Uncertainty Based Short Term Planning in Open Pit mines – Simulation Optimization Approach

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Abstract

Accuracy in predictions leads to better planning and substantial gains by minimal opportunity lost over the course of execution. In open pit mining context, the complexity of operations coupled with highly uncertain and dynamic production environment, poses a limitation on accurate predictions and forces reactive planning approach to mitigate the deviations from what was planned. A simulation optimization framework/tool is presented in this paper to account for uncertainties in mining operations for best possible short term production planning and taking actions proactively during the planning process. The simulation optimization framework/tool uses a discrete event simulation of mine operations, which interacts with a goal programming based mine operational optimization tool (MOOT), to capture the performance and develop uncertainty based short term schedule. This framework through scenario analysis allows the planner to take proactive decisions to achieve the operational and long term objectives of the mine. This paper details the development of simulation and optimization models and presents the implementation of the framework on an iron ore mine case study for the verification through scenario analysis.

1. Introduction

Planning is a critical component of any successful execution to achieve desired results. Accurate predictions of the outcome serve as the backbone of any planning activity. This paper aims at presenting an approach where discrete event simulation in conjunction with an optimization tool is used for accurate prediction based efficient short term mine production planning. This paper describes how a detailed mine operational discrete event simulation model can be developed, keeping it flexible enough for easy scenario analysis and re-usability over the course of mine life, along with modeling techniques for truck haulage, haulage road network and interaction with external intelligent decision support systems for operational decision making. The proposed simulation optimization framework works in a bottom up approach by simulating the operations to generate short term plans. The external decision support system used is a mine operational optimization tool (MOOT) which provides shovel allocation decisions based on strategic schedule, thus linking operations directly with strategic schedule to generate uncertainty based short term plans.

Open pit mines usually have very large operations consisting of a number of equipment and years in mine life. Huge capital investments, bulk production demand and market dynamics have made it imperative for mining industries to focus on best and efficient mining practices to sustain in the market over the mine life. This makes planning a very critical process which is carried out in stages, as strategic plans, short term plans and operational plans based on the planning time horizon. The main objectives of short term plans are to achieve operational objectives of quality and quantity requirements of process plants and maximum utilization of equipment, and a high

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level of compliance with the strategic plans. The compliance of short term plans through operational executions is essential for compliance of strategic plans and in turn achieving economic objectives of the mine. Also, optimal equipment planning can only be realized with efficient utilization of all the assets involved during operations. Optimal use of available equipment is also essential to realize the strategic economic objectives, as approximately 60% of total operating cost in open-pit mines is accounted to truck and shovel operations. The whole planning process to achieve organizational objectives may go void if short term and operational planning are inefficient to reflect back. Short term planning thus may be regarded as very critical in achieving both operational objectives and strategic targets of the mine.

Malhotra and List (1989) describes the various complexities and challenges faced by the planners in short term planning process, whereas in another paper Henderson and Turek (2013) stress the plans to be as realistic as possible so that expectations can be delivered. Complexities in planning are usually dealt with assumptions, but such assumptions must be small and should not affect the practicality of the plans developed. Practicality of short term plans is a big problem which poses limitation on its achievability and the realization of operational objectives during executions. L'Heureux et al. (2013) proposed a detailed mathematical optimization model for short term planning for a period of up to three months by incorporating operations in detail. Gholamnejad (2008) proposed a binary integer programming model to solve the short term mine scheduling problem. Similar models have been proposed by Eivazi and Askari-Nasab (2012), Gurgur et al. (2011), Kumral and Dowd (2002) and others for short term mine planning accounting for various required details such as incorporating multiple destinations, precedence requirements and also incorporating multiple competing objectives. Although some of the existing models incorporate various details of the operations, they does not account for the uncertainties involved. Also the fixed nature of production rates from shovels and the tonnage haulage capacity by trucks poses a limitation on the achievability of the generated schedule, which depends greatly on the haulage profile, available number of trucks in the system, and also the truck dispatching efficiency. Practical applicability or achievability of the schedules is a major limitation observed in most models. A practical short term plan would be one which accounts for the shovel movement times and production lost during such movements between faces, equipment failures, equipment availabilities, real time grade blending and fluctuations, and changing rates of production from shovels based on their locations, available trucks, haul road gradients and truck dispatching efficiency.

Simulation models also find a large scope in mining industry and are being used widely for prediction based decision making for specific problems. Sturgul (1999) reviews the application of simulation in mining in United States and credits Rist (1961) for the first published application of computer simulation in mining. Kolonja and Mutmansky (1994), Ataeepour and Baafi (1999) and many others used simulation to prove the positive impact of truck dispatching strategies in mining. Awuah-Offei et al. (2003) and Upadhyay et al. (2013) used simulation to determine optimal number of truck and shovel requirement in open pit mines. Similarly Yuriy and Vayenas (2008) applied simulation with a reliability assessment model to predict the impact of failures on production, availabilities and utilizations of equipment. Most of the simulation models on mining, published in literature, focus on specific problems and do not detail the development of the models as such. Also the models find very limited scope and are designed to tackle specific problems.

Modeling accurate truck haulage system is crucial to model realistic simulation of mine operations. Most simulation models, as noted by Jaoua et al. (2009), model the transportation system as a macroscopic process, which do not account for platoon formations and interaction of trucks on haul roads leading to decreased travel speeds. But at the same time, incorporating a real time control in a microscopic process to model accelerations and decelerations may be resource intensive. In most cases a faster truck slows down to the speed of a leading slower truck and travels in platoon if overtaking is not allowed, which is the case in most mining systems. Thus, inhibiting the overtaking, forcing the faster truck to move with the same speed as the leading slower truck may be considered sufficient to model the truck haulage system for the scale and objectives of the simulation model presented in this paper. It is also important to model the truck speeds based on haul road characteristics, as trucks don't travel with constant speed throughout the road network. The main parameters affecting the speed of trucks include: driver behavior, rimpull curve characteristics of trucks, haul road gradient and rolling resistances, and certain other factors related to safety such as visibility (day and night). The driver behavior is a critical factor which requires a thorough study before modeling it into the simulation. It was considered sufficient to model an average driver behavior for all trucks and thus not considered into modeling the process. The truck speeds, thus, are modeled based on rimpull curve characteristics of trucks and haul road characteristics in this paper.

Simulation optimization is a fairly new approach in mining industry. Fioroni et al. (2008) used simulation in conjunction with a mixed integer linear programming model to reduce mining costs by optimal production planning. Jaoua et al. (2012) used a simulation optimization approach to develop a simulation based real time control tool for truck dispatching. There is not so much application of this approach yet in mining industry, but it bears a great potential for developing robust tools for decision making purposes.

Most research in the area of short term and operational planning has been limited to mathematical programming based optimization techniques. But L'Heureux et al. (2013) observes that modeling a mining operation in detail by incorporating multiple periods, faces, shovel movements, truck allocations and plants poses a limitation on solvability due to the size of such models. Such models will be too big in size that even state of the art hardware and software will be unable to handle their complexity and size (Bjørndal*, et al.*, 2012). A simulation optimization approach provides a better alternative to handle this problem, where less number of periods can be considered in mathematical optimization model, and more details can be incorporated within simulation models, thus providing an opportunity to incorporate all the operational details into the planning process. Also the proposed approach generates the short term schedule based on the simulated operations, and thus remains practical and achievable, while providing opportunity for proactive planning through scenario analysis.

This paper briefly presents a goal programming based tool MOOT for optimal operational decision making and details the development of a discrete event simulation model in Arena which is flexible and reusable over time. The emphasis is given to modeling techniques for haul road network, truck travel and an interaction mechanism to communicate with external decision support system (MOOT) for optimal shovel and truck allocation decision making. The rest of the paper is structured as follows: the simulation optimization framework is presented first which describes the overall approach, followed by MOOT and a detailed development of the simulation model. The implementation of the simulation optimization model is then presented on a case study, followed by discussion and conclusions.

2. Simulation optimization framework

The overall framework of this research is presented in Fig. 1, which shows the application of an intelligent operational decision making tool (MOOT) for short term mine planning and in parallel for dynamic operational decision making in real mine operations. As mine operations are complex, a very intelligent MOOT would be required for a successful implementation of it in real mine operations, which can be carried out as a future research. The context of this paper is limited to the applicability of MOOT with a discrete event simulation model as simulation optimization approach for short term mine planning, the extent of modeling for which is considered satisfactory in this paper.

Fig. 1 show that for the short term mine planning, the strategic schedule and the designed haul road network are first translated into a configuration input file, which serves as input to the simulation model and MOOT. The configuration file is also updated with fitted distribution times based on the historical operational data. The model then simulates the operations for the planning horizon of the input schedule, interactively seeking shovel and truck allocation decisions from MOOT. The simulation data is then uploaded into the simulation database, which is then queried to fetch uncertainty based schedule and the observed KPIs of the mine operations. The observed achievability of the strategic schedule and the KPIs are then analyzed to run further scenarios, by improving poor performance processes, to develop best and practical short term schedule.

One major difference between the conventional mathematical optimization based short term planning process and the proposed simulation optimization approach is that planning in this approach is carried out by capturing the simulated operations. The conventional mathematical models optimize the overall operations for the planning period to generate a schedule which contains high level of uncertainty over higher periods, which is taken into account as real operations continues; and updated regularly. In the proposed simulation optimization approach, overall operations are optimized in a similar manner for a limited number of periods of the planning time horizon. But this approach also implements the generated schedule into the simulation to capture the uncertainty, and re-optimizes each time system state changes. This basic difference allows a planner to generate realistic schedules and take proactive decisions so that perceived deviations in operational and strategic objectives can be minimized.

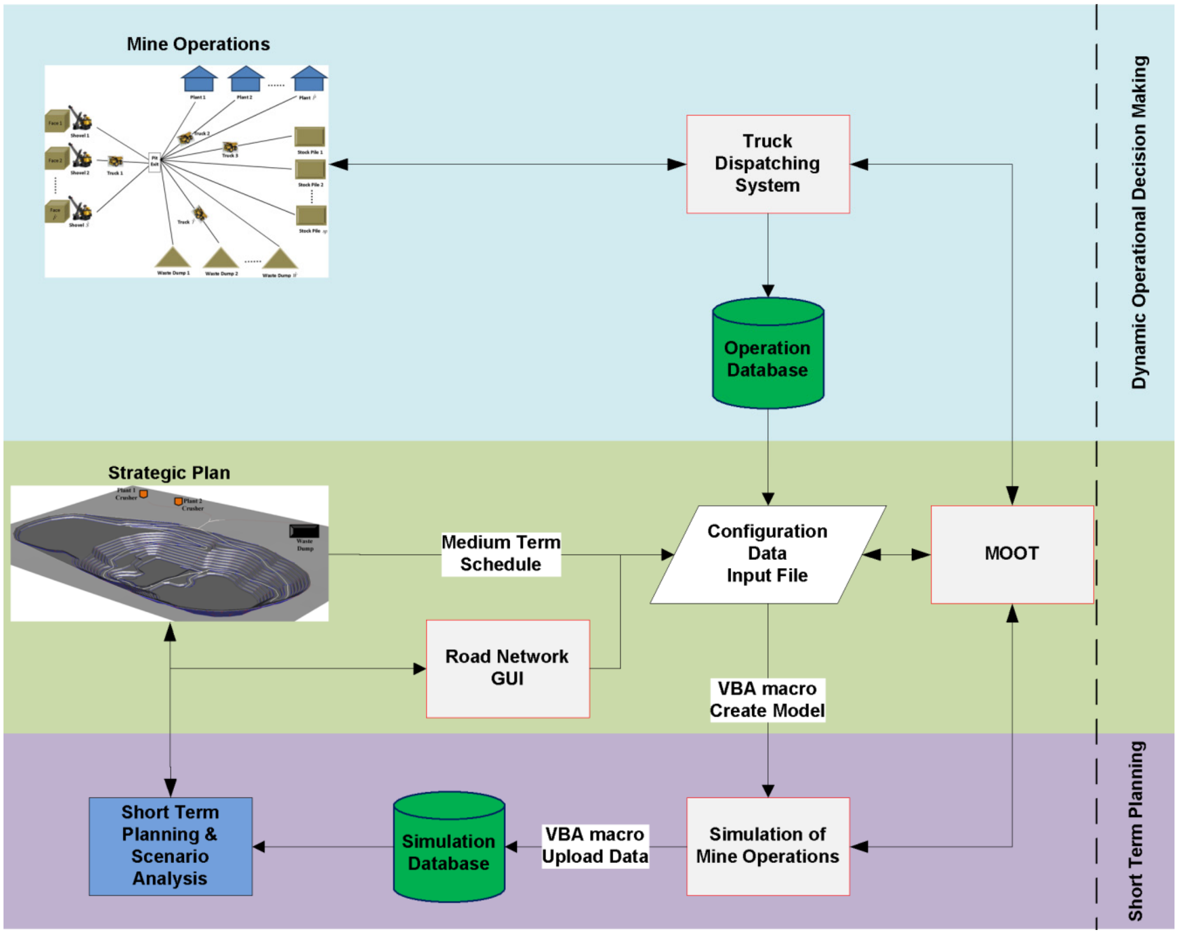

Fig. 1. Framework of the simulation optimization approach and the applicability of MOOT for short term mine planning and real time dynamic operational decision making

