Incorporating Cut-Off Grade Optimization and Stockpiling into Oil Sands Production Scheduling and Waste Management

By

Navid Seyed Hosseini

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Thesis Examiners/Examinateurs de thèse:

Dr. Eugene Ben-Awah
(Supervisor/Directeur(trice) de thèse)

Dr. Marty Hudyma
(Committee member/Membre du comité)

Dr. Lorrie Fava
(Committee member/Membre du comité)

Dr. Michael Hitch
(External Examiner/Examinateur externe)

Approved for the Faculty of Graduate Studies
Approuvé pour la Faculté des études supérieures
Dr. David Lesbarrères
Monsieur David Lesbarrères
Dean, Faculty of Graduate Studies
Doyen, Faculté des études supérieures

Abstract

In achieving maximum benefit in oil sands mining, the long-term production schedule should have the time and sequence of removing ore, dyke material and waste from the final pit limit. An optimum cut-off grade profile and stockpiling will ensure the segregation between these materials meet economic and regulatory requirements. In-pit waste management strategy for oil sands mining requires dyke construction to occur simultaneously with the advancement of mining operations. This research seeks to determine: 1) the optimum life of mine cut-off grade profile and its corresponding tonnages; 2) the time and sequence for removal of ore, dyke material and waste to maximize NPV; 3) the dyke material schedule for dyke construction to minimize construction costs; and 4) the associated impacts of stockpiling and stockpile reclamation with limited time duration.

Cut-off grade optimization was used to generate an optimum grade schedule which specifies the cut-off grade, duration of mining of the grade and tonnage mined during the mine life. A heuristic framework, referred to as the Integrated Cut-Off Grade Optimization (ICOGO) model was developed in this research. It generates an optimum cut-off grade policy and a schedule for mining ore and waste, as well as overburden, interburden and tailings coarse sand dyke material for long-term production planning. Subsequently, a mathematical programming framework based on Mixed Integer Linear Goal Programming (MILGP) model was developed to generate a detailed production schedule for removal of ore, waste and dyke materials from the final pit limit. Stockpiling scenarios investigated during the study include: i) no stockpiling; ii) stockpiling and reclaiming at the end of mine life; and iii) stockpiling for one year or two years prior to reclamation.

The developed models were applied to two oil sands case studies to maximize the Net Present Value (NPV) of the operations. In both case studies, the NPV generated by the ICOGO model for one year stockpiling scenario was higher than other stockpiling scenarios. For the MILGP the NPV generated for the two year stockpiling scenario was higher than the one year stockpiling scenario. In comparison, whereas the ICOGO model solved the optimization problem faster, the MILGP model results provide detailed mining-cut extraction sequencing for mining.

Keywords

oil sands mining, scheduling optimization, waste management, Mixed Integer Linear Goal Programming (MILGP), Integrated Cut-Off Grade Optimization (ICOGO) model

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List of Abbreviations

AER	Alberta Energy Regulator
GP	Goal Programming
IB	Interburden
ICOGO	Integrated Cut-Off Grade Optimization
LP	Linear Programming
LTPP	Long-Term Production Planning
MILGP	Mixed Integer Linear Goal Programming
MILP	Mixed Integer Linear Programming
MPM	Mathematical Programming Model
NPV	Net Present Value
OB	Overburden
TCS	Tailings Coarse Sand
UPL	Ultimate Pit Limit

List of Nomenclature

Indices and Sets

$c \in C$, $\mathrm{C} = \{1, 2, ..., \mathrm{C}\}$ index and set for all the possible processing destinations.

$d \in D$, $\mathrm{D} = \{1, 2, ..., \mathrm{D}\}$ index and set for all the possible destinations for materials.

$e \in \mathrm{E}$, $\mathrm{E} = \{1, 2, ..., \mathrm{E}\}$ index and set for all the elements of interest in each mining-cut.

$k \in \mathrm{K}$, $\mathrm{K} = \{1, 2, ..., \mathrm{K}\}$ index and set for mining-cuts.

$l \in \mathrm{L}$, $\mathrm{L} = \{1, 2, ..., \mathrm{L}\}$ index and set for all the possible mining location.

$m \in \mathrm{M}$, $\mathrm{M} = \{1, 2, ..., \mathrm{M}\}$ index and set for all the phases (pushbacks).

$p \in \mathrm{P}$, $\mathrm{P} = \{1, 2, ..., \mathrm{P}\}$ index and set for mining-panels.

$t \in \mathrm{T}$, $\mathrm{T} = \{1, 2, ..., \mathrm{T}\}$ index and set for all the scheduling periods.

$s \in S$, $\mathrm{S} = \{1, 2, ..., \mathrm{S}\}$ index and set for all stockpiles.

$C_p(V)$ for each mining-panel p, there is a set $C_p(V) \subset \mathrm{K}$ defining the mining-cuts that belongs to the mining panel p, where V is the total number of mining-cuts in the set $C_p(V)$.

$C_m(H)$ for each phase m, there is a set $C_m(H) \subset \mathrm{P}$ defining the mining-panels within the immediate predecessor pit phases (pushbacks) that must be extracted prior to extracting phase m, where H is an integer number representing the total number of mining panels in the set $C_m(H)$.

$F_p(L)$ for each mining-panel p, there is a set $F_p(L) \subset \mathrm{P}$ defining the immediate predecessor mining-panels above mining-panel p that must be extracted prior to extraction of mining-panel p, where L is the total number of mining-panels in the set $F_p(L)$.

$R_p(Z)$ for each mining-panel p, there is a set $R_p(Z) \subset \mathrm{P}$ defining the immediate predecessor mining-panels in a specified horizontal mining direction that must be extracted prior to extraction of mining-panel p at the specified level, where Z is the total number of mining-panels in the set $R_p(Z)$.

Decision variables

$b_p^t \in [0,1]$ a binary integer variable controlling the precedence of extraction of mining-panels. If the extraction of mining-panel p has started by or in period t, b_p^t is equal to one, otherwise it is zero.

$gd_1^{-,l,t}$ the amount of negative deviation from the mining target (tonnes) at location l in period t.

$gd_2^{-,c,t}$ the amount of negative deviation from the processing target (tonnes) at processing destination c in period t.

$gd_3^{-,d,t}$ the amount of negative deviation from the overburden dyke material target (tonnes) at destination d in period t.

$gd_4^{-,d,t}$ the amount of negative deviation from the interburden dyke material target (tonnes) at destination d in period t.

$gd_5^{-,d,t}$ the amount of negative deviation from the tailings coarse sand dyke material target (tonnes) at destination d in period t.

$gd_6^{-,c,t}$ the amount of negative deviation from average head grade target (%mass) at processing destination c in period t.

$gd_6^{+,c,t}$ the amount of positive deviation from average head grade target (%mass) at processing destination c in period t.

$n_k^{d,t} \in [0,1]$ a continuous variable representing the interburden dyke material portion of mining-cut k to be extracted and used for dyke construction at destination d in period t.

$u_k^{d,t} \in [0,1]$ a continuous variable representing the overburden dyke material portion of mining-cut k to be extracted and used for dyke construction at destination d in period t.

$x_k^{c,t} \in [0,1]$ a continuous variable representing the ore portion of mining-cut k to be extracted and processed at destination c in period t.

$x_{k,s}^{c,t} \in [0,1]$ a continuous variable representing the ore portion of mining-cut k to be extracted and sent to stockpile s in period $t-kd$ and reclaimed to be processed at destination c in period t.

$y_p^{l,t} \in [0,1]$ a continuous variable representing the ore portion of mining-panel p to be mined in period t from location l, which includes ore, overburden and interburden dyke material and waste from the associated mining-cuts.

$z_k^{d,t} \in [0,1]$ a continuous variable representing the tailings coarse sand dyke material portion of mining-cut k to be extracted and used for dyke construction at destination d in period t.

Parameters

bc the cost per tonne of overburden dyke material for dyke construction.

$bc^{d,t}$ the cost in present value terms per tonne of overburden dyke material for dyke construction at destination d.

$c_k^{l,t}$ the discounted cost of mining all the material in mining-cut k as waste from location l in period t.

$c_p^{l,t}$ the discounted cost of mining all the material in mining-panel p as waste from location l in period t.

$d_k^{d,t}$ the discounted economic mining-cut value obtained by extracting mining-cut k and sending it to destination d in period t.

$d_{k,s}^{d,t}$ the discounted economic mining-cut value obtained by extracting mining-cut k and sending it to stockpile s and reclaiming it to destination d in period t.

$ei_k^{d,t}$ the extra discounted cost of mining all the material in mining-cut k as interburden dyke material for construction at destination d in period t.

$eo_k^{d,t}$ the extra discounted cost of mining all the material in mining-cut k as overburden dyke material for construction at destination d in period t.

$et_k^{d,t}$ the extra discounted cost of mining all the material in mining-cut k as tailings coarse sand dyke material for construction at destination d in period t.

F the annual fixed cost.

F^t the discounted annual fixed cost in period t.

f_n the opportunity cost.

fi_k^e the average percent of fines in ore portion of mining-cut k.

$\underline{fi}^{c,t,e}$ the lower bound on the required average fines percent of ore at processing destination c in period t.

$\overline{fi}^{c,t,e}$ the upper bound on the required average fines percent of ore at processing destination c in period t.

fi_k^{id} the average percent of fines in interburden dyke material portion of mining-cut k.

$\underline{fi}^{d,t,id}$ the lower bound on the required average fines percent of interburden dyke material at dyke construction destination d in period t.

$\overline{fi}^{d,t,id}$ the upper bound on the required average fines percent of interburden dyke material at dyke construction destination d in period t.

g_{avg_n} the average head grade.

g_k^e the average head grade of element e in ore portion of mining-cut k.

$g_{opt}^{c,t,e}$ the cut-off grade of element e at processing destination c in period t.

g_l the minimum acceptable cut-off grade.

g_m the mining limited cut-off grade.

G_{mp} the balancing cut-off grade between mining and processing.

G_{mr} the balancing cut-off grade between mining and refinery.

g_p the processing limited cut-off grade.

G_{pr} the balancing cut-off grade between processing and refinery.

g_r the refinery limited cut-off grade.

$HT^{c,t}$ the average head grade target at processing destination c in period t.

i the discount rate.

ic	the cost per tonne of interburden dyke material for dyke construction.
$ic^{d,t}$	the cost in present value terms per tonne of interburden dyke material for dyke construction at destination d .
id_k	the interburden dyke material tonnage in mining-cut k .
id_p	the interburden dyke material tonnage in mining-panel p .
$IT^{d,t}$	the interburden dyke material target (tonnes) at destination d in period t .
kc	the cost of mining a tonne of ore from stockpile.
$kc_s^{c,e,t}$	the extra cost in present value terms per tonne of ore for re-handling from stockpile s and processing at processing destination c in period t .
kd	the duration of stockpiling the material.
kt_n	the amount of material (tonnes) sent to the stockpile in each period.
mc	the cost of mining a tonne of waste.
$mc^{l,t}$	the cost in present value terms of mining a tonne of waste in period t from location l .
$MT^{l,t}$	the mining target (tonnes) at location l in period t .
o_k	the ore tonnage in mining-cut k .
o_p	the ore tonnage in mining-panel p .
od_k	the overburden dyke material tonnage in mining-cut k .

od_p the overburden dyke material tonnage in mining-panel p.

$OT^{d,t}$ the overburden dyke material target (tonnes) at destination d in period t.

pc the extra cost per tonne of ore for mining and processing.

$pc^{c,e,t}$ the extra cost in present value terms per tonne of ore for mining and processing at processing destination c in period t.

pe_1 the penalty paid per tonne in deviating from the mining target.

pe_2 the penalty paid per tonne in deviating from the processing target.

pe_3 the penalty paid per tonne in deviating from the overburden dyke material target.

pe_4 the penalty paid per tonne in deviating from the interburden dyke material target.

pe_5 the penalty paid per tonne in deviating from the tailing coarse sand dyke material target.

pe_6 the penalty paid per tonne in deviating from the average head grade target.

pe_7 the penalty paid per tonne in deviating from the average head grade target.

pl_1 the priority level associated with minimizing the deviations from the mining target.

pl_2 the priority level associated with minimizing the deviations from the processing target.

pl_3 the priority level associated with minimizing the deviations from the overburden dyke material target.

pl_4 the priority level associated with minimizing the deviations from the interburden dyke material target.

pl_5 the priority level associated with minimizing the deviations from the tailings coarse sand dyke material target.

pl_6 the priority level associated with minimizing the deviations from the average head grade target.

pl_7 the priority level associated with minimizing the deviations from the average head grade target.

PP_1 the prioritize penalty parameter associated with the deviation from the mining target.

PP_2 the prioritize penalty parameter associated with the deviation from the processing target.

PP_3 the prioritize penalty parameter associated with the deviation from the overburden dyke material target.

PP_4 the prioritize penalty parameter associated with the deviation from the interburden dyke material target.

PP_5 the prioritize penalty parameter associated with the deviation from the tailings coarse sand dyke material target.

PP_6 the prioritize penalty parameter associated with the deviation from the average head grade target.

PP_7 the prioritize penalty parameter associated with the deviation from the average head grade target.

pr_n the annual profit.

$PT^{c,t}$ the processing target (tonnes) at processing destination c in period t.

QM the maximum mining capacity in terms of tonnes per year

qm the amount of material to be mined (tonnes)

QP the maximum processing capacity in terms of tonnes per year

qp the amount of material to be processed (tonnes)

QR the maximum refinery capacity in terms of tonnes per year

qr the amount of material to be refined (tonnes)

r_{avg} the weighted average processing recovery factor.

$r_{avg,s}$ the weighted average processing recovery factor for the stockpiled material.

$r_{avg}^{c,e}$ the proportion of element e recovered if it is processed at processing destination c (weighted average processing recovery).

$r_{avg,s}^{c,e}$ the proportion of element e recovered if it is reclaimed from stockpile s and processed at processing destination c (weighted average processing recovery).

R_{IB} the ratio of the total amount of interburden dyke material over the total amount of waste material.

R_{OB} the ratio of the total amount of overburden dyke material over the total amount of waste material.

R_{TCS} the ratio of the total amount of tailings coarse sand dyke material over the total amount of ore material.

sp the selling price per unit of product.

$sp^{e,t}$ the selling price of element e in present value terms per unit of product.

sc the refinery and selling cost per unit of product.

$sc^{e,t}$ the refinery and selling cost of element e in present value terms per unit of product.

$sv_{k,s}^{c,t}$ the discounted revenue obtained by selling the final products within mining-cut k if it is sent to processing destination c in period t from stockpile s, minus the extra discounted cost of mining all the material in mining-cut k as ore from location l and processing at processing destination c; minus the extra discounted cost of re-handling for stockpile material; and minus the discounted annual fixed cost.

tc the cost per tonne of tailings coarse sand dyke material for dyke construction.

$tc^{d,t}$	the cost in present value terms per tonne of tailings coarse sand dyke material for dyke construction at destination d .
td_k	the tailings coarse sand dyke material tonnage in mining-cut k .
$TT^{d,t}$	the tailings coarse sand dyke material dyke material target (tonnes) at destination d in period t .
$v_k^{c,t}$	the discounted revenue obtained by selling the final products within mining-cut k if it is sent to processing destination c in period t, minus the extra discounted cost of mining all the material in mining-cut k as ore from location l and processing at processing destination c; and minus the discounted annual fixed cost
w_k	the waste tonnage in mining-cut k .
w_p	the waste tonnage in mining-panel p .

CHAPTER 1

1. INTRODUCTION

1.1. Background

Surface mining provides a considerable amount of minerals to meet the increasing demand of today's technology. Accessing an orebody to extract minerals by opening up a large stretch of ground to expose the ore to air is known as surface mining or open pit mining. Initially, mining operations start with a small pit on the surface and expands to a larger pit that encloses the initial one. This process continues until the final pit also known as the final pit limit or Ultimate Pit Limit (UPL) is reached (Shishvan and Sattarvand, 2015). The UPL is the final pit limit which attains the greatest profit (Akbari et al., 2008). In order to maximize the overall discounted net revenue of the UPL, the existing economic, technical, environmental and regulatory constraints for mining should be followed. Next, the best extracting sequence which is known as the mine planning process should be found. Before mining operations can start, the order of extraction of ore, waste, overburden and interburden mining blocks should be determined for the life of mine (Whittle, 1989).

The mine plan can be divided into short, medium and long-term plans depending on the scope of time it represents. The results from the Long-Term Production Planning (LTPP) process are used as guide for medium and short-term planning. Hence, LTPP optimization is one of the important parts of mine planning. In pursuit of achieving the maximum benefit from a mining operation, the long-term production schedule should consider the time and sequence for removing the ore and waste material mining blocks from the UPL. The best extraction schedule maximizes the Net Present Value (NPV) of the deposit. In the mining industry, deviations from the optimal mine plan may lead to significant financial losses. The mine management investment strategies, potential mine expansions and processing plant capacity should be defined based on the optimum long-term production plan in order to avoid possible future financial liabilities.

There are two main research areas used in optimizing the production scheduling process: 1) heuristic algorithms and 2) exact solution methods (Askari-Nasab and Awuah-Offei, 2009). Determining the cut-off grade is an essential aspect of optimizing the mine strategy and should be an outcome of an optimization process. Lane (1964) developed a comprehensive heuristic optimization model to determine the optimum cut-off grade policy and generate the life of mine production schedule. The model does not take into consideration waste management cost as required for integrated oil sands mine and waste disposal planning. This lead to the development of a modified version of Lane's model referred to in this research as the Integrated Cut-Off Grade Optimization (ICOGO) model.

These cut-off grade optimization models do not take into account detailed mining block extraction sequencing during optimization. A mathematical programming model referred to as a Mixed Integer Linear Goal Programming (MILGP) model was subsequently developed to generate detailed long-term production plans with integrated waste management for oil sands mining. Mathematical Programming Models (MPMs) with exact solution methods have proven to be strong tools for solving long-term production scheduling problems with known extent of optimality. The main limitation with mathematical programming frameworks is the cost of computation which increases exponentially with problem size (Ben-Awuah and Askari-Nasab, 2011). Because heuristic methods follow an iteration process to generate the best results among alternate options, they are usually computationally faster and cheaper than MPMs. However, the optimality of their outcome cannot be guaranteed.

1.2. Oil Sands Mining

Oil sands deposits contain five main rock types, namely: 1) Muskeg/peat, 2) Pleistocene unit, 3) Clearwater formation, 4) McMurray formation and 5) Devonian carbonates. Figure 1.1 shows the vertical soil profile of an oil sands deposit. The desired mineral is bitumen, which can be found in the McMurray formation. In order to gain access and mine the McMurray formation, the overburden materials which include muskeg, pleistocene unit and clearwater formation should be removed (Masliyah, 2010).

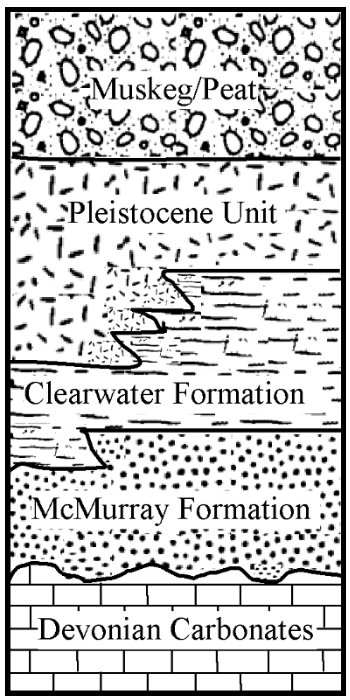

Figure 1.1: Vertical soil profile of an oil sands deposit modified after Dusseault (1977)

Materials with a specific amount of bitumen that also meets fines requirements are considered ore. After mining and processing oil sands ore, more than 80% of the processed ore is deposited in tailings dams (Masliyah, 2010). These tailings dams are constructed at designated areas outside of the final pit limit, or in mined out areas of the active pit. The large volumes of tailings material generated during mining have caused several environmental issues. In this regard, the regulatory requirements of the Alberta Energy Regulator (AER) Directive 085 (formerly interim directive ID 2001-7) require oil sands mining companies to integrate their waste management strategy into their long-term production plans (Ellis, 2016b).

To reduce the environmental footprints for oil sands mining, simultaneous in-pit dyke construction and tailings deposition has been introduced as the mine advances. This can be achieved by dedicating the area of each pushback that becomes available for dyke construction to generate a tailings containment area. The material required for dyke construction primarily comes from the mining operation, which includes overburden (OB), interburden (IB) and tailings coarse sand (TCS) dyke material. These materials must meet the fines requirements for dyke construction. Material that cannot be classified as ore or dyke material are considered to be waste material (Ben-Awuah and Askari-Nasab, 2011; Ben-Awuah et al., 2012).

1.3. Statement of the Problem

In current oil sands mining practices, scheduling for the waste management processes must happen for the same time period as the mining operation. Due to regulatory requirements and limited lease areas, the maximum use of in-pit tailings dams should be achieved during the life of mine in order to have a sustainable mining operation with reduced environmental footprint. Taking waste management into consideration during long-term production scheduling poses challenges related to creating an optimized mining schedule. The integration of the production schedule and waste management strategy increases the size of the optimization problem significantly. Incorporating various material types, elements, and destinations as well as providing an available in-pit area for construction of the dyke are a few of the parameters which result in a large scale optimization problem that can be difficult to solve.

For open pit mine design and scheduling optimization, the orebody is divided into a three-dimensional array of cubical blocks called a block model. The block model has attributes such as rock type, economic data, densities and grade which can be represented numerically. Dimensions of the block model are mainly selected based on the deposit's geology and the size of mining equipment. Depending on the size of the deposit and the blocks, a block model can be made of millions of blocks (Askari-Nasab et al., 2011). Figure 1.2 illustrates the strategic production planning for an oil sands deposit containing K mining-cuts and M pushbacks. Using an agglomerative hierarchical clustering algorithm developed by Tabesh and Askari-Nasab (2011), mining-cuts are formed. Mining-cuts are made up of blocks within the same level that are grouped based on their attributes; location, rock type and grade. The intersection of a group of mining-cuts belonging to the same mining bench and a mining-phase (pushback) is referred to as a mining-panel. Each mining-cut within a mining-panel contains: 1) ore material with bitumen grade higher than a specified value which also meets the fines requirements, 2) dyke material from processed ore known as TCS, 3) OB and IB which are materials with bitumen grade less than a specified value which also meets the dyke construction material requirements in terms of fines and 4) waste.

