Simulation optimization of mine operations for uncertainty based short term and operational planning in open pit mines

by

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ABSTRACT

The objective of this PhD thesis is to develop, implement and verify a theoretical framework to generate practical, achievable and robust uncertainty based short term plans meeting operational objectives and short term planning targets. This thesis intends to develop a mathematical optimization model as mine operational optimization tool (MOOT), a discrete event simulation model of mine operations and in turn an integrated simulation optimization model through an interaction mechanism that links the simulation model with MOOT as a multi-stage dispatching system for dynamic shovel and truck allocation optimization. The goal is to develop a simulation optimization framework/tool which integrates simulation with MOOT for dynamic operational decision making based on a feedback loop. This framework/tool must capture the operational uncertainty, achieve operational objectives of production and grade blend requirements, and project practical uncertainty based short term plans with a higher confidence on the deliverability of operational targets and key performance indicators (KPIs) of the system.

The MOOT is developed as a Mixed Integer Linear Goal Programming (MILGP) model in this thesis. The MILGP model is a multi-period optimization tool to optimally allocate shovels to available faces from strategic schedule and determine production targets and number of truck trips from each shovel so that operational objectives of maximum production and plant requirement of target tonnage and grade blend can be achieved. We showed the applicability of MOOT as dynamic decision making tool in real mine operations, and in parallel with a simulation model for dynamic shovel and truck allocation decision making. The MOOT is analogues to a planner in real mine operations who provides shovel and truck allocation *decisions based on operational objectives and schedule; and updates short term plans based on current system state.*

This thesis also presents the development of a discrete event simulation model of mine operations, including loading, spotting, dumping, queuing, hauling, plant crushers and equipment failures. Since truck haulage is a critical and limiting component in mine operation systems, a microscopic modeling approach of truck haulage is presented in this thesis. This approach captures the truck interactions and variable speeds along the haul road network of the mine based on gradients and rolling resistances of roads, and rimpull curve characteristics of the trucks, so that practical deliverables can be estimated.

This thesis finally presents the integration, implementation and verification of the simulation optimization model with an iron ore mine case study. The 11^{th} year strategic schedule and the designed haul road network of the mine, along with operational process distribution times are used as inputs to the simulation optimization model. The detailed verification and implementation through scenario analysis showed the strength of the model and the approach in capturing the realistic operational behavior, along with practical operational decision making leading to the development of confident, achievable and robust short term plans. The implementation also shows the strength of the model for proactive decision making by analyzing several desired scenarios for haulage planning and grade blending strategies. The proactive decision making is made easy by this approach due to the increased confidence in the derived plans through operational executions in simulation.

The main contributions of this thesis to the research community in mining applications are: i) a novel simulation optimization approach for uncertainty based short term planning that captures the deliverability of production and grade blend targets during practical operational executions,

and accounts for the mine operational details, ii) The MOOT developed as a mixed integer linear goal programming model for dynamic operational decision making with its applicability in real mine operations and simulation for shovel and truck allocation decisions, iii) a discrete event simulation model of mine operations that accounts for realistic truck travel behavior and interactions on haul road network of the mine, and iv) a proactive decision making capability because of the higher confidence in the achievability and practicality of the short term plans developed.

PREFACE

This thesis is an original work by Shiv Prakash Upadhyay. Some parts of this work are published as: Upadhyay, S. P., & Askari-Nasab, H. (2016). Truck-shovel allocation optimization: a goal programming approach. Mining Technology, 125 (2), 82-92. I was responsible for designing the conceptual model, the algorithms and case studies, running the case studies, documenting and analyzing the results and writing the manuscripts. H. Askari-Nasab was the supervisory author, who was involved with concept formation and manuscript composition.

This Thesis is Proudly Dedicated to My Family

My Father & Mother:

Mr. Kedarnath and Mrs. Pushpa Upadhyay

My Father & Mother-in-law:

Mr. Chandrashekhar & Mrs. Kritika Nirkhey

My Brothers & Sisters-in-law:

Omprakash and Anuradha Upadhyay

Bhanu Prakash and Asmita Upadhyay

My Cute little nephews and niece

Kanha, Dhruv & Pari

&

My Lovely Wife

Preeti Nirkhey

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Shiv Prakash Upadhyay

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LIST OF ABBREVIATIONS

AI	Artificial intelligence
CI	95% Confidence interval
CI-Max	Upper limit of 95% confidence interval
CI-Min	Lower limit of 95% confidence interval
GAMM()	Gamma distribution function in Arena simulation
GP	Goal programming
LP	Linear programming
MILGP	Mixed integer linear goal programming
MILP	Mixed integer linear programming
MIP	Mixed integer programming
MOOT	Mine operational optimization tool
NOH	Net operating hours
NPV	Net present value
SR	Stripping ratio
TBF	Time between failures
TPH	Ton per hour
TTR	Time to repair
WEIB	Weibull distribution function in Arena simulation

LIST OF NOMENCLATURES

Indices

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)

Parameters

D_t	Dumping time of truck type *t* (minutes)
E_t	Spotting time of truck type *t* (minutes)
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 (ton)
V_t	Average speed of truck type *t* when empty (Km/hr)
$\overline{V}_t$	Average speed of truck type *t* when loaded (Km/hr)
C_t	Cost of empty truck movement ($/Km)
$\overline{C}_t$	Cost of loaded truck movement ($/Km)
$M_{t,s}^T$	Binary match parameter, if truck type *t* can be assigned to shovel *s*
X_s	Shovel bucket capacity (ton)
X_s^+	Maximum possible shovel production in decision time frame '*T*' (ton)
X_s^-	Minimum shovel production desired in decision time frame '*T*' (ton)
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 (ton/hr)
$\Lambda_{d^c}^+$	Maximum positive deviation in tonnage accepted at crushers/processing plants (ton/hr)
$\Lambda_{d^c}^-$	Maximum negative deviation in tonnage accepted at crushers/processing plants (ton/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 (ton)
$O_{\min}$	Minimum material at face below which a face is considered mined
Q_f	1 if material at face is ore, 0 if it is waste (binary parameter)
T	Decision time frame (hr)
Π^-	Lower limit on desired stripping ratio
Π^+	Upper limit on desired stripping ratio
Γ_{f^1,f^2}^F	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.
$\Gamma_{f,d}^D$	Distance of destinations from faces, based on the haulage profile in short term schedule (meters)
$\tau_{s,f}$	Movement time of shovel *s* from initial face to face *f* (minutes)
$\bar{T}_{t,f,d}$	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}	0 if shovel *s* is locked to an ore face, 1 if locked to waste and 2 if not locked
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)
h	Discrete time increment (micro-simulation)
$x_i(t)$	Position of truck *i* at time *t* (micro-simulation)
$v_i(t)$	Velocity of truck *i* at time *t* (micro-simulation)
$a_i(t)$	Acceleration of truck at time *t* (micro-simulation)
$a_{\max}$	Maximum acceleration allowed (micro-simulation)
$v_i^{desired}$	Desired velocity of truck when not interacting with any other truck (micro-simulation)
$x_i^{front}(t)$	Position of truck in from of truck *i* (micro-simulation)
L_{truck}	Length of truck (micro-simulation)
SF	Minimum safety distance between the trucks (micro-simulation)
K_i^1, K_i^2, K_i^3	Binary constants which determine the needed acceleration depending on the extent of interaction (micro-simulation)
$V_{\max}$	Maximum obtainable velocity (Km/Hr) (micro-simulation)
Kw	Vehicle engine power in Kw (micro-simulation)
TR	Total resistance (decimal) (micro-simulation)
W	Vehicle weight, in Kg (micro-simulation)

INTRODUCTION

1. INTRODUCTION

1.1. Background

Mining is the process of extraction of ore from the ground and delivering it to processing plants, to be processed and sold to generate revenue. Mining can be broadly classified into two main categories: Open pit and underground mining. Open pit mining, with truck shovel operations, is the most commonly used technique around the world responsible for bulk productions to satisfy the market demand. Such open pit mining operations are usually large scale, involving a long operating life and huge investments. Due to long life and huge capital involved, mining activities are carried out following a systematically designed mine plan, so that economic objectives can be realised over mine life. Mine planning has received sufficient attention of the researchers in the field of mining, operations research, mathematics and computer algorithms. Many years of research show that mine planning is usually carried out in stages, which can account for uncertainties and unknowns at corresponding planning stages, which becomes knows as operations continue. According to Hustrulid & Kuchta (2006), mine planning is generally carried out in stages due to limitations of the computing power and complexity of the problem. Mine planning activities are therefore divided into two main categories: *Strategic* and *Tactical* planning based on the planning time horizon (Fig. 1.1). Strategic planning is further divided into long term and medium term planning and serves as reference to the pit boundary and the schedule of extraction and destination of blocks, mining panels or mining polygons which eventually maximize the net present value (NPV) of the mine. Tactical planning, on the other hand, involves short term and operational plans which consider operational activities in detail and associated uncertainties to achieve the strategic targets. Mine planning literature does not distinctly demarcate individual stages but clearly divides the planning stages into long term and short term based on planning time horizon. Similarly, short term planning and operational planning do not find clearly defined boundaries in literature (Hartman & Mutmansky, 2002). Hartman & Mutmansky (2002) try to distinguish the production schedule or operational plans as the ones which are for periods of less than a month or so and looks in details at the hour-to-hour or shift-to-shift basis constrained by short term plans and updated daily or more often. Long term and medium term schedules are generated at the management level, whereas operating staff on site remain responsible for meeting the medium and long term plans, by developing and achieving short term and operational plans. Operational plans are then implemented within mine operations by manual shovel allocations and real-time truck dispatching systems Fig. 1.1.

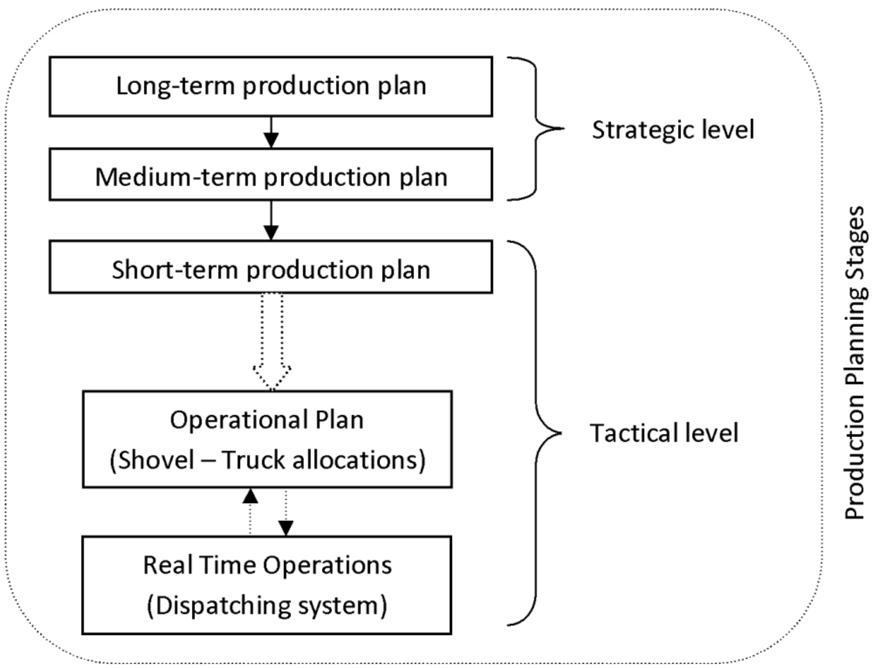

Fig. 1.1. Mine production planning stages

In the whole mine planning process the short term mine plans remain weakly linked to operational plans through planners on site, who provide shovel allocations and target productions to be achieved by truck dispatching systems. Moreover, the short term production plans suffer greatly from the uncertainty at the operational stage which leads to deviations from the short term and eventually strategic plans. The grade blending is one of the important considerations at the operational stage which can only be achieved by proper combination of ore faces being mined at that time in the operations; and optimal target productions from ore faces to ore destinations.

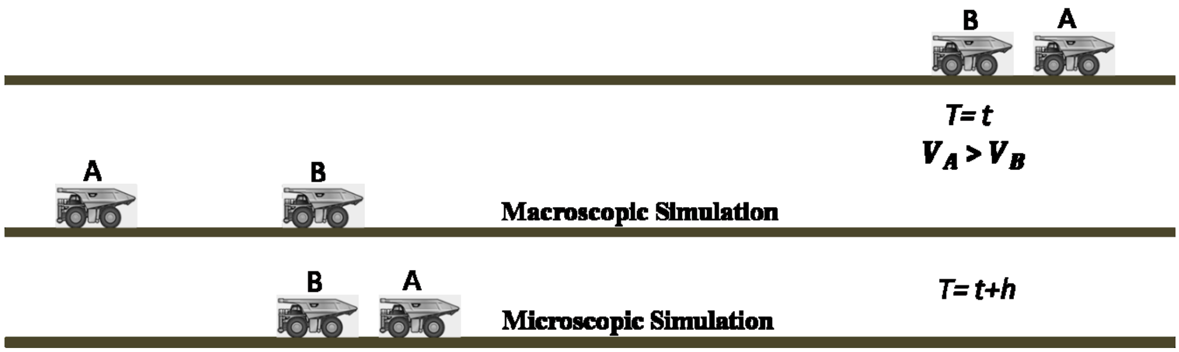

Fig. 1.2. Difference between the approaches of Micro and Macro-simulation

Discrete event simulation has also evolved as a powerful tool for decision making in mine planning. Simulation models mimic the various processes involved in the mine operations and provide a tool for understanding the impact of various scenarios on the key performance indicators (KPIs) of the system and thus the operational objectives. A true representative simulation model therefore becomes necessary to provide right and accurate predictions, which is possible only if the individual processes and their distributions are modeled accurately. One such major process is truck haulage. In the recent years micro-simulation has started to gain attention of the researchers to study the interaction of trucks on the haul roads so as to predict the travel times of the trucks accurately. Such micro-simulation models try to capture the effect shown in Fig. 1.2, where, in the context of single lane traffic in mines, a truck with higher velocity is forced to follow a slower truck, leading to platoon formations on the haul roads. Micro-simulation, through capturing the behavior of trucks while traveling, may provide a robust tool to predict the truck travel times and help developing more accurate macro-simulation models of the entire system.

1.2. Statement of the problem

1.2.1. *Introduction*

Based on the strategic plans, optimal number with required capacities of equipment is employed in the mine for regular excavation and hauling operations. This optimality can only be realized with efficient utilization of all the assets involved. Since truck and shovel operations account for approximately 60% of total operating costs in open pit mines, optimal use of these equipment is also essential for realizing the strategic objective of maximizing the NPV. The whole strategic planning process to achieve organizational objectives may be moot if short term and operational planning are inefficient to reflect back.

Short term plans must also be practical enough to predict a confident picture of the mine for advance planning to mitigate long term effects. The practicality of short term plans here refers to whether it accounts for shovel movement time between faces and production lost during these movements, equipment failures and availabilities, real-time grade blending objectives and changing rates of production of shovels based on their locations, trucks , haul road network and truck dispatching efficiency. As short term and operational plans need to be updated very frequently to reflect the state of the mining system, they remain constantly changing over time and thus may be regarded as mere guidelines to follow which is hard to strictly adhere to. Instead a dynamic *Mine Operational Optimization Tool* (MOOT), can be beneficial, which captures the state of the mine using a dynamic feedback loop and provide shovel allocations based on strategic schedules in real-time. The tool in conjunction with a simulation model may provide the state of the system over the course of time, such as short term plans, with improved confidence for better strategic decision making related to ramp designing, equipments or improvement to any other system component. The MOOT tool can be implemented using the traditional top down approach by first creating a short term plan and then implementing it at the operational level where MOOT provides dynamic shovel and truck allocations and target productions to the dispatching system. This thesis focuses on developing short term plans using a bottom up approach by implementing MOOT for real-time decision making within simulation, where MOOT provides operational decisions based on strategic plans. Fig. 1.3 shows a representative placement of MOOT in the production planning stages and the bottom up approach when implemented with simulation of mine operations.

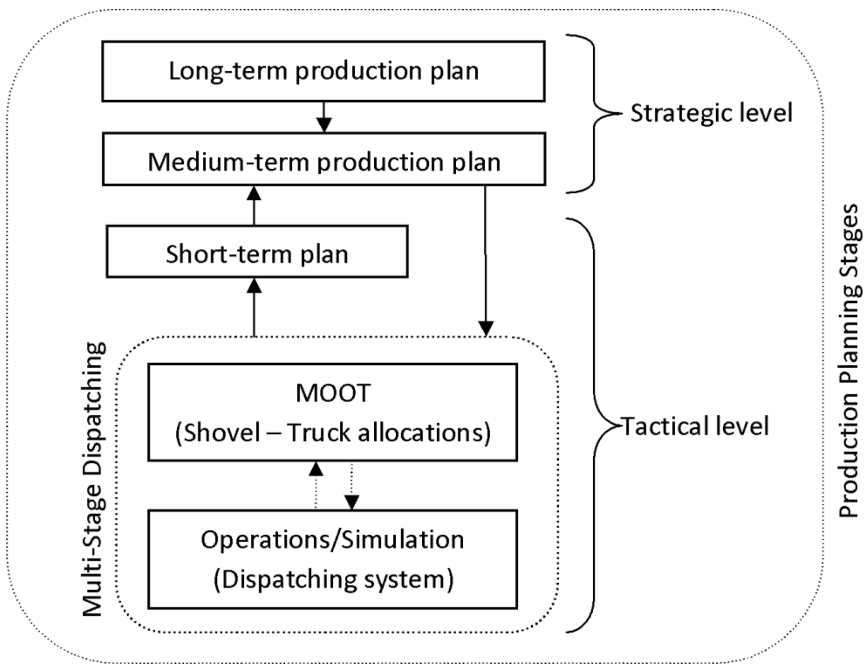

Fig. 1.3. Proposed system in the production planning stages

Based on the literature reviewed very little work has been carried out in short term mine planning and optimization, out of which only few approaches consider the operations in detail. The problem addressed in this thesis is the short term and operational mine planning and scheduling problem. The problem can be stated as:

Can a simulation optimization model be developed which integrates simulation with a dynamic Mine Operational Optimization Tool (MOOT), for operational decision making, based on a feedback loop, which captures operational uncertainty, achieves operational objectives, deliver realistic real-time grade blends, and can project practical short term plans with a higher confidence on the deliverability of operational targets and system KPIs?

1.2.2. *Description*

This research thesis is aimed at developing a tool for dynamic decision making at operational stage and using it in conjunction with a discrete event simulation model, as a simulation optimization tool, for developing uncertainty based short term production plans. The short term plans developed must:

- achieve operational objective of realizing strategic schedule
- achieve operational objective of maximum production
- achieve operational objective of feeding the plants at the desired rates
- achieve operational objective of grade blending requirements at ore destinations
- incorporate varying rates of shovel productions based on their locations, available trucks, haulage route gradients and other associated uncertainties
- incorporate shovel movement times leading to production losses
- incorporate scheduled maintenance and unavailability of equipment, and
- incorporate uncertain failures of equipment

In this research, the development of dynamic decision making tool (MOOT) and the short term production plan is based on following assumptions:

- Blocks, that are scheduled to be mined in the given period based on strategic plan, are considered for shovel allocations.

- Blocks are aggregated together into reasonable sized clusters which serves as basic mining units, here after referred to as faces.

- Vertical precedence of blocks are taken directly from the strategic schedule, which are clubbed together for all the blocks within clusters to serve as vertical precedence for the faces.

- Horizontal precedence of faces are manually defined based on the desired mining direction and sequential availability of faces.

- Block attributes are averaged to calculate face attributes, such as grades of various elements in the ore and coordinate location of faces. The homogeneity of blocks being clustered, in terms of grades and rock types, is essential for reasonable solutions.

- The existing haul road network is used to determine the distance between faces and destinations. This haulage distance is the sum of straight line distance to ramp access point on the face bench and distance to destination from the ramp access point following the haul road.

- Distance between faces, for shovel movements, is approximated as straight line distance, if they are located on the same bench. If two faces lie on different benches, distance is approximated as the sum of distances to ramp access points on the face benches and the haul road distance between ramp access points.

- A shovel is not allowed to move to a different face until, the face it is assigned to, is completely mined. Therefore, reasonable sized clusters need to be generated, which will be blasted and mined as a whole. There is no other constraint put on the shovel movement. Allocations are guided by the accessibility of the faces and objectives of the model.

1.3. Summary of literature review

The mine planning literature broadly show three different approaches applied into mine planning activities: Operations research, Queueing theory and Simulation. Operations research is the most common approach which has found its applicability at all different stages of mine planning process. Queuing theory is another approach which has been used by some researchers for decision making at the dispatching stage. Linear queuing models have also been used by some researchers within linear programming models. Simulation has started to gain increasing attention from the researchers for its capability to capture highly uncertain aspects of the mining environment.

1.3.1. *Operations research*

Although strategic mine planning has found sufficient attention using operations research, very little is worked upon short term mine planning. Modeling the detailed mine operations over multiple periods incorporating all the faces, shovel movements between faces, truck allocations and plants, increases the problem size and poses limitation on the solvability of the model as observed by L'Heureux*, et al.* (2013). Similarly, Bjørndal*, et al.* (2012) observes that even state of the art hardware and software cannot handle the size and complexity of such detailed scheduling models. On the other hand, operational planning has not received sufficient attention of the researchers, which finds most relevance in the literature related to multi-stage dispatching in mining. Most researchers emphasize on a multi-stage optimization approach, where upper stages provide optimal executable plans and the lower stage implements the plans through real-time truck dispatching systems. In one of such approaches, Elbrond and Soumis (1987) presents a three stage dispatching approach where the first stage provide shovel allocation decisions through man-machine interaction. Researchers have proposed one or two stages for the upper stage, which provide decisions regarding optimal number of equipment and the target productions from various production shovels to various destinations.

Following are the major limitations of the existing models, in short term and operational planning, as reviewed in chapter 2:

- Very few models exist for operational planning that can provide shovel allocation decisions.
- A missing link is observed between short term plans and operational decision making, which can be mitigated using a dynamic decision making system such as MOOT presented in this study.
- Deterministic short term plans need constant updating due to operational uncertainties, and thus may not be very helpful in confident strategic decision making.
- Most of the models in short term planning or dynamic models in multi-stage dispatching, do not incorporate all or some of the major objectives of production planning, such as steady desired feed to processing plants, minimize shovel movements to minimize production lost and cost of movement, and minimizing the operating cost, apart from maximizing production and grade blending.
- Most of the models, in multistage dispatching systems, do not incorporate mixed fleet systems at the upper stage.

Shovel assignment is a major decision making problem which has not received sufficient attention from the researchers, and has remained the task of the planner who manually creates and updates the operational plans. Although the model of Gurgur*, et al.* (2011) provides shovel assignments, it does so based only on the strategic considerations, which not necessarily will provide optimal shovel allocations. To the best of author's knowledge, model presented by L'Heureux*, et al.* (2013) is the only one that presents a detailed model for short term planning providing shovel assignments and incorporating their movement within the mine; and model presented by Fioroni*, et al.* (2008) is the only model in literature for dynamic shovel allocations but fails to incorporate precedence amongst faces, and thus fails to link operations with short term or strategic plans. For a detailed review of the existing models and their limitations see chapter 2.

1.3.2. *Simulation*

The simulation models are primarily used for analyzing the impact of changes on the KPIs of the system for strategic decision making. They are proven to be significantly helpful in determining the applicability of various dispatching algorithms and the corresponding impact on the mining system.

Simulation models are gaining the attention of researchers and industry recently, particularly due to their capability to confidently predict the system performance and help in strategic decision making. Such simulation models are usually case specific and are developed for specific projects. In context to objectives of this study, following limitations are generally observed in the simulation models, which will be accounted in this research:

- Simulation models generally remain very specific to the problem domain of a specific mining site being analyzed, limiting their applicability to that mining system and problem domain.
- Most simulation models provide limited user flexibility towards various stochastic parameters of the system. Selection of appropriate distributions and their parameters and related user flexibility is necessary for practical and realistic models.
- Truck haulage time is a major part of the total production time, which is generally modeled using probability distributions. The commonly used approach fail to model the truck interactions on haul roads, which in reality leads to platoon formations and has significant impact on production.

- Models do not incorporate mining schedules, or do not model the unavailability of faces due to precedence requirements and thus fail to analyze the operations in longer time frames; mainly because of shovel allocation requirements.

1.4. Objectives of the study

In relation to the statement of the problem considered in this project, the objective of this study is to develop and implement a simulation optimization framework that is capable of projecting robust and practical uncertainty based short term plans and verify by varying the number of trucks in single and mixed fleet systems. The framework/tool is required to account for mine operational objectives of maximum production and, tonnage and grade requirements of the plants. Moreover, the shovel allocation decisions must reflect the strategic plan, so that short term plans thus developed are aligned with the strategic schedule.

Due to unavailability of relevant data and unique nature of the proposed approach, no validation is proposed for the framework/tool in this research thesis, and only a verification study is carried out. Three tasks are set for this study to address the problem statement and attain the objectives of this study:

1. Develop a mine operational optimization tool (MOOT).
2. Develop a discrete event simulation model of mine operations and integrate the MOOT as an external engine for dynamic decision making.
3. Develop a micro-simulation tool for truck haulage and integrate it with the simulation model of mine operations.

The MOOT as such is a dynamic decision making tool and its applicability will be verified with a simulation model to develop uncertainty based short term production plans as shown in Fig. 1.3 and Fig. 1.4. The three objectives stated above are set to develop a simulation optimization model to solve the problem statement of this research thesis. The simulation optimization model and interaction between the three objectives is presented in Fig. 1.4.

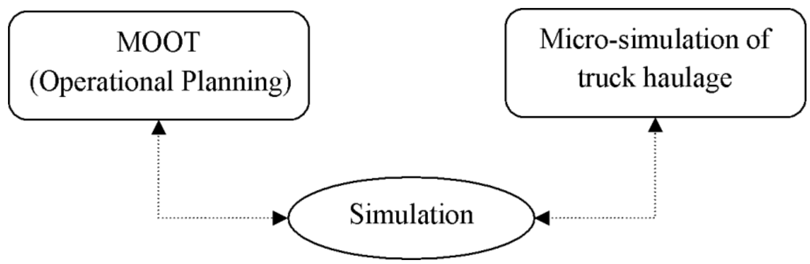

Fig. 1.4. Simulation optimization model and interaction between the objectives of this research

1.4.1. *Objectives for MOOT*

The main objectives set for the development of mine operational optimization tool (MOOT) are to:

- Comply with the strategic schedules.
- Incorporate shovel movements and production lost during these movements.
- Be flexible to work as dynamic decision making tool with feedback logic to update changing system states over time.
- Incorporate major operational objectives of maximizing production and constantly feeding the plants with desired tonnage and grades of ore.
- Incorporate precedence constraints for face availabilities, face material tonnage and quality constraints, grade blending constraints, processing rate and shovel mining rate constraints, along with truck haulage capacity constraints.

1.4.2. *Objectives for simulation model*

The main objectives set for the simulation model are to:

- Model mine operational processes accurately.
- Provide flexibility to change the model inputs and process distributions externally.

- Be general enough for wider applicability and over time in the same mining system without changing the model as such.

- Incorporate multi-stage dispatching system using MOOT as external operational decision making tool at the upper stage and a truck dispatching logic at the lower stage within simulation.

- Incorporate a micro-simulation tuck haulage submodel to capture truck travel times on haul road network based on exact location of shovels in the mine and truck interactions on haul roads.

1.4.3. *Objectives for micro-simulation of truck haulage*

The main objectives for the micro-stimulation submodel of truck haulage systems are to:

- Models single lane traffic of trucks on the haul roads, i.e. no overtaking of trucks to capture truck interactions and platoon formations leading to decreased productions.

- Captures truck velocities based on gradients and rolling resistances of haul roads and rimpull characteristics of the trucks.

1.5. Scope and limitations of the research

This research study is aimed at developing a simulation optimization model for short term and operational planning by developing a mine operational optimization tool (MOOT), a discrete event simulation model of mine operations and a micro-simulation submodel for truck haulage. The major limitations and scope of individual tools are summarized in this section.

1.5.1. *Mine operational optimization tool (MOOT)*

The MOOT is developed to optimize the existing state of the mining system and provide optimal shovel allocation and target production decisions to achieve the operational objectives of the mine.

- MOOT uses strategic schedule as an input for shovel allocation decisions. Development of these strategic schedules is out of the scope of this research.

- A clustering algorithm, as block aggregation technique, is used to develop mining cuts or faces out of the scheduled blocks in the strategic schedule. Any suited block aggregation technique, which may maintain the homogeneity of the grades and rock types in the aggregated blocks, can be used here. The development and details of the clustering technique is out of the scope of this research.

- Face development activities such as drilling and blasting are not part of the MOOT, and it assumes that the allocated face is ready for the shovel to start working. As MOOT is a multi-period optimization model, the sequential allocations provided by MOOT are assumed to be used for carrying out face development activities.

- Although vertical precedence among faces is taken directly from the strategic schedule, horizontal precedence among faces is defined manually considering mining direction and availability of faces.

- The shovel movement time between faces on the same bench is estimated for straight line movement between faces. Although it is a reasonable assumption, it is not exact and can be solved by creating a connection matrix between all adjacent faces. Due to increased resource requirements, straight line movement assumption is used in this study. However shovel movement time between faces on different benches are modeled as sum of movement time to ramp access points on the benches and the movement time on the ramp between benches.

1.5.2. *Discrete event simulation model*

The discrete event simulation model of the mine operations is created to simulate the mine operations and model the mine uncertainties related to equipment failures, truck travel times, queues, real-time throughputs of processing plants and shovel movements.

- The model uses a heuristic logic as truck dispatching system within the simulation model to attain the operational targets set by MOOT. The development of a truck dispatching system is out of the scope of this research.

- MOOT uses a deterministic value for the probability distributions used in the simulation. Data fitting and computation of probability distribution functions is out of the scope of this research.

- The simulation model does not include the processing plant components, but to the extent of rate of flow of ore out of hoppers to the downstream processes at the plants.

1.5.3. *Micro-simulation of truck haulage*

A separate study was conducted to verify the micro-simulation modeling of truck haulage systems and its understanding was implemented using the existing features of the simulation model.

- Although truck movements are restricted on the haul roads to avoid any overtaking, no other control is put during the interaction between trucks such as accelerations, decelerations or driver factors to respond to situations. This is a reasonable assumption, because the overall effect of such interactions is that the trailing truck slows down and follows with the same speed as that of the leading truck. The detailed behavioural modeling is out of the scope of this research.

- No traffic flow logic is implemented at intersections and trucks move on the first come first serve basis at the intersections.

1.6. Research methodology

This research is aimed at creating a simulation optimization model by developing and integrating the mine operational optimization tool (MOOT), a discrete event simulation tool and a micro-simulation framework for truck haulage. The discrete event simulation and micro-simulation of truck haulage are aimed at modeling the mining operations, whereas the MOOT is aimed at modeling the decision making process of the planner.

The MOOT is required to provide shovel allocation decisions to the available faces with the similar considerations as by the planners. The major difference between the decisions is that planners consider available faces in the short term schedule, whereas the MOOT looks at the strategic schedule aimed at generating a short term schedule each time before making a shovel allocation decision. Although it seems like a different approach, this is analogous to the periodic updates made by the planners in the short term schedule to reflect the current mining system state.

The MOOT is also required to take into consideration various mine operational objectives, similar to planners, before making shovel and truck allocation decisions. As there are multiple objectives to be considered, the operational decision making process is a multi-objective decision making problem. The MOOT is thus developed following a goal programming approach. Goal programming has also been used by researchers to tackle the operational decision making problem in multi-stage dispatching systems. Major operating objectives, among others, considered in this study are: maximizing production, minimizing the deviation in tonnage feed rate requirements at processing plants, minimizing the deviation in grade feed requirements at ore destinations and minimizing the shovel movements. These four operational objectives were combined together using a weighted sum approach, developing a mixed integer linear goal programming (MILGP) model, and solved using a non-preemptive goal programming approach. The MOOT is developed in Matlab® and optimization is carried out using Cplex/ILOG solver.

A block clustering algorithm developed by Tabesh & Askari-Nasab (2013) is used for block aggregation to develop mining cuts or faces, which are used as basic mining units in MOOT. The size of clusters and block aggregation technique is carefully chosen to maintain homogeniety in grade and tonnage. As block aggregation determines the total number of faces and thus the number of binary variables in the model, it affects the solution time as well as the overall solution. The determination of the number of blocks per cluster (face) must be primarily made based on equivalent drilling and blasting areas of the mine. For practicality of the generated schedule a face will be drilled, blasted and mined as a whole. Horizontal precedence among these faces is then defined manually to guide the direction of mining and feasible sequence of extraction of faces.

MOOT was required to model the continuous nature of mining operation by modeling the shovel movements over multiple faces in due course of time (optimization time frame), enabling the model to provide decisions for the current state looking ahead in the future. This was required based on the observations of an initial model developed (Upadhyay & Askari-Nasab, 2016). To model it, optimization time frame was divided into multiple periods (equivalent to shifts), and at maximum one shovel movement was allowed in any period. The decision for the first period constitutes the optimal decision for the dynamic mining operation and the face assignments in further periods may be used for face development activities.

Discrete event simulation model was then developed to mimic the mine production operations with inherent uncertainties using Rockwell Automation's Arena Simulation package. Simulation includes loading, hauling, dumping and queuing of trucks at shovels and dumps; shovel loading, idling and movement between faces, and crushers with fixed hopper capacities and flow rates to processing plants. Model also includes maintenance schedules and failures of trucks and shovels. Operations at processing plants are not modeled in the simulation model. The simulation model is developed such that the distributions and parameters can be updated using an external Excel input interface. MOOT and Simulation models use the same input parameter file to maintain consistency. The simulation model is integrated with MOOT using VBA. Each time the system state changes, simulation calls MOOT which runs using MATLAB/CPLEX environment to write the results in an output file, which is read back using VBA into the simulation model.

A small micro-simulation study was carried out in MATLAB® to model the truck velocities and their interactions on haul roads and intersections; and validated against *Talpac* software results. Based on the observations and requirements of this study, controlling the truck velocities during interactions was deemed resource consuming and not necessary. As Arena provides a capability to model AGVs (autonomous guided vehicles) which can model the required extent of interaction between trucks, it was used to model the truck haulage. A MATLAB® application based GUI was created to read the road network '*dxf*' files and generate input for Arena, which is then used to create the road network within the simulation model using VBA. This capability provides flexibility to update the road networks without touching the model. A submodel in simulation was created to assign the truck velocities based on the gradients and rolling resistance of the haul roads and rimpull characteristics of the trucks. This enables the simulation model to accurately predict the truck cycle times based on shovel locations within the mine and thus predict changes in rates of productions.

Finally, the simulation optimization model was developed by running the simulation model in conjunction with MOOT as an external engine for operational decision making. Using a case study, the simulation optimization model was first verified based on a deterministic simulation model by removing all the uncertainty from the simulation model. This deterministic model verified the application of MOOT for dynamic operational decision making. Multiple scenarios were then run under full uncertainty to generate uncertainty based short term mining schedules and determine optimum number of trucks required in the system. The scenario analysis was also run to predict the best strategy for the systems to achieve operational objectives.

1.7. Original scientific contribution and industrial significance of the study

The problem considered in this research is the short term and operational mine planning problem. The goal is to develop a simulation optimization approach for short term production planning and operational decision making under stochastic mining environment. This is a unique approach which streamlines the mine production operations and provides confident predictions over the course of time so that better strategic decisions can be made to improve the productivity and efficiency of mining operations.

The main scientific contribution of this research is the new approach for tactical mine planning by following a bottom up simulation optimization approach to develop uncertainty based short term plans for strategic decision making. MOOT and the simulation optimization model bear a great industrial potential to improve operational productivity and efficiency of mining operations. The associated contributions of this research are given below.

- Simulation optimization framework provides a novel approach to mine planning at the tactical stage.
- Shovel allocations, based on strategic schedules and operational objectives of grade blending, tonnage feed rate requirements at plants and maximum production, provides great value to this research. The MOOT can be implemented for real-time operational decision making for shovel and truck allocations in actual mine operations.
- If MOOT is implemented for operational decision making in actual mining systems, the parallel planning process using the simulation optimization approach would provide a close imitation of the reality.

- Inclusion of available truck fleet, haul road network and changing truck velocities with gradient and rimpull characteristics of trucks, makes the operational decisions, and hence the short term plans, practical. This allows the framework to capture the varying rates of productions from shovels based on their locations within the mine.

- MOOT employs a goal programming approach which provides user with flexibility to guide the operational decisions based on any specific requirement by changing weights of the objectives. Model also provides flexibility to lock trucks to shovels and shovels to material types.

- The simulation optimization tool can handle mixed fleet systems which makes it more general to be implemented in most open pit mining systems having shovel-truck operations.

- The microscopic approach to truck operations in simulation models provides opportunity to detect any increase in platoon formations and decrease in haulage capacities in the short term plans to adopt the counter measures in a proactive approach.

1.8. Organization of thesis

Chapter 1 of this thesis gives the background and provides an introduction to the problem considered in this research. It states the problem, associated objectives and brief summary of literature reviewed in the relevant area. A summary of scope and limitations, research methodology and contributions of this research are also provided in this chapter.

Chapter 2 reviews the research carried out in the relevant field by other researchers in the past. This chapter first gives an overview of various techniques used by other researchers in mine planning area. The subsequent sections review in detail the literature and their limitations with a focus on short term and operational mine planning.

Chapter 3 provides a theoretical framework of this research. It details the development and implementation of mine operational optimization tool (MOOT), the simulation model and the microscopic submodel for truck haulage. This chapter also details the integrated simulation optimization model and how it can be implemented.

Chapter 4 presents the implementation of the simulation optimization approach using a case study of an iron ore mine. This chapter presents the implementation results of the simulation optimization model with single and mixed truck fleet mining systems. The implementation for proactive decision making for haulage planning and optimal grade blending strategy is also presented in this chapter. Finally, this chapter presents the developed short term plans for the iron ore mine case study.

Chapter 5 provides conclusions of this research and associated future research possibilities. This chapter also points out the limitations of the models developed by drawing a comparison with the objectives of this study.

LITERATURE REVIEW

2. LITERATURE REVIEW

2.1. Background

Surface mining, employing shovel and trucks, is the most favored mining method nowadays. About 85% of mineral production in North America comes from open pit mines (Hartman & Mutmansky, 2002). Due to bulk production capacity coupled with high sensitivity of production cost and increasing competition and demand, surface mining companies are forced to efficiently use the available resources to sustain in the market. Mining companies are constantly striving to adopt best practices to survive in the current market dynamics. But highly uncertain mining operations impose a limitation on prediction, making the industry stubborn to changes; hence efficient decision tools/frameworks have become imperative to measure the effect of proposed technological and strategic decisions and assist in decision making and adopting to changes.

Literature show mainly three approaches to assist in decision making in mine operational planning: Operations research, queuing theory and simulation. Topuz & Duan (1989) mention some of the potential areas in mining such as equipment selection, production planning, maintenance, mineral processing and ventilation, where operations research techniques can act as a helping tool for decision making purposes. Newman et al. (2010) provides a comprehensive review of the application of operations research in mining.

Mine production planning is one of the key areas affecting the profitability and sustainability of the mine in long term. The first and foremost task in this planning process is to determine the optimum pit limit (Lerchs & Grossmann, 1965; Shi*, et al.*, 1997) to maximize the NPV of the mine for the life of the mine. After the ultimate pit limit is determined, production plans are developed for the life of the mine. Production scheduling is thoroughly covered in literature both for underground mines (Kuchta*, et al.*, 2004; Topal, 2008) and open pit mines (Dimitrakopoulos

& Ramazan, 2004; Eivazy & Askari-Nasab, 2012; L'Heureux*, et al.*, 2013). Due to the limitations of the computing power and complexity of the problem, production planning problem is generally solved in stages (Hustrulid & Kuchta, 2006). Based on the period and planning time horizon, production scheduling is achieved in three stages: long term, medium term and short term (Osanloo*, et al.*, 2008). Uncertainty and unavailability of certain data, which becomes available only as mining operations continues, is another reason for this classification. Most of the research in the mine production scheduling has remained confined to long term; and short term production scheduling has seen very little development over the years (Eivazy & Askari-Nasab, 2012). Henderson and Turek (2013) describe the systematic planning procedures in place at Kinross Gold and stress the plans to be as realistic as possible so that expectations can be delivered. In another paper Malhotra and List (1989) discusses the short term planning process at Syncrude oil sand mine and describes the complexities and challenges faced by the planners. They emphasize on the need of efficient computer based techniques to assist in short term planning process to meet the increasing production demands.

Long and medium term strategic plans can only be realized with efficient short term and operational production planning. Early researches were mostly using queuing theory for studying and optimizing the shovel – truck systems, but due to limited scope, it finds less presence in literature nowadays. With the evolution in computing capability and optimization techniques, mathematical optimization models have started to gain more attention. Simulation is another technique which has evolved over the years and is now frequently used for understanding the behavior of the system and for decision making purposes. Jaoua et al. (2012) proposed a simulation optimization approach to develop a simulation based real-time control (SRTC) tool for truck dispatching, which dynamically determines the control law for the control horizon using an internal simulation model. Simulation optimization is a fairly new approach in the industry, which bears great potential for developing robust tools for static or dynamic decision making purposes.

This chapter reviews the existing approaches in short term and operational planning using mathematical optimization techniques and the application of simulations in mining. The approach proposed in this study is to develop the short term plans by optimizing mine operations using a multi-stage dispatching approach hence multi-stage dispatching algorithms in operational planning are discussed in detail. Truck haulage being a critical process in mining, micro-simulation approach within simulation of mine operations is also discussed in detail apart from simulation. Upadhyay and Askari-Nasab (2016) and Askari-Nasab et al. (2014) presents the framework of the approach adopted in this study, which describes the use of combination of micro-simulation of truck haulage, macro-simulation of mine operations and an operational optimization decision making tool/framework to develop uncertainty based short term production schedules.

2.2. Short term mine planning

Mine planning and scheduling has received sufficient attention of the researchers but has remained limited to long term or operational planning through truck dispatching. Short term planning and scheduling problem is addressed by very few researchers. Modeling the detailed mining operations over multiple periods incorporating all the faces, shovel movements between faces, truck allocations and plants increases the problem size and poses the limitation on the solvability of the model as observed by L'Heureux et al. (2013). Bjørndal et al. (2012) observes that even state of the art hardware and software cannot handle the size and complexity of such detailed scheduling models. Smith (1998) describes the importance of mathematical modeling using AMPL in conjunction with a mine modeling package by presenting various examples showing the strength of MIP methods and the strategies to deal with the limitations of algorithms in these mine modeling packages.

In one of the very early works Wilke and Reimer (1979) describe the importance of grade blending in short term production planning for a very irregular iron ore deposit where grades changes within very short distances. The production schedule in such cases is very hard to satisfy quality requirements, which, according to Wilke and Reimer (1979), also affects the operations through variable equipment utilizations and deviations from prescribed mining sequence and in-turn long term plans. Chanda and Wilke (1992) describe various objectives of the short term production scheduling as:

- Determining ore and waste mining faces and the sequence of extraction within the planned faces based on long term production schedule, the rates of ore and waste mining, stripping ratios and composition of head grades,
- The schedule must minimize the absolute deviations in head grade delivered to plants, as it may significantly affect the mill recovery,
- The schedule must provide detailed allocation of shovels and trucks for dispatching,
- Efficiently utilize the equipment and mining resources,
- The schedule must be flexible and practically executable.

Chanda and Dagdelen (1995) emphasizes on the importance of grade blending to achieve economic objectives and market requirements to meet the quality requirements of the customers. They proposed a goal programming model for maximization of economic value of ore mined and minimization of the grade and tonnage deviations of the plants from their target values. Chanda and Wilke (1992) propose a model based on the combination of linear goal programming and deterministic simulation for short term production scheduling in strata-form ore bodies. The GP model maximizes the metal content in the processed ore and minimizes the deviations in grade and tonnage from the target values.

Gershon (1987) proposed two heuristic approaches to improve the mine production scheduling process based on blending optimization and ranked positional weight. They describe the practicality of the schedule as more important than finding the best schedule, as the schedule must also meet the restrictions on the mobility of equipment, balance strip ratios and blending requirements. Kim (1987) proposes the application of geostatistics for short term mine planning and concludes economic and political motives as prime reason for its non-application in US at that time. Fytas et al. (1993) describes the problems associated with long term and short term planning and proposes a computer package to develop alternative short and long range production schedule. They proposed simulation for long range and linear programming for short range planning by maximizing revenue constrained by head grade, concentrate production and stripping ratio targets.

Youdi et al. (1992) describe handling the relation between long term plan and short term plan to realize the economic objectives as a major problem. Youdi proposes a two step procedure to carry out short term planning in a large surface coal mine. The first step uses goal programming for coal seam allocation and scheduling to carry out multi-objective optimization for coal quality and production over a period of a year or a quarter. The second step generates detailed arrangement of production and stripping schedule using graphic design system and systems simulation.

Kumral and Dowd (2002) describe short term planning as a tool for quality control rather than profit maximization, and describe the problem as the one with several competing objectives.

Thus they propose the problem as a multi-criteria decision making problem, and solve it using lagrangian parameterization and multi-objective simulated annealing (MOSA) to generate optimal short term production schedules. Their proposition involves determining the pit-blend limit using linear programming and Lerchs-Grossman algorithm (Lerchs & Grossmann, 1965), solving the problem for the blocks within this pit limit to generate sub-optimal schedule using Lagrangian parameterization, and finally applying multi objective simulated annealing (MOSA) to improve the sub-optimal schedule to generate near optimal short term production schedule.

Samanta et al. (2005) proposed a genetic algorithm approach to solve the grade control problem in a bauxite mine. Although the schedule generated is quite promising in terms of grade control objectives, practicality of the schedule remains a problem as only precedence constraints are considered.

Gurgur et al. (2011) proposed a LP model for short term planning, but do not consider mine operations in detail. The model provided by Gurgur et al. (2011) uses an LP model for truck allocation with a five dimensional continuous variable to determine the material flow rate from the blocks by the shovels using the specific type of truck, and sent to the destinations for every time period. The LP model minimizes the deviation of the mine progress from the target provided by the MIP model. Although model provides shovel assignments in every time period, it does so, based on the amount of material to be moved from the blocks in that time period, given by the MIP model. The major drawback of this model is that the shovel movements may not be optimal and realistic, as no other constraints related to shovel movement between blocks have been incorporated.

Eivazi and Askari-Nasab (2012) proposed a multi-destination mixed integer linear programming model to minimize the overall operating cost, including mining, processing, rehabilitation, rehandling and haulage cost, to generate short term production schedules. The MILP model proposed allows choosing the direction of mining and haulage paths for mining blocks. One major limitation of the model as observed is the missing horizontal precedence constraint, which poses a serious limitation on the practicality of the generated schedule.

Gholamnejad (2008) proposes a binary integer programming model to solve the short term mine scheduling problem. They emphasized on the practicality of the solution in terms of accessibility of the blocks to be mined based on the precedence requirements, and proposed cone template for vertical block precedence and horizontal cones in four directions of every block for horizontal precedence on the same bench. They proposed a single objective approach to optimize a long term goal or a goal programming approach to minimize the deviation variables from the targets.

Dimitrakopoulos and Ramazan (2004) emphasized on a risk based approach for long term production scheduling. An uncertainty based production scheduling formulation is presented to integrate uncertainties in grade, ore quality and quantity and risk quantification. They try to capture the risk of not meeting production targets caused by uncertainty in estimated grades. Dimitrakopoulos and Jewbali (2013) presented a joint stochastic optimization approach for short and long term production scheduling using four stages and show significant gain in the NPV of a gold mine. Although the uncertainty in grades at the short term planning horizon is very less, the uncertainties related to realization of blending objectives in operations still remains a challenging task. A predetermined sequence of extraction, which accounts for blending, may not be practical to realize the blending objectives at the operations, as the combination of ore faces being mined together may not be exactly same as determined by the short term plans.

L'Heureux et al. (2013) presents a detailed model for short term planning for a period of up to three months, where they consider precedence among blocks, precedence among operational activities, drilling, blasting, transportation, processing, movement of shovels, drills and more in detail as operating constraints.

Lestage et al. (1993) propose a computerized tool for daily operational decision making by optimizing the system over a given time horizon. The proposition is similar to what is proposed in this study in its approach to provide dynamic optimal operational decisions by optimizing the system over a given period of time. Nehring et al. (2010) proposed a similar approach for short term production scheduling in underground mines using dynamic machine allocation through mathematical programming for sublevel stoping copper operation.

Caccetta and Hill (2003) propose a branch and cut strategy for solving the large scale scheduling problem incorporating all the desired constraints and critically examines the existing approaches and software in the industry to tackle scheduling problem. They describe the advantage of heuristic based approach used in XPAC (Runge Pincock Minarco Ltd., 2015), which uses the weighted function to determine the extraction sequence in each period, in terms of speed but solutions may be far from optimal. MineSight (Huang, *et al.*, 2009) is another commercial tool for medium and short term production scheduling which formulates MILP model to solve the multiple models, multiple processes, multiple destinations and grade blending requirements.

One major limitation of the existing approaches is that grade blending objectives optimized at the short term planning stage are hard to achieve at the operational stage, due to the mismatch between the planned and operating ore faces; and realized mainly through truck dispatching systems. High grade variability in scheduled faces and mismatch between the scheduled and operating faces at any time, also leads to decreased equipment utilizations due to poor dispatching requirements for grade blending. Optimal truck allocation is another requirement which must be provided by the short term schedules for optimal dispatching, which still lakes from most short term plans. Another major drawback of the existing models is that they fail to consider the dynamic nature of the mining operations leading to frequent updates of the operational plans as well as short term plans. The dynamic components of the system which must be accounted at this stage include equipment availabilities due to failures, changing rates of production from shovels based on their location, haulage capacities, and unavailability of faces due to precedence requirements. The capturing of dynamic nature of the mining systems may provide opportunities to develop more robust mine plans and thus support an opportunistic proactive planning framework by determining the bottlenecks of the mining operation.

2.3. Operational planning

Dispatching by definition tries to allocate trucks to source and destinations in real-time so that operating efficiency of the trucks and associated equipments (loaders, plants etc.) can be maximized and short term production schedule can be realized. Apart from mining industry, cement industry requires similar application of truck dispatching for ready mixed concrete supply (Yan & Lai, 2007; Yan*, et al.*, 2008). The problem in mining becomes slightly deviated when many other objectives gets associated with dispatching decisions, such as grade blending objectives, varying and multiple source and destinations and respective flow requirements and handling mixed fleet systems. At this stage dispatching algorithms finds a shift from simple truck dispatching systems to operational planning and execution tools.

Queueing theory is a robust theoretical tool for modeling simple truck shovel operations. Koenigsberg (1958) can be considered as the first person who applied queuing theory in mining. Carmichael (1986, 1987) provide queueing models based on steady state assumptions of shovel truck operations and emphasized on the use of finite source queuing model with erlang distributions for loading and backcycle times. Similarly Kappas and Yegulalp (1991), Muduli and Yegulalp (1996) and Trivedi et al. (1999) used closed queueing network theory to minimize the error of performance parameters, for mixed truck fleet operational analysis and optimizing truck shovel capacities to minimize equipment idle times respectively. Alkass et al. (2003) used queueing theory to develop a computer model for optimum equipment fleet selection in mining operations. Ta et al. (2010) used linearized queueing models within linear integer programming for optimal truck allocations in open pit mines. Due to limited scope of queuing theory and wide scope provided by other techniques, it does not find most applicability nowadays, but instead it is used in conjunction with other techniques for developing robust models (Ercelebi & Bascetin, 2009; Ta*, et al.*, 2010).

Major research in the area of computer based operational planning and dispatching in mining started in 1980's. Elbrond and Soumis (1987) emphasize on a two-step optimization proposed by White and Olson (1986). The first stage chooses the shovels, the sites and the production rates. The second stage also determines the rates of the shovels but this time it considers the operation in more detail. Soumis et al. (1989) proposed a three stage dispatching procedure, namely equipment plan, operational plan and dispatching plan. Based on the overall approach, similar procedures have evolved as multi-stage dispatching systems.

White and Olson (1986) describes the limitations of the then existing dispatching models and concludes the need of a model which could concurrently maximize the production, minimize the re-handle, meet blending limits and feed the plant. The major limitation of their model is that LP models do not take into account the mixed fleet, which poses a limitation on the solution provided by the model and its applicability in mixed fleet systems. For the dynamic allocation of trucks, their model finds out the path requiring a truck allocation soonest, and assigns the closest truck to that path. The dynamic dispatching model also does not account for the sizes of the trucks, and thus cannot provide optimal allocation solutions for the mixed fleet systems. White and Olson (1993) also reviewed the then existing dispatching algorithms and proved the need of efficient dispatching systems by reviewing the significant productivity improvement in various mines.

The three stage model proposed by Soumis et al. (1989) uses man – machine interaction in the first stage. Authors describe the mixed integer programming in the first stage for shovel assignments as structurally bad and impossible to be solved within reasonable time. As an alternative to the optimal solution, authors suggested an increased human intervention to finally get 10 best alternatives for the shovel assignments to choose from in the reasonable time. The major limitation of the first stage is an increased human intervention which poses a limitation on the optimality of the shovel assignments and renders the model non-dynamic. The second stage determines the production rates of the shovels and truck assignments using non-linear programming with three objectives: maximize shovel productions, minimize the squared difference between computed and available truck hours and minimize the grade deviations (blending). One unique characteristic of the proposition is the use of queuing theory to calculate the truck waiting so as to compute the truck hours. Although the paper does not provide the mathematical formulations, the conceptual proposition provides a significant contribution. The truck dispatching is achieved by solving the classical assignment problem over the next 10-15 trucks.

Li (1990) proposed a three stage methodology for automated truck dispatching system. Equipment matching stage determines the number of trucks to be employed to best match the production objectives using a least square criterion. The haulage planning stage determines the target tonnage to be produced along a path in the network using linear programming. And the truck dispatching stage based on maximum inter-truck-time deviation. The haulage planning stage minimizes the transportation work (amount of material transported on a haulage path multiplied by the haul length), which is regarded as directly proportional to the transportation cost involved. This stage, instead of maximizing the production, attempts to achieve the desired productions from individual loading units within desired limits. Their model does not account for the desired plant feed or the grade requirements of the mine. The dispatching stage, using the optimal path flow rates provided by the haulage planning stage, determines the optimal inter truck time on the paths. The dispatching decisions are based on the time difference between the last truck dispatched on various paths and the next truck to be dispatched. The dispatching algorithm proposed contains various drawbacks, such as it does not account for the mixed fleet systems, the next trucks needing assignments and the travel times along various paths. But the simplistic approach makes the algorithm quite efficient to be easily implemented in real-time dispatching systems.

Temeng et al. (1998) developed a goal programming formulation as an upper stage of a two-stage dispatching system. Their paper describes goal programming to be better compared to linear programming using the results obtained. The major limitation of their model is that they do not provide any information regarding shovel assignments. Shovel assignment is an important decision making problem which has a direct impact on achieving the production targets and thus need to be accounted by the upper stage of the dispatching system. Although the model developed by Temeng et al. (1998) account for mixed fleet, it does so by taking the average payload of trucks, which would not be a realistic way of modeling this system. A better approach would be to optimize the operation by considering the actual capacities of every truck type in the system and their respective payloads.

The dispatching system developed by Temeng, Otuonye, and Frendewey (1997) uses the target production provided by the upper stage, to dispatch trucks to those shovels falling short of their targets, so as to minimize the total waiting time of both trucks and shovels. They propose a transportation algorithm, where available trucks are supplied to fulfill the demand of the shovels, with the objective of minimizing the waiting time of trucks and shovels.

Alarie et al. (2002) review different types of dispatching strategies and classified them broadly into three categories: 1 truck for N shovels, M trucks for 1 shovel and M trucks for N shovels. They describe a multi-stage dispatching system to be ideal which updates the guidelines representing not only the actual state of the mine, but also accounts for the forthcoming events that will affect the operational conditions in the near future. They emphasize the use of M trucks for N shovels strategy (the best among the three) in a multi stage dispatching algorithms, as the computing power and the technology for the real-time management of such systems is now available.

Ta et al. (2005) provide a stochastic optimization approach to improve the initial truck allocation and reallocation based on observed mine operation. The first stage is a probabilistic chance – constraint optimization model which is converted into a non-linear deterministic model; and the second stage is a mixed integer linear optimization model to provide ultimate discrete truck solutions. The truck allocation models minimize the truck resources needed to meet the production constraint or in other words minimize the operating and capital cost of ore delivery. Though the model provides a good conceptual background for stochastic optimization approach to solve the multi-stage optimization problem, it takes into account the probabilistic nature of truck travel times only. Also the model formulation is very much specific to a mining case and cannot be generalized to other mining systems.

Another model provided by Subtil et al. (2011) is used in commercial package SmartMine® marketed by Devex SA. It uses LP in the upper stage to determine the maximum production capacity of the mine and the optimal size of the truck fleet required to meet this production. The allocation planning stage does not provide any information for shovel assignments which still remains the task of the planner completely. Also the model do not take into consideration other desired characteristics, such as grade blending, constant desired feed to plants etc. The dynamic allocation or the truck dispatching is achieved by adopting M trucks for N shovels strategy. Using M trucks, best possible solutions are generated and each solution is simulated 50 times to get a desired confidence interval. The best solution is found using a multi-criteria optimization, which is to maximize productivity of transport fleet and minimize queue time at shovels and idle time of shovels. A fuzzy logic expert is then used to evaluate the solution and if passed dispatch the truck to the allocated shovel. The major drawback of the approach can be the cumbersome time consuming methodology adopted at the dynamic allocation stage, which demands quick and real-time decisions. Authors mention some situations where fuzzy logic rejects the best solution, which demands re-running of the entire model to get another solution. The solution is rejected only if the solution obtained is not good, where as the model estimated that solution to be the best, which poses a contradiction in the estimation and evaluation. The alternate solution generated after rejecting the first one will be the second best solution, which may again get rejected, leading the method into a loop and consuming lot of time.