An efficient simulation model is a prime requirement in this approach, which needs to model the individual operational processes accurately and replicate the mining system. It is also essential in this approach that the simulation model is flexible and reusable over time, so that planning activities can be carried out over the mine life. Although overall mining system does not change over the mine life, the mine layout consisting of scheduled blocks, haul road design and equipment may change along with the process time distributions for various equipments. Thus Matlab (The MathWorks Inc.) and VBA based interfaces have been created to translate existing mine layout into simulation (Fig. 2**Error! Reference source not found.**). The truck travel process is also modeled in detail which captures the speeds based on rimpull curve characteristics of trucks and the haul roads, and any interaction between trucks while travelling leading to platoon formations.

3. Mine operational optimization tool (MOOT)

The main objective of mine operational optimization tool (MOOT) is to optimize the mine operations over a fixed number of periods such that operational objectives of maximum production and, quality and quantity requirements of plants can be achieved by providing truck allocations and shovel assignments within the mining faces provided by strategic schedule. Thus MOOT presented in this paper is developed as a mixed integer linear goal programming (MILGP) model to optimize multiple operational objectives following a non preemptive approach. This section presents the variables, objectives and constraints formulated to develop MOOT (see Appendix for the Indices and parameters used).

3.1. Variables

The MILGP model is constructed using 14 types of variables to incorporate various operational constraints and modeling objectives. Shovel allocations to faces is modeled using a binary assignment variable. Another binary variable is used to keep track of mined out faces over multiple periods. The movement of shovels is also controlled using the same assignment variable and the mined out variable. To model the continuous movement of shovel over two periods i.e. if a shovel starts movement in one period but ends in next period, another binary variable is used to keep track of remaining movement time in that period. Truck allocations are modeled for every truck type in the system using an integer variable. The remaining variables are continuous in nature and are used to model the production from faces, deviations in production from shovel, deviations in grades and tonnage at destinations, tonnage available at faces and movement times of shovels. All the variables considered in the model are explained in Table 1.

Table 1: Variables considered in the MILGP model (MOOT)

$a_{s,f,p}$	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 $r^{rem}_{s,p}$ 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*'

3.2. Goals

Although there can be various operational objectives, this model considers four main operational objectives as goals: (1) maximize production by minimizing the negative deviation in production by shovels compared to their capacities, (2) minimize the deviation in production received at processing plants compared to their capacities, (3) minimize the deviation in grades delivered to ore destinations compared to desired grades, and (4) minimize the movement times of shovels.

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

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

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

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

3.3. Objective function

The model is optimized using a non-preemptive approach, thus the four objectives considered in the model are normalized and combined as the weighted sum, given in Eq. (5). The weights assigned to individual objectives are based on the desired preference of the objective over others. The normalization of individual objectives is carried out by optimizing each objective separately to determine their values in pereto optimal space (Grodzevich & Romanko, 2006).

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

Where:

$$\overline{\Psi}_i = \left(\Psi_i - Utopia_i\right) / \left(Nadir_i - Utopia_i\right) \tag{6}$$

3.4. Constraints

The constraints in the model are formulated to model the shovel assignments constrained by precedence requirements, movements, production by each shovel, production received at process plants, grades received at ore destinations and the number of truck trips required by each truck type.

$$\sum_s a_{s,f,p} \le 1 \qquad \forall f \,\&\, \forall p \tag{7}$$

$$a_{s,Fi_s,p} = 1 \qquad \forall s \,\&\, p = 1 \tag{8}$$

$$\sum_f a_{s,f,p} \le 2 \qquad \forall s \,\&\, \forall p \tag{9}$$

$$\sum_{f} a_{s,f,p} \le a_{s,f,p} + m_{f,p} + (1 - a_{s,f,p-1}) + (1 - a_{s,f,p}) \times BM \qquad \forall s, \forall f, \forall p \tag{10}$$

$$a_{s,f,p+1} \ge a_{s,f,p} - m_{f,p} \qquad \forall s, f, p = 1 \ldots P-1 \tag{11}$$

$$a_{s,f,p+1} \le 1 + a_{s,f,p} - m_{f,p} \qquad \forall s, f, p = 1 \ldots P-1 \tag{12}$$

$$a_{s,f,p+1} \ge 2 \times a_{s,f,p} - \sum_{f} a_{s,f,p} \qquad \forall s, f, p = 1 \ldots P-1 \tag{13}$$

$$r_{s,p} \ge \sum_{f^1} a_{s,f^1,p} \times \Gamma^{F}_{f^1,f} \Big/ S_s - (1 - a_{s,f,p}) \times BM \qquad \forall s, \forall f \;\&\; p \tag{14}$$

$$r_{s,p} = r^{act}_{s,p} + r^{rem}_{s,p} \qquad \forall s \;\&\; \forall p \tag{15}$$

$$r_{s,p} \le \left(\sum_{f} a_{s,f,p} - 1 \right) \times BM \qquad \forall s \;\&\; \forall p \tag{16}$$

$$\sum_{d} x_{s,f,d,p} \le \left(1 - a_{s,f,p} + a_{s,f,p-1}\right) \times BM + y_{s,p} \times BM \qquad \forall s, \forall f \;\&\; \forall p \tag{17}$$

$$r^{rem}_{s,p} \ge \left(1 - y_{s,p}\right) \times \left(2 \times \varepsilon\right) \qquad \forall s \;\&\; \forall p \tag{18}$$

$$r^{rem}_{s,p} \le y_{s,p} \times \varepsilon + \left(1 - y_{s,p}\right) \times BM \qquad \forall s \;\&\; \forall p \tag{19}$$

$$\sum_{f} \sum_{d} x_{s,f,d,p} \times O_f + \left(r^{rem}_{s,p-1} + r^{act}_{s,p} \right) \times 60 \times X_s \Big/ L_s \le T \times 3600 \times X_s \times \alpha^{S}_{s} \Big/ L_s \qquad \forall s \;\&\; \forall p \tag{20}$$

$$l_{f,p} = O_f \qquad \forall f \;\&\; p = 1 \tag{21}$$

$$l_{f,p+1} = l_{f,p} - \sum_{s} \sum_{d} x_{s,f,d,p} \times O_f \qquad \forall f \;\&\; p = 1 \ldots P-1 \tag{22}$$

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

$$l_{f,p} - \sum_{s} \sum_{d} x_{s,f,d,p} \times O_f \le m_{f,p} \times O_{\min} + \left(1 - m_{f,p}\right) \times BM \qquad \forall f \;\&\; \forall p \tag{24}$$

$$m_{f,p+1} \ge m_{f,p} \qquad \forall f \;\&\; p = 1 \ldots P-1 \tag{25}$$

$$\sum_{d} \sum_{f} x_{s,f,d,p} \times O_f \Big/ X^{+}_{s} + x^{-}_{s,p} = 1 \qquad \forall s \;\&\; \forall p \tag{26}$$

$$\sum_{d} x_{s,f,d,p} \le a_{s,f,p} \qquad \forall s, \forall f \;\&\; \forall p \tag{27}$$

$$\sum_{s} \sum_{d^{o}} x_{s,f,d^{o},p} \times O_f \le l_{f,p} \times Q_f \qquad \forall f \;\&\; \forall p \tag{28}$$

$$\sum_{s} \sum_{d^{w}} x_{s,f,d^{w},p} \times O_f \le l_{f,p} \times (1 - Q_f) \qquad \forall f \;\&\; \forall p \tag{29}$$

$$N^{F}_{f} \times \sum_{s} a_{s,f,p} - \sum_{f'} m_{f',p} \le 0 \qquad \forall f, \forall p \;\&\; f' \in PrecedenceSet_f \tag{30}$$

$$\sum_{s}\sum_{f}x_{s,f,d^c,p}\times O_f\Big/\left(Z_{d^c}\times T\right)+\delta^-_{d^c,p}-\delta^+_{d^c,p}=1 \qquad \forall d^c \;\&\; \forall p \tag{31}$$

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

$$\delta^+_{d^c,p}\le \Lambda^+_{d^c}\Big/Z_{d^c} \qquad \forall d^c \;\&\; \forall p \tag{33}$$

$$\sum_{s}\sum_{f}x_{s,f,d^o,p}\times O_f\times \bar{G}_{f,k}+g^-_{k,d^o,p}-g^+_{k,d^o,p}=\sum_{s}\sum_{f}x_{s,f,d^o,p}\times O_f\times G_{k,d^o} \qquad \forall k,\forall d^o \;\&\; \forall p \tag{34}$$

$$\sum_{s}x_{s,f,d,p}\times O_f\le \sum_{t}n_{t,f,d}\times H_t \qquad \forall d,\forall f \;\&\; p=1 \tag{35}$$

$$\sum_{s}x_{s,f,d,p}\times O_f+J\ge \sum_{t}n_{t,f,d}\times H_t \qquad \forall d,\forall f \;\&\; p=1 \tag{36}$$

$$\sum_{d}n_{t,f,d}\times H_t\le \sum_{s}\left(\sum_{d}x_{s,f,d,p}\times O_f+a_{s,f,p}\times J\right)\times M^t_{t,s} \qquad \forall t,\forall f \;\&\; p=1 \tag{37}$$

$$\sum_{f}\sum_{d}n_{t,f,d}\times \bar{T}_{t,f,d}\le T\times 60\times N^T_t\times \alpha^T_t \qquad \forall t \tag{38}$$

$$\sum_{f}\sum_{d}x_{s,f,d,p}\le \left(1-\phi_s\right)\times BM \qquad \forall s \;\&\; p=1 \tag{39}$$

$$a_{s,f,p}\le \min\Big(1,abs\left(M^{ore}_s-Q_f\right)\Big) \qquad \forall s,\forall f \;\& \forall p \tag{40}$$

The assignment of shovels to faces is modeled by constraints (7) to (13). The model assigns shovels to their initial faces in the first period by constraint (8), and limits only one shovel to be working on any face in any period by constraint (7). Constraint (9) is used to model the shovel movement to a new face within the same period, which limits a shovel be allocated to maximum two faces during any period. Constraint (10) looks over all the available faces and limits the maximum number of faces assigned to a shovel in a period to two, only if one of the assigned faces is mined out completely, otherwise limits it to one. The right hand side of this constraint takes a very large value for all the faces where shovel is not assigned by using a very large value (BM), and does not do anything. For the faces shovel is assigned, constraint looks at the assignment in the previous period, which if false constraint behaves similar to constraint (9). If the shovel is found to be assigned to the face in previous period, constraint now looks if that face is mined out completely by that period, which if true shovel is allowed to be assigned to two faces otherwise shovel is allowed to be assigned to maximum one face in that period. The continuity in shovel assignment is incorporated by constraint (11), which forces the shovels to remain on the same face in next period if the face is not mined out completely by that period. Constraint (12) prohibits a shovel to be assigned to a new face which is already mined out. It however lets a shovel sit on a face where that shovel was working in previous period. Constraint (13) works in conjunction with constraint (11) to model the specific case when a face is mined out towards the end of a period and the remaining time is not sufficient to complete the movement of shovel to the new face. In such a case, without this constraint, model finds flexibility to assign the shovel to the new face in the next period, without modeling the movement. Thus constraint (13) is used to force any shovel which was working only on one face during any period to remain on the same face in the next period, in turn forcing the model to capture and start shovel movement in the previous period itself.

Shovel movement times are modeled using constraints (14) to (19). Constraint (14) models the movement time of a shovel in a period. Due to the dimensionality of the variables considered, this constraint could not be formulated as equality. Thus constraint (14) models the movement time as greater than or equal to the actual movement time, which takes the equality value because model want the minimum movement time in the objective function. The constraint looks over all the faces and right hand side of the constraint takes a negative value for all the faces shovel is not assigned to. The right hand side takes a positive value only for two faces where shovel is actually assigned. If shovel is only assigned to one face in a period, right hand side takes a value of zero for the assigned face, thus no movement time during that period.

The movement time is further split into actual time spent in movement during that period and remaining movement time for the next period by constraint (15). Constraint (16) ensures a zero movement time if shovel was assigned to only one face in a period. Constraints (17) to (19) prohibit any production from the assigned faces if remaining movement times are not zero, i.e. if shovels have not moved to them completely in that period.

The total production capacity of the shovels is modeled by constraint (20), limited by the time lost during movement and maximum production possible by the shovels. Constraints (21) to (25) model the tonnage available at faces in each period and sets value to the mined out binary variable for each face.

Production by shovels is modeled by constraints (26) to (29). Constraint (26) models the negative deviation in production by shovel compared to its capacity and constraint (27) do not allow any production from a face where the shovel is not assigned during that period. Constraint (28) and (29) model the maximum ore and waste production possible from the assigned faces.

The accessibility of faces is modeled using the precedence requirement by constraint (30), which lets an assignment variable of a face to take a value of one, only if all the precedence faces are already mined out by that period.

The deviation in production received at processing plants, compared to capacity, is modeled by constraint (31), and limited by constraints (32) and (33). Constraint (34) models the deviation in grades received at ore destinations in the form of deviation in metal content received.

Truck allocation is required only for the decision time frame (first period) which is used within the simulation. Thus only first period of the optimization is considered for truck allocations. The required number of truck trips is modeled using constraints (35) to (38). As production is not always an integer multiple of truck capacities and to induce a flexibility in the production, Constraint (35) and (36) determine the required number of truck trips to haul the produced tonnage. Constraint (37) is similar to constraint (36), but it also models the matching of truck types to shovels, i.e. no trip is possible by a truck type from a face where a non matching shovel is assigned. Constraint (38) models the maximum number of truck trips possible based on the number of trucks and production time available.

Constraint (39) is used to indicate shovel failures to the model when running with the simulation. It lets shovel sit on the face but forces zero production from the assigned face in the first period (the decision time frame for simulation), assuming shovel will be back from next period. Shovels can also be locked to work only in ore or waste or allowed to work in both using Constraint (40).

4. Discrete event simulation

The discrete event mine simulation model is developed in Arena . The VBA capability of Arena has been extensively used to build the simulation model and update the existing layout of the mining system. Fig. 2 shows the steps which are carried out in the simulation. Step 1 is a manual process which is carried out only if the mining system changes i.e. road network, schedule, number of shovels and number of truck types and shovel types in the system changes. A Matlab based GUI is created which reads the dxf file of the designed haul road to generate readable input for Arena, which is then used by a VBA macro written in Arena to generate the haul road network within the simulation model. The same VBA macro also reads other system characteristics from a common configuration input file to build various variables, expressions, shovel resources and truck transporter resources. After the model is manually built, rest of the system does not require any manual operation. General system characteristics such as number of trucks of each type, capacities of equipment, process times and distributions can be readily changed into the common configuration input file which remains linked to Arena, making the model flexible enough for easy scenario analysis.

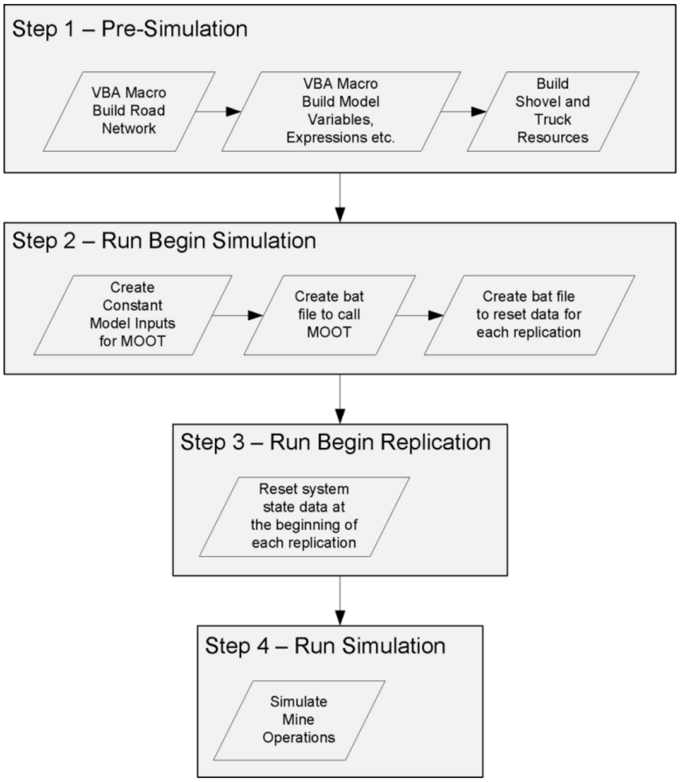

Fig. 2: Steps for translating the existing mining layout into the model and simulation run

Once the simulation model is run, at the beginning of the simulation before compiling the model, a Matlab function is run through the VBA in Arena to read and create a constant parameter matrix from the common input configuration file, which is used by MOOT for decision making purposes. This is necessary because once the simulation is under process the input configuration file becomes inaccessible from outside Arena. Also this reduces the run time of MOOT for reading the inputs from the external file each time it is run. The second step also creates bat files for calling the Matlab functions to run MOOT and resetting the schedule at the end of each replication. The interaction between MOOT and Arena occurs through VBA and text files. The current state of the system including the available tonnage at faces, current face of working of each shovel and shovel states are provided as input to MOOT through a text file and the output of MOOT is also returned through a text file.

Step 3 occurs after the simulation model is compiled just before the start of simulation, and each time a new replication starts. At this step the system state is re-initialized, i.e. shovel positions are reset to their initial faces in the schedule and the tonnages of polygons are reset to their original values. The simulation model is then run in step 4 for multiple replications to capture the mining operational data.

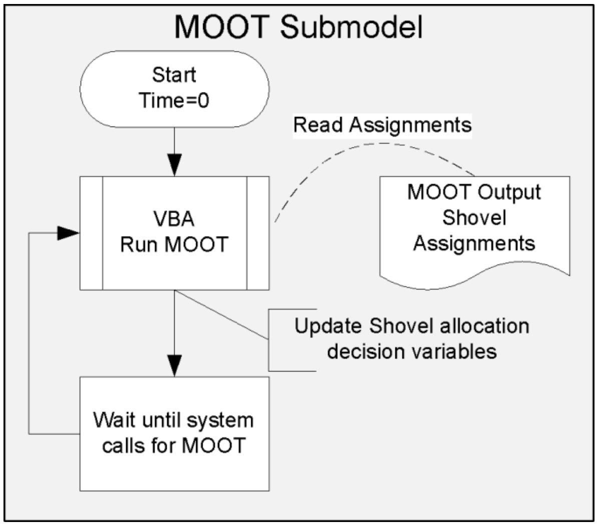

Fig. 3: Submodel to call MOOT as external decision support system for shovel and truck allocations optimization

Fig. 3 shows a submodel for running the external decision support system MOOT. This model is run in the beginning of each replication at simulation time of zero and each time the system state changes, i.e. a shovel comes up after failure or any face gets depleted. The MOOT is called through VBA and its outputs are read-in to reassign shovels, target productions and number of truck trips by each truck type on various paths.

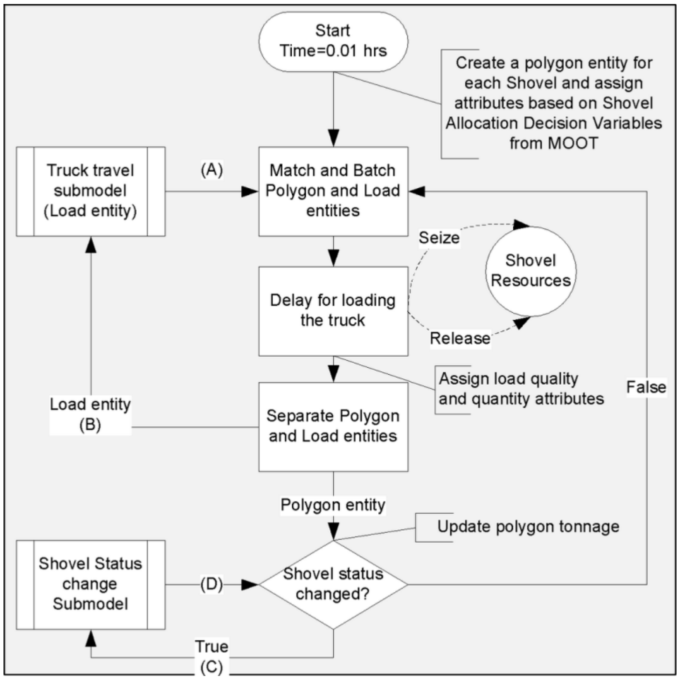

Fig. 4: Flow of the mine operation simulation model

Fig. 4 shows the flow of the main simulation model. This main model consists of a polygon (face) entity and a load entity. Polygon entities are created for each shovel in the system in the beginning of the simulation after MOOT output is recorded. Each of these polygon entities are then assigned the polygon attributes based on the shovel assignments provided by MOOT. Similarly a load entity is created for each truck and truck attributes are assigned to them after the MOOT is run in the beginning of simulation (Fig. 9). In the main model, once a load entity reaches a shovel, it is matched with the polygon entity of the corresponding shovel and batched together into a single entity temporarily to model the loading process at the shovels. Now the shovel resource is seized and loading is carried out based on the number of buckets, bucket cycle time distributions and the total tonnage for the shovel and truck type combination. Shovel resource is released after the loading process is finished and load quality, quantity and time attributes are assigned to the batch entity, which is then separated back into load and polygon entities carrying their respective attributes along with loading attributes. Load entity is then sent into the truck travel submodel where hauling, dumping and return travel of trucks back to shovel takes place. Polygon entities are updated with their remaining tonnages and then checked for any change of status, which includes if polygon is completely depleted, or corresponding shovel is failed, or put on standby (Fig. 8); otherwise it goes back to match process where shovel sits idle until next load entity (truck) arrives.

The dumping process is shown in Fig. 5. After the load entity gets its load from the polygon entity, it is transported to its assigned dump location by the truck transporters following the haulage road network. The haul road network, created in the beginning, contains dump points on the network based on the number of simultaneous dumps possible at each dump location. One of the dump points is then chosen based on number of trucks in queue at each dump point once a truck reaches its dump location. The trucks are then moved to the chosen dump point for the dumping process. If the dump location is a hopper, for the crushers, load entities wait until there is enough room for the dumping to take place, otherwise go directly for the dumping process where the load entities seize a dump location resource and carry out the dumping process with the dumping process time delays. Load entities then move back into the travel submodel to travel to an assigned shovel by the truck dispatching logic.

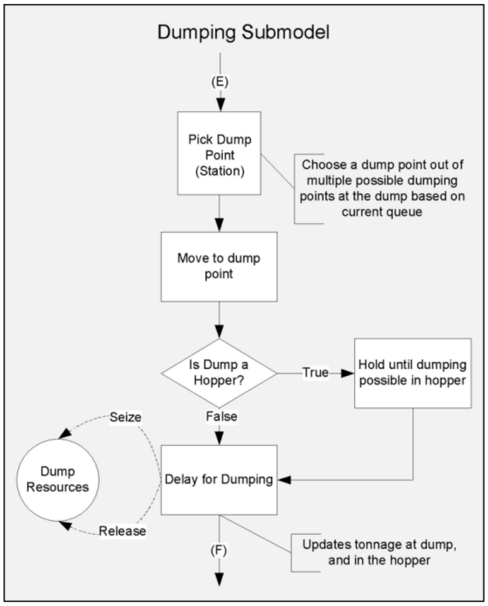

Fig. 5: Flow of the dumping submodel

Although processing plant operations are not modeled in detail into the simulation model, the flow out of hoppers into the crushers is critical to model the flow of ore from mining system into process plants. Thus process plants – flow out of hoppers submodel is created to model the continuous flow out-of hoppers (Fig. 6). The hoppers in the simulation are modeled as tanks containing regulators to remove material out into further processes which are not modeled here. This submodel creates a flow entity for each hopper in the system at the start of simulation and assigns hopper attributes. The entities are then duplicated. The flow entities then seize the regulators for corresponding hoppers and start removing material continuously out of hoppers based on crusher capacities until the end of replication when they release the regulators and get disposed. The duplicated flow entities are looped with fixed delays to record the periodic statistics at the hoppers.

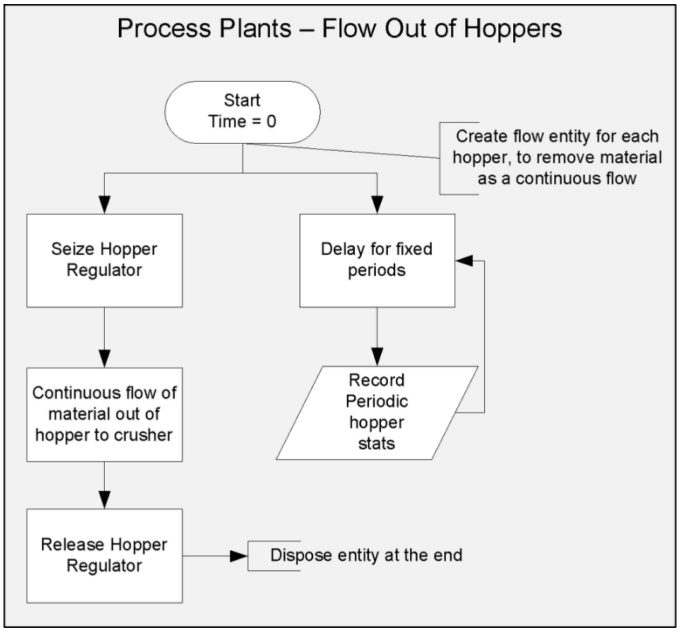

Fig. 6: Flow of the process plant submodel

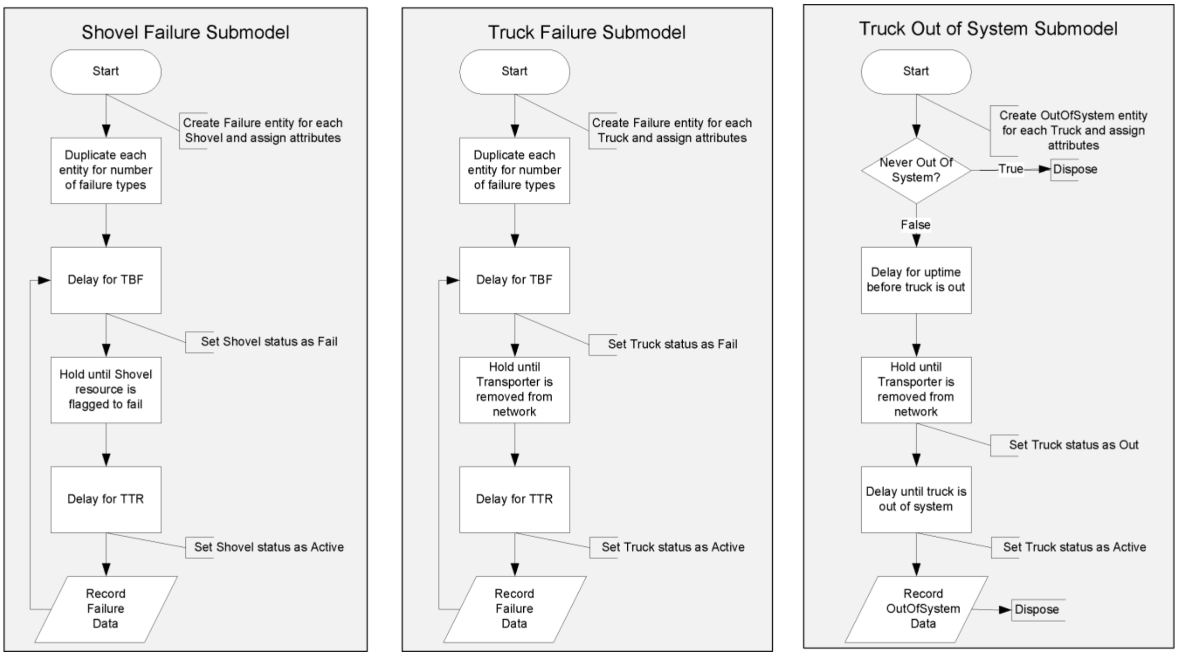

Fig. 7: Shovel and truck failure submodels and truck out of system submodel

Shovel and truck failures and truck out of system based on schedule are modeled separately, as shown in Fig. 7. Truck and shovel resources are failed in these submodels, after which they are removed from the main simulation logic of Fig. 4. A failure entity is created for each shovel and each truck in the system at the start of simulation in both shovel and truck failure submodels respectively. The entities are then duplicated for number of failure types. Time between failures (TBF) and time to repair (TTR) are then determined based on failure time distributions. Entities then wait for TBF after which truck or shovel status is changed to fail. Then entities wait until actual truck or shovel resource is taken out of main simulation logic, after which entities are delayed for the repair time (TTR) and status is changed back to active. The actual resources are then taken back into operation in the main simulation logic as the status is changed to active. Truck out of system submodel is developed in the similar fashion, but as it follows a fixed schedule it is modeled separately. In this submodel out of system entities are created at the start of replication and assigned the start and end times for the scheduled out of system for each truck. If any truck does not have any out of system hours scheduled, the corresponding entities are disposed off right away, otherwise they are delayed until the start of scheduled out of system, and the truck status is changed as out of system to intimate the main simulation logic to remove the truck from operation. The out of system entity then waits until actual truck resource is removed from the main logic and then delayed until the end of scheduled out of system when the truck status is changed back to active and the entity is disposed after recording the out of system times data.

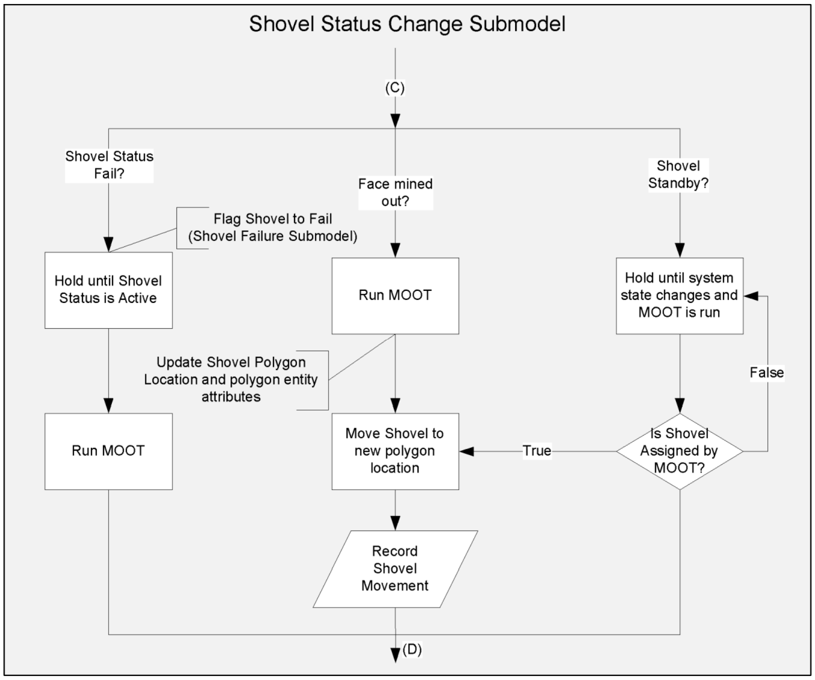

Fig. 8: Flow of shovel status change submodel controlling shovel failures, standby, and reallocation

Fig. 8 shows shovel status change submodel which models the shovel movements, standby and failures in the main simulation logic. After each truck load the status of shovel is checked if it is ready to go for the next load. If the material at the assigned face is depleted, or shovel is not assigned to work (standby) or failed then polygon entity is moved into shovel status change submodel. If the shovel status is ‘fail’, it is flagged as failed in the main logic to start failure time in the failure submodel. The polygon entity waits until shovel status is changed back to active in the failure submodel, after which MOOT is called again to re-optimize the system and reassign faces and target productions for all the shovels. If status change of shovel is because the material of the polygon entity is completely depleted, MOOT is called to re-optimize and assign new face to the shovel. After which polygon attributes are updated to new face assignment and shovel is delayed for the movement time to the new face and shovel movement is recorded. If instead a shovel is not assigned to work, i.e. MOOT output assigns zero target production to a shovel, corresponding polygon entity waits until system is re-optimized by MOOT. Each time MOOT is run, polygon entities waiting as standby are checked if corresponding shovels are assigned to work. If they remain on standby, corresponding polygon entities continue to wait for the next optimization, otherwise shovel is moved to the newly assigned face and movement data is recorded. The polygon entities then move and wait for a truck to arrive.

4.1. Truck haulage

Trucks in the simulation model are modeled as guided path transporters in Arena. Guided path transporters are provided in Arena to model the AGVs (automated guided vehicles), which are restricted to travel on fixed paths, by seizing and releasing the zones of length equal in length of the

AGVs. This characteristic allows us to model the traffic congestions and platoon formations of trucks on haul roads, as overtaking is prohibited for AGVs.

The haul road network of the mine is created as Network consisting of unidirectional network links. To model two way haul roads with single lanes, unidirectional network links are duplicated in opposite direction to model the upcoming travel paths. Each network link connects two points on the haul road and is divided into number of zones. Trucks are moved zone by zone in Arena by seizing the next zone and releasing the occupied zone. This seizing and releasing process restricts the movement of trucks and do not allow the trailing trucks to overtake. To incorporate a safety distance between trucks while traveling, zones of length equal to the summation of average truck length and a safety distance are constructed. By selecting the zone control rule as 'start', transporters are made to release a zone when next zone is seized and thus safety distance is maintained between trucks.

A Matlab GUI is created which reads the dxf input of the designed haul road network and converts into a formatted input, which is then used by the VBA in Arena to construct the Network, Network Links and zones. This instills flexibility into the model to change the haul road network very easily over the course of mine life.

In Arena, transporters or the entity seizing the transporter remain out of the main logic when travelling and thus cannot be controlled unless they reach their destination. Thus, although transporters in arena can be sent directly from its position to any other position on the Network, trucks in this simulation model are moved link by link on the haul roads. This is done to assign speed to trucks based on varying haul road characteristics, model the truck failures and have control at least intermittently while travelling. The modeling of truck haulage logic of mine operations is shown in Fig. 9, which is designed to move the trucks link by link on their path to respective destinations and keep a control on their movement.

Fig. 9 shows the truck travel submodel logic and the initialization logic for the trucks in the model. At the start of simulation, after MOOT has provided shovel and truck allocation decision, a load entity is created for each truck in the system and truck attributes are assigned to them. These load entities are then assigned a shovel using a truck dispatching logic and following truck allocation decision given by MOOT. A transporter is then allocated to each load entity and dispatched directly to their assigned shovel stations on the haul road network. Entities then travel out of the main logic through the haul road network with the transporter to the haul road station of their corresponding shovel.

In the truck travel submodel, entities coming after loading (B), or after dumping (F) are first assigned a destination station on the road network based on dispatching. Then using Arena functions next intersection to travel is determined based on shortest path to reach their destinations. After the next intersection is assigned to the entities, failure status of trucks is checked. If the truck status is 'fail' or 'out', trucks are moved to a failure intersection which remain out of main road network, where trucks wait until their status is active when they move back to their original intersection in the road network and start normal travel. If the trucks are found active, trucks are transported to the next intersection with a velocity based on the trucks rimpull curve characteristic and haul road gradient and rolling resistance of the next segment to travel. The load entities appear back into the logic at the haul road stations module where a condition is checked whether the current station is the destination station for the load entity. If the current station is found as the dumping station assigned as destination to the load entity, it is moved to the dumping submodel; or if the current station is found as loading station, it is moved to the loading station; otherwise load entity is assigned its next intersection to travel and transported. Before moving the load entity to the loading submodel, shovel status is checked. If shovel status is found 'fail', the truck is redirected to a different shovel using the truck dispatching logic. The data is collected for every load dumped at dump location. Truck dispatching in simulation is performed by modeling the Dispatch logic given by White and Olson (White & Olson, 1986).

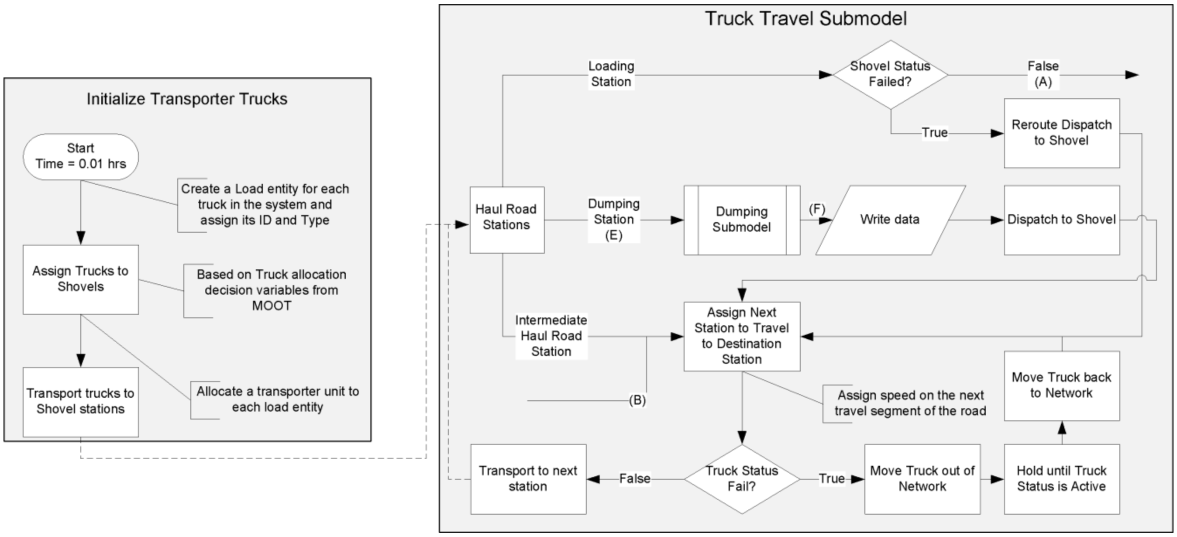

Fig. 9: Flow of the truck travel submodel and the initialization of transporters as trucks

5. Model Implementation

The simulation optimization model presented in this paper is implemented with an iron ore mine case to carry out a detailed verification study. The simulation optimization model is implemented to develop an efficient short term plan for year 11 of the long term schedule. The schedule in year 11 requires mining on four benches 1745, 1730, 1610 and 1595, consisting of 16.42 MT of ore and 39.11 MT of waste. The mining operation is carried out using three waste shovels and two ore shovels with two plant crushers and a waste dump. Both plant crushers operate at an average 2000 ton per hour with hopper capacities of 500 ton each. Plant 1 and plant 2 crusher desire ore with MWT grades of 65% and 75% respectively from the available grade and tonnage distribution in the schedule as given in Fig. 10.

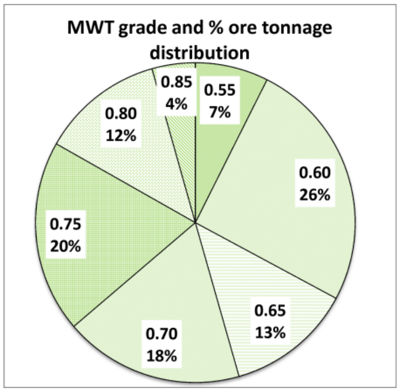

Fig. 10: MWT grade and ore tonnage distribution in schedule

Mine employs two Hit 2500 shovels to work in ore and three Hit 5500EX shovels to mine waste. Mine also employs Cat 785C trucks (truck type 1) with nominal capacity of 140 ton and Cat 793C trucks (truck type 2) with nominal capacity of 240 ton to haul the material.

Mine management want to determine the best short term schedule and the number of trucks to maximize the efficiency of the production operations and meet the strategic schedule. The simulation optimization model is thus implemented on the case study to run over 6 months and 10 replications, to analyze the operations with target ore production of 8.21Mt and waste production of 19.56Mt. The model is not run for the whole year, as such longer time predictions are undesired due to increased uncertainty.

Two cases were analyzed during this implementation, C1: only Cat 785C trucks (truck type 1) in the system, and C2: mixed fleet with Cat 785C trucks locked to ore shovels and Cat 793C trucks (truck type 2) locked to waste shovels. Due to large capacity of Cat 793C trucks, they are locked to large waste shovels, and Cat 785C trucks are locked to ore shovels in case C2.

5.1. Model verification

The results were first analyzed as part of the verification process by comparing the model outputs with the expectations. Key performance indicators (KPIs) of the system were plotted with increasing number of trucks in the system for both cases C1 and C2 to verify the model by comparing the output with the expectations.

Fig. 11 and Fig. 18 show the mean value of observed ore and waste productions with increasing number of trucks in the system over 10 replications for both cases C1 and C2. The total production is expected to increase with increase in number of trucks, till shovels operate at their maximum operating efficiency, which is also observed in both the cases. But Ore productions are not observed to be affecting much in C1. This is because MOOT tries to meet the plant feed rate, which in case of C1 can be achieved by diverting more trucks to work in ore from waste. In case of C2, if number of trucks in ore is not sufficient, due to trucks locked to ore or waste, MOOT cannot divert more hauling capacity to ore shovels. Thus, in C2, ore or waste productions are affected only by changes in number of trucks working with ore or waste shovels specifically. This pattern can also be observed in Fig. 17 and Fig. 23 which shows the individual shovel operating efficiencies in C1 and C2. Ore shovels (S1 and S2) are found to have higher operating efficiencies compared to waste shovels (S3, S4 and S5) in C1, which increases very gradually with increasing number of trucks, whereas operating efficiencies of ore and waste shovels in C2 are found to follow the number of ore and waste trucks in the system. Fig. 23 also shows very less operating efficiency for shovel 5 in the beginning, which happens because of distant location of shovel S5. As number of trucks with waste shovels for scenarios 1 to 4 is very small in C2, MOOT allocates more trucks to closer shovels S3 and S4 to maximize the production.

Average shovel and truck operating efficiencies are shown in Fig. 14 and Fig. 15 for C1 and Fig. 21 and Fig. 22 for C2. The observations show clear and expected relationship between truck and shovel operating efficiencies. As number of trucks in the system increases, hang time of shovels decreases as shown in Fig. 16, increasing shovel operating efficiencies; but at the same time queue times of trucks increases leading to decreased truck operating efficiencies.

Fig. 12, Fig. 13, Fig. 19 and Fig. 20 show the average ton per hour (tph) ore delivered to both plants in both cases. The behavior is found to be following the expectation, but the TPH observed falls short of the target TPH of the plants (2000 tph). The main reason for this is attributed to the operating efficiencies of ore shovels and an average 94% availability of shovels observed. It should be noted here that due to maximum 2000 tph feed capacity to crusher and very limited 500 ton hopper capacity, the delivery rate to hoppers cannot exceed 2000 tph, leading to increased dumping times and queuing times at the plants when delivery rate is higher. But the delivery rate falls short at times shovels are failed, decreasing the tph delivered to plants; and thus average tph observed falls short of target.

The scenarios analyzed have found conformity with the expected behavior of the mining system and desired decision making by MOOT, verifying the model for its correctness and efficiency in capturing the system performance.

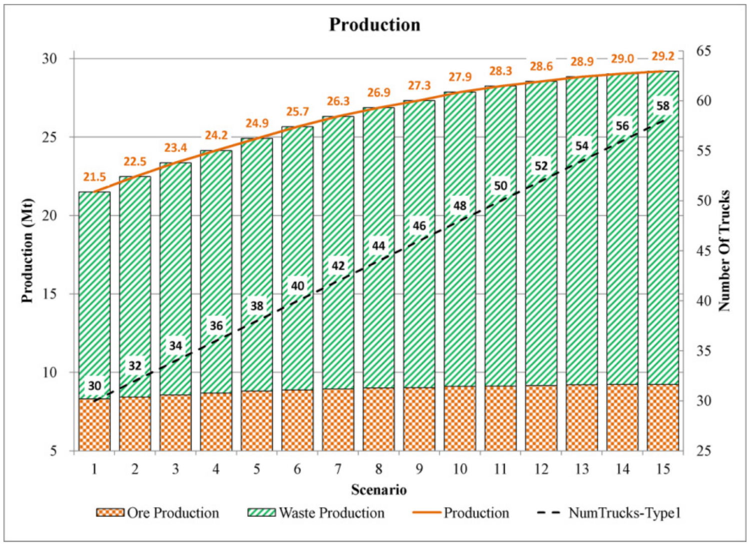

Fig. 11: Ore and waste production observed with increasing number of trucks for case C1

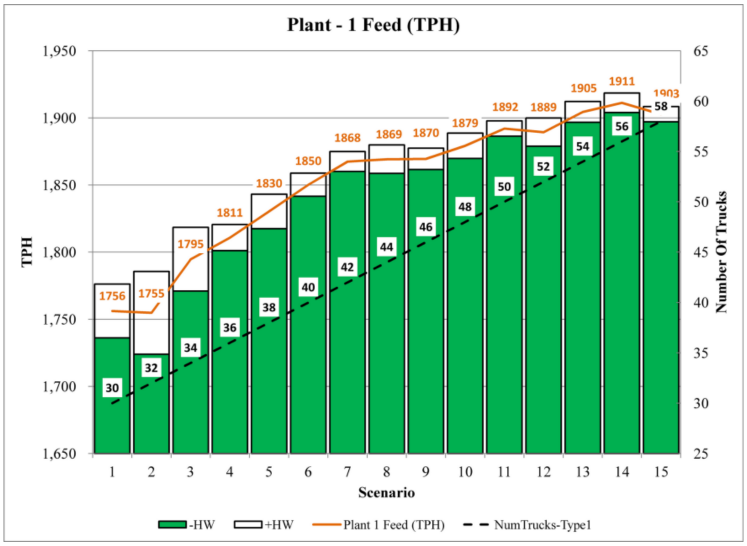

Fig. 12: Ton per hour (TPH) delivered to Plant 1 with increasing number of trucks in case C1

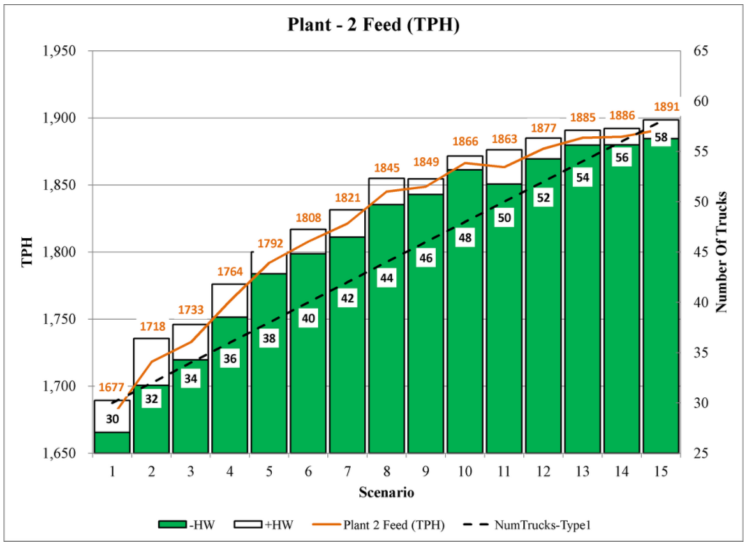

Fig. 13: Ton per hour (TPH) delivered to Plant 2 with increasing number of trucks in case C1

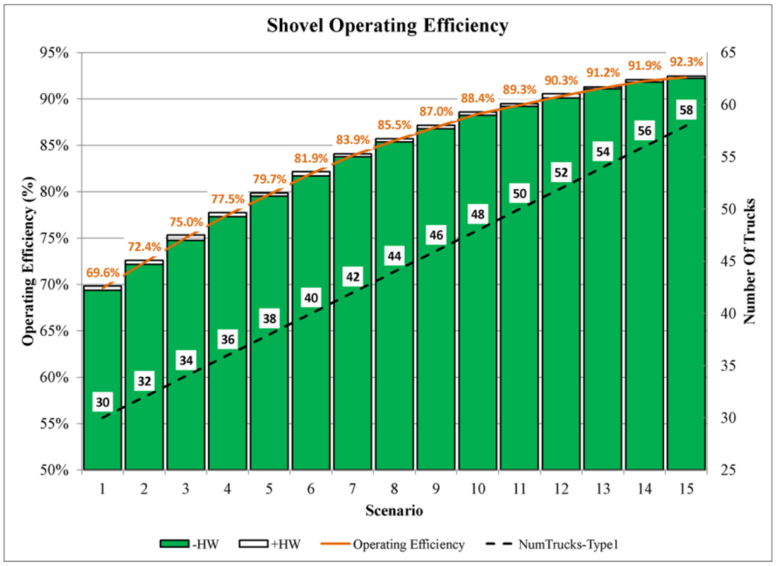

Fig. 14: Shovel operating efficiencies observed with increasing number of trucks in case C1

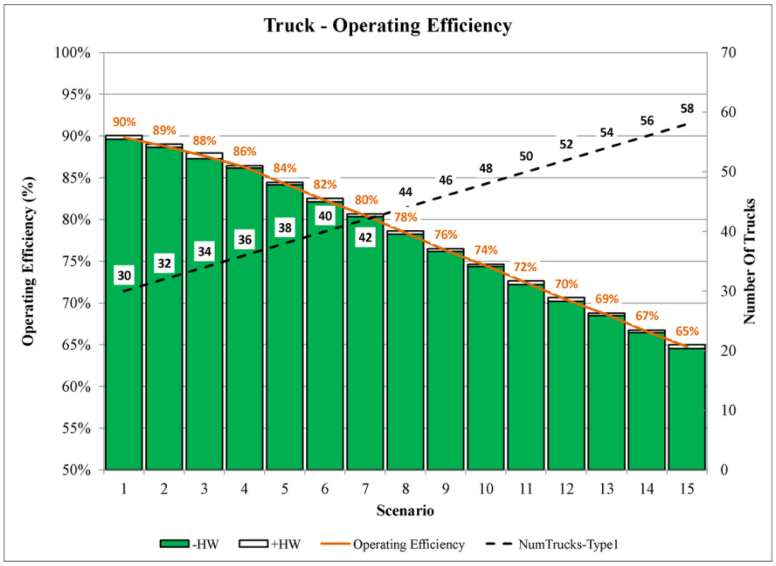

Fig. 15: Truck operating efficiencies observed with increasing number of trucks in case C1

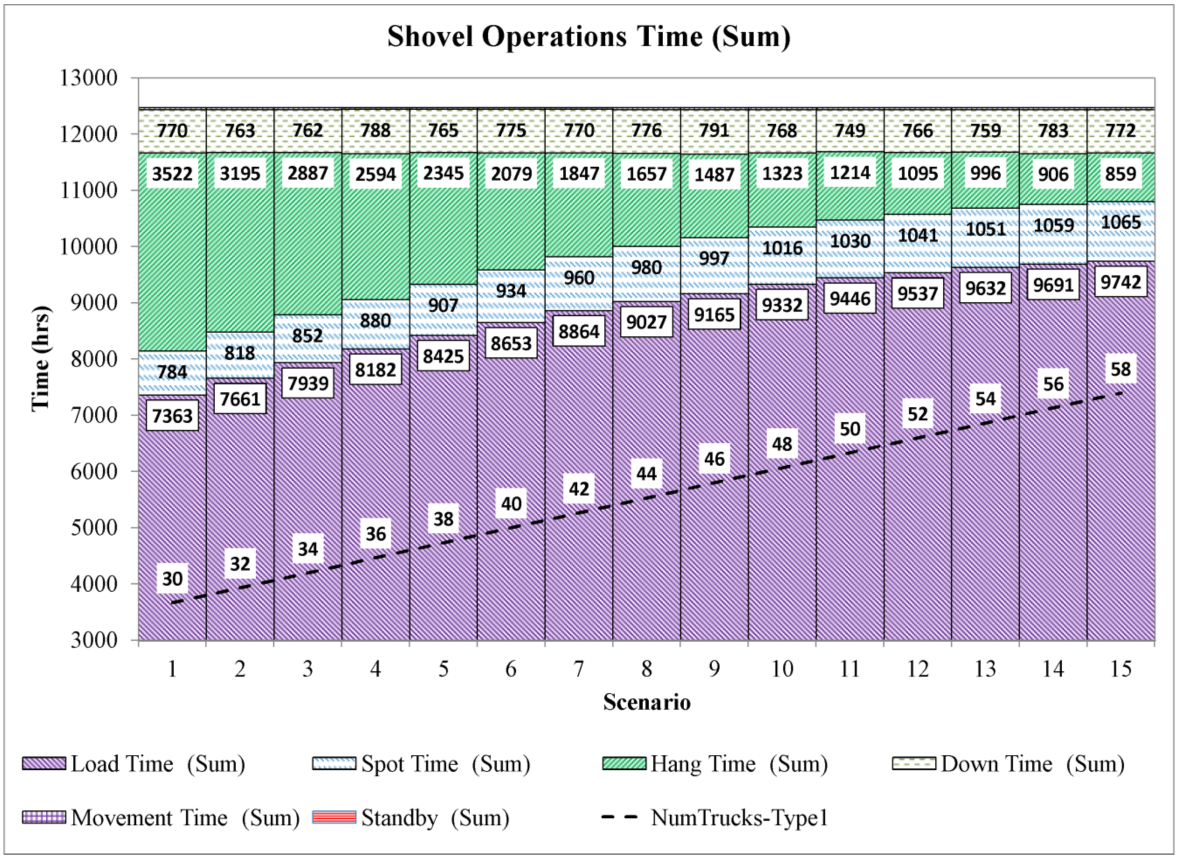

Fig. 16: Distribution of shovel operation times (combined all shovels) with number of trucks in case C1

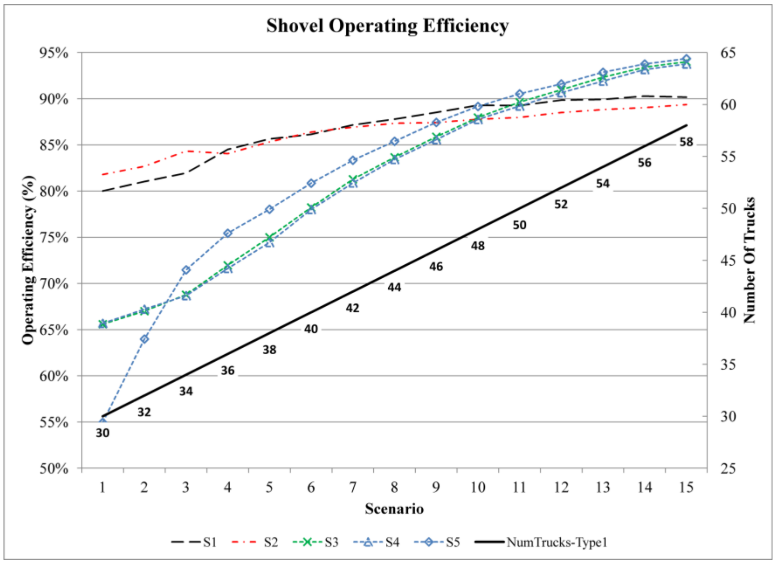

Fig. 17: Individual shovel operating efficiencies observed with number of trucks in case C1

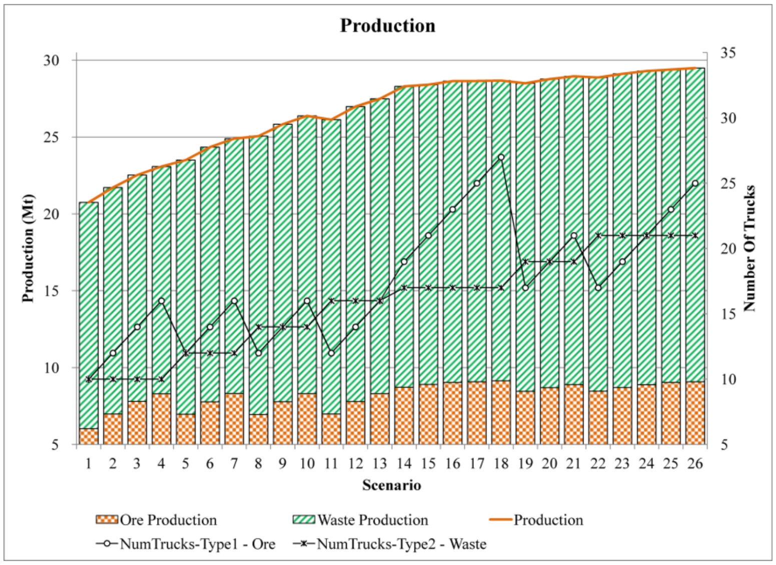

Fig. 18: Ore and waste production observed with increasing number of trucks for case C2

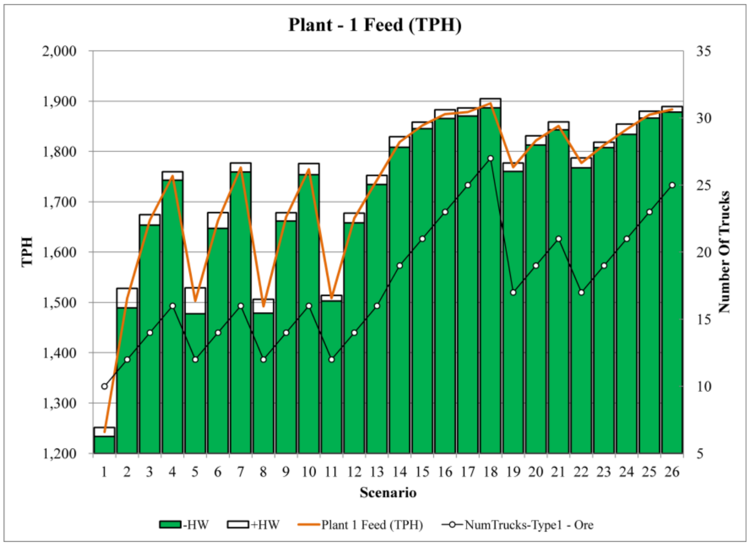

Fig. 19: Ton per hour (TPH) delivered to Plant 1 with increasing number of ore trucks in case C2

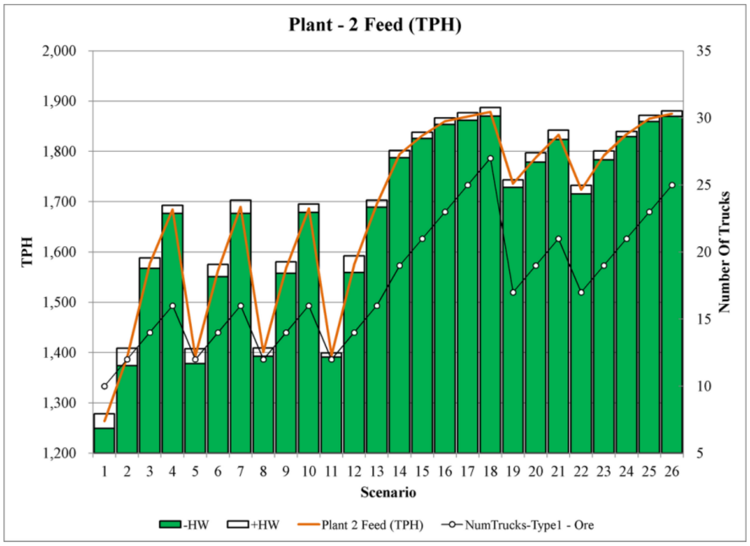

Fig. 20: Ton per hour (TPH) delivered to Plant 2 with increasing number of ore trucks in case C2

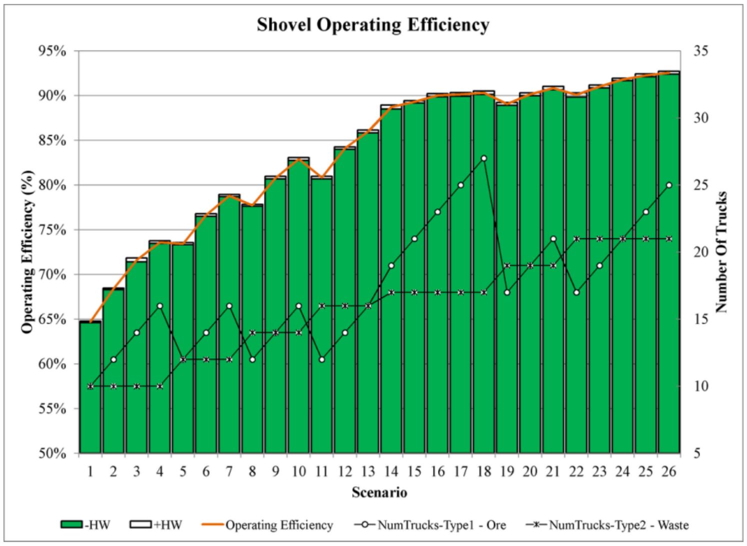

Fig. 21: Shovel operating efficiencies observed with increasing number of trucks in case C2

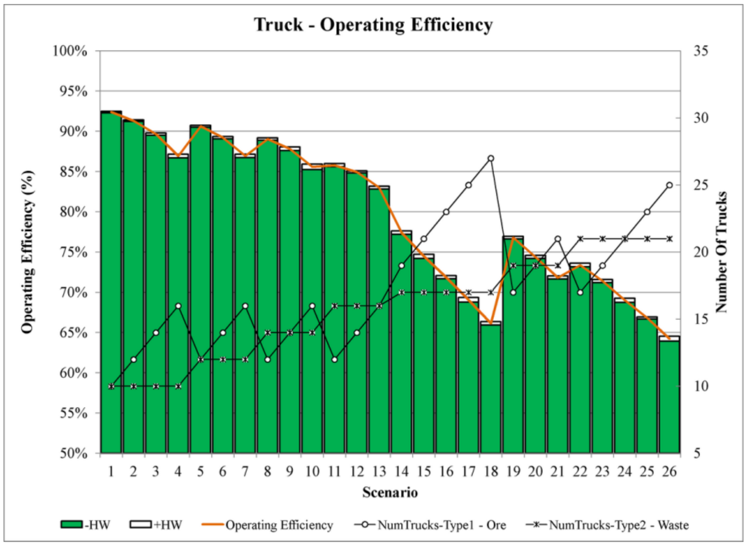

Fig. 22: Truck operating efficiencies observed with increasing number of trucks in case C2

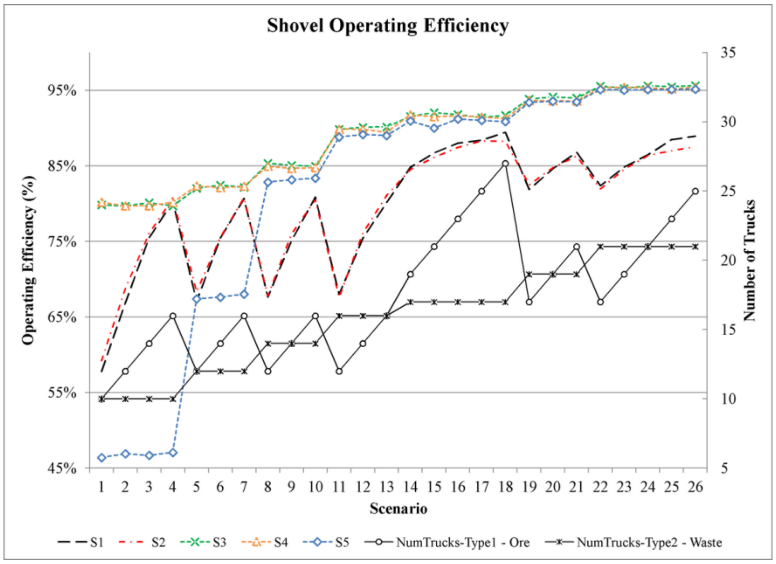

Fig. 23: Individual shovel operating efficiencies observed with number of trucks in case C2

5.2. Scenario selection and analysis

The two cases were analyzed against the target ore and waste productions of 8.21Mt and 19.56Mt respectively, and the operating efficiencies of shovels and trucks to determine the best scenario. In the case C1, scenario 13 was found to be the best scenario which meets the targeted ore and waste productions and provides satisfactory operating efficiencies of 91.2% and 68.63 % respectively. Scenarios 14 and 15 also satisfy the target productions, but are rejected due to further decreasing truck operating efficiencies and very less gain in shovel operating efficiencies.

Similarly in the case C2, scenarios 16, 17 and 19 to 26 satisfy both ore and waste target productions. As shovel operating efficiencies of all the selected scenarios are approximately 90% or above, they were analyzed against truck operating efficiencies. Having a target of above 70% truck efficiency, scenarios 16, 19, 20, 21, 22, and 23 were further screened to be analyzed against TPH delivered to plants where scenario 16 is selected as the best scenario which satisfied plant requirements to the most and found satisfactory for production and operating efficiencies of the equipments for case C2.

Table 2: Comparison of the selected scenarios for case C1 and C2

	C1 – Scenario 13		**C2 – Scenario 16**	
	Mean	Half Width	Mean	Half Width
Ore Production (ton)	9,216,802	25,832	9,036,840	26,665
Waste Production (ton)	19,642,130	73,585	19,605,509	45,807
TPH – Plant 1 (ton/h)	1905	8	1874	9
TPH – Plant 2 (ton/h)	1885	6	1860	6
Shovel Operating Efficiency (%)	91	0.1	90	0.2
Truck Operating Efficiency (%)	69	0.1	72	0.2
Empty Haul Distance (Km)	648,547	1,586	474,020	716
Full Haul Distance (Km)	652,436	1,602	476,068	736

Comparing the selected scenarios from C1 and C2 in Table 2, we can see that best scenario for C1 performs slightly better than best scenario for C2, except truck operating efficiency. But the total haulage distance covered in C2 is much lesser than in C1, which is because of less number of higher capacity trucks used as mixed fleet system in C2. This is an important criterion for an efficient operation, as it affects the life of truck tires and trucks as such, and has a substantial impact on mining cost. Thus best scenario for C2 should be selected. Although due to the mixed fleet system, locking of trucks to shovels becomes necessary that decreases the dispatching efficiency in C2, it is favorable over C1 due to the impact on cost and increased traffic on haul roads with large fleet of smaller trucks in C1.

The selected scenario for C2 is further analyzed for the weekly ore and waste productions (Fig. 24 and Fig. 25), average weekly tph delivered to both plants (Fig. 26 and Fig. 27) and average weekly MWT grade delivered to both the plants (Fig. 28 and Fig. 29). Fig. 24 to Fig. 29 show the efficiency of MOOT in meeting the mine operational objectives of maximizing the production and meeting the quantity and quality requirements of the plants. The average weekly grades delivered to plant 1 (Fig. 28) and plant 2 (Fig. 29) show the efficient grade blending obtained compared to the available grades in schedule as shown in Fig. 10. The grade blending in this approach is not obtained merely by truck dispatching, but also by optimally allocating the shovels to the best faces so that blending can be achieved by truck dispatching. As decisions made by MOOT takes into account shovel allocations in further periods as well, the decisions are far sighted as well so that operations are efficient throughout the production period.

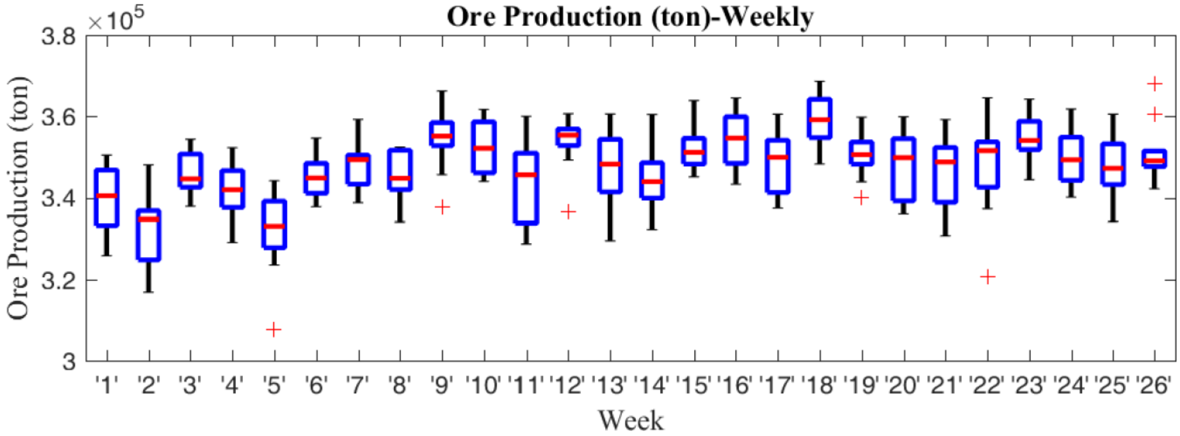

Fig. 24: Weekly ore production for the selected scenario in C2

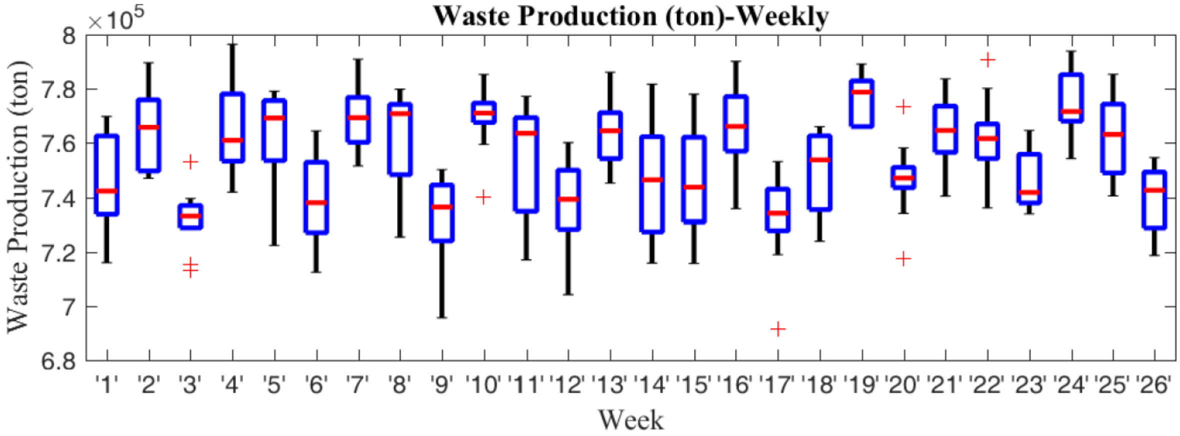

Fig. 25: Weekly waste production for the selected scenario in C2

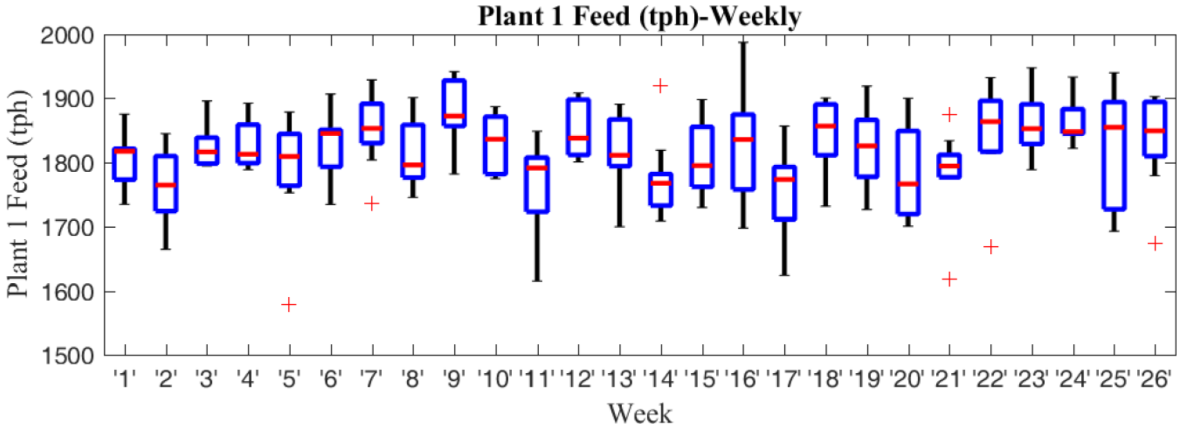

Fig. 26: Weekly average ton per hour delivered to plant 1 for the selected scenario in C2

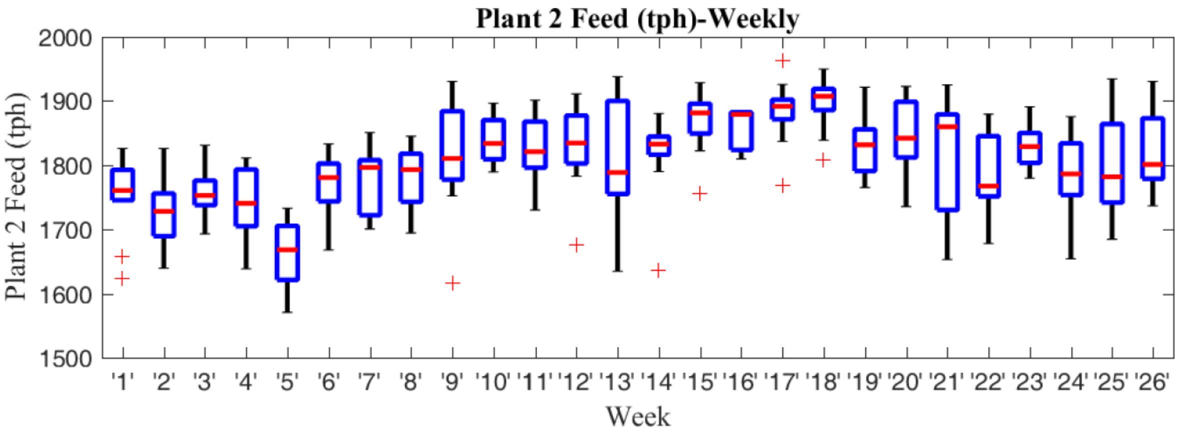

Fig. 27: Weekly average ton per hour delivered to plant 2 for the selected scenario in C2

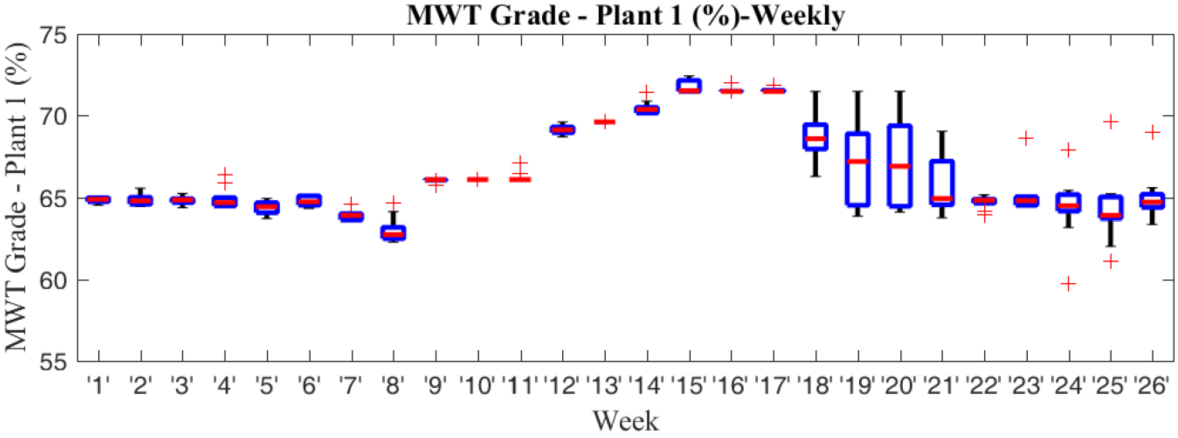

Fig. 28: Weekly average MWT grade delivered to plant 1 for the selected scenario in C2

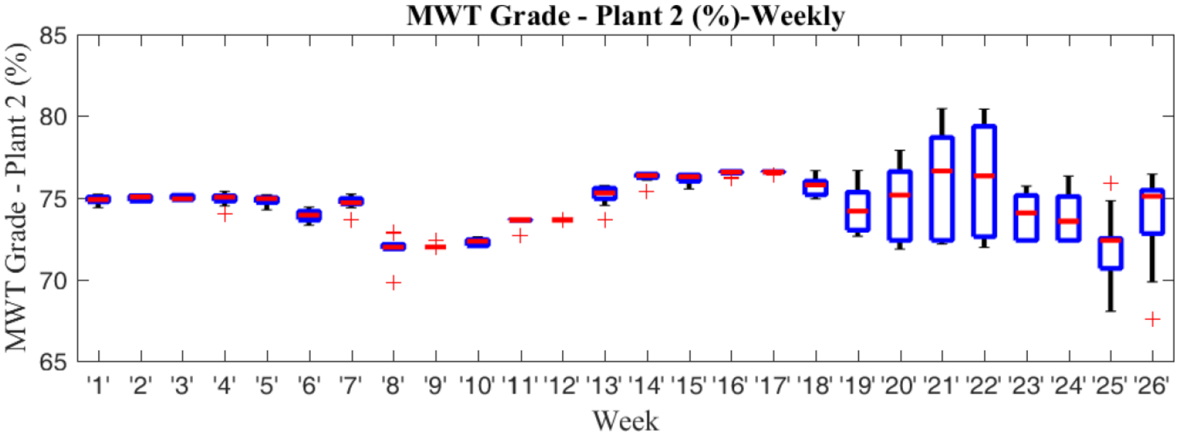

Fig. 29: Weekly average MWT grade delivered to plant 2 for the selected scenario in C2

Various other scenarios can be run at this stage by changing other system characteristics, such as mine haul road design, different weight to blending objectives for both plants if desired and increased hopper capacities etc. to optimize the mine operations performance based on desired objectives. The shovels assignments for the best replication result in the selected scenario can be used to create the short term schedule to be implemented into actual mine operations.

6. Conclusions and recommendations

This paper presented a novel approach towards short term mine production planning and optimization. The detailed verification studies of the simulation optimization model presented show its capability in modeling the mine operations and providing efficient mine operational decisions using MOOT. Also, the flexibilities provided in modeling the system using VBA and Matlab tools make the model easily implementable and reusable over time. The model in its current form is capable of efficient short term planning by analyzing the impact of different haul road designs, haul road conditions, traffic congestions, different dispatching strategies and varying plant requirements on mine operations.

The very unique characteristic addition of the proposed simulation optimization approach in the short term mine planning process is the ability to incorporate minor details of mine operations in the planning process and help in proactive decision making. Including further characteristics into the simulation model, the approach is capable of providing realistic and practical short term schedule by capturing:

- Effect of haul road conditions on tire cost expenditures of trucks
- Effect of accidents on truck speeds and in-turn on production
- Effect of different dispatching algorithms or truck locking strategies
- Detailed cost estimations in production operations

7. References

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8. Appendix

8.1. Indices

Table 3: Indices 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. Parameters

Table 4: Parameters of systems considered

N_t^T	Number of trucks of type t
H_t	Tonnage capacity of truck type t
J	Flexibility in tonnage produced, to allow fractional overloading of trucks (tonne)
V_t	Average speed of truck type t when empty (Km/hr)
$\bar{V}_t$	Average speed of truck type t when loaded (Km/hr)
C_t	Cost of empty truck movement ($/Km)
$\bar{C}_t$	Cost of loaded truck movement ($/Km)
$M_{t,s}^T$	Binary match parameter, if truck type t can be assigned to shovel s
X_s	Shovel bucket capacity (tonne)
X_s^+	Maximum possible shovel production in decision time frame ‘*T*’ (tonne)
X_s^-	Minimum shovel production desired in decision time frame ‘*T*’ (tonne)
L_s	Shovel loading cycle time (seconds)
U_s^+	Maximum desired shovel utilization (%)
U_s^-	Minimum desired shovel utilization (%)
A_s	Cost of shovel movement ($/meter)
S_s	Movement speed of shovel (meter/minute)
α_t^T	Truck availability (fraction)
α_s^S	Shovel availability (fraction)
Fi_s	Face where shovel is initially located (start of the shift)
D_f^{FE}	Distance to exit from face f

D_d^{ED}	Distance to destination d from the pit exit
Z_{d^c}	Maximum capacity of the crushers/processing plants (tonne/hr)
$\Lambda^+_{d^c}$	Maximum positive deviation in tonnage accepted at crushers/processing plants (tonne/hr)
$\Lambda^-_{d^c}$	Maximum negative deviation in tonnage accepted at crushers/processing plants (tonne/hr)
G_{k,d^o}	Desired grade of material types at the ore destinations
G^-_{k,d^o}	Lower limit on grade of material type k at ore destinations
G^+_{k,d^o}	Upper limit on grade of material type k at ore destinations
F_f^x, F_f^y, F_f^z	x, y, z coordinates of the faces available for shovel assignment (meters)
N_f^F	Number of precedence faces required to be mined before mining face *f*
$\bar{G}_{f,k}$	Grade of material type k at face f
O_f	Tonnage available at face f at the beginning of optimization (tonne)
$O_{\min}$	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)
T	Decision time frame (hr)
Π^-	Lower limit on desired stripping ratio
Π^+	Upper limit on desired stripping ratio
$\Gamma^F_{f^1,f^2}$	Distance between available faces (meters), calculated as linear distance between faces on the same bench, and following the haul road and ramps between faces on different benches.
$\Gamma^D_{f,d}$	Distance of destinations from faces, based on the haulage profile in short-term schedule (meters)
$\tau_{s,f}$	Movement time of shovel s from initial face to face f (minutes)
$\bar{T}_{t,f,d}$	Cycle time of truck type t from face f to destination d (minutes)
ϕ_s	0 or 1 binary variable if shovel *s* is working or failed
M_s^{ore}	Parameter, if shovel *s* is locked to an ore face 0, waste face 1 otherwise 2
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)