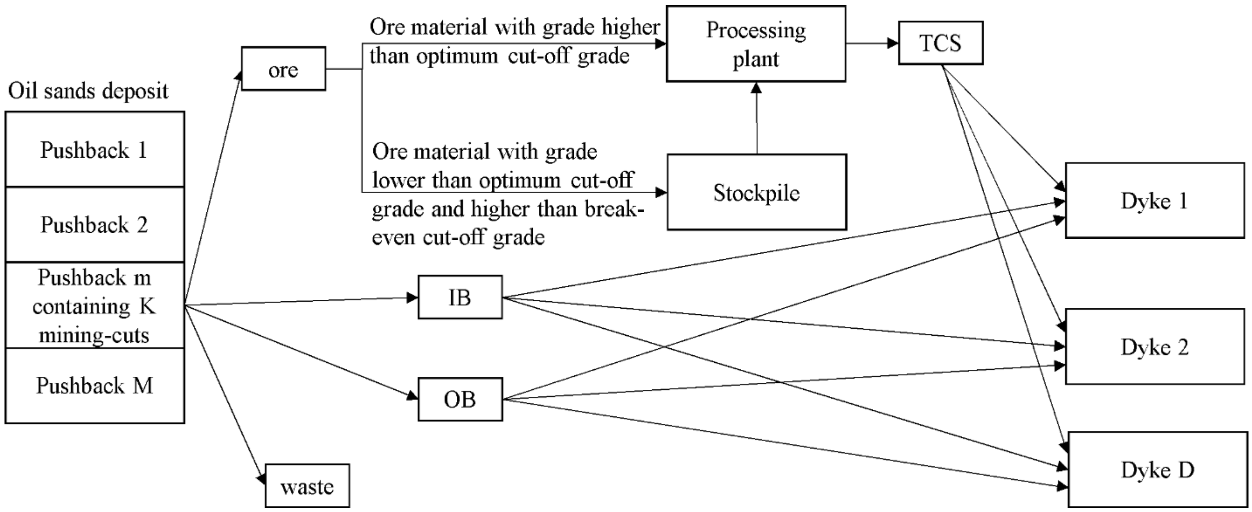

Figure 1.2: Material flow for oil sands production planning and waste management modified after Ben-Awuah et al. (2012)

In incorporating cut-off grade optimization into oil sands production and waste disposal planning, our objective is to focus on the following research tasks:

1. Determining the life of mine optimum cut-off grade profile and the corresponding production schedule to maximize the NPV of the operation.
2. Determining the time and sequence for removing the ore, dyke material and waste from the UPL to maximize NPV and minimize dyke construction cost.
3. Assessing the impacts of stockpiling and stockpile reclamation with limited time duration.

In Section 1.7, the methodology used to study the aforementioned research tasks are briefly discussed and more details provided in Chapter 3.

1.4. Summary of Literature Review

One of the simplest methods to calculate the cut-off grade is break-even analysis. The grade at which the obtained revenue is equal to the cost of generating that revenue is called the break-even cut-off grade. The break-even calculation is only based on economic parameters and does not include the mining, processing and refinery capacities or the geology of the deposit (Taylor, 1972; Hall, 2014). Although break-even cut-off grade is widely used in the mining industry, it does not guarantee generating the maximum NPV for the deposit.

Poniewierski and Hall (2016) stated that break-even calculation is not accurate enough. They illustrated that an error of 0.1 grams per tonne in the break-even calculation for a low grade gold deposit can result in 50-60 percent of the ore being considered as waste material. Some main reasons that can cause errors in the break-even calculation are the use of fixed recovery and the exclusion of sustaining capital costs. In most cases, a fixed recovery percentage is used in calculating the break-even grade even though in practice low and high grade materials do not have the same recovery percentages. Additionally, exclusion of sustaining capital costs required for maintaining capital items during the life of the equipment will result in noticeable errors in the break-even calculation (Poniewierski and Hall, 2016). The break-even calculation does not include geological and operational capacity parameters. In 1950, Mortimer described a new cut-off grade model which included geological parameters or grade distribution and cost parameters (Mortimer, 1950). The focus of his model were that the minimum grade of material mined must pay for itself and that a minimum profit per tonne must be provided by the average grade of material mined.

A general cut-off grade model was introduced by Lane in 1964 (Lane, 1964), which accounts for parameters including costs, grade distribution and operational capacities. The goal of Lane's model is to maximize the NPV, which is the most common goal in the mining industry. He explains that any mining operation has three main stages: mining, processing and refinery. Of the six potential cut-off grades calculated in his model, the first three are called limiting cut-off grades and are calculated based on economic parameters. The second three are called balancing cut-off grades and are dependent on the grade distribution of the deposit. Lane (1964) introduced an algorithm to find the optimum cut-off grade between the six potential cut-off grades. It has been proven that it is only by applying optimization methods like Lane's model, that the precision of the cut-off grade decision can be guaranteed (Lane, 1964, 1988, 1997; Hall, 2014). The primary disadvantage of Lane's model is that it requires the extraction sequence prior to the optimization process. Lane's model may result in sub-optimal results due to its heuristic nature (Dagdelen and Kawahata, 2008).

The optimality of the production scheduling results can be guaranteed if mathematical programming models (MPMs) are used in formulating long-term production planning (LTPP) problems and solved with exact solution methods. The NPV generated by such MPMs is usually higher than that from heuristic models as the solution gets closer to optimality. Linear Programming (LP), Mixed Integer Linear Programming (MILP) and Goal Programming (GP) are the main tools used in developing MPMs for mining applications. These models result in large scale optimization problems which may be difficult to solve (Johnson, 1967; Gershon, 1983; Akaike and Dagdelen, 1999). The main challenge in solving large scale optimization problems is the number of integer variables. Askari-Nasab et al. (2010) and Askari-Nasab et al. (2011) used block clustering algorithms to reduce the size of the optimization problem, specifically the number of integer variables in order to solve large scale optimization problems in an acceptable time.

Ben-Awuah and Askari-Nasab (2011) and Ben-Awuah et al. (2012) introduced a Mixed Integer Linear Goal Programming (MILGP) model for oil sands production scheduling and waste management optimization. The objective of their model was to maximize the NPV of the operation while minimizing the waste management cost. The model considered multiple elements, material types and destinations for ore and dyke material used in constructing in-pit and external tailings facilities. In order to reduce their MILGP solution time, they used a pre-processing approach to reduce the number of non-zero variables in the optimization problem. Results from their case studies showed a reduction in the solution time by more than 99% (Ben-Awuah and Askari-Nasab, 2013).

The research question here is; how can an optimum cut-off grade policy and an optimum production schedule for ore and dyke material be generated in order to maximize the NPV of an oil sands mining operation, while satisfying all of the physical, economic and regulatory requirements?

1.5. Objectives of the Study

In order to maximize the Net Present Value (NPV) of oil sands mining operations with respect to processing capacity, an Integrated Cut-Off Grade Optimization (ICOGO) model has been developed. The ICOGO model allows for determining the optimum cut-off grade policy in the presence of waste management for dyke construction and stockpiling with limited duration. The developed model considers stockpile re-handling and waste management costs and also generates a production schedule for multiple material types. The model has been implemented for an operation which is limited by the processing plant, as is mostly the case in oil sands mining. The results from the ICOGO model is used as a guide for defining the input parameters in oil sands production scheduling and waste management for medium and short-term mine planning.

In addition to the ICOGO model, this research developed and implemented a theoretical mathematical programming framework based on Mixed Integer Linear Goal Programming

(MILGP) model for detailed oil sands mine planning and waste management. The MILGP model focuses on the following objectives:

a) Maximize the NPV and minimize dyke construction cost of the operation by determining the time and sequence for removal of the ore, dyke material and waste from the final pit limit;

b) Minimize deviations from production goals (grade and tonnage) which are outcomes from the ICOGO model.

c) Evaluate the impact of stockpiling and stockpile with limited duration in oil sands mining

1.6. Scope and Limitations of Research

The main focus of this research is to develop an Integrated Cut-Off Grade Optimization (ICOGO) model considering waste management costs in dyke construction and stockpiling with a limited duration in oil sands mine planning. The general extraction sequence in terms of mining phases (pushback) should be provided to the ICOGO model prior to the optimization process. This model generates a production schedule in terms of ore and dyke material tonnage to support the processing plant and waste management strategies for an oil sands mining operation. The ICOGO model does not take into consideration detailed mining-cut extraction sequencing during mining. To overcome this limitation, a Mixed Integer Linear Goal Programming (MILGP) model was developed to determine the time and sequence for removal of ore, dyke material and waste from the final pit limit. For practical mining operation, mining-cuts are used to control processing and mining-panels are used to control mining. Both the ICOGO and MILGP models were developed based on the following assumptions and limitations:

- No grade uncertainty was considered;

- Future cost and price are constant;
- Geotechnical design of dyke construction was not evaluated.

1.7. Research Methodology

Waste management is an important aspect of oil sands mining, which drives the sustainability and profitability of the mining operation. In the first part of this research, a heuristic cut-off grade optimization model was developed considering waste management cost for ex-pit and in-pit dyke construction and stockpile with limited duration. Lane's (1964) model is used as the starting point for this research (Lane, 1964). The main objective is to develop and implement an Integrated Cut-Off Grade Optimization (ICOGO) model to generate an optimum life of mine cut-off grade profile and production schedule for different material types. Because Lane’s basic model does not consider waste management cost and stockpiling with limited duration as required in oil sands mining, an extension to this model referred to as the ICOGO model was developed for oil sands mining. The ICOGO model was coded in Matlab (Mathworks, 2015).

The ICOGO model does not take into consideration detailed mining-cut extraction sequencing during mining. Using Ben-Awuah et al. (2012) model as the starting point, the second part of the study focuses on developing a Mixed Integer Linear Goal Programming (MILGP) model to generate a detailed production schedule for different material types and destinations. The Ben-Awuah et al. (2012) model does not provide information on how initial grade boundaries and production targets were defined and they do not consider stockpiling in their model development. The MILGP model developed in the second part of this research uses the cut-off grade profile and schedule generated by the ICOGO model as guide to define the grade constraints and production goals required by the MILGP model. The developed model features stockpiling with limited duration for long-term production scheduling.

The MILGP model was coded in Matlab (Mathworks, 2015) and IBM CPLEX (IBM ILOG, 2012) was used to solve the resulting optimization problem. IBM CPLEX (IBM ILOG, 2012) uses branch-and-cut algorithm which is a hybrid of branch-and-bound algorithm and cutting plane methods to solve the optimization problem. The termination criterion, which is known as the gap tolerance (EPGAP), needs to be set by the user. EPGAP sets a relative tolerance on the gap between the best integer objective and the objective of the best node remaining in the branch-and-cut algorithm. CPLEX will terminate the optimization process when a feasible integer solution within the set EPGAP has been reached.

In order to verify the ICOGO and MILGP models, two oil sands case studies were evaluated. The results from the two models were analyzed and compared in terms of head grade, production schedule and stockpiling. Figure 1.3 is a schematic representation of the methodology used in this research.

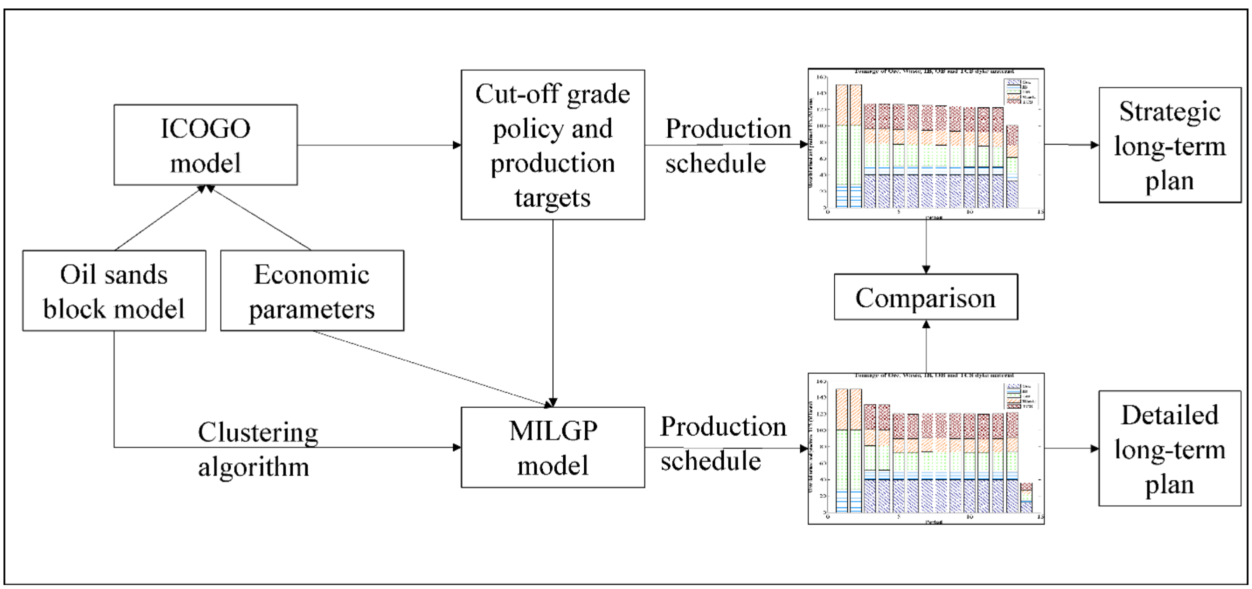

Figure 1.3: Summary of research methodology

The following is a list of the main research tasks completed to achieve the objectives of the study:

- Classify the oil sands block model into different material types based on regulatory, economic and technical requirements.
- Develop a heuristic cut-off grade optimization model to integrate waste management costs into cut-off grade optimization, considering stockpiling with limited duration for long-term production planning.
- Test and verify the cut-off grade optimization model (ICOGO model) with a hypothetical case study of a gold deposit presented in Dagdelen (1992) model.
- Implement the ICOGO model for two oil sands case studies to generate an optimum cut-off grade policy for the life of mine and corresponding ore and dyke material tonnages.
- Assess the impact of stockpiling and stockpile with limited duration.
- Develop a MILGP model to generate a detailed production schedule for different material types and destinations for oil sands mining and waste management.
- Implement the MILGP model for two oil sands case studies using the cut-off grade profile and production targets generated by the ICOGO model to define the grade boundaries and production goals for the MILGP model.
- Compare and analyze the results of the two models.

1.8. Scientific Contributions and Industrial Significance of the Research

The main contribution of this research is the integration of cut-off grade optimization into oil sands production scheduling and waste management. In summary, the major contributions of this study are as follows:

1. Developed an integrated cut-off grade optimization (ICOGO) model that allows the incorporation of waste management costs into the cut-off grade optimization framework.

2. The ICOGO model considers stockpiling with limited duration in the long-term production schedule. The ICOGO model can generate fast solution for long-term production scheduling problems for large mining projects.
3. Developed a mixed integer linear goal programming (MILGP) model that features stockpiling with limited duration for detailed integrated long-term production and waste management planning.
4. Provided a workflow that uses the ICOGO model to generate initial life of mine planning targets which are subsequently used as guides in setting up production goals for detailed medium and short-term production planning.
5. The ICOGO and MILGP models and workflow seek to support the oil sands mining industry in integrating mine planning and waste management in accordance with Directive 085 issued by the Alberta Energy Regulator (AER) on Fluid Tailings Management for Oil Sands Mining Projects.

1.9. Organization of Thesis

Chapter 1 of this thesis covers the background of the study and identifies the main problems that this research is going to study. The objectives and scope of the study, as well as the applied methodology used in the research are outlined. The scientific and industrial contributions are also discussed.

Chapter 2 reviews relevant literature related to cut-off grade optimization and open pit production planning algorithms, as well as discussions on clustering algorithm.

Chapter 3 contains two parts; the first part discusses the theoretical framework and implementation of an ICOGO model for oil sands mining operation. The second part discusses the theoretical framework and mathematical formulation for a MILGP model for production planning of oil sands mining operations.

Chapter 4 highlights the application of the ICOGO and MILGP models for two case studies. This chapter has two main sub-sections. In each section, application of the two models on each oil sands case study is discussed and the advantages and limitations outlined.

Chapter 5 is the concluding chapter. It contains the summary and conclusions of the thesis. The contributions of this research as well as future research work are discussed.

CHAPTER 2

2. LITERATURE REVIEW

2.1. Background

This chapter reviews literature related to cut-off grade optimization and algorithms developed based on Lane's model (1964), which has been used as the basis of this research. Mathematical programming for open pit mine production scheduling has also been discussed. Block clustering which is a technique used in providing practical mining widths and simplifying the complexity of the optimization problem are highlighted.

2.2. Cut-Off Grade Optimization

The most important economic criterion that separates ore from waste material is the cut-off grade. It specifies the grade of material that goes to the processing plant and to the waste dump (King, 1999). If the cut-off grade is determined to be too low, it will result in increasing the life of the operation with no economic justification. On the other hand, if the cut-off grade is set too high, it will result in the waste of some valuable materials (Bascetin and Nieto, 2007). Therefore, choosing the optimum cut-off grade has a significant impact on the economic viability of the operation.

A simple break-even calculation can generate the processing cut-off grade within the pre-defined pit limit. The results of the break-even calculation will generate a constant cut-off grade schedule for the life of mine (Taylor, 1972; Lane, 1988). However, it has been proven that a break-even calculation cannot maximize the NPV of the operation since it ignores the geology of the deposit and the operational constraints (Taylor, 1972; Poniewierski and Hall, 2016).

In 1964, Lane developed a cut-off grade optimization model that considers economic factors, grade-tonnage distribution and operational capacities. The objective function of Lane's model is to maximize the NPV of the operation with respect to capacities of the mining, processing and refinery processes. He considered the concept of opportunity costs in his model. Hall (2014)(1) stated that "the concept of opportunity cost is rigorously accounted for to indicate to what extent future production can be deferred to immediately treat additional material as ore". Lane's model generates a dynamic cut-off grade policy based on the concept of opportunity costs for the life of mine. During the early years of mining operation, Lane's model generates a higher cut-off grade, which decreases towards the end of the life of the operation (Lane, 1964). The dynamic nature of Lane's model requires the use of stockpiling. The material between the optimum grade and the lowest cut-off grade can be stockpiled during the mining operation for possible future reclamation (Asad et al., 2016).

Dagdelen (1992) presented the steps of Lane's theory for the case of a hypothetical gold deposit, where the capacity of the operation is only limited by the processing plant. He showed the difference between using dynamic cut-off grades versus constant break-even cut-off grades for production scheduling. He concluded that the optimized cut-off grade policy generates 90% higher NPV than the simple break-even cut-off grade. He also presented the complete steps of Lane's theory in the following year (Dadgelen, 1993).

Other researchers such as Osanloo et al. (2008) and Gholamnejad (2008; 2009) tried to incorporate environmental issues and related costs into the cut-off grade calculation. Osanloo et al. (2008) modified the basic Lane model to consider two different destinations for acidic and non-acidic waste. They incorporated the cost of dumping different kinds of waste in their

(1) Hall, B. (2014). *Cut-off Grades and Optimising the Strategic Mine Plan.* The Australian Institute of Mining and Metallurgy, Australia, Page 99.

formulation. Their case study showed an improvement of NPV compared to Lane's basic model as well as the environmental sustainability of the operation.

Gholamnejad (2008; 2009) used Lane's theory to determine the optimum cut-off grade in the presence of rehabilitation costs, which should be determined prior to optimization, so it can be used to generate more realistic results. He stated that by considering rehabilitation costs, the optimum cut-off grade will be reduced. This increases the amount of ore to be processed and decreases the amount of waste to be rehabilitated, which consequently results in an increase in the total NPV of the project (Gholamnejad, 2008, 2009).

In the algorithm presented by Lane, the mining, processing and refinery capacities are assumed to be constant. However, Abdollahisharif et al. (2012) tried to introduce variable production capacities into Lane's model. In comparison with Lane's basic model and the modified version of Lane's model developed by Gholamnejad (2009), the NPV was higher than these two models.

During the past four decades, many researchers have developed extensions to Lane's model for deposits with a single economic mineral. Mol and Gillies (1984) developed a cut-off grade model that maximizes material blending to help gain the required grade specification, as defined by market driven contracts. In the Lane's model iterative process, the concept of opportunity costs was modified by introducing an optimization factor to deal with the convergence of NPV, which resulted in an enhancement of NPV of the operation (Nieto and Bascetin, 2006). The generalized reduced gradient algorithm was used to generate a solution to the modified cut-off grade optimization model (Bascetin and Nieto, 2007).

In 1984, Lane introduced an important extension to the original model that made it capable of calculating the cut-off grades for multiple economic mineral deposits (Lane, 1984, 1988). For instance, a deposit with two economic minerals needs refinery details for two minerals and requires modifications to the formulation. In order to provide solutions for these kinds of problems, Lane used the grid search technique and provided a case study to illustrate the implementation of the approach.

Asad (2005) developed a stockpiling option extension to the Lane's original theory for deposits containing two economic materials. The stockpile acts as an additional pushback when active pit mining is completed. The material with grade between break-even grade and optimum cut-off grade is sent to the stockpile every year. He cautions that long-term stockpiling could result in problems such as leaching, deterioration of material and oxidation, which can lead to poor recovery in the treatment process. He also showed in a hypothetical case study that his model could increase the NPV of the mining operation. Asad (2007) used the concept of varying the annual commodity price and operating costs escalation and reported the effect of these modifications on the NPV of the mining operation by applying the model to a hypothetical copper deposit. Asad and Topal (2011) extended Asad's model (Asad, 2007) by adding a stockpiling scenario after pit mining is completed. They demonstrated the advantages of the model by comparing the cut-off grade policy with and without the stockpiling option and the improved NPV of the operation.

Other studies have been undertaken to make improvements to Lane's model for deposits with single and multiple economic minerals. In order to find the optimum cut-off grade policy, Osanloo and Ataei (2003) presented a golden section search method with equivalent grade factor for Lane's model. Genetic algorithm, golden section search, equivalent grade method and iterative grid search have been used by Ataei and Osanloo (2003a; 2003b; 2004) to generate the optimum cut-off grade policy in complex ore deposits. An application of the grid search technique for deposits with more than two economic minerals was also discussed by Cetin and Dowd (2013).