Ahangaran et al. (2012) uses a two stage model for truck dispatching, where the first stage uses a network analysis technique to determine the best routes between departure and destination points and second stage provides dynamic truck assignments. The second stage adopts a binary integer programming model to minimize the function of the total cost of loading and transportation. This dispatching model is significantly different compared to previous models in terms of the objective function and the mixed fleet considerations in the modeling equations. One of the major drawbacks of this model is that it does not consider any predetermined objectives of the operations to achieve desired grade blending or constant feed to plants etc.

Munirathinam and Yingling (1994) provide a review of truck dispatching in mining and Lizotte et al. (1989) describe different heuristic methods used for truck assignments at that time. Bonates and Lizotte (1988) emphasize on the accuracy of the model in the upper stage in terms of the true representation of the mining system, so that realistic targets could be fed to the dispatching model in the lower stage. The major problems arise due to inaccurate input data at the upper stage. The truck cycle time is one of the major input data that can affect the predictions. Chanda and Gardiner (2010) provide multiple regression and artificial neural network based approaches to be better compared to the cycle times predicted by software such as TALPAC (Talpac, 2011), which uses manufacturers' specifications and rimpull curves. The more precise the data used at the upper stage, the better the performance of the model can be.

It is noted by reviewing the existing models in the multi-stage dispatching that very few models try to link the operational plans with the strategic plans of the mine. Models try to improve the efficiency of the mining operations but miss to incorporate the shovel assignments which still remain the sole responsibility of the planners to meet medium to long term targets. This missing link leads to frequent updates in the short term plans and may eventually lead to deviations from the strategic targets. Also many models do not incorporate or provide flexibility to incorporate major objectives of the operations. Not accounting for mixed fleet systems for optimum truck allocations and different truck types within truck dispatching algorithms is another major drawback which leads to inefficient utilization of equipment.

2.4. Modeling and solution approaches

2.4.1. *Goal programming*

Goal programming (GP) is an efficient and important technique for multi-objective decision making (MODM) problems (Chang, 2007). Charnes and Cooper (1957) are considered to be the very first to introduce goal programming, which was further refined and developed by Lee (1972) and Ignizio (1985). De Oliveira et al. (2003) used goal programming for Brazilian forest planning problem. Temeng et al. (1997, 1998) and many others used goal programming in mine operational planning decision making. Romero (2004) describes the structures of the achievement function to measure the degree of minimization of deviation variables in the goal programming formulation by critically examining the efficiency of widely used approaches for achievement functions and concludes to choose an approach based on the requirements of the decision makers (DMs). Tamiz et al. (1998) provides an overview of developments in goal programming and elaborates on various modeling approaches including normalization techniques for efficient results. Grodzevich and Romanko (2006) describes the zero one normalization technique by formulating a meaningful achievement function and elaborating on the pareto optimal space. Although zero one normalization technique is time consuming, the resultant achievement function remains meaningful and priority weights assigned to individual deviational variable in the achievement function generate desired prioritized results for individual objectives.

2.4.2. *Heuristic approaches*

Souza et al. (2010) proves that open pit mine operational planning problem belongs to NP-hard class by deriving an analogy with the Multiple Knapsack Problem (MKP) which belongs to NP-hard class (Papadimitriou & Steiglitz, 1982), and proposes a heuristic algorithm as a combination of Greedy Randomized Adaptive Search Procedures (GRASP) and General Variable Neighborhood Search (GVNS) to solve the Open pit mine operational planning problem. Ching-Jong (1994) proposed a node selection strategy for the branch and bound search and claimed it to be more efficient in storage space and computation time compared to conventional best bound rule. Pryor and Chinneck (2011) addresses the problem of best branching heuristic by assigning probability of satisfying a constraint at the child node for a variable, direction pair. Bley et al. (2010) present an integer programming model for mine production scheduling and strengthened their formulation by adding extra inequalities, by combining precedence and production constraints, that assist in reaching to solution faster. Khan and Niemann-Delius (2014) proposed Particle Swarm optimization algorithm as a meta-heuristic algorithm to solve long term scheduling problem, to reduce computation time and generate solutions comparable to those obtained by CPLEX solver. Krause and Musingwini (2007) describe the importance of optimal number of trucks in the system; and propose a modified Machine Repair model to determine, as a second estimation tool, the actual truck requirement in the mine for improved confidence. Although many heuristic and meta-heuristic approaches exist to improve the solution time of the problem or the sub-problems in short term and operational planning, this research does not intend to develop or implement any heuristic at this stage, which can be worked upon as a future research. As solution time is a critical factor, preprocessing strategies adopted by (Bley*, et al.*, 2010; Caccetta & Hill, 2003; L'Heureux*, et al.*, 2013; Smith, 1998), which attempts at fixing some of the variables based on the initial knowledge, have been implemented to improve the solution time of the problem.

2.5. Simulation in mining

The application of simulation in mine planning and design can be traced back to around 1940. With the evolution and familiarization with simulation, its power has been accepted worldwide. Simulation has been widely accepted as the most powerful tool for modeling the processes and analyzing the system responses with changing parameters of the system, and in-turn optimizing the system performance. Sturgul (2001) describe the importance of modeling and simulation in the mine planning operations by presenting its applicability in modeling conveyor belts, room and pillar mining operations, material handling and truck haulage in open pit mines. Paper describes GPSS/H and SIMAN based ARENA (Rockwell Automation Inc.), as two most commonly used discrete event simulation languages. Though there is an enormous opportunity for simulation in mining, it has been mainly used for material handling and mine planning purposes (Yuriy & Vayenas, 2008). Ataeepour and Baafi (1999), Sturgul and Eharrison (1987), Bonates and Lizotte (1988), Forsman et al. (1993) and Kolonja and Mutmansky (1994) used simulation models to analyze various dispatching strategies and proved the positive impact of dispatching systems in mining. Peng et al. (1988) used simulation models to link the discrete (truck-shovel) and continuous (belt conveyor) elements of the mining system. Awuah-Offei et al. (2003) used simulation models to determine the optimal truck and shovel requirements in a mine. Upadhyay et al. (2013) used simulation to determine optimal number of trucks for continuous surface mining operations.

Sturgul (1999) provides a historic review of discrete mine system simulation in United States and credits Rist (1961) for the first published work of a computer simulation of a mining system. Vagenas (1999) and Konyukh et al. (1999) provide a review of application of simulations in Canada and Asia respectively. As noted by Vagenas (1999), Canadian mining mostly used simulations for 3D animations to visualize entire ore-bodies, reliability assessment of mining equipment, integrating simulation with real-time mine management systems and analyzing the short term and long-term requirements of operations.

Vagenas (1999) and Sturgul (1999) present an evolution of various simulation languages and packages over the years, such as GASP V, SLAM, GPSS (GPSS II, GPSS360, GPSS V/S, GPSS/PC, GPSS/H) and SIMAN. Since then many other simulation languages have evolved and are being used. Yuriy and Vayenas (2008) describe “the availability of adequate debugging and error diagnostics, the ability to import data from other software such as spreadsheets and computer-aided-design packages, availability of an animation environment for visualization of the operation and the quality and variety of output reports and graphs” as the various criteria to be kept in mind for the selection of a simulation package. Another major criterion for the selection of any simulation package would be the strength of the package in generating the random numbers for modeling the processes.

Askari-Nasab et al. (2007) developed the open pit production simulator (OPPS) to simulate the dynamic expansion of the open pit mine geometry. Paper concludes that stochastic simulation with artificial intelligence can prove to be very efficient for modeling the random fields and dynamic processes in open pit mine planning. Fioroni et al. (2008) uses simulation in conjunction with a mixed integer linear programming model to reduce mining costs by optimal production planning.

Yuriy and Vayenas (2008) use discrete event simulation in conjunction with a reliability assessment model based on genetic algorithms to analyze the impact of equipment failures on production, mechanical availability and equipment utilizations. In another paper Hodkiewicz (2010) provide a broad review of simulation modeling in mining and describe the applicability of the simulation modeling in understanding the impact of preventive and corrective maintenance on the production. Raj et al. (2009) provides a critical review of the application of simulation techniques for production optimization in mining.

The researchers, through various simulation models, have proved the power of simulation and in-turn proved the opportunity to improve the mining operations through efficient planning. A generalized mine simulation program can provide ample scope and opportunity to improve the production operations by experimenting with various multi-stage dispatching models and comparing the effects on the system and desired objectives of the production operations. Following are the major shortcomings of the simulation models that will be incorporated in this research:

- Simulation models remain very much specific to any particular mining site.
- Models provide less user flexibility towards various stochastic parameters of the system, such as shovel bucket cycle time, truck spotting, hauling on various gradients, payload, dumping, and queuing etc.
- Models generally do not link the discrete production with continuous processing operation to enable analyzing the overall system.
- Models do not incorporate block by block excavation, as determined by the operational planning stage and hence fail to analyze the operation in short term planning horizons. This is mainly due to the manual decisions regarding shovel assignments.
- Models generally provide very less flexibility towards analyzing different optimization approaches at the dispatching stage.

2.6. Micro-simulation of truck haulage

It is evident that the power of simulation lies within the precise modeling of the system processes. One of such processes is the transportation of haul trucks in mines. Burt and Caccetta

(2007) and many others pointed out the importance of tracking the inherent traffic behavior in the internal and congested haulage networks, especially when large number of trucks travels through common shared haul road segments. Burt and Caccetta (2007) and Jaoua et al. (2012) describe the existing dispatching software as inefficient in accounting for the stochastic nature of the transportation system.

Jaoua et al. (2009) proposed a micro-simulation tool for accurately modeling the truck interactions on haul roads and described its benefits in capturing the affect of accidents on haul road segments and improved haul road design on the production. Meech and Juliana (2011) developed a human driver model in simulation to study autonomous trucks. Meech and Juliana (2011) used their human driver model to assign aggressiveness and stability of human drivers working in a mine and also to compare the tire wear, fuel consumption, cycle times and production between less variable autonomous trucks and manual trucks.

Jaoua et al. (2012) describe the importance of trucks haulage micro-simulation models for efficient truck dispatching systems as well. They describe that most of the dispatching algorithms are based on precompiled and deterministic truck cycle times and assume that for the next period trucks will spend on average the same time to accomplish the mission. However in reality of mining operation, the duration of truck travel is very sensitive to the real-time traffic state as well as the road condition.

Koppa et al. (2001) describe the vehicle movement in a traffic stream to be loosely coupled with other vehicles via the driver’s processing of information and execution of control inputs. The driver perceives the speed or acceleration of other vehicles and executes the control which guides his movement. Considering the general case of multi-lane road, two situations appear relevant here which determines the movement of any vehicle 1) the vehicle ahead and 2) the vehicle alongside. In case of Mining Haul roads, which generally have only one lane for one way traffic, only 1st situation comes into play.

In another study Rothery (2001) finds out that though it seems that the actions of any driver are continuous, there is some evidence that driver of any vehicle acts in a discontinuous way. There is a period of time during which the operator having made a decision to react is in an irreversible state and that the response must follow at an appropriate time, which later is consistent with the task. So, although the driver perceives the movement of other vehicles continuously, he/she processes it and then executes controls discontinuously. Hence a discrete event simulation, by modeling actions at discrete intervals of time can actually simulate the process. Another study by Kesting and Treiber (2008) suggest that drivers compensate for the human reaction time by anticipation. Hence a reaction time of zero seconds would be a reasonable assumption to model the process.

Human visual perception to distinguish acceleration from constant velocity is very difficult unless the object is observed for a relatively long period of time (10 to 15 sec) (Boff & Lincoln, 1988). Mortimer (1988) estimates that a driver can detect a relative movement with respect to a leading vehicle when distance between them has varied by approximately 12 percent. Mortimer notes that the major factor for this perception is the change in visual angle.

The concept of car following model has been used in this study to simulate the truck movements. According to Rothery (2001) car following model assumes that, in single lane traffic, there exists a correlation between two vehicles within a range of inter-vehicle spacing from zero to about 100 to 125 meters. This model assumes that each driver in a following vehicle is an active and predictable control element. It is this interaction that determines the acceleration or deceleration of the vehicle when two vehicles are interacting.

In normal case, when there is no interaction between vehicles, they try to move freely on their normal driving speed. According to Bonates (1996) maximum obtainable speed by any truck can be determined by the rimpull curves generally provided by the manufacturers. He describes the rimpull as the force exerted on ground by the drive wheels to get the truck in motion. This force is generated by the torque that the engine develops and it is a function of the gear ratios. Maximum achievable speed by truck on any haul road segment can be calculated as given in Eq. (1) (Bonates, 1996)

$$V_{max} = \frac{366.97 \times Kw \times Efficiency}{TR \times W} \quad (1)$$

Where: V_{max} = Maximum obtainable velocity (Km/Hr)

Kw = Vehicle engine power in Kw

$Efficiency$ = Motor efficiency (decimal)

TR = Total resistance (decimal)

W = Vehicle weight, in Kg

The maximum velocity calculated in Eq. (1) is multiplied with a speed factor to determine the average velocity of trucks along any haul road segment (Table 2-1).

Table 2-1: Factors for converting maximum speed to average speed (Bishop, 1968)

Length of Haul Road Section (meter)	Factors for Converting Maximum Speed to Average Speed	
	Unit Starting from Stop	Unit in Motion when Entering Road Section
0-107	0.25-0.5	0.50-2.00
107-229	0.35-0.6	0.60-0.75
229-457	0.5-0.65	0.70-0.80
457-762	0.6-0.70	0.75-0.80
762-1067	0.65-0.75	0.80-0.85
Over 1067	0.70-0.85	0.80-0.90

The concept of micro-simulation in mining is very new and bears enormous potential to analyze the mining operations precisely. The scope of this research is limited to the modeling of truck travel times as accurately as possible; to be used for development of a precise simulation model for the truck-shovel based open pit mining system.

2.7. Summary and conclusions

The research in the area of mine planning and optimization can be traced back to 1950's where very basic models were used in planning. Queueing theory was widely used for truck shovel optimizations in the beginning, which was later replaced by operations research techniques, simulation and mixed optimization techniques with the evolution in computing capabilities. Although lot of work can be found for long term and medium term mine planning, short term and operational mine planning haven't received sufficient attention of the researchers. Short term mine production scheduling still bears a tremendous scope for research to improve the mine operations and achieve strategic goals of maximum NPV.

Mixed Integer Programming, Goal programming and simulation have been found as the major approaches to solve the short term and operational planning optimization problem in the literature. Most of the literature in short term planning focus on the objectives of meeting plant feed and grade blending requirements and determining an optimum sequence of block extraction defined within pit limit based on medium or long term production schedule. The literature in operational planning and multi-stage dispatching focuses on the determination of path flow rates from mining shovels to respective destinations, to be fed into truck dispatching systems, to achieve desired grade blend, tonnage feed to plants and maximum production during operations. The scope of simulation models have been limited to specific problem domains and mining systems they were created for. In recent years simulation optimization has also seen great development across different problem domains, an application of which has been found for truck dispatching in mining. Truck haulage being a critical component in the mining operations has also seen development over the past decade. Some researchers have made an attempt to model the truck travel behavior on the haul roads, through micro-simulation systems, which leads to platoon formations and decreased productions. They have used these micro-simulation models to predict the impact on production due to haul road designs, increased traffic, accidents, and driver behaviors.

A thorough review of the existing approaches in short term and operational planning; simulation and micro-simulation models, following limitations have been observed which will be accounted in this project.

2.7.1. *Short term and operational planning*

Literature on the optimal decision making in allocation planning unanimously emphasizes on a multi stage optimization approach for optimal allocation planning at the operational level. The upper stages optimize the systems to determine optimal number of equipment, allocation and targets for the shift, whereas the lower stage implements the executable plan provided by the upper stage. The decisions at the upper stage are based on the operational objectives of the mine. The lower stage performs the dynamic truck allocations based on the decisions of the upper stage. On the other hand, based on the literature reviewed, the objectives of short term production planning are to provide sequence of extraction of blocks within pit limit defined by medium or long term plan, to achieve the strategic production targets and minimize the fluctuations in target tonnage feed and grades delivered to plants in daily operations. The short term schedule must also provide optimal truck allocations for truck dispatching, maximize equipment utilizations and must be flexible and practical for execution. Following are the major shortcomings of the existing models in short term and operational planning as reviewed in this chapter:

- There exist no direct link between the short term plan and the operation, which is filled by the planners on site who provide shovel allocations to blocks based on experience to meet short term plans and operational objectives.
- Due to manual shovel allocations and not accounting for inherent uncertainties of the mining operations, short term plans need frequent updating which may eventually lead to deviations from short term and in turn long term plans; affecting economic objectives of the mine.
- Not accounting for highly uncertain mining environment during short term planning and manual shovel assignments during operations, instills lower confidence on the plans and the expected status of the system after the planning period; which forces for reactive planning instead of pro-active decision making for an efficient production system.
- To the best of authors knowledge, except L'Heureux et al.(2013), no other literature considers the effects of shovel movement for short term production planning, leaving the practicality of the schedules in question.
- Truck allocation requirement is not accounted by any literature reviewed in short term planning, which poses a limitation on the achievability of the schedules due to limited available haulage capacity and increasing distances of scheduled faces; which again forces reactive planning.
- Predicting the fluctuations in head grade and tonnage feed to plants is also considered important at the short term planning stage, which is not provided by any planning model in short term planning.
- Most of the models in multi-stage dispatching fail to include, or provide flexibility to include all the major objectives of the production operations. The major objectives that can be considered at the operational planning stage include maximizing production, minimizing grade deviation, providing constant and desired feed to the processing plants and minimizing

the operating cost and minimizing shovel movement times between faces, which also bear importance in shift production planning.

- Modeling the material transport as flow rate or in other cases not considering the truck characteristics make most of the multi stage dispatching models inappropriate to be implemented in mixed fleet systems.

2.7.2. *Simulation*

Discrete event simulation bears great scope towards decision making in mining industry, and it has been successfully applied to assess the impact of changes in the operating strategy and system parameters and hence to optimize the system by analyzing various scenarios. Very little work has been found in literature which applies discrete event simulation models directly for decision making purposes, such as simulation optimization models. In context to the objectives of this study, following limitations are generally observed in the simulation models discussed in literature:

- Models generally do not link the discrete production with continuous processing operation to enable analyzing the overall production system, as the production rate is limited by the feeding capacity to plants.

- Models do not incorporate block by block excavation, as determined by the short term planning stage and hence fail to analyze the operation in longer time frames. This is mainly due to the manual decisions regarding shovel assignments. An optimization model/tool for operational planning, like the one presented in this study would enable developing such a simulation model and thus help understand the production behavior and short term production planning in short term planning time horizons.

- Most simulation models do not construct the actual haulage network and do not model the interactions among trucks, which may lead to platoon formations and greatly affect the production.

- Truck velocities are usually modeled using distribution functions, which assigns a fixed speed to trucks between a source and a destination. This is a big assumption in most models, where in reality speed of trucks varies throughout the haul road network depending on the haul road characteristics (gradient, rolling resistance etc.), rimpull characteristics of trucks and truck interactions on individual road segments and at intersections.

- Determination of optimal fleet size is a major problem faced by organizations, which is usually calculated through scenario analysis of simulation models. However, not accounting for haul road network, road characteristics, truck interactions and the dispatching system, introduces error in estimation, which leads to poor productivity in operations.

- Due to inherent nature of discrete event simulation models, they are made with respect to particular mining sites and remain limited to the problem domain being analyzed. The reusability of the model over time is still possible, which must be accounted while developing the model. The flexibility must be provided to incorporate changing haul road network, change distribution functions and alter the equipment and their characteristics, to ease the applicability of the model over time for efficient returns over the life of the mine.

THEORETICAL FRAMEWORK

3. THEORETICAL FRAMEWORK

3.1. Introduction

Mine planning is usually classified as strategic plans constituting long term and medium term plans; and tactical plans constituting short term and operational plans. Due to longer life spans of mines, optimal and practical planning is essential for maximum NPV and smooth operations; however on a reverse perspective, operational executions dictate achievements of planned targets and schedules. This anomaly creates a cyclic behavior in the planning process, where actual planning follows the sequence: long term – medium term – short term – operations; operational executions necessitates reverse path to update and recalculate actual plans. Operational planning and executions thus become very important to achieve the economic objectives and long term life of mine plans. Pro-active planning and decision making tools may help mitigate this cyclic effect, by foreseeing the deviations in operations from the strategic plans, to undertake timely actions to minimize the deviations. A bottom-up approach is therefore proposed in this research, which generates uncertainty based short term plan by simulating operations to achieve medium to long term plans. This approach links operations directly to strategic plans, in turn creating the short term plan which is practically feasible and achievable, and enabling pro-active actions to minimize any perceived deviations from the strategic targets.

Fig. 3.1 shows the layout of an open pit mining system which consists of available excavator/shovel resources, trucks, existing haul road network, process plants, stock piles and waste dumps. Short term planning in open pit mining environment, with truck – shovel operations, deals with planning the sequence of allocation of excavators/shovels to the blocks available within the pit boundary determined by long term schedule, and the production targets limited by shovel and destination capacities. Short term schedules are generated to guide the operations to meet medium or long term production schedules and on the other hand achieve operational requirements. The problem becomes complex with the processing plants, which require grades within desired range for efficient recovery of final product. Higher fluctuations in head grade delivered to plants may affect the recovery of the final product substantially. High grade variability within the ore deposit may sometimes make it practically impossible to maintain a steady head grade to plants by blending through optimal dispatching. Such a case enforces the requirement of blending stock piles, making problem further complex to solve.

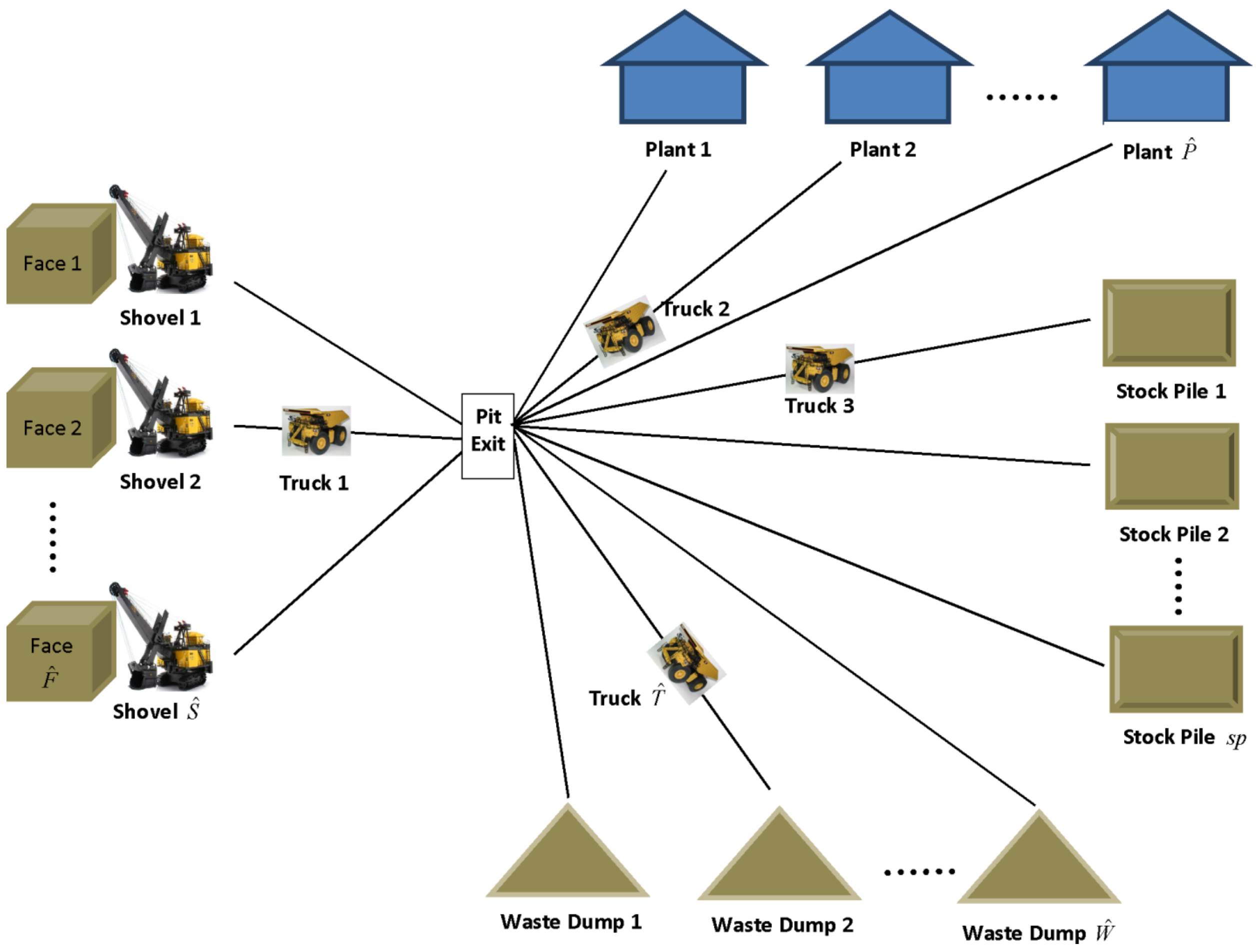

Fig. 3.1. Mining system and components for short term planning in open pit mines

The major objectives for the short term production scheduling based on Chanda and Wilke (1992) and the requirements for an efficient plan are:

- Determining ore and waste mining faces and the sequence of extraction within the planned faces based on medium or long term production schedule, the rates of ore and waste mining, stripping ratios and composition of head grades,
- The schedule must minimize the absolute deviations in head grade delivered to plants, as it may significantly affect the mill recovery,
- The schedule should predict the fluctuations in head grades delivered to plants,
- The schedule must provide detailed allocation of shovels, and trucks for dispatching,
- The schedule must efficiently utilize the equipment and mining resources,
- The schedule must be flexible and practically executable,
- The scheduling tool must reflect the operational environment, such as haul road network, haul road characteristics, equipment conditions and availabilities, truck dispatching system efficiency and other operational uncertainties.

This chapter presents a theoretical framework for the development of an efficient and practical short term and operational planning tool. The next section elaborates the framework of the planning tool, presenting the steps required and the interactions among components of the tool for the development of short term plans and operational decision making. Then the mathematical optimization model for the development of Mine Operational Optimization Tool (MOOT) is presented. The development of simulation and micro-simulation of mine haulage is presented next in this chapter followed by summary and conclusions.

3.2. Definitions

3.2.1. *Faces*

Faces in the model refers to the cluster of blocks, grouped together based on similarity in material content and rock types, also known as scheduling polygons (Fig. 3.2). The basic mining unit considered in the model is a face.

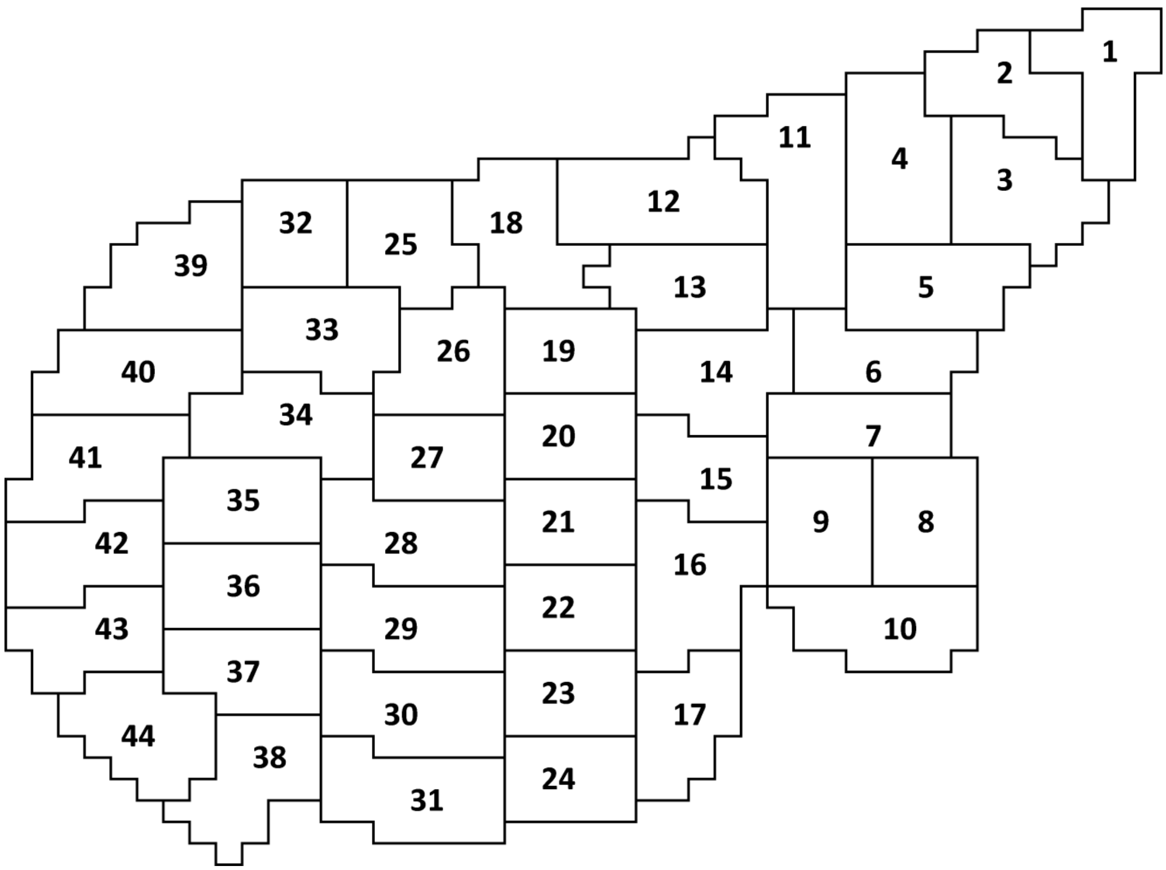

Fig. 3.2 Mining blocks on a bench clustered as faces

3.2.2. *Decision and optimization time frame*

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

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

Fig. 3.3. Decision and optimization time frames considered in this research

3.3. Short term mine planning

The process of short term planning starts with the long term plans. The blocks within the pit boundary determined in the long term plan are selected and scheduled in the short term planning time horizons. In the conventional approach, the short term plans are then executed through operational plans and updated periodically to achieve strategic planning targets. This research proposes a bottom up approach where operations are simulated with dynamic operational decisions to meet strategic plans, within uncertain mining environment, to generate uncertainty based short term plans. Although this approach does not guarantee that short term plans would be exactly followed during operations and no reverse updating of plans would be required, the pro-active approach help reduce the deviations and frequent updating of the plans. The conceptual framework of the process is given in Fig. 3.4, which presents the applicability of the dynamic operational decision making tool, the MOOT, developed in this research for mine operational decision making and in a parallel process through simulation optimization approach for short term planning and optimization. Although conceptual framework for implementing the MOOT as a dynamic operational decision making tool exist in actual operations, similar to multi-stage dispatching systems such as Dispatch (Modular Mining Systems Inc.), current research is focused on its applicability as a simulation optimization tool for uncertainty based short term planning.

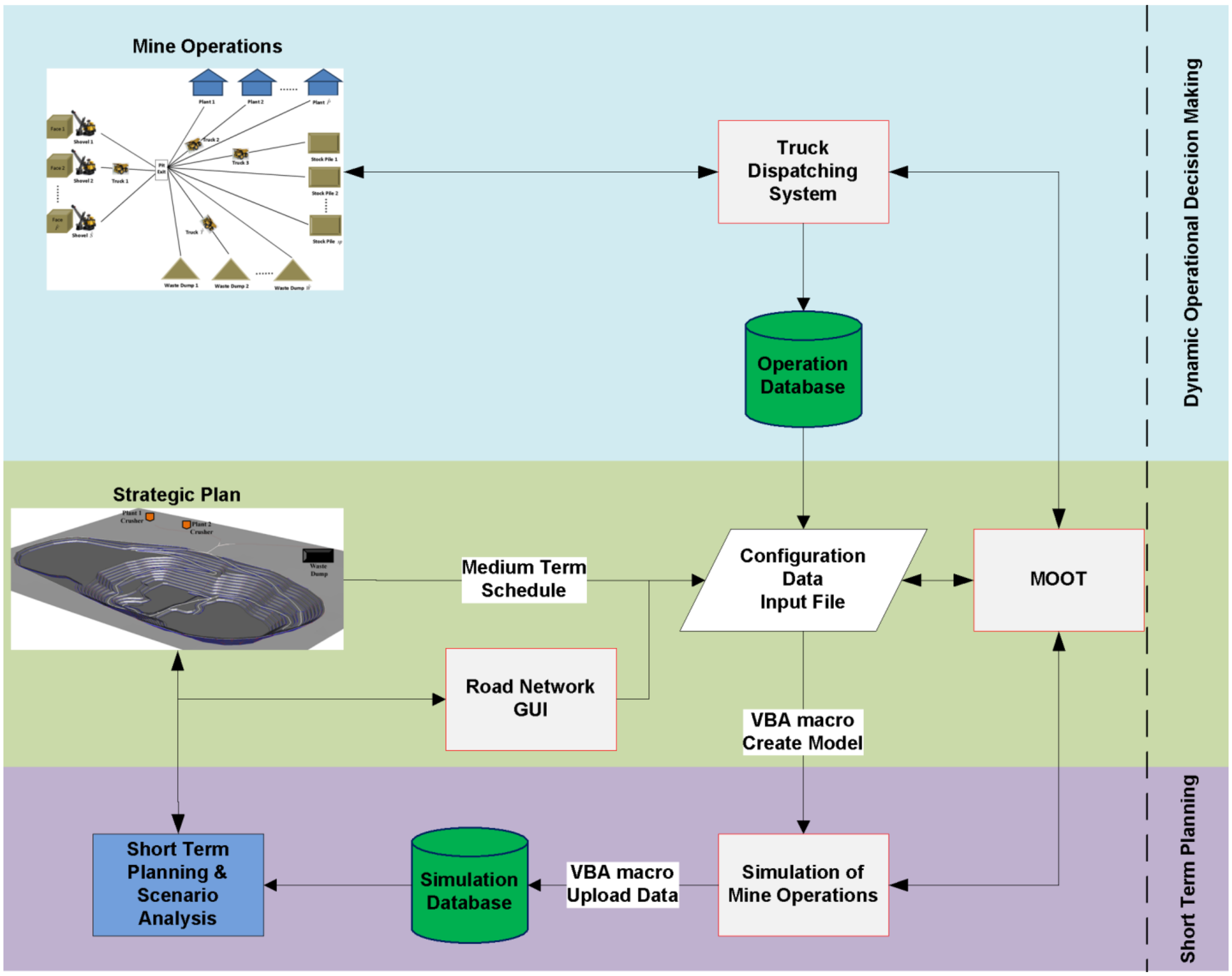

Fig. 3.4. Conceptual framework for implementing MOOT as a short term planning and dynamic operational decision making tool

The steps involved in the proposed process for uncertainty based short term mine planning are given in Fig. 3.5.

Strategic schedule

- Select the blocks scheduled in the strategic plan.
- Group similar blocks together into faces.
- Determine mining precedence requirements based on practical accessibility of faces.
- Determine initial shovel location at the start of the planning time horizon.

Excel input interface

- Generate probability distributions to model process times, based on historical data.
- Create Excel input interface file with strategic schedule, systerm components and various process time distributions.
- Calculate multiplier factors to model truck speeds based on rimpull curve characteristics.
- Translate haul road network based on strategic plan by creating nodes and segments into the Excel input interface file.

Simulation optimization

- Run the VBA macro created within Arena to generate the model variables, resources and road network.
- Run the simulation model for the short term planning time horizon
- Run the upload VBA macro created within Arena to upload the simulation outputs into SQL database.
- Run the Matlab result analysis tool to query the database to estimate and plot the KPIs of the system.
- Run different scenarios by making changes in the Excel input interface file.

Fig. 3.5. Steps to run the proposed simulation optimization model

The very first and important requirement for carrying out the proposed approach is the development of clusters for the blocks selected from the strategic plan. Although generating clusters is not a requirement for MOOT, and it can work with blocks as well; clusters reduce the number of available faces for assignment, thus reducing the run time of the model. It also brings schedule closer to reality, as blasting and extractions are usually carried out over much wider areas compared to blocks. Thus clustering is recommended in this research for improved and better results. The clustering must be carried out to group similar blocks together to develop larger size faces for shovel assignments. The blocks constituting a cluster must have:

- Similar grades

- Same rock types
- Same bench
- Between minimum and maximum limit on the number of blocks

Clusters created by following the given criterion will have similar mining and destination characteristics and will be almost of equal size as the blast areas in the mine operations. A clustering algorithm developed by Tabesh and Askari-Nasab (2013) is used in this research to generate clusters for the case study implemented in the following chapter.

The next important step involves determining the horizontal precedence face matrix. As the shapes of clusters are usually irregular, a direct mathematical approach is not possible to determine horizontal accessibility requirements of faces. Also depending on the equipment sizes and practicality of the schedule, manual determination of precedence matrix is considered in this research. This also provides flexibility to the planner to control the mining direction. The vertical precedence faces are taken directly from the medium term schedule, which are combined with horizontal precedence face matrix to determine the practical precedence requirement. Changes in the precedence matrix may change the final solutions, as the mining directions might change.

Model provides shovel allocations based on their locations at any time. This makes the starting position of shovels very critical for accurate results. Shovel position here refers to the coordinates of the actual faces where shovels will be initially placed. To provide a warm-up to simulation, this initial position refers to large dummy faces located exactly at the same location as the original faces. The simulation starts with working on these dummy faces and moves to original faces after the warm-up time.

After the initial positions are determined and dummy faces are created, the schedule is created within an Excel input interface/configuration file which contains all the faces scheduled within the strategic plan including dummy faces. This schedule sheet contains the coordinates, tonnages, average grades of all the material types present in the ore, face IDs and the precedence faces determined before. In the process of constructing input configuration file, general inputs are provided in the sheet *general* which provides information on number of scheduled polygon faces, shovels, truck types, material types present in the ore, number of plant crushers, stock piles and waste dumps. The general inputs also includes number of optimization periods and decision time frame (period in hours) for the MOOT, hours per shift, number of shifts per day, working days per week and weights assigned to individual goals for optimization. Dump location information is provided in the sheet *DumpLocations* which contains coordinates and simultaneous dump capacity of each dump including each plant crusher, stockpile (if any) and waste dump. Information on trucks in the system are provided in the sheet *Trucks*, which provides number of trucks of each type available and respective mean dump time, spot time and tonnage capacities, along with distribution functions for dump times and spot times. Mean values are used by MOOT for deterministic decision making purposes, while distributions are used within simulation. Compatibility of each truck type to work with a shovel is also provided here. This sheet also provides a schedule for each truck, i.e. the duration a truck will be out of system. This schedule enables the user to include any contractor trucks if required for part of the scheduling horizon. All the shovels are listed in the sheet *Shovels*, which provides mean bucket tonnage capacities, bucket cycle times, travel speed of shovels, and initial face IDs for each shovels. Distributions are also provided for bucket tonnage capacities and bucket cycle times to be used within simulation. Truck failures for each truck type are provided in the sheet

TruckFailures and shovel failures for each shovel are provided in the sheet *ShovelFailures*. These sheets provide distributions for time between failures (TBF) and time to repair (TTR) for each failure type. Crusher rate (tph) and corresponding hopper capacities are provided in the sheet *Plants*, which also provides desired grades of each material type at each crusher location. Weights are also provided here depending on desirability and criticality of material types at each plant crusher location for the MOOT to provide optimal grade blending.

A Matlab® function is created to determine the speed factors of each truck type to adjust the speed of trucks while travelling on varying road gradients. Based on rimpull curve characteristics and, empty and loaded gross vehicle weights, this function determines the maximum possible speed of each truck type on different total resistance (gradient + rolling resistance) haul roads, which is divided by the maximum possible speed on flat hauls to calculate speed factors by which the speed of trucks will be adjusted within simulation on different haul road segments. These speed factors are written down within *TruckSpeeds* sheet of input configuration file, which also contains mean flat haul speeds and respective distributions for each truck type calculated based on historical data for an average driver.

The next task in the process is to translate designed haul road network into readable input for Arena to create haul road network for simulation. A Matlab® based GUI is created, which takes designed polylines as dxf input and creates nodes and segments into the input file, which will be used during model building stage to construct haul road network within Arena simulation. The inputs thus created contain haul road information on gradients, rolling resistances and maximum allowed speed at each segment of the road. The user can then manually adjust the maximum allowed speed and rolling resistances of individual haul roads. The GUI also creates face loading nodes and dumping nodes for each polygon face and dump defined in the input file based on their coordinates.

At this stage the input configuration file is complete, which is then used to develop the simulation model of the mining operation within Arena simulation. A VBA macro is created within the simulation which is then run to generate various variables, expressions, sets, stations, resources, resource capacities, transporters, and haul roads within the simulation model.

Finally simulation model is run for the duration of short term plan. The operational decisions regarding shovel relocations and target productions for dispatch are provided by the MOOT through VBA – Matlab® interactions. Each time system state changes which demands a decision, the MOOT is executed in Matlab® through VBA, which generates a text file as its output, which is then read into simulation. Both simulation and MOOT use the same input configuration file during this process to maintain the consistency in the process. The simulation outputs are recorded in the plain text format for each load carried by trucks, failures, plants and shovel allocations. The simulation model at the end of simulation provides a VBA based form to upload this data to the SQL server database. This process also removes the data generated during the warm-up period within simulation.

A Matlab® function is created which is then run to analyze and plot the results for detailed analysis of the scenario. This function queries the database through ODBC within windows to fetch the required data. Queries on shovel movements provide details on shovel working faces during the course of simulation time to determine the uncertainty based schedule for each replication.

Several scenarios can now be analyzed by changing the desired parameters in the input configuration file to meet the strategic target, in turn selecting the best scenario to be implemented in mine operations following a pro-active decision making approach.

3.4. Mine operational optimization tool (MOOT)

3.4.1. *Notations*

Table 3-1: 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)

Table 3-2: Parameters of systems considered

D_t	Dumping time of truck type t (minutes)
E_t	Spotting time of truck type t (minutes)
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 (ton)
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 (ton)

X_s^+	Maximum possible shovel production in decision time frame '*T*' (ton)
X_s^-	Minimum shovel production desired in decision time frame '*T*' (ton)
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 (ton/hr)
$\Lambda_{d^c}^+$	Maximum positive deviation in tonnage accepted at crushers/processing plants (ton/hr)
$\Lambda_{d^c}^-$	Maximum negative deviation in tonnage accepted at crushers/processing plants (ton/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 (ton)
$O_{\min}$	Minimum material at face below which a face is considered mined
Q_f	1 if material at face is ore, 0 if it is waste (binary parameter)
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)
$\overline{T}_{t,f,d}$	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^{ore}_{s}	0 if shovel *s* is locked to an ore face, 1 if locked to waste and 2 if not locked
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)

3.4.2. *Preliminary model (M_0)*

3.4.2.1. Variables

Table 3-3: Variables considered in the preliminary model

$a_{s,f}$	Assignment of shovel *s* to face *f* (binary)
$n_{t,f,d}$	Number of trips made by truck type *t*, from face *f*, to destination *d* (integer)
$x_{s,f,d}$	Tonnage production sent by shovel *s*, from face *f*, to destination *d*
x^{-}_{s}	Negative deviation of shovel production from the maximum capacity in a shift
$\delta^{-}_{d^c}, \delta^{+}_{d^c}$	Negative and positive deviation of production received at the processing plants d^c
$g^{-}_{k,d^o}, g^{+}_{k,d^o}$	Negative and positive deviation of tonnage content of material type *k* compared to tonnage content desired, based on desired grade at the ore destinations d^o

3.4.2.2. Model formulation

Goals:

$$\Psi_1 = \sum_{s} x^{-}_{s} \tag{2}$$

$$\Psi_2 = \sum_{d^o}\sum_{k}(g^{-}_{k,d^o} + g^{+}_{k,d^o}) \tag{3}$$

$$\Psi_3 = \sum_{d^c}(\delta^{-}_{d^c} + \delta^{+}_{d^c}) \tag{4}$$

$$\Psi_4 = \sum_s \sum_f \Gamma^F_{F_s,f} \times A_s \times a_{s,f} + \sum_t \sum_f \sum_d n_{t,f,d} \times \Gamma^D_{f,d} \times (C_t + \bar{C}_t) \quad (5)$$

Equation (2) represents the difference between the maximum target production and production achieved by the shovels over a shift. Equation (3) represents the difference between the material content received at the ore destinations and the material content based on desired grade. Equation (4) represents the difference between the quantities of ore supplied to the processing plants compared to the target quantities desired over the optimization period. Equation (5) represents the total cost of shovel movement (if any shovel is reassigned to a new face) and truck operating cost.

Constraints:

$$\sum_s a_{s,f} \le 1 \qquad \forall f \quad (6)$$

$$\sum_f a_{s,f} \le 1 \qquad \forall s \quad (7)$$

$$\sum_d \sum_f x_{s,f,d} + x_s^- = X_s^+ \qquad \forall s \quad (8)$$

$$\sum_d \sum_f x_{s,f,d} \ge X_s^- \qquad \forall s \quad (9)$$

$$\sum_s x_{s,f,d} \le \sum_t n_{t,f,d} \times H_t \qquad \forall d \;\&\; \forall f \quad (10)$$

$$\sum_s x_{s,f,d} + J \ge \sum_t n_{t,f,d} \times H_t \qquad \forall d \;\&\; \forall f \quad (11)$$

$$\sum_{d^o} x_{s,f,d^o} \le a_{s,f} \times O_f \times Q_f \qquad \forall s \;\&\; \forall f \quad (12)$$

$$\sum_{d^w} x_{s,f,d^w} \le a_{s,f} \times O_f \times (1 - Q_f) \qquad \forall s \;\&\; \forall f \quad (13)$$

$$\sum_{d} n_{t,f,d} \times H_t \le \sum_{s} \left(\sum_{d} x_{s,f,d} + a_{s,f} \times J \right) \times M_{t,s}^{T} \qquad \forall t \,\&\, \forall f \qquad (14)$$

$$\sum_{f} \sum_{d} n_{t,f,d} \times \bar{T}_{t,f,d} \le T \times 60 \times N_t^T \times \alpha_t^T \qquad \forall t \qquad (15)$$

$$\sum_{d} x_{s,f,d} \le \left(T \times 60 - \tau_{s,f} \right) \times 60 \times X_s \times \alpha_s^S \times a_{s,f} \big/ L_s \qquad \forall s \,\&\, \forall f \qquad (16)$$

$$\sum_{s} \sum_{f} x_{s,f,d^c} + \delta_{d^c}^{-} - \delta_{d^c}^{+} = Z_{d^c} \times T \qquad \forall d^c \qquad (17)$$

$$\delta_{d^c}^{-} \le \Lambda_{d^c}^{-} \times T \qquad \forall d^p \qquad (18)$$

$$\delta_{d^c}^{+} \le \Lambda_{d^c}^{+} \times T \qquad \forall d^p \qquad (19)$$

$$\sum_{f} \sum_{s} x_{s,f,d^o} \times \bar{G}_{f,k} + g_{k,d^o}^{-} - g_{k,d^o}^{+} = \sum_{s} \sum_{f} x_{s,f,d^o} \times G_{k,d^o} \qquad \forall k \,\&\, \forall d^o \qquad (20)$$

Constraints (6) and (7) assure that only one shovel is assigned to any face and also that any shovel is assigned to only one face. Constraint (8) is a soft constraint on the production by any shovel with a deviational variable that is minimized in the objective function. Constraint (9) is a hard constraint that puts a lower limit on the production by any shovel. Constraint (10) assures that total production by any shovel from its face to a destination is less than or equal to the total material hauled by trucks between the face and the destination, which in turn is equal to the product of number of trips between the face and destination, and the truck capacity. The inequality constraint makes sure that total material hauled may not be an integer multiple of truck capacity and so some trips may have slightly less load hauled. This constraint enables the model to excavate the faces completely and reduces infeasibility of the model to a great extent due to the tight equality constraint. To counter the effect caused by the inequality, constraint (11) has been included which puts a lower limit on production deviation as equal to a predefined value *J*. To optimize the objective function, *J* is considered as the minimum of the truck capacities in the truck fleet. It means, at the end of the shift, the maximum allowed difference between the shovel production from a face to a destination and the material hauled based on number of truck trips is *J*. In other words, constraints (10) and (11) allow the shovels to load the trucks slightly less than the capacity of the trucks if required. Constraints (12) and (13) make sure that total ore or waste production by any shovel from its assigned face cannot exceed the total available ore or waste material at that face. This constraint also makes sure that no production is possible by the shovel from the face it is not assigned to. Constraint (14) assures that a particular truck type will have zero trips from any non-matching shovel. Part of the right hand side of the inequality is included to incorporate what is modeled in constraint (11). Constraint (15) limits the maximum possible trips by any truck type considering the truck availability and optimization time. Constraint (16) limits the total production possible by a shovel taking into account its availability and the movement time to the face (if assigned to a different face from where it initially was). Constraints (17), (18) and (19) are the processing constraints on the desired tonnage feed to the processing plants and maximum allowable deviation in tonnage accepted at the plants. Constraint (20) tries that the average grade sent to the processing plants is of the desired grade and deviation is within the upper and lower acceptable limits.

3.4.3. *Main model (M)*

3.4.3.1. Variables

Another index *p* is added to the variables considered in the preliminary model, apart from adding few other variables to build MOOT, which are given as:

Table 3-4: Variables considered in the main 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
$r^{rem}_{s,p}$	Remaining movement time (minutes) to be covered in next period
$r^{act}_{s,p}$	Actual movement time (minutes) covered in period '*p*'

3.4.3.2. MILGP formulations

Four operational objectives have been considered here as goals:

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

$$\Psi_1 = \sum_p \sum_s \left(\frac{1}{p}\right) \times x^{-}_{s,p} \tag{21}$$

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

$$\Psi_2 = \sum_{d^c}\sum_{p}\left(\frac{1}{p}\right)\times(\delta^-_{d^c,p} + \delta^+_{d^c,p}) \tag{22}$$

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

$$\Psi_3 = \sum_{p}\sum_{d^o}\sum_{k}\left(\frac{1}{p}\right)\times(g^-_{k,d^o,p} + g^+_{k,d^o,p}) \tag{23}$$

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

$$\Psi_4 = \sum_{s}\sum_{p} r_{s,p} \tag{24}$$

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

Objective function:

The problem is optimized following a non-preemptive weighted sum approach as described by Grodzevich & Romanko (2006). Before optimizing the goal, individual objectives are optimized to determine their respective values in pareto optimal space. Individual objectives are then normalized and combined to generate the goal as given in eq. (25).

$$\Psi = W_1 \times \overline{\Psi}_1 + W_2 \times \overline{\Psi}_2 + W_3 \times \overline{\Psi}_3 + W_4 \times \overline{\Psi}_4 \tag{25}$$

Constraints:

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

Constraint eq. (26) to (32) control the shovel allocation to faces in each period. As the optimization time frame of the model is divided into multiple periods, an assignment variable indexed over multiple periods is used for shovel assignment in each period. Constraint eq. (26) does not let multiple shovels to be assigned to any one face, which means any face can be mined by only one shovel. Eq. (27) assigns shovels in the first period to their initial faces where shovels were working at the start of optimization. Constraint eq. (28) allows any shovel to be assigned to at maximum two faces in any period. This constraint allows the shovels move to their new faces when their working face is mined out.

$$\sum_{s} a_{s,f,p} \leq 1 \qquad \forall f \;\&\; \forall p \tag{26}$$

$$a_{s,Fi_s,p} = 1 \qquad \forall s \;\&\; p = 1 \tag{27}$$

$$\sum_{f} a_{s,f,p} \leq 2 \qquad \forall s \;\&\; \forall p \tag{28}$$

Eq. (29) models the same constraint as eq. (28), but also controls *when* a shovel can work at two faces. Left hand side of the constraint is the maximum number of faces a shovel is assigned to in any period. The right hand side of the constraint (29) looks over all the faces and takes a very large value if shovel ‘s’ is not assigned to the face in that period. For the faces shovel is assigned to, last part of the constraint will become zero and remaining portion may take a value of 1 or 2. If the shovel was working on the face in the previous period and still hasn’t finished mining it, maximum number of faces that shovel can work on can be 1, but if the face is mined out completely, $m_{f,p}$ will become 1 and thus the shovel will be allowed to be assigned to another face. For the new face $a_{s,f,p-1}$ and $m_{f,p}$ will be zero and thus the constraint will still hold true and allow the shovel to be assigned to two faces in that period. Constraint (30) force a shovel to remain assigned to a face in the next period, if it is not mined out in that period, i.e. a shovel will continue working on a face until it is completely mined.

$$\sum_{f} a_{s,f,p} \le a_{s,f,p} + m_{f,p} + (1 - a_{s,f,p-1}) + (1 - a_{s,f,p}) \times BM \qquad \forall s, f, p \qquad (29)$$

$$a_{s,f,p+1} \ge a_{s,f,p} - m_{f,p} \qquad \forall s, f, p = 1 \ldots P-1 \qquad (30)$$

Constraint (31) ensures that shovels cannot be assigned to a face which is already mined, except if face was mined by itself and shovel is sitting idle. Constraint (32) ensures that if shovel ‘s’ was assigned to face ‘f’ and to only one face in period ‘p’, it will continue to be assigned to face ‘f’ in the next period. Constraint (32) works in conjunction with constraint (30) to eliminate any scenario where a face is mined out in a period and shovel movement cannot be finished in that period, model tries to assign the shovel to the new face in the next period without modeling the movement time and the loss in production.

$$a_{s,f,p+1} \le 1 + a_{s,f,p} - m_{f,p} \qquad \forall s, f, p = 1 \ldots P-1 \qquad (31)$$

$$a_{s,f,p+1} \geq 2 \times a_{s,f,p} - \sum_{f} a_{s,f,p} \qquad \forall s, f, p = 1...P-1 \qquad (32)$$

Constraints eq. (33) to eq. (38) control the travel time of shovels from one face to the next one. Eq. (33) determines the travel time of shovels in a period. As travel time variable is indexed over shovel and period only, it is not possible to formulate as equality constraint. Thus travel time is formulated as greater than or equal to the required travel time between faces. As travel time will incur loss in production, model will make travel time variable equal to the required travel time. Constraint (33) is formulated for all the faces and to determine the travel time between the assigned faces. For those faces, where shovel is not assigned, last part of the constraint makes the right hand side negative and thus does not affect the value of the travel time variable. For the faces shovel is assigned to, it calculates the distance as the sum of distance from that face to all other assigned faces, which includes the same face itself and the second face. As the distance between the same face is zero, constraint (33) makes the travel time variable $r_{s,p}$ greater than or equal to the required travel time between the assigned faces.

$$r_{s,p} \geq \sum_{f^1} a_{s,f^1,p} \times \Gamma^F_{f^1,f} \big/ S_s - (1 - a_{s,f,p}) \times BM \qquad \forall s, \forall f \ \& \ p \qquad (33)$$

Constraint (34) is included to model the continuous nature of shovel movement. If a shovel starts traveling towards the end of a period, it may finish the travel in the next period. $r^{act}_{s,p}$ and $r^{rem}_{s,p}$ variables divide the required travel time into actual travel time in that period and the remaining travel time for the next period. Constraint (35) is included to make sure travel time is zero, if shovel is assigned to only one face in a period.

$$r_{s,p} = r^{act}_{s,p} + r^{rem}_{s,p} \qquad \forall s \ \& \ \forall p \qquad (34)$$

$$r_{s,p} \le \left(\sum_{f} a_{s,f,p} - 1 \right) \times BM \qquad \forall s \,\&\, \forall p \qquad (35)$$

Constraints (36), (37) and (38) are formulated to ensure that no production is possible from the newly assigned face in a period if shovel hasn't finished traveling in that period. Constraints (37) and (38) make sure that binary variable $y_{s,p}$ becomes true if remaining travel time is zero and false if greater than zero. Then this binary variable $y_{s,p}$ is used in constraint (36) to control production from the newly assigned face. Constraint (36) is formulated for all the faces and right hand side takes a very large value for all other faces where shovel is not working and thus do not put any constraint on the production from those faces. For the face where shovel was initially working, first part of the right hand side takes a very large value, thus do not affect the production from that face as well. For the newly assigned face, first part of the right hand side of constraint (36) becomes zero and production from the new face is controlled by the binary variable $y_{s,p}$, which ensures that if remaining travel time is greater than zero, ($y_{s,p}$=0), no production is possible from the newly assigned face in that period.

$$\sum_{d} x_{s,f,d,p} \le \left(1 - a_{s,f,p} + a_{s,f,p-1}\right) \times BM + y_{s,p} \times BM \qquad \forall s, \forall f \,\&\, \forall p \qquad (36)$$

$$r_{s,p}^{rem} \ge \left(1 - y_{s,p}\right) \times \left(2 \times \varepsilon\right) \qquad \forall s \,\&\, \forall p \qquad (37)$$

$$r_{s,p}^{rem} \le y_{s,p} \times \varepsilon + \left(1 - y_{s,p}\right) \times BM \qquad \forall s \,\&\, \forall p \qquad (38)$$

Constraint (39) controls the total production possible by the shovels in any period, which has to be less than the maximum production capacity of the shovels in any period. First part of the constraint (39) is the total production by the shovel from all the faces in that period and the second part is the production lost due to the travel in that period, which includes remaining travel time from the last period and the new travel time, if any, in the current period.

$$\sum_{f}\sum_{d} x_{s,f,d,p} \times O_f + \left(r^{rem}_{s,p-1} + r^{act}_{s,p}\right) \times 60 \times X_s / L_s \le T \times 3600 \times X_s \times \alpha^S_s / L_s \qquad \forall s \,\&\, \forall p \tag{39}$$

Constraints (40) to (44) determine mined out faces and the material available at faces. Eq. (40) is the equality constraint to read the material available at the faces initially and eq. (41) determines the material available at the faces in the subsequent periods based on the production by shovels. Eq. (42) and (43) determines if a face is mined out completely during a period. Eq. (42) is a strict in-equality constraint and thus is modelled using a very small decimal value 'epsilon', which converts it to a general in-quality constraint in the model to be solved directly using CPLEX solver (CPLEX, 2014). Eq. (44) ensures that if a face is mined out during a period, it will remain mined out in the subsequent periods.

$$l_{f,p} = O_f \qquad \forall f \,\&\, p = 1 \tag{40}$$

$$l_{f,p+1} = l_{f,p} - \sum_{s}\sum_{d} x_{s,f,d,p} \times O_f \qquad \forall f \,\&\, p = 1...P-1 \tag{41}$$

$$l_{f,p} - \sum_{s}\sum_{d} x_{s,f,d,p} \times O_f \ge \left(1 - m_{f,p}\right) \times \left(O_{\min} + \varepsilon\right) \qquad \forall f \,\&\, \forall p \tag{42}$$

$$l_{f,p} - \sum_{s}\sum_{d} x_{s,f,d,p} \times O_f \le m_{f,p} \times O_{\min} + \left(1 - m_{f,p}\right) \times BM \qquad \forall f \,\&\, \forall p \tag{43}$$

$$m_{f,p+1} \ge m_{f,p} \qquad \forall f \,\&\, p = 1...P-1 \tag{44}$$

Eq. (45) is an equality constraint on the production to capture the negative deviation in production by a shovel compared to its maximum capacity. Eq. (46) ensures that there is no production possible from a face by a shovel if the shovel is not assigned to that face in that period. Eq. (47) and (48) limit the total production from a face to ore or waste destinations based on the amount of material available at the face and whether it is ore or waste.

$$\sum_{d}\sum_{f} x_{s,f,d,p} \times O_f \big/ X_s^{+} + x_{s,p}^{-} = 1 \qquad \forall s \;\&\; \forall p \qquad (45)$$

$$\sum_{d} x_{s,f,d,p} \le a_{s,f,p} \qquad \forall s, \forall f \;\&\; \forall p \qquad (46)$$

$$\sum_{s}\sum_{d^o} x_{s,f,d^o,p} \times O_f \le l_{f,p} \times Q_f \qquad \forall f \;\&\; \forall p \qquad (47)$$

$$\sum_{s}\sum_{d^w} x_{s,f,d^w,p} \times O_f \le l_{f,p} \times (1 - Q_f) \qquad \forall f \;\&\; \forall p \qquad (48)$$

One major requirement of the model is to provide realistic shovel allocations. Thus it is necessary to include precedence requirements within the model. To ensure that a shovel is assigned to a face only if the face is available for mining, eq. (49) is included in this model. Eq. (49) specifies that assignment variable for a face cannot take a value of one unless all the faces in its precedence set are mined out completely.

$$N_f^F \times \sum_{s} a_{s,f,p} - \sum_{f'} m_{f',p} \le 0 \qquad \forall f, \forall p \;\&\; f' \in PrecedenceSet_f \qquad (49)$$

The tonnage of ore delivered at the processing plants is controlled using eq. (50) to (52). Eq. (50) is a soft constraint which determines positive or negative deviation in production received at processing plants and eq. (51) and eq. (52) puts a limit on the allowed deviation from the capacity. Eq. (53) is an equality constraint which determines the positive or negative deviation in tonnage content of material types received at ore destinations which is minimized in the objective function.

$$\sum_{s}\sum_{f} x_{s,f,d^c,p} \times O_f \Big/ \left(Z_{d^c} \times T \right) + \delta_{d^c,p}^{-} - \delta_{d^c,p}^{+} = 1 \qquad \forall d^c \;\&\; \forall p \qquad (50)$$

$$\delta^{-}_{d^c,p} \le \Lambda^{-}_{d^c} / Z_{d^c} \qquad \forall d^c \;\&\; \forall p \qquad (51)$$

$$\delta^{+}_{d^c,p} \le \Lambda^{+}_{d^c} / Z_{d^c} \qquad \forall d^c \;\&\; \forall p \qquad (52)$$

$$\sum_s \sum_f x_{s,f,d^o,p} \times O_f \times \bar{G}_{f,k} + g^{-}_{k,d^o,p} - g^{+}_{k,d^o,p} = \sum_s \sum_f x_{s,f,d^o,p} \times O_f \times G_{k,d^o} \qquad \forall k, \forall d^o \;\&\; \forall p \qquad (53)$$

Constraint eq. (54) to (57) provide truck allocations to shovels. As only first period in the optimization time corresponds to decision time frame and truck allocation decisions do not significantly affect the objectives of the model (if sufficient haulage capacity is available), truck allocations are made only for the first period. Eq. (54) specifies that total number of truck trips from a face to a destination should be sufficient to transport the material produced by the shovel in the first period. Eq. (55) puts an upper limit on the total number of truck trips specifying that even if some over-loading or under-loading of trucks takes place, total tonnage haul capacity by the number of truck trips should be less than the specified deviation, which is considered as one truck load in this model. Eq. (56) controls the total number of truck trips based on the truck type. Eq. (56) specifies that if a truck type is not desired to work with a shovel, number of truck trips from the corresponding face has to be zero. Eq. (56) also specifies that number of truck trips from a face with no shovel assigned to it, has to be zero. Eq. (57) puts a limit on the possible number of truck trips based on the available time and number of trucks of each type available.

$$\sum_s x_{s,f,d,p} \times O_f \le \sum_t n_{t,f,d} \times H_t \qquad \forall d, \forall f \;\&\; p = 1 \qquad (54)$$

$$\sum_s x_{s,f,d,p} \times O_f + J \ge \sum_t n_{t,f,d} \times H_t \qquad \forall d, \forall f \;\&\; p = 1 \qquad (55)$$

$$\sum_d n_{t,f,d} \times H_t \le \sum_s \left(\sum_d x_{s,f,d,p} \times O_f + a_{s,f,p} \times J \right) \times M^{t}_{t,s} \qquad \forall t, \forall f \;\&\; p = 1 \qquad (56)$$

$$\sum_{f}\sum_{d} n_{t,f,d} \times \overline{T}_{t,f,d} \leq T \times 60 \times N_t^T \times \alpha_t^T \qquad \forall t \qquad (57)$$

To run the model in a dynamic environment in conjunction with a simulation model eq. (58) is added to model the shovel failures. Eq. (58) specifies that no production is possible by a failed shovel although it will remain assigned to its current face. Shovels are locked to material types (ore or waste) using eq. (59)

$$\sum_{f}\sum_{d}\sum_{p} x_{s,f,d,p} \leq (1-\phi_s) \times BM \qquad \forall s \qquad (58)$$

$$a_{s,f,p} \leq \min\left(abs\left(M_s^{ore} - Q_f\right), 1\right) \qquad \forall s, \forall f \,\&\, \forall p \qquad (59)$$

3.4.3.3. Model size

Although model size changes with time when applied for dynamic decision making through simulation optimization approach, the maximum model size is observed in the first optimization. To have an idea of the model size and complexity, model size for first optimization considering the case study presented in Chapter 4 is given in Table 3-5.

Table 3-5: Model size for the case study presented in Chapter 4

Number of variables	20,969
Number of binary variables	5,395
Number of integer variables (including binary variables)	6,469
Number of continuous variables	14,500
Number of constraints	42,847

3.4.3.4. Preprocessing

Although no heuristic technique is applied to solve the model, certain preprocessing techniques as discussed in Chapter 2 are applied to improve the run time of the model. The main variable in the model which account for increased run time is the assignment variable. Based on the knowledge of the data and certain desirability of the planner, some of the assignment variables can be fixed prior to solving the model which will not be branched during branch and bound algorithm in Cplex solver.

As will be discussed for the case presented in the next chapter, the shovel working in waste and assigned to bottom bench of the strategic schedule in the beginning, is not desired to move to upper benches, hence all the assignment variables for that shovel to all the faces in the upper benches can be set zero prior to solving the model, limiting it only to the bottom benches. Similarly if certain shovels are restricted to work in ore or waste but not in both, their assignment variables can also be set accordingly to ore or waste faces.

Solution to some assignment variables for initial periods are also known prior to optimization, such as if a shovel is working on a face 'f' initially and it is not mined out completely, shovel will continue to remain assigned to face 'f' until it is mined out. Thus based on the maximum rate of production of the shovel, number of periods can be determined in the beginning for which shovel shall have to remain assigned to face 'f', and assignment variables can be set for those many periods.

3.5. Simulation

The discrete event mine simulation model is developed in Arena (Rockwell Automation Inc.). The VBA capability of Arena has been extensively used to build the simulation model and update the existing layout of the mining system. Fig. 3.6 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.

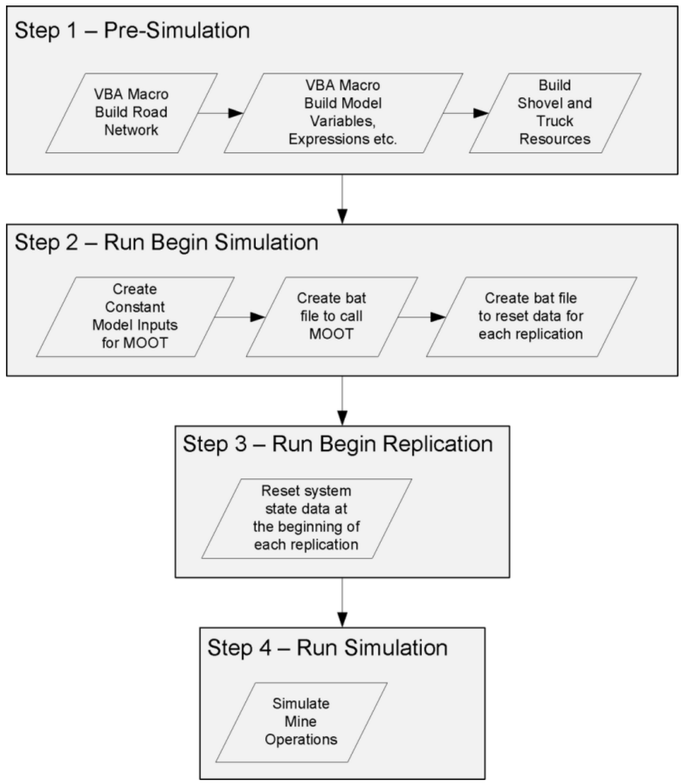

Fig. 3.6: Steps for translating the existing mining layout into the model and simulation run

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.

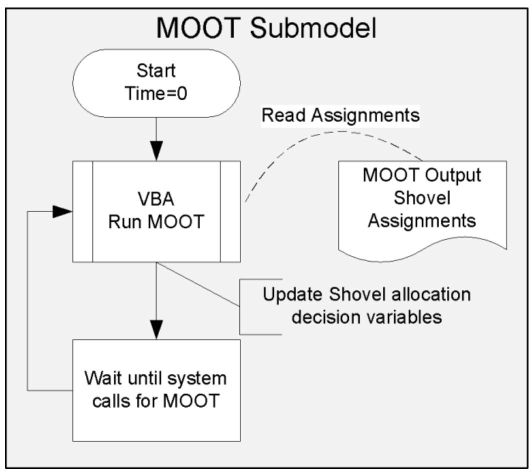

Fig. 3.7: Submodel to call MOOT as external decision support system for shovel and truck allocations optimization

Fig. 3.7 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.

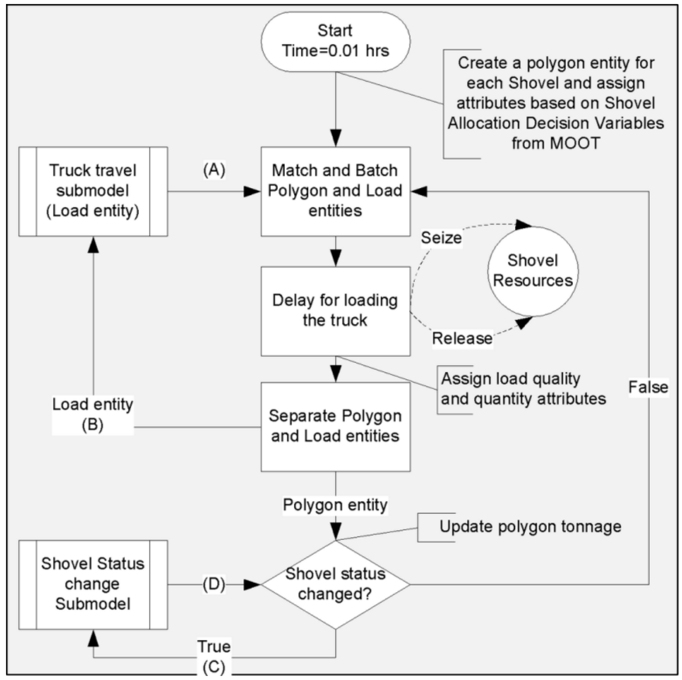

Fig. 3.8: Flow of the main simulation model

Fig. 3.8 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. 3.14). 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. 3.12); otherwise it goes back to match process where shovel sits idle until next load entity (truck) arrives.

The dumping process is shown in Fig. 3.9. 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.

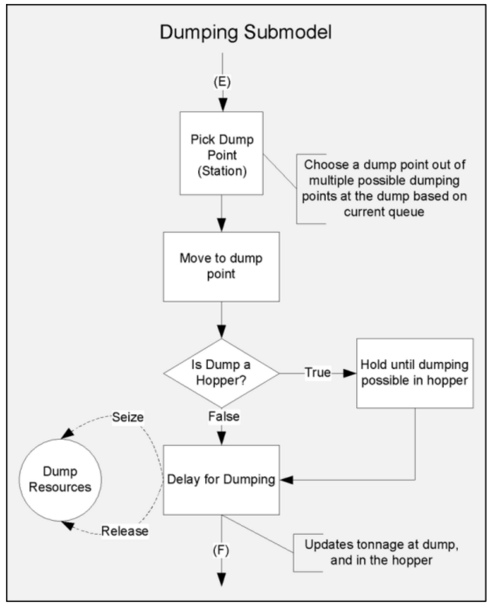

Fig. 3.9: Flow of the dumping submodel

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. 3.10). 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.

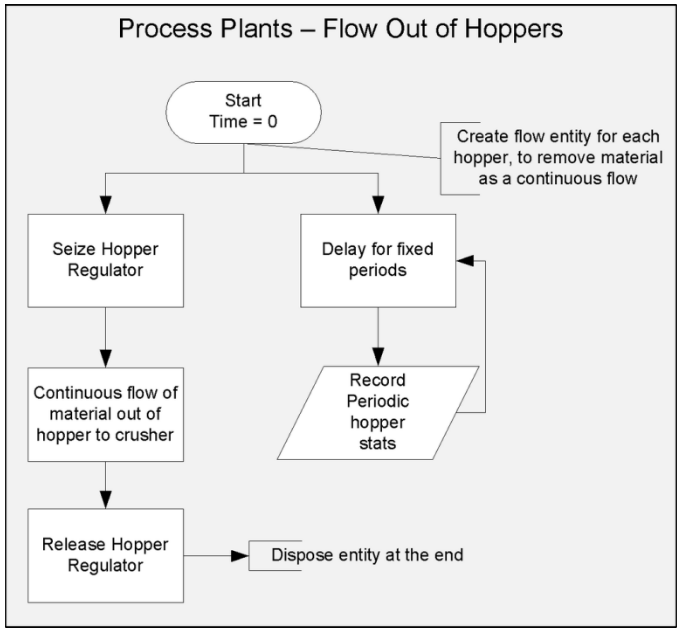

Fig. 3.10: Flow of the process plant submodel

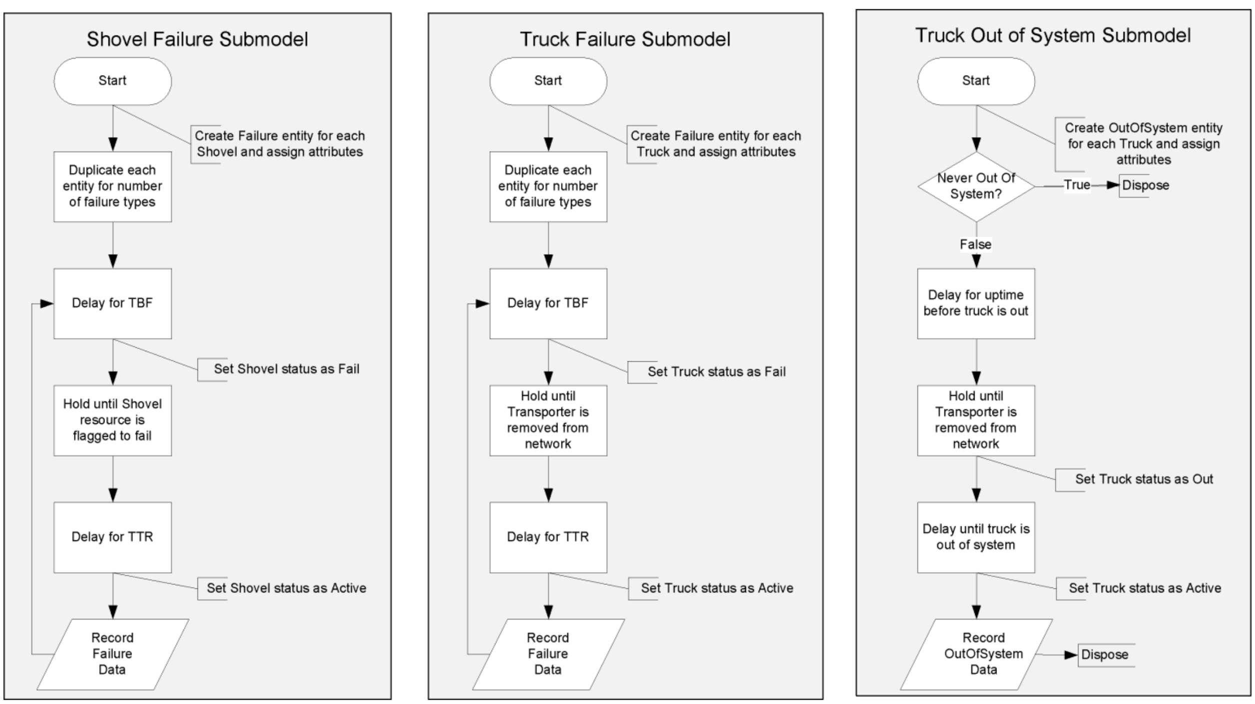

Fig. 3.11: Shovel and truck failure submodels and truck out of system submodel

Shovel and truck failures and truck out of system based on schedule are modeled separately, as shown in Fig. 3.11. Truck and shovel resources are failed in these submodels, after which they are removed from the main simulation logic of Fig. 3.8. 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.

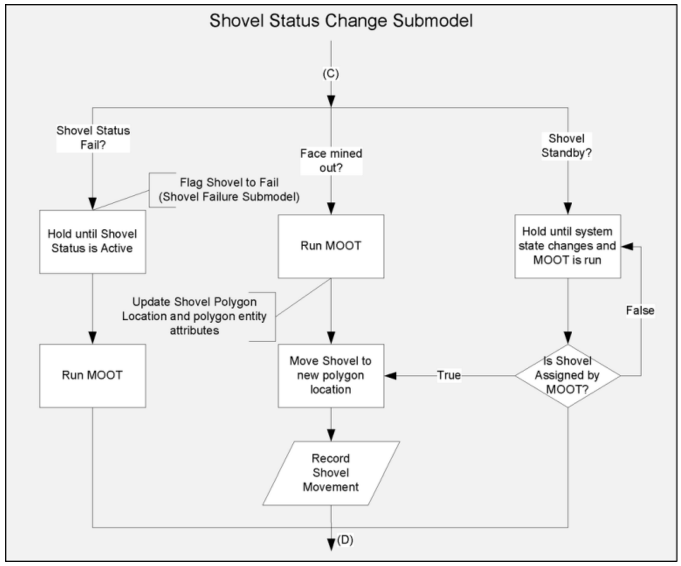

Fig. 3.12: Flow of shovel status change submodel controlling shovel failures, standby, and reallocation

Fig. 3.12 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.

3.5.1. *Truck haulage*

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. A micro-simulation study is thus conducted to model the truck travel behavior on haul roads, which gave the basis for modeling the truck haulage system in the macro-simulation of the mine operations presented in this study.

3.5.1.1. Micro-simulation of truck haulage

Two types of interactions are possible on haul roads which result in platoon formations:

1. Interactions due to high relative velocity between trucks on shared haul roads,
2. Interaction of trucks at intersections.

First type of interaction is more common in mixed fleet systems where trucks may have comparatively high relative velocities, affecting the speeds of faster trucks. Second type of interaction occurs if the inflow rate of trucks on the shared path segment is very high; it may even result in extra delay due to queue formation at the junctions.

This micro-simulation model uses Newton's equations of motion to determine the desired acceleration and deceleration to avoid any collision and maintain a safe distance while having any of the given interactions. Model uses Eq. (60) to Eq. (65) to determine the position and velocity of trucks at any time.

$$x_i(t+h) = x_i(t) + v_i(t) \times h + 0.5 \times a_i(t) \times h^2 \qquad (60)$$

$$v_i(t+h) = v_i(t) + a_i(t) \times h \tag{61}$$

$$a_i(t) = K_i^1 \times A_i(t) - K_i^2 \times B_i(t) - K_i^3 \times C_i(t) \tag{62}$$

$$A_i(t) = \min\left\{\left(v_i^{desired} - v_i(t)\right) / h, a_{\max}\right\} \tag{63}$$

$$B_i(t) = \frac{0.5 \times v_i^2(t)}{x_i^{front}(t) - L_{truck} - SF - x_i(t)} \tag{64}$$

$$C_i(t) = v_i(t) / h \tag{65}$$

Where i = truck index; h=discrete time increment; $x_i(t)$ = position of truck at time t; $v_i(t)$ =velocity of truck at time t; $a_i(t)$ = acceleration of truck at time t; $a_{\max}$ =maximum acceleration allowed; $v_i^{desired}$ = desired velocity of truck when not interacting with any other truck; $x_i^{front}(t)$ = position of truck in front of truck *i*; L_{truck} =length of truck; and SF = minimum safety distance between the trucks when they stop. K_i^1, K_i^2 and K_i^3 are the binary constants which determine the needed acceleration depending on the extent of interaction between two trucks.

Here it should be noted that position of any truck is the position of the head of the truck. So the minimum safe distance for a following truck to avoid collision can be calculated using Eq. (66) (Rothery, 2001).

$$S = L_{truck} + \left(T_{reaction} \times v\right) + \left(0.5 \times v^2 / a_{\max}\right) \tag{66}$$

Considering the hypothesis of Kesting and Treiber (2008), this model assumes the reaction time to be zero; because the actions are based on the current state of the system, which is anticipated by the drivers in the past.

Un-signalized intersections are also modeled which work on the principle of first come first serve basis. So the truck from any path segment that has the minimum distance to intersection is allowed to pass through and the rest are decelerated to stop at a distance of SF until the intersection is free to serve others.

The model was verified against the desired characteristics. One of the important features the model is desired to have is to capture the interacting behavior of the trucks on the haul road. Given below is a position versus time plot for the trucks coming back to dump after loading. Fig. 3.13 clearly shows the deceleration of the trucks to follow the truck in front of it (as no overtaking is allowed).

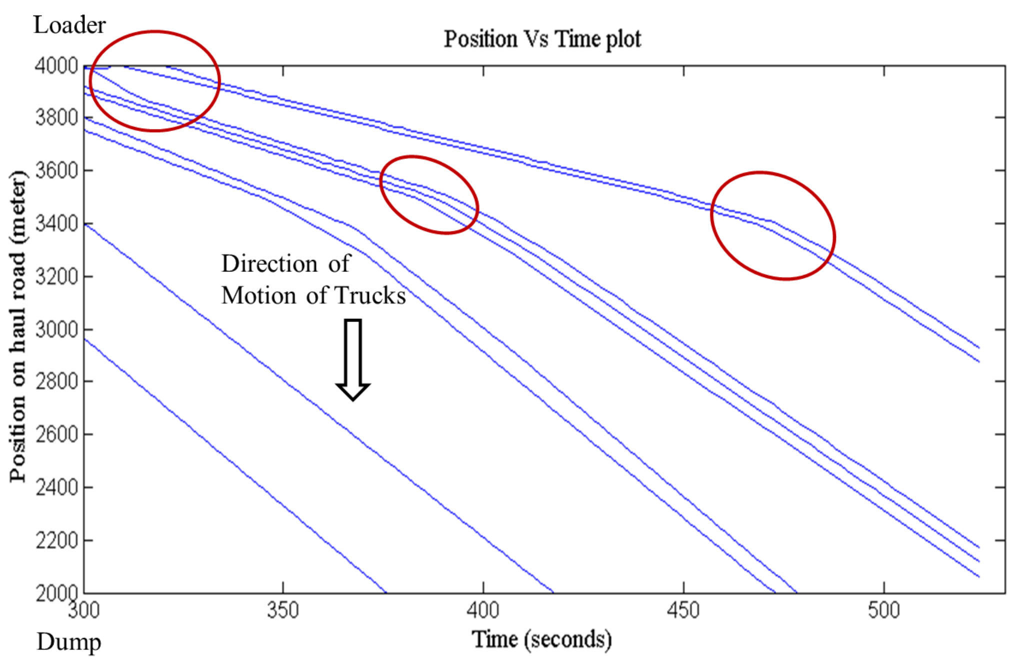

Fig. 3.13. Truck Positions (distance from dump) versus Time graph showing the interaction between trucks (no overtaking)

3.5.1.2. Truck haulage in macro simulation model of mine operations

Although accounting for truck interactions while travelling on haul roads is necessary, incorporating a real-time control in a microscopic approach to model accelerations and decelerations may be resource intensive. In general 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 current research. But it is 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 study.

Trucks, in the macro simulation model presented in this study, 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. 3.14, which is designed to move the trucks link by link on their path to respective destinations and keep a control on their movement.

Fig. 3.14 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 (1986).

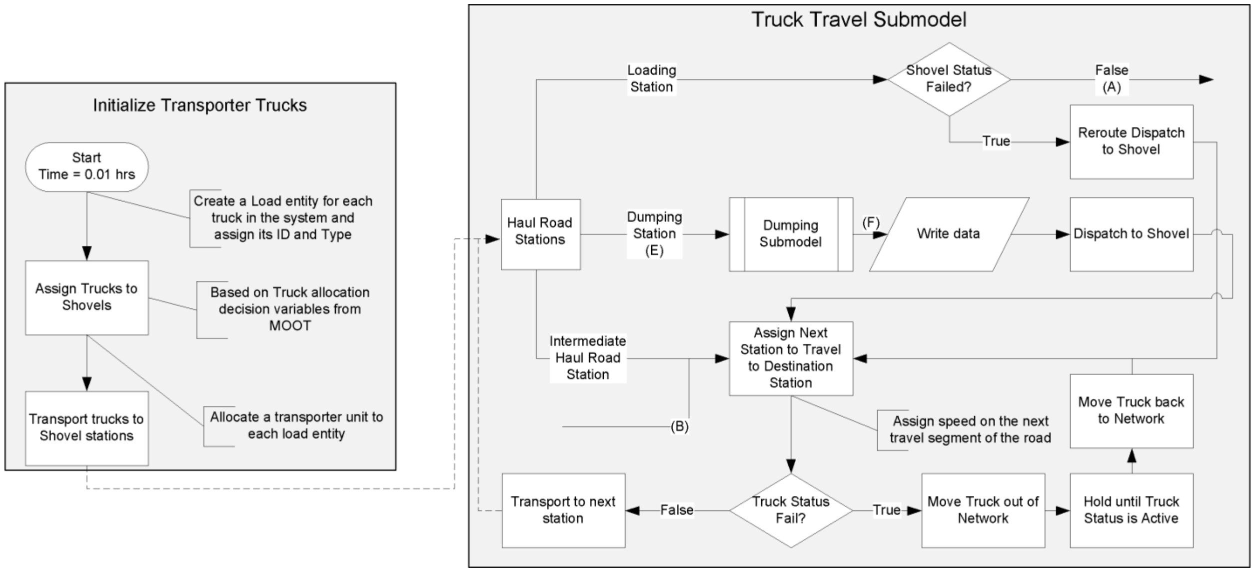

Fig. 3.14: Flow of the truck travel submodel and the initialization of transporters as trucks

3.6. Tools developed

As the model proposed is supposed to provide short term plans over the course of mine life, it is considered essential for it to be flexible enough for reconstruction, running and analyzing the data easily. Thus several other tools have been created to accomplish the steps shown in Fig. 3.6.

3.6.1. *RoadNetwork GUI*

A Matlab® GUI is created to translate the haul road network from designing software to a formatted input for Arena. The designed haul road network is exported as dxf file from the designing software (Autocad, Gems etc.), which is then browsed as input for the GUI shown in Fig. 3.15. The application then creates three worksheets in the common configuration input file, namely ‘Nodes’, ‘Links’ and ‘FailureNetwork’. The worksheet ‘Nodes’ contains all the intermediate node stations on the road network which are connected by network links given in ‘Links’ worksheet. The worksheet ‘Links’ provides information about the road segments joining two intermediate node stations, length of each zone and number of zones to form total distance between stations, their total resistance (to determine speeds based on rimpull curve characteristics), and the maximum designated speed of travel on the road segments. The segments created here form unidirectional links, thus a reverse segment is also created to model bidirectional roads.

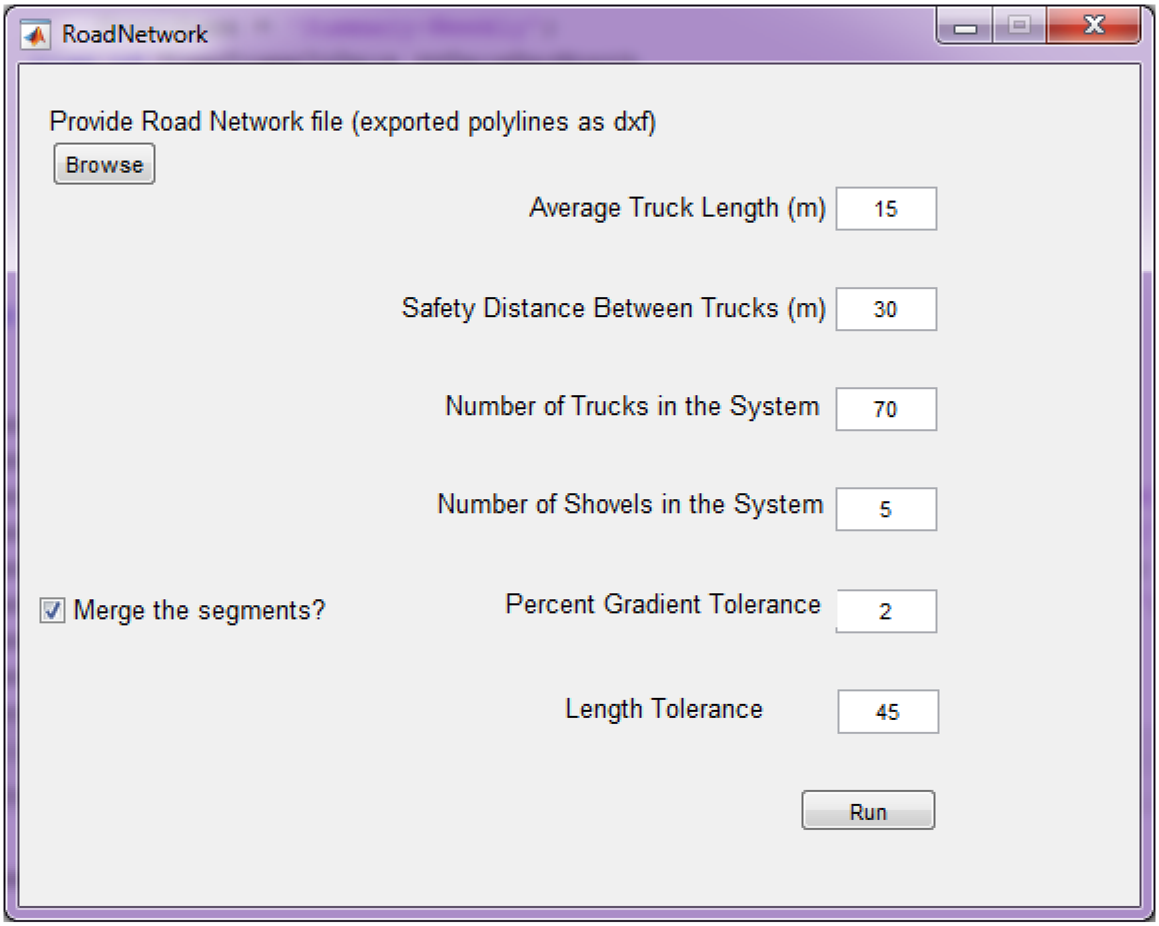

Fig. 3.15: RoadNetwork GUI to create formatted input for creating road network in Arena

The 'FailureNetwork' worksheet does not contain any road network data. This worksheet is created to model truck failures explicitly. The Matlab® GUI application creates one station for each transporter (truck) in the system where they may stay when failed or out of system. The logic of truck movement through Guided Path Transporters, used in this study, does not allow truck overtaking. Thus if a truck/transporter fails on the haul road, other trailing trucks would stop behind it, forming a queue until the leading truck is active again and starts movement. But in reality, trailing truck drivers would recognize the failure, and overtake the truck and continue the travel. To model this scenario, the failed trucks are removed from the main network and moved to their failure stations to stay until fixed and active; when they are moved back into the system to continue their travel towards destination following the road network. The failure network thus contains one station for each transporter. There are two other intermediate stations which remain connected to and from the failure stations; which in turn remain connected to all intermediate node stations on the actual haul road network.

To create the required worksheets, RoadNetwork GUI shown in Fig. 3.15, requires average truck lengths and the desired safety distance between trucks to determine the appropriate zone lengths forming the road segments. The number of trucks is required to construct a failure station for each transporter/truck in the system. As the designed road network might have connecting points very close to each other, the road segments thus constructed may be very small to create even a single zone in a segment. Also too many segments are undesired to minimize the resource consumption in modeling the transportation system in Arena. Thus, merging of segments is also provided in this application, which allows the user to merge the segments based on gradient and length tolerance. If the difference between gradients of two consecutive road segments is less than the percent gradient tolerance, or total length of the combined segment is less than length tolerance; the merge segment function joins the two segments together to form a single segment.

3.6.2. *Other supporting tools developed*

- BuildSimulationModel Macro: This is a macro written in VBA of Arena to construct the model if the basic layout of the mining system changes, which includes haul road network, strategic schedule, number of dump stations, number of shovels and number of truck types which changes the named ranges defined in the common configuration input file. This macro recreates all the variables, expressions, sets and the road network and reconnects them to the named ranges in the common configuration input file. It is not required to recreate the model if basic structure of the input file, i.e. dimensions of the named ranges in input file, does not change.

- ImportSimData Macro: This is a macro written in VBA of Arena, which runs automatically at the end of simulation and lets the user import the recorded data in SQL Database. The GUI interface allows the user to enter the address and user information of the database to import the recorded data directly into the database for further data analysis.

- ResultAnalysis: This is a Matlab® application which takes ODBC and user inputs to connect to the SQL database and generate detailed statistics on the recorded simulation data. The application allows user to generate a summary or monthly, weekly or daily statistics on the simulation data.

3.7. Model Assumptions

- Most models found in literature consider partial extraction of faces which consist of a block or a cluster of blocks. The MOOT does not allow partial extractions, forcing an assigned shovel to mine the entire face during one assignment. The main reason for this assumption is that the sizes of faces are (should be) equivalent to the blast areas; and that a blasted area will be mined completely before moving the shovel to a new face (blasted area). Thus it is essential to pay careful consideration on the development of cluster of blocks as faces, equivalent in sizes to the blast areas.

- Grade of ore within a face is assumed constant, which is average of the grades in the individual blocks constituting the face (cluster). This is a reasonable assumption, if enough attention is paid while grouping blocks together to generate clusters of reasonable sizes. If high grade variability exists within the deposit, size of the clusters must be reduced to account for realistic grade deliverability.

- The MOOT, in its current form, does not account for different rock types existing within the mine, which might affect the loading times, and may affect the choice of dumping destinations as well.

- Although there can be multiple access directions to a face, MOOT considers only one precedence set at this stage. It means a mining face will be accessible only from one direction as guided by the precedence matrix. This assumption does not allow a face to be mined, which has although become accessible from a different direction but its precedence requirement is not met based on the precedence matrix.

- Based on the model architecture, if a shovel starts moving in a period, it must finish the movement before the end of next period. If it is estimated that shovel movement times may be longer, the decision time frames must be increased to accommodate such movements.

- Loading times to calculate truck cycle times within MOOT are estimated as average loading times by all the shovels to the given truck type. This assumption was necessary as no shovel index is considered while calculating truck cycle times for a truck type from a face to a destination. Including shovel index would make the number of truck trips integer variable four dimensional, and substantially increase the size and run time of the optimization.

- Haul road network is assumed fixed throughout the simulation period, which might change slightly during the course of operations depending on haulage road construction planning. Considering the simulation time to be somewhere between a quarter to six months for the purpose of short term planning, this is a reasonable assumption as major haul roads do not change that frequently.

3.8. Scope and limitations

The MOOT can be applied in various ways for optimal decision making in mine operations.

- The MOOT can be used stand alone with optimization time frame equal to the planning period to generate conventional short term production schedules.

- It can be used in combination with a deterministic mine discrete event simulation model for deterministic short term production schedule, providing detailed KPIs of the operations.

- It can also be used in conjunction with a stochastic discrete event simulation model for scenario analysis and developing uncertainty based short term schedules for opportunistic proactive planning.

- The MOOT also finds a scope in actual production operations as part of a multi-stage dispatching system for shovel allocation decisions and target productions to be fed directly to the dispatching system in place.

The scope of this research is limited to the application of the MOOT in conjunction with a stochastic discrete event simulation model for uncertainty based short term production planning and scheduling. Although MOOT, developed as MILGP model in this study, considers most critical operational constraints and objectives, there remain so many factors to be accounted for in actual mine operations which require human intervention, such as changing dump locations for road development or other activities, safety considerations due to drilling and blasting operations, face development activities etc. This renders implementation of the MOOT, in its current form, not feasible in actual mine operations. However, if improved, the MOOT bears a great potential towards automation in mining industry which would also require artificial intelligence techniques to account for mining operational dynamics. Such a tool, if implemented in actual operations, would provide most accurate predictions through simulation in the parallel planning process towards improving the system efficiency due to established harmony between planning and execution.

3.9. Summary and conclusion

This chapter presented a detailed theoretical framework of the proposed simulation optimization approach and the model developed in this research. At first the requirements and objectives of short term mine production planning are presented detailing the mine operational system and a need of pro-active decision making to minimize opportunity lost and deviations from the strategic targets. Then applicability of the MOOT in conjunction with a discrete event simulation model is presented, detailing the steps required in the short term mine planning process using the proposed bottom-up approach. The MILGP model is then presented which works as MOOT in the developed model, detailing the objectives, constraint equations and the pre-processing strategies. The development of simulation model is also presented in this chapter detailing the micro-simulation study conducted to model the truck haulage system in the macro-simulation of mine operations, followed by assumptions and scope of the research.

This chapter proposes a dynamic mine operational optimization tool (MOOT) which is an intelligent external decision support system and provides operational decisions. The applicability of the MOOT is presented in Figure 3.4 which proposes its use as an operational decision making tool in actual mine operations and in parallel with a simulation model for uncertainty based short term planning. This parallel planning system which works in synergy with actual mine operations provide ample scope for maximizing the efficiency of operations by taking pro-active decisions with a robust confidence on the predicted outcomes. The MOOT is proposed to incorporate more details of mine operations using complex and intelligent decision making systems to replace human decision making in mine operations and establish a streamlined planning and execution process. Although the MOOT presented in this chapter is not mature and intelligent enough for implementation in actual mine operations, it is sufficient enough to be applied for short term planning process using simulation optimization approach presented. The MOOT presented in this chapter is a mixed integer linear goal programming (MILGP) model which provides shovel and truck allocation decisions to achieve operational objectives of maximum production and meeting the desired quality and quantity requirements at the plants.

The development of a mine operational simulation model is also described in this chapter which presents the modeling of various interacting and stochastic processes involved in mine operations. With the emphasis on modeling the truck haulage system accurately, this chapter details the modeling of truck haulage system by developing the existing mine haul road network within simulation and moving trucks following their rimpull curve and haul road characteristics. This chapter also presents a separate micro-simulation study conducted in Matlab® to model the truck interactions on haul roads which is then applied in the development of the truck haulage system in the macro-simulation model of mine operations in Arena. The development of the simulation model, for the proposed scope, requires flexibility and reusability so that the model could be readily applied for short term planning process over the mine life. Flexibility is also required to model various user scenarios to optimize the mining system to determine the best strategy for implementation and the development of corresponding short term mine plan. This chapter presents the use of Matlab® and VBA macros within Arena to instill flexibility in the simulation model, so that various system characteristics can be easily changed and the same model could be used over time within the mining system it is designed for.

VERIFICATION IMPLEMENTATION AND DISCUSSION OF RESULTS

4. VERIFICATIOIN, IMPLEMENTATION AND DISCUSSION OF RESULTS

4.1. Introduction

This chapter presents the implementation of the simulation optimization model on an iron ore mine case study. First an open pit mine case is presented with the schedule and operational data that act as input to the model. The verification study of the model is presented through a detailed scenario analysis and comparing the individual process values with the expectations. Due to unavailability of historical dataset, a complete validation study is not presented in this thesis. This chapter also presents the selection of optimum number of trucks of each truck type to achieve desired production and equipment utilization objectives. Effect of haul road designs are also presented by analyzing, what if a particular ramp is not used at all and not maintained to save operational costs? Also the best grade blending strategy is derived by analyzing the effect of different priority to plants quality objectives. Finally the short term plans are generated out of the best replication of the best scenario selected.

4.2. Case study

The implementation of the simulation optimization model requires two types of data, strategic schedule and operational data. Due to unavailability of complete data from an existing operating mine, a case is developed where strategic schedule is created using the drill hole prospecting data of an iron ore mine, and operating equipments are assumed. The operating process distributions for the selected equipment are taken from the operational database of an existing operational mine.

4.2.1. *Strategic schedule*

The strategic schedule for the case is developed using the drill hole prospecting data of GolGohar iron ore mine situated in southern Iran, in the southwest of Kerman province. The drill hole data is used for ore body modeling in Gems (Dassault Systemes GEOVIA Inc.) and scheduling in Whittle (Gemcom Software International Inc.). The yearly schedule for the mine life is given in Fig. 4.1. The schedule requires 516.963 Mt of material movement consisting of 172.654 Mt of ore, with an average stripping ratio of 1.99. Apart from waste, the material types constituting ore rock types are Iron (MWT), Sulfur (S), and Phosphorous (P). The main material of interest is MWT, with S and P as impurities. Year 11 is chosen for the case study implementation, the schedule details for which are given in Table 4-1. To develop the schedule for the case implementation, all the scheduled blocks were extracted for year 11 in Whittle schedule. It can be noted here that scheduled tonnages are fairly high in the case compared to whittle schedule. This is because, in the development of the case, partial extraction of blocks in multiple years is not considered. This leads to increase in the total tonnage scheduled in one year.

Table 4-1: Scheduled tonnage and grades obtained from Whittle and considered in Case

Year 11	Ore (t)	Waste (t)	SR	Grade MWT
Whittle	13,000,000	28,000,000	2.15	64.78 %
Case	16,414,560	39,105,881	2.38	68.58 %
Case-6 months	8,207,280	19,552,941	2.38	68.58 %

As detailed prediction for the whole year is undesired due to increased uncertainty, the simulation optimization model is proposed to run for 6 months to analyze and generate short term production schedules over daily or weekly resolution for 6 month period. The target production schedule for 6 months is given in Table 4-1.

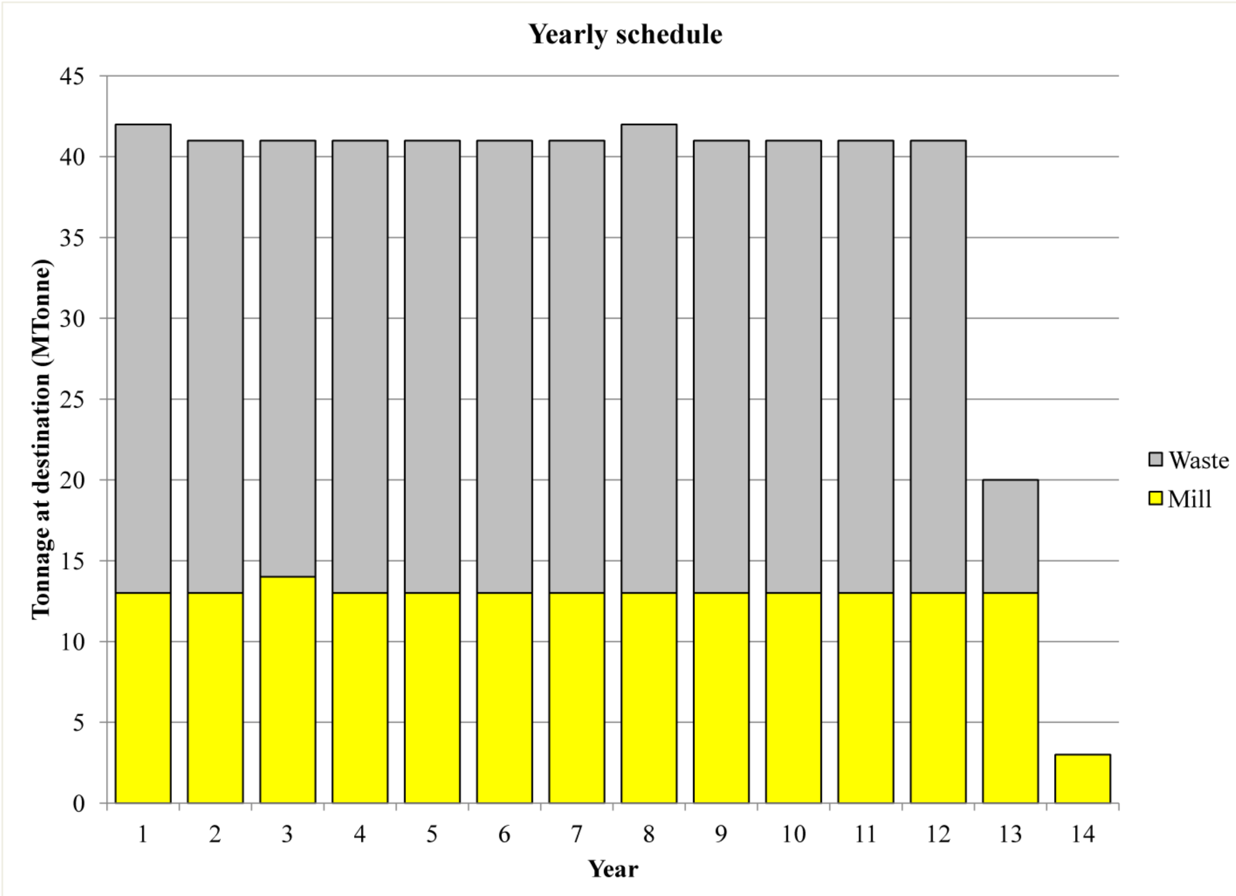

Fig. 4.1. Yearly strategic schedule created using Whittle

The schedule requires working on four benches namely 1745, 1730, 1610 and 1595 based on respective elevations. The scheduled ore is present only on the bottom two benches along with waste, whereas top two benches contains only waste. The schedule consists of mining 4227 blocks which are grouped together into faces using the clustering algorithm devised by Tabesh et al. (2013), resulting in 174 mining faces (also referred to as cuts, clusters or polygons). Based on the scheduled mining blocks, the pit with haul ramps and roads to dump locations are designed in Gems (Dassault Systemes GEOVIA Inc.) and shown in Fig. 4.2.

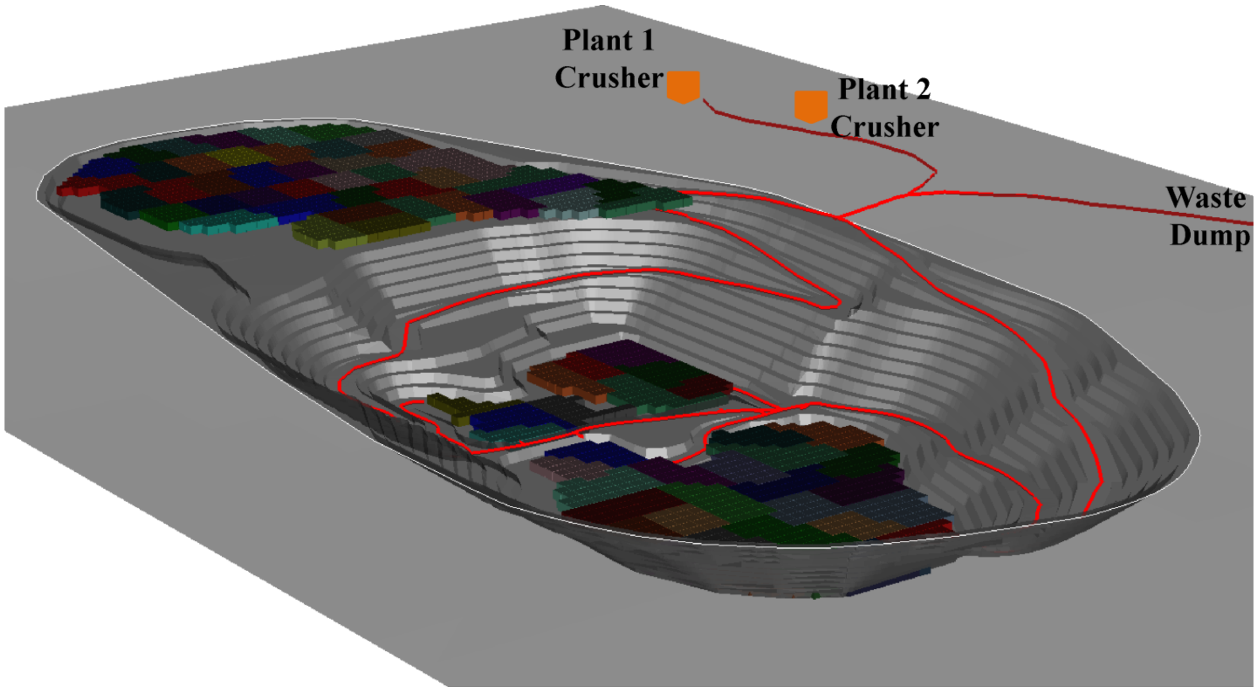

Fig. 4.2. The designed pit with scheduled blocks on top and bottom benches and dump destinations

4.2.2. *Operational data*

The mine is designed to have two crushers and a waste dump location. Two scrappers are assigned at waste dump location to enable two simultaneous truck dumps. The crushers have a hopper associated to them to provide a continuous feed. The hoppers are designed to have single dumping point, i.e. only one truck dump is possible at a time. Based on the downstream process requirements of the plants, both plant crushers are desired to have specific grade requirements. Plant characteristics and target requirements are given in Fig. 4.2.

Table 4-2: Plant characteristics and targets

Dump	Target (tph)	Hopper Capacity	MWT grade desired
Plant 1 Crusher	2000	500	65 %
Plant 2 Crusher	2000	500	75 %

Based on scheduled target and working on four benches, 5 shovels are employed to carry out mining activity in the pit. Mine employs two Hit 2500 shovels to work in ore, which are smaller in capacity and suitable for meeting plant requirements; and three Hit 5500Ex shovels to mine waste in the pit. The implementation of the simulation optimization model requires deterministic mean values of bucket capacities and bucket cycle times within MOOT for deterministic optimization which are shown in Table 4-3. The probabilistic distribution functions are fitted on the real dataset to generate continuous distribution functions, which are used within the simulation model. It should be noted here that mean values of the probabilistic distribution functions are same as mean values supplied to MOOT which are shown in Table 4-3, to maintain a consistency between decisions and implementations.

Table 4-3: Shovel characteristics (mean values to be used in MOOT)

Equipment	Type	Number	Bucket capacity (t)	Bucket cycle time (sec)
Shovels (S1 and S2)	Hit 2500	2	12	18
Shovels (S3, S4 and S5)	Hit 5500Ex	3	22	23

Mine employs two types of trucks, Cat 785C and Cat 793C, to haul the material from the pit to destinations. The probabilistic distribution functions are fitted on the real dataset for the given truck types to generate continuous distribution functions. The respective mean values of the truck characteristics are given in Table 4-4, which are used in MOOT for deterministic decision making purposes. By matching the shovels with the trucks, based on capacities, Cat 793C trucks (truck type 2) are prohibited to work with smaller capacity Hit 2500 shovels. Although Cat 785C trucks (truck type 1) can work with both types of shovels, based on dispatching requirements they can be locked to Hit 2500 shovels only.

Table 4-4: Truck characteristics (mean values to be used in MOOT)

Equipment	Type	Capacity (t)	Dump time (sec)	Spot time (sec)
Truck Type 1	Cat 785C	140	52	12
Truck Type 2	Cat 793C	240	56	20

The failure of equipment is modeled only in simulation. MOOT only accounts for the status of equipment at the time of optimization instead of modeling the failure times. Thus only probabilistic distribution functions are required for failures in the model. Two types of truck failures and one type of shovel failure is considered in this case study. The time between failures

(TBF) and time to repair (TTR) distribution functions considered in this case study are given in Table 4-5. Plant failures are not considered in this study.

Table 4-5: Time between failures (TBF) and time to repair (TTR) distribution functions for equipment

Equipment	Fail type	TBF	TTR
Hit 2500	1	WEIB (32, 116)	GAMM (1.4, 1.5)
Hit 5500Ex	1	WEIB (32, 116)	GAMM (1.4, 1.5)
Cat 785C	1	WEIB (27, 200)	GAMM (1.4, 1.5)
Cat 785C	2	WEIB (65, 200)	GAMM (0.25, 24)
Cat 793C	1	WEIB (27, 200)	GAMM (1.4, 1.5)
Cat 793C	2	WEIB (65, 200)	GAMM (0.25, 24)

4.3. Model verification

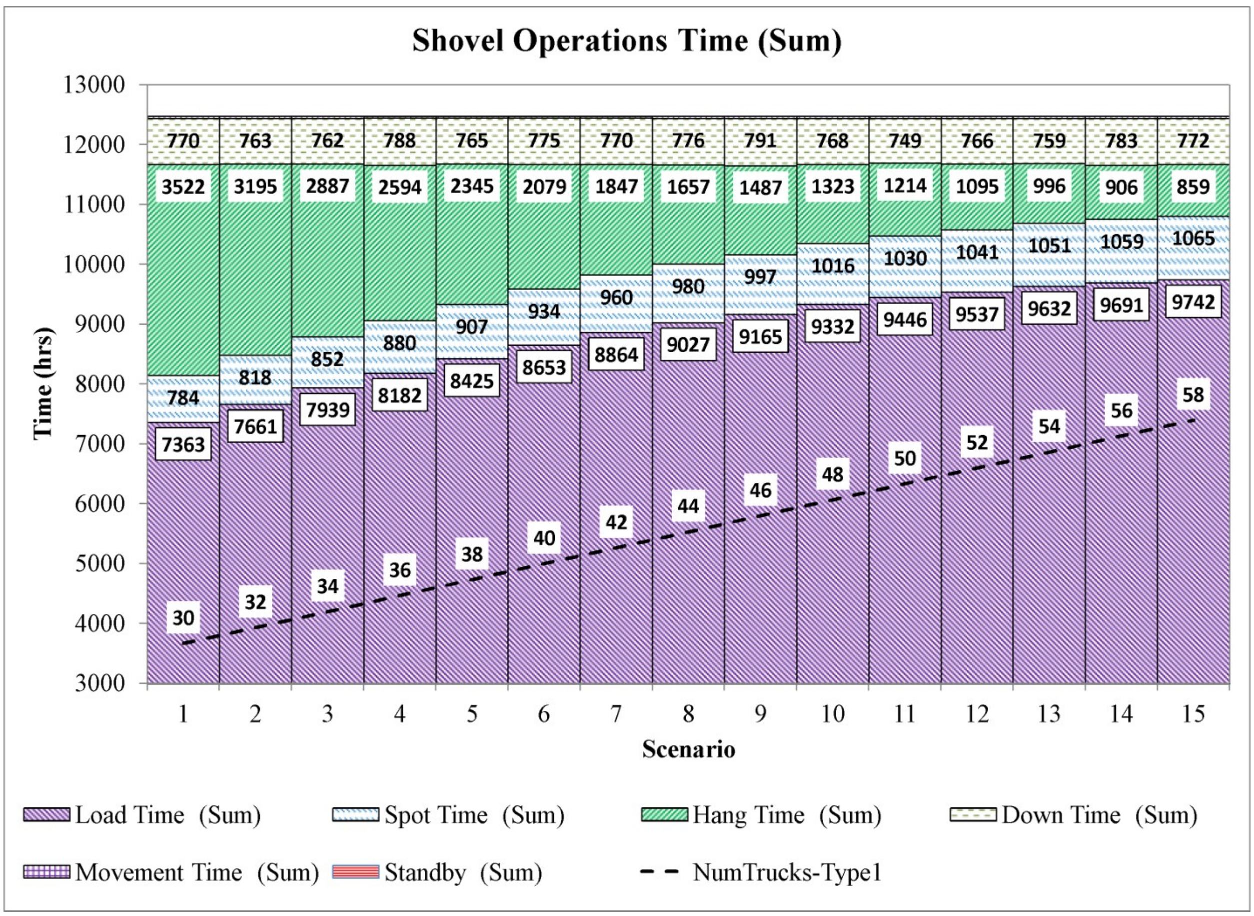

Fig. 4.3. Distribution of summation of shovel operations time with increasing number of trucks in single fleet mining system

As part of model verification, total time distributed between various processes and failures is analyzed for shovels as shown in Fig. 4.3. Total available time for all 5 shovels in the system for

16 hours per day and 156 days of working in six months is 5x16x156 = 12480 hours, which is observed in Fig. 4.3. It also shows the transfer of hang time to loading time and spot time with increasing number of trucks in the system as expected and observed in actual mine operations. As number of shovels is fixed for the scenarios, total failure times remain almost constant. Comparatively negligible amount of time is spent in shovel movements (approx average 40 hours per shovel), which is not clearly visible in Fig. 4.3. Also, shovels were never on standby (not assigned) throughout simulation. Individual shovel loading and spotting times along with truck dumping, load tonnages and other characteristics are also verified compared with the data fed into simulation. The scenario analysis provided in further sections of this chapter also verifies the model behavior observed as expectations.

The model is also verified against few characteristics such as shovel ton per net operating hour (ton/NOH), truck ton/NOH and shovel effective utilizations. For single fleet systems, shovel and truck ton/NOH and shovel effective utilizations should not change with increase in number of trucks in the system as observed in Fig. 4.4, Fig. 4.5 and Fig. 4.6 respectively. For mixed fleet systems shovel ton/NOH and shovel effective utilizations should not change with increasing number of trucks in the system as observed in Fig. 4.7 and Fig. 4.9, but truck ton/NOH should change because of changing hauling capacity of system per unit truck as observed in Fig. 4.8. The observations clearly verify the model behavior in capturing the mine operations.

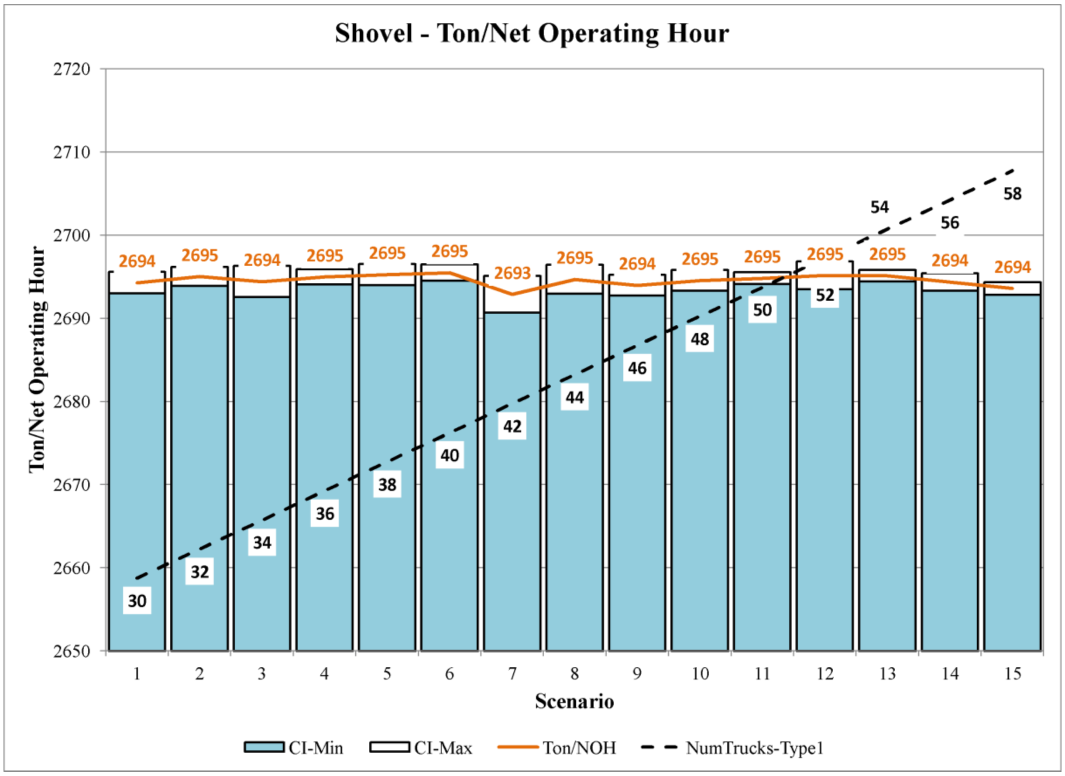

Fig. 4.4. Shovel ton per net operating hour with increasing number of trucks in single fleet system

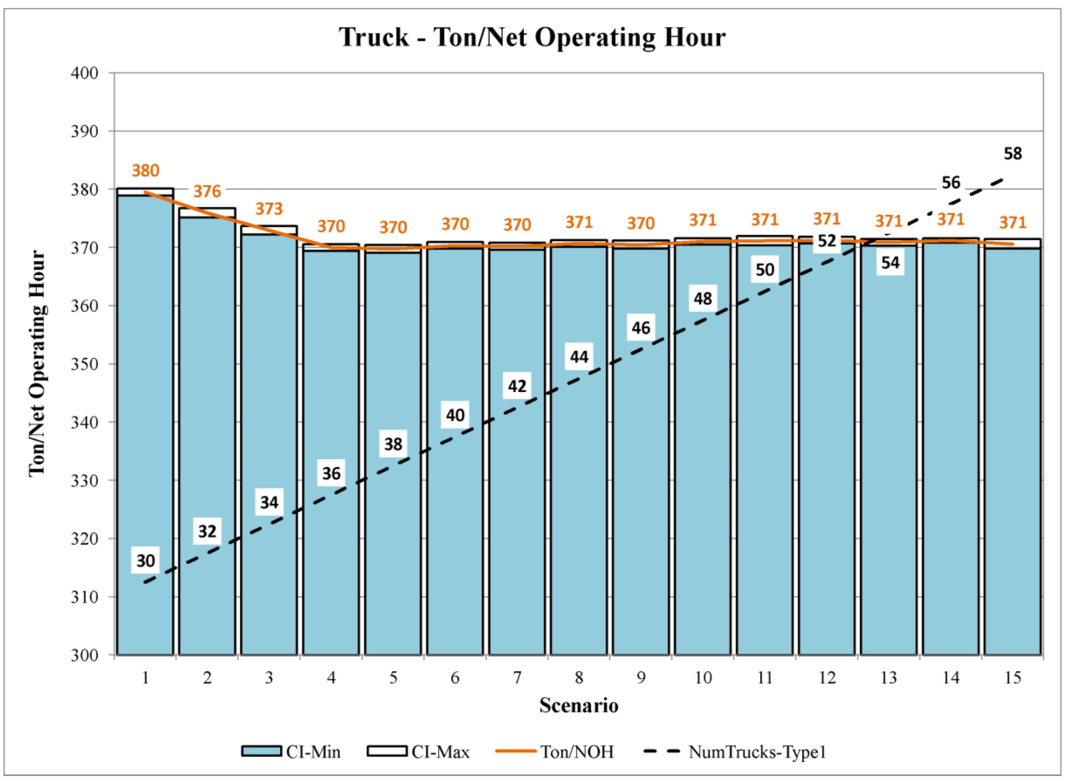

Fig. 4.5. Truck ton per net operating hour with increasing number of trucks in single fleet system

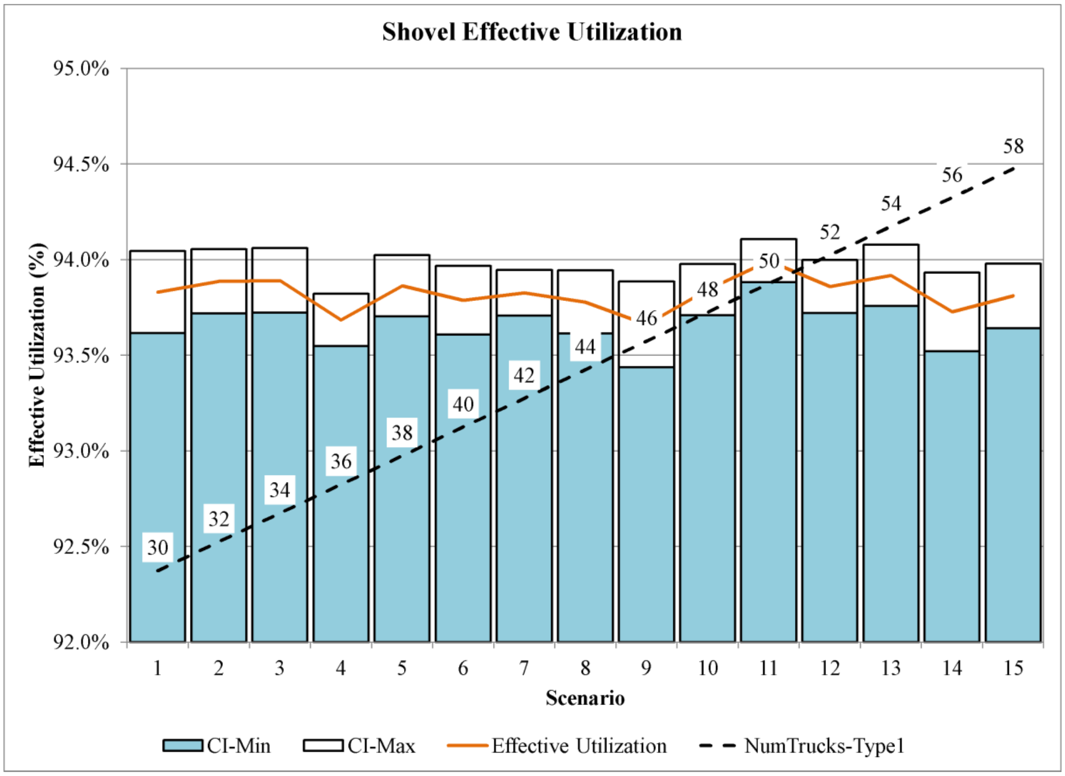

Fig. 4.6. Shovel effective utilizations with increasing number of trucks in single fleet systems

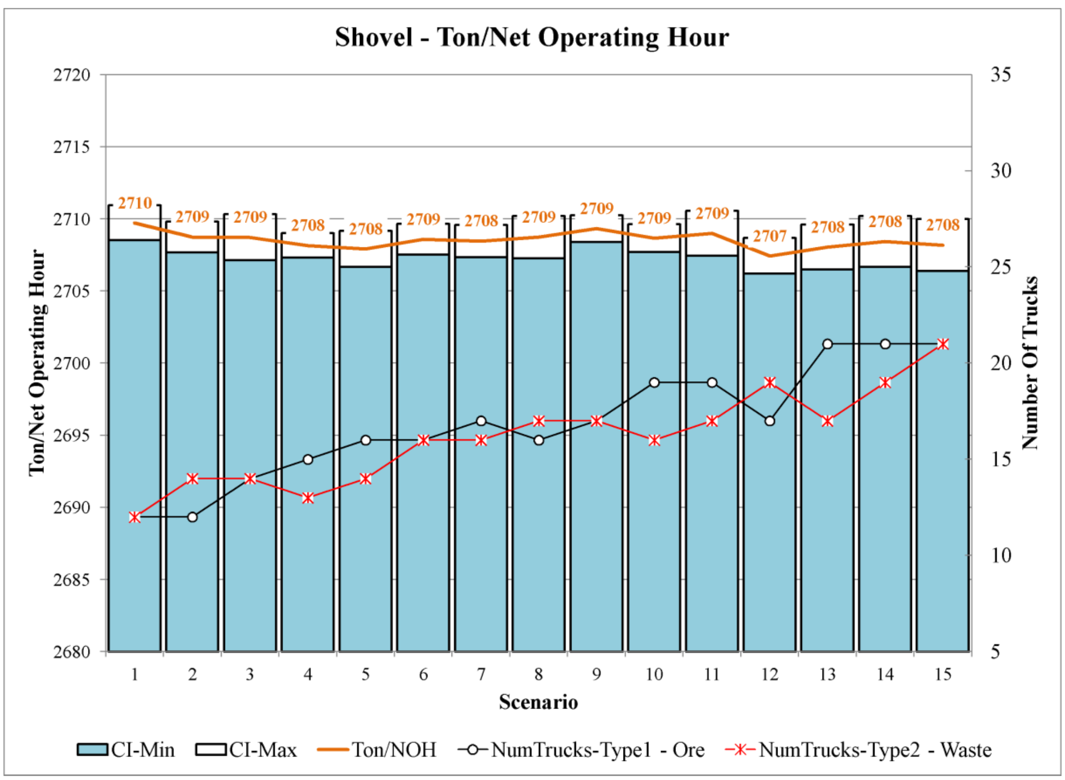

Fig. 4.7. Shovel ton per net operating hour with increasing number of trucks in mixed fleet system

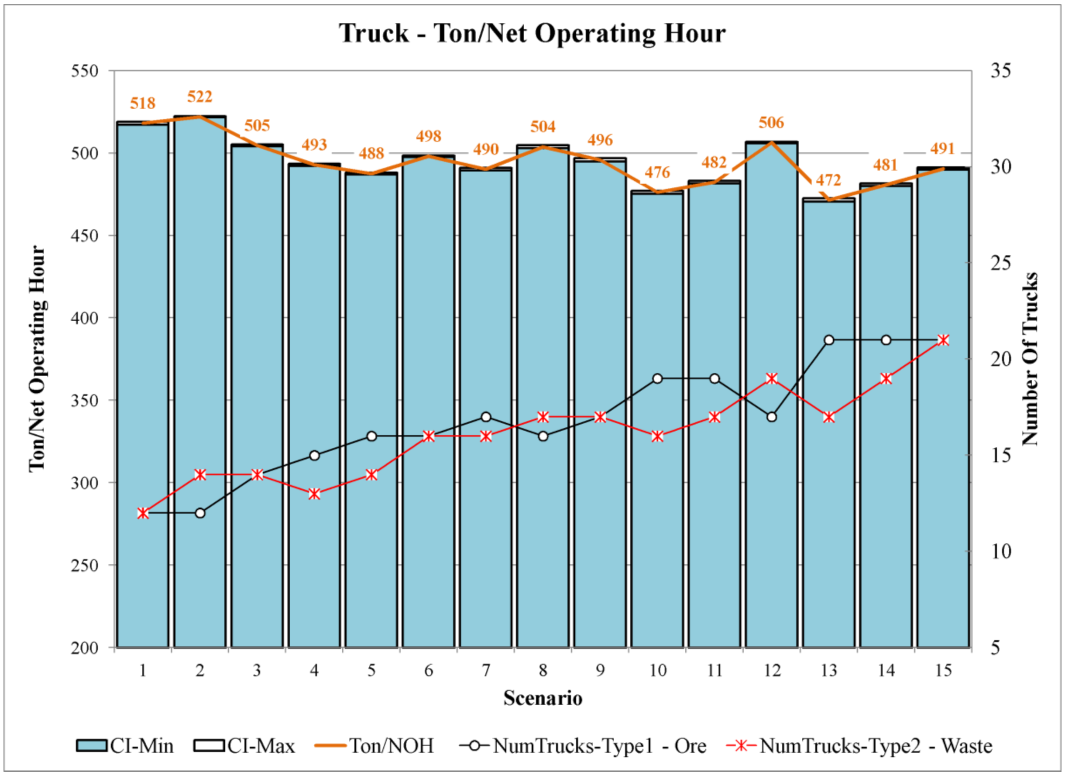

Fig. 4.8. Truck ton per net operating hour with increasing number of trucks in mixed fleet system

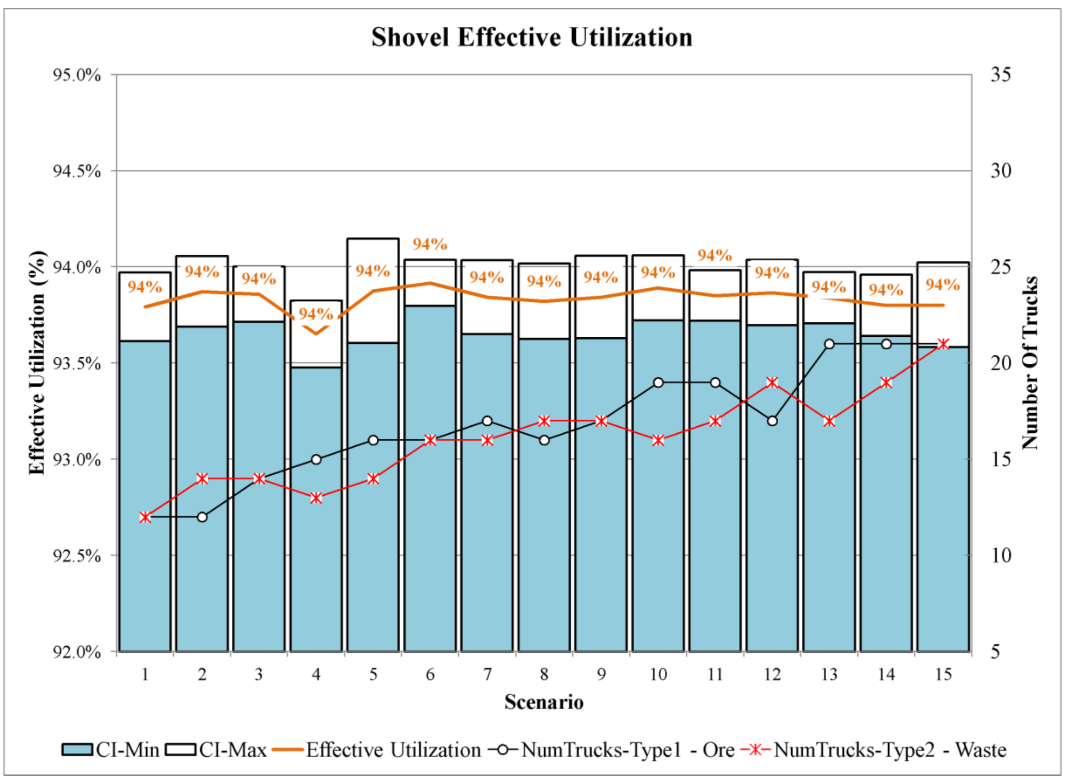

Fig. 4.9. Shovel effective utilizations with increasing number of trucks in mixed fleet systems

4.3.1. *Capturing truck interactions*

One of the simulation modeling objectives was to capture the truck interactions on haul roads. As overall interactions are hard to capture between trucks of the same type, as mean truck velocities remain same for any specific truck type, which is also the case in actual mining operations, major interactions occur between trucks of different types due to difference in mean truck velocities. To verify whether truck interactions are accounted for in the simulation, two verification scenarios were run in the mixed fleet system. A scenario is selected from the mixed fleet system in case C2, and compared against two other scenarios T1 and T2. To see a visible effect of interactions, speed of truck type 1 is increased by 20% in scenario T1, keeping truck type 2 at its original speed. Similarly, speed of truck type 2 is increased by 20% in scenario T2, keeping truck type 1 at its original speed.

Based on the bench and haulage road layout as shown in Fig. 4.2, and worked positions of shovels (shovel 3 and 4 on top benches 1745 and 1730; and shovel 1, 2 and 5 on bottom benches 1610 and 1595), we can see that type 2 trucks working with shovel 3 and 4 (waste shovels) find a very small shared path with the type 1 trucks working with shovel 1 and 2 (ore shovels). So, they will have negligible interaction amongst them. However, type 1 trucks working with ore shovel 1 and 2 share most of their haulage path with type 2 trucks working with waste shovel 5 on bottom benches. Thus the effect of 20% increase in velocities was analyzed based on shovels for both the cases T1 and T2 as shown in Fig. 4.10 and Fig. 4.11.

For case T1, Fig. 4.10 shows the empty and full velocities in comparison with the base case. As type 2 trucks working with shovel 3 and 4 have negligible interaction with other trucks, there is no perceived effect of velocity change of type 1 trucks on them. Similarly for case T2, a 20% increase in velocities is observed for type 2 trucks working with shovel 3 and 4. The major interactions are observed for type 1 trucks working with ore shovel 1 and 2, and type 2 trucks working with waste shovel 5.

Fig. 4.10 shows a 19% and 18% increase in empty and 16% and 18% increase in full velocity of trucks working with shovels 1 and 2, marginally less than 20% due to interactions with type 2 trucks working with shovel 5. No interaction effect was observed for empty velocities of type 2 trucks, as they run slower than type 1 trucks, with their actual running velocities. Full velocities of type 2 trucks with shovel 5 are observed to have increased marginally by 3%, which might be because type 1 trucks now run faster than base case, causing no hindrances to type 2 trucks with shovel 5.

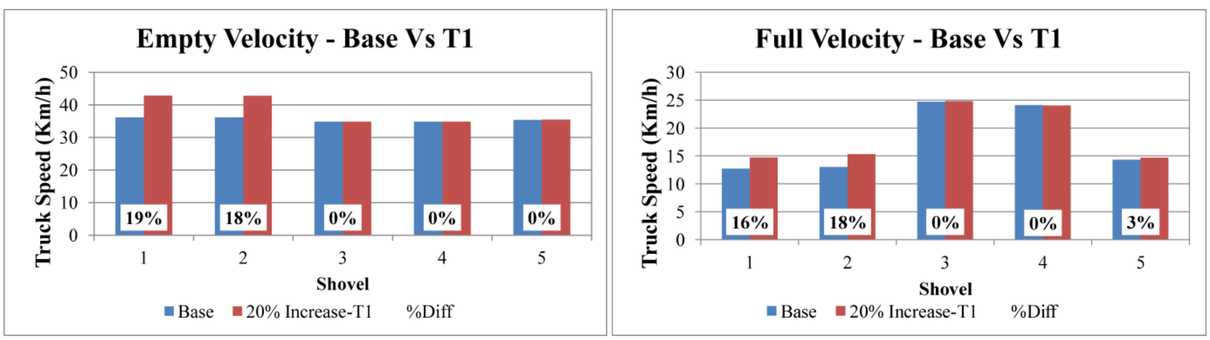

Fig. 4.10. Effect of truck interactions for trucks working with different shovels for case T1

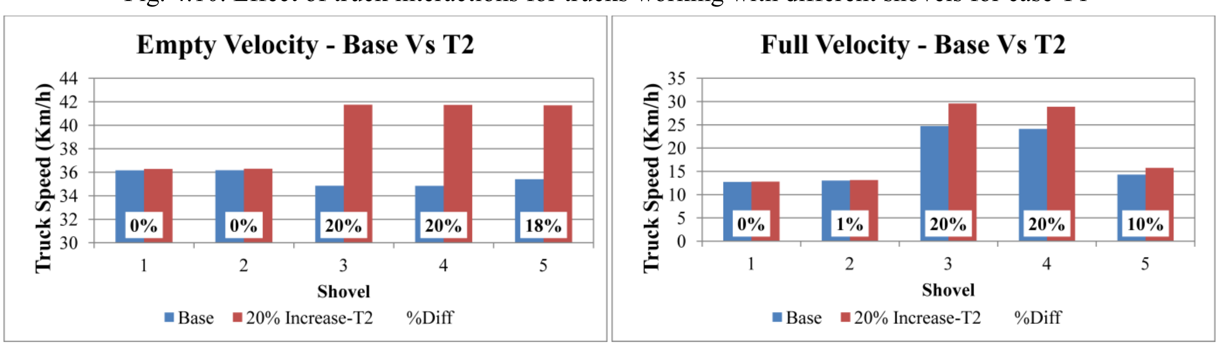

Fig. 4.11. Effect of truck interactions for trucks working with different shovels for case T2

For case T2, as shown in Fig. 4.11, none or negligible effect is observed on type 1 truck speeds working with shovel 1 and 2 due to higher speed of type 2 trucks working with shovel 5. However slower type 1 trucks poses hindrances to faster type 2 trucks working with shovel 5.

This causes increase in empty and full truck velocities of type 2 trucks working with shovel 5 to be only 18% and 10% respectively.

The observed behavior of truck speeds as discussed above verifies that model accounts for the truck interactions reasonably. Only 10% increase in type 2 truck full velocity working with shovel 5, for a 20% increase in type 2 velocity shows the drastic effect of truck interactions on haul roads that significantly affects the production. Observed differences in the effect on empty and loaded velocities are due to different rimpull curve characteristics of both truck types.

4.4. Determination of optimal number of trucks

This section presents the implementation of the model to predict the truck requirements in single and mixed fleet system for the mine. As there is no single parameter defining the efficiency of the mining system, at this scale all major KPIs must be analyzed to select the best strategy that satisfies the operating and short term objectives. Short term objectives include the ore and waste production targets, whereas operating efficiencies of equipment (shovel, trucks and plants) and grade blend requirements constitutes operating objectives. The decision on the truck requirements is thus made based on the analysis of various operational KPIs, including ore and waste productions, operating efficiencies of shovels and trucks, and the truck operating costs.

4.4.1. *Single fleet system – Scenario C1*

This section presents the variation in various KPIs of the mine operations for increasing number of trucks in a single fleet system. Only type 1 trucks are used in this configuration, which are allowed to work with both types of shovels in ore and waste.

Fig. 4.12 shows the variation in production with increasing number of trucks in the system. It is observed that production increases mostly due to the increase in the waste produced, which is more clearly visible in Fig. 4.13 and Fig. 4.14. The increase in trucks from 30 to 58 increased the ore production merely by about one million ton as compared to about 7Mt in waste production. This behavior can be better explained in Fig. 4.30, which shows high operating efficiencies of ore shovels even with smaller number of trucks, which increases only marginally with the increase in the trucks. The reason for this behavior is that MOOT allocates more haulage capacity to ore shovels to meet the plant requirement. As the number of trucks in the system increases plant requirements are almost satisfied, resulting in more allocated haulage capacity to waste shovels. This results in steep increase in waste shovel operating efficiencies as compared to ore shovels. This is the reason why no major increase in ore production is observed with increasing number of trucks in the system, because system was already operating at high efficiency for ore production due to MOOT.

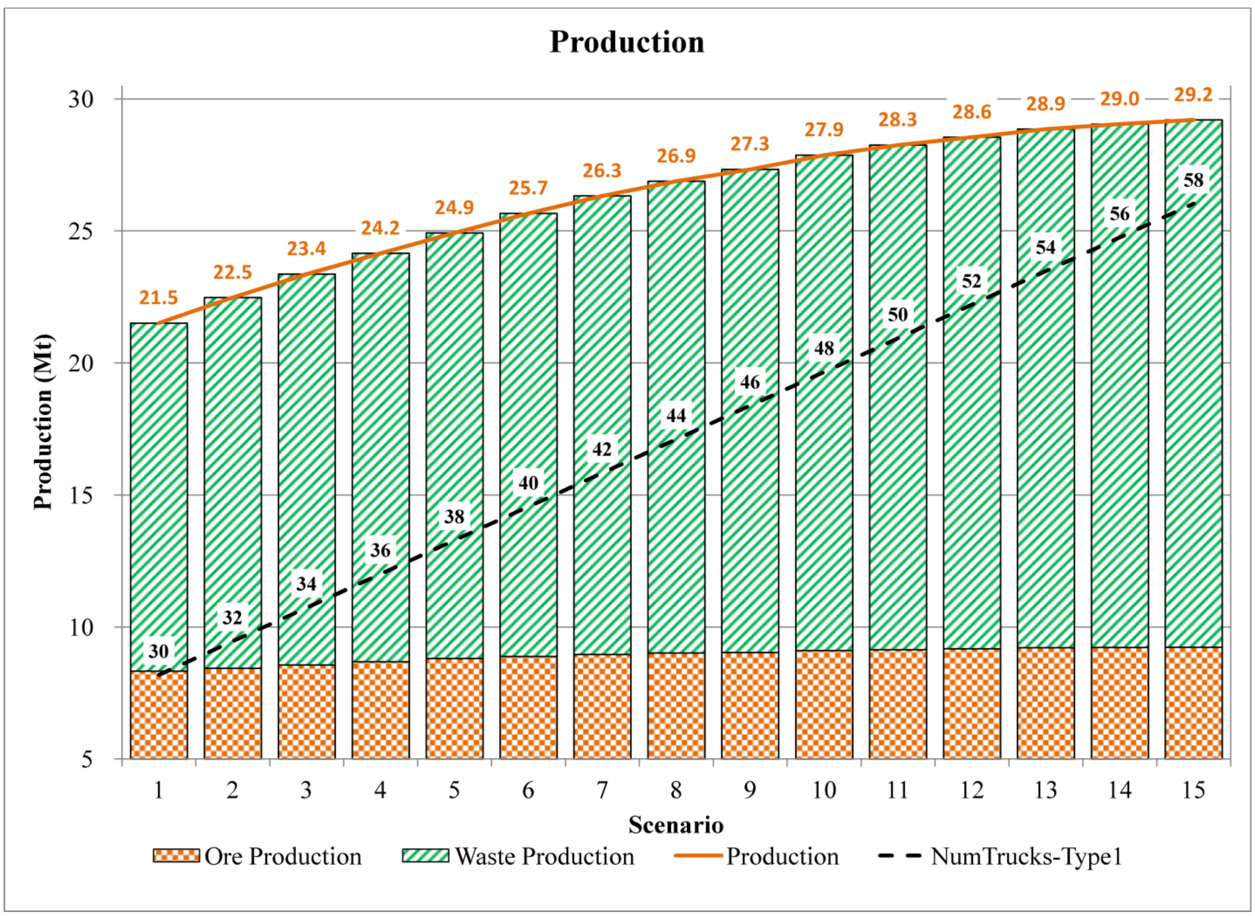

Fig. 4.12. Mean ore and waste productions with increasing number of trucks in case C1

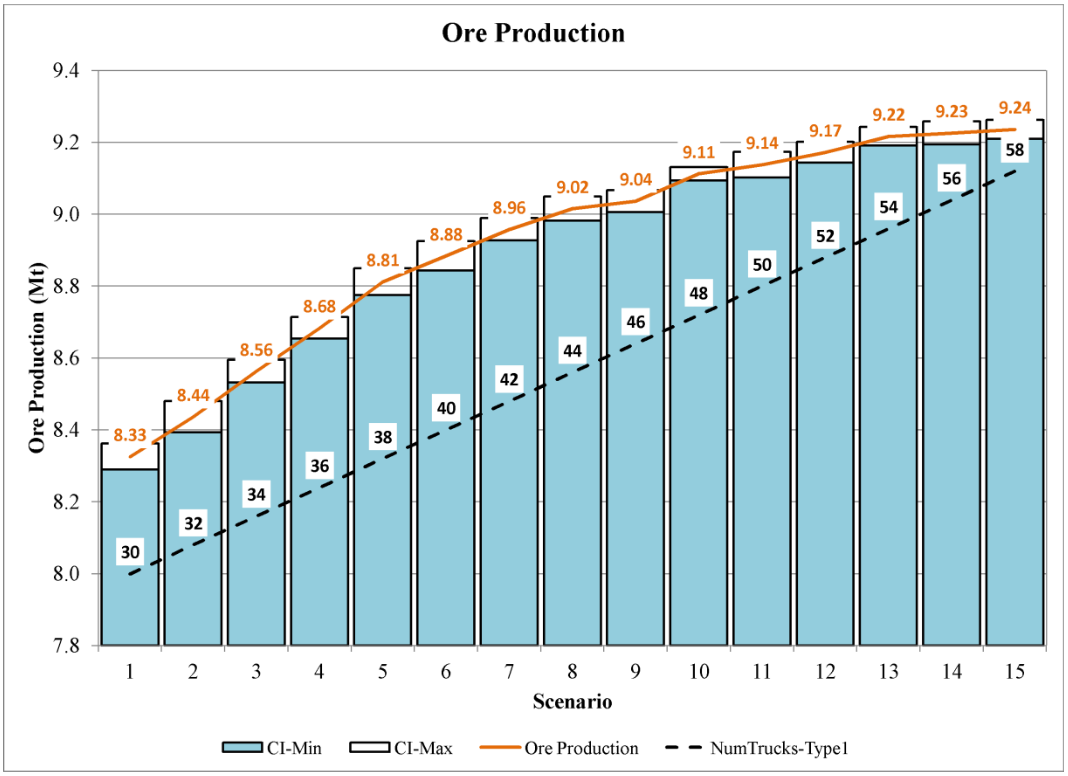

Fig. 4.13. Ore production with increasing number of trucks in case C1

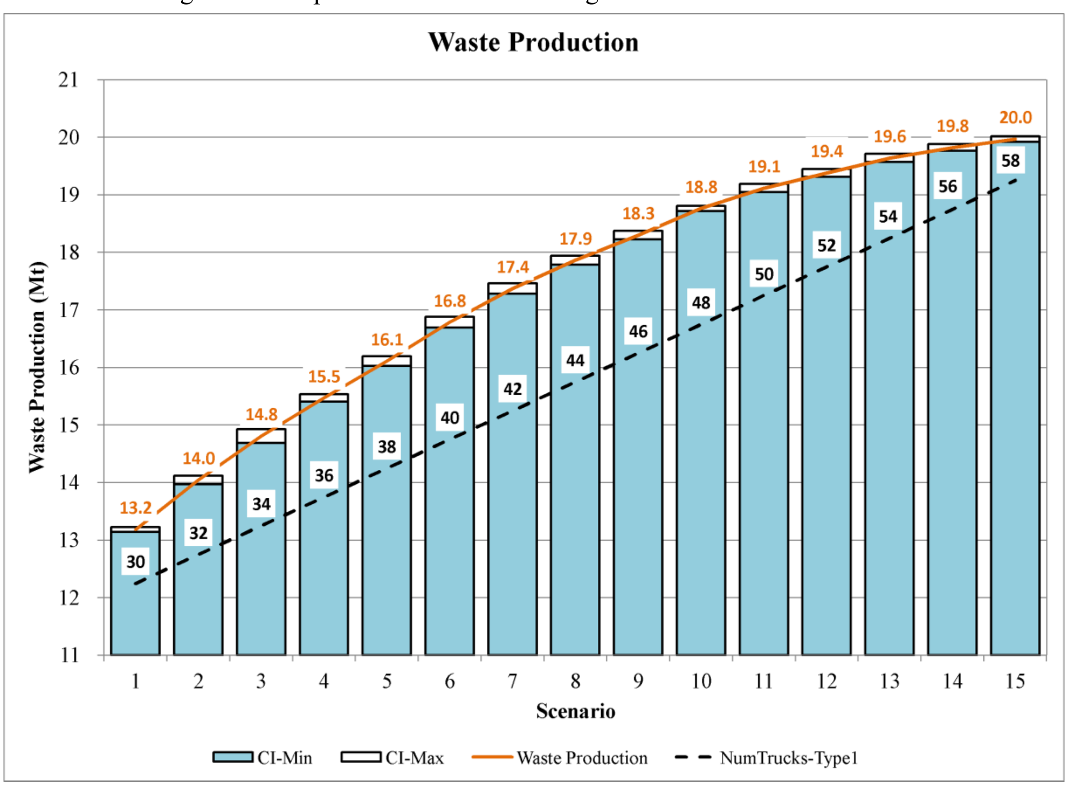

Fig. 4.14. Waste production with increasing number of trucks in case C1

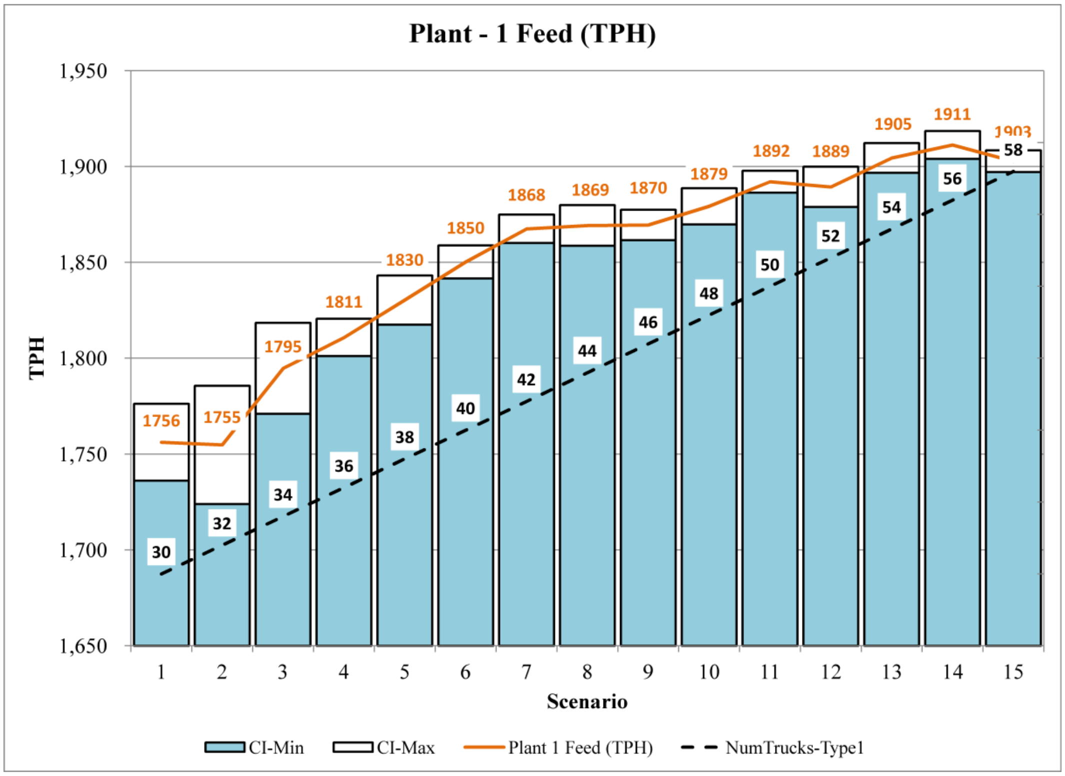

Fig. 4.15. Plant 1 average ton per hour delivered with increasing number of trucks in case C1

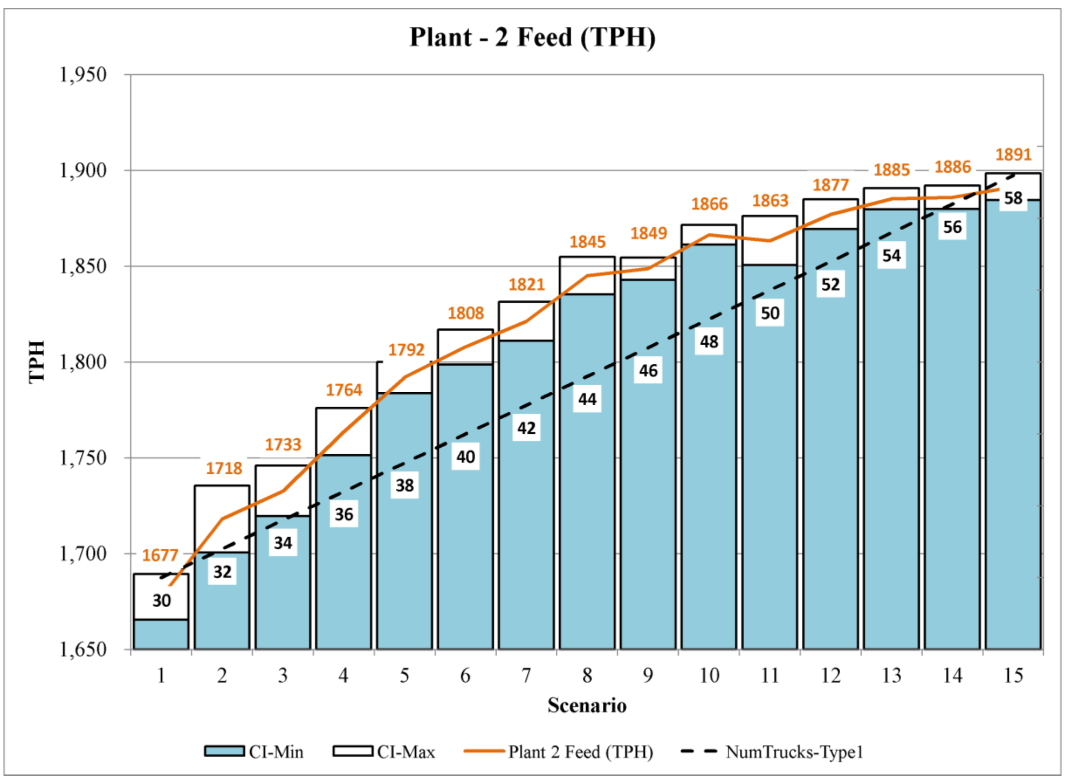

Fig. 4.16. Plant 2 average ton per hour delivered with increasing number of trucks in case C1

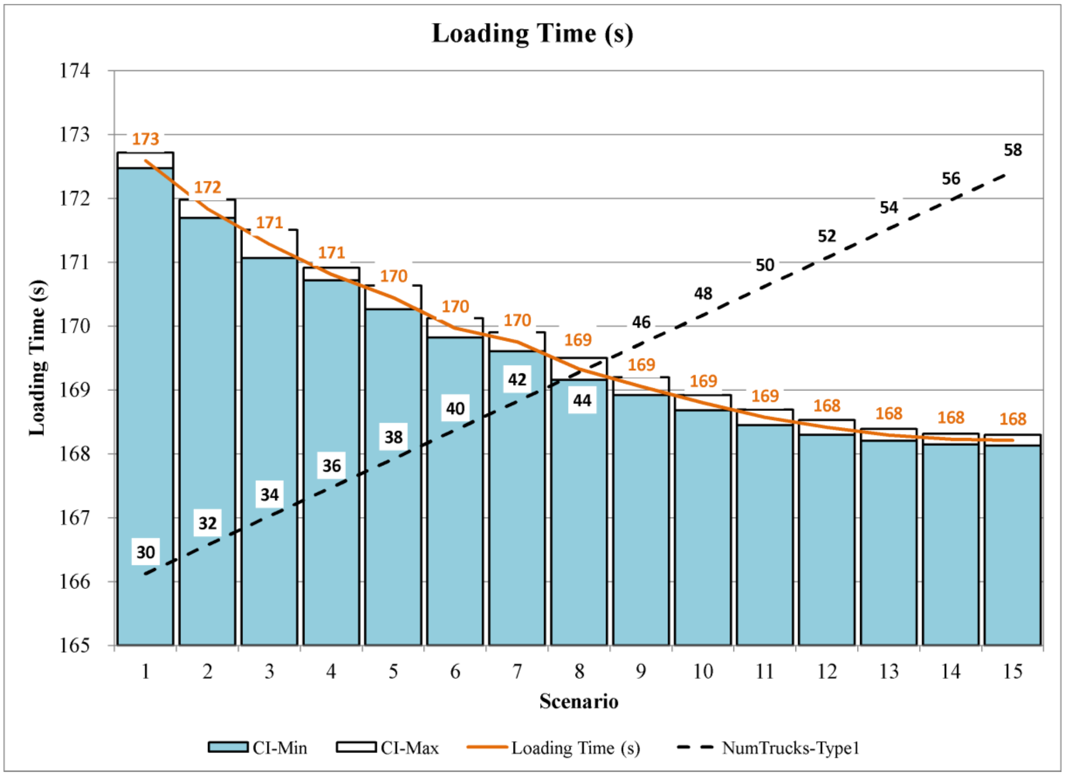

Fig. 4.17. Mean value of loading times with increasing number of trucks in case C1

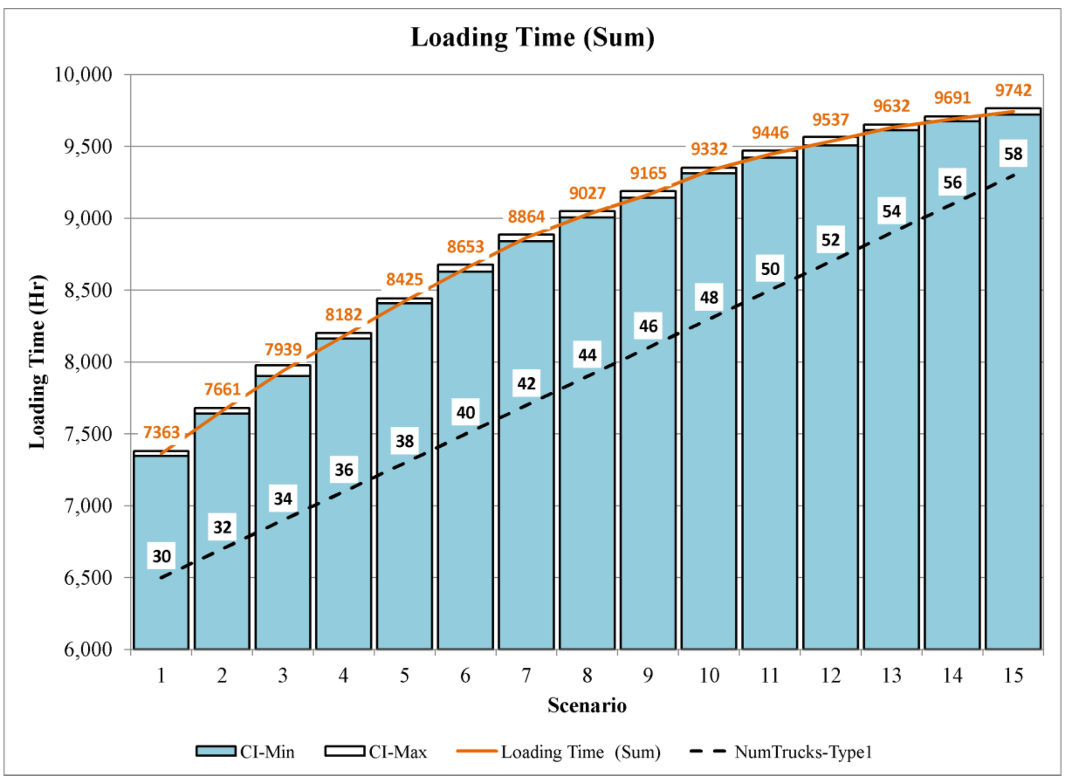

Fig. 4.18. Total time in loading with increasing number of trucks in case C1

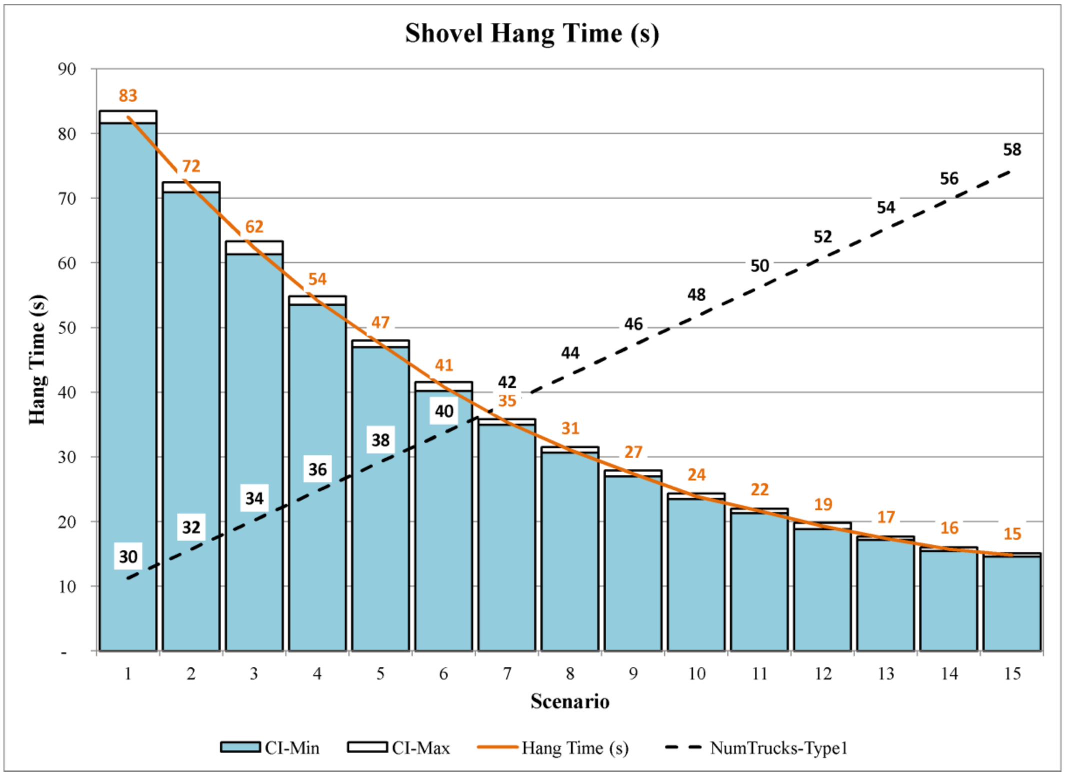

Fig. 4.19. Mean hang times with increasing number of trucks in case C1

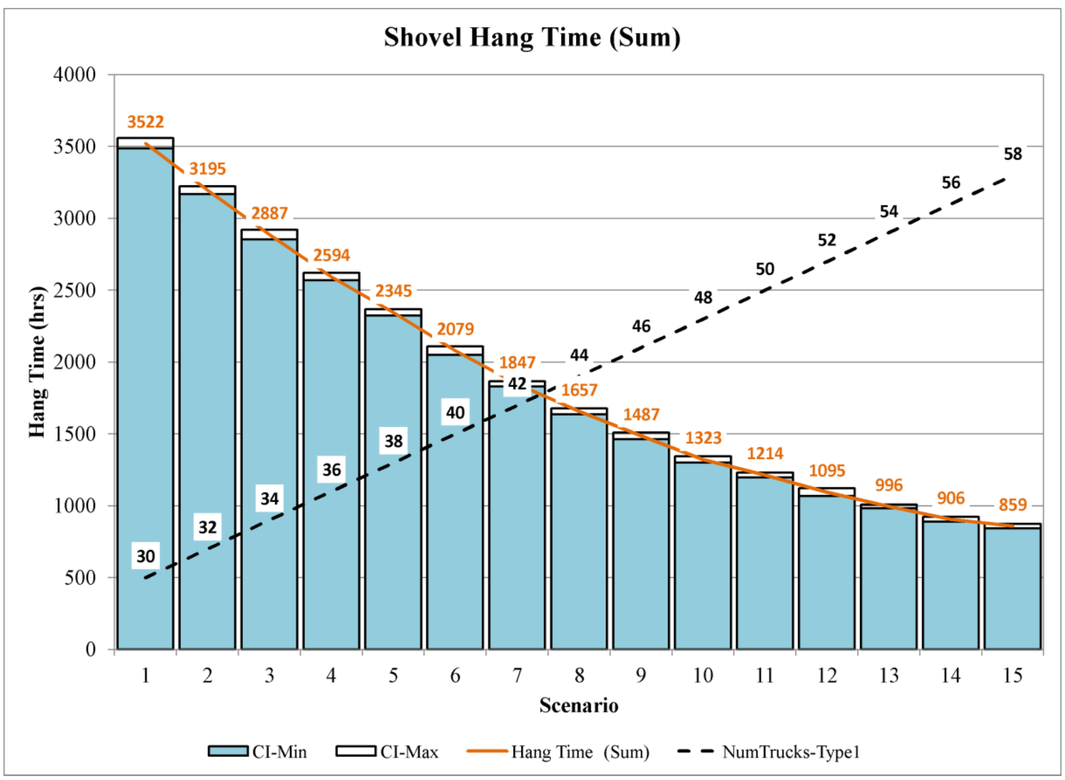

Fig. 4.20. Total hang time with increasing number of trucks in case C1

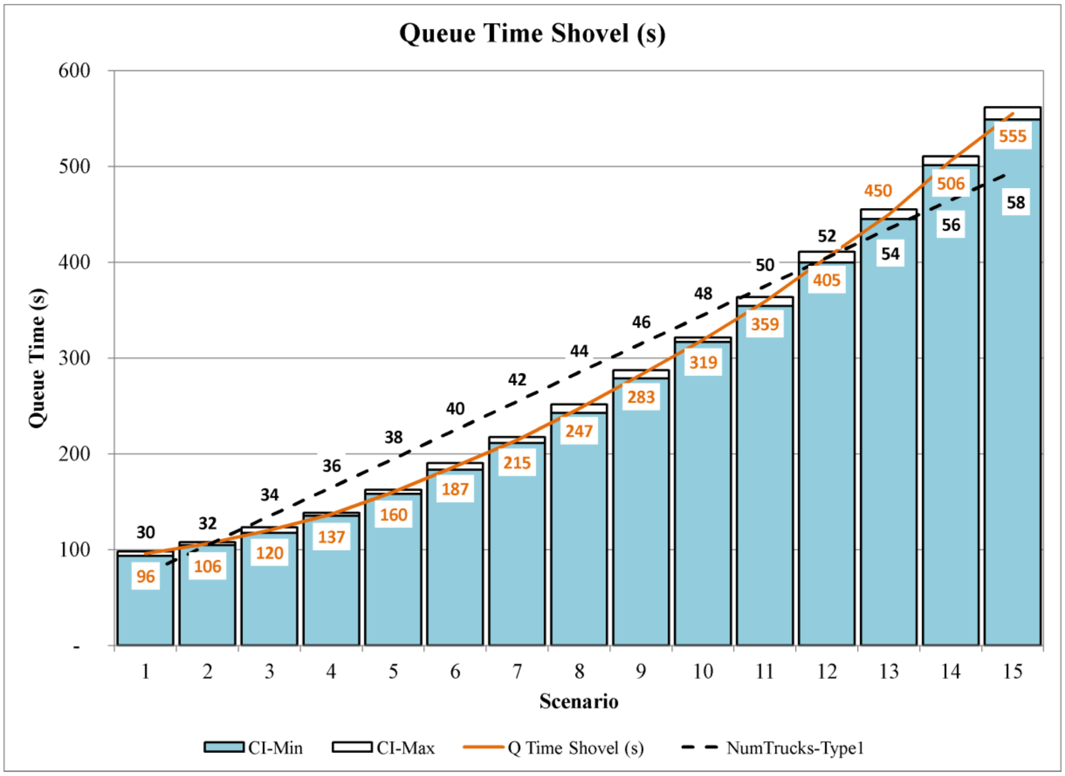

Fig. 4.21. Mean queue times at shovels with increasing number of trucks in case C1

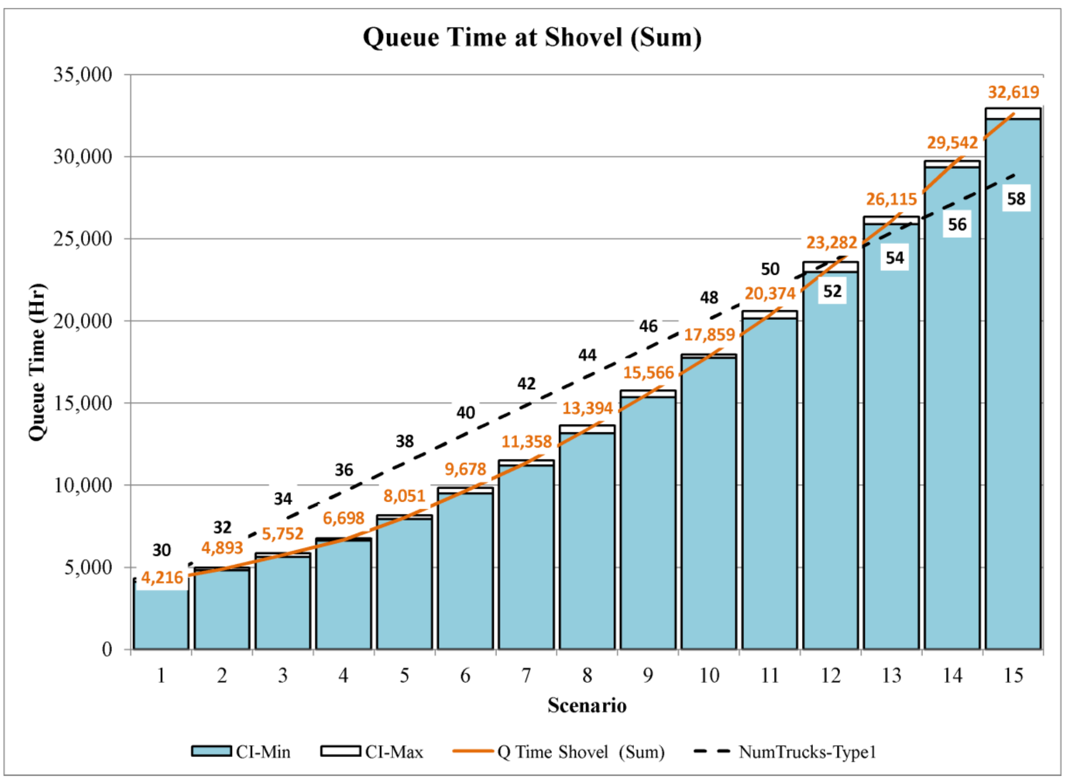

Fig. 4.22. Total queuing time at shovels with increasing number of trucks in case C1

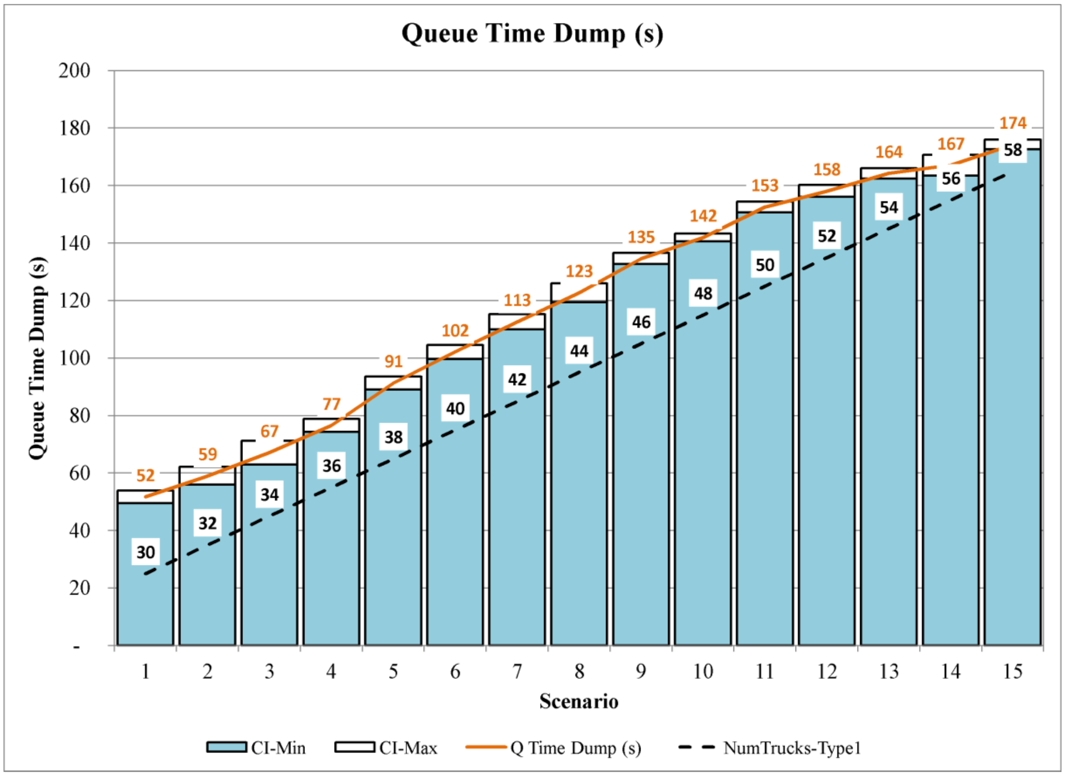

Fig. 4.23. Mean queue time at dumps with increasing number of trucks in case C1

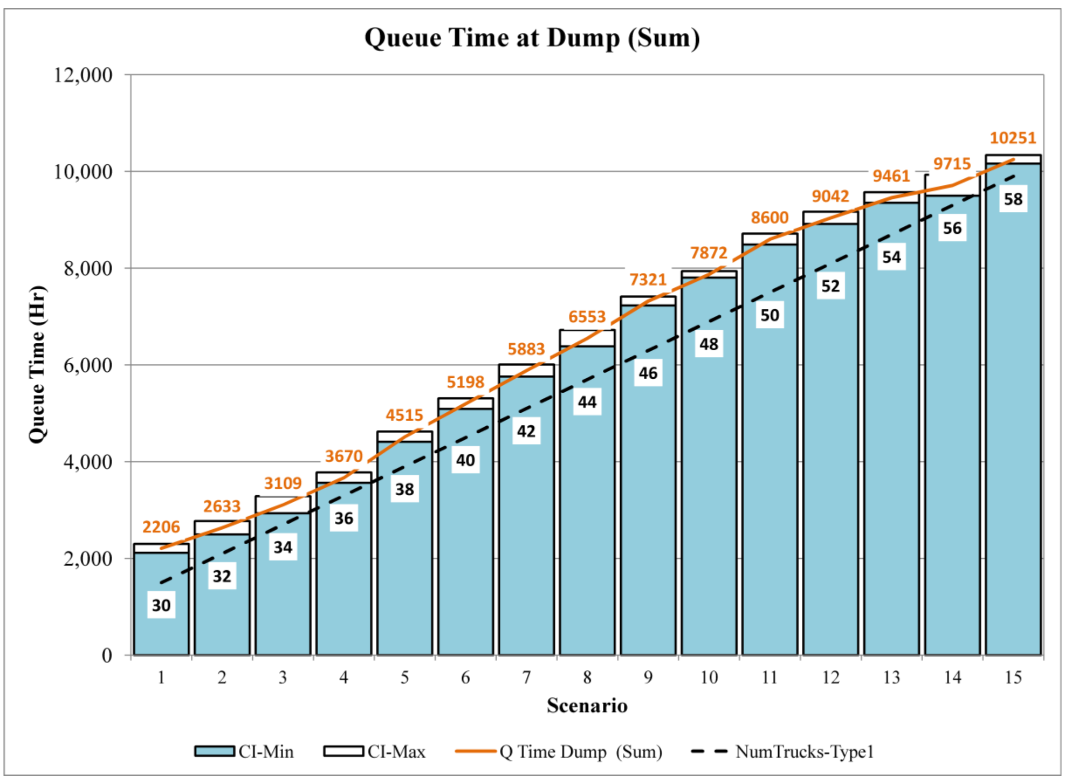

Fig. 4.24. Total queuing time at dumps with increasing number of trucks in case C1

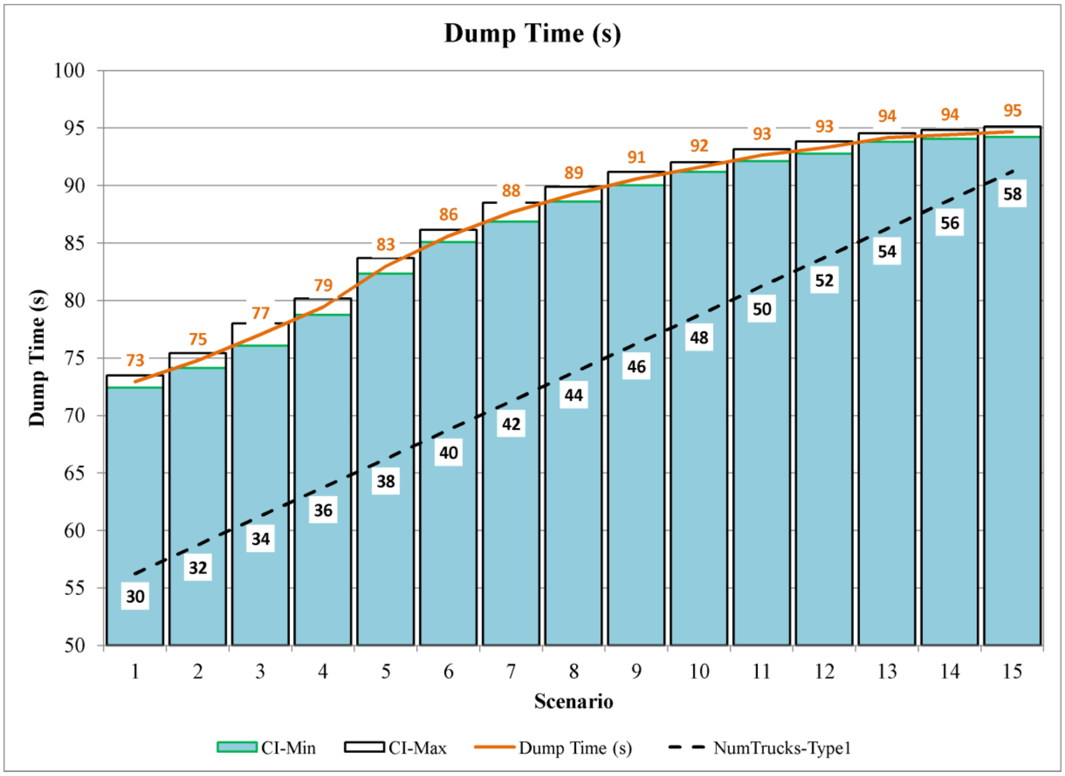

Fig. 4.25. Mean dump times with increasing number of trucks in case C1

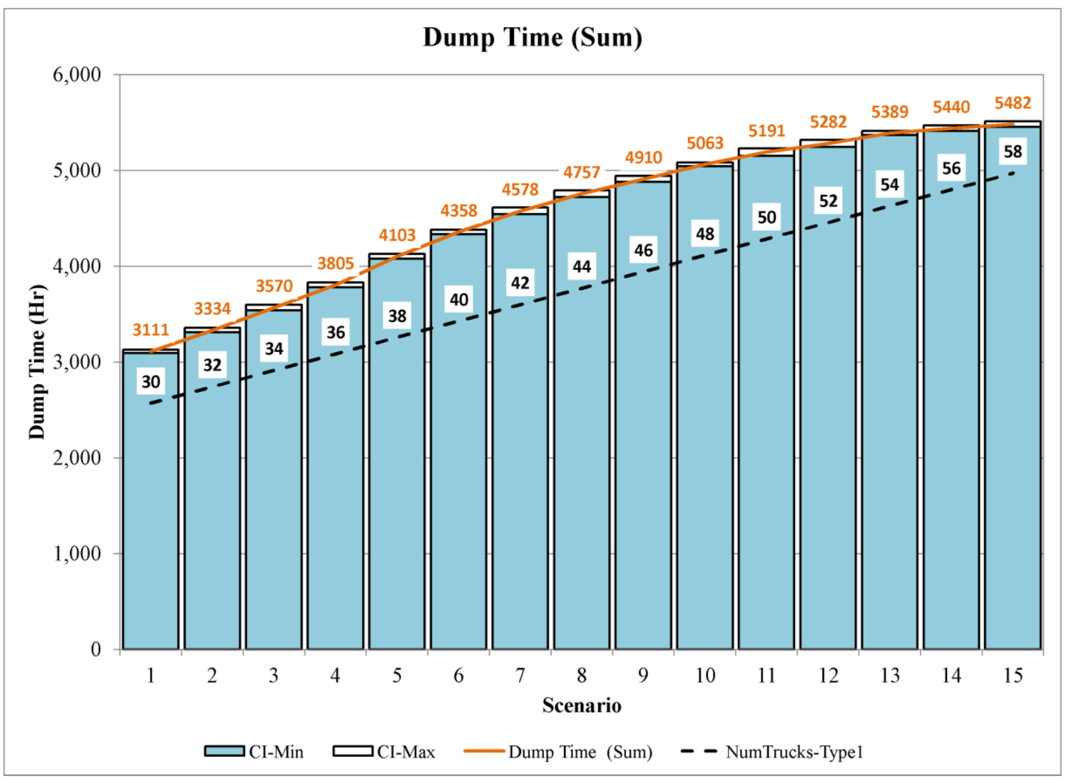

Fig. 4.26. Total dumping time with increasing number of trucks in case C1

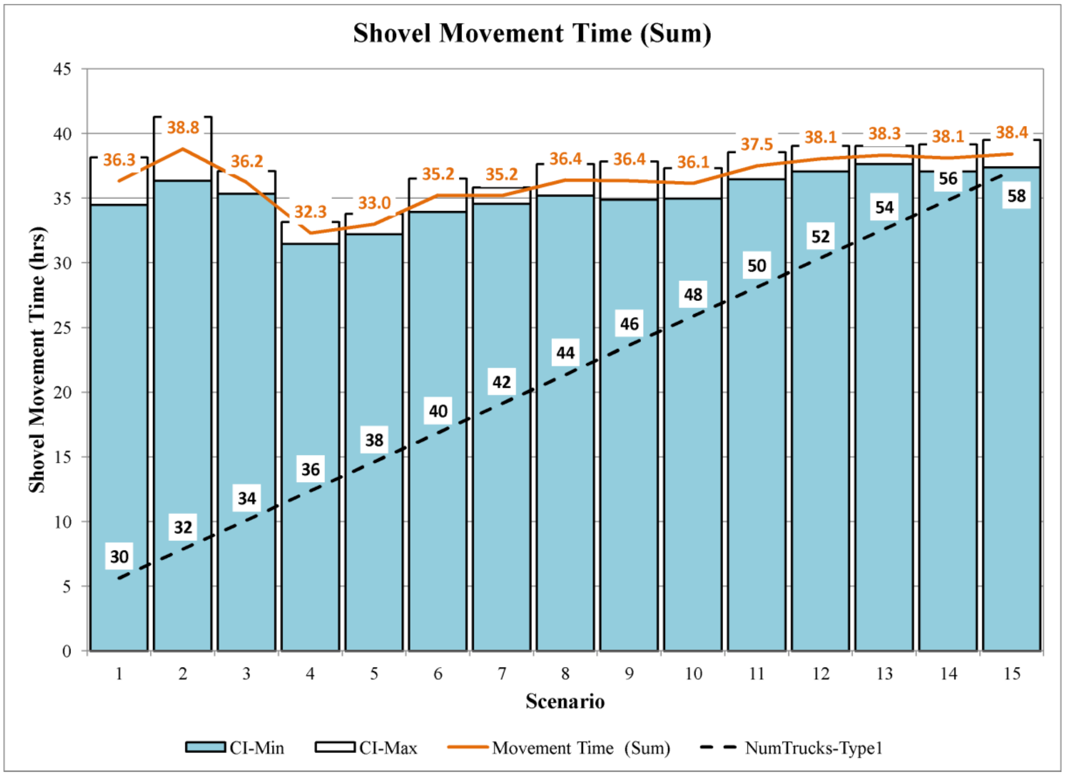

Fig. 4.27. Total time shovels devoted towards movement to other faces with increasing number of trucks in case C1

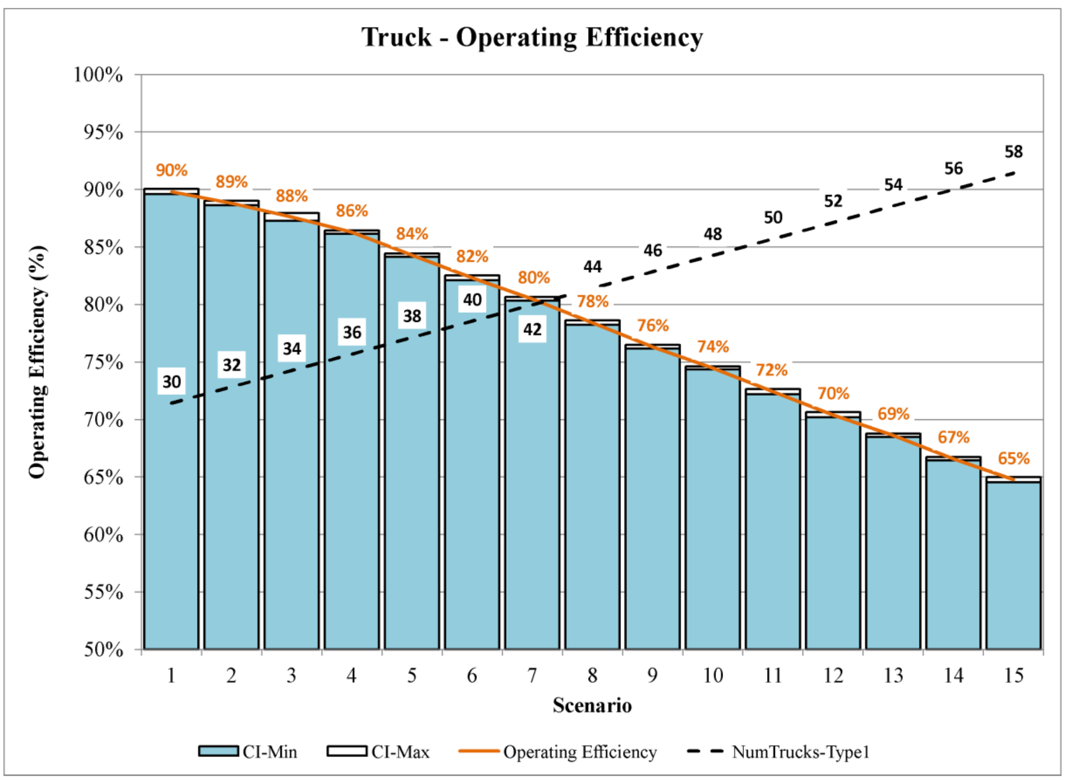

Fig. 4.28. Truck operating efficiencies with increasing number of trucks in case C1

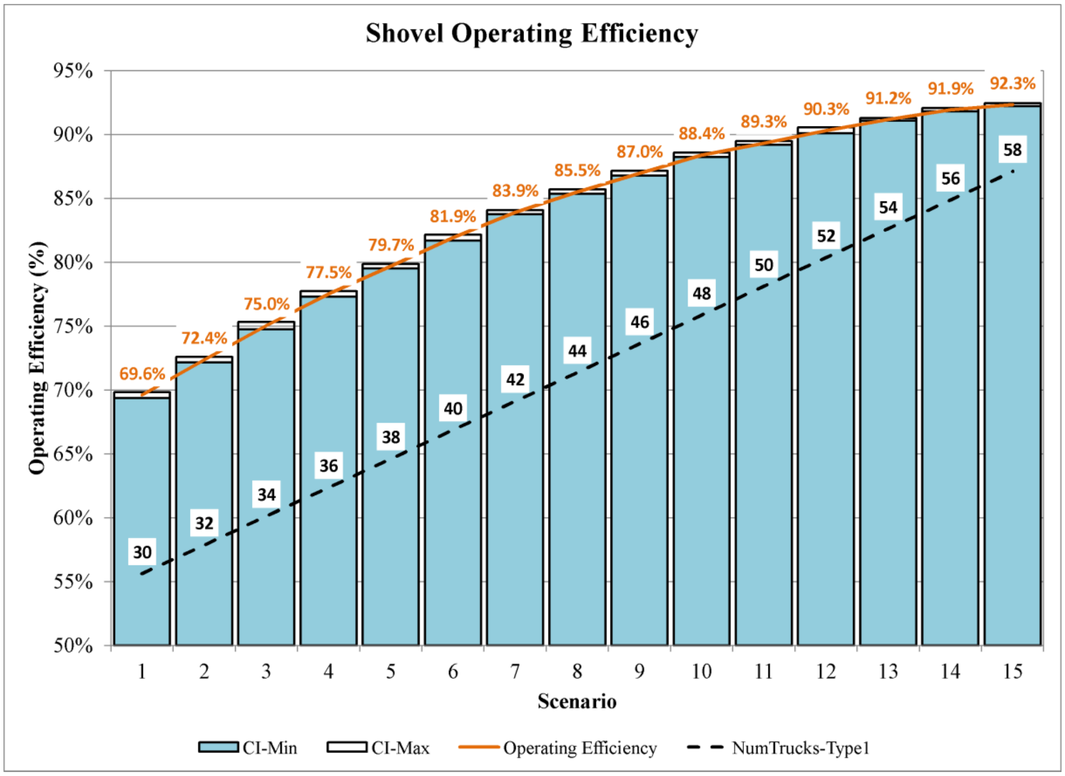

Fig. 4.29. Shovel operating efficiencies with increasing number of trucks in case C1

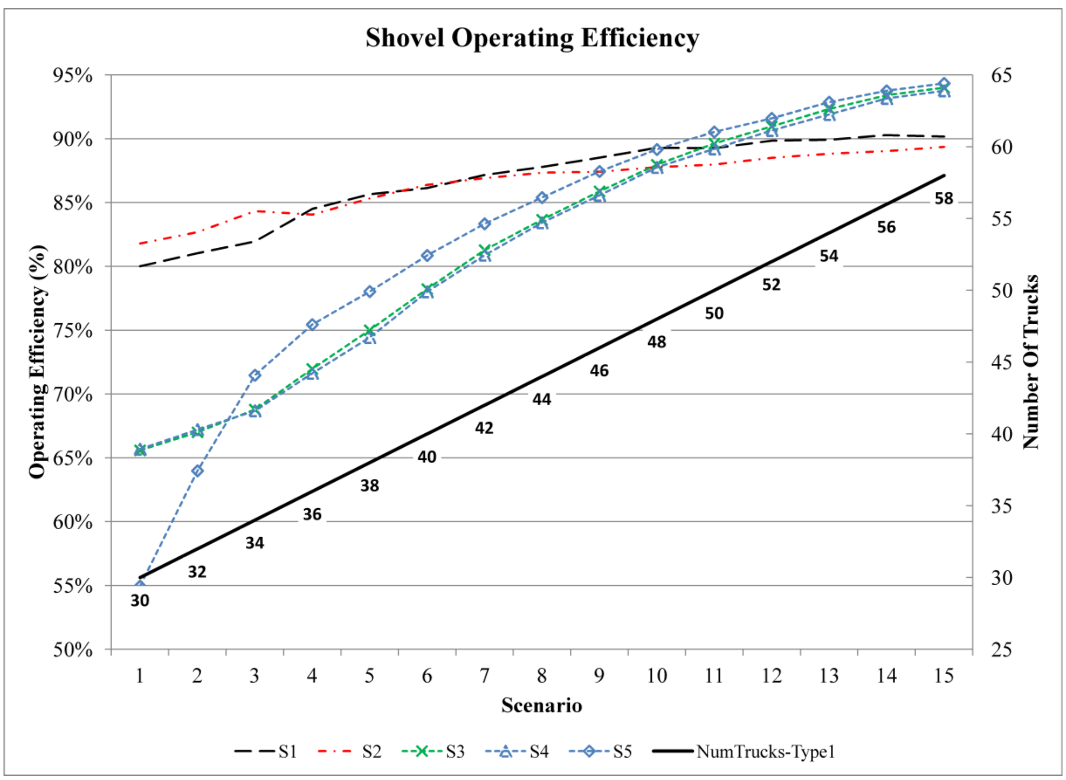

Fig. 4.30. Mean value of Individual shovel efficiencies with increasing number of trucks in case C1

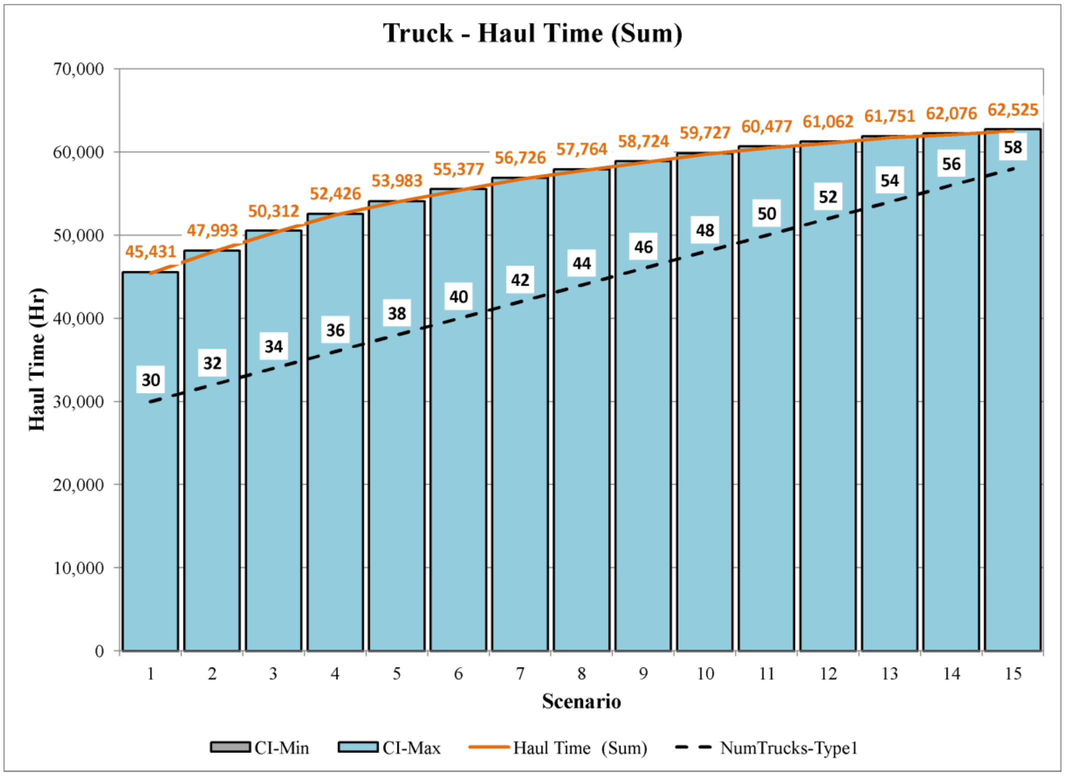

Fig. 4.31. Total time involved in truck movements (empty and full) with increasing number of trucks in case C1

Fig. 4.15 and Fig. 4.16 present the TPH delivered to plant 1 and 2 respectively. As this is one of the objectives in MOOT, the plants received ore almost at desired rates. The increase in TPH is not substantial with increase in number of trucks, as plants are already receiving ore at the almost the desired rate. The increase in number of trucks cause further queuing at the plants as visible in queue time at dump (Fig. 4.23 and Fig. 4.24), and an increase in dump times due to limited hopper capacities as visible in dump times (Fig. 4.25 and Fig. 4.26). This behavior lead to only marginal increase in TPH delivered to plants. Other KPIs recorded, loading times (Fig. 4.17 and Fig. 4.18), shovel hang times (Fig. 4.19 and Fig. 4.20), queue times at shovel (Fig. 4.21 and Fig. 4.22), truck and shovel operating efficiencies (Fig. 4.28 and Fig. 4.29) and total truck haul times (Fig. 4.31) are observed to behave as expected. The shovel movement times are observed to be mostly same in almost all the scenarios as visible in Fig. 4.27.

4.4.2. *Mixed fleet system – Scenario C2*

Mixed fleet scenarios are run with increasing number of trucks locked in ore and waste as shown in Table 4-6. As trucks are locked to ore and waste, MOOT does not find extra haulage capacity to divert from waste to ore to meet plant requirements. Thus ore and waste productions shown in Fig. 4.32 and separately in Fig. 4.33 and Fig. 4.34 are observed to follow the number of trucks locked to ore and waste shovels individually. This behavior is also observed in individual shovel operating efficiencies as shown in Fig. 4.50.

Table 4-6: Number of trucks of each type locked to ore or waste used in case C2 scenarios

Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Num Trucks – Type 1 (Ore)	12	12	14	15	16	16	17	16	17	19	19	17	21	21	21
Num Trucks – Type 2 (Waste)	12	14	14	13	14	16	16	17	17	16	17	19	17	19	21

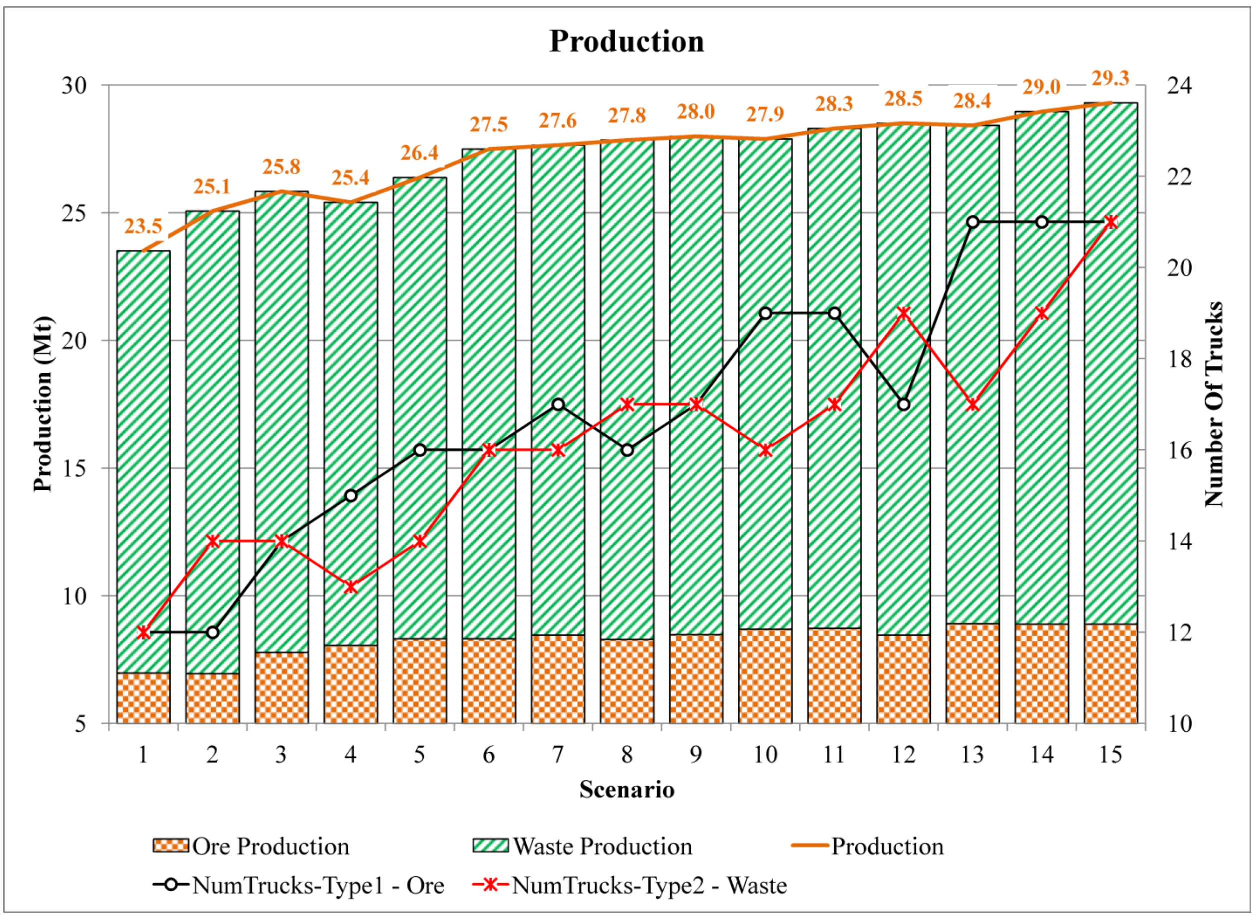

Fig. 4.32. Mean ore and waste productions with increasing number of trucks in case C2

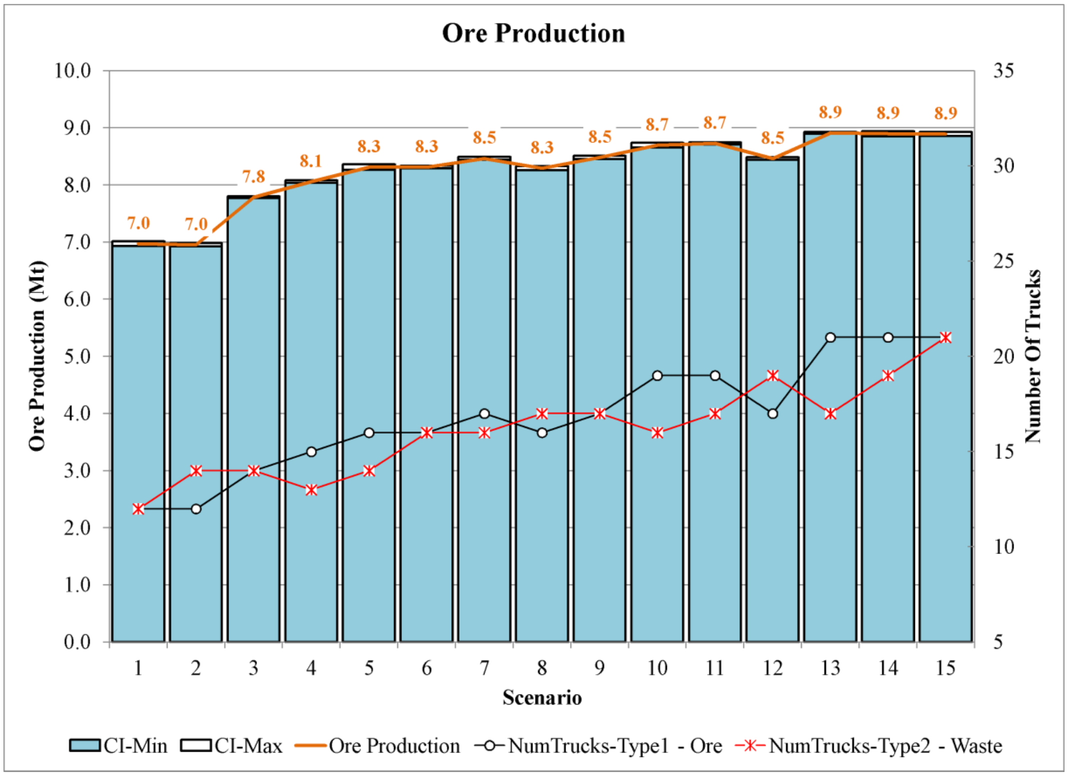

Fig. 4.33. Ore production with increasing number of trucks in case C2

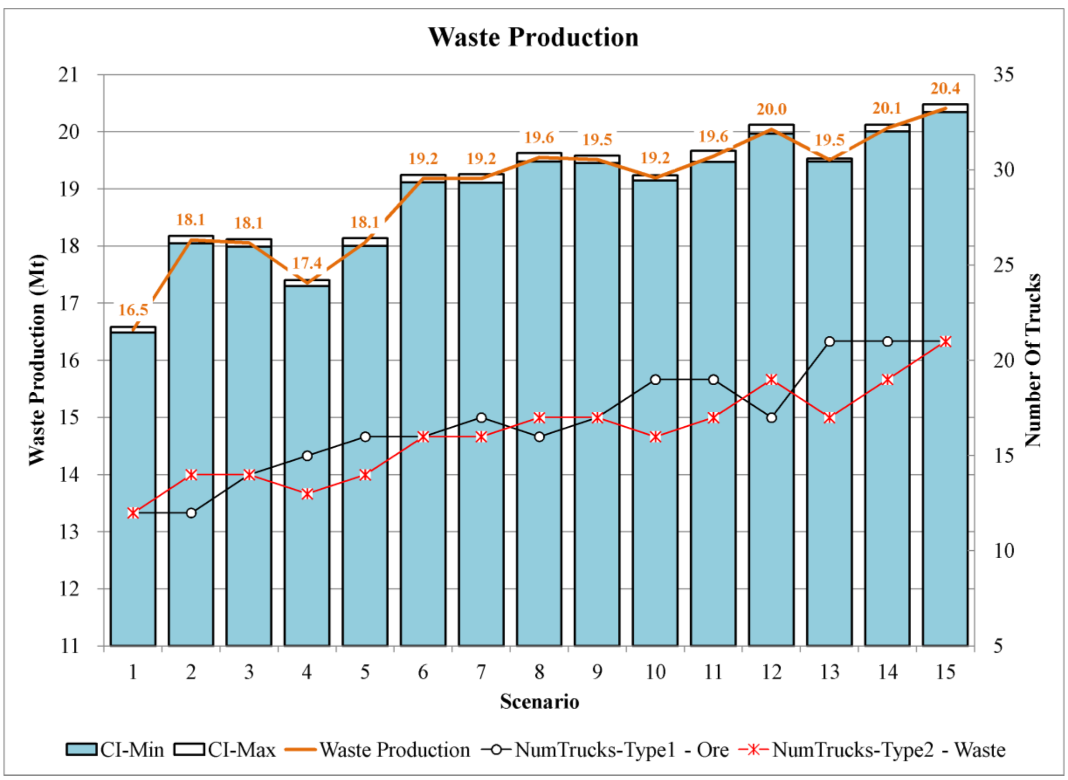

Fig. 4.34. Waste production with increasing number of trucks in case C2

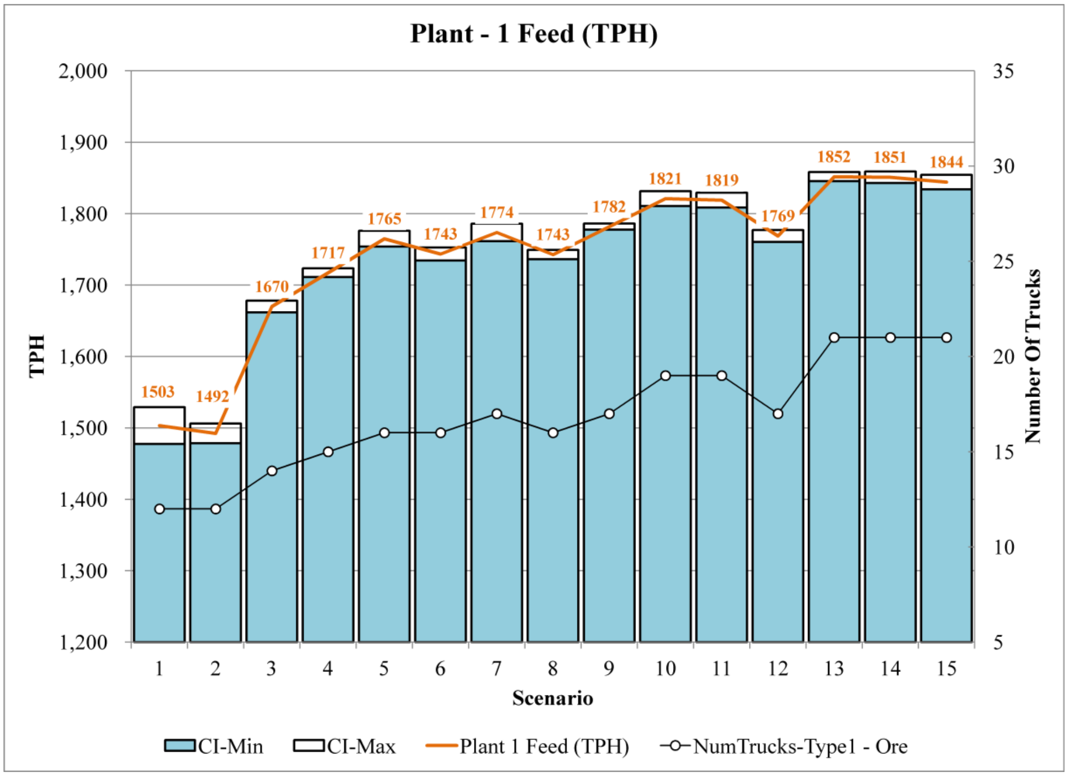

Fig. 4.35. Plant 1 average ton per hour delivered with increasing number of trucks in case C2

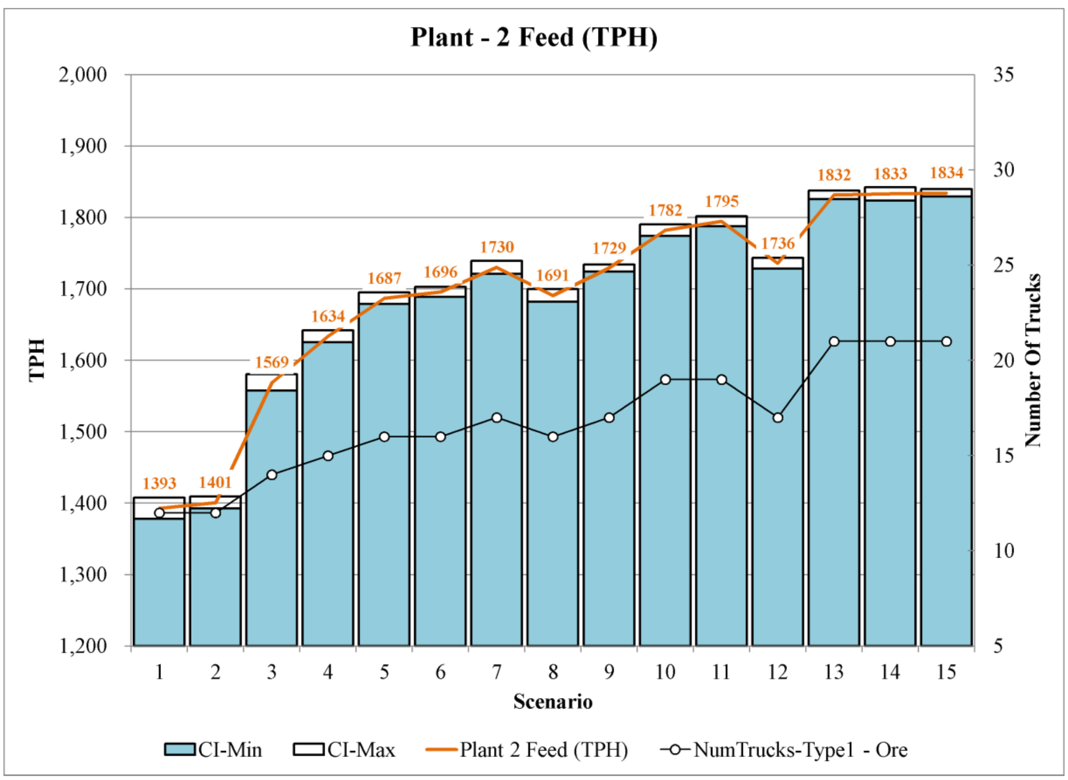

Fig. 4.36. Plant 2 average ton per hour delivered with increasing number of trucks in case C2

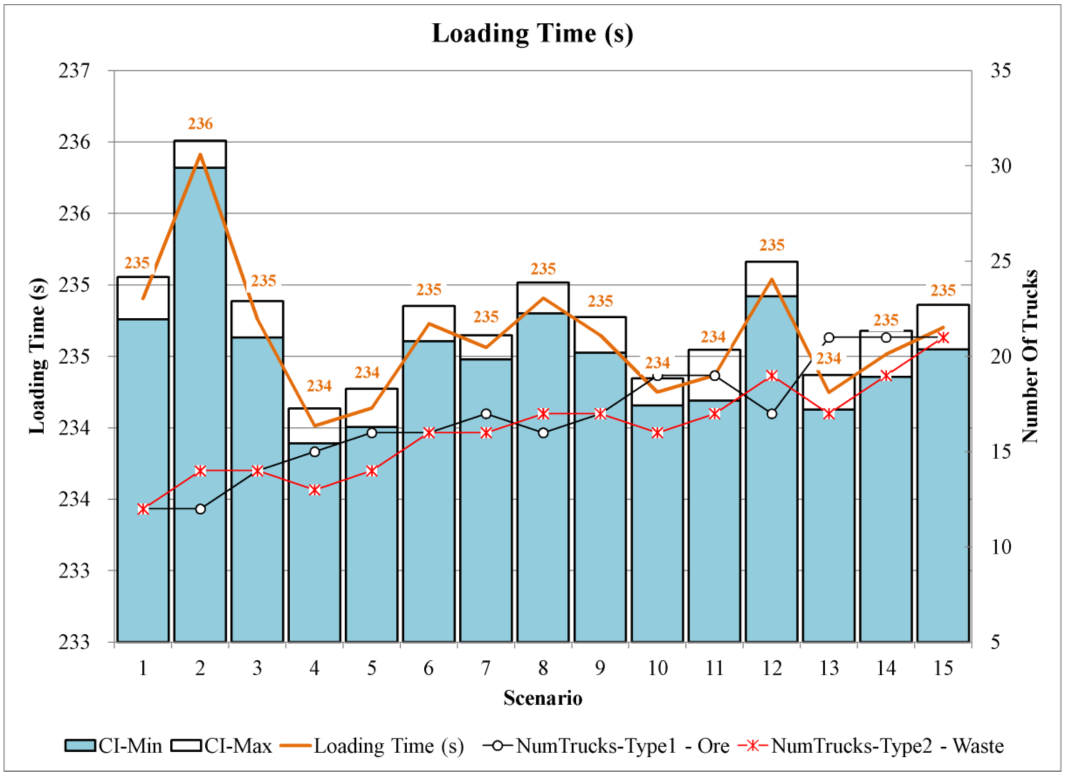

Fig. 4.37. Mean value of loading times with increasing number of trucks in case C2

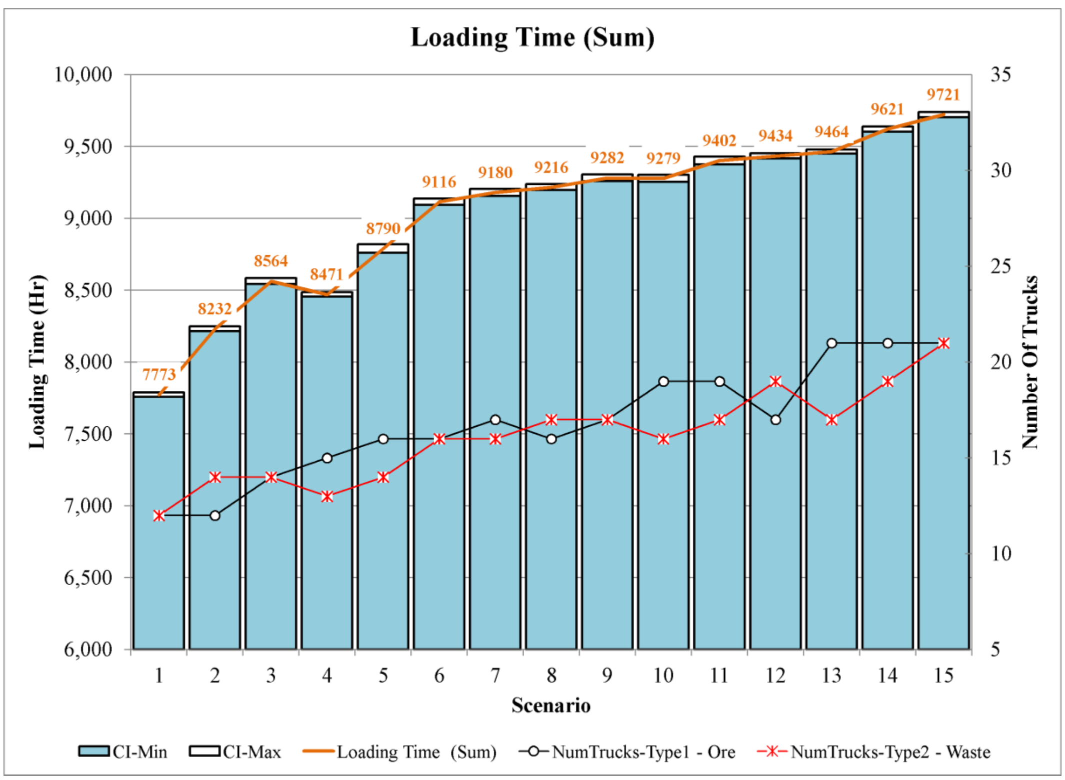

Fig. 4.38. Total time in loading with increasing number of trucks in case C2

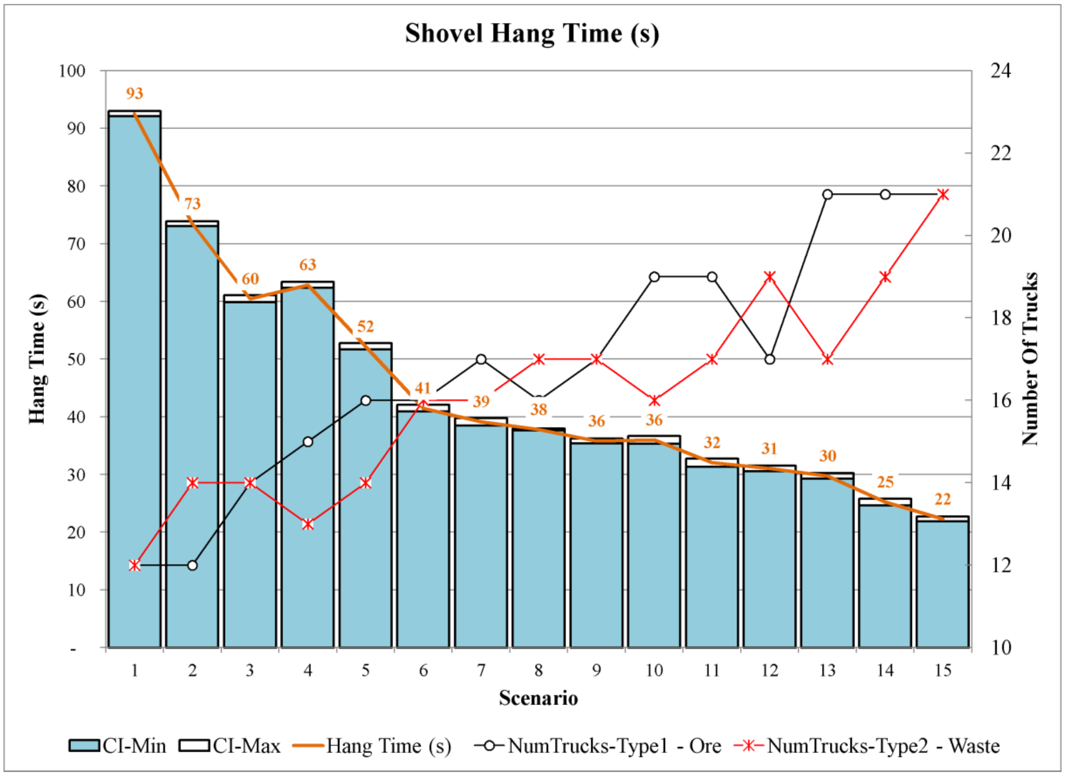

Fig. 4.39. Mean hang times with increasing number of trucks in case C2

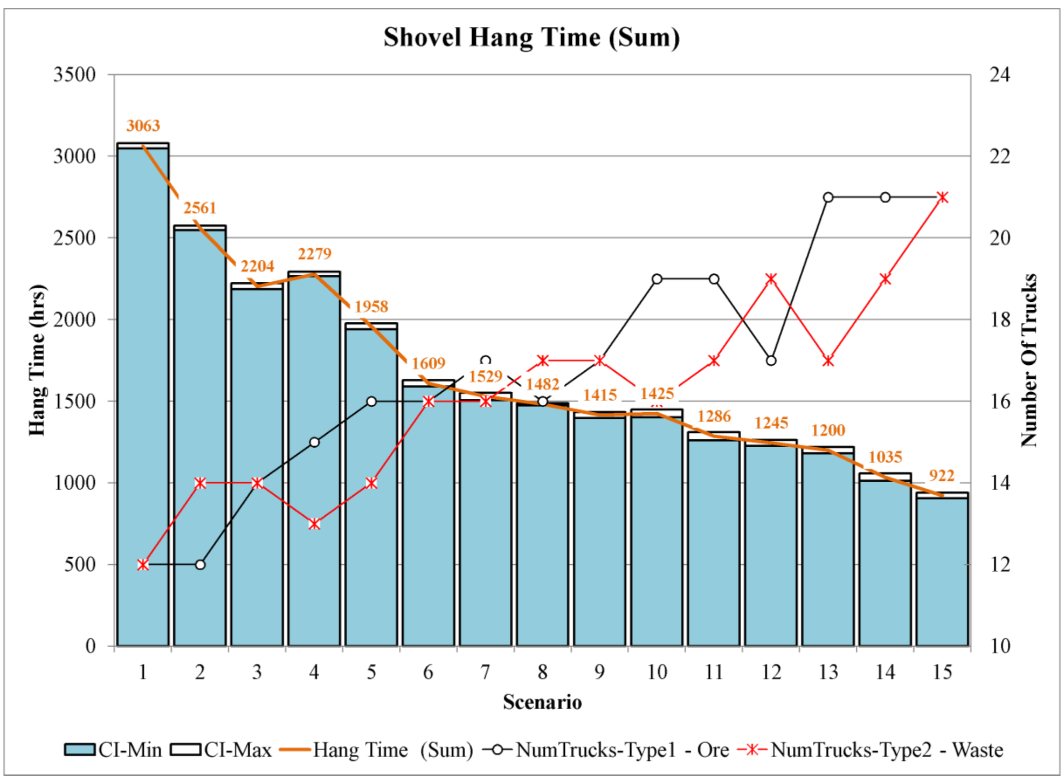

Fig. 4.40. Total hang time with increasing number of trucks in case C2

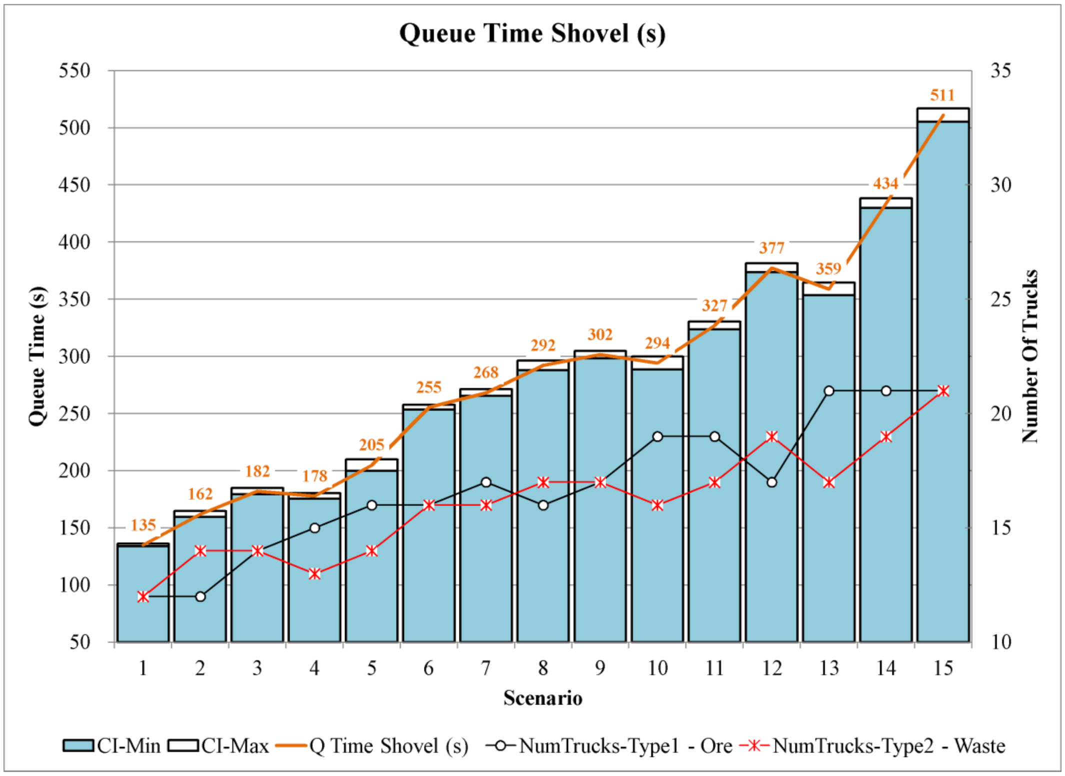

Fig. 4.41. Mean queue times at shovels with increasing number of trucks in case C2

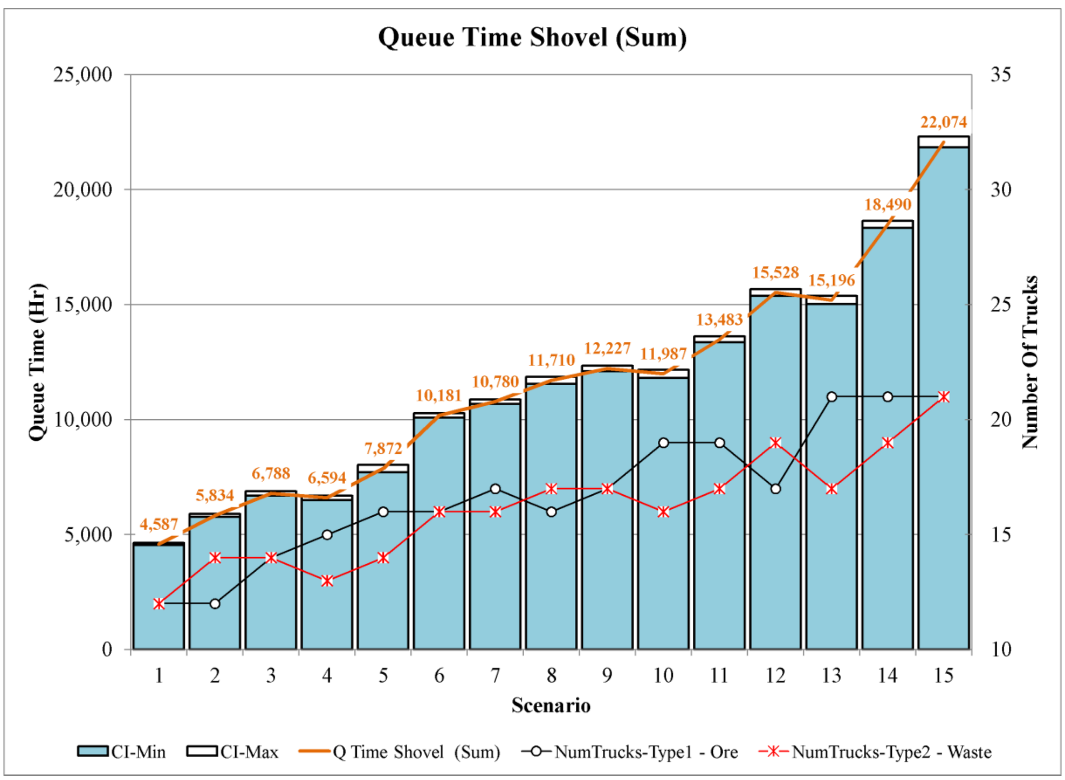

Fig. 4.42. Total queuing time at shovels with increasing number of trucks in case C2

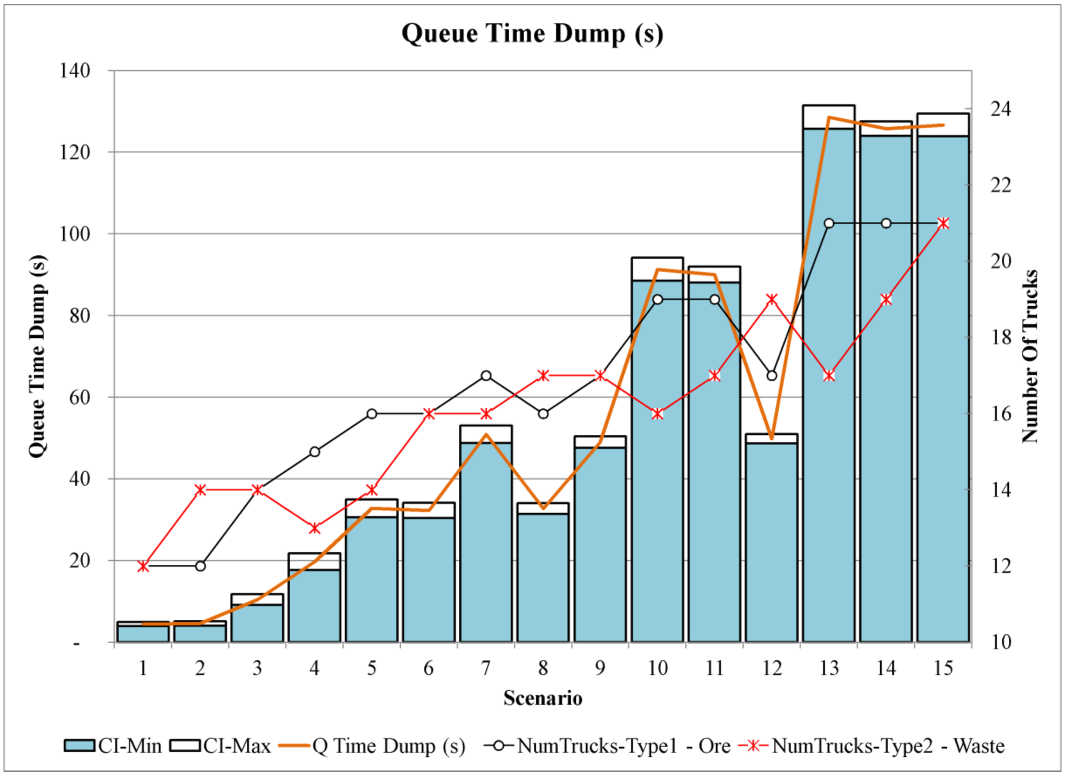

Fig. 4.43. Mean queue time at dumps with increasing number of trucks in case C2

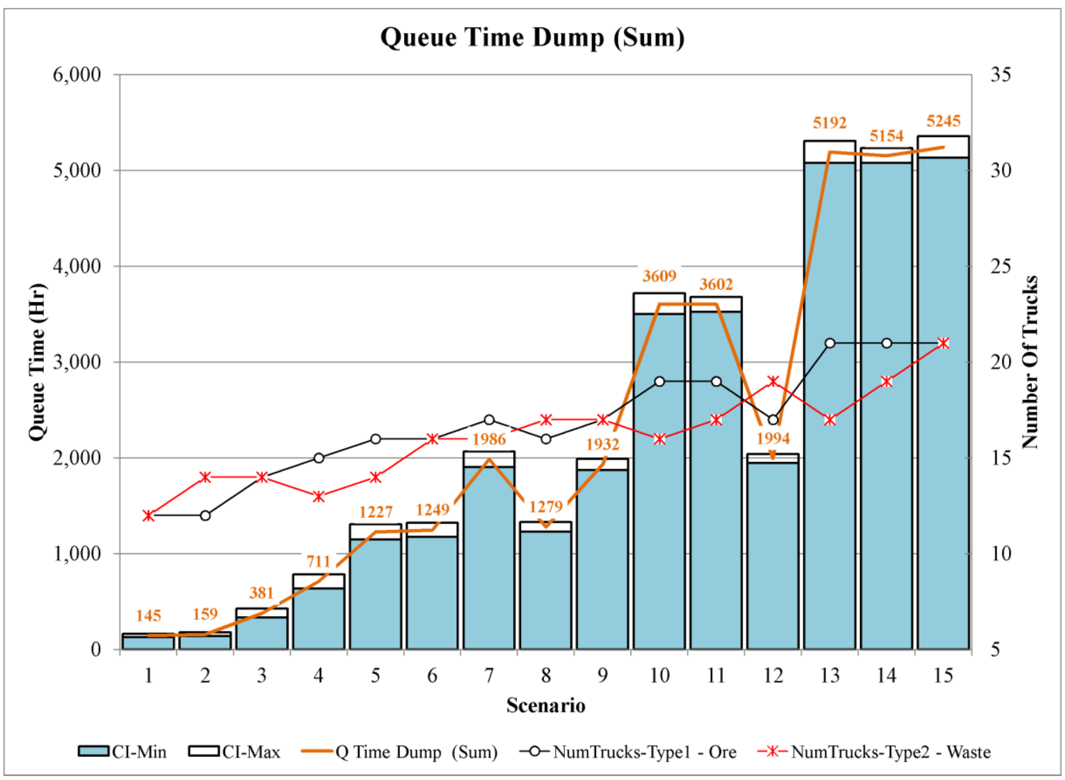

Fig. 4.44. Total queuing time at dumps with increasing number of trucks in case C2

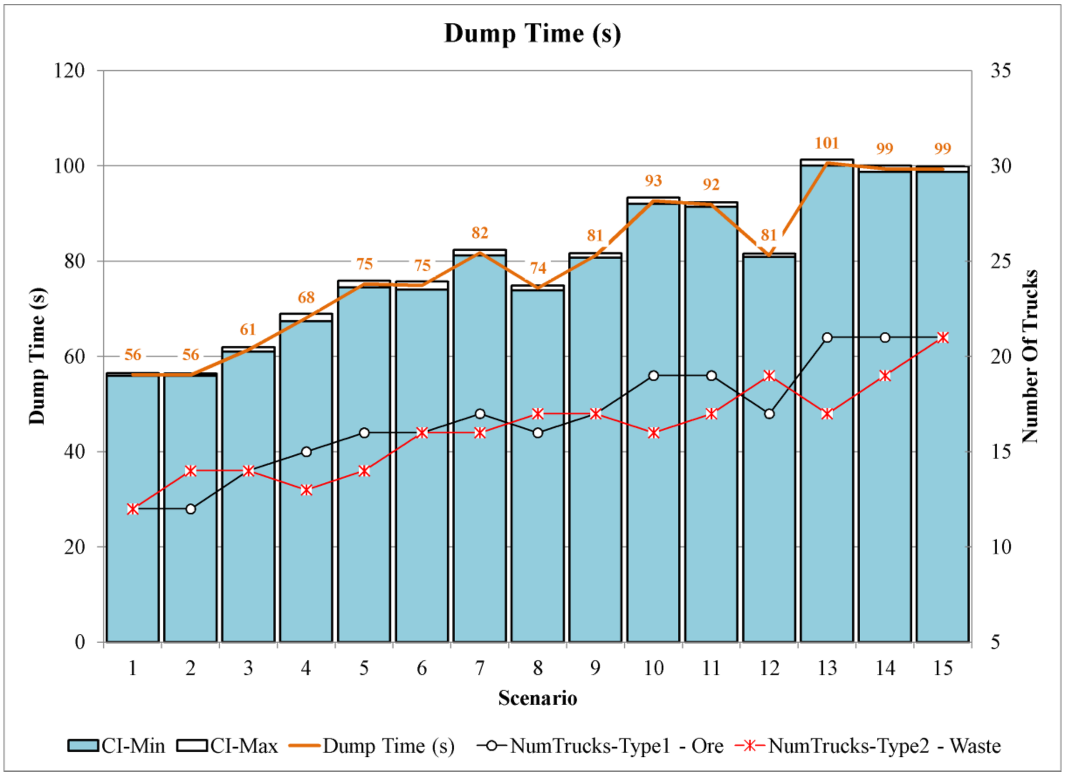

Fig. 4.45. Mean dump times with increasing number of trucks in case C2

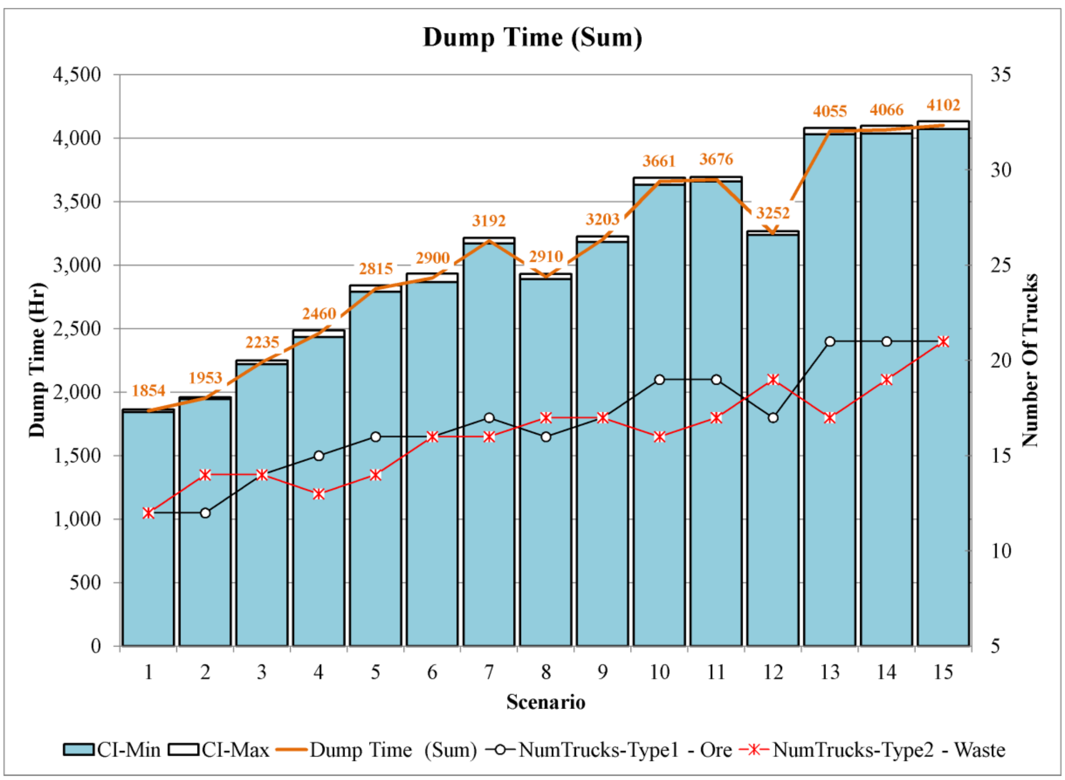

Fig. 4.46. Total dumping time with increasing number of trucks in case C2

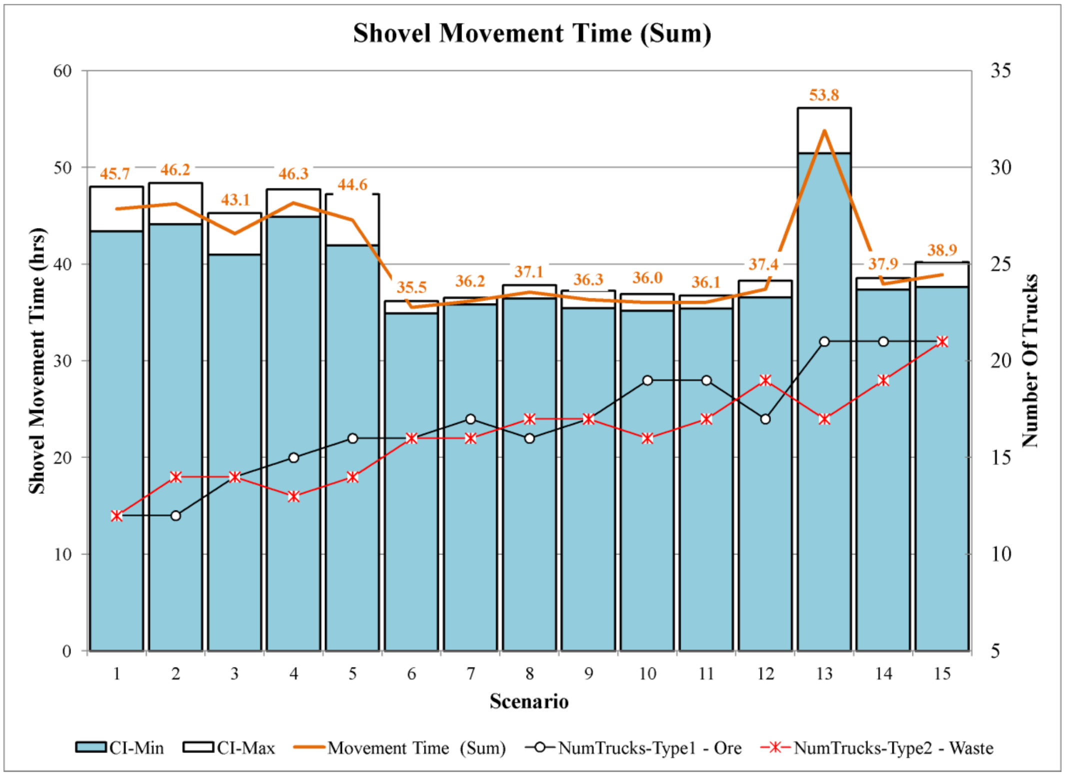

Fig. 4.47. Total time shovels devoted towards movement to other faces with increasing number of trucks in case C2

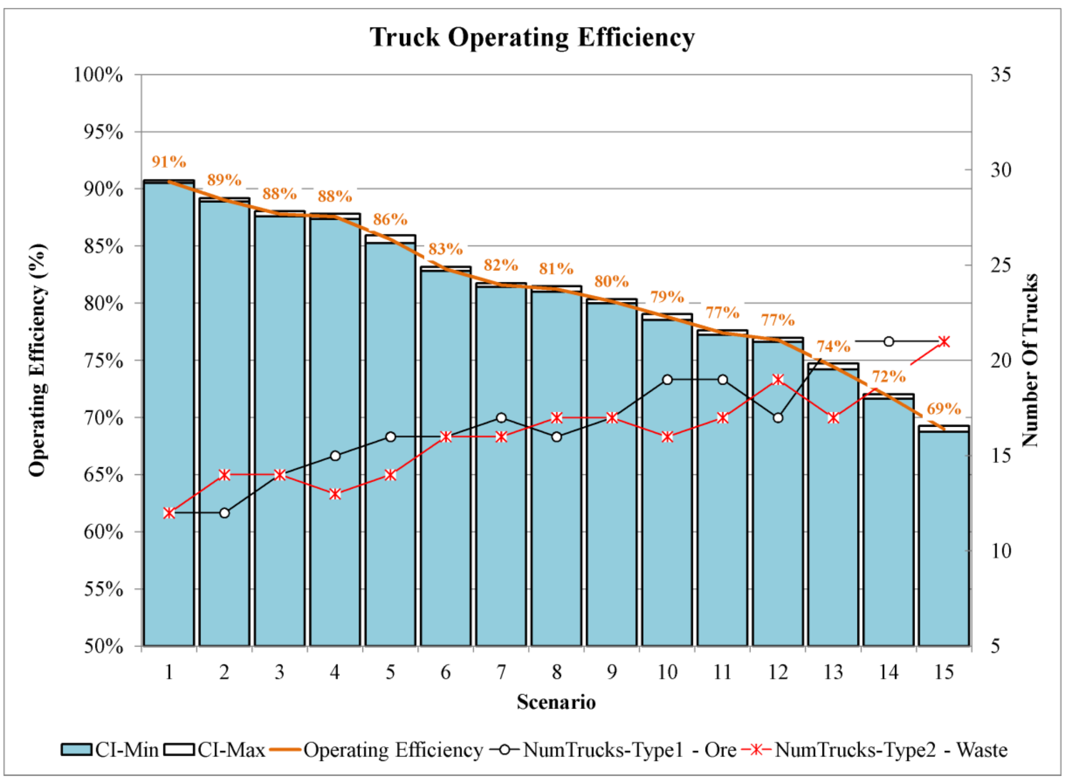

Fig. 4.48. Truck operating efficiencies with increasing number of trucks in case C2

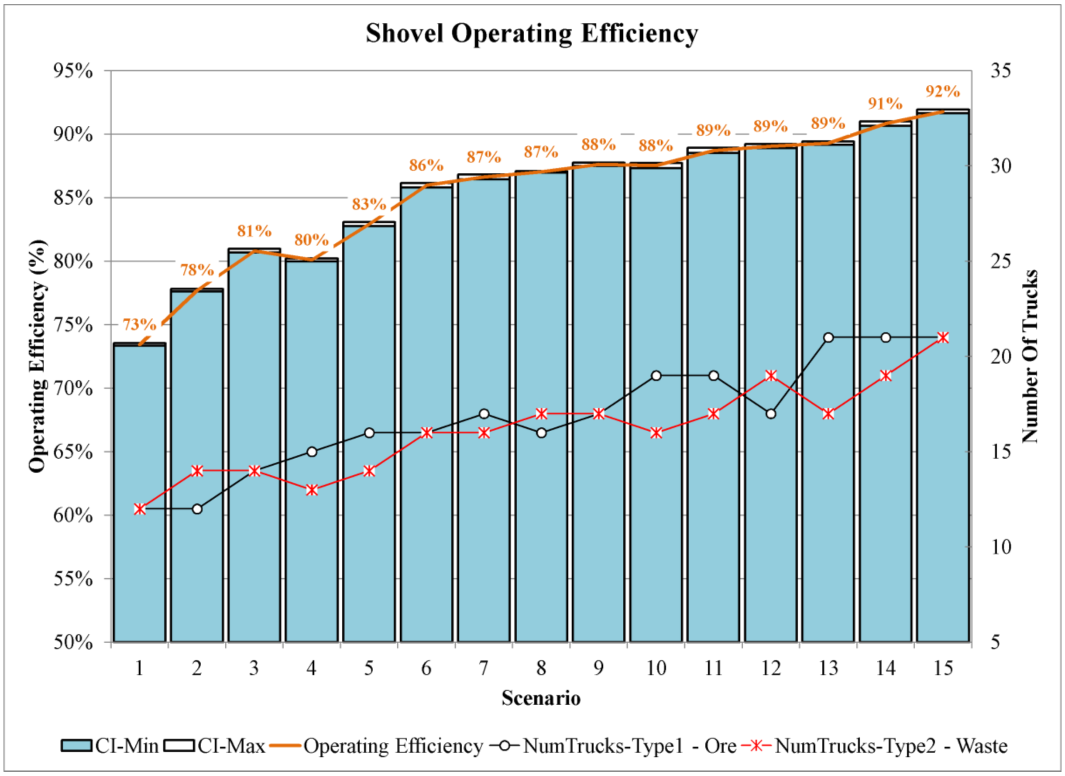

Fig. 4.49. Shovel operating efficiencies with increasing number of trucks in case C2

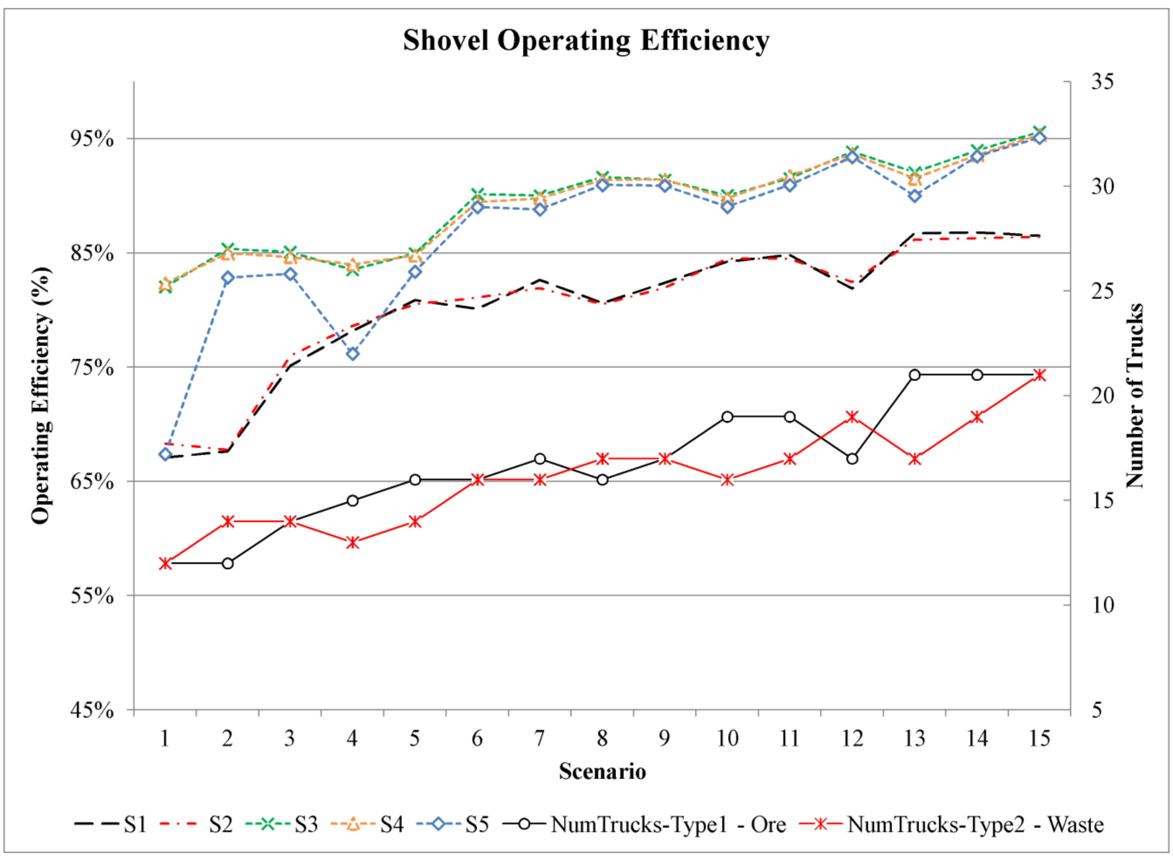

Fig. 4.50. Mean value of Individual shovel efficiencies with increasing number of trucks in case C2

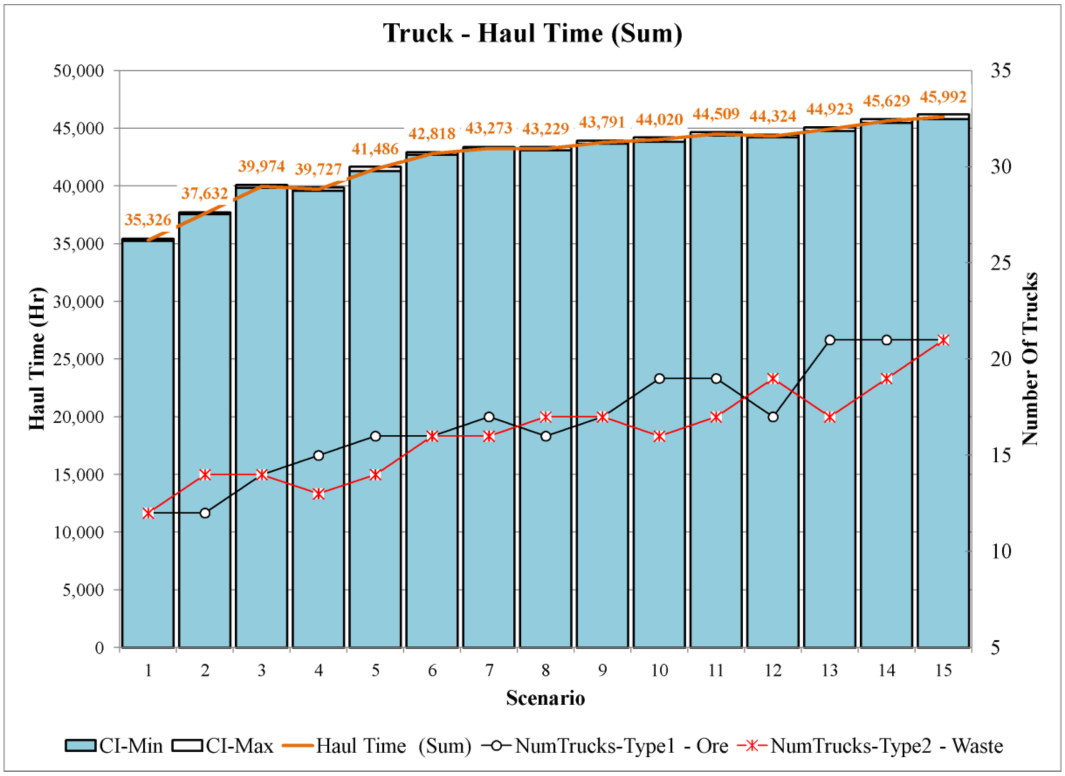

Fig. 4.51. Total time involved in truck movements (empty and full) with increasing number of trucks in case C2

The behavior of TPH curves, shown in Fig. 4.35 and Fig. 4.36, vary with the changing number of trucks locked to ore shovels and thus slightly different as compared to the single fleet system. Moreover as the TPH nears to the capacity of the plants, only marginal increase is observed similar to the single fleet system with increase in haulage capacity. This is also observed in queue times at dump graphs (Fig. 4.43 and Fig. 4.44) which show high variation in dump times with number of ore trucks (type 1) as compared to waste trucks (type 2). Dump times (Fig. 4.45 and Fig. 4.46) also show variation with ore trucks due to the limited capacity of the hoppers at the plants which forces trucks to wait for space in the hoppers before dumping can finish. Other KPIs of the operation, loading times (Fig. 4.37 and Fig. 4.38), shovel hang times (Fig. 4.39 and Fig. 4.40), queue times at shovel (Fig. 4.41 and Fig. 4.42), truck and shovel operating efficiencies (Fig. 4.48 and Fig. 4.49) and total truck haul times (Fig. 4.51) are observed to behave as expected. Total shovel movement times (Fig. 4.47) show slightly greater variation in this case C2 compared to C1.

4.4.3. *Establishing base case scenario*

The base case scenario is selected as the most efficient configuration of the system from amongst case C1 and C2 scenarios. First a theoretical estimate of the required number of trucks is determined as shown in

Table 4-7 and Table 4-8. The formulation used is given in Eq. (67). Average values of load, spot, full haul, dump, and empty haul times are estimated from the simulation outputs. This allows us to accurately predict the requirement, because haul times vary with polygons being worked upon by the shovels, as well as the velocities of trucks on different segments.

$$n = \frac{FullHaulTime + DumpTime + EmptyHaulTime}{LoadTime + SpotTime} + 1 \tag{67}$$

Table 4-7: Theoretical estimation of required number of trucks in case C1 (single fleet system)

Shovel	Load time (s)	Spot time (s)	Full Haul time (s)	Dump time (s)	Empty Haul time (s)	Required number of trucks	Total truck requirement
1	211.19	18.43	1034.23	157.27	401.18	7.94	36
2	210.90	18.35	1066.24	173.34	397.67	8.14	
3	148.28	18.38	364.12	50.87	224.11	4.83	
4	148.30	18.42	364.52	50.89	227.24	4.85	
5	148.42	18.34	1109.59	50.91	416.64	10.46	

Table 4-8: Theoretical estimation of required number of trucks in case C2 (mixed fleet system)

Shovel	Load time (s)	Spot time (s)	Full Haul time (s)	Dump time (s)	Empty Haul time (s)	Required number of trucks	Total truck requirement
1	210.54	18.37	1038.47	55.00	384.36	7.46	15
2	210.30	18.36	1036.92	55.00	391.91	7.49	
3	253.01	29.57	347.81	55.68	242.57	3.29	13
4	252.85	29.39	337.62	55.73	240.94	3.25	
5	252.88	29.23	1073.54	55.39	438.97	6.56	

For case C1, the theoretical calculations show a requirement of 36 trucks of type 1 to work with all the shovels, whereas for case C2, 15 type 1 trucks are required to work with ore shovels 1 and 2, and 13 type 2 trucks are required to work with waste shovels 3, 4 and 5. Calculating the equivalent of type 2 trucks in terms of type 1 trucks based on capacity gives a value of 1.7, i.e. one type 2 truck is equivalent to 1.7 type 1 trucks. Using this equivalent in case C2 shows that 22 type 1 trucks (13*1.7) are required to work with waste shovels, i.e. a total of (22+15) 37 type 1 trucks for case C1, which is almost same as determined separately for case C1 in Table 4-7.

Table 4-7Based on the theoretical estimates, multiple scenarios are run in the vicinity of the required number of trucks, the results of which are given in previous sections 4.4.1 and 4.4.2. The best case scenario at this stage must be selected judiciously. As it may seem that total ore and waste productions increases with increasing number of trucks, queue times also increases. This causes poor efficiencies of trucks as shown in Fig. 4.28 and Fig. 4.48 and increasing operating costs. The truck operating costs are shown in Fig. 4.54 and Fig. 4.55 and estimated based on Table 4-9. Thus it is necessary to analyze the scenarios together based on most important operating KPIs of the system, which must include Ore and Waste productions, shovel and truck operating efficiencies and truck operating costs.

Table 4-9. Truck operating cost parameters based on various sources

	Cat 785C (Truck type 1)	Cat 793C (Truck type 2)
Fuel consumption (liter per hour per truck)	95	160
Fuel cost ($/liter)	1	1
Tire life hours (hours/tire)	2530	2530
Number of tires	6	6
Tire costs ($)	20,000	38,000
Operator wages ($/hour)	30	30

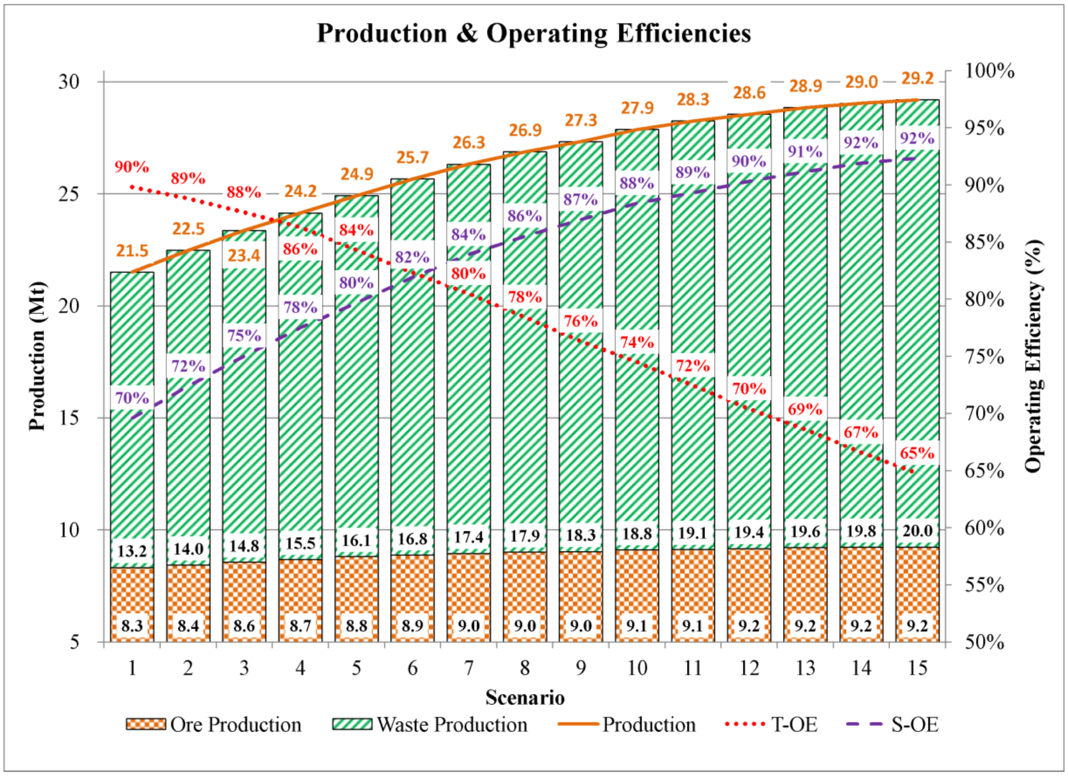

Fig. 4.52. Ore and waste productions, along with operating efficiencies of trucks and shovels in case C1

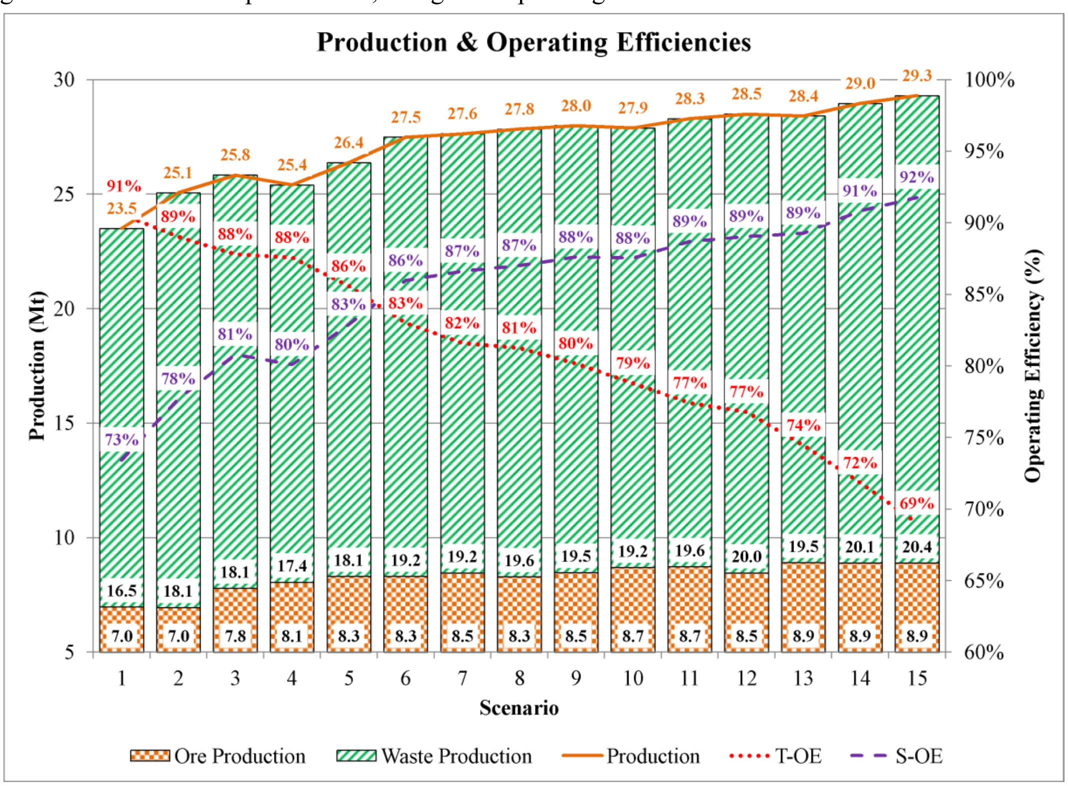

Fig. 4.53. Ore and waste productions, along with operating efficiencies of trucks and shovels in case C2

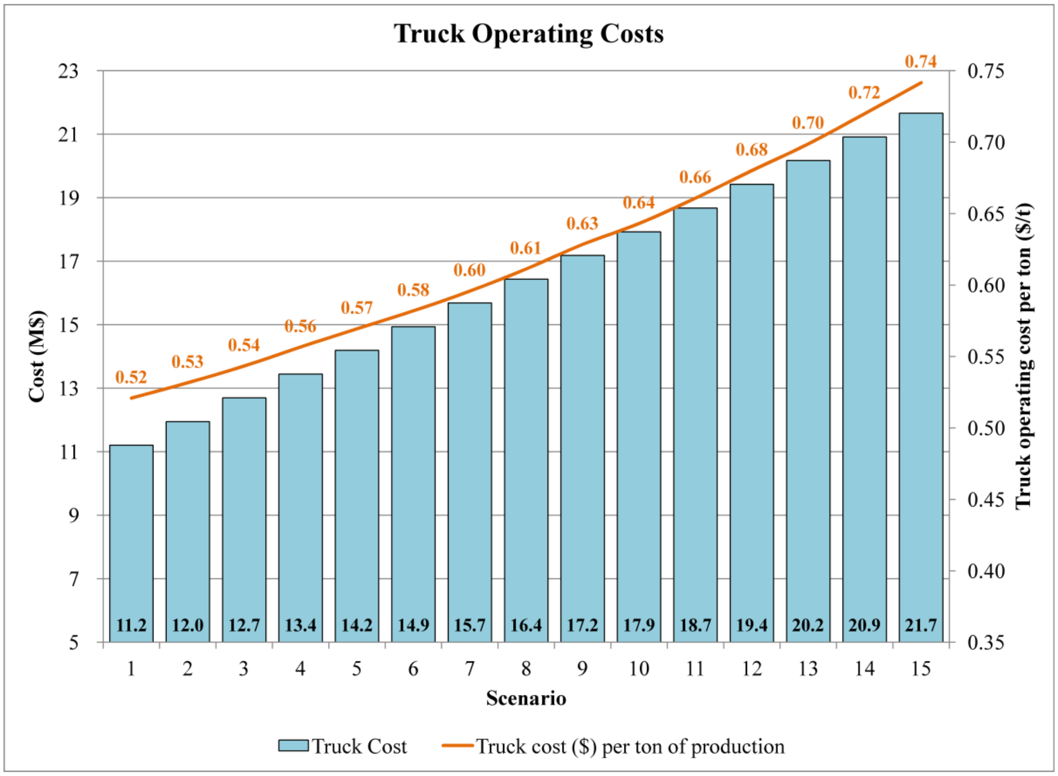

Fig. 4.54. Truck operating costs for the scenarios in case C1

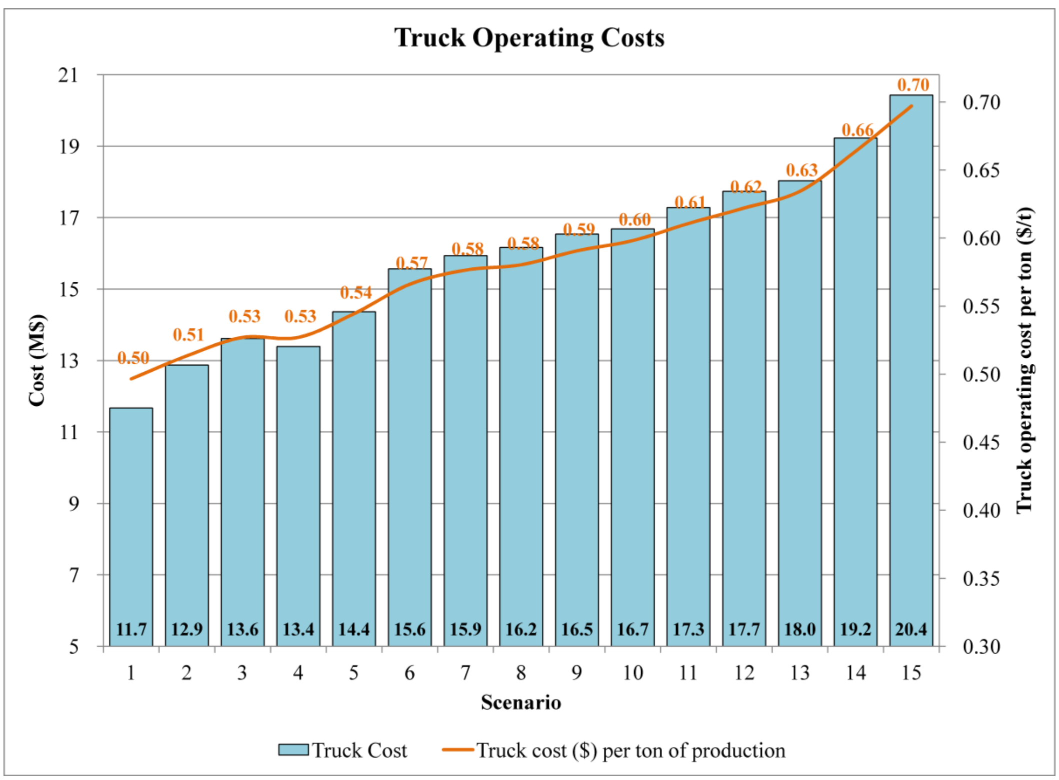

Fig. 4.55. Truck operating costs for the scenarios in case C2

In case C1 scenario 8 is selected as most efficient. Although it is not very much clear in Fig. 4.52, individual shovel operating efficiencies given in Fig. 4.30 shows poor performance of waste shovels up to scenario 8. After scenario 8, overall shovel operating efficiencies grows very marginally along with a rapid decrease in truck operating efficiencies as shown in Fig. 4.52. Also no improvement in ore production is observed in further scenarios with steep rise in operating costs. The improvement in total production is due to increasing waste productions. As case C1 provides flexibility to divert more trucks to ore shovels, MOOT always aims at improving ore productions, resulting in better performance of ore shovels. This results in increased queuing at plant (bottleneck of system, as will be explained later), which might be mitigated with locking of trucks to ore and waste shovels. Thus scenario 8, with 44 type 1 trucks, is selected as most efficient in C1 configuration of the mining system. Further scenarios might be run with locking of trucks to ore and waste shovels for an improved system configuration and better estimation of number of trucks, which is followed in case C2, where trucks are locked to ore and waste shovels.

For case C2, scenario 6 is considered as most efficient. Total production, along with ore and waste productions increases significantly up to scenario 6, and improves very marginally in further scenarios. Also shovel operating efficiencies show very marginal improvement in further scenarios along with poor truck operating efficiencies and increasing costs. Thus scenario 6 is selected as most efficient in C2 configuration of the mining system. Compared to the theoretical estimate of 15 type 1 and 13 type 2 trucks, the required number of trucks is determined as 16 type 1 and 16 type 2, a total of 4 extra trucks.

There is no quantitative measure of mining system performance in literature. The detailed analysis presented in this study shows various competing scenarios, one of which might be selected, but may not be the optimal one for the system. The best approach would be to include the operating cost of the system for a quantitative measure. A quantitative measure can also be created based on carefully calculated weights of various performance measures of the system.

Table 4-10: Comparison of selected scenarios for cases C1 and C2

Case	C1	C2
Scenario	Scenario 8	Scenario 6
Production (ton)	26,881,723	27,493,171
Ore Production (ton)	9,015,225	8,312,802
Waste Production (ton)	17,866,498	19,180,369
Truck Operating Efficiency	78.43%	82.99%
Shovel Operating Efficiency	85.52%	85.97%
Total Haulage Distance (Km)	1,217,163	900,689
Total truck operating cost ($)	16,434,272	15,564,717

A comparison of the selected scenarios for cases C1 and C2 is given in Table 4-10. It is clearly visible that C2 performs better than C1. Although performance of C1 can be improved by locking of trucks, which might improve truck operating efficiencies and in turn improve the production; the operating cost of trucks is the major factor which would guide the selection. Due to all smaller size and thus large number of trucks in C1, the total truck operating costs are much higher compared to C2. Thus mixed fleet system in C2 is selected as the best configuration with scenario 6 as the base case scenario for further analysis.

The base case scenario can be further analyzed to develop best short term plan which meets operating objectives. Two main scenarios have been implemented in further sections to analyze the system performance 1) if only one haul road (instead of two routes available for bottom benches) is maintained and used for operation to save haul road maintenance costs; and 2) if grade blending strategy is changed, i.e. prioritizing the grade blend requirements of plants.

4.5. Establishing haul road design

The approach presented in this study allows the planner to analyze different haul road designs, for better performance of trucks. Although the case study considered in this thesis do not provide enough scope related to haul road designs, the impact of available roads is analyzed here.

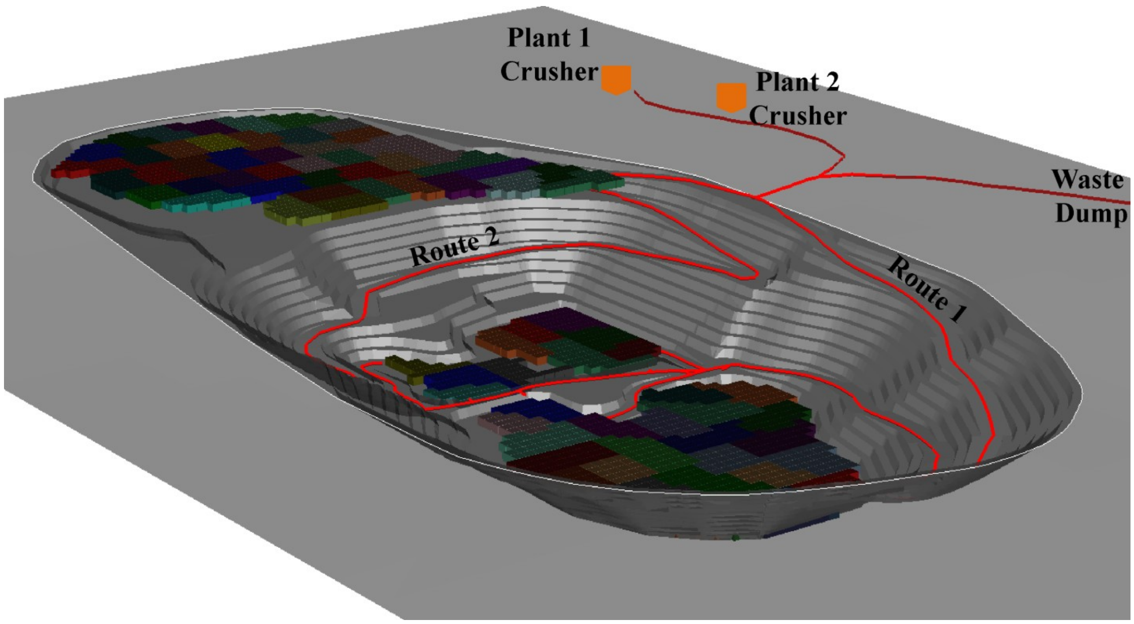

Fig. 4.56. Pit showing two different routes to haul material from bottom benches

As haul road maintenance also adds to the operating cost in mines, base case scenario is analyzed for the impact of using one route instead of two available routes as shown in Fig. 4.56. Two scenarios are analyzed here: R1 with only route 1 and R2 with only route 2, and compared with the base case scenario.

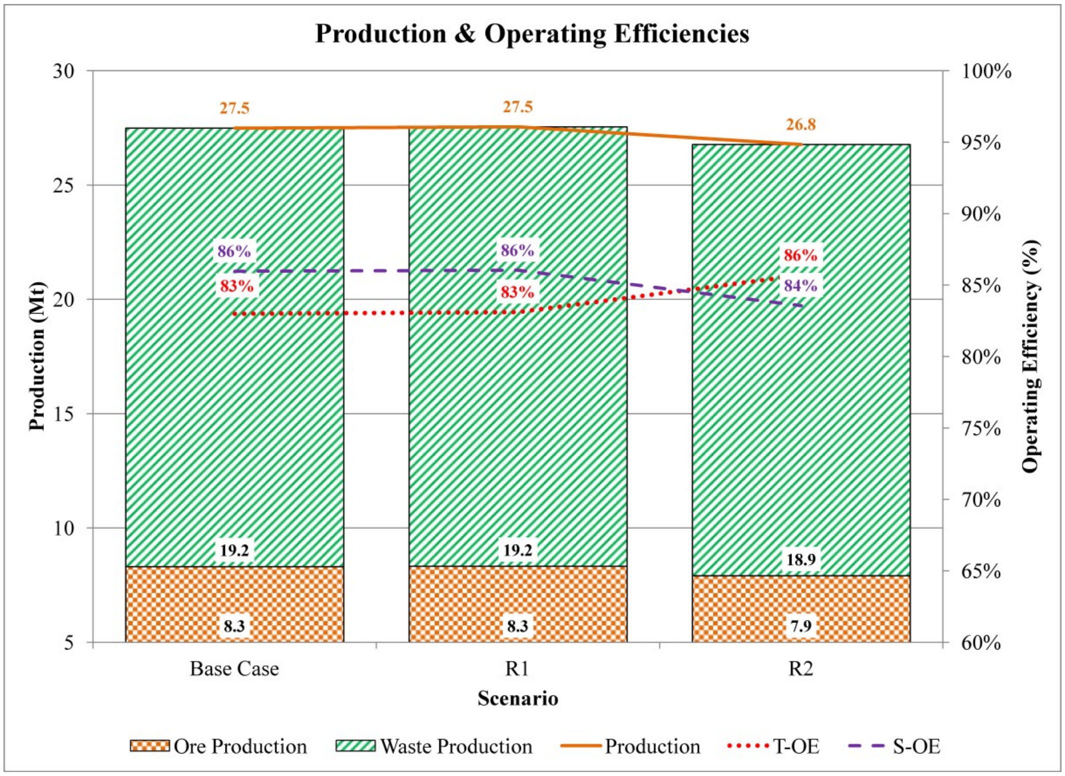

Fig. 4.57. Production and operating efficiencies of trucks and shovels for base case and scenarios R1 and R2

Fig. 4.57 shows that scenario R1 performed almost same as base case, but R2 performs poorer comparatively. Average TPH delivered to plants is also almost same for scenario R1, but lesser for scenario R2. The main reason for the difference observed is because of higher haul distances in R2 compared to R1. For the base case as well, the most used haulage path is route 1, making R1 results similar to base case. Average full distance of trucks in base case is 3238m which is same as that observed in R1 which is 3239m, but higher in R2 which is 3570m. This leads to more time devoted to travel in R2, increasing truck operating efficiencies as shown in Fig. 4.57 and shovel hang times as shown in Fig. 4.60.

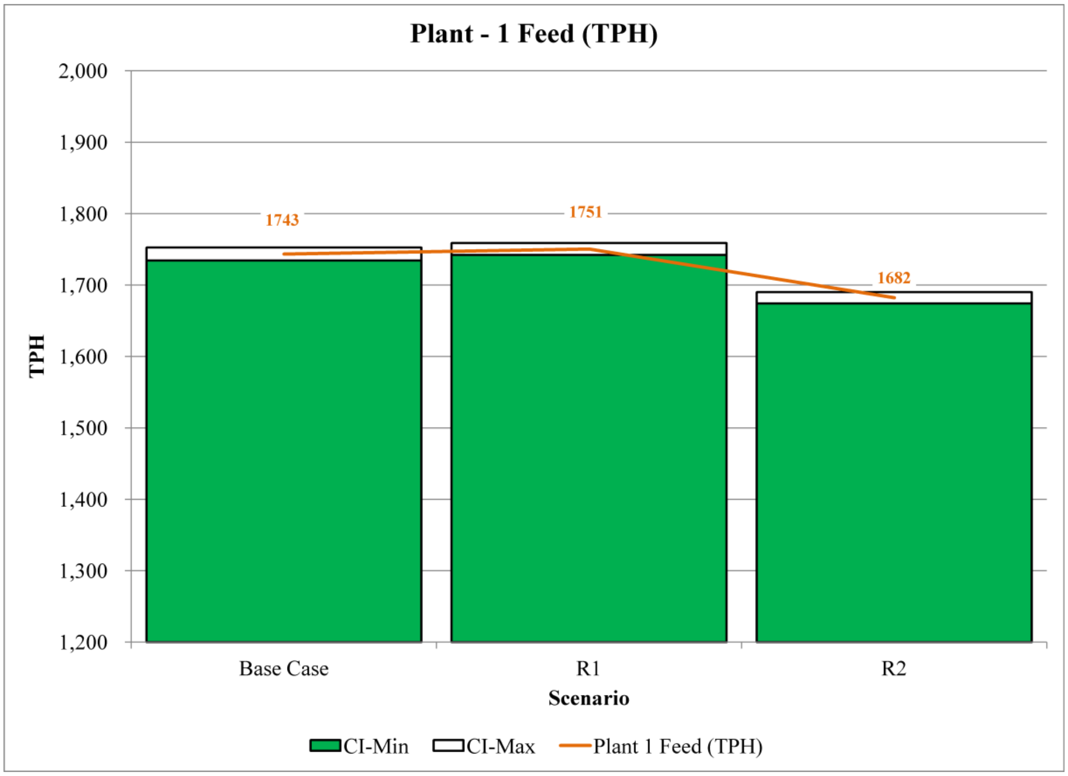

Fig. 4.58. Comparison of average TPH delivered to Plant 1 between base case and scenarios R1 and R2

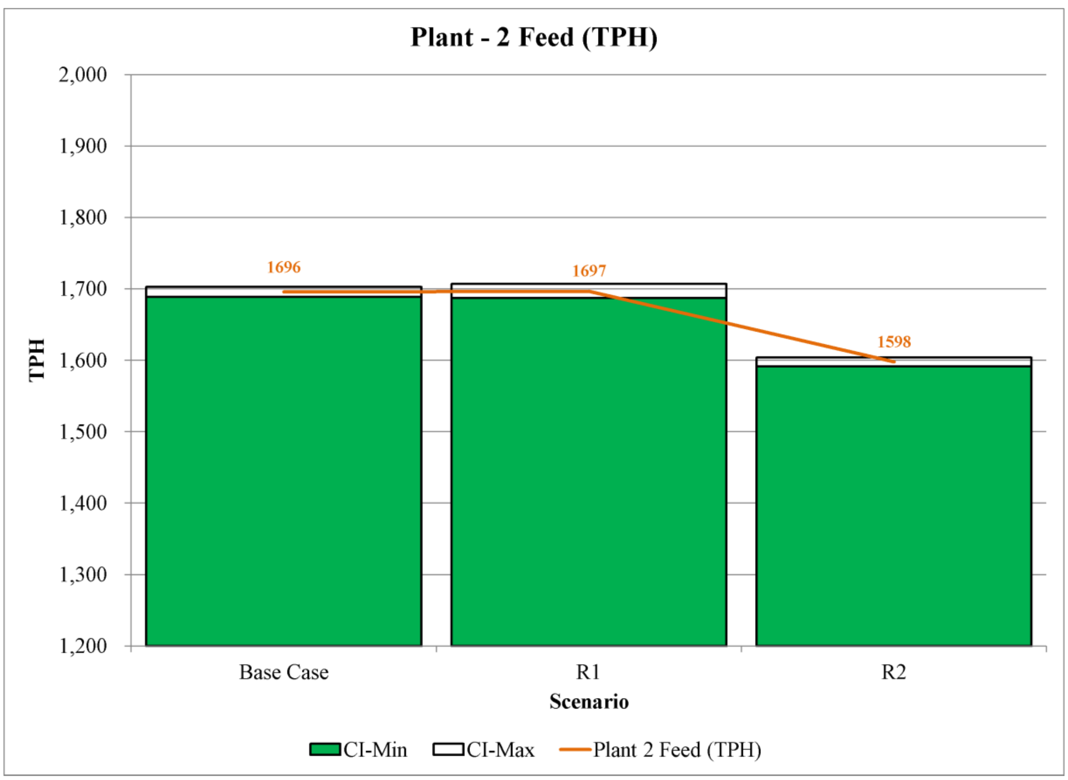

Fig. 4.59. Comparisons of average TPH delivered to Plant 2 between base case and scenarios R1 and R2

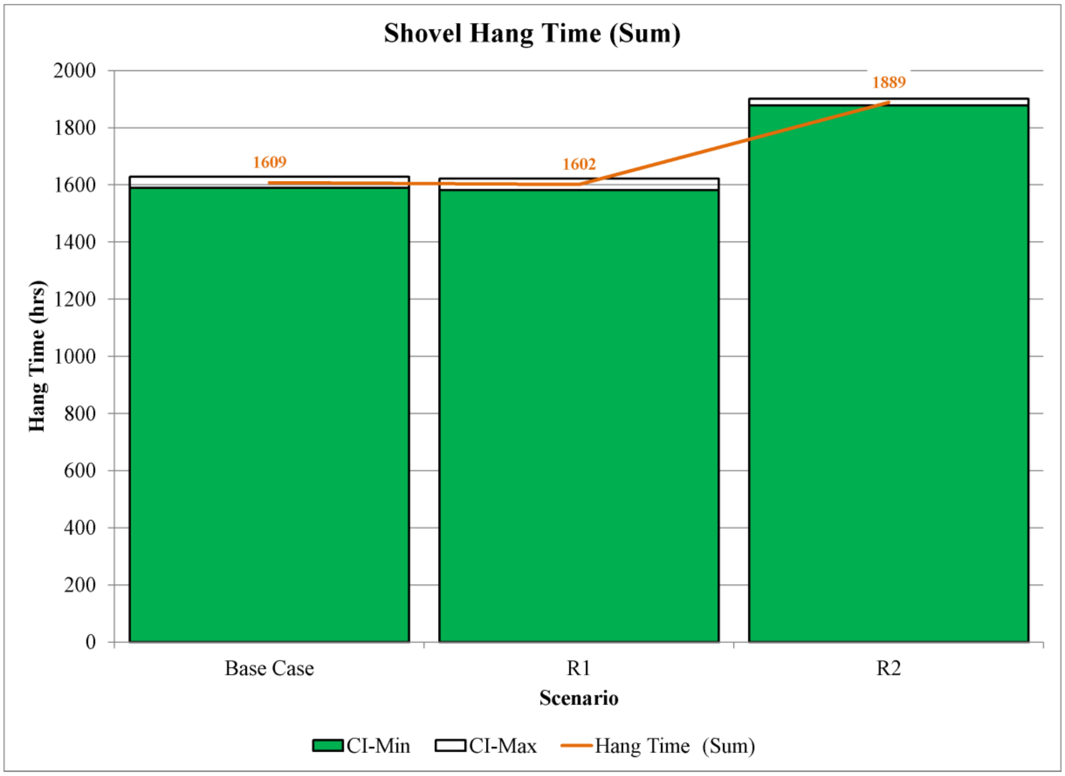

Fig. 4.60. Comparisons of total shovel hang times between base case and scenarios R1 and R2

This scenario analysis signifies that if only route 1 is used, there will be no or very little impact on the overall production and operating efficiencies of trucks and shovels. But this might provide significant savings in operating cost, as maintenance of route 2 would not be required.

4.6. Grade blending strategy

The base case scenario is also analyzed to adopt the best grade blending strategy. As the case study contains two processing plants requiring grades at their desired targets, sometimes it might not be possible to satisfy both plant requirements simultaneously based on available grades in the strategic schedule. In such cases best strategy can be analyzed for grade blending, prioritizing specific plant depending on the requirement.

The base case provides grade blending prioritizing both plants equally. Two other scenarios G1 and G2 are analyzed by prioritizing grade blend at plant 1 and plant 2 respectively, which are presented in this section.

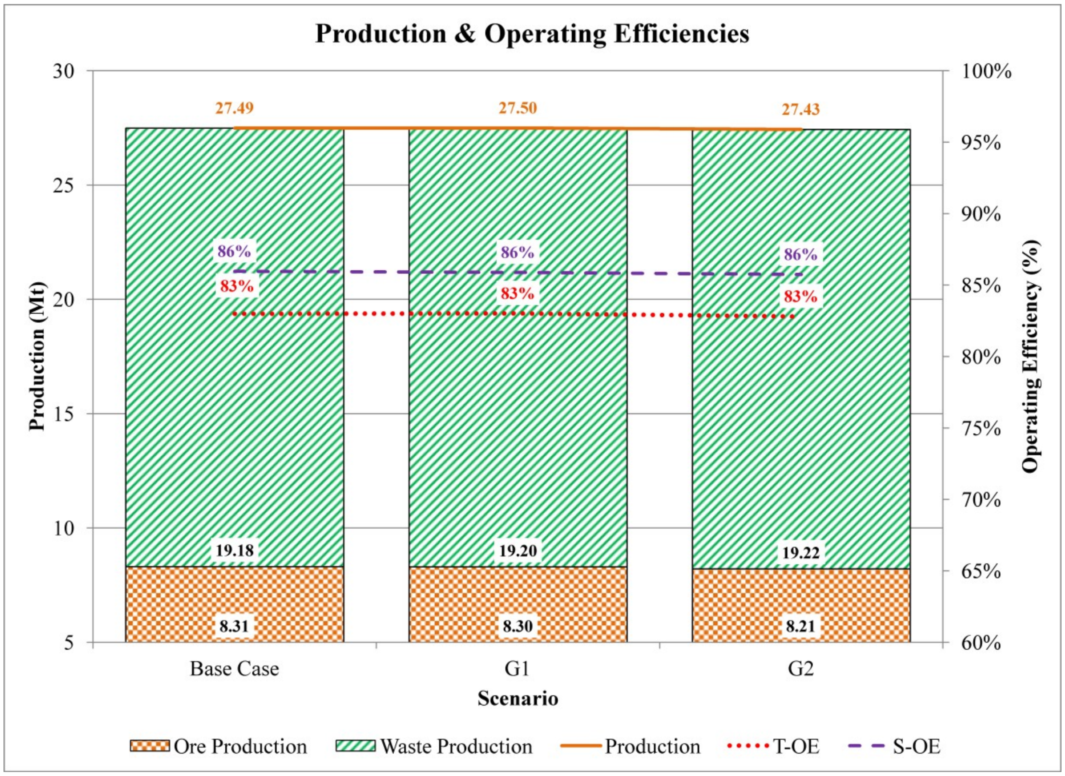

Fig. 4.61. Production and operating efficiencies of trucks and shovels for base case and scenarios G1 and G2

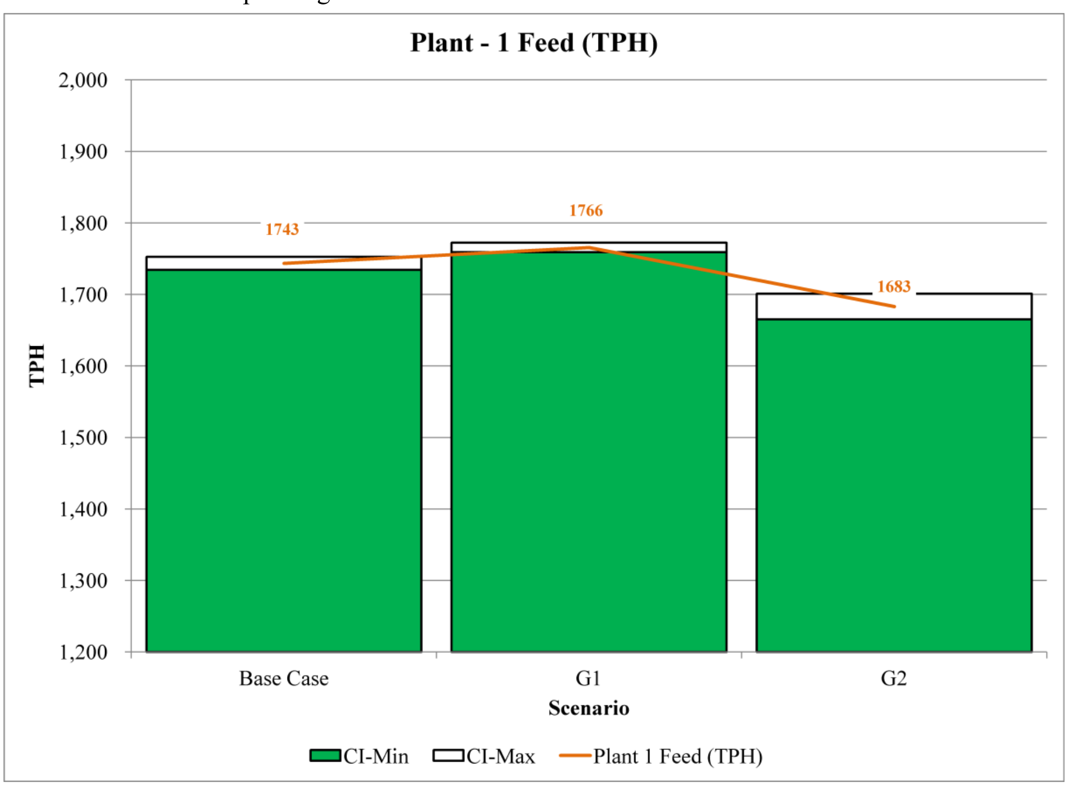

Fig. 4.62. Comparison of average TPH delivered to Plant 1 between base case and scenarios G1 and G2

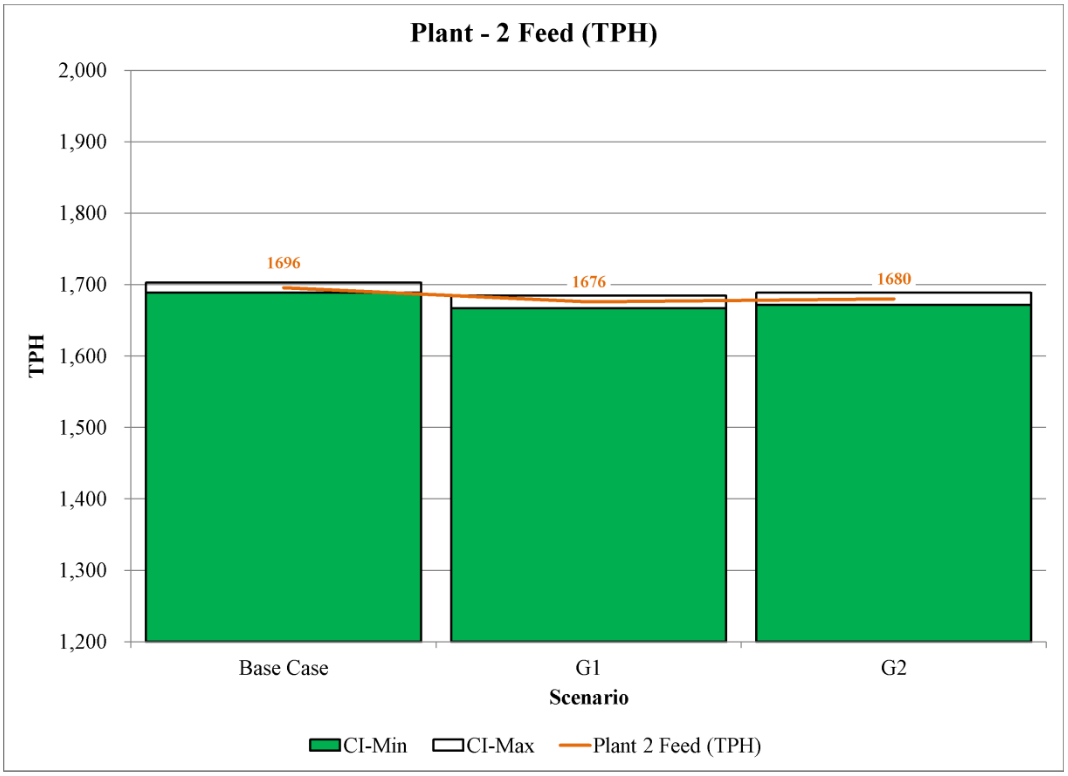

Fig. 4.63. Comparison of average TPH delivered to Plant 2 between base case and scenarios G1 and G2

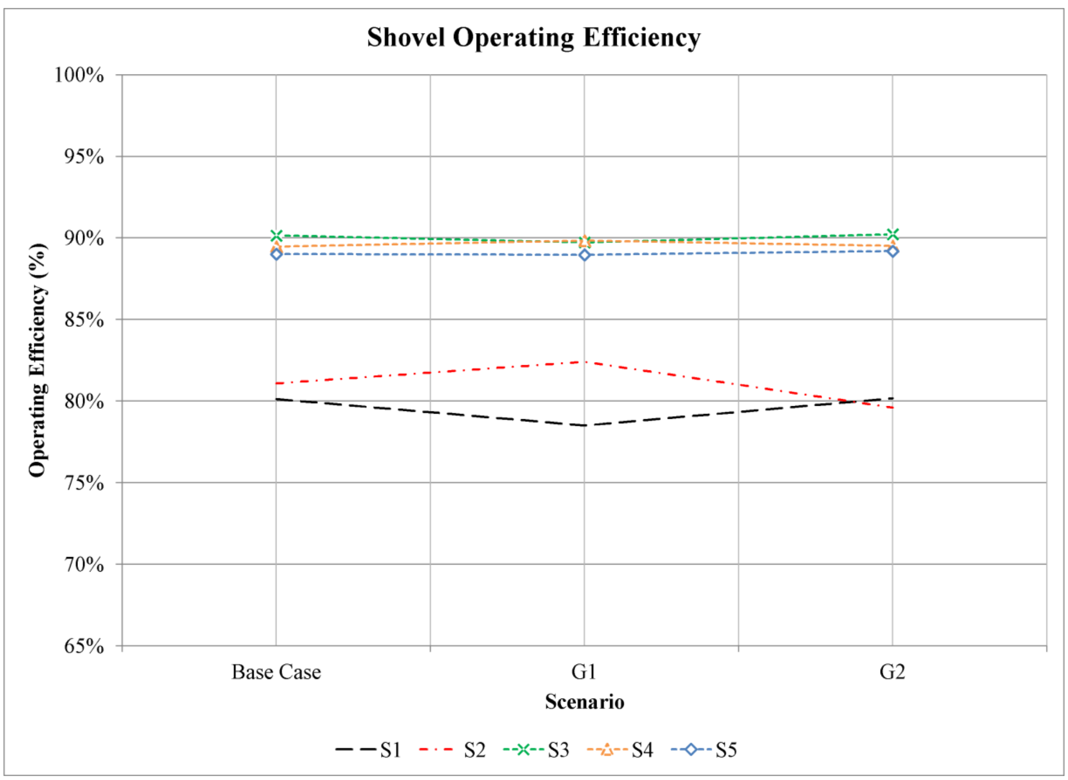

Fig. 4.64. Comparison of operating efficiencies of shovels between base case and scenarios G1 and G2

The grade blending is achieved in real-time through truck dispatching. Although shovel allocations provided by MOOT also account for grade blending requirements, it might not be possible to achieve the specific grade blend at times when available faces for shovel allocations do not have suitable grades. Such situations affect the tonnage delivered to plants as well, which is shown in Fig. 4.62 and Fig. 4.63. Although the three scenarios provide almost same production and operating efficiencies of trucks and shovels (Fig. 4.61), the individual ore shovel operating efficiencies are found varying in Fig. 4.64. This happens based on the area of working and the available grades for ore shovels.

The main difference between the three scenarios is the average grade delivered to plants. Thus weekly grades delivered to plants are analyzed to select the best blending strategy.

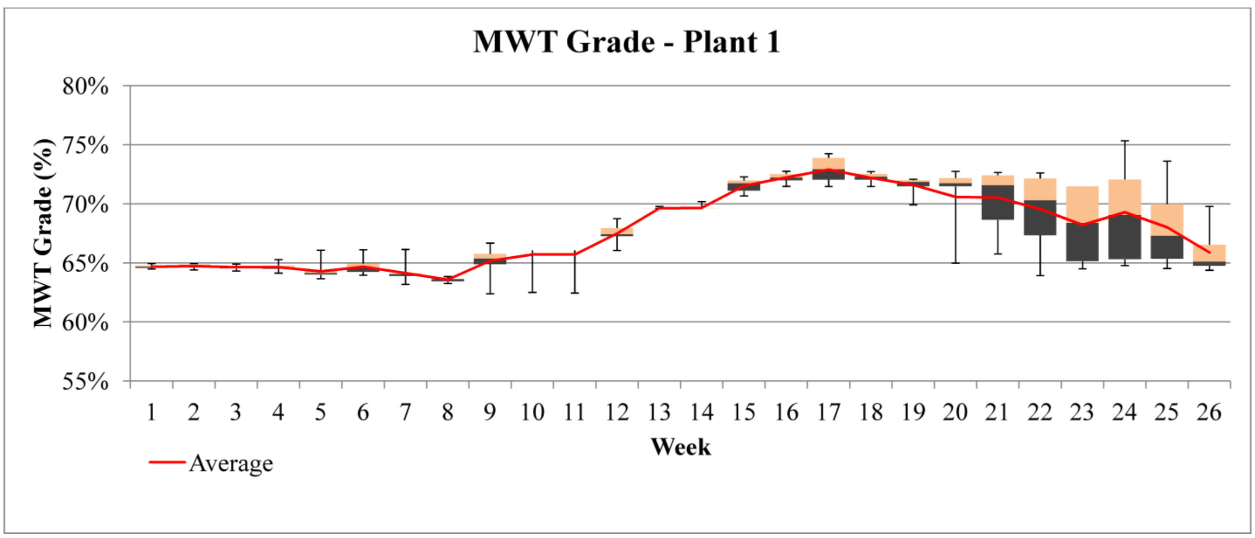

Fig. 4.65. Box plot of weekly average grades delivered to plant 1 in Base case scenario

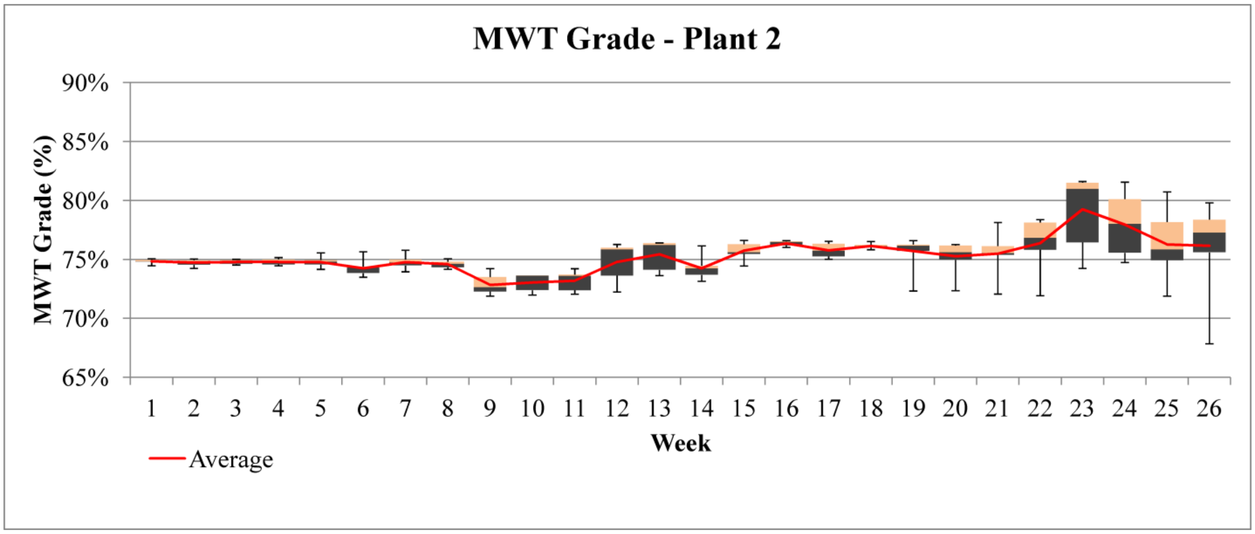

Fig. 4.66. Box plot of weekly average grades delivered to plant 2 in Base case scenario

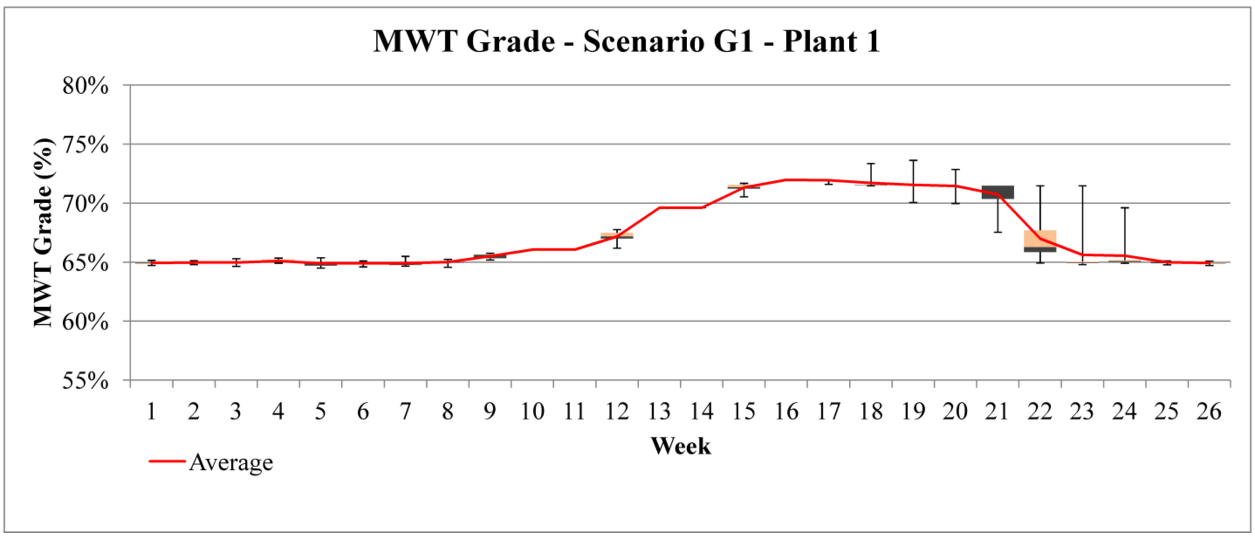

Fig. 4.67. Box plot of weekly average MWT grades delivered to plant 1 in scenario G1

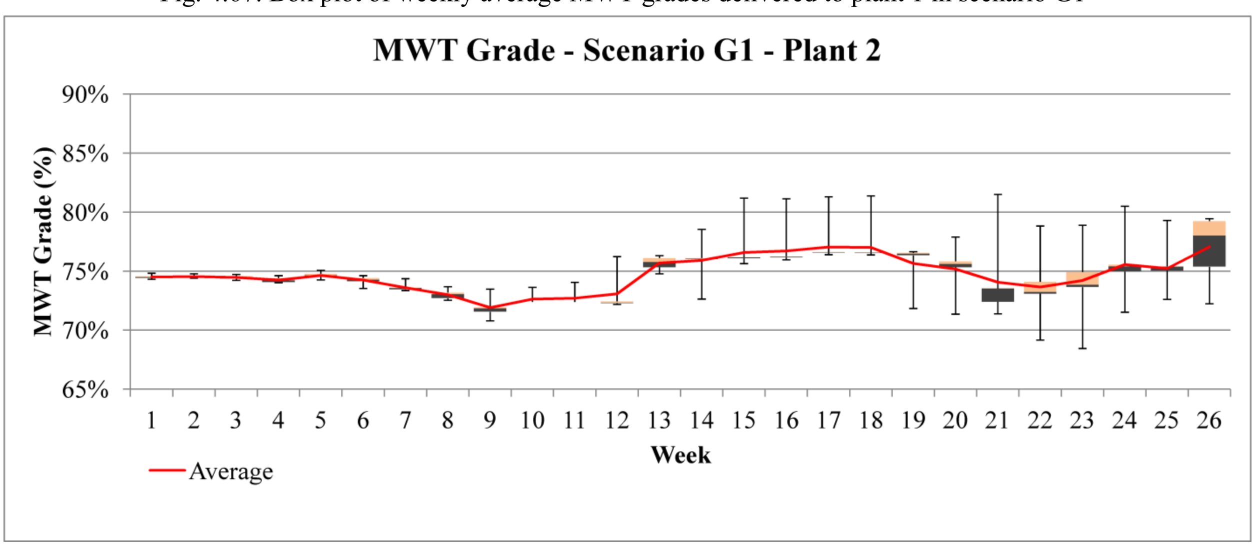

Fig. 4.68. Box plot of weekly average grades delivered to plant 2 in scenario G1

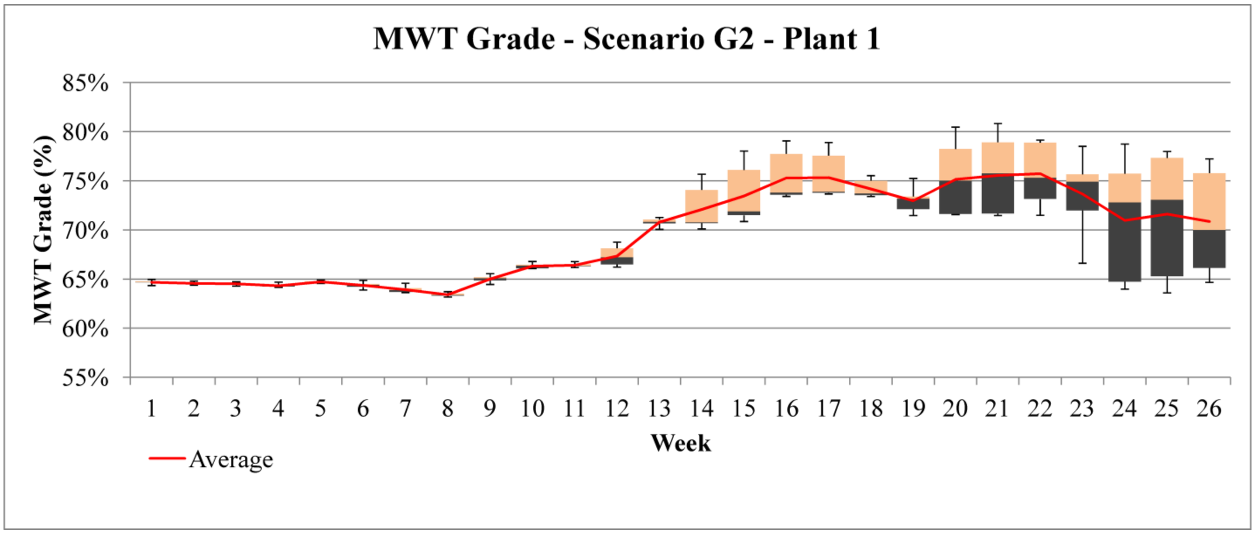

Fig. 4.69. Box plot of weekly average grades delivered to plant 1 in scenario G2

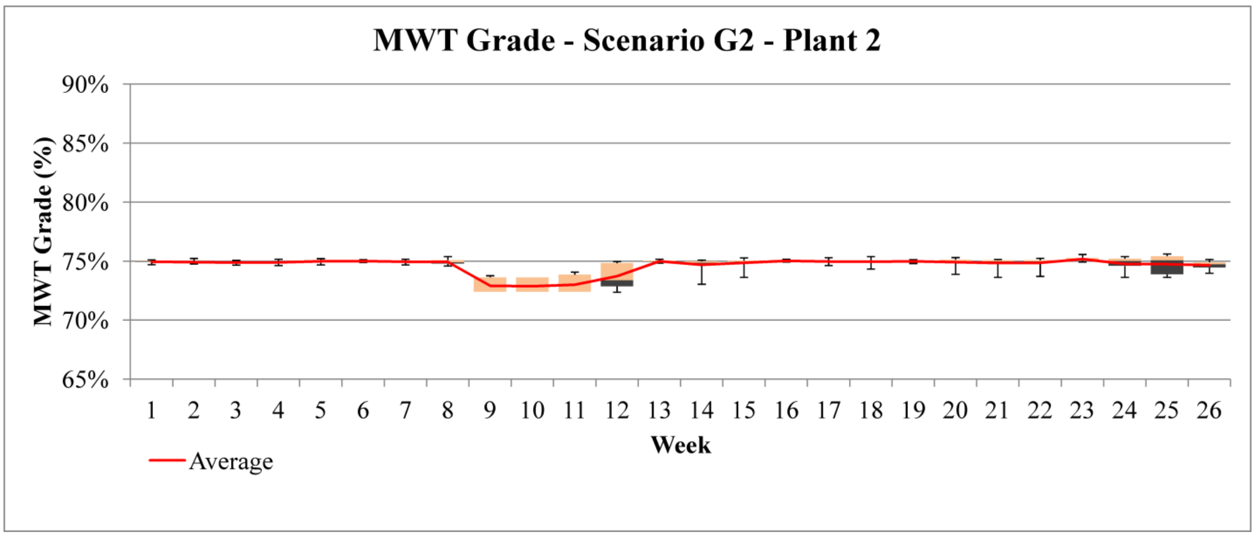

Fig. 4.70. Box plot of weekly average grades delivered to plant 2 in scenario G2

Fig. 4.65 to Fig. 4.70 shows the weekly average grades delivered to both plants in base case, and scenarios G1 and G2. The effect of prioritizing the plants is clearly visible in grade blends achieved at plants. Higher priority to plant 2 in G2 shows a very high compliance with the grade requirement at plant 2. Higher priority to plant 1 in G1 is unable to provide the grade blend exactly as required, but performs better compared to base case and G2. On an aggregated basis, base case seems to be performing better in meeting grade blend requirement of both the plants compared to scenarios G1 and G2. Although plant 2 blend can be better in scenario G2, performance of both plants are reasonable enough to select base case scenario for implementation.

4.7. Short term plan

After a detailed analysis, and selection of best haul road configuration and grade blending strategy, an optimized short term plan is generated that meets the operational requirements. The assigned faces to shovels and production output from simulation, based on days or weeks, is extracted to serve as the short term plan. As simulation provides multiple replications, best replication can be selected as the short term plan, keeping in mind the confidence interval provided by simulation. Probability based plans can also be generated based on shovel and period of working at faces over multiple replications.

As base case scenario is the best scenario selected through detailed analysis, short term plan is derived out of its simulation result. Observed distributions, weekly planned production and KPIs of operation are presented in this section with box plots showing the expected variability. The distribution of various process times are analyzed as histogram plots given by Fig. 4.71 to Fig. 4.80. Long tales observed in some of the distributions is due to the certain specific situations, such as long tale in queue times occurs when one or more other shovels are not working due to failure or standby. Similarly higher rate of arrival of trucks at plant crushers sometimes leads to higher queue times. One bottleneck is observed from dump time distribution in Fig. 4.75 which shows a bimodal distribution. This happens due to small hopper capacity of the plant crushers. The crusher feed rate is much smaller than dump times of the trucks, which sometimes leads to extra waiting time of trucks for space to be created in hoppers for dumping. In such situations the total dumping time tends to crusher feed rate. The lower tale observed in plant TPH in Fig. 4.73 and Fig. 4.74 is accounted to the shovel failures which affect the plant feed.

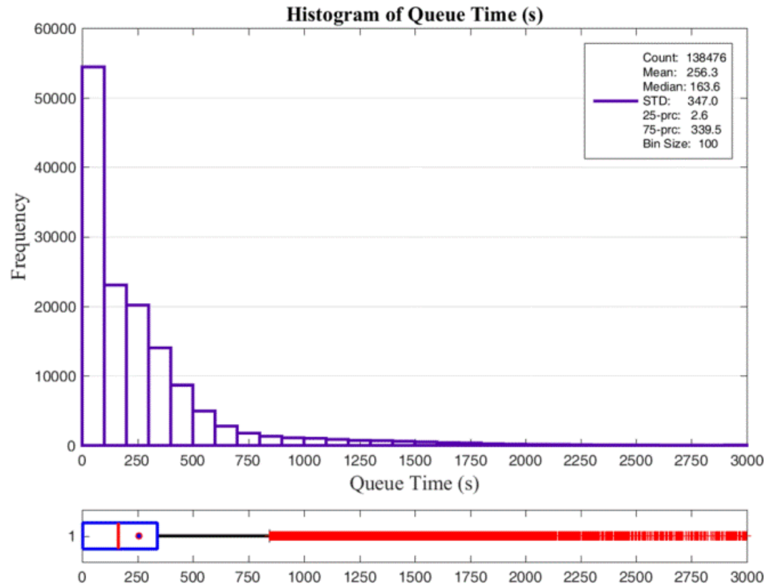

Fig. 4.71. Histogram of Queue times at shovel

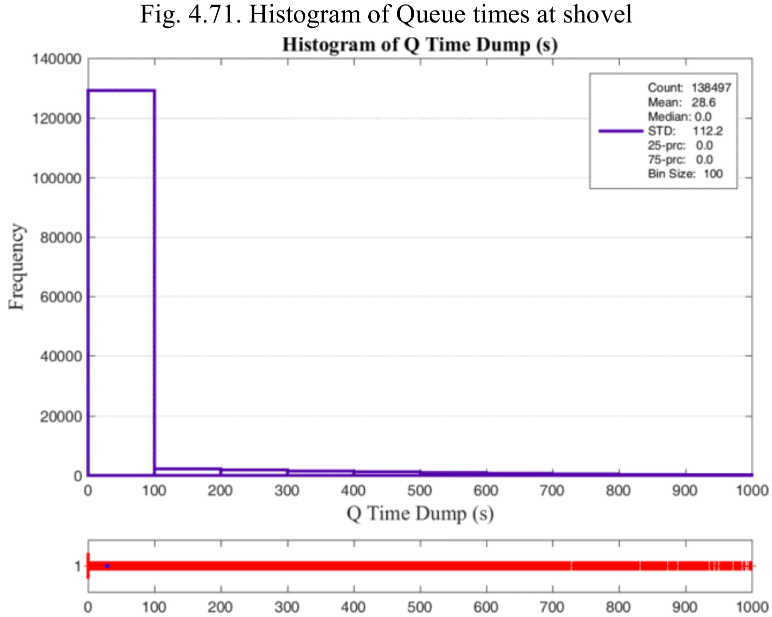

Fig. 4.72. Histogram of Queue times at dump

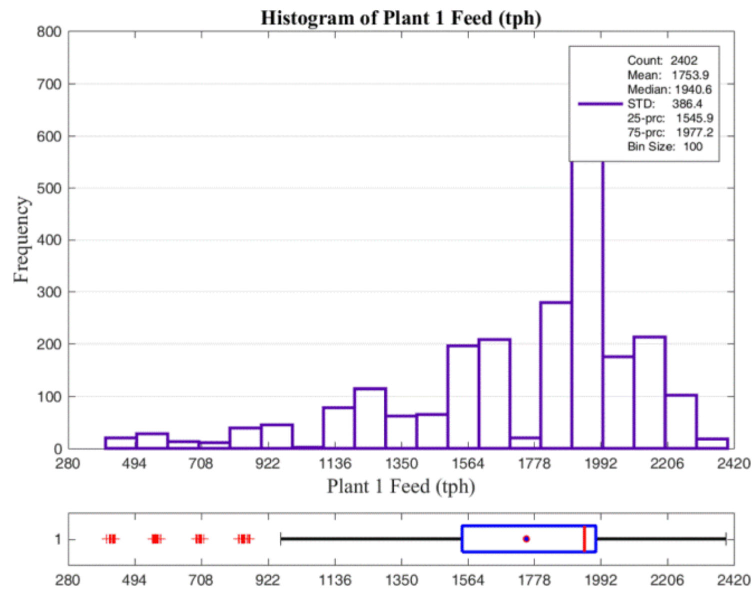

Fig. 4.73. Histogram of TPH delivered to plant 1

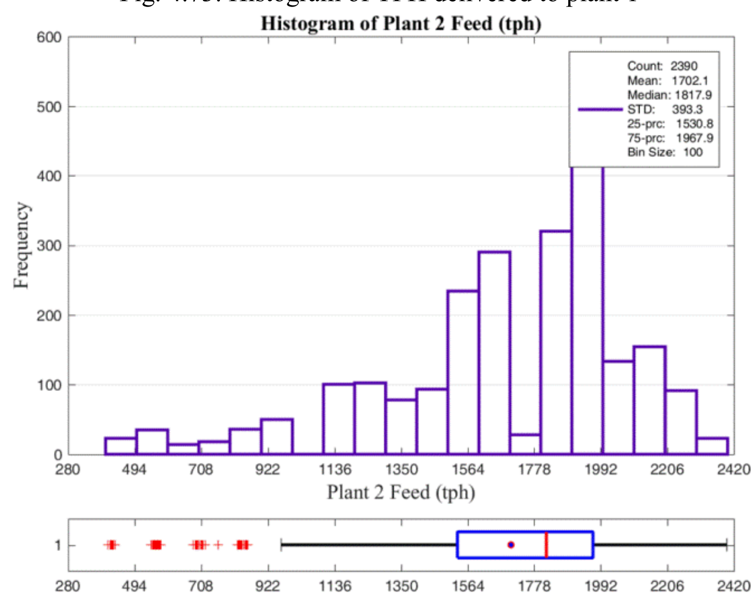

Fig. 4.74. Histogram of TPH delivered to plant 2

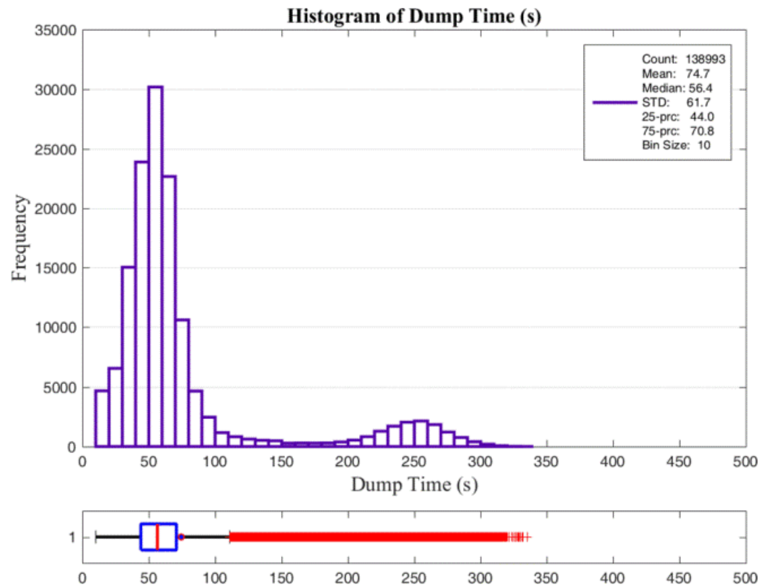

Fig. 4.75. Histogram of dump times

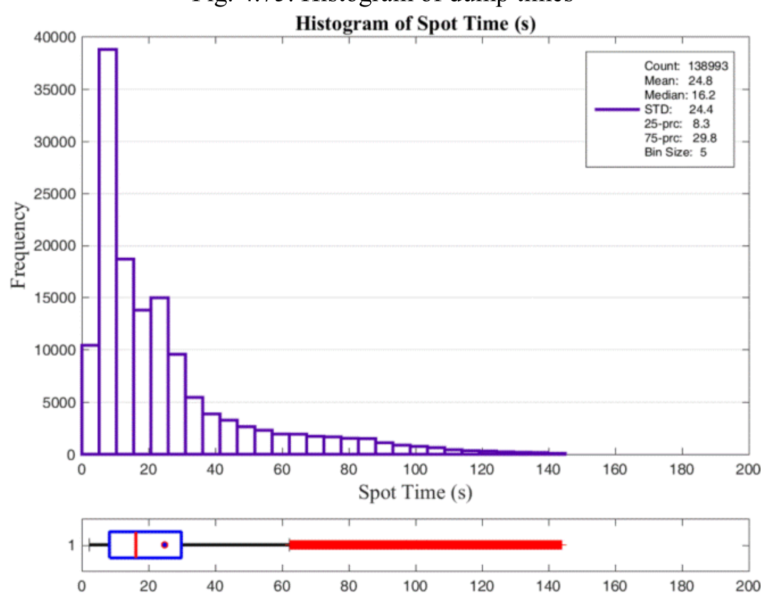

Fig. 4.76. Histogram of spot times at shovels

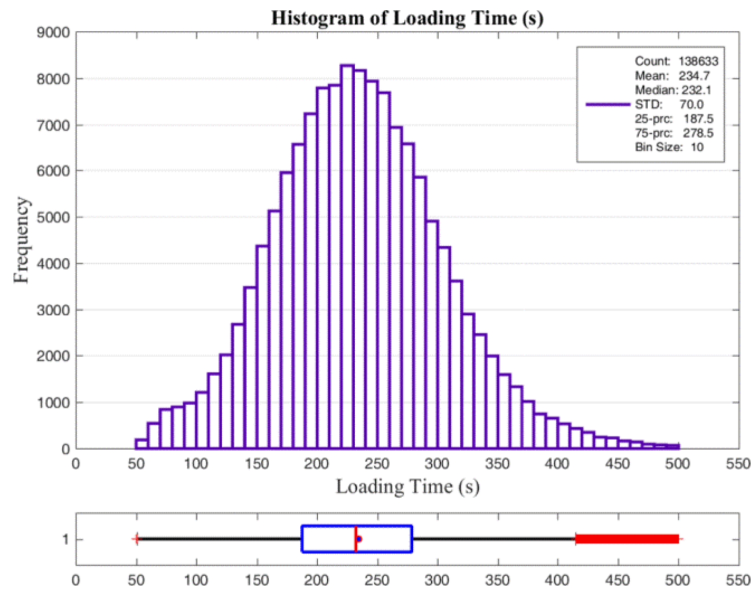

Fig. 4.77. Histogram of loading times

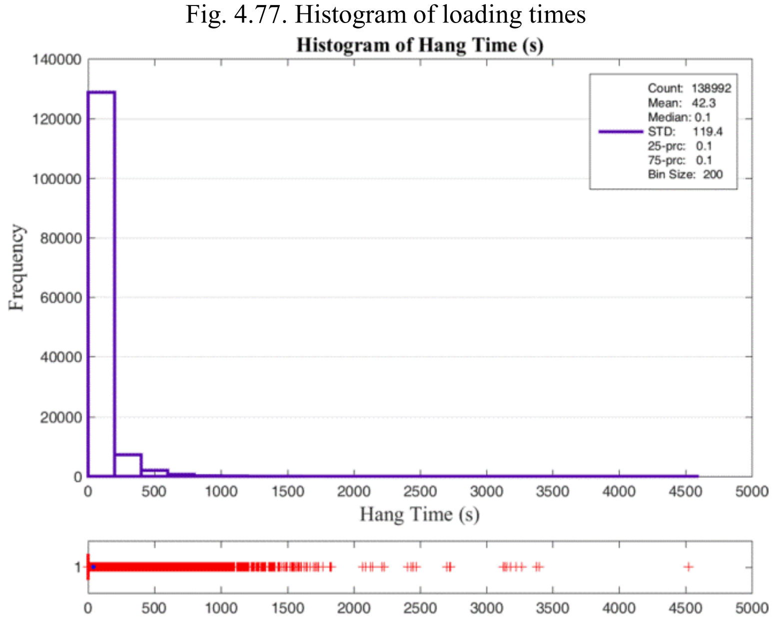

Fig. 4.78. Histogram of hang times of shovels

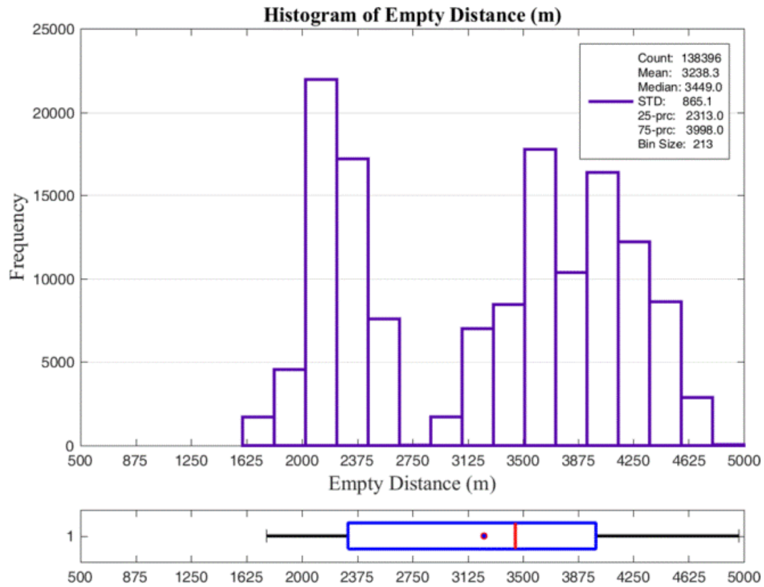

Fig. 4.79. Histogram of empty haul distance by trucks

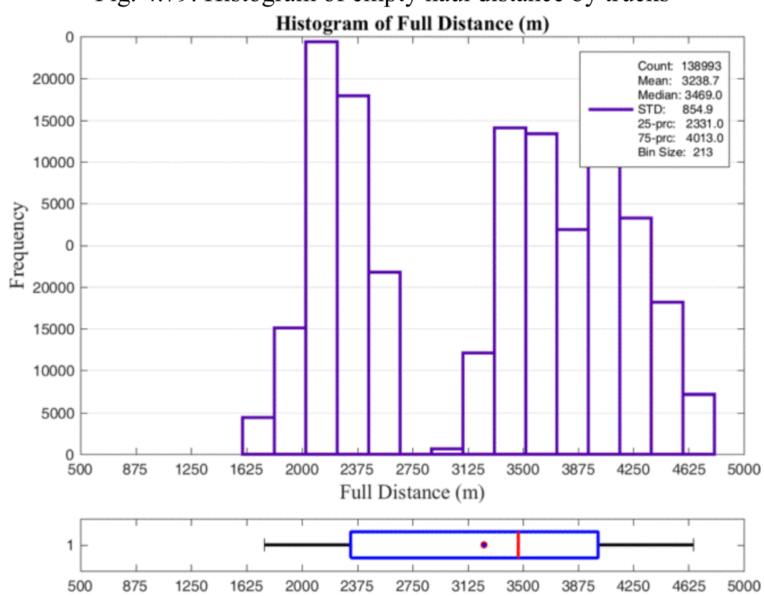

Fig. 4.80. Histogram of full haul distance by trucks

The box plots of weekly productions with average over 10 replications are given in Fig. 4.81, which shows approximately 1.06Mt of production per week. Similarly weekly box plots of waste (Fig. 4.82) and ore productions (Fig. 4.83), and other expected operational performances are given in Fig. 4.84 to Fig. 4.93. The weekly average grades (Fig. 4.84 and Fig. 4.85) and TPH (Fig. 4.86 and Fig. 4.87) delivered to plants are realistic and within desired range for the current system configuration. The empty and full haul distances (Fig. 4.88 and Fig. 4.89) show an increase towards the middle and end of the planning time horizon based on the location of the working faces and the haul road network. One important observation can be made in the box plots for queue times at dumps and at shovels (Fig. 4.90 and Fig. 4.91) which is also reflected from the increasing trend in truck operating efficiencies (Fig. 4.93) is that, number of trucks are slightly more than desired in the initial few weeks due to the shorter haul distances. Further scenarios can be analyzed by removing few trucks and adding them back in the system after few weeks of the operation. Shovel operating efficiencies were observed to be fairly high throughout the planning time horizon.

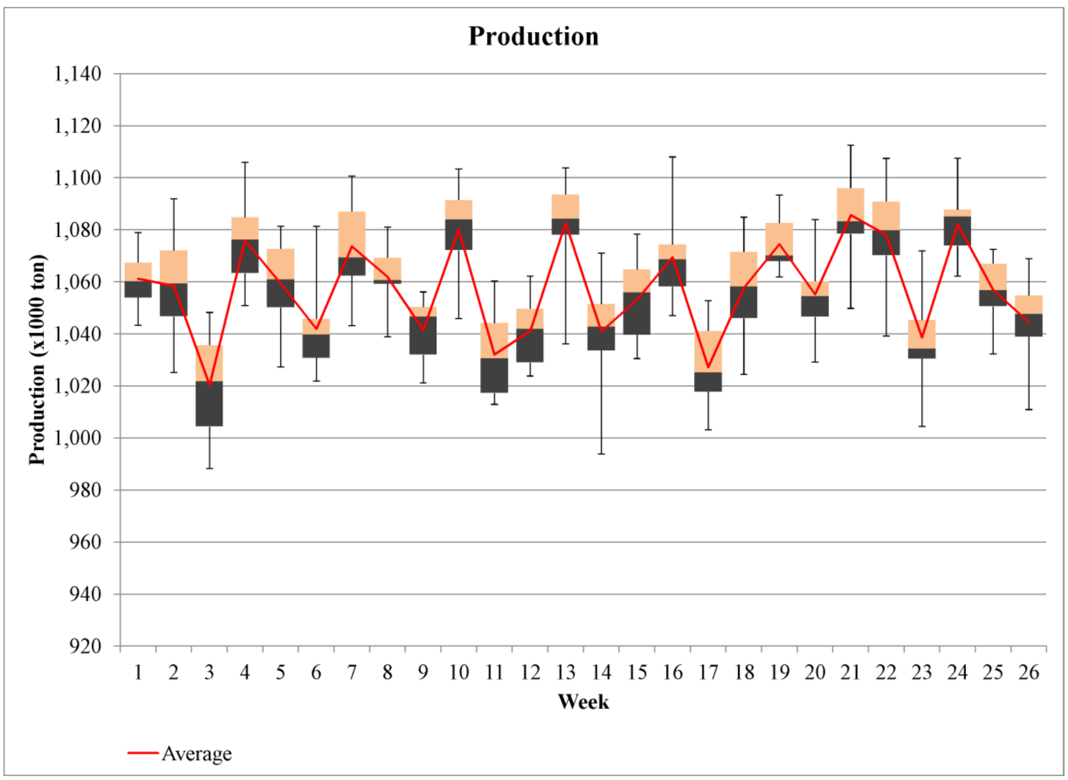

Fig. 4.81 Box plots for weekly production

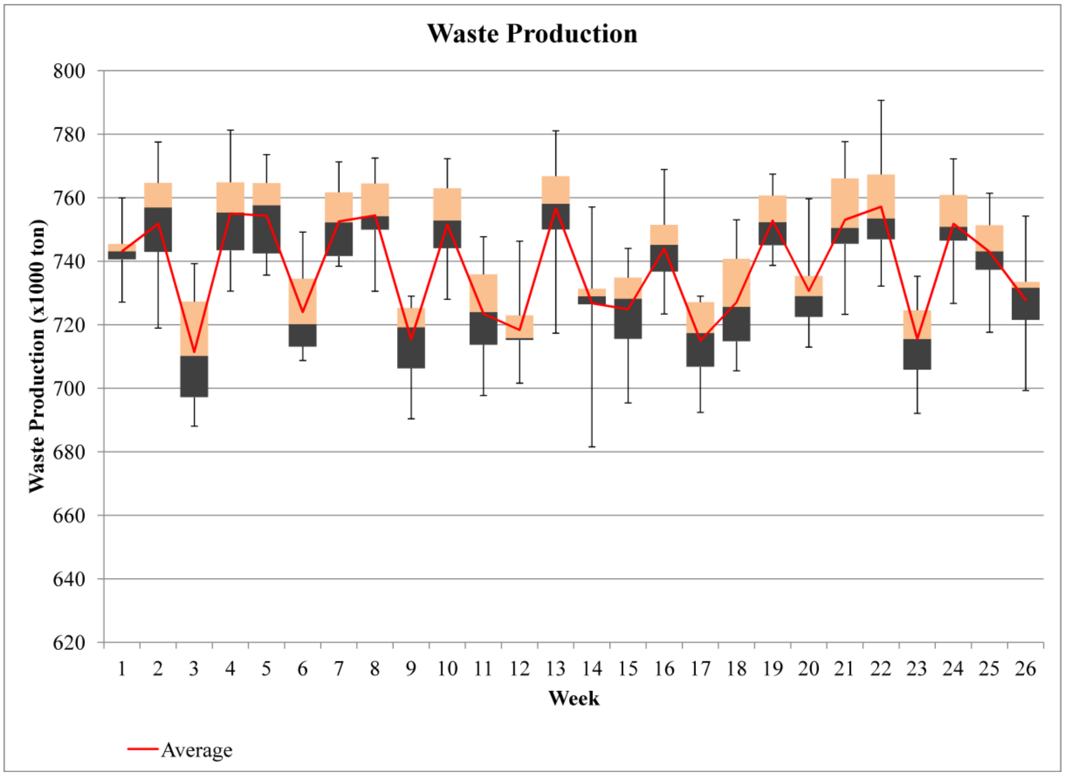

Fig. 4.82 Box plots for weekly waste production

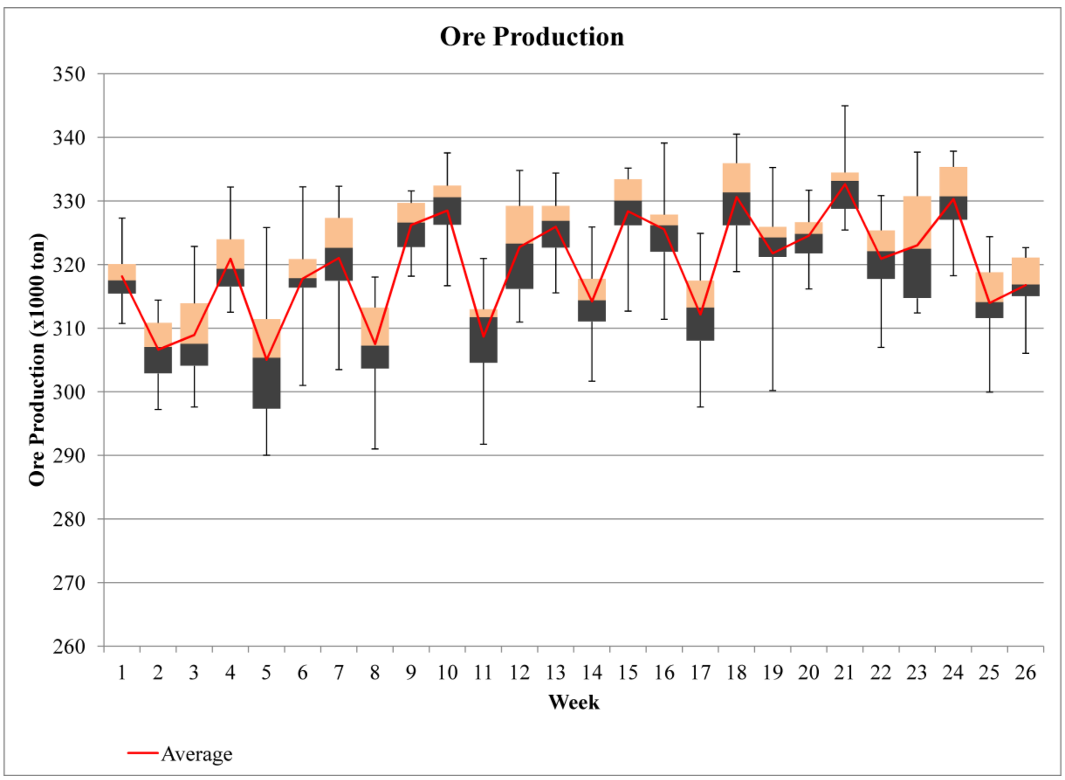

Fig. 4.83 Box plots for weekly ore production

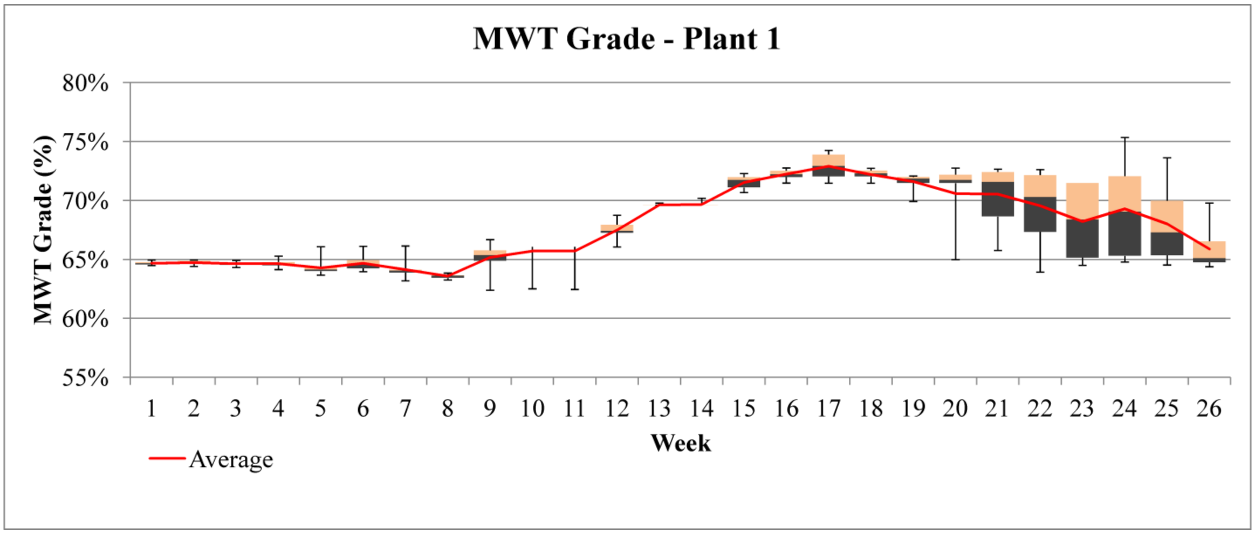

Fig. 4.84 Box plots for weekly average MWT Grades delivered to plant 1

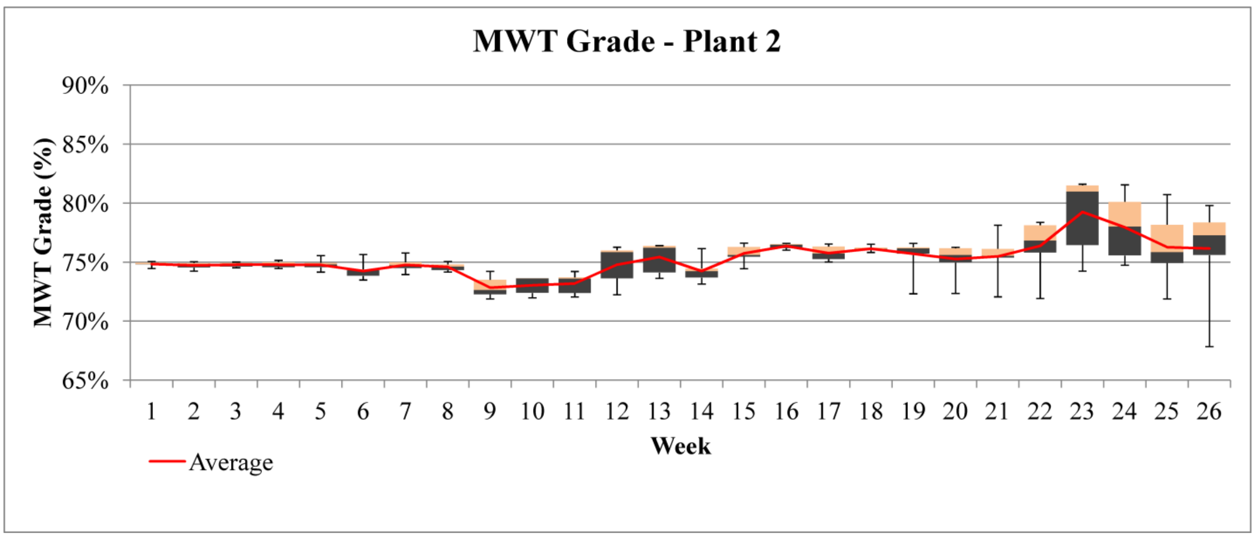

Fig. 4.85 Box plots for weekly average MWT grades delivered to plant 2

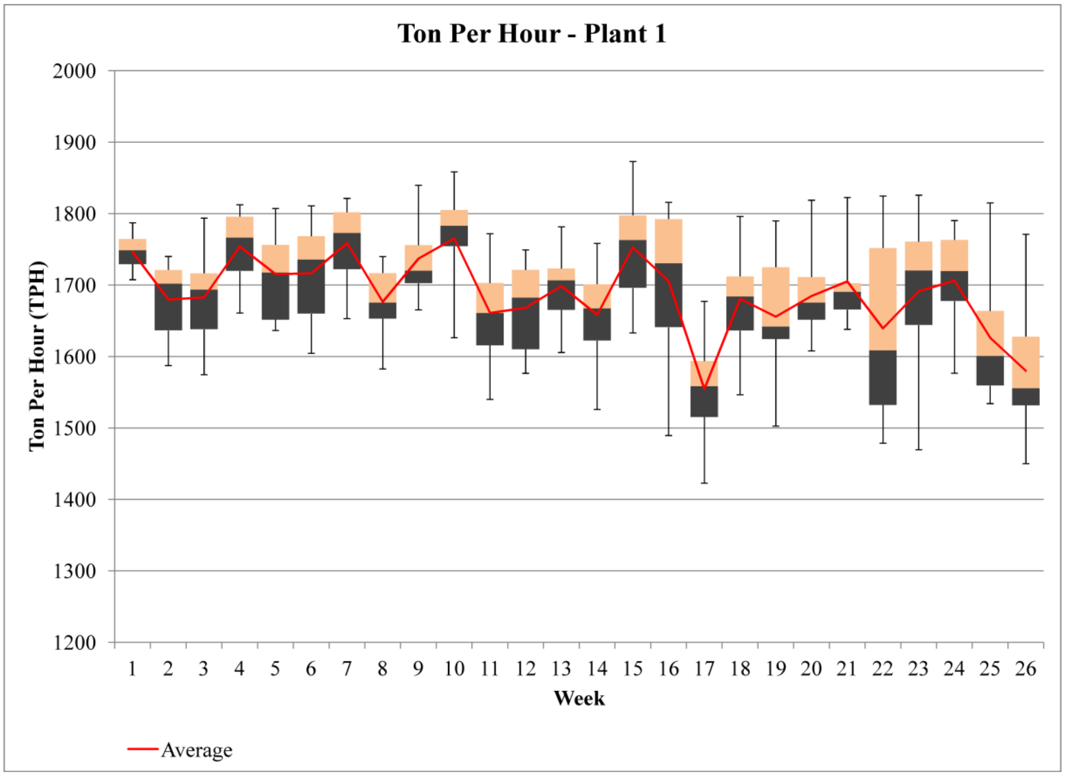

Fig. 4.86 Box plots for weekly average ton per hour delivered to plant 1

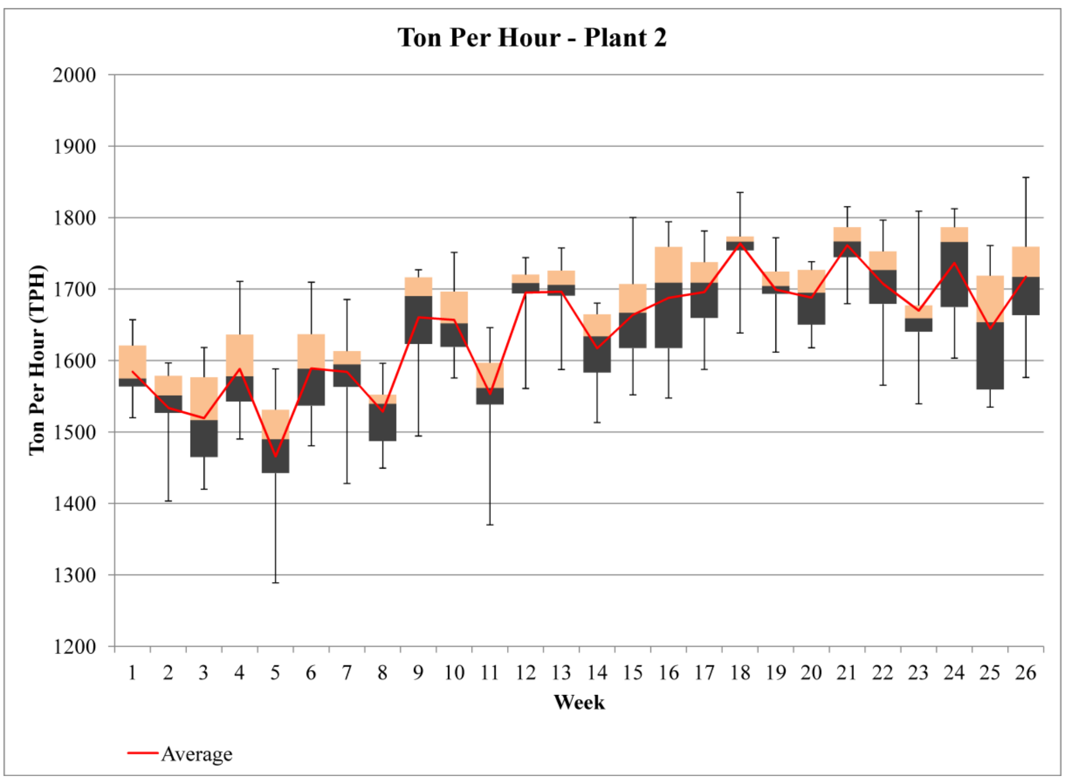

Fig. 4.87. Box plots for weekly average ton per hour delivered to plant 2

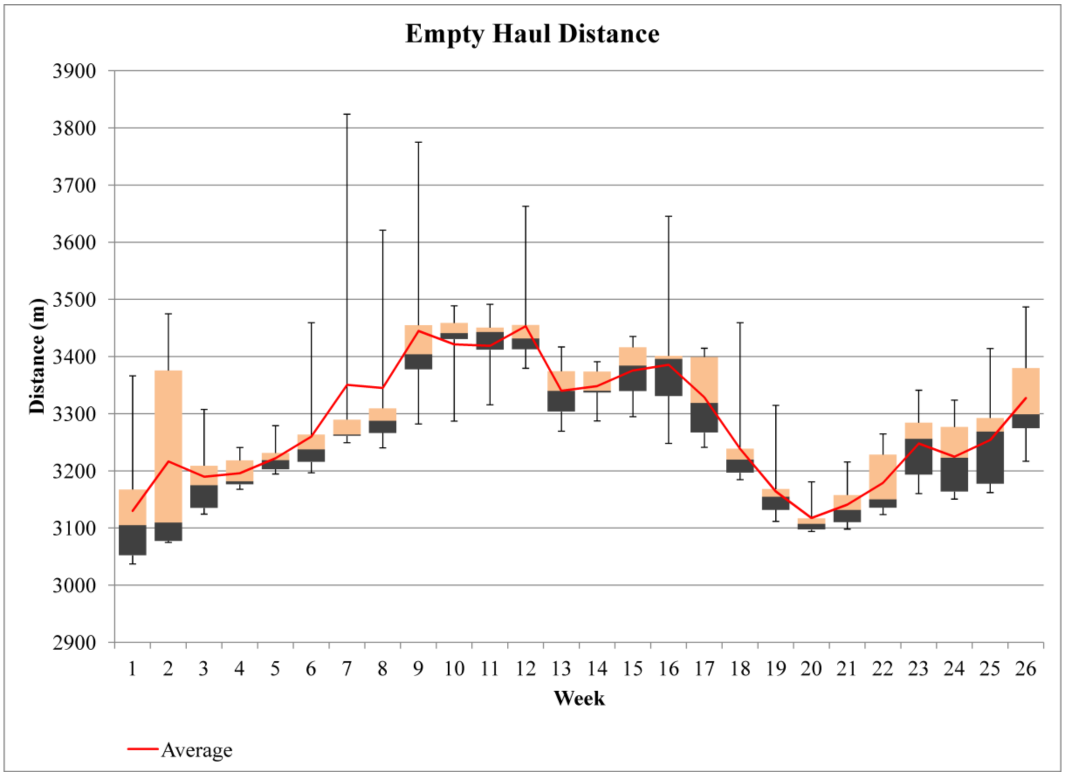

Fig. 4.88. Box plots for weekly average empty haul distances travelled by trucks

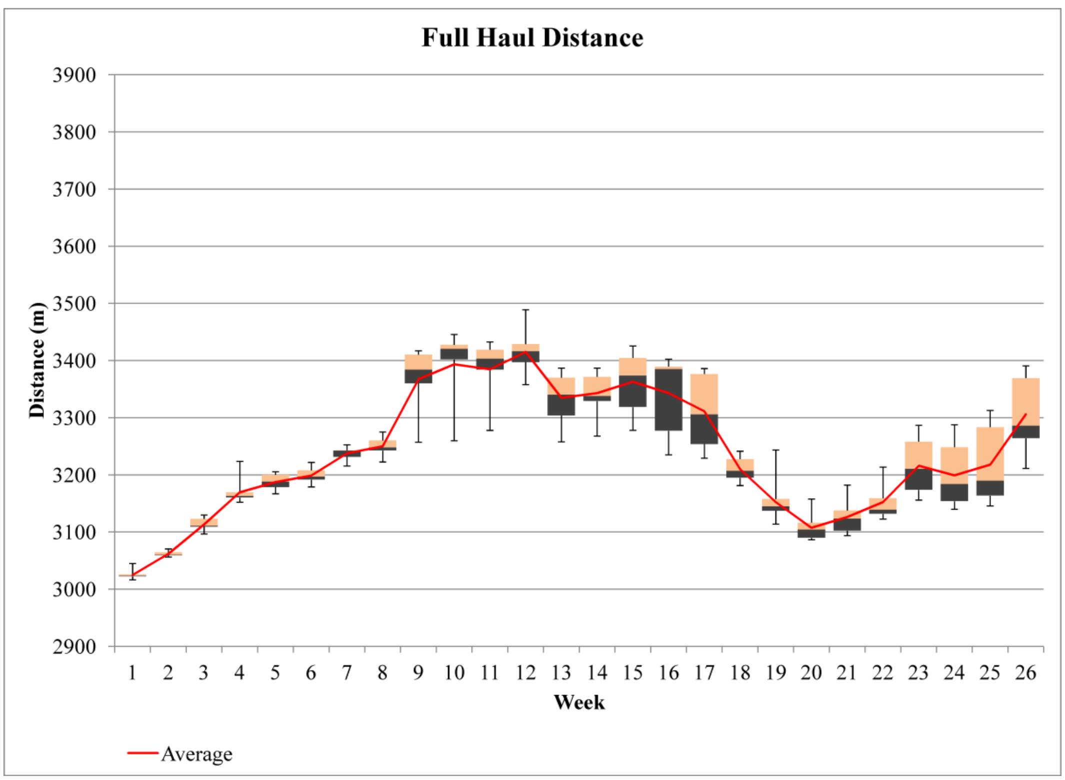

Fig. 4.89. Box plots for weekly average full haul distances travelled by trucks

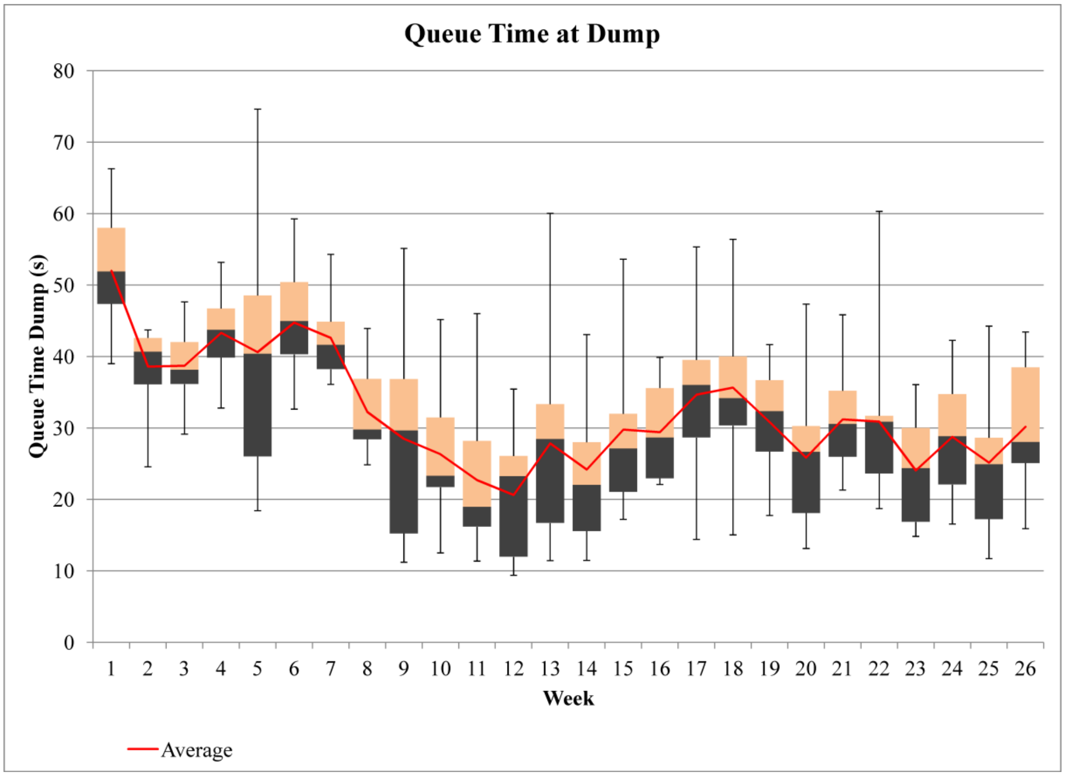

Fig. 4.90. Box plots for weekly average queue times at Dumps

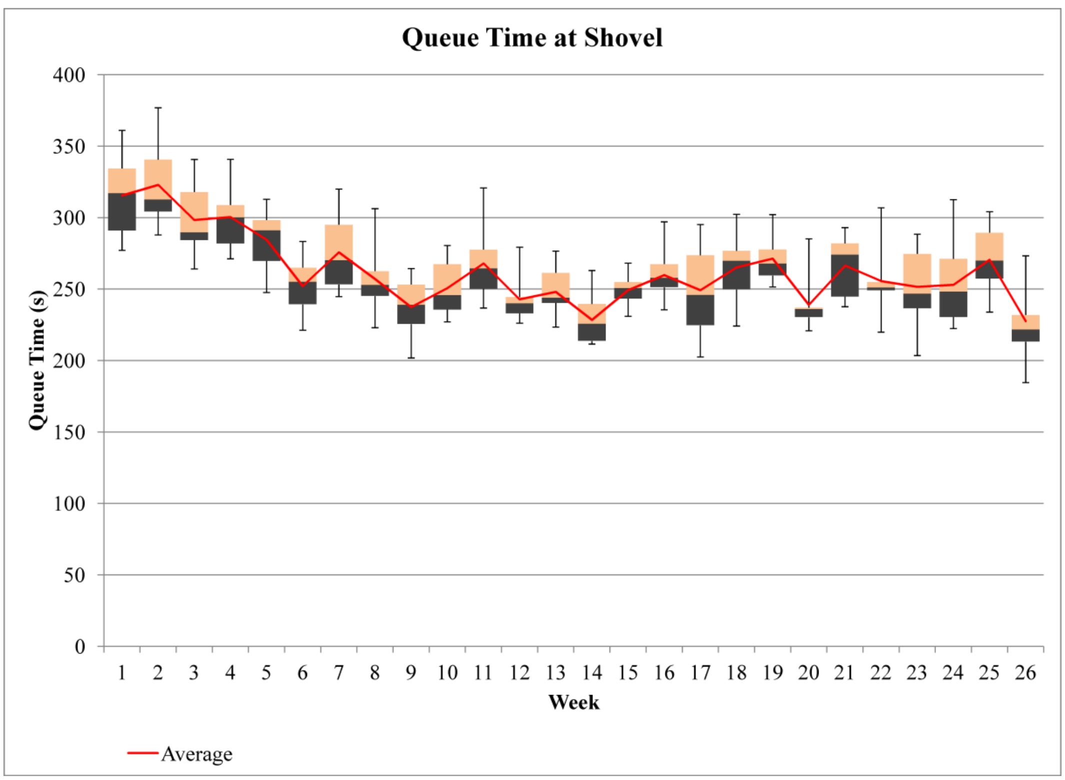

Fig. 4.91. Box plots for weekly average queue times at shovels

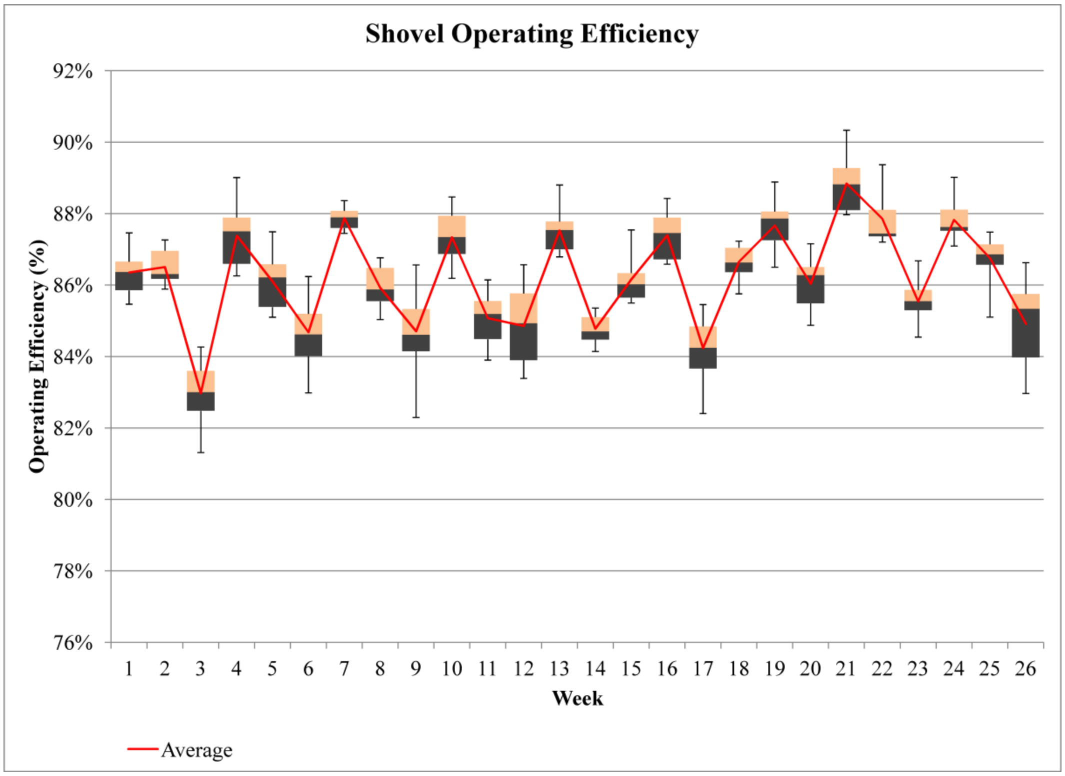

Fig. 4.92. Weekly shovel operating efficiency box plots

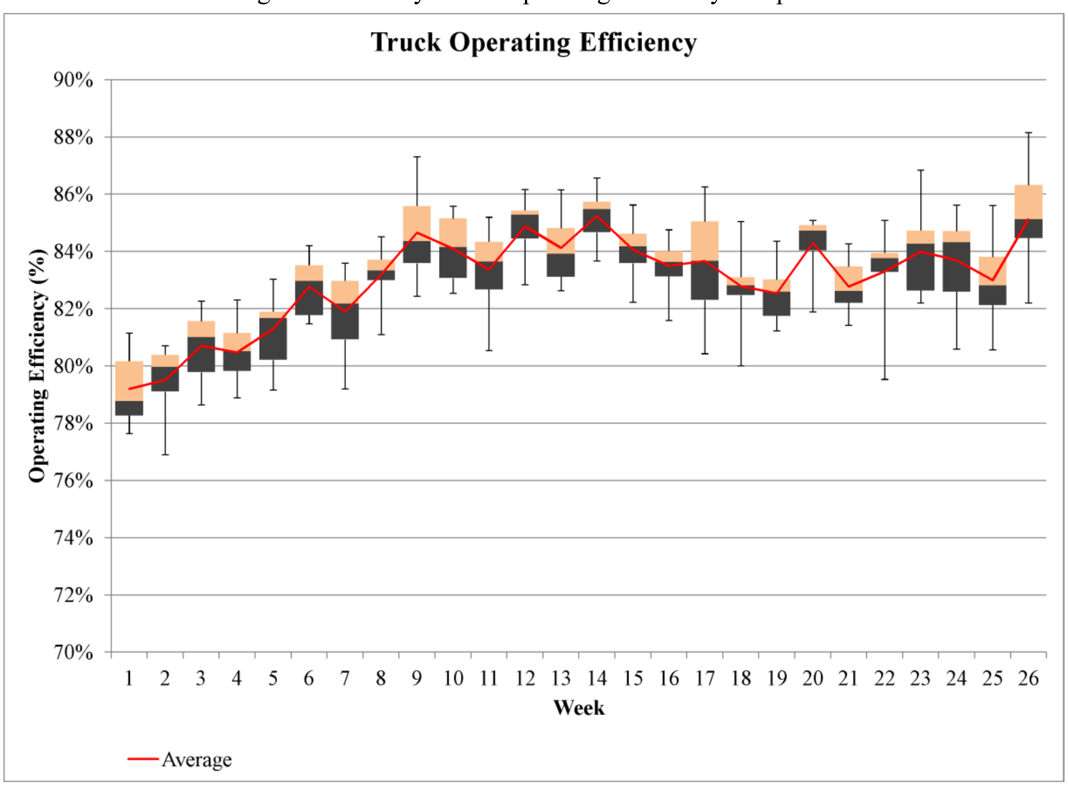

Fig. 4.93. Weekly truck operating efficiency box plots

Replication 6 is selected as best replication based on ore and waste productions and operating efficiencies of trucks and shovels to derive a deterministic plan of shovel allocations which are shown in Fig. 4.94, Fig. 4.95, Fig. 4.96, and Fig. 4.97. Although in general this shovel allocation plan does not bear much significance because this is one out of many replications possible, it can be used as deterministic short term plan if MOOT is not applied within mine operations for dynamic operational decision making. The overall approach is that MOOT is implemented within operations as well which will bring a synergy between the plan and executions. In that case a deterministic shovel allocation short term plan would not be required.

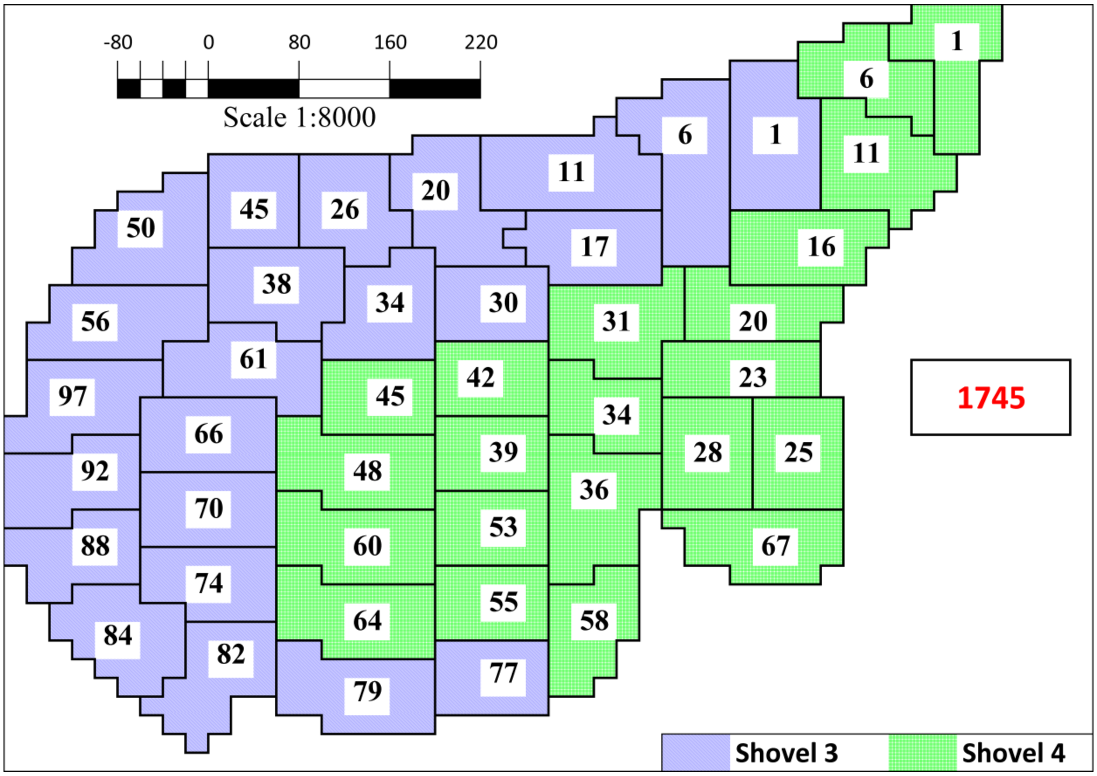

Fig. 4.94. Schedule for bench 1745 for replication 6

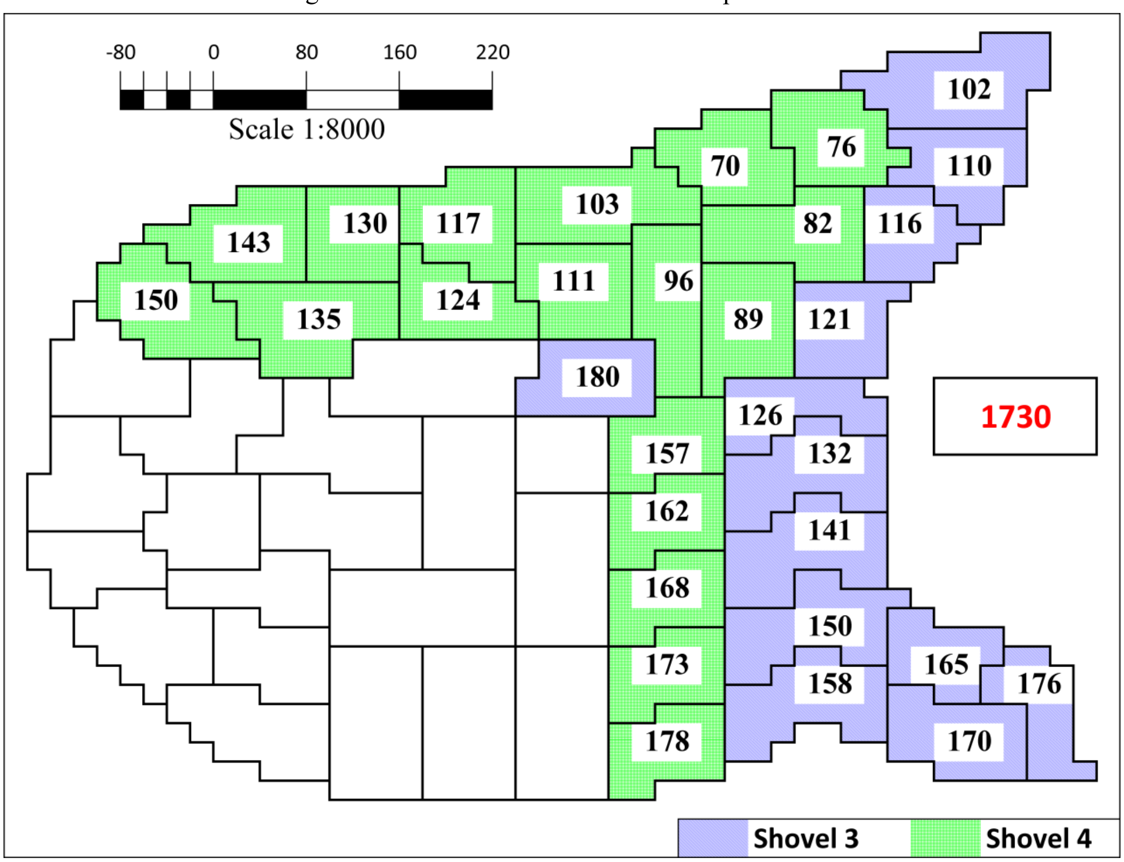

Fig. 4.95. Schedule for bench 1730 for replication 6

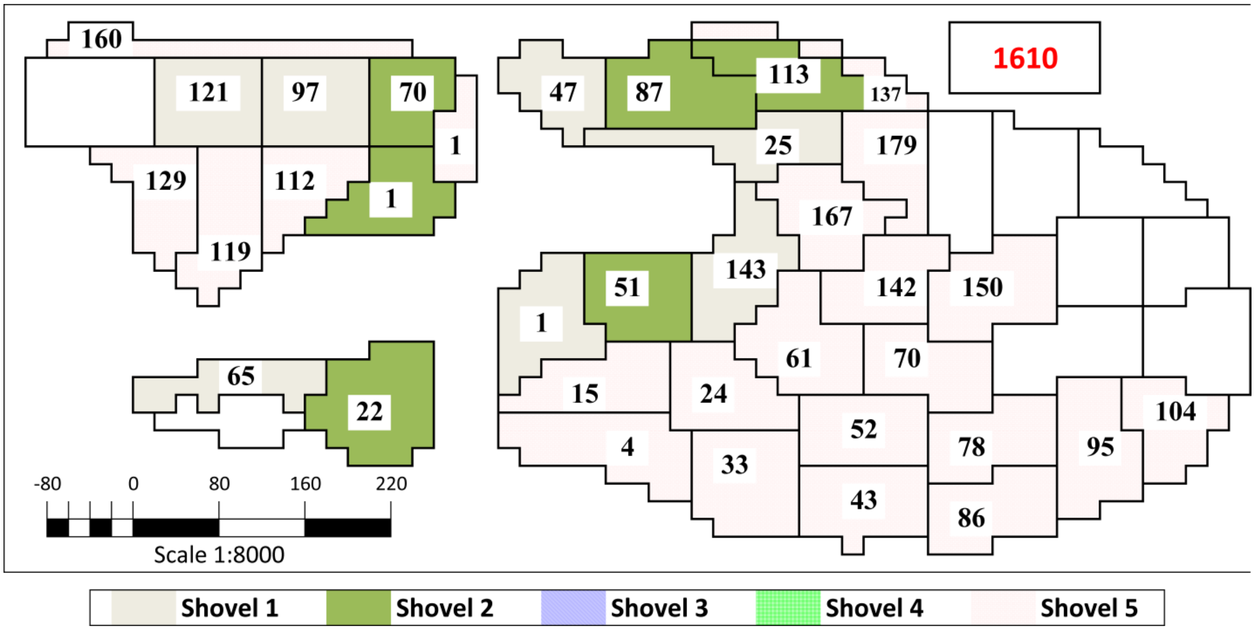

Fig. 4.96. Schedule for bench 1610 for replication 6

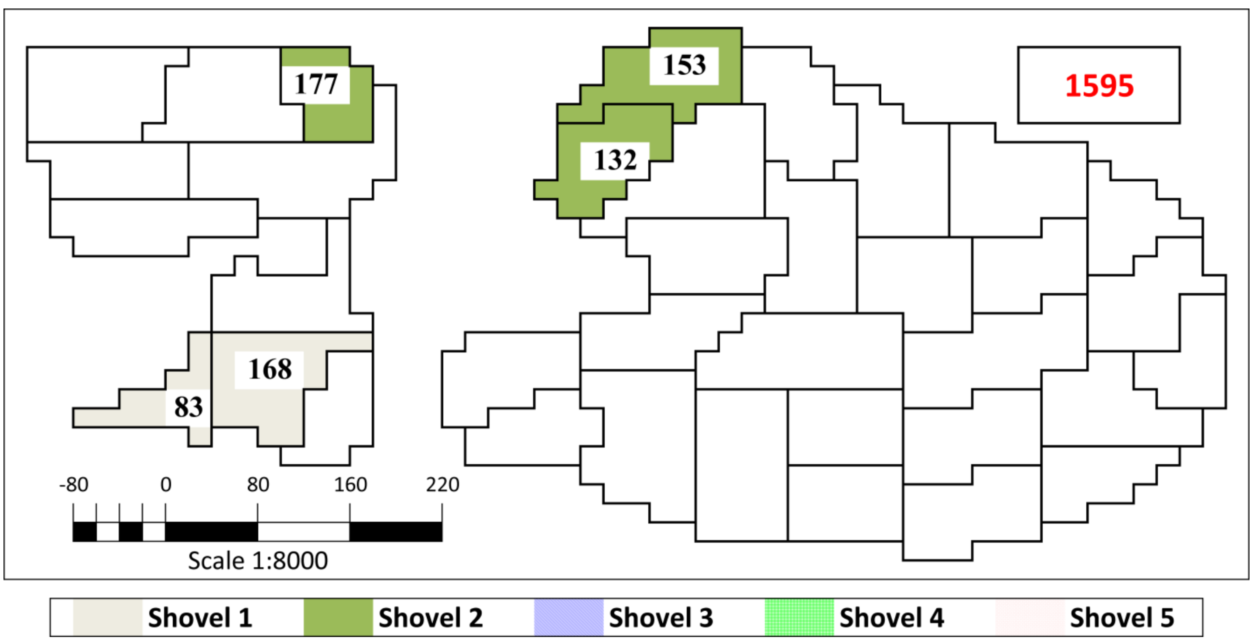

Fig. 4.97. Schedule for bench 1595 for replication 6

4.8. Summary and conclusions

Verification of the proposed approach is presented in this chapter using an iron ore mine case study. Detailed analysis and scope of the approach is also presented showing the robustness of the simulation optimization based short term planning framework/tool.

First an iron ore mine case is presented describing the strategic schedule, designed pit with haulage road network available in year 11 of the mine life. The case study consists of two plant crushers with specific tonnage feed and grade requirements, and a waste dump. Due to unavailability of historical operational data, theoretical probability distributions were derived out of a separate historical mine operational database to model truck and shovel characteristics.

The verification of the model is presented by studying the behavior of scenarios under changing number of trucks in single and mixed fleet systems. The simulation optimization model provided reasonable and expected results accounting for total available time. The distribution of total time distributed among various processes for shovels also verified the functionality of the model. The shovel ton per net operating hours and effective utilizations did not change with changing number of trucks in both single and mixed fleet systems as expected. Similarly truck ton per net operating hours is found stable in single fleet system, but behaved according to the number and capacity of trucks in mixed fleet systems as expected. The model behavior is also analyzed in detail based on other KPIs of the systems and provided reasonable results verifying the model.

One important characteristic of the developed simulation model is to capture the truck interactions on haul roads, thus a verification study is also conducted to analyze the truck interactions. It was not possible to capture truck interactions as a measurable value, thus the verification is conducted using three scenarios. Comparing a scenario in the mixed fleet system with two other scenarios where the speed of one specific truck type is increased by 20% in each scenario, it is shown that trucks travelling on routs which are shared by both types of trucks do not show a 20% increase in truck speeds, whereas those trucks which do not interact with trucks of other type show a 20% increase in truck velocities. In one case the interaction caused the increase to be only 10% within simulation instead of 20% theoretical increase. This proved that the speed of slower truck types affected the speed of faster trucks on routes where they interact.

After the detailed verification, the case study is implemented to determine the optimal number of trucks to achieve operational objectives of the mine and for short term mine planning purposes. Several scenarios are run in both single fleet system (case C1) and mixed fleet system (case C2). The best scenario from both the cases is selected based on total ore and waste productions, and operating efficiencies of trucks and shovels. The comparison between the best scenarios from both cases resulted in the selection of scenario 6 in mixed fleet system of case C2, which performed much better compared to best scenario of C1, especially in terms of total haulage distance. As less number of large capacity trucks are used in mixed fleet system for mining waste, the total travel distances remain lower than with large number of smaller trucks in case C1. This is an important consideration with respect to tire costs and truck life in mine and thus case C2 is considered better than case C1. The selected scenario is chosen as base case for further analysis.

After the base case scenario is selected, several other scenarios can be compared against base case to select the best strategy to be implemented within operations that achieve operational objectives. In this chapter haulage planning and grade blending strategies are shown as two of the many different areas where this model can be implemented for proactive decision making.

Based on the available haulage routes in the designed pit, lower benches have two access routes to exit the pit. As part of haulage planning, two scenarios are compared to analyze the impact if only one route existed. The analysis showed base case to be performing very close to scenario where only route 1 existed within the mine. A careful analysis showed that only few of the loads in base case take route 2, which make base case and scenario with route 1 only very similar. This behavior occurs due to shorted path based dispatching implemented within the mine. The comparison of scenarios suggests that route 2 is rarely used, where maintenance costs can be saved. But a careful decision on maintenance of roads should be taken considering futuristic requirements of the mine as well.

An optimal grade blending strategy is also analyzed by prioritizing the plants. Depending on the grade distribution available in the schedule and the accessibility of the faces, sometimes one plant requirements can be easily met, while it is hard to satisfy the other plants. To analyze such situations and to adopt the best strategy that satisfies the requirements; the base case scenario which provides equal priority to both the plants is compared against two other scenarios prioritizing one plant over other in each scenario. The analysis proved the effectiveness of MOOT in achieving grade blending objectives under desired scenarios. The analysis showed that plant 2 requirements can be very precisely met by prioritizing it, but other plant performs poorly. Thus equal priority based base case is selected to generate the short term plan.

Finally weekly productions and KPIs of the operations are extracted from the simulation of the base case to develop the short term plan. The best replication of base case is selected to develop and plot the shovel allocation plan. As probability based shovel allocation plans would be hard to perceive, deterministic plans are provided, which are not used for any operational decision making. MOOT is proposed to provide operational decisions in actual operations based on strategic plans. Although a shovel allocation plan based on single replication does not signify much, it provides an idea about shovel working positions during the planning time horizon. Probability plans based on shovel and period of extraction can also be generated.

CONCLUSION AND FUTURE WORK

5. CONCLUSION AND FUTURE WORK

5.1. Summary of research

Planning is a critical component in every operation. In open pit mining context, the longevity of mine life makes it even critical to realize the long term economic objectives. Short term and operational mine plans are as crucial as strategic plans, because operational executions determine the compliance of short term plans and in turn strategic goals. Also short term and operational plans need to meet the operational objectives dealing with high uncertainty at the operational execution level. The complex details and high uncertainty at the operational level makes it impossible to account for every operational detail within a mathematical optimization model and solve it to generate practical short term plans as observed by L'Heureux et al. (2013) and Bjørndal et al. (2012). The complexity of operational details is usually handled by approximations in conventional mathematical optimization models, posing a limitation on their practicality and achievability through executions. Also, such deterministic short term plans need to be regularly updated to reflect the running state of the mining operations, making them merely a guideline to be followed by the planners. The real-time decisions about shovel allocations to meet operational objectives are mostly made by planners through experience and may not be optimal. The conventional process thus bears a gap between planning and execution, leading to lesser confidence on the achievability of short term plans. The conventional approaches do not allow proactive decision making as well, leading to reactive planning through regular updates in short term plans.

Short term planning deals with a number of operational objectives some of which are described by Chanda and Wilke (1992) that includes: minimization of absolute deviations in head grade delivered to plants so as to maximize recovery of the plants; efficiently utilize the mining resources; detailed shovel and truck allocations for optimal dispatching; and the flexibility and practicality of the generated schedule.

Chanda and Dagdelen (1995) and Wilke and Reimer (1979) describe the importance of grade blending objective in short term planning citing very irregular ore deposits that may affect equipment utilizations during operations. Such extreme situations require frequent decision making on part of planners for optimal shovel allocations, where conventional short term planning approaches fail to add much value into the operational executions, posing a question on their practicality. Gershon (1987) describe the practicality of the schedules as more important than finding the best schedule, as the schedule must also meet the restrictions on the mobility of equipment along with other operational details.

The literature reviewed, as given in chapter 2, show the need of a better approach in short term and operational planning that may handle the issues of flexibility, practicality and achievement of operational objectives through executions. The major limitations of conventional short term and operational planning approaches, as noted in this thesis, are:

- The gap between deterministic short term planning and its operational executions under highly stochastic environment.
- Not accounting for operational details and associated uncertainties is another major limitation. Short term plans must account for available haul routes, haulage capacity available and possible through dispatching and other operational details related to real-time deliverables of tonnage and head grades to plants, shovel movements and precedence requirements.
- Most conventional models studied in literature do not account for shovel movements.
- Truck allocations and the expected haulage capacity are never accounted in the short term planning models, which significantly affect shovel productions.

- Predicting the head grade fluctuations is another major limitation of conventional approaches. Such predictions may enable proactive decisions to minimize these fluctuations to some extent.

Based on the detailed review of literature and problems associated with conventional approaches, theoretical framework of a simulation optimization approach is presented in Chapter 3 that may provide practical and robust uncertainty based short term plans and account for major limitations observed in the conventional approaches. The simulation optimization framework for robust short term planning is presented in Fig. 3.4. Fig. 3.4 proposes a mine operational optimization tool (MOOT) that optimizes the mine operations over multiple periods and provides dynamic shovel and truck allocation decisions to achieve operational objectives. The MOOT, being a dynamic decision making tool, can be implemented in actual operations as part of a multi stage dispatching system; and with simulation models as external decision support tool. The implementation with simulation can be used for generating robust, practical and achievable short term plans. The parallel framework, where the MOOT is implemented in actual operations as well as for planning purposes, makes the simulation optimization framework robust in predicting the future of mine operations, and gives a strong confidence on the developed plans for proactive decision making. Fig. 3.4 also describes the use of Matlab® GUI and VBA interfaces developed for easy implementation of the mining configuration along with the haul road designs. The developed tools induce flexibility and reusability to the developed simulation optimization model for implementation with changing mining states over time and easy scenario analysis.

5.1.1. *MOOT*

Four operational objectives are considered for shovel and truck allocation optimization in this study, based on the mine operational requirements:

1. Maximum production, i.e. minimizing the negative deviation in production by shovels compared to their maximum capacity;
2. Tonnage feed requirement of plants, i.e. minimizing the negative and positive deviation in production received at processing plants;
3. Grade blending requirement of plants, i.e. minimizing the negative and positive deviation in grades received at processing plants; and
4. Minimizing the movement time of shovels between faces.

As the problem is a multi-objective optimization problem, a mixed integer linear goal programming (MILGP) approach is adopted to solve the optimization. Also, due to different dimensions of the objectives, a non-preemptive weighted sum approach is implemented to solve the optimization problem.

Chapter 3 first presents a model (M0), that was developed initially, which models the mining operations over a single period only. In this case the optimization model do not account for futuristic requirements of the system. The operations are optimized only for the duration of a shift or a day where shovels are not allowed to move during the optimization period, i.e. allocations are made only at the beginning of the optimization time and any shovel that need to be reallocated is assigned, keeping other shovels at their initial location for the rest of the optimization time. Due to the optimality issues regarding overall operations over time, and accounting for futuristic requirements, it was considered necessary to adopt multi-period optimization approach which may account for shovel movements during the optimization time frame as well. This model should be similar to conventional short term planning models, so that all decisions made by the MOOT are based on an optimal short term plan developed based on the current state of mining operations. Thus a multi-period optimization model (M) is then presented, which serves as the MOOT in chapter 3 and 4.

The definitions of optimization time frames in the MOOT and decision time frame that is implemented within simulation are explained in Fig. 3.3. Mining blocks in the strategic schedule are grouped together based on similarity in grade, rock type, distance and size of group, to have a manageable size of the problem. Clustering of blocks is also justified from the operational point of view where instead of a single block a group of blocks are blasted and extracted as faces. These groups of blocks or clusters are then used within the model as faces which are presented in Fig. 3.2.

The MOOT is developed with some assumptions. The MOOT does not allow partial extraction of faces, i.e. once a shovel is assigned to a face it does not move until it mines out all the material available at the face. Another assumption is that grades within a cluster of blocks, considered as faces are assumed constant within the model. Also rock types are not considered in the model in its current form. Detailed assumptions in the MOOT and simulation optimization model are presented in Chapter 3.

5.1.2. *Simulation*

Chapter 3 also presents a detailed development of a simulation model of mine operations. The simulation model is developed to replicate the actual mine operations which models loading, hauling, dumping, queuing, spotting, shovel movements, plant crushers and hoppers, and equipment failures. Truck haulage being a critical part in open pit mine operations, special emphasis is given to modeling the haulage road network and the truck travel behavior on haul roads. First a small micro-simulation study is conducted by modeling the truck travel behavior on a microscopic scale. Based on the micro-simulation study it was considered sufficient to prohibit the overtaking of trucks forcing the faster truck to move with the same speed as the leading truck, instead of devising real-time control architecture to model the truck movements. Thus truck travel model is developed in Arena simulation package using the concept of AGVs, without controlling the microscopic movement of trucks. Also the truck velocities are modeled based on the rimpull curve characteristics of trucks provided by the manufacturers, and haul road gradients and rolling resistances of haul road segments. This modeling captures the realistic variability in truck speeds throughout the travel paths coupled with the impacts on other trucks traveling on shared paths leading to platoon formations.

Description of other tools developed towards easy implementation of the simulation optimization models is also presented in chapter 3, detailing the RoadNetwork GUI and the VBA interfaces for creating the simulation and optimization models.

Chapter 4 presents the implementation of the simulation optimization model with an iron ore mine case study. First the case study is presented by detailing the strategic schedule, designed pit and haulage road network along with equipment characteristics and requirements in the mining system. Then model verification is presented by implementing the simulation optimization model on the case study and analyzing the total shovel operation times, expected ton per net operating hours and operating efficiencies of trucks and shovels under changing scenarios with increasing number of trucks in single and mixed fleet systems. Model is also verified for accurately modeling the truck interactions using two scenarios with 20% increase in truck velocities of each type. The detailed verification study and the observed behavior of the model in further scenarios presented in chapter 4, proved the correctness of the model in modeling the mine operations and the decisions provided by the MOOT. The implementation of the model is then presented for the selection of optimal number of trucks in both single and mixed fleet mining systems, and proactive decision making in haulage planning and selecting optimum grade blending strategy based on available strategic schedule.

5.2. Conclusions

The short term and operational planning approach, and the model developed in this research is evaluated against the limitations of the conventional approaches reviewed in chapter 2.

- The approach presented in this research (Fig. 3.4) creates a direct link between the short term planning and operational executions with the help of MOOT. The conventional approach requires a planner to make operational decisions which may not be optimal. The use of a common tool for operational decisions within simulation replicates the decisions made by the same tool during real-time operational executions, providing robust uncertainty based short term plans. This approach creates a synergy between short term plans and the operational executions.

- Conventional approaches require regular updating of short term plans reflecting the existing state of the mine. This process is replaced by the MOOT presented in this research, which recreates the short term plans each time a shovel allocation decision is required. As this approach creates uncertainty based plans, the variability in operations is already accounted for in the short term plans.

- Due to high level of uncertainty in mine operations, the conventional short term plans do not possess the confidence of mine management, which is not the case with the model presented in this research. The simulation optimization approach provides robust estimates of mine operations over time with desired confidence intervals, enabling proactive decision making instead of conventional reactive planning.

- Accounting for shovel movements during operations based on shovel characteristics and precedence requirements of faces, this approach provides more practical plans compared to most of the conventional short term planning models.

- Incorporating truck haulage capacity based on number of trucks, available haul routes and dispatching is another addition of the model compared to conventional approaches. Apart from trucks and haulage paths, the model captures the intrinsic details of mining operations through simulation which is missing in conventional planning tools.

- The deliverability of head grade requirements and predicting the fluctuations in head grades at ore destinations is a unique characteristic of the proposed approach compared to conventional models. The deterministic nature of conventional planning tools fails to predict the real-time deliverables.

- The MOOT developed as upper stage of a multi-stage dispatching system bears the potential to incorporate multiple objectives of mine operations, compared to conventional tools in multi-stage dispatching systems. Also the inclusion of shovel allocation decisions at this stage, help achieve better results for operational objectives.

The developed simulation optimization framework thus bears a great potential over conventional short term and operational planning models. This research can be concluded by comparing the developed approach and model against the objectives set in Chapter 1 for the thesis. The major conclusions drawn out of the developed approach, model and its implementation on a case study can be summarized as below:

- A theoretical framework of mine operational optimization tool (MOOT) is developed as an MILGP model and tested in this thesis,

- A detailed development of a discrete event simulation model is presented and tested in this thesis

- Based on a micro-simulation study, truck haulage is modeled in the discrete event macro-simulation model of the mine operations, capturing the extent of modeling required. The truck interactions are verified through scenario analysis.

- The MOOT provides shovel allocation decisions to available faces based on strategic schedule and precedence requirements, incorporates shovel movements within a multi-period optimization, capable of providing dynamic mine operational decisions and incorporates the major operational objectives; thus satisfactorily achieves the objectives set for the MOOT.

- The detailed model of mine operations developed within a discrete event simulation model, along with the developed Matlab® and VBA interfaces to provide flexibility and reusability to the model over time, VBA based interaction with the external decision support system (the MOOT) and micro-simulation based model of truck haulage to capture truck interactions on haul roads satisfactorily achieves the objectives set for the simulation model.

- The simulation optimization model developed in this thesis is capable of providing uncertainty based short term plans, capturing the intrinsic details of mine operations.

- Through the scenario analysis approach, model is capable of proactive decision making, such as truck allocation planning, haulage planning, selecting optimum grade blending strategy for the plants etc.

- The short term schedules created by this model are practical and achievable through mine operations.

5.3. Contribution of PhD research

This PhD research has developed and implemented a simulation optimization approach for the development of practical, proactive and robust short term and operational plans. The major contributions include a MOOT developed as a mixed integer linear goal programming model for mine operational optimization, and a simulation model with a realistic modeling of truck haulage systems capturing the interactions among trucks on shared paths. The major contributions and improvements in the short term and operational planning, along with real-time operational executions provided by this research are as follows:

- The MOOT can be implemented in actual mine operational decision making for shovel and truck allocations, increasing the automation in the industry.
- If implemented in conventional approach, accounting for shovel movements along with other required operational constraints makes the MOOT a better tool for deterministic short term mine planning compared to most models reviewed in literature.
- The simulation optimization approach lets us account for the intrinsic details of mine operations in short term and operational planning, which is usually missing from conventional short term planning tools.
- The simulation optimization approach also enables planners to foresee the fluctuations in head grades delivered to plants.
- Use of simulation optimization approach for planning, coupled with the use of the MOOT in actual mine operational decision making, creates a synergy between planning and operational executions, leading to robust and confident predictions. This helps in otherwise hard proactive decision making.
- Capturing the truck interactions on haul roads also enables the planners to foresee possible increase in platoon formations due to close proximity or shared paths from multiple shovels.
- Modeling truck travel through haul roads based on gradients and rolling resistances of segments enables planners to estimate accurate truck requirements apart from tire wear and truck operating costs including fuel costs.

5.4. Recommendations for future work

The major contribution of this research is the simulation optimization approach for uncertainty based short term and operational planning. The MOOT and the simulation models presented in this thesis are developed to verify the applicability of the approach. Several improvements can be made in the developed tools by interested researchers which are given here as future work.

- At this stage the MOOT is developed as MILGP model, which can be made more intelligent using AI techniques so that it may be satisfactorily implemented for real-mine operational decision making.

- The solution time of MILGP model needs improvement, which can be achieved through a befitting heuristic algorithm.

- Drilling and blasting related delays are not modeled in the MILGP model, which should be included for more practical operational decision making.

- The MOOT can be improved to dynamically recognize precedence requirements, i.e. instead of recognizing a fixed precedence requirement model can be made more flexible to recognize the accessibility from any direction.

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6. REFERENCES

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APPENDIX

7. APPENDIX – I: HAULAGE MODELING IN SIMULATION

7.1. Concepts and terminology (Rockwell Automation Inc.)

7.1.1. *Transporters*

Transporters are one type of device that moves entities through the system. They can be used to represent material-handling or transfer devices such as fork trucks or delivery vehicles. Transporters can also be used to model personnel whose movement is important to modeling a system, such as a nurse or a food server. When transporters are used, you provide information defining the transporter's speed and the travel distances between stations served by the transporter.

7.1.2. *Free-path transporters*

Free-path transporters move freely between stations and are not influenced by other transporter traffic.

7.1.3. *Guided-path transporters*

Guided transporters are restricted to run on fixed paths such as tracks or rails. Movement may be affected by traffic congestion from other vehicles.

7.1.4. *Distance*

The Distance module defines the distance between two stations in the distance set of a free-path transporter device. The beginning station, ending station, and distance are used to create the appropriate distance set, which is used during the simulation run by the transporter moving between the specified stations.

7.1.5. *Network*

The Network module defines a system map that a set of guided transporters will follow. A network encompasses the set of links specified in its Network Links repeat group. The parameters of a network link (e.g., length, intersections, directions), are defined in the Network Link module.

7.1.6. *Network link*

The Network Link module defines the characteristics of a guided transporter path between an intersection pair Beginning Intersection Name and Ending Intersection Name. The Network module then references a set of network links to define a network that guides transporters follow for movement. Each link is composed of a Beginning Intersection ID, an Ending Intersection ID, and one or more Number of Zones -- each Length of Each Zone units long.

7.1.7. *Link type*

The link type — Unidirectional, Bidirectional, or Spur — dictates whether the simulation will allow transporters to move from Ending Intersection Name toward Beginning Intersection Name. When traveling on a unidirectional link, a guided transporter may only move from Beginning Intersection Name toward Ending Intersection Name. A bidirectional link allows vehicles to move either from Beginning Intersection Name toward Ending Intersection Name or from Ending Intersection Name toward Beginning Intersection Name. In the case of spurs, the Ending Intersection Name must be a "dead end" — not connected to the network by any links other than the spur. When the transporter arrives at the Ending Intersection Name of a spur, it does not give up control of the link zones between Ending Intersection Name and Beginning Intersection Name; instead, the transporter keeps control of the entire link to ensure that it can return to the main path intersection (Beginning Intersection Name).

7.1.8. *Beginning and ending directions*

The fields Beginning Direction and Ending Direction are used to define the direction of the link (in degrees) as it leaves the beginning intersection and as it enters the ending intersection; the direction entering the ending intersection defaults to the direction leaving the link's beginning intersection. The value entered should be an integer value between 0 and 360 representing direction of travel in degrees (0 and 360 represent right or east). These directions are used in conjunction with the turning velocity of a vehicle to slow down a transporter as it turns a corner.

7.1.9. *Number of zones*

The *number of zones* operand is used by SIMAN to determine how to move transporters through the links. If the number of zones is one, then SIMAN simply moves the transporter through the link as a single event. If the number of zones is greater than one, then SIMAN moves the transporter through the link zone by zone. The entity controlling the transporter seizes the first zone in the link before commencing movement. When it gets the first zone, it moves through the new zone, and depending upon the vehicle size and zone control policy, it releases trailing zones as they are no longer needed. When the transporter arrives at the end of the zone, it waits to seize the next zone on the link. When it gets this next zone, it commences movement through the new zone. This process repeats until the entity arrives at the end of the link.

7.1.10. *Length of zones*

The Length of Each Zone is the same for all zones in a link. The product of Number of Zones and Length of Each Zones is the total length of the link. The units used to measure Length of Zone should be consistent with all other measurements for the transporters using this link.

7.1.11. *Velocity change factor*

The Velocity Change Factor specifies a multiplier that is to be applied to the current velocity of any vehicle moving through the link only during travel through the link. The value entered is multiplied by the transporter unit's current velocity to determine the travel velocity through the link.

7.2. MATLAB® Application for generating haul road networks in Arena

To generate the haul road network in Arena, a text file containing the road information is required. We can export the road information from within a dxf file representing the road network of the mine as polylines. Before exporting the polylines, it is necessary that:

- Polylines are connected.
- Polylines start and end at junctions or end points, i.e. any polyline must not extend beyond a junction.

The polyline data is then exported as ASCII file. The exported ASCII file must be formatted as Line Number, Line Type, Y, X, Z, Tag. It should be noted that this format is essential for the text file so that we may use it with MATLAB® application, RoadNetwork.m GUI, to create road network in Arena. Line Type and Tag fields in the exported output can take any value as it is discarded during reading the file.

Create an excel file named “Config.xlsx”. Create two sheets “DumpLocations” and “Schedule” within the excel file. Provide all the dump locations, their coordinates as X, Y, Z and each dump locations capacities i.e. how many simultaneous dumps are possible at each dump location. Name the ranges as “DumpCoordinates” and “DumpCapacities”. Provide all the scheduled mining polygons and respective coordinates as X, Y, Z in the “Schedule” sheet. Name the coordinate range as “PolygonLocations”. Also provide the scheduled shovels to mine respective polygons. Name this range as “ShovelScheduled”.

Run the “RoadNetwork.m” GUI. Browse the ASCII file containing the road network information that we exported as polylines. Provide the other required data in the GUI and click on run to generate three sheets “Nodes”, “Links” and “FailureNetwork” in the Config.xlsx file. The data from these sheets is read into Arena to generate the road network.

Average truck length and safety distance between trucks is required to model the zone lengths for individual network links in Arena. Zone length provides the length of the part of a road segment that a truck (transporter unit) seizes when it is stationary. A truck unit moves through the network zone by zone by seizing the next zone and releasing the previous zone for the trailing transporters. The zone control rule thus can be defined as 'Start', i.e. a truck releases a zone, to be seized by a trailing truck, as soon as it is given the next required zone. This setting enables trucks not to overtake and maintain a safe following distance on the haul roads.

Check the "Merge the segments?" checkbox if the road network is very large. This will enable merging the road segments based on the length and gradient tolerance. If the difference between the gradients of two consecutive road segments is less than percent gradient tolerance or total length of the combined segment is less than length tolerance, the segments will be merged together to form a single segment.

7.3. MATLAB® Application for modeling truck speeds

In normal case, when there is no interaction between vehicles, they try to move freely on their normal driving speed. According to Bonates (1996), maximum obtainable speed by any truck can be determined by the rimpull curves generally provided by the manufacturers. He describes the rimpull as the force exerted on ground by the drive wheels to get the truck in motion. This force is generated by the torque that the engine develops and it is a function of the gear ratios.

To model the velocities of trucks in simulation, a table is created which provides a speed factor for each truck type on different total resistance haul roads. Total resistance of haul roads is the summation of haul road gradient resistance and rolling resistance. Based on the total resistance of each haul road segment, which we created in previous section, and referring to this table, we can determine the maximum possible speed of each truck type while traveling on that haul road segment.

To generate the speed factor table, a MATLAB® application is created which reads in truck payloads and rimpull characteristics from a separate excel workbook and writes down the speed factors table in “Config.xlsx” file. To run this application:

- Create an excel file “RimpullRetardCurves.xlsx”.
- Create a sheet “TruckSpecification”.
- Write down the names of all truck types employed followed by their gross empty and full vehicle weights. Name the range as “Specifications”

Table 7-1: Formatted tabular input of weights of truck types

Name of the truck type	Truck Type 1	Truck Type 2
Gross Empty Vehicle Weight	283495	278690
Gross Loaded Vehicle Weight	610082	623690

- Create two worksheets for each truck type. Name the worksheets as “Rimpull-” and “Retard-” followed by name of the truck type given in truck specifications.
- Provide the rimpull and retard curve data as Point, Rimpull/Retard Force (Kg. force), Speed (Km/h).
- Save the excel file and run the MATLAB® application TruckSpeedsByRimpull.m”.

The MATLAB® application will create a table in “Config.xlsx”, sheet “RimpullSpeeds”.

7.4. Haulage modeling in Arena

A flowchart of the haulage simulation model, incorporating the interaction between trucks on haul roads and intersections, is given in Fig. 3.14. Prior to building the simulation model a VBA macro is run which uses the data in “Nodes” sheet of “Config.xlsx” file to create stations and intersections. A Network, along with Network Links, is created between the intersections using the data in "Links" and "FailureNetwork" sheet. All the stations coupled with their corresponding intersections are written in a station set module in sequential order. This station set module is the module where entity enters back into the model after being transported to next node.

To model the truck interactions on haul roads, guided path transporters will be used which move from zone to zone by seizing next zone and releasing the occupied zone on the network link. This characteristic prohibits overtaking of trucks and models the truck interactions precisely. Moving the trucks from node to node on haul roads also provides opportunity to control the speeds of trucks based on the haul road gradient and rolling resistance.

7.4.1. *Definitions of terminology*

7.4.1.1. VBA Macro

- BuildModelFromExcel: A macro is written in the VBA editor of Arena to read the data in "Config.xlsx" file and build the sets, expressions, variables, transporters, network, network links and stations in the model to avoid manual work to enter each data, create haulage road network and formulate expressions in the model.

7.4.1.2. Entities

- entLoad: load entities associated, each associated with a transporter (truck).

7.4.1.3. Attributes

- atrTruckID: unique ID associated with each transporter (truck).
- atrTruckType: Truck type represented by the transporter
- atrTruckInitSpeed: Sampled speed of truck on a flat haul road (m/hr)
- atrVelocity: Velocity of the transporter on a Network Link (road segment)
- atrIsLoaded: 0 or 1 if travelling empty or loaded

- atrCurrentStation: Station name of the current node of the transporter.
- atrNextStation: Station name of the next node to travel
- atrNextLinkNum: Network Link sequence number of the next network link (road segment) to travel
- atrDumpStation: Station name of the dump station node
- atrDigStation: Station name of the node at which shovel loads the trucks

7.4.1.4. Variables

- v2DNetworkLinks: Variable containing information about each Network Link (road segment), i.e. start node, end node, Angle of segment from the east direction, zone lengths, Number of zones, Gradient, rolling resistance and total resistance of the road segment.

7.4.1.5. Station

- setStnNodes: A set of all the nodes in the haulage road network including the shovel reach node and dump nodes is created as stations associated with their corresponding intersections. It is created by the user macro "BuildModelFromExcel" written in VBA.

7.4.1.6. Network link

Network Links are created by the user macro written in VBA. Individual network links are named as "Network Link 1", "Network Link 2" and so on. Each network link is created as unidirectional in nature between a pair of intersections, with a beginning direction, number of zones, zone length and the default velocity change factor; which are taken directly from the "Config.xlsx" file by the VBA macro "BuildModelFromExcel".

7.4.1.7. Network

It contains the names of all the links which were created in Network Link. Arena provides flexibility to create separate Networks using different Network Links.

7.4.1.8. Transporter

Transporter: Created by the user macro written in VBA "BuildModelFromExcel". All the trucks in the system are modeled as transporters. Number of units equals number of trucks in the system. Network Name is "Network" which is the haulage road network used by trucks. A default velocity is given as 40,000 per hour. The basic distance unit is considered as meter, so the velocity is in meter per hour. Rest is left as default. Initial position of transporters is assigned sequentially on haulage road intersections.

7.4.1.9. Files

- filConfig: Input file "Config.xlsx" containing information about number of trucks, types, rimpull speed factors, flat haul velocities, haulage road intersections (nodes), links (segments) and haul road characteristics.

7.4.1.10. Advanced sets

- setIntersections: Set containing names of all intersections in the model in sequential order
- setLinks: Set containing names of all the network links (haul road segments) in sequential order
- setTruckSpeed: Set of expressions as e2DTruckSpeed1, e2DTruckSpeed2 and so on for each truck type in sequential order
- setSpeedFactors: Set of expressions as e2DSpeedFactor1, e2DSpeedFactor2 and so on for each truck type

7.4.1.11. Expressions

- e2DTruckSpeed: Expressions e2DTruckSpeed1, e2DTruckSpeed2 and so on, refer to the recordsets in filConfig representing flat haul empty and loaded speeds of each truck type.

- e2DSpeedFactor: Expressions e2DSpeedFactor1, e2DSpeedFactor2 and so on, refer to the recordsets in filConfig representing empty and loaded speed factors for each truck type on various total resistances of haul roads.

- expVelocityTransporter: Expression to determine the speed of a truck on a haul road segment:

- atrTruckInitSpeed * 1000 * EXPR (MEMBER (setSpeedFactors, atrTruckType), atrIsLoaded + 1, AINT(v2DNetworkLinks (atrNextLinkNum, 8)) + 11)

- expNextStation: Expression to determine the next station to travel to reach the destination: MEMIDX(setIntersections,NEXTX(Network,INXNUM(setStnNodes(atrCurrentStation)),INXNUM(setStnNodes(atrDestStation))))

7.4.2. *Pseudo code*

1. Check current station if it is not the destination station

2. Assign the next station and velocity of the transporter on the next road segment

3. Transport the truck through the next network link

4. Station: Receive the transporter (truck) on the next station and update the current station

5. Go to step 1.