utilization is being defined as the percent of time a shovel is busy working in faces in a period in this equation. A comparison of shovel efficiencies for all the five shovels for the scenarios with and without IPCC is presented in Figure 29.

The shovel efficiency is slightly higher for the ore shovels compared to waste shovels in both the scenarios. The difference in shovel efficiency between scenarios is negligible. The general trend, however, is that all the shovels have slightly higher efficiency in scenario 1 (no IPCC) than in scenario 2 (IPCC). The reason behind this is the slightly higher ore and waste production in scenario 1 with regular truck haulage. The ore production is significantly low in the last period of scenario 2 with IPCC because of the unavailability of ore faces. The waste production in this scenario is also about 0.5MT less than scenario 1.

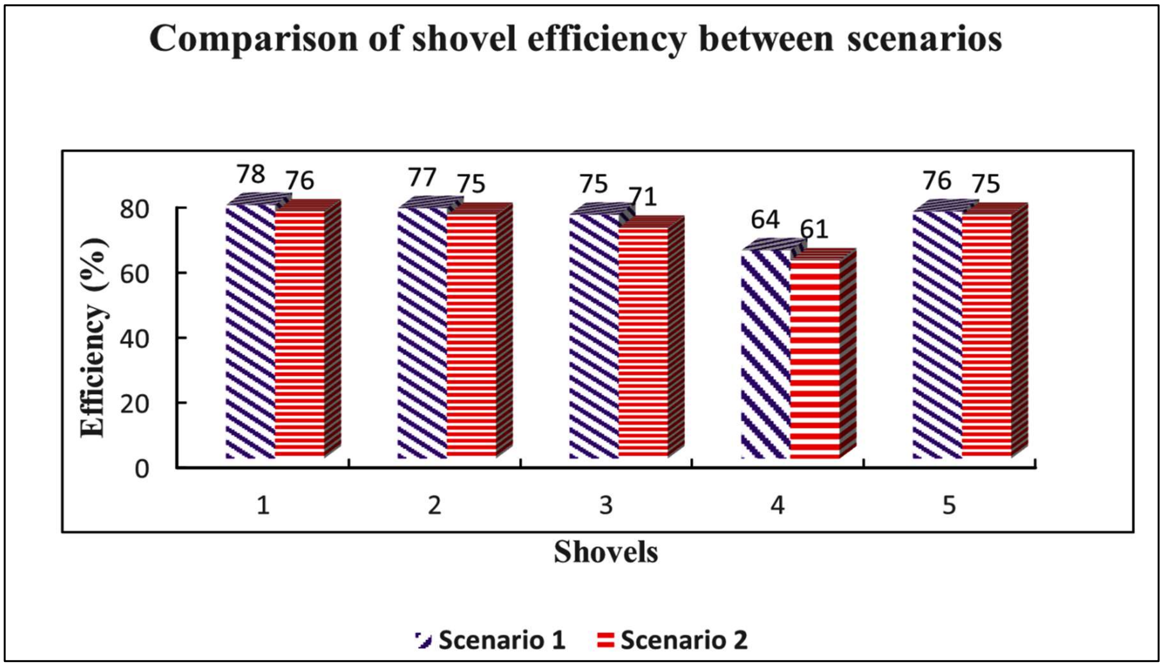

Figure 29. Shovel efficiency comparison between scenarios.

Figure 30 shows the optimal objective function values for both the scenarios. The objective function value is $12M 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.

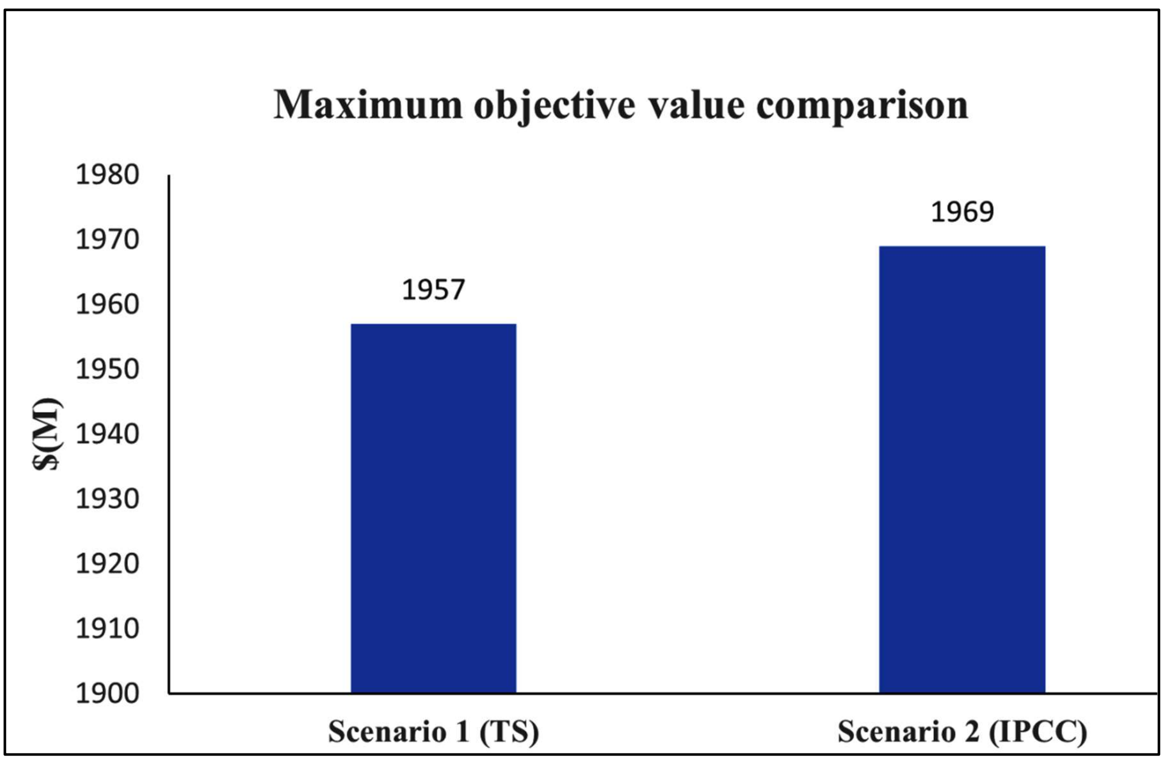

Figure 30. Comparison of (revenue - cost) between scenario 1 and scenario 2.

10. Conclusion 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 objective function value, which is the difference between revenue and haulage cost, compared to the scenario with no IPCC, scenario 1. The truck requirement and ore haulage cost in scenario 2 is also 35% and 43% lower than scenario 1, respectively. 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 for the case study, it has the following discrepancies.

- The model allocates shovels without considering ore blending requirements.
- The model does not consider shovel movement cost and does not constraint shovel movements between benches. This is the reason why in several periods, the model does not look for the nearest face to make the next shovel allocation. However, the model makes sure that the shovel movements are restricted within the immediate upper or lower bench once a face is mined out.
- 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 by blending requirements and shovel movement between benches to minimize 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 compelling and provide a more comprehensive tool for short-term production planning and analysis purposes.

11. References

[1] Awuah-Offei, K., and H. Askari-Nasab, 2009. Valuation of Belt Conveyor and Truck Haulage Systems in an Open Pit Mine using Life Cycle Assessment. The Canadian Institute of Mining, Metallurgy and Petroleum Bulletin 102:1-6.

[2] Blom, M., A. R. Pearce, and P. J. Stuckey, 2017. Short-term scheduling of an open-pit mine with multiple objectives. Engineering Optimization 49(5):777-795.

[3] Eivazy, H., and H. Askari-Nasab, 2012. A mixed integer linear programming model for short-term open pit mine production scheduling. Transactions of the Institutions of Mining and Metallurgy, Section A: Mining Technology 121(2):97-108.

[4] Erkayaoğlu, M., and N. Demirel, 2016. A comparative life cycle assessment of material handling systems for sustainable mining. Journal of Environmental Management 174:1-6.

[5] Fuming, L., C. Qingxiang, and C. Shuzhao, 2015. A comparison of the energy consumption and carbon emissions for different modes of transportation in open-cut coal mines. International Journal of Mining Science and Technology 25(2):261-266.

[6] Gholamnejad, J., 2008. A zero-one integer programming model for open pit mining sequences. Journal- South African Institute of Mining and Metallurgy 108:759-762.

[7] Gong, Hongshuo, A. Moradi Afrapoli, and H. Askari-Nasab, 2023a. Integrated simulation and optimization framework for quantitative analysis of near-face stockpile mining. Simulation Modelling Practice and Theory 128:102794.

[8] Gong, Hongshuo, et al., 2023b. Near-face stockpile open pit mining: a method to enhance NPV and quality of the plant throughput. International Journal of Mining, Reclamation and Environment 37(3):200-215.

[9] Konak, G., A. H. Onur, and D. Karakus, 2007. Selection of the optimum in-pit crusher location for an aggregate producer. Journal of the Southern African Institute of Mining and Metallurgy 107(3):161-166.

[10] Kozan, E., and S. Q. Liu, 2016. A new open-pit multi-stage mine production timetabling model for drilling, blasting and excavating operations. Mining Technology 125(1):47-53.

[11] Kozan, E., S. Liu, and R. Wolff, 2013. A short-term production scheduling methodology for open-pit mines. Proceedings of the 36th Application of Computers and Operations Research in The Mineral Industry (APCOM) Symposium, 2013, pp. 465 - 473.

[12] L'Heureux, G., M. Gamache, and F. Soumis, 2013. Mixed integer programming model for short term planning in open-pit mines. Transactions of the Institutions of Mining and Metallurgy, Section A: Mining Technology 122(2):101-109.

[13] Liu, D., and Y. Pourrahimian, 2021. A Framework for Open-Pit Mine Production Scheduling under Semi-Mobile In-Pit Crushing and Conveying Systems with the High-Angle Conveyor. Mining 1(1):59-79.

[14] Liu, S. Q., and E. Kozan, 2017. Integration of mathematical models for ore mining industry. International Journal of Systems Science: Operations & Logistics 6:1-14.

[15] Manríquez, F., J. Pérez, and N. Morales, 2020. A simulation–optimization framework for short-term underground mine production scheduling. Optimization and Engineering 21(3):939-971.

[16] Mirzaei-Nasirabad, Hossein, et al., 2023. An optimization model for the real-time truck dispatching problem in open-pit mining operations. Optimization and Engineering.

[17] Moradi Afrapoli, A., and H. Askari-Nasab, 2017. Mining fleet management systems: a review of models and algorithms. International Journal of Mining, Reclamation and Environment 33(1):1-19.

[18] Moradi Afrapoli, A., M. Tabesh, and H. Askari-Nasab, 2019a. A stochastic hybrid simulation-optimization approach towards haul fleet sizing in surface mines. Mining Technology: Transactions of the Institute of Mining and Metallurgy 128(1):9-20.

[19] Moradi Afrapoli, Ali, and Hooman Askari Nasab, 2020. A stochastic integrated simulation and mixed integer linear programming optimisation framework for truck dispatching problem in surface mines. International Journal of Mining and Mineral Engineering 11:257.

[20] Moradi Afrapoli, Ali, Mohammad Tabesh, and Hooman Askari-Nasab, 2019b. A multiple objective transportation problem approach to dynamic truck dispatching in surface mines.

[21] Moradi Afrapoli, Ali, Shiv Prakash Upadhyay, and Hooman Askari-Nasab, 2022. A nested multiple-objective optimization algorithm for managing production fleets in surface mines. Engineering Optimization:1-14.

[22] Norgate, T., and N. Haque, 2013. The greenhouse gas impact of IPCC and ore-sorting technologies. Minerals Engineering 42:13-21.

[23] Paricheh, M., 2017. In-pit crusher location as a dynamic location problem. Journal of the Southern African Institute of Mining and Metallurgy 117:599-607.

[24] Paricheh, M., and M. Osanloo, 2019a. Concurrent open-pit mine production and in-pit crushing–conveying system planning. Engineering Optimization 52(3):1-16.

[25] Paricheh, M., and M. Osanloo, 2019b. A New Search Algorithm for Finding Candidate Crusher Locations Inside Open Pit Mines. Proceedings of the 28th International Symposium on Mine Planning and Equipment Selection, 2019b.

[26] Paricheh, M., M. Osanloo, and M. Rahmanpour, 2016. A heuristic approach for in-pit crusher and conveyor system's time and location problem in large open-pit mining. International Journal of Mining, Reclamation and Environment 32(1):35-55.

[27] Rahmanpour, M., M. Osanloo, and N. Adibi, 2013. An approach to determine the location of an in pit crusher in open pit mines. 23rd International Mining Congress and Exhibition of Turkey, IMCET 2013 1:141-149.

[28] Samavati, M., D. Essam, and M. Nehring, 2020. Production planning and scheduling in mining scenarios under IPCC mining systems. Computers & Operations Research 115:104714.

[29] Shamsi, M., Y. Pourrahimian, and M. Rahmanpour, 2022. Optimisation of open-pit mine production scheduling considering optimum transportation system between truck haulage and semi-mobile in-pit crushing and conveying. International Journal of Mining, Reclamation and Environment 36(2):142-158.

[30] Smith, M. L., 1998. Optimizing short-term production schedules in surface mining: Integrating mine modeling software with AMPL/CPLEX. International Journal of Surface Mining, Reclamation and Environment 12(4):149-155.

[31] Tabesh, M., and H. Askari-Nasab, 2013. Automatic Creation of Ore-Selection and Blast Polygons using Clustering Algorithms.

[32] Tabesh, Mohammad, and Hooman Askari-Nasab, 2019. Clustering mining blocks in presence of geological uncertainty. Mining Technology 128(3):162-176.

[33] Taheri, M., M. Irannajad, and P. Ataee, 2009. An approach to determine the locations of in-pit crushers in deep open-pit mines. 9th International Multidicsciplinary Scientific Geoconference and EXPO, SGEM 2009, June 14, 2009 - June 19, 2009, Albena, Bulgaria, 2009. Vol. 1, pp. 341-347. International Multidisciplinary Scientific Geoconference.

[34] Upadhyay, S. P., and H. Askari-Nasab, 2016. Truck-shovel allocation optimisation: A goal programming approach. Transactions of the Institutions of Mining and Metallurgy, Section A: Mining Technology 125(2):82-92.

[35] Upadhyay, S. P., and H. Askari-Nasab, 2017. Dynamic shovel allocation approach to short-term production planning in open-pit mines. International Journal of Mining, Reclamation and Environment 33(1):1-20.