Lane's model has a heuristic nature and follows an iteration process. It needs the general extraction sequence as an input to the optimization process and generates the production schedule in terms of material tonnages and grades. Due to these factors, Lane's model may give sub-optimal solution to the optimization problem (Dagdelen and Kawahata, 2008). In order to find the optimal solution, mathematical programming cut-off grade models can be used, yet few studies have been conducted in this area (Asad et al., 2016). Dagdelen and Kawahata (2007; 2008) defined the optimal cut-off grade policy for an open pit mining operation by applying a MILP method. The mining operation in their study was comprised of various mines as material sources as well as several dumps, stockpiles and processing streams as material destinations.

An integer programming formulation was suggested by Moosavi et al. (2014). Their model concurrently provided solutions to mining sequence and cut-off grade optimization problems using various ore destinations or processing flows in conjunction with likely scenarios for the orebody. Their methodology was verified with a gold deposit, however, the mathematical model size and computational complexity were not reported (Moosavi et al., 2014).

In the case of oil sands mining, the planning engineer must schedule for both ore and dyke material (overburden, interburden and tailings coarse sand). The stockpiled material must also be processed within a limited timeframe due to oxidation that affects processing recovery efficiency. The first part of this research presents an extension of Lane's model that features concurrent production scheduling and waste management with limited stockpile duration and generates an optimum cut-off grade profile and schedule for different material types. The outcome of this integrated cut-off grade optimization model can be used to define the production targets and grade boundaries for detailed medium and short-term production scheduling.

2.3. Open Pit Production Scheduling

The problem of open pit production scheduling can be described as specifying the sequence in which mining blocks should be removed in order to maximize the NPV of the deposit, with respect to physical and economic constraints. The main constraint for production scheduling is the block extraction sequencing (Whittle, 1989). Some MILP models for mine production planning define production levels in terms of tonnage and grade. This concept can reduce complex computations, however, it ignores the detailed block extraction sequencing, which is the most important part of mine production planning (Gershon, 1983).

There are two main research areas in the development of production scheduling algorithms: 1) heuristic algorithms and 2) exact optimization methods (Askari-Nasab and Awuah-Offei, 2009). Heuristic methods follow an iterative process to generate the best results with alternate routes. However, the iteration process does not guarantee optimality. MPMs have proven to be strong tools for solving long-term production scheduling problems. Application of MPMs results in solutions with known extent of optimality. However, the computational cost of MPMs increases exponentially compared to heuristic methods. Consideration of thousands of variables by a MPM will cause a considerably large computational overhead, which may require deployment of high capacity computing resources (Ben-Awuah and Askari-Nasab, 2011).

Samavati et al. (2016) developed a metaheuristic technique called local branching. In their model, they combined local branching with an adaptive branching scheme and developed a heuristic method to generate an initial feasible solution prior to solving the production planning problem. They stated that within a given time limit, their algorithm outperformed both branch and cut and Lagrangian relaxation techniques. Shishvan and Sattarvand (2015) used ant colony optimization to develop a metaheuristic approximation method. The model was implemented using max-min ant system and ant colony system. They applied their model on a copper-gold deposit. Although the model cannot guarantee a global optimum schedule, it improved the value of the initial mining schedule generated by traditional algorithms in a reasonable computational time.

LP and MILP models are some of the most robust techniques used for solving mine production scheduling problems since the 1960s. These models can take into account thousands of decision variables and constraints. LP and MILP problems are solved using exact optimization methods which provide a single solution within the set optimality tolerance. The LP and MILP models are generated as a system of equations which makes them easy to use for multiple projects, requiring only minor changes to be made to them. On the other hand, like other MPMs, LP and MILP models are computationally costly, which can be difficult to handle for large problems with thousands of variables and equations (Huttagosol and Cameron, 1992).

Manula (1965), Johnson (1969) and Meyer (1969) were among the firsts to initiate development of LP and MILP models in mine planning optimization. One of the main obstacles that all of these authors encountered was solving the large integer programming problems. Despite the models' remarkable success, LP and MILP have not become the preferred method for mine planning due to computational difficulties (Gershon, 1983). One of the most critical parts of the production scheduling process is to determine a feasible mining sequence. Therefore, it is vital to follow the block extraction precedence relationships in the optimization process to ensure the long-term plan is feasible (Gershon, 1983).

During the past three decades, many authors have made efforts to overcome the problem of solving large scale optimization problems in a timely manner. The lagrangian relaxation algorithm is one of the methods that was adopted by Dagdelen (1985) and Dagdelen and Johnson (1986). Another method is the branch-and-cut algorithm which was used by Caccetta and Hill (2003) to solve large scale optimization problems. Binary variables are the main reason which makes solving the optimization problem difficult. One technique in solving the large scale problem is to reduce the size of the problem prior to optimization. Ramazan and Dimitrakopoulos (2004) reduced the number of binary variables to solve the optimization problem faster. In order to reduce the number of binary variables even more, Ramazan et al. (2005) and Ramazan (2007) used an aggregation method and solved the problem with a fundamental tree algorithm. However, using their method can eliminate the overall optimum solution due to the method of reduction of the problem size.

Askari-Nasab et al. (2010) applied MILP formulations to an open pit iron ore mine production schedule and compared their results to an industry strategic mine planning software, Whittle (Gemcom Software International Inc., 2013). In order to reduce the size of the optimization problem, they aggregated the mining blocks into mining-cuts using a clustering algorithm and claimed that the generated NPV of the MILP model was 2.6% higher than the NPV generated by Whittle Milawa Balanced algorithm (Gemcom Software International Inc., 2013). Askari-Nasab et al. (2011) stated that MILP formulations for open pit mine production scheduling have two primary weaknesses. First, generating global optimal life of mine production schedules within an acceptable timeframe cannot be achieved with current MILP formulations. Second, geological uncertainties in the form of grade and rock type are not fully integrated in the MILP formulations. In their study, they investigated four MILP formulations with different numbers of integer variables. In each model, extraction and processing can be controlled at either the block or mining-cut level. However, all the models designed to maximize the NPV of the open pit production scheduling problem had different assumptions and constraints. CPLEX environment was used to solve the MILP formulation (Askari-Nasab et al., 2011). Their results showed that the block level formulation generates a higher NPV compared to the rest of the models. However, this formulation is not suitable for long-term scheduling and is more appropriate for short-term planning. MILP formulations based on processing and extraction at mining-cut level, are models that maximize the NPV and are also suitable for long-term planning with an efficient computation time. They applied their models on a case study with 2,598 number of blocks. The block level formulation model solved the problem in 4 hours with 31,176 number of integer variables while the mining-cut level model solved the problem in 35 seconds with 5,232 number of integer variables. They concluded that the efficiency of the developed MILP formulations and NPV are affected by clustering algorithms and the number of mining-cuts (Askari-Nasab et al., 2011). They also acknowledged in their work that geological uncertainty and different material types were not considered in their study.

Another MPM used for LTPP problems is Goal Programming (GP). The benefit of using GP over other mathematical programming methods is the level of interaction between the user and the optimization process to be able to prioritize one goal over another. Zhang et al. (1993) used GP for LTPP of a mining operation with a single ore type process. They verified their model by applying it to an open pit coal mine. Chanda and Dagdelen (1995) and Esfandiri et al. (2004) also applied GP to the LTPP problem; however, they mentioned that the application of GP is impractical due to the size of the problem and large number of constraints. Research shows that there is a greater advantage using MILP and GP together. Industries such as manufacturing and operations management are taking advantage of the application of Mixed Integer Linear Goal Programming (MILGP) models (Selen and Hott, 1986; Liang and Lawrence, 2007; Sen and Nandi, 2012).

Ben-Awuah and Askari-Nasab (2011) formulated, implemented and tested a theoretical MILGP framework for oil sand production scheduling and waste management. Their model could handle multiple material types and elements in LTPP, and maximize the NPV of the operation. Ben-Awuah et al. (2012) completed their work by considering multiple destinations for dyke material, including in-pit and external tailings facilities for waste management. They used MILGP because the formulation structure allows the optimizer to achieve a set of goals, whilst some goals can be traded off against others based on their priority. In addition, hard constraints that could result in infeasible solutions can be changed to soft constraints. Their formulation used two sets of variables: integer variables to control mining precedence and continuous variables to control mining of ore and dyke material. They used mining-cuts and mining-panels from block clustering techniques to develop their model to create a practical, smooth and uniform schedule for ore and dyke material. The schedule resulted in maximum NPV while creating timely tailings storage areas. It should be mentioned that the main limitation with their model is the long runtime (Ben-Awuah et al., 2012).

In order to reduce the solution running time, Ben-Awuah and Askari-Nasab (2013) used a pre-processing approach to reduce the number of non-zero variables. For this purpose, they used an initial production schedule with a periodic tolerance generated based on a practical oil sands directional mining strategy and the annual mining capacity. In addition, to control mining precedence, they used pushback mining constraints for the production scheduling problem to reduce the number of integer decision variables. Results from their case studies showed a reduction in the solution time by more than 99% (Ben-Awuah and Askari-Nasab, 2013). Ben-Awuah et al. (2015) investigated concurrent production scheduling and different waste management strategies for an oil sands mining operation with a MILP model. Their results showed that the NPV of the operation reduces with an increased number of in-pit tailings facilities; however, this strategy supports sustainable mining and reduces the environmental footprint of the mining operation.

The second part of this thesis focuses on developing a MILGP framework to generate a detailed production schedule for different material types and destinations. The MILGP model presented here is a modified version of the Ben-Awuah et al. (2012) model. The Ben-Awuah et al. (2012) model does not provide information on how initial grade boundaries and production targets were defined and they do not consider stockpiling in their model development. The MILGP model developed in this research uses the cut-off grade profile and production schedule generated by the ICOGO model to define the grade and production targets required by the MILGP model. The MILGP model also features stockpiling with limited duration for long-term production scheduling.

2.4. Clustering and Paneling

A substantial challenge in finding the long-term optimal production schedule is a lack of adequate computer memory space during optimization calculations, due to exponential growth of the problem size with an increase in the number of blocks (Askari-Nasab and Awuah-Offei, 2009). The integer decision variables used in constructing the block mining precedence constraints require large computational resources during optimization. Employing clustering and paneling approaches reduces the optimization problem size and ensures minimum mining width is practical for the large mining equipment used in oil sands mining. Figure 2.1 shows the relation between blocks, mining-cuts and mining-panels on a level.

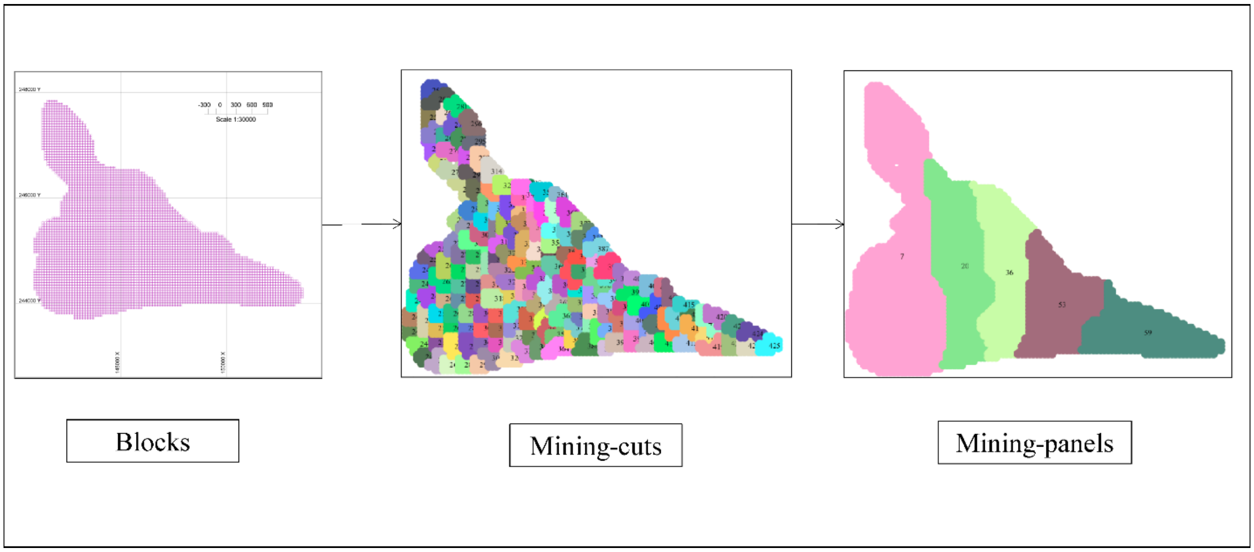

Figure 2.1: Relation between blocks, mining-cuts and mining-panels on a level

Combining similar entities in order to maximize intracluster similarity and intercluster dissimilarity is known as clustering. Clustering is categorized as either partitional or hierarchical. The partitional method divides data objects into various groups, while the hierarchical method forms a hierarchy of clusters. Hierarchical clustering is more efficient than partitional clustering. Heuristic methods have been proposed to solve these clustering algorithms by determining the extent of similarity and dissimilarity. Another classification of clustering algorithm is based on their usage; specific or general purpose algorithm. The general purpose algorithm deals with a set of attributed objects and tries to create a number of clusters in order to achieve a predefined intracluster similarity or intercluster dissimilarity. The specific purpose algorithm creates clusters according to an objective function for the clustering problem (Johnson, 1967; Feng et al., 2010; Tabesh, 2015).

In this research, hierarchical clustering algorithm is used in aggregating mining blocks into mining-cuts for solving the mine production scheduling problem. The clustering algorithm used here is customized for solving mine production planning problems. Using this method, ore data is summarized as well as modeling the total quantity of contained elements in the blocks for mining-cuts. Also, the separation of lithology is maintained (Tabesh and Askari-Nasab, 2011; Ben-Awuah and Askari-Nasab, 2013; Mathworks, 2015).

2.5. Summary

Over the past decades, researchers have improved the cut-off grade optimization framework introduced by Lane in 1964 by incorporating different parameters into the cut-off grade calculation. Due to the heuristic nature of Lane's model, it may result in sub-optimal solution to the optimization problem. It also generates a production schedule in terms of material tonnages for strategic planning.

In order to generate a detailed production schedule which specifies the time and sequence for removing the ore and waste material blocks from the final pit limit, MPMs are used. Application of MPMs results in solutions with known extent of optimality. However, using MPMs for production scheduling generates large scale optimization problems which may be difficult to solve. Applying clustering algorithms will reduce the size of the optimization problem as well as provide reasonable mining widths for practical mining.

CHAPTER 3

3. THEORETICAL FRAMEWORK

3.1. Background

In this chapter, a conceptual mining model will be developed, which takes into account the regulatory requirements of the Alberta Energy Regulator (AER) Directive 085 (Ellis, 2016b) and Directive 082 (Ellis, 2016a) for oil sands mining operations. The applied methodology used to integrate a waste management strategy into cut-off grade optimization will be explained. The cut-off grade optimization model developed in this work considers waste management costs, stockpile re-handling costs and a limited stockpile reclamation duration. The theoretical framework of the Integrated Cut-Off Grade Optimization (ICOGO) model will be presented, as well as steps for implementation of the ICOGO model. The optimized cut-off grade results from the ICOGO model can be used as guidance for a detailed production scheduling optimization process.

Subsequently, in this research a Mixed Integer Linear Goal Programming (MILGP) mathematical formulation is presented for long-term production scheduling. The MILGP model uses the output of the ICOGO model to define production targets and grade boundaries, and considers stockpiling with limited reclamation duration.

3.2. Block Clustering and Assumptions

For design and scheduling optimization of an open pit mine, the orebody is discretized as a block model comprised of three-dimensional arrays of cubical blocks. The number of blocks in the block model is related to the size of the deposit. The geology of the deposit and the preferred size of mining equipment can be used to identify the dimensions of the blocks in the block model. Characteristics of the blocks including rock type, density, grade and economic data can be expressed numerically (Askari-Nasab et al., 2011).

The blocks of the block model consist of smaller units called parcels, which contain information on rock-type, tonnage and element content. The waste from unknown rock-type is labeled as undefined waste. The overall tonnage of parcels and undefined waste should be equal to the block tonnage. The ore tonnage and the block grade can be used to estimate the quantity of minerals in a block. The spatial location of each block within the block model is determined by the coordinates of its center. However, the shape and location of the parcels within each block are not specified (Askari-Nasab and Awuah-Offei, 2009). The ultimate pit limit (UPL) can be generated using the block model as input to Whittle (Gemcom Software International Inc., 2013) strategic mine planning software which is developed based on the Lerchs and Grossmann (LG) algorithm (Lerchs and Grossmann, 1965).

In order to maximize the Net Present Value (NPV) for extracting the orebody with respect to physical and economic constraints, the optimized long-term production schedule should specify the sequence and time that blocks should be removed from the ultimate pit limit. An increase in the number of blocks will result in exponential growth of the production scheduling optimization problem size; to avoid this phenomenon, a clustering algorithm can be used. For the purpose of this research, mining-cuts are assumed to be made up of blocks within the same level that are grouped based on their attributes; location, rock type and grade, using an agglomerative hierarchical clustering algorithm developed by Tabesh and Askari-Nasab (2011). Mining-panels are made up of mining-cuts and can be used to control the mine production sequence. A mining-panel is the intersection of the material in a push back and a mining bench (Ben-Awuah and Askari-Nasab, 2013).

One of the main characteristics with the oil sands ore recovery process is that the processing plant recovery factor is a function of the average bitumen content. Figure 3.1 shows the processing plant recovery factor based on average weight percent bitumen content according to Directive 082 (Ellis, 2016a).

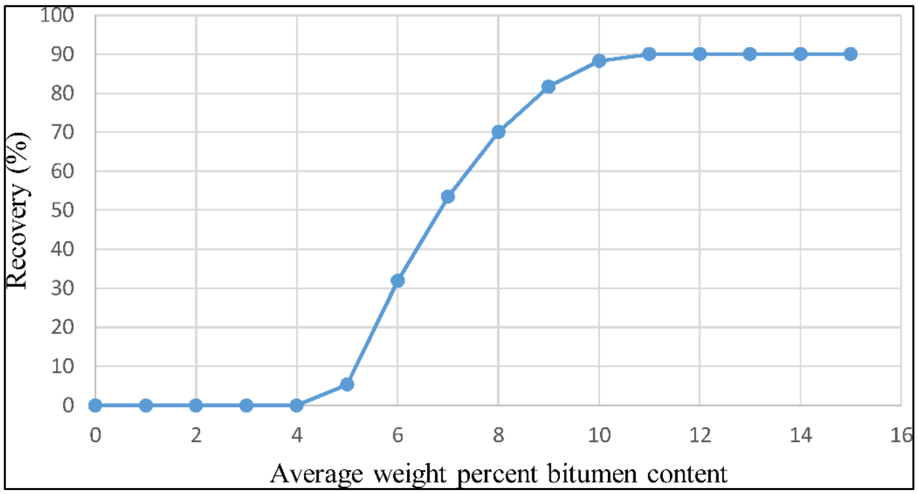

Figure 3.1: Processing plant recovery factor

In this research, the term 'lowest acceptable grade' refers to the break-even cut-off grade for oil sands mining and can be calculated based on the grade-recovery relationship. Initial cut-off grade analysis with Whittle (Gemcom Software International Inc., 2013) generated the lowest acceptable cut-off bitumen grade of 6% for the oil sands ore. Material with a bitumen grade less than 6% have less than 31% recovery and are therefore not economical to process. In addition when the extracted oil sands ore is stockpiled, the processing recovery begins to deteriorate as a result of oxidation. For this research, an assumed annual processing recovery deterioration of 1% is applied to the stockpiled ore during the mine life.

3.3. Conceptual Mining Model

Determining the cut-off grade policy is one of the most important steps for optimizing the long-term production schedule since it is the criterion that separates ore material from waste material. Materials with a grade higher than the cut-off grade value are classified as ore and materials with a grade lower than the cut-off grade value are classified as waste. The objective of determining the optimum cut-off grade profile is to achieve economic goals such as maximizing the NPV of the operation with respect to some constraints. Each operation has its own constraints including mining, processing and refinery capacity, environmental issues and extraction sequence.

In the case of oil sands mining, the waste management strategy drives the sustainability and profitability of the mining operation and makes it necessary to consider the waste management costs and its constraints in the cut-off grade optimization process for long term production planning (LTTP). According to the regulatory requirements of the Alberta Energy Regulator (AER) Directive 085 (formerly interim directive ID 2001-7) (Ellis, 2016b), oil sands mining companies are required to integrate their waste management strategy into the long-term production plans. The Directive 082 also requires mining companies not to leave behind any material containing more than 7% bitumen during mining (Ellis, 2016a).

The conceptual mining model used in this research considers waste management and re-handling costs of stockpiled material. It follows the regulatory requirements and provides in-pit tailings facilities for dumping tailings. The strategic production planning for an oil sands deposit containing K mining-cuts and M pushbacks was illustrated in Figure 1.2. Each mining-cut contains: 1) ore material with a bitumen grade higher than 6%, 2) dyke material from processed ore known as TCS, 3) OB and IB which are materials with bitumen grade less than 6% and also meet the dyke construction material requirements, and 4) waste.

3.4. The Integrated Cut-Off Grade Optimization (ICOGO) Model

In order to maximize the NPV of the oil sands mining operation with respect to processing capacity, an extension of Lane's cut-off grade optimization model (Lane, 1964) was developed to determine the optimum cut-off grade policy in the presence of waste management for dyke construction and stockpiling with limited duration. The limited stockpile duration is required for oil sands ore due to processing recovery deterioration resulting from oxidation of the stockpiled material. The cut-off grade optimization model developed in this work considers stockpile re-handling cost, waste management cost and generates a production schedule for multiple material types. The model is implemented for an operation which is limited by the processing plant, as is mainly the case in oil sands mining.

Lane (1964) developed a comprehensive model to determine the optimum cut-off grade and the amount of material to be mined, processed and refined in each period for the life of mine. The optimum cut-off grade policy in Lane's model (Lane, 1964) is dependent on economic parameters, limiting operational capacities and the grade distribution of the deposit. The model developed in this research is a modified version of Lane's model and is referred to as the Integrated Cut-Off Grade Optimization (ICOGO) model. The ICOGO model for oil sands mining incorporates waste management for dyke construction and limited stockpile time laps during the cut-off grade optimization process. Using stockpiling, the NPV of the operation can be improved significantly. The stockpiled material can be reclaimed in two ways: after pit mining is finished, or simultaneously during active pit mining (Ali and Khan, 2004). The two stockpiling options and a no stockpiling scenario are presented in this work. Dagdelen (1992) applied Lane's basic model to a hypothetical case study of a gold deposit. In order to verify the developed formulation, the ICOGO model was implemented for the hypothetical case study with the waste management cost set to zero and the outcomes compared with the results presented by Dagdelen (1992).

As mentioned in Section 1.4, one of the challenges in the cut-off grade calculation is the assumption of fixed processing recovery factor while oil sands ore has grade dependent processing recovery characteristics (Figure 3.1). To deal with this challenge, the ICOGO framework features the use of a weighted average recovery factor which is more representative of the entire deposit. In addition the processing recovery from the stockpile is assumed to be reduced by one percent each year until stockpile reclamation.

The pushback extraction sequence is a fundamental input for the ICOGO model. For the case of the presented work, the directional mining of the pushbacks are considered to be the main extraction sequence. In order to provide the required in-pit area for dyke construction and tailings deposition, each pushback should be completely mined out before starting to mine the next pushback in the mining direction.

3.4.1. Optimum Cut-Off Grade

Considering the lowest acceptable bitumen cut-off grade of 6%, the material in the final pit limit has been classified into ore, dyke material and waste. The tonnages of ore, OB, IB, TCS and waste material are estimated from the block model. In order to incorporate the cost of waste management into the cut-off grade optimization process, the ratio of the amount of dyke construction material should be related to the total amount of ore and waste as presented in Equations (3.1) to (3.3). The ratio of the TCS dyke material to the total amount of ore is R_{TCS} in Equation (3.1). Equation (3.2) shows R_{OB}, which is the ratio of OB dyke material to the total amount of waste and Equation (3.3) shows R_{IB}, which is the ratio of the total amount of IB dyke material to the total amount of waste.

$$R_{TCS} = \frac{Total\ amount\ of\ TCS\ dyke\ material}{Total\ amount\ of\ ore} \tag{3.1}$$

$$R_{OB} = \frac{Total\ amount\ of\ OB\ dyke\ material}{Total\ amount\ of\ waste} \tag{3.2}$$

$$R_{IB} = \frac{Total\ amount\ of\ IB\ dyke\ material}{Total\ amount\ of\ waste} \tag{3.3}$$

A mining operation is made up of three main stages namely: mining, processing and refinery. Each stage is limited by its costs and operational capacity. Lane (1964) established that any operation can have two groups of cut-off grades: limiting cut-off grades and balancing cut-off grades. The modifications applied to each of the two cut-off grades as presented in the ICOGO model for oil sands mining are discussed in the following sub-sections.

ICOGO Limiting Cut-Off Grade

These cut-offs are calculated based on economic parameters. Each of the mining, processing and refinery stages can be the limiting factor for mine production. Equation (3.4) shows the profit expression for an oil sands mining and waste management operations. The variables used in developing the equations have been defined in the List of Nomenclature section.

$$\text{Profit} = \text{Revenue} - \text{Processing Cost} - \text{Mining Cost} - \text{TCS Cost} - \text{OB Cost} - \text{IB Cost} - \text{Annual Fixed Cost}$$

$$pr = (sp - sc)\,qr - pc.qp - mc.qm - tc.R_{TCS}.qp - bc.R_{OB}.(qm - qp) - ic.R_{IB}.(qm - qp) - FT \tag{3.4}$$

- If the maximum mining rate is the overall constraint:

  The time (mine life) required to extract the total amount of material when the mining rate is the main constraint is calculated by Equation (3.5)(1). The amount of product is determined based on the amount of ore that is sent to the processing plant. Equation (3.6) shows the relation between the amount of ore and the amount of product.

$$T_m = \frac{qm}{QM} \tag{3.5}$$

$$qr = g_{avg}.r_{avg}.qp \tag{3.6}$$

For mining limited cut-off grade, Equation (3.10) can be calculated by substituting Equations (3.5) and (3.6) into Equation (3.4) to get Equation (3.7); and taking the derivative of Equation (3.7) with respect to the grade and setting it to zero (Equation (3.8)) for the optimum cut-off grade calculation.

$$pr = \left((sp - sc).g_{avg}.r_{avg} - pc - tc.R_{TCS} + bc.R_{OB} + ic.R_{IB}\right).qp - \left(mc + bc.R_{OB} + ic.R_{IB} + \frac{F}{QM}\right).qm \tag{3.7}$$

$$\frac{dpr}{dg} = \left((sp - sc).g_{avg}.r_{avg} - pc - tc.R_{TCS} + bc.R_{OB} + ic.R_{IB}\right).\frac{dqp}{dg} - \left(mc + bc.R_{OB} + ic.R_{IB} + \frac{F}{QM}\right).\frac{dqm}{dg} = 0 \tag{3.8}$$

(1) Lane, K. F. (1964). Choosing The Optimum Cut-off Grade. *Colorado School of Mines Quarterly*, *59* (4), page 816.

The cut-off grade affects the amount of processing material and product. The amount of material to be mined is independent from the grade, which makes $\frac{dqm}{dg}=0$. Hence, to make Equation (3.8) equal to zero, Equation (3.9) should be set equal to zero, which gives us the mining limited cut-off grade, Equation (3.10).

$$\left((sp-sc).g_{avg}.r_{avg}-pc-tc.R_{TCS}+bc.R_{OB}+ic.R_{IB}\right)=0 \tag{3.9}$$

$$g_m=\frac{pc+tc.R_{TCS}-bc.R_{OB}-ic.R_{IB}}{(sp-sc).r_{avg}} \tag{3.10}$$

- If the maximum processing rate is the overall constraint:

  The time (mine life) is determined by the processing rate using Equation (3.11). For processing limited cut-off grade, Equation (3.14) can be calculated by substituting Equations (3.6) and (3.11) into Equation (3.4) to get Equation (3.12); and taking the derivative of Equation (3.12) with respect to the grade and setting it to zero for the optimum cut-off grade calculation.

$$T_p=\frac{qp}{QP} \tag{3.11}$$

$$pr=\left((sp-sc).g_{avg}.r_{avg}-pc-tc.R_{TCS}+bc.R_{OB}+ic.R_{IB}-\frac{F}{QP}\right).qp-\\(mc+bc.R_{OB}+ic.R_{IB}).qm \tag{3.12}$$

Similarly, for $\frac{dpr}{dg}=0$, Equation (3.13) should be set equal to zero, which gives us the processing limited cut-off grade, Equation (3.14).

$$\left(\left(sp-sc\right).g_{avg}.r_{avg}-pc-tc.R_{TCS}+bc.R_{OB}+ic.R_{IB}-\frac{F}{QP}\right)=0 \tag{3.13}$$

$$g_p=\frac{pc+tc.R_{TCS}-bc.R_{OB}-ic.R_{IB}+\dfrac{F}{QP}}{\left(sp-sc\right).r_{avg}} \tag{3.14}$$

- If the maximum refinery rate is the overall constraint:

  The time (mine life) is determined by the refinery rate calculated by Equation (3.15). For refinery limited cut-off grade, Equation (3.18) can be calculated by substituting Equations (3.6) and (3.15) into Equation (3.4) to get Equation (3.16); and taking the derivative of Equation (3.16) with respect to the grade and setting it to zero for the optimum cut-off grade calculation.

$$T_r=\frac{qr}{QR} \tag{3.15}$$

$$pr=\left(\left(sp-sc-\frac{F}{QP}\right).g_{avg}.r_{avg}-pc-tc.R_{TCS}+bc.R_{OB}+ic.R_{IB}\right).qp-\left(mc+bc.R_{OB}+ic.R_{IB}\right).qm \tag{3.16}$$

Similarly, for $\frac{dpr}{dg}=0$, Equation (3.17) should be set equal to zero to give the refinery limited cut-off grade, Equation (3.18).

$$\left(\left(sp-sc-\frac{F}{QP}\right).g_{avg}.r_{avg}-pc-tc.R_{TCS}+bc.R_{OB}+ic.R_{IB}\right)=0 \tag{3.17}$$

$$g_r = \frac{pc + tc.R_{TCS} - bc.R_{OB} - ic.R_{IB}}{\left(sp - sc - \frac{F}{QR} \right).r_{avg}} \tag{3.18}$$

ICOGO Balancing Cut-off Grade

The balancing cut-off grade is the grade that balances two stages of operational capacity for the mining operation. As defined by Lane (1964), "balancing cut-off grades are independent of economics altogether being directly determined by the grade distribution. Also they are dynamic in that, in an irregular orebody, they can vary rapidly as mining progresses".

- If mining and processing are the limiting constraints:

  The balancing cut-off grade between these two stages given by Equation (3.19) is the grade which satisfies both the mining and processing limit.

$$\frac{qm}{QM} = \frac{qp}{QP} \Rightarrow g_{mp} \tag{3.19}$$

- If processing and refinery are the limiting constraints:

  The balancing cut-off grade between these two stages given by Equation (3.20) is the grade which satisfies both the processing and refinery limit.

$$\frac{qp}{QP} = \frac{qr}{QR} \Rightarrow g_{pr} \tag{3.20}$$

- If mining and refinery are the limiting constraints:

  The balancing cut-off grade between these two stages given by Equation (3.21) is the grade which satisfies both the mining and refinery limit.

$$\frac{qm}{QM} = \frac{qr}{QR} \Rightarrow g_{mr} \tag{3.21}$$

When the six potential cut-off grades $\left(g_{m,} g_p, g_r, g_{mp}, g_{pr}, g_{mr}\right)$ are determined, one should choose the optimum cut-off grade after following the steps of Lane's method in Equations (3.22) and (3.23) [(1)]. Equation (3.23) shows the optimum cut-off grade (Lane, 1964, 1988).

$$G_{mp} = \begin{cases} g_m \ if \ g_{mp} < g_m \\ g_p \ if \ g_{mp} > g_p \\ g_{mp} \ otherwise \end{cases} G_{pr} = \begin{cases} g_r \ if \ g_{pr} < g_r \\ g_p \ if \ g_{pr} > g_p \\ g_{pr} \ otherwise \end{cases} G_{mr} = \begin{cases} g_m \ if \ g_{mr} < g_m \\ g_r \ if \ g_{mr} > g_r \\ g_{mr} \ otherwise \end{cases} \tag{3.22}$$

$$g_{opt} = middle\ value\left(G_{mp}, G_{pr}, G_{mr}\right) \tag{3.23}$$

The optimal production and waste disposal schedule with a processing limited optimum cut-off grade policy can be generated with an iterative algorithm as presented in the following section.

3.4.2. Implementation of the ICOGO Model

In the case of oil sands mining, mine production is mainly limited by the processing plant capacity. Dagdelen (1992) presented a model to optimize the cut-off grade by Lane's method when the mining operation is only limited by the processing capacity (Darling, 2011). In this research, the ICOGO model is presented using Lane's model and a modified version of Dagdelen's algorithm (Darling, 2011). The ICOGO model generates an optimum production schedule for oil sands mining considering waste management for dyke construction and stockpiling with limited duration for a processing limited operation. Figure 3.2 presents the

(1) Lane, K. F. (1964). Choosing The Optimum Cut-off Grade. *Colorado School of Mines Quarterly*, *59* (4), page 821.

schematic steps of the algorithm implementing the ICOGO model for a processing limited operation.

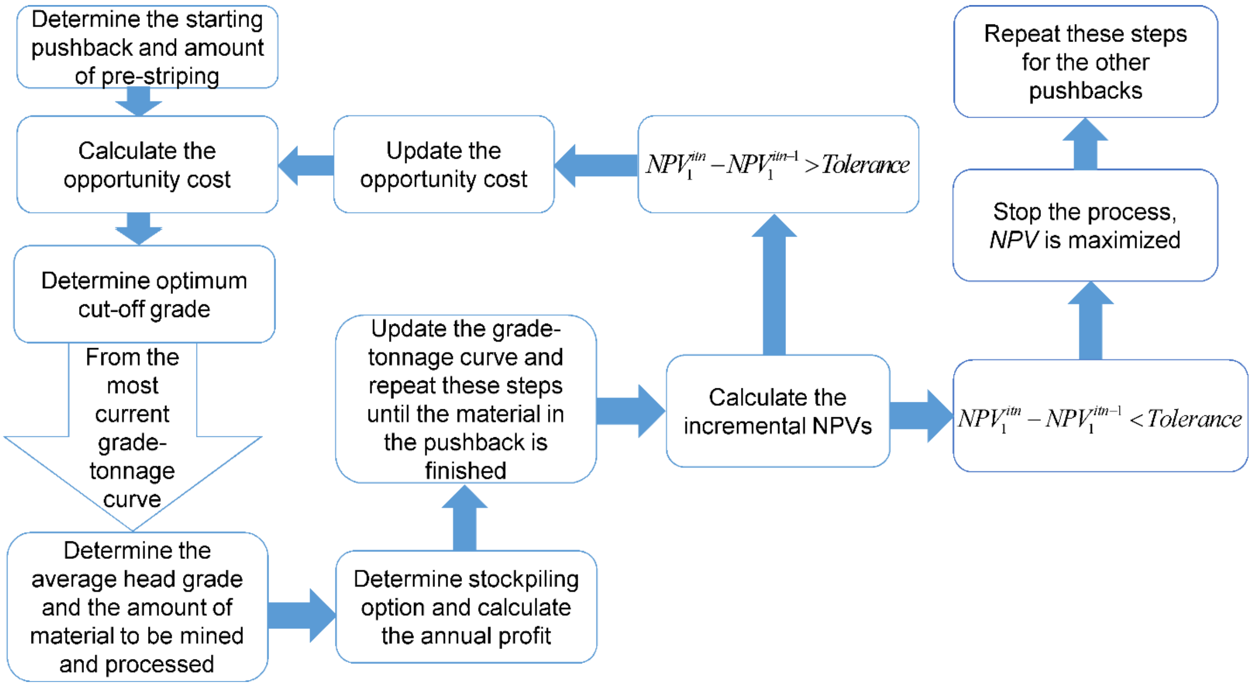

Figure 3.2: Flow diagram of algorithm steps

Steps of Iterative Algorithm

1. Gather the input data, including economic parameters, operational capacities and grade-tonnage curves for all pushbacks.

$$mc, pc, sc, kc, kd, sp, tc, bc, ic, R_{TCS}, R_{OB}, R_{IB}, r_{avg}, i, F, QM, QP, QR$$

2. Determine the time, the cost and the amount of pre-striping tonnage of material for each pushback.

    - Calculate the ratio of the available waste tonnage in each pushback over the total available waste tonnage in the final pit.

- Based on the calculated ratios, determine the time and the amount of pre-striping material that has to be removed from each pushback and calculate the cost of pre-striping using Equation (3.24).

$$pr_n = -\left(mc + bc.R_{OB} + ic.R_{IB}\right)qm \quad (3.24)$$

3. Update the grade-tonnage curve(s) starting from pushback one.
4. Determine the lowest acceptable grade, g_l.
5. Calculate the opportunity costs $\left(f_n\right)$ by Equation (3.25).
   - Set the initial $NPV_n = 0$
   - Cut-off grade should pay for the opportunity cost of not receiving the future cash flow from higher grade material in addition to the processing and waste management cost.
6. Determine processing cut-off grade in the year n by Equation (3.26)

$$f_n = \frac{i \times NPV_n}{QP} \quad (3.25)$$

$$g_{p_n} = \frac{pc + tc.R_{TCS} - bc.R_{OB} - ic.R_{IB} + f_n + \dfrac{F}{QP}}{\left(sp - sc\right).r_{avg}} \quad (3.26)$$

7. If the calculated g_{p_n} is less than g_l , set $g_{p_n} = g_l$
8. Based on the most recent grade-tonnage curve, determine:
   - q_o: The amount of ore tonnage above the cut-off grade

- g_{avg_n} : The weighted average ore grade above the cut-off grade

- q_w : The amount of waste tonnage below the cut-off grade

- $R_{sr} = \frac{q_w}{q_o}$: The stripping ratio

9. At this point the stockpile option should be decided and implemented; 1) without stockpile, 2) utilizing the stockpile after the mine is exhausted, or 3) utilizing the stockpile simultaneously with the mining operation.

   9.1) Without stockpile:

   - If $q_o \geq QP$
   - For the year n set the $qp = QP$
   - Otherwise set $qp = q_o$
   - Calculate the amount to be mined in a year by Equation (3.27)

$$qm = qp.(1 + R_{sr}) \tag{3.27}$$

   - Adjust the grade-tonnage curve without changing the shape: subtract the proportionate amount of qp from the ore tonnes and the proportionate amount of $(qm - qp)$ from the current waste tonnes of the grade-tonnage curve.
   - Calculate the annual profit for the mining operation by Equation (3.28)

$$pr_n = \left(\left((sp - sc).g_{avg_n}.r_{avg} \right) - pc - tc.R_{TCS} + bc.R_{OB} + ic.R_{IB} - \frac{F}{QP} \right) qp - \left(mc + bc.R_{OB} + ic.R_{IB} \right) qm \quad (3.28)$$

9.2) Utilize the stockpile after the mine is exhausted:

The stockpile is being considered as an extra pushback when the mine is exhausted.

- If $q_o \geq QP$
- For the year n set the $qp = q_o$
- Otherwise set $qp = q_o$
- Calculate the amount to be mined in a year by Equation (3.27)
- Adjust the grade-tonnage curve without changing the shape: subtract the proportionate amount of qp from the ore tonnes and the proportionate amount of $(qm - qp)$ with grades between g_{p_n} and g_l, which represents stockpile tonnes (kt_n) to be sent to the appropriate stockpile bin from the current waste tonnes of the grade-tonnage curve. Also, subtract the proportionate amount of $(qm - qp)$ with grades below g_l to be sent to the waste dump from the current waste tonnes of the grade-tonnage curve.
- Calculate the annual profit for the mining operation by Equation (3.29)

$$pr_n = \left(\left((sp - sc).g_{avg_n}.r_{avg} \right) - pc - tc.R_{TCS} + bc.R_{OB} + ic.R_{IB} - \frac{F}{QP} \right) qp - \left(mc + bc.R_{OB} + ic.R_{IB} \right) qm \tag{3.29}$$

- After depletion of pit reserves, start reclaiming stockpile. If total stockpile tonnage is more than QP, repeat the algorithm from step 5 for the cut-off grade optimization of stockpile reclamation; otherwise proceed.
- Calculate the annual profit for stockpile reclamation (qk) by Equation (3.30) while adjusting the processing recovery factor accordingly with the mine life duration.

$$pr_n = \left(\left((sp - sc).g_{avg_n}.r_{avg,s} \right) - pc - tc.R_{TCS} + bc.R_{OB} + ic.R_{IB} - \frac{F}{QP} \right) qp - (kc) qk \tag{3.30}$$

9.3) Utilize the stockpile simultaneously with the mining operation:

Determine the stockpile duration, kd. For instance, when the stockpile duration is one year, it means any material that is stockpiled should be reclaimed after one year.

- If $q_o \geq QP$
- For the year n set the $qp = QP - kt_{n-kd}$
- Otherwise set $qp = q_o - kt_{n-kd}$
- Calculate the amount to be mined in year n by Equation (3.27)
- Adjust the grade-tonnage curve without changing the shape: subtract the proportionate amount of qp from the ore tonnes and the proportionate amount of

$(qm - qp)$ with grades between g_{p_n} and g_l , which represents stockpile tonnes (kt_n) , to be sent to the appropriate stockpile bin from the current waste tonnes of the grade-tonnage curve. Also, subtract the proportionate amount of $(qm - qp)$ with grades below g_l to be sent to the waste dump from the current waste tonnes of the grade-tonnage curve.

- Calculate the annual profit for the mining operation and stockpile reclamation by Equation (3.31).

$$pr_n = \left(\left((sp - sc).g_{avg_n}.r_{avg} \right) - pc - tc.R_{TCS} + bc.R_{OB} + ic.R_{IB} - \frac{F}{QP} \right)(qp) + \left(\left((sp - sc).g_{avg_n}.r_{avg,s} \right) - pc - tc.R_{TCS} + bc.R_{OB} + ic.R_{IB} - \frac{F}{QP} \right)(kt_{n-kd}) - (mc + bc.R_{OB} + ic.R_{IB})qm - (kc).kt_{n-kd} \tag{3.31}$$

10. If qp is less than processing capacity QP
    - Set $T = n$ and go to the next step, step 11.
    - Otherwise set $n = n + 1$ and go to step 6.
11. Calculate the incremental NPV_n from year n to T by using Equation (3.32)

$$NPV_n = \sum_{k=n}^{T} \frac{pr_k}{(1+i)^{k-n+1}} \tag{3.32}$$

12. If the calculated NPV_1 is not in the specified tolerance from the previous iteration, update the opportunity cost and go to step 6. Otherwise, stop the process. The NPV of the pushback is maximized and the cut-off grades g_{p_n} for years 1 to T (life of each pushback) is the optimum cut-off grade policy. Repeat steps 3 to 12 until the material in

all pushbacks are extracted. Then, the cut-off grade policy and NPV of each pushback is maximized.

13. Calculate the overall NPV of the operation from the maximized cashflows of all the pushbacks including the cost of pre-striping with Equation (3.32) for the life of mine.

3.5. Mixed Integer Linear Goal Programming (MILGP) Model

In pursuit of achieving the maximum benefit in oil sands mining, the long-term production schedule should consider the time and sequence of removing the ore, dyke material and waste blocks from the ultimate pit limit (UPL) and their destinations. The MILGP model has the capability of considering multiple mining locations and pushbacks, as well as different types of materials and destinations (Ben-Awuah et al., 2012).

3.5.1. Economic Mining-cut Value

Each mining-cut has an economic value based on mining blocks which can be mined selectively within the mining-cut. The total discounted cost involved in excavating each mining-cut are the base discounted mining costs for excavating mining-cut *K* as waste; the extra discounted costs of processing the ore parcels contained in the mining-cut *K* at the designated processing destination; the extra discounted costs of excavating OB, IB and generated TCS dyke material from mining-cut *K* for dyke construction at designated destination, and the discounted annual fixed cost. Discounted profit generated from extracting each mining-cut can be defined based on the discounted revenue generated from selling the final product within each mining-cut minus the total discounted cost involved in extracting each mining-cut. Mining-panels are made up of mining-cuts that belong to the same pushback and mining bench. The sum of the discounted economic mining-cuts values within each mining-panel determines the discounted economic mining-panel value.

Equation (3.33) shows the discounted economic mining-cut value for mining-cut *K* that is sent from the mine to the plant. Equation (3.34) shows the discounted economic mining-cut value for mining-cut *K* that is sent from the stockpile to the plant.

$$d_k^{d,t} = v_k^{c,t} - c_k^{l,t} - eo_k^{d,t} - ei_k^{d,t} - et_k^{d,t} \tag{3.33}$$

$$d_{k,s}^{d,t} = sv_{k,s}^{c,t} - c_k^{l,t} - eo_k^{d,t} - ei_k^{d,t} - et_k^{d,t} \tag{3.34}$$

Equations (3.35) to (3.40) define the parameters in Equations (3.33) and (3.34). Equation (3.35) defines the discounted revenue generated from selling the final product within each mining-cut *K* minus the discounted cost of processing, minus the discounted annual fixed cost. Equation (3.36) defines the discounted revenue generated from selling the final product within each mining-cut *K* minus the discounted cost of processing, minus the extra discounted cost of re-handling the stockpile material, minus the discounted annual fixed cost. Equation (3.37) defines the base discounted mining cost for extracting mining-cut *K* as waste. Equations (3.38) to (3.40) show the extra discounted cost of mining OB, IB and TCS dyke material respectively, from mining-cut *K* to the appropriate dyke construction destinations.

$$v_k^{c,t} = o_k g_k^e r_{avg}^{c,e} (sp^{e,t} - sc^{e,t}) - o_k pc^{c,e,t} - o_k \left(\frac{F^t}{PT^{c,t}} \right) \tag{3.35}$$

$$sv_{k,s}^{c,t} = o_k g_k^e r_{avg,s}^{c,e} (sp^{e,t} - sc^{e,t}) - o_k pc^{c,e,t} - o_k kc_s^{c,e,t} - o_k \left(\frac{F^t}{PT^{c,t}} \right) \tag{3.36}$$

$$c_k^{l,t} = (o_k + od_k + id_k + w_k) mc^{l,t} \tag{3.37}$$

$$eo_k^{d,t} = od_k bc^{d,t} \tag{3.38}$$

$$ei_k^{d,t} = id_k ic^{d,t} \tag{3.39}$$

$$et_k^{d,t} = td_k tc^{d,t} \tag{3.40}$$

Using these equations, the economic mining-cut value of material from mine to plant or from stockpile to plant can be evaluated.

3.5.2. MILGP Objective Function

In order to maximize the NPV of the mine operation, the MILGP model objective function should contain all of the following parameters: determining the time and the sequence for removal of ore, dyke material and waste from the UPL; minimizing the dyke construction cost; and minimizing deviations from production goals which are inputs from the ICOGO model. Here, we used the Ben-Awuah et al. (2012) model as a starting point. The MILGP model uses two sets of decision variables: binary integer decision variables to control precedence relation of mining-panels extraction and continuous decision variables to control mining, processing, stockpiling, OB, IB and TCS dyke material production requirements. In addition, continuous deviational variables have been defined to control the mining, processing, OB, IB and TCS dyke material production goals, and processing plant head grade goals. These variables provide an option for the user to set a continuous range of units for the optimization process to achieve the targeted goals. In order to prioritize goals and set precedence for achieving one goal over another, priority parameters were defined. The main goal that the user wants to achieve can have the highest priority parameter, ensuring that the optimization process will achieve that goal. For any deviation from the targeted goals, a penalty cost exists that reduces the NPV. Prioritized penalty parameters were defined to control deviations from the targeted goals. These are presented in Equations (3.41) through to (3.47) for each of the deviational variables.

$$PP_1 = pl_1 \times pe_1 \tag{3.41}$$

$$PP_2 = pl_2 \times pe_2 \tag{3.42}$$

$$PP_3 = pl_3 \times pe_3 \tag{3.43}$$

$$PP_4 = pl_4 \times pe_4 \tag{3.44}$$

$$PP_5 = pl_5 \times pe_5 \tag{3.45}$$

$$PP_6 = pl_6 \times pe_6 \tag{3.46}$$

$$PP_7 = pl_7 \times pe_7 \tag{3.47}$$

Based on the regulatory requirements (Ellis, 2016a), oil sands mining companies cannot leave behind any unprocessed material containing more than 7% bitumen. Moreover, based on our initial scheduling analysis with Whittle Milawa Balanced algorithm (Gemcom Software International Inc., 2013), we determined that materials containing more than 6% bitumen have economic potential. During production, it is assumed that all material sent to the stockpile will be reclaimed after a specified stockpiling duration (kd). This assumption supports the regulatory requirements because keeping oil sands ore in the stockpile for a long time will result in oxidation that causes challenges in the bitumen extraction process. In order to add a stockpile to the MILGP model, we introduced a new set of decision variables, $x_{k,s}^{c,t}$. Tabesh (2015) used a stockpiling decision variable in a MILP model. He stated that to avoid a non-linear problem when adding stockpiling to the production scheduling problem, stockpile bins with known grade ranges should be considered for each period. In the MILGP model developed in this research, we consider that for every period there are stockpile bins available where material can be sent, and after the stockpiling duration, the exact amount of material with known grades can be reclaimed.

The maximization of NPV and minimization of dyke construction costs for an oil sands mining operation is determined using Equations (3.48) and (3.49). In these equations, continuous decision variables $y_p^{l,t}, x_k^{c,t}, x_{k,s}^{c,t}, u_k^{d,t}, n_k^{d,t}$ and $z_k^{d,t}$ are controlling mining, processing, stockpiling, OB, IB and TCS dyke material production, respectively. Equation (3.50) shows the minimization of the deviation variables from the set targets. For mining, processing, OB, IB and TCS dyke material production goals, we only defined negative deviational variables which are $gd_1^{-,l,t}, gd_2^{-,c,t}, gd_3^{-,d,t}, gd_4^{-,d,t}, gd_5^{-,d,t}$ respectively. However, for an average processing plant head grade goal, we defined negative $\left(gd_6^{-,c,t}\right)$ and positive $\left(gd_6^{+,c,t}\right)$ deviational variables.

$$Max\sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{s=1}^{S}\sum_{c=1}^{C}\sum_{t=1}^{T}\left(\sum_{\substack{k\in C_p\\ p\in C_m}}\left(v_k^{c,t}x_k^{c,t}+sv_{k,s}^{c,t}x_{k,s}^{c,t-kd}-c_p^{l,t}y_p^{l,t}\right)\right) \tag{3.48}$$

$$Min\sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{t=1}^{T}\left(\sum_{\substack{k\in C_p\\ p\in C_m}}\left(eo_k^{d,t}u_k^{d,t}+ei_k^{d,t}n_k^{d,t}+et_k^{d,t}z_k^{d,t}\right)\right) \tag{3.49}$$

$$Min\sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{t=1}^{T}\left[\sum_{\substack{k\in C_p\\ p\in C_m}}\begin{pmatrix}PP_1gd_1^{-,l,t}+PP_2gd_2^{-,c,t}+PP_3gd_3^{-,d,t}+PP_4gd_4^{-,d,t}\\ +PP_5gd_5^{-,d,t}+PP_6gd_6^{-,c,t}+PP_7gd_6^{+,c,t}\end{pmatrix}\right] \tag{3.50}$$

To formulate a single objective function for the MILGP model, Equations (3.48) to (3.50) are combined to generate Equation (3.51).

$$Max\sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{s=1}^{S}\sum_{c=1}^{C}\sum_{t=1}^{T}\left[\sum_{\substack{k\in C_p\\ p\in C_m}}\left[\begin{matrix}\left(v_k^{c,t}x_k^{c,t}+sv_{k,s}^{c,t}x_{k,s}^{c,t-kd}-c_p^{l,t}y_p^{l,t}\right)-\left(eo_k^{d,t}u_k^{d,t}+ei_k^{d,t}n_k^{d,t}+et_k^{d,t}z_k^{d,t}\right)-\\ \begin{pmatrix}PP_1gd_1^{-,l,t}+PP_2gd_2^{-,c,t}+PP_3gd_3^{-,d,t}+PP_4gd_4^{-,d,t}+PP_5gd_5^{-,d,t}+\\ PP_6gd_6^{-,c,t}+PP_7gd_7^{+,c,t}\end{pmatrix}\end{matrix}\right]\right] \tag{3.51}$$

3.5.3. MILGP Goal Functions

The MILGP model uses goal functions to accomplish the long-term production targets generated by the ICOGO model. The goal functions for production targets are defined by Equations (3.52) to (3.56) for mining, processing, OB, IB and TCS dyke material in terms of tonnage. The average head grade goal function, Equation (3.57), is defined in terms of grade unit (%mass).

$$\sum_{m=1}^{M}\left(\sum_{p\in C_m}\left(o_p+od_p+id_p+w_p\right)y_p^{l,t}\right)+gd_1^{-,l,t}=MT^{l,t} \tag{3.52}$$

$$\left[\sum_{p=1}^{P}\left(\sum_{\substack{k\in C_p\\ p\in C_m}}\left(o_kx_k^{c,t}\right)\right)+\sum_{p=1}^{P}\left(\sum_{\substack{k\in C_p\\ p\in C_m}}\left(o_kx_{k,s}^{c,t-kd}\right)\right)\right]+gd_2^{-,c,t}=PT^{c,t} \tag{3.53}$$

$$\sum_{p=1}^{P}\left(\sum_{\substack{k\in C_p\\ p\in C_m}}\left(od_ku_k^{d,t}\right)\right)+gd_3^{-,d,t}=OT^{d,t} \tag{3.54}$$

$$\sum_{p=1}^{P}\left(\sum_{\substack{k\in C_p\\ p\in C_m}}\left(id_k n_k^{d,t}\right)\right)+gd_4^{-,d,t}=IT^{d,t} \tag{3.55}$$

$$\sum_{p=1}^{P}\left(\sum_{\substack{k\in C_p\\ p\in C_m}}\left(td_k z_k^{d,t}\right)\right)+gd_5^{-,d,t}=TT^{d,t} \tag{3.56}$$

$$\frac{\sum_{p=1}^{P}\left(\sum_{\substack{k\in C_p\\ p\in C_m}} o_k g_k^e x_k^{c,t}\right)+\sum_{p=1}^{P}\left(\sum_{\substack{k\in C_p\\ p\in C_m}} o_k g_k^e x_{k,s}^{c,t-kd}\right)}{\sum_{p=1}^{P}\left(\sum_{\substack{k\in C_p\\ p\in C_m}} o_k x_k^{c,t}\right)+\sum_{p=1}^{P}\left(\sum_{\substack{k\in C_p\\ p\in C_m}} o_k x_{k,s}^{c,t-kd}\right)}+gd_6^{-,c,t}-gd_7^{+,c,t}=HT^{c,t} \tag{3.57}$$

Equation (3.52) is the mining goal function that controls the total amount of material to be mined in each period. In this equation, $gd_1^{-,l,t}$ controls the acceptable deviation from the mining target defined by the user. Equation (3.53) is the processing goal function that defines the total amount of ore sent to the processing destination in each period from the mine and the stockpile, and should be equal to the processing target. The amount of material sent to the processing destination from the stockpile in period *t* is equal to the amount of material that was sent to the stockpile in period *t-kd*. In this equation, $gd_2^{-,c,t}$ controls the acceptable deviation from the set processing target. Equations (3.54) to (3.56) are the dyke material goal functions. Using the goal function, the planner can set the dyke material production target for different dyke construction destinations, which can provide a practical schedule for dyke construction. Equation (3.57) controls the average head grade of the material being sent to the processing destination from the mine and stockpile. The acceptable negative and positive deviations from the set targets are controlled by $gd_6^{-,c,t}$ and $gd_6^{+,c,t}$ respectively. Equation (3.57) has a nonlinear format. The numerator of the first part of the equation is equal to the amount of element content in each production period and the denominator is equal to the amount of material processed in each period. Dividing these two, will generate the grade of the material processed. In order to convert Equation (3.57) to a linear format, the head grade target and deviational variables are multiplied by the processing target to generate element content target.

In general, these goals are defined with guidance from the production targets generated by the ICOGO model.

3.5.4. MILGP Cut-Off Grade Constraints

The optimum cut-off grade profile was generated by the ICOGO model. Here, the cut-off grade values for each period are used to control the grade of the material that can be sent to the processing destination. Equation (3.58) controls the grade of material that can be sent to the processing destination in each period. Based on this equation, if the grade of the mining-cut *K* is less than the optimum cut-off grade of period *t*, then mining-cut *K* cannot be sent to the processing destination in period *t*. Equation (3.59) controls the grade of material that can be sent to the stockpile in each period. Based on this equation, if the grade of mining-cut *K* is higher than the optimum cut-off grade of period *t* or is less than the minimum acceptable grade, mining-cut *K* cannot be sent to the stockpile in period *t*.

$$x_k^{c,t} \leq 0 \qquad \forall\ \mathrm{g}_k^e < g_{opt}^{c,t,e} \tag{3.58}$$

$$x_{k,s}^{c,t} \leq 0 \qquad \forall\ \mathrm{g}_k^e \geq g_{opt}^{c,t,e} \ \ or \ \ \mathrm{g}_k^e < g_l \tag{3.59}$$

3.5.5. MILGP Fines Blending Constraints

In order to ensure the quality of the material sent to the processing plant and dyke construction destinations, materials should meet the fine requirements. The ore material that have been sent to the processing destination should have the quality required at the processing destination. Inequality Equations (3.60) and (3.61) ensure that the ore material sent to the processing destination is between the minimum and maximum fines requirements. Furthermore, the inequality Equations (3.62) and (3.63) verify the same requirements for the ore material that has been sent to the stockpile, since they will all be reclaimed in the following years.

Based on the dyke construction requirements, IB dyke material should have the required fines content. Inequality Equations (3.64) and (3.65) guarantee that the IB dyke material sent to the different dyke construction destinations have between the minimum and maximum fines requirements.

$$\underline{fi}^{c,t,e}\sum_{p=1}^{P}\left(\sum_{\substack{k\in C_p\\ p\in C_m}} o_k x_k^{c,t}\right)-\sum_{p=1}^{P}\left(\sum_{\substack{k\in C_p\\ p\in C_m}} o_k\, fi_k^{e} x_k^{c,t}\right)\leq 0 \tag{3.60}$$

$$\sum_{p=1}^{P}\left(\sum_{\substack{k\in C_p\\ p\in C_m}} o_k\, fi_k^{e} x_k^{c,t}\right)-\overline{fi}^{c,t,e}\sum_{p=1}^{P}\left(\sum_{\substack{k\in C_p\\ p\in C_m}} o_k x_k^{c,t}\right)\leq 0 \tag{3.61}$$

$$\underline{fi}^{c,t,e}\sum_{p=1}^{P}\left(\sum_{\substack{k\in C_p\\ p\in C_m}} o_k x_{k,s}^{c,t}\right)-\sum_{p=1}^{P}\left(\sum_{\substack{k\in C_p\\ p\in C_m}} o_k\, fi_k^{e} x_{k,s}^{c,t}\right)\leq 0 \tag{3.62}$$

$$\sum_{p=1}^{P}\left(\sum_{\substack{k\in C_p\\ p\in C_m}} o_k\, fi_k^{e} x_{k,s}^{c,t}\right)-\overline{fi}^{c,t,e}\sum_{p=1}^{P}\left(\sum_{\substack{k\in C_p\\ p\in C_m}} o_k x_{k,s}^{c,t}\right)\leq 0 \tag{3.63}$$

$$\underline{fi}^{d,t,\mathrm{id}} \sum_{p=1}^{P} \left(\sum_{\substack{k \in C_p \\ p \in C_m}} id_k n_k^{d,t} \right) - \sum_{p=1}^{P} \left(\sum_{\substack{k \in C_p \\ p \in C_m}} id_k \, fi_k^{id} n_k^{d,t} \right) \leq 0 \tag{3.64}$$

$$\sum_{p=1}^{P} \left(\sum_{\substack{k \in C_p \\ p \in C_m}} id_k \, fi_k^{id} n_k^{d,t} \right) - \overline{fi}^{d,t,\mathrm{id}} \sum_{p=1}^{P} \left(\sum_{\substack{k \in C_p \\ p \in C_m}} id_k n_k^{d,t} \right) \leq 0 \tag{3.65}$$

3.5.6. MILGP Mining-Panels Extraction Precedence Constraints

Integer variables are one of the principal reasons making the optimization problem difficult to solve. The extraction precedence of blocks in mining operations needs to be controlled by integer variables. Mining-panels have been used to reduce the number of integer variables and to help solve the optimization problems in a more efficient manner. Mining-panels also provide good minimum mining width for the large cable shovels and trucks used in oil sands mining.

In order to control the mining-panels extraction precedence, a set of binary integer variables $\left(b_p^t \in [0,1]\right)$ are used. If the extraction of mining-panels *p* has started in or by period *t*, b_p^t is equal to one, otherwise it is zero. Equation (3.66) ensures that all of the immediate preceding mining-panels above mining-panel *p* are extracted before mining-panel *p* can be extracted. $F_p(L)$ is the set containing all of the immediate predecessor mining-panels above mining-panel *p*. Equation (3.67) ensures that all of the immediate preceding mining-panels in the horizontal mining direction of mining-panel *p* are extracted before mining-panel *p* can be extracted. $R_p(Z)$ is the set containing all of the immediate preceding mining-panels in the horizontal mining direction, preceding mining-panel *p*. Equation (3.68) ensures that before mining-panel *p* can be extracted, all of the immediate predecessor mining-panels in a mining phase, are extracted.

$C_m(H)$ is the set containing all the immediate preceding mining-panels to mining-panel *p* in a mining phase. Equation (3.69) confirms that if mining-panel *p* has not been extracted in previous steps, then the extraction of that mining-panel can be processed. Equation (3.70) ensures that if mining-panel *p* extraction starts in period *t*, then mining-panel *p* will be available for extraction in the proceeding periods.

$$b_p^t - \sum_{v=1}^{l}\sum_{i=1}^{t} y_w^{v,i} \le 0 \qquad w \in F_p(L) \tag{3.66}$$

$$b_p^t - \sum_{v=1}^{l}\sum_{i=1}^{t} y_j^{v,i} \le 0 \qquad j \in R_p(Z) \tag{3.67}$$

$$b_p^t - \sum_{v=1}^{l}\sum_{i=1}^{t} y_g^{v,i} \le 0 \qquad g \in C_m(H) \tag{3.68}$$

$$\sum_{v=1}^{l}\sum_{i=1}^{t} y_p^{v,i} - b_p^t \le 0 \tag{3.69}$$

$$b_p^t - b_p^{t+1} \le 0 \tag{3.70}$$

3.5.7. MILGP Variables Control Constraints

In the MILGP model, the variables logic that indicates mining, processing, dyke materials and goal deviations are controlled by applying the variables control constraints, ensuring the requirements of each variable are met. Inequality Equation (3.71) makes sure that the material mined as ore and dyke material from mining-cuts belonging to mining-panel *p* in period *t* are less or equal to the total material mined from mining-panel *p* in period *t* from any mining location. Equation (3.72) is a reserve constraint that ensures that the total available ore in each mining phase will be mined. This facilitates in-pit tailings deposition once a phase is completely extracted. Inequality Equations (3.73) to (3.76) ensure that the summation of the portions of the mining-panels and mining-cuts scheduled for different destinations in different periods are less than or equal to one. Since the TCS dyke material is produced from processed ore, Equation (3.77) ensures that the fraction of TCS produced in each period is less than or equal to the fraction of ore processed in that period.

$$\sum_{d=1}^{D}\sum_{s=1}^{S}\sum_{c=1}^{C}\sum_{\substack{k\in C_p\\ p\in C_m}}\left(o_k x_k^{c,t} + o_k x_{k,s}^{c,t} + od_k u_k^{d,t} + id_k n_k^{d,t}\right) \le \sum_{l=1}^{L}\sum_{p\in C_m}\left[y_p^{l,t}\left(o_p + od_p + id_p + w_p\right)\right] \tag{3.71}$$

$$\sum_{s=1}^{S}\sum_{c=1}^{C}\sum_{t=1}^{T} x_k^{c,t} + x_{k,s}^{c,t} = 1 \tag{3.72}$$

$$\sum_{d=1}^{D}\sum_{t=1}^{T} y_p^{d,t} \le 1 \tag{3.73}$$

$$\sum_{d=1}^{D}\sum_{t=1}^{T} u_k^{d,t} \le 1 \tag{3.74}$$

$$\sum_{d=1}^{D}\sum_{t=1}^{T} n_k^{d,t} \le 1 \tag{3.75}$$

$$\sum_{d=1}^{D}\sum_{t=1}^{T} z_k^{d,t} \le 1 \tag{3.76}$$

$$\sum_{d=1}^{D}\sum_{t=1}^{T} z_k^{d,t} \le \sum_{c=1}^{C}\sum_{t=1}^{T} x_k^{c,t} + \sum_{s=1}^{S}\sum_{t=1}^{T} x_k^{s,t-kd} \qquad t-kd>0 \tag{3.77}$$

3.5.8. MILGP Non-Negativity Constraints

Equation (3.78) ensures that the decision variables for mining, processing, stockpiling, OB, IB and TCS dyke material production cannot be a negative number. In order to support the goal functions, Equation (3.79) ensures that the deviational variables cannot be negative.

$$y_p^{l,t}, x_k^{c,t}, x_{k,s}^{c,t}, u_k^{d,t}, n_k^{d,t}, z_k^{d,t} \geq 0 \tag{3.78}$$

$$gd_1^{-,l,t}, gd_2^{-,c,t}, gd_3^{-,d,t}, gd_4^{-,d,t}, gd_5^{-,d,t}, gd_6^{-,c,t}, gd_7^{+,c,t} \geq 0 \tag{3.79}$$

3.6. Summary

In this chapter, the theoretical framework and implementation of the ICOGO model was presented. The optimum cut-off grade policy and the production schedule generated by the ICOGO model is used as a guide for defining the input parameters of medium and short-term production scheduling.

In addition, a mathematical formulation based on MILGP framework was presented. The initial production targets of the goal functions in the MILGP model are defined based on the results from the ICOGO model. The grade boundaries were also defined based on the optimum cut-off grade profile generated by the ICOGO model.

CHAPTER 4

4. APPLICATION OF MODELS

4.1. Background

In this chapter, the Integrated Cut-off Grade Optimization (ICOGO) model and the Mixed Integer Linear Goal Programming (MILGP) framework developed in Chapter 3 are applied to two oil sands case studies. For each of the case studies, the ICOGO model was first applied and the results used as a guide to define the production targets and grade boundaries for the MILGP model. Different stockpiling scenarios are investigated to assess the impact of the stockpile and its duration on the mining operation. The results from the ICOGO and MILGP models for each case study are compared.

In both case studies, the main focus of the ICOGO model is to generate a uniform production rate for ore material and complete extraction of all pushbacks. For the first case study, the MILGP model was forced to extract all the materials for different destinations to verify the model. All the dyke material deviations were chosen to ensure complete dyke material extraction for dyke construction.

In the second case study, the prioritized penalty parameters for dyke material were set to higher values to ensure we can achieve most of the dyke material goals. The main focus of the second case study experiment was to generate a uniform production rate for ore material and the outcome would be based on the mining economics.

4.2. First Case Study

The final pit limit for the first case study was generated with Whittle (Gemcom Software International Inc., 2013) software using the LG algorithm (Lerchs and Grossmann, 1965). No pushbacks were considered prior to the final pit limit. In order to create mining-panels, the final pit was divided into five pseudo pushbacks. Using a hierarchical clustering algorithm (Tabesh and Askari-Nasab, 2011), blocks in each mining-panel were grouped together as mining-cuts. Table 4.1 reports information about the oil sands deposit for the first case study. The economic data in Table 4.2 was extracted and compiled based on Ben-Awuah (2013) and Burt et al. (2012). Since all the input parameters are considered to be deterministic, the discount rate of 15% is used among other things to consider the risks associated with the mining of oil sands resources. Figure 4.1 represents the cumulative bitumen grade-tonnage distribution of the deposit and Figure 4.2 shows the bitumen grade distribution in the first case study area on level 287.5m.

Table 4.1: Oil sands deposit final pit characteristics for first case study

Description	Value
Total tonnage of material (Mt)	1338.7
Total ore tonnage (Mt)	451.8
Total TCS dyke material tonnage (Mt)	341.7
Total OB dyke material tonnage (Mt)	426.8
Total IB dyke material tonnage (Mt)	167.6
Total waste tonnage (Mt)	292.5
Number of blocks	18,301
Number of mining-cuts	1,055
Number of mining-panels	44
Number of benches	9

Table 4.2: Economic parameters for first case study (Ben-Awuah, 2013; Burt et al., 2012)

Parameter	Value
Mining cost ($/tonne)	2.5
Processing cost ($/tonne)	5.03
Stockpiling cost ($/tonne)	0.5
Selling price ($/bitumen %mass)	4.5
Annual fixed cost (M$/year)	530
TCS dyke material cost ($/tonne)	0.92
OB dyke material cost ($/tonne)	0.95
IB dyke material cost ($/tonne)	0.95
Discount rate (%)	15

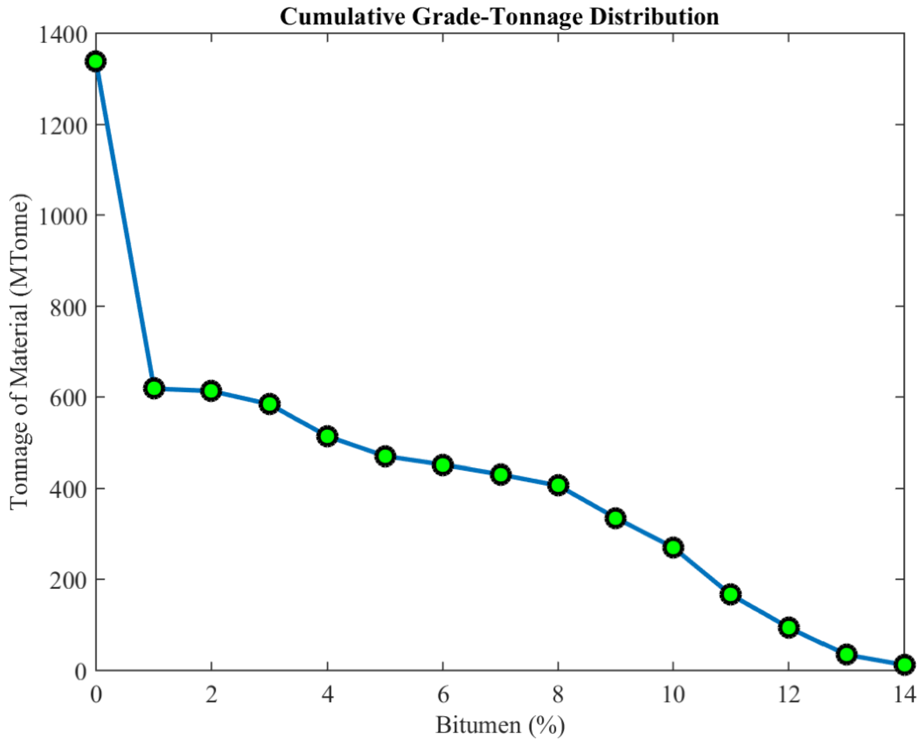

Figure 4.1: Cumulative bitumen grade-tonnage distribution of the oil sands deposit (first case study)

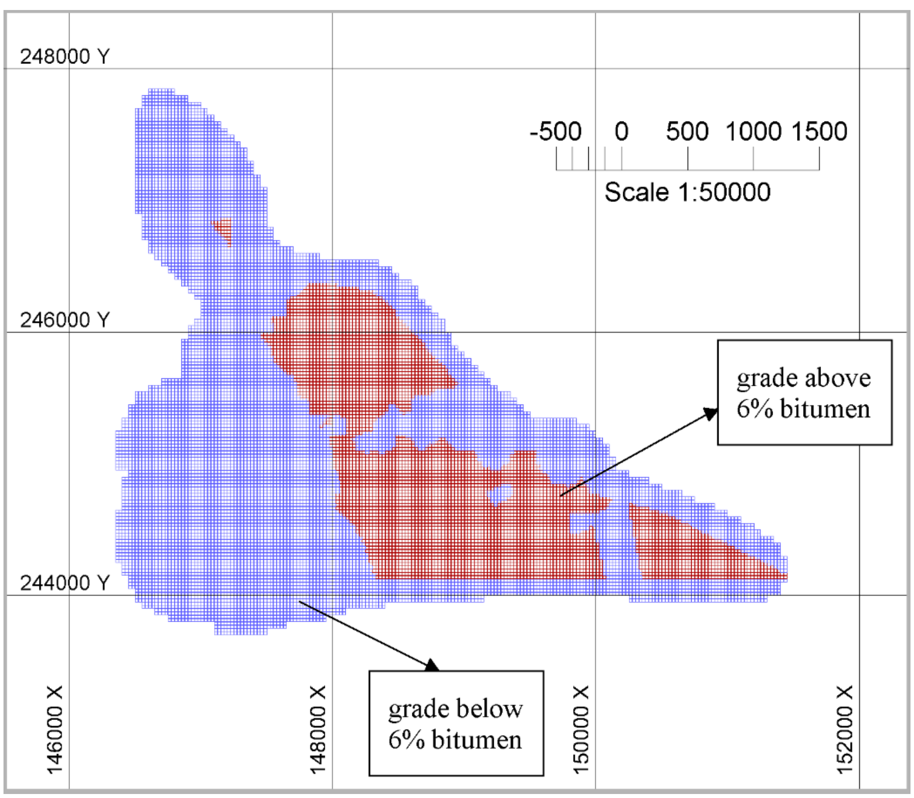

Figure 4.2: Bitumen grade distribution in the first case study area on level 287.5m

4.2.1. Application of ICOGO Model

The ICOGO model was coded in Matlab (Mathworks, 2015) and implemented on the oil sands deposit. The bitumen grade-tonnage distribution of the deposit which is needed for the ICOGO model is presented in Table 4.3. The ratio of the TCS (R_{TCS}) dyke material to the total quantity of ore and the ratio of OB (R_{OB}) and IB (R_{IB}) dyke material to the total quantity of waste as well as the required operational capacities for the ICOGO model are presented in Table 4.4.

Table 4.3: Grade-Tonnage distribution of the oil sands deposit (first case study)

Bitumen Grade (%)	Tonnage (Mt)
0 – 6	886.9
6 – 7	21.2
7 – 8	24.2
8 – 9	70.9
9 – 10	65.2
10 – 11	104.1
11 – 12	71.7
12 – 13	59.8
13 – 14	22.4
Above 14	12.3

Table 4.4: Operational capacities for the first case study

Description	Value
Ratio of TCS dyke material (R_{TCS})	0.7563
Ratio of OB dyke material (R_{OB})	0.4813
Ratio of IB dyke material (R_{IB})	0.1890
Mining capacity (Mt/year)	Unlimited
Processing capacity (Mt/year)	40
Refinery capacity (Mt/year)	Unlimited
Processing weighted average recovery (%)	84

The model was implemented on the case study based on different stockpiling management scenarios: 1) without stockpile, 2) reclaiming stockpile at the end of the mine life, 3) reclaiming stockpile simultaneously with the mining operation after one year and 4) reclaiming stockpile simultaneously with the mining operation after two years. The termination criterion for the cut-off grade heuristic optimization algorithm is a NPV tolerance of $5 M. If the calculated NPV_1 is in a $5 M tolerance from the previous iteration, then the optimization process will stop.

The results for each of the production schedule scenarios after cut-off grade optimization are presented in Table 4.5 to Table 4.8.

Table 4.5: Scenario 1 - Production schedule with optimum cut-off grade policy without stockpile

Year	Cut-off grade (%)	Average head grade (%)	Material mined (Mt/year)	Material processed (Mt/year)
1	0	0	150	0
2	0	0	150	0
3	7.74	10.70	100.7	40
4	7.62	10.68	99.9	40
5	7.47	10.66	99.1	40
6	7.30	10.62	98.1	40
7	7.11	10.59	97.1	40
8	6.89	10.55	95.9	40
9	6.64	10.50	94.8	40
10	6.36	10.45	93.6	40
11	6.03	10.38	92.1	40
12	6.00	10.37	91.9	40
13	6.00	10.37	75.5	32.9

Table 4.6: Scenario 2 - Production schedule with optimum cut-off grade policy and stockpile reclamation after pit mining is exhausted

Year	Cut-off grade (%)	Average head grade (%)	Material mined (Mt/year)	Material to stockpile (Mt/year)	Material from stockpile (Mt/year)	Material processed (Mt/year)
1	0	0	150	0	0	0
2	0	0	150	0	0	0
3	7.75	10.71	100.7	3.8	0	40
4	7.62	10.68	99.9	3.5	0	40
5	7.47	10.66	99.1	3.1	0	40
6	7.30	10.62	98.1	2.6	0	40
7	7.10	10.59	97.1	2.2	0	40
8	6.88	10.54	95.9	1.7	0	40
9	6.63	10.50	94.8	1.2	0	40
10	6.35	10.44	93.6	0.76	0	40
11	6.02	10.38	92.1	0.04	0	40
12	6.00	10.37	91.9	0	0	40
13	6.00	10.37	75.5	0	0	32.9
14	6.00	6.77	0	0	18.9	18.9

Table 4.7: Scenario 3 - Production schedule with optimum cut-off grade policy and simultaneous stockpile reclamation after one year duration

Year	Cut-off grade (%)	Average head grade (%)	Material mined (Mt/year)	Material to stockpile (Mt/year)	Material from stockpile (Mt/year)	Material processed (Mt/year)
1	0	0	150	0	0	0
2	0	0	150	0	0	0
3	7.88	10.73	101.5	4.1	0	40
4	7.77	10.71	90.3	3.5	4.1	40
5	7.61	10.68	91.2	3.2	3.5	40
6	7.44	10.65	91.1	2.8	3.2	40
7	7.25	10.61	91.1	2.4	2.8	40
8	7.03	10.57	90.8	1.9	2.4	40
9	6.78	10.53	90.8	1.4	1.9	40
10	6.50	10.47	90.7	0.9	1.4	40
11	6.19	10.41	90.6	0.3	0.9	40
12	6.00	10.37	91.1	0	0.3	40
13	6.00	10.37	92.3	0	0	40
14	6.00	10.37	27.2	0	0	11.8

Table 4.8: Scenario 4 - Production schedule with optimum cut-off grade policy and simultaneous stockpile reclamation after two years duration

Year	Cut-off grade (%)	Average head grade (%)	Material mined (Mt/year)	Material to stockpile (Mt/year)	Material from stockpile (Mt/year)	Material processed (Mt/year)
1	0	0	150	0	0	0
2	0	0	150	0	0	0
3	7.87	10.73	101.5	4.1	0	40
4	7.75	10.71	100.7	3.8	0	40
5	7.62	10.68	89.7	3.1	4.1	40
6	7.45	10.65	89.5	2.7	3.8	40
7	7.25	10.61	90.2	2.4	3.1	40
8	7.03	10.57	89.9	1.9	2.7	40
9	6.79	10.53	89.8	1.4	2.4	40
10	6.50	10.47	89.7	0.9	1.9	40
11	6.20	10.41	89.4	0.4	1.4	40
12	6.00	10.37	89.9	0	0.9	40
13	6.00	10.37	91.2	0	0.4	40
14	6.00	10.37	27.2	0	0	11.8

Discussion of results

In the case study, the mining operation was only limited by the processing capacity. The main target of the ICOGO model was to achieve the maximum processing capacity throughout the mine life and to generate a production schedule for extracting all the material in the final pit limit. Before starting the ore mining operation, two years of pre-striping waste was planned to provide a uniform ore production rate when the ore mining starts. It was assumed that pre-striping operations will be done by a contractor. In the first scenario, the total NPV generated together with waste management cost is $1,411.5 M. From year three when the ore mining started, the mine operates at the maximum processing capacity until the last year when the material in the final pit limit is exhausted. Figure 4.3 shows the schedule for material mined and the amount of TCS dyke material produced. The model generated a uniform production schedule for ore, IB, OB and TCS dyke material over the life of mine.

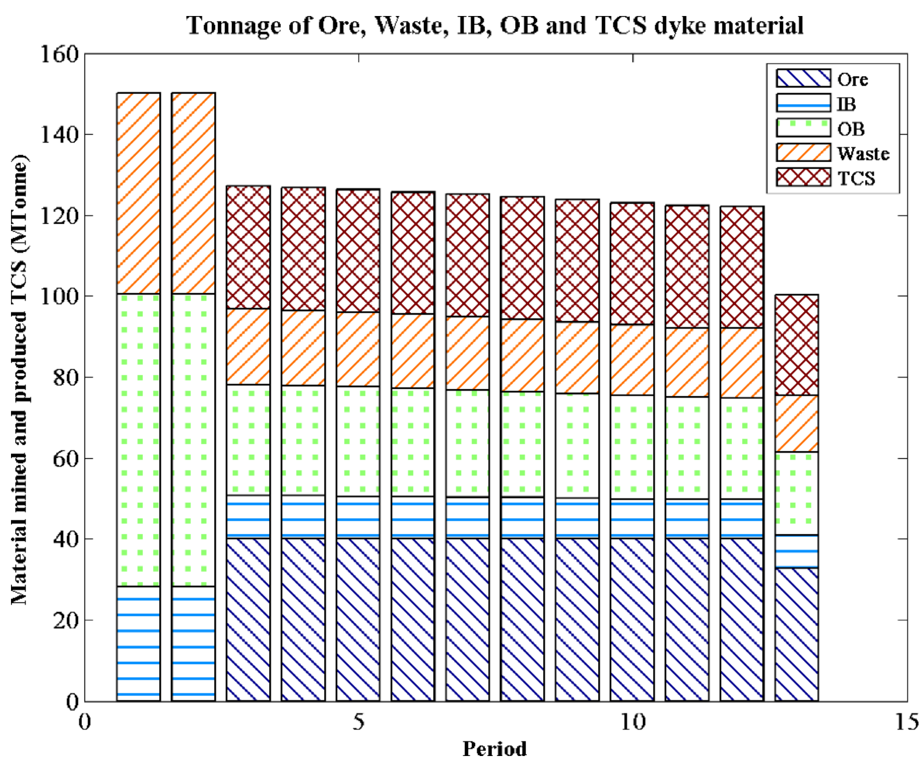

Figure 4.3: Scenario 1 - Schedule for material mined and produced TCS

In Scenario 2, the life of mine was increased by one year and the generated NPV showed an increase of $39.8 M in the total NPV of the operation. This improvement was due to the reclamation of the stockpile after closure of pit mining. The total amount of ore that was processed increased by 18.9 Mt compared to Scenario 1 where the 18.9 Mt of material were below the optimum cut-off grade and hence sent to the waste dump. Figure 4.4 shows the schedule for material mined, reclaimed and the amount of TCS dyke material produced in Scenario 2. Figure 4.5 shows the amount of material sent to and reclaimed from the stockpile. It should be noted that some portions of the stockpiled material can be used in year 13 due to the processing capacity not being at its maximum.

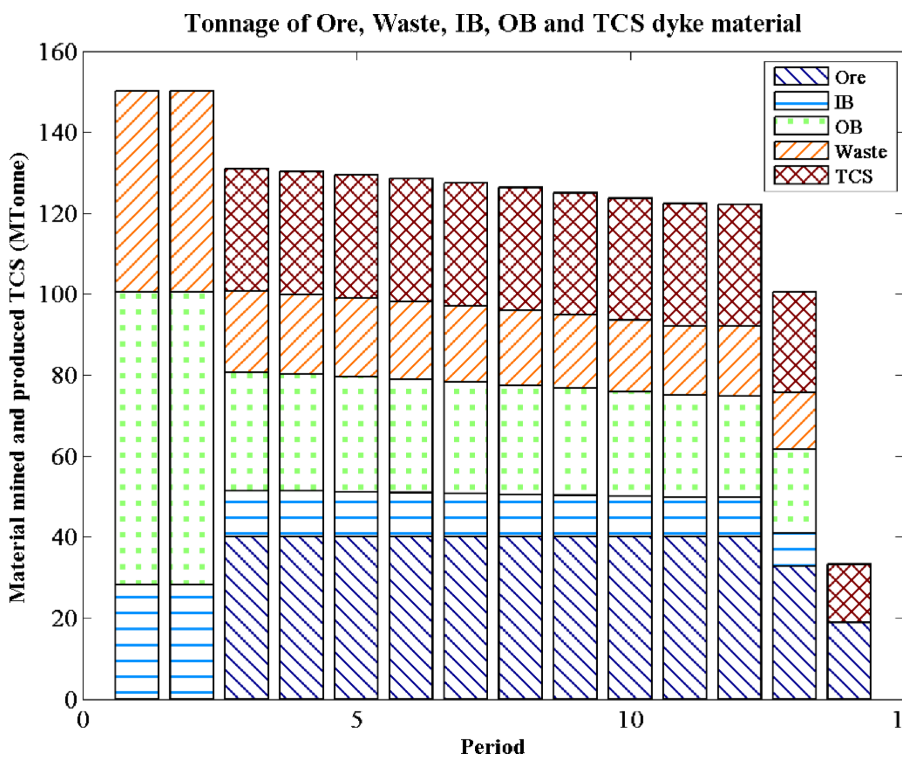

Figure 4.4: Scenario 2 - Schedule for material mined, reclaimed and produced TCS

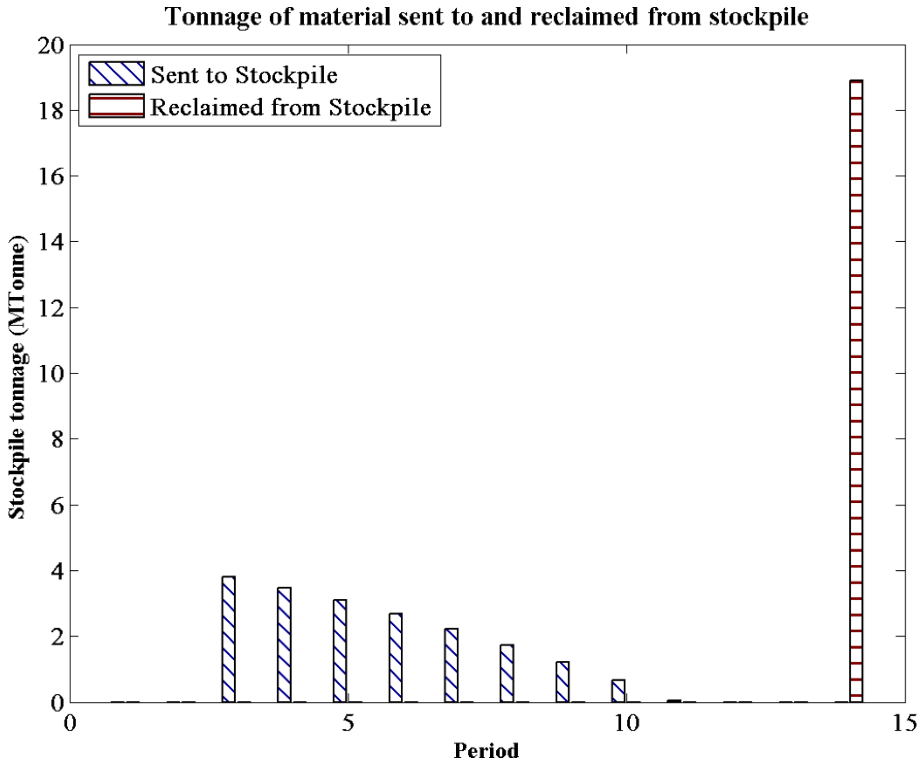

Figure 4.5: Scenario 2 - Schedule for material stockpiled and reclaimed

In oil sands mining, maintaining a uniform average head grade is very important. Due to the fact that we only stockpile the low grade ore material, we miss the opportunity of blending the low grade and high grade materials when we want to reclaim the stockpile material. Table 4.6 shows that when we start reclaiming the stockpile material after the mine is exhausted, the average head grade drops significantly which directly reduces the generated profit. The processing recovery will also be reduced by about 11%, which will negatively impact the bitumen extraction process. In order to prevent these problems, we can utilize the stockpile reclamation parallel to the mining operation. To prevent oxidation of ore material affecting processing recovery, minimum stockpiling duration are often preferred. In Scenario 3, it was assumed that the production schedule is based on the optimum cut-off grade policy and reclamation of the stockpile is conducted simultaneously with the mining operation after one year stockpiling. This means all material sent to the stockpile in a given period must be completely reclaimed in the subsequent period. Since some of the processing capacity will be used up by reclaimed material, less material with grades above cut-off grade will be mined each time.

It can be observed from Table 4.5 and Table 4.6, that the mining capacity for Scenarios 1 and 2 have a decreasing gradient from the first year to the last year due to the dynamic nature of the optimum cut-off grade policy. However in Scenario 3, as a consequence of using stockpile material from years 4 to 12 to achieve the processing capacity, the mining capacity is less than the first two scenarios for those years. Also after year 12, the mining capacity increases since the stockpile is depleted. Figure 4.6 represents the schedule for material mined, reclaimed and the produced TCS dyke material for the third scenario. Figure 4.7 shows the schedule of the material sent to and reclaimed from the stockpile after one year duration.

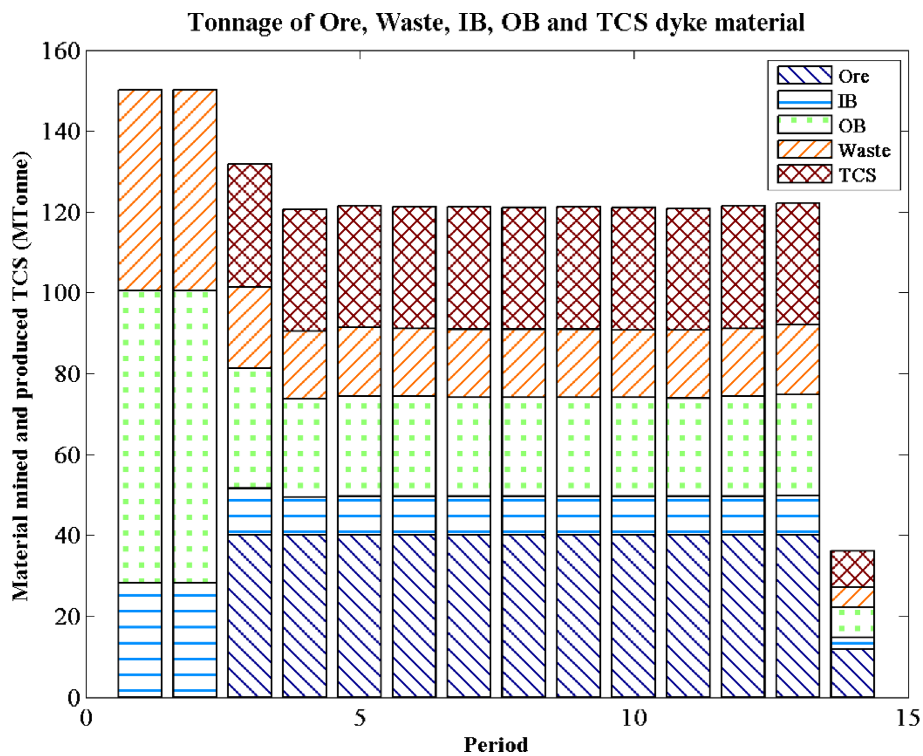

Figure 4.6: Scenario 3 - Schedule for material mined, reclaimed and produced TCS

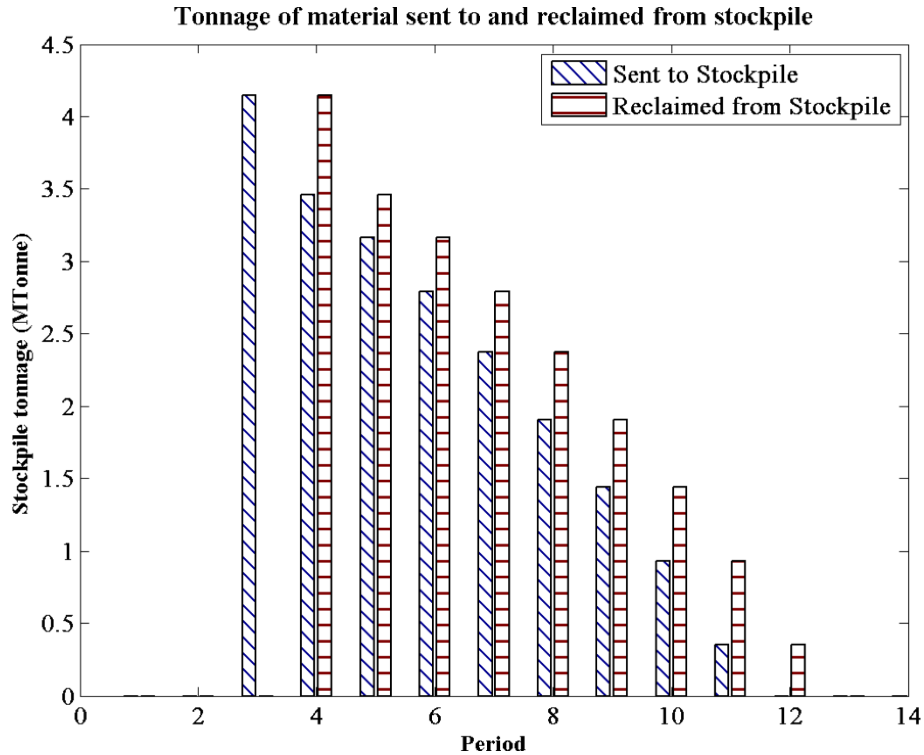

Figure 4.7: Scenario 3 - Schedule for material stockpiled and reclaimed after one year duration

Utilizing the stockpile material simultaneously during the mining operation provides a blending opportunity, maintains the average head grade for plant feed, and prevents the high reduction in processing recovery due to oxidation. Scenario 3 generated an overall NPV of $1,543.5 M. Compared to Scenarios 1 and 2, it improved the NPV by $132 M (9.4%) and $92.2 M (6.5%) respectively.

In Scenario 4, the stockpile duration was selected to be two years. This means the quantity of material sent to the stockpile in a given year must be completely reclaimed within two years. Similar to the third scenario, Scenario 4 allows the average head grade for plant feed to be maintained and a limited reduction in processing recovery. Here, the stockpile processing recovery was reduced by 2% which resulted in a 0.69% decrease in NPV compared to the third scenario where stockpile processing recovery was reduced by 1%. The NPV generated based on this scenario was $1,532.8 M. Figure 4.8 represents the schedule for the material mined, reclaimed and the produced TCS dyke material for Scenario 4. Figure 4.9 shows the schedule of the material sent to and reclaimed from the stockpile after two years duration.

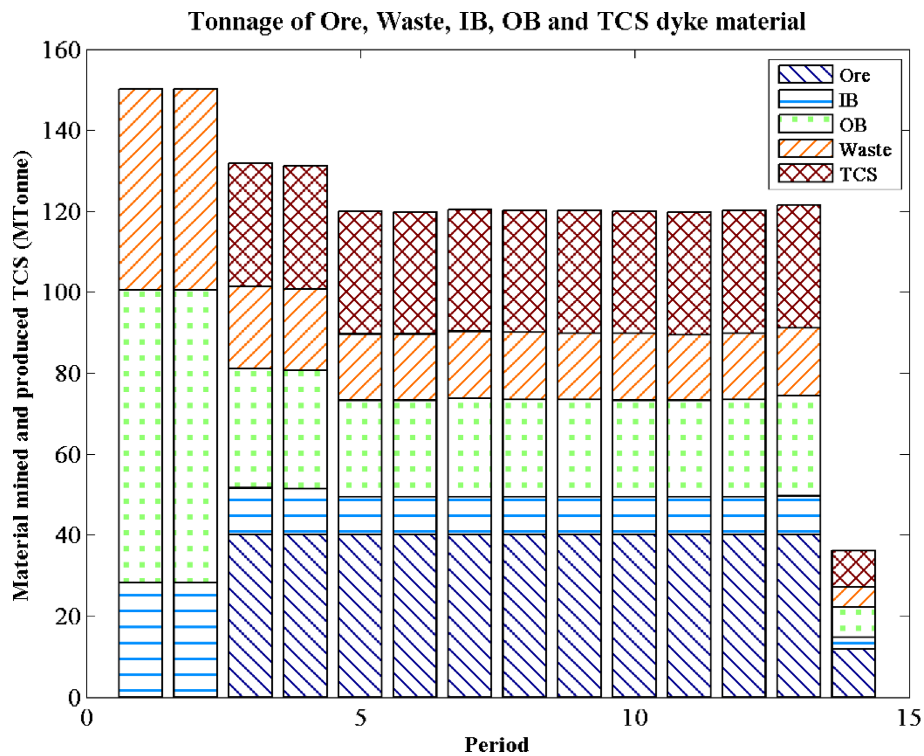

Figure 4.8: Scenario 4 - Schedule for material mined, reclaimed and produced TCS

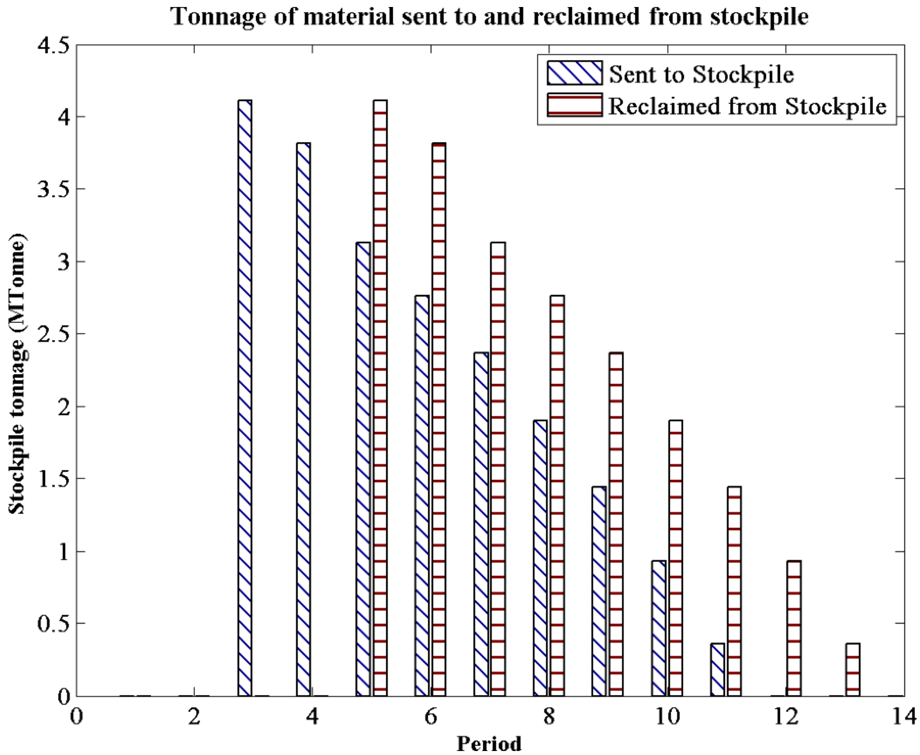

Figure 4.9: Scenario 4 - Schedule for material stockpiled and reclaimed after two years duration

Figure 4.10 shows the cut-off grades profile for all four scenarios. The cut-off grades generated for Scenarios 1 and 2 are very similar except that the mine life for Scenario 2 is one year more than Scenario 1. This is because of utilizing the stockpile after pit mining is complete. The cut-off grades generated for Scenarios 3 and 4 are also close to each other; but Scenario 3 has the highest cut-off grade profile compared to the other three scenarios.

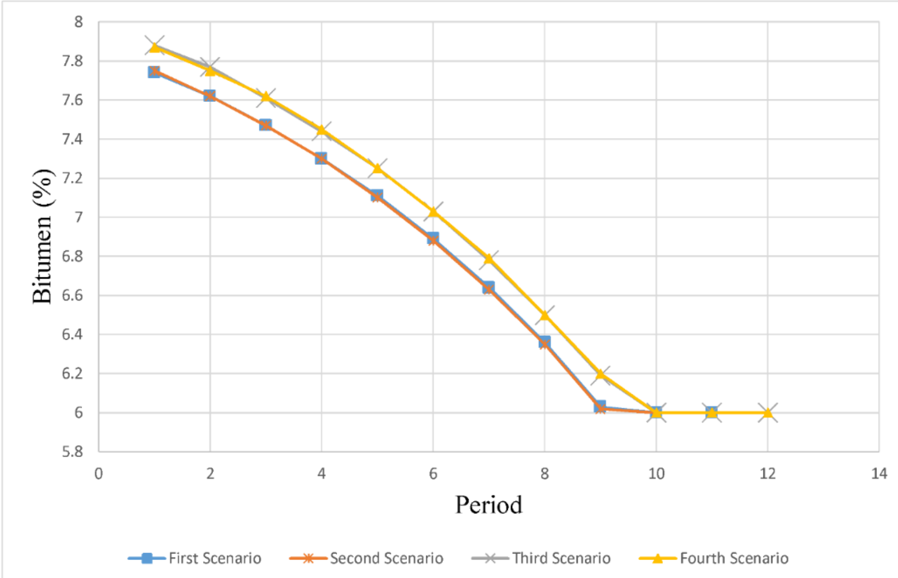

Figure 4.10: Case study 1 - Cut-off grade profiles for the four scenarios

4.2.2. Application of MILGP Model

The production schedule generated by the ICOGO model is used as a guide for setting up the MILGP mine planning model. In the ICOGO model Scenario 1, cut-off grade optimization was applied without utilizing the stockpile. Based on the regulatory requirements of Alberta Energy Regulator (AER) Directive 082, oil sands mining companies cannot leave behind any material containing more than 7% bitumen (Ellis, 2016a). The optimum cut-off grade can be set higher than 7% in certain years through the application of the cut-off grade optimization results. If the stockpile does not get utilized, some portions of the ore material with a grade higher than 7% will be sent to the waste dump, which is against regulatory requirements. Moreover, based on the results of the ICOGO model presented in section 4.2.1, utilizing the stockpile can improve the NPV of the operation. Hence for the MILGP model, the scenario without a stockpile (Scenario 1) is not evaluated.

Scenario 2 proved that utilizing the stockpile at the end of the mine life does not improve the NPV of the operation significantly. Keeping the ore material for a long time will result in oxidation of the ore which reduces the processing recovery. Scenario 2 will also not be evaluated using the MILGP model.

The MILGP model was coded in Matlab (Mathworks, 2015) and IBM CPLEX (IBM ILOG, 2012) was used as the optimization solver. An EPGAP of 1% was set as the termination criterion for the optimization process. The MILGP model was implemented on a Core i5 Lenovo E550 computer at 2.2 GHz with 8 GB of RAM. The optimization problem was solved in 4.4 minutes for the scenario with one year stockpile duration (referred to here as Scenario 3b) and 5.4 minutes for the scenario with two years stockpile duration (referred to here as Scenario 4b).

Table 4.9 shows the material quality requirements for different destinations. The results of the ICOGO model were used to define the production tonnages. The average head grade goal function and the cut-off grade boundaries were also defined from the generated ICOGO model results. The cut-off grade boundaries and average head grade target for Scenarios 3b and 4b are reported in Table 4.7 and Table 4.8 respectively.

Table 4.9: Material quality requirements

Parameter	Value
Ore fines percent upper/lower bounds (wt%)	30/0
IB dyke material fines percent upper/lower bounds (wt%)	50/0

One of the main advantages of using the MILGP model is the ability to setup production goals with allowable deviational variables which ensures that comprised results can be achieved each time whereas an infeasible solution will have been reported for other mathematical programming frameworks. The prioritized penalty parameters provide options for planners to achieve some goals whilst trading off the NPV of the operation. In this research, the processing goal and the mining goal are the most important targets. If the processing target is achieved, that ensures the processing plant will function at its maximum capacity. Similarly, if the mining target is achieved, the mining equipment fleet will be fully utilized. Table 4.10 shows the details of production scheduling results achieved for the life of mine for Scenario 3b.

Table 4.10: Production scheduling results for Scenario 3b

	Period (yrs)													
Production schedule	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Processing target (Mt)	0	0	40	40	40	40	40	40	40	40	40	40	40	40
Processing schedule (Mt)	0	0	14.5	40	40	40	40	40	40	40	40	40	40	37.3
Mining target (Mt)	150	150	95	95	95	95	95	95	95	95	70	70	70	70
Mining schedule (Mt)	150	150	95	95	95	95	95	95	95	95	70	70	70	68.7
OB dyke material target (Mt)	110	110	30	30	30	30	30	20	20	20	0	0	0	0
OB dyke material schedule (Mt)	110	110	30	30	30	30	30	20	20	15	0	0	0	0
IB dyke material target (Mt)	8	8	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
IB dyke material schedule (Mt)	8	8	12.5	12.5	12.3	12	12	12	12	12	12	12	12	1.1
TCS dyke material target (Mt)	0	0	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5
TCS dyke material schedule (Mt)	0	0	11.4	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5

Discussion of results

As presented in Table 4.10, the mining target was achieved for all of the years except for the last year when the material in the final pit limit was exhausted. The processing production target could not be achieved in year three. This is due to the location of the ore material in the pit and mining precedence of the mining-cuts. The ICOGO model does not take into consideration the actual mining precedence of mining-cuts and hence generated a production target which was unachievable in year three. In the remaining years, all processing targets were achieved until the last year when the ore material was finished. Some portions of the processing target are made up of stockpile material reclaimed. Figure 4.11 shows the schedule for material mined, reclaimed and the amount of TCS dyke material produced and Figure 4.12 shows the stockpile material scheduled for processing.

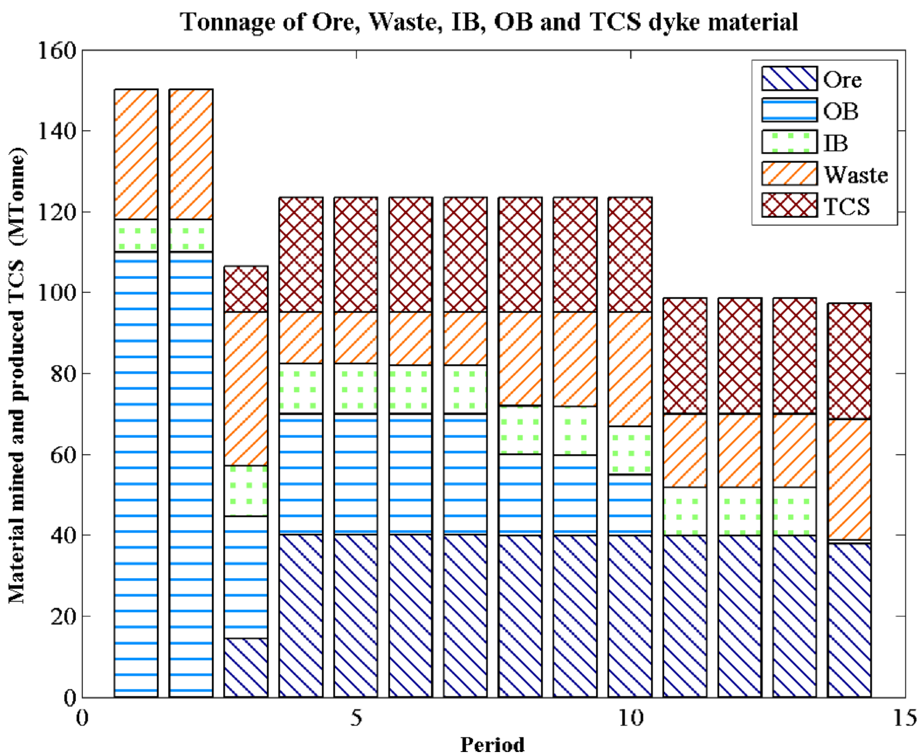

Figure 4.11: Scenario 3b - Schedule for material mined, reclaimed and produced TCS

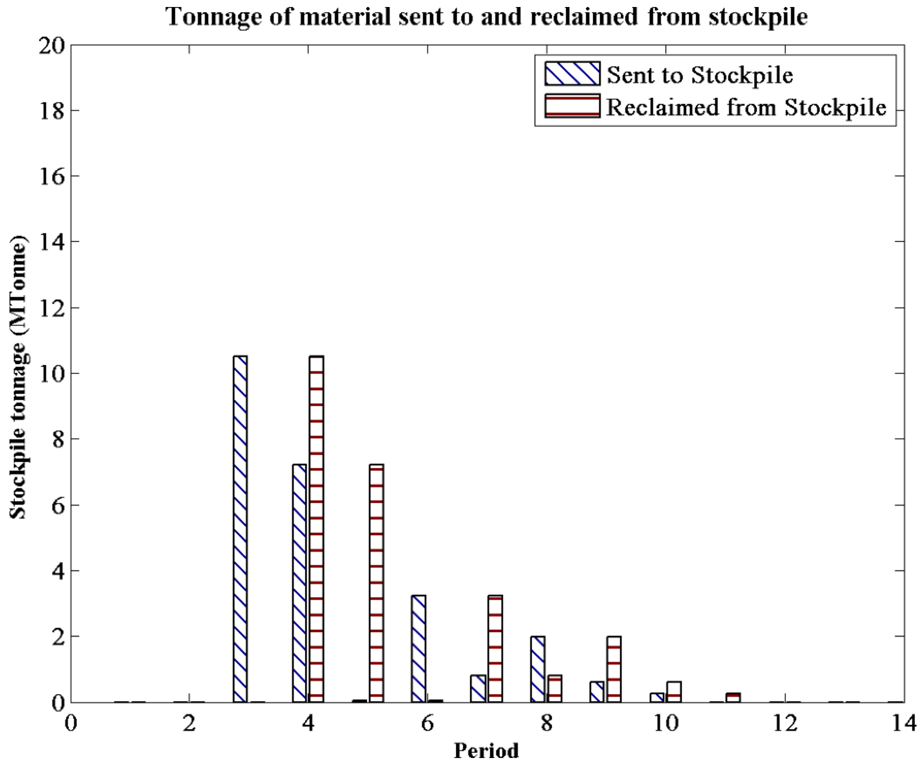

Figure 4.12: Scenario 3b - Schedule for material stockpiled and reclaimed after one year duration

Since TCS dyke material is a by-product of ore processing, the TCS dyke material target could not be achieved in year 3 due to a short fall in ore production. The production targets for OB dyke material were however achieved throughout the mine life. The OB dyke material target was set to zero after year ten since most of the dyke construction will be finished by that time. Due to the location of OB dyke material in the pit, during the early years the OB targets was set higher than the production schedule generated by the ICOGO model for OB dyke materials. On the other hand, the production targets for IB dyke material were set to lower amounts than the schedule generated by the ICOGO model during the early years due to the spatial location of IB dyke materials. The production targets for IB dyke material were achieved from year one until year five. The IB dyke material production deviate 0.5 Mt from its targets after year 6 to 13 and in the last year it deviates around 11.4 Mt. The total amount of IB dyke material mined from the pit was 151.1 Mt. The mine planner can set the production deviation to a tighter boundary or place a higher priority to ensure more IB dyke material gets mined. In our case study, the main focus was to get a uniform production schedule for all material mined.

The MILGP model generated a NPV of $1,354.5 M for the life of mine for Scenario 3b (production with one year stockpile duration). The MILGP model generated $189 M (12%) less NPV compared to the ICOGO model. This reduction in NPV is caused by not providing all the required material for processing in year three due to mining precedence constraints. Figure 4.13 illustrates the mining sequence on level 287.5m.

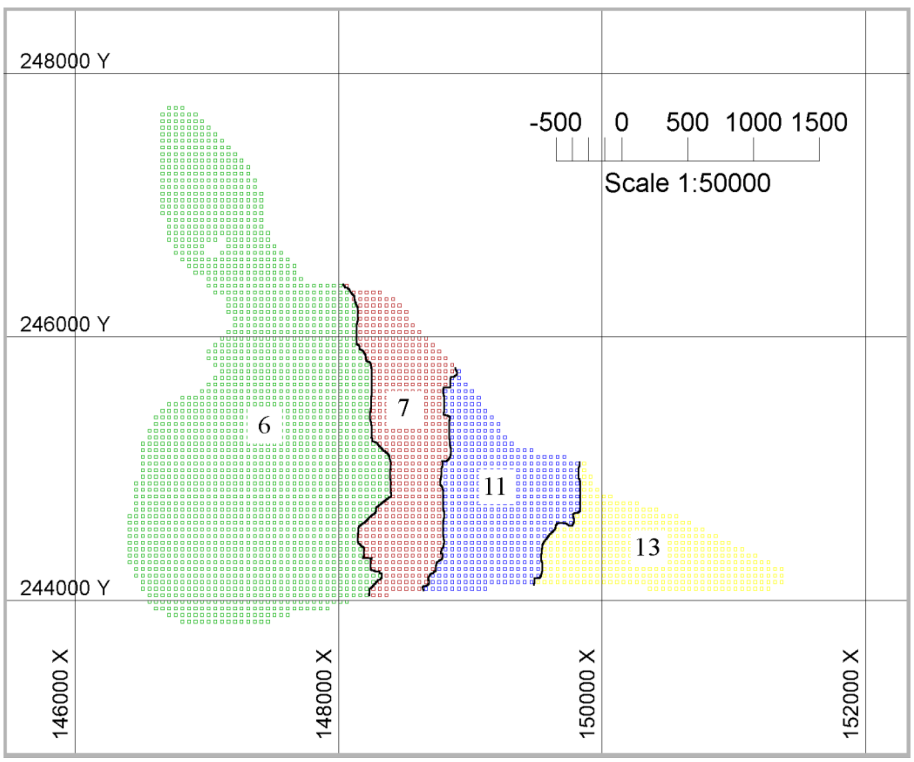

Figure 4.13: Scenario 3b - Mining sequence on level 287.5m

On the other hand, the average bitumen head grade achieved for each period using the MILGP model compared to the ICOGO model is more consistent. In the MILGP model, the average bitumen head grade was calculated based on the mining-cuts that are extracted in each period, while the average bitumen head grade achieved with the ICOGO model was based on a weighted average of the overall available ore tonnage above the cut-off grade. Figure 4.14 shows the average bitumen head grade targets for each period and the scheduled average bitumen head grade with the MILGP model. It can be seen that the MILGP average bitumen head grade in the early years of mine life is less than the targets whereas other years are more than the target. This fluctuation happens since allowable negative and positive deviations were provided for the average bitumen head grade goal function. Figure 4.15 and Figure 4.16 show the average fines percent for the material delivered to the processing destination and the dyke construction destination respectively.

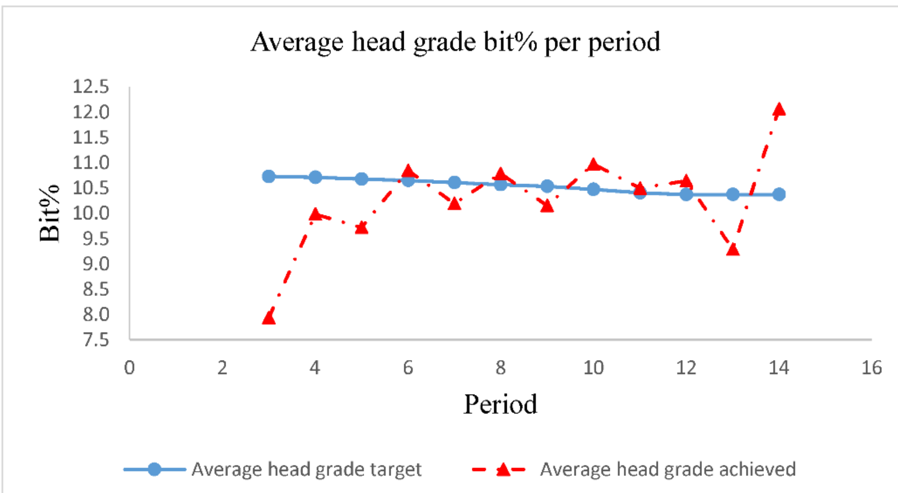

Figure 4.14: Scenario 3b - Average bitumen head grade target and scheduled

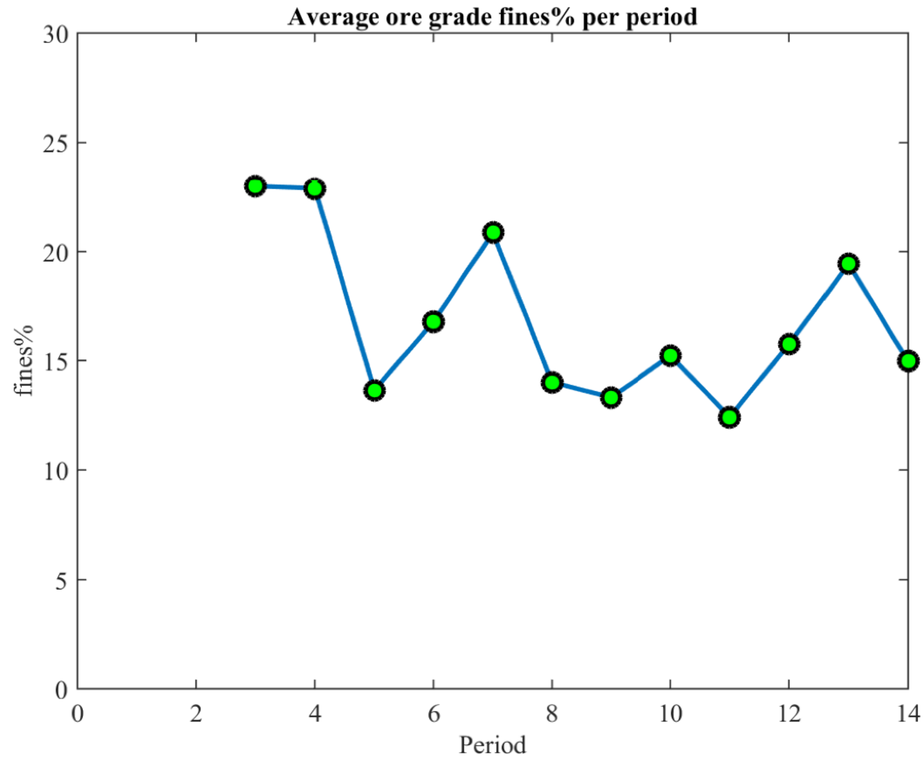

Figure 4.15: Scenario 3b - Average ore fines%

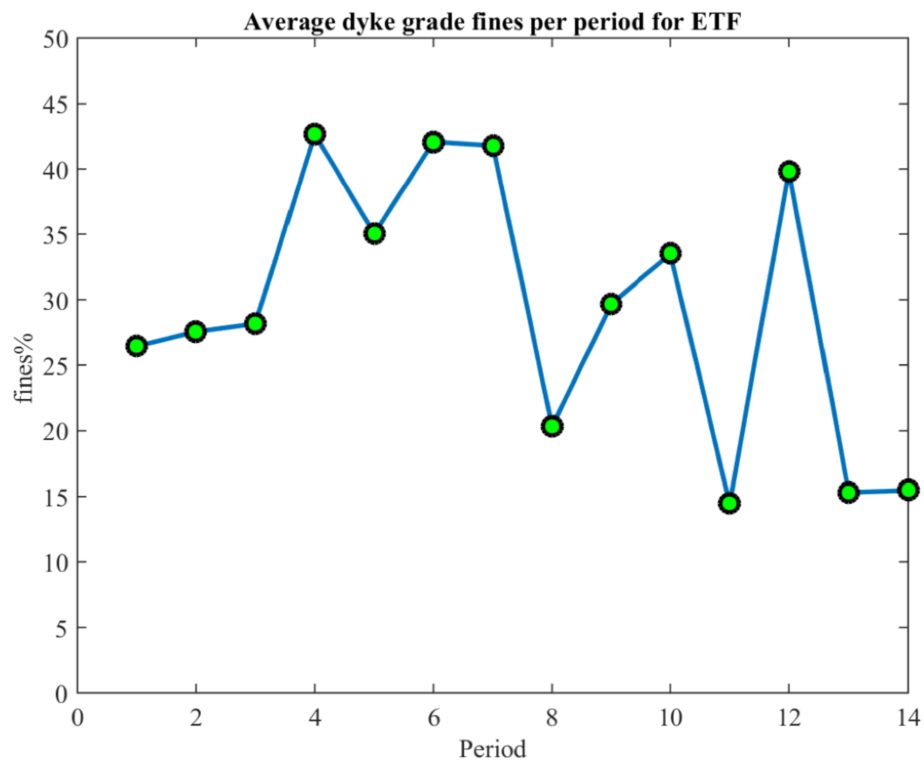

Figure 4.16: Scenario 3b - Average IB dyke material fines%

Subsequently, the MILGP model was applied to Scenario 4b (production with two year stockpile duration). The ICOGO model did not show significant differences between the scenarios for one year and two year stockpile reclamation durations. The NPV generated by the MILGP model for the scenario with two year stockpile duration (Scenario 4b) was $3 M higher than the one year stockpile duration scenario (Scenario 3b). This increase in NPV is due to more flexibility in stockpiling and reclamation allowing the optimizer to send higher grades for processing in early years to generate more profit. Figure 4.17 shows the comparison between the average bitumen head grade target and the achieved average bitumen head grade for Scenarios 3b and 4b.

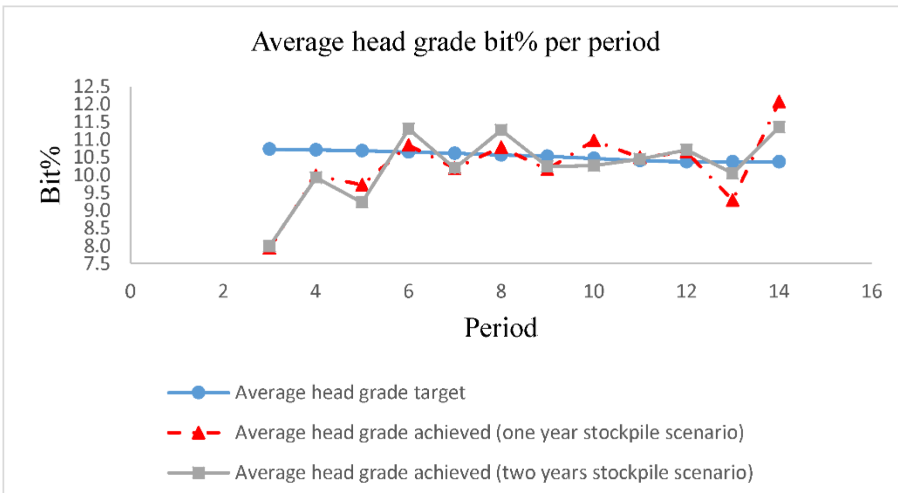

Figure 4.17: Average bitumen head grade for Scenarios 3b and 4b

Comparing the results of the MILGP and ICOGO models for two year stockpile duration scenarios, it can be understood that the results from the ICOGO model were relatively optimistic, due to the fact that the ICOGO model does not consider the detailed mining-cut extraction sequence during mining. The NPV generated from the MILGP model was $1,357.5M, which is 11% less than that of the ICOGO model. The production schedules generated by the MILGP model for the two year stockpile duration scenario for different material types are available in Appendix A. These figures show a uniform production rate for ore material which was the main focus of the experiment.

4.3. Second Case Study

In the second case study, the final pit limit was divided into fifteen pseudo pushbacks to create mining-panels. Blocks in each mining-panel were clustered together to create mining-cuts by using a hierarchical clustering algorithm (Tabesh and Askari-Nasab, 2011). The final pit limit for this case study was generated with Whittle software (Gemcom Software International Inc., 2013) using the LG algorithm (Lerchs and Grossmann, 1965). The final pit limit was considered to have three main pushbacks for phased mining. The horizontal mining precedence is defined based on these three main pushbacks. Figure 4.18 shows the three main pushbacks within the final pit limit on level 302.5m.

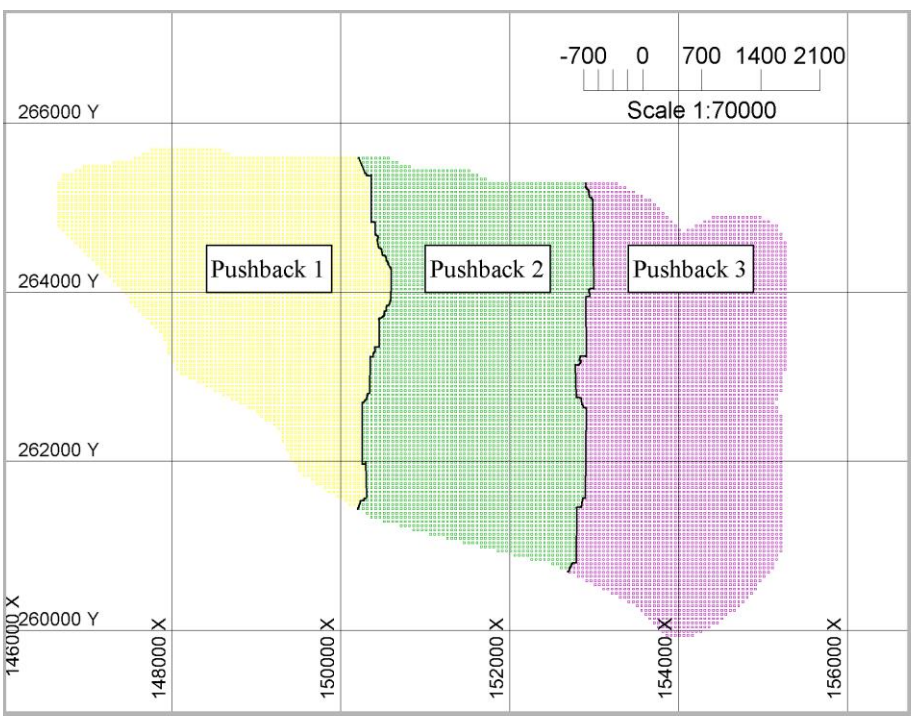

Figure 4.18: Final pit limit pushbacks in the case study area on level 302.5m

Table 4.11 reports information about the oil sands deposit for the second case study. Table 4.12 shows the economic parameters for the mining operation used for the second case study (Ben-Awuah, (2013) Burt et al., (2012). Figure 4.19 represents the cumulative bitumen grade-tonnage distribution of the deposit and Figure 4.20 shows the bitumen grade distribution on level 302.5m.

Table 4.11: Oil sands deposit pushbacks and final pit characteristics for second case study

Description	Value			
	Pushback 1	Pushback 2	Pushback 3	Final pit (Total)
Total tonnage of material (Mt)	1989.3	2294.6	2246.3	6530.2
Total ore tonnage (Mt)	695.4	875.8	728.4	2299.6
Total TCS dyke material tonnage (Mt)	476.1	582.4	573.5	1632
Total OB dyke material tonnage (Mt)	600.7	676.8	595.2	1872.7
Total IB dyke material tonnage (Mt)	448.3	579.3	600.7	1628.4
Total waste tonnage (Mt)	244.8	162.6	321.9	729.3
Number of blocks	26,334	30,129	28,706	85,169
Number of mining-cuts	754	858	814	2,426
Number of mining-panels	45	41	39	125
Number of benches	9	9	9	9

Table 4.12: Economic parameters for second case study (Ben-Awuah, 2013; Burt et al., 2012)

Parameter	Value
Mining cost ($/tonne)	2.5
Processing cost ($/tonne)	5.03
Stockpiling cost($/tonne)	0.5
Selling price ($/bitumen %mass)	4.5
Annual fixed cost (M$/year)	1,590
TCS dyke material cost ($/tonne)	0.92
OB dyke material cost ($/tonne)	0.95
IB dyke material cost ($/tonne)	0.95
Discount rate (%)	15

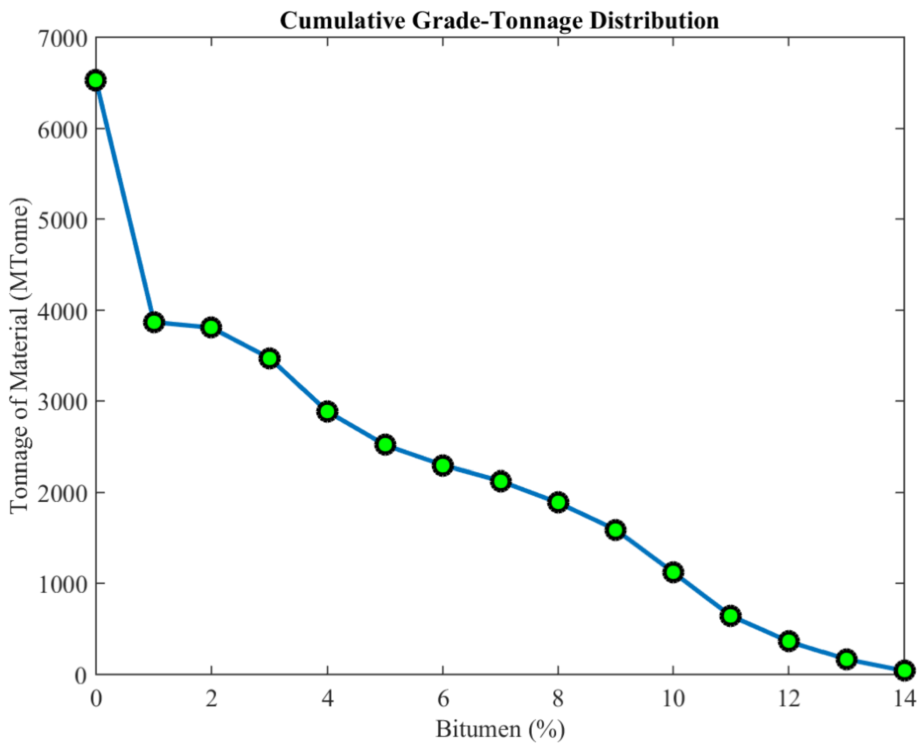

Figure 4.19: Cumulative bitumen grade-tonnage distribution of the oil sands deposit (second case study)

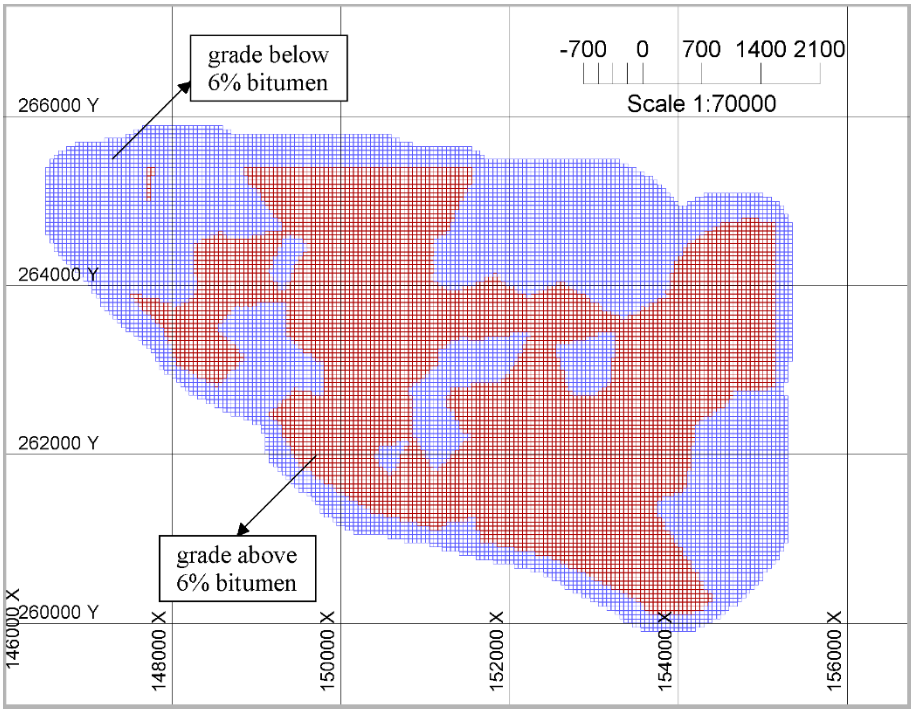

Figure 4.20: Bitumen grade distribution in the second case study area on level 302.5m

4.3.1. Application of ICOGO Model

The ICOGO model was implemented on the second case study with three main pushbacks. The bitumen grade-tonnage distribution of each pushback used as input information for the ICOGO model is presented in Table 4.13. Table 4.14 shows the ratio of TCS dyke material to the total quantity of ore (R_{TCS}), the ratio of OB dyke material to the total quantity of waste (R_{OB}), the ratio of IB dyke material to the total quantity of waste (R_{IB}), and the required operational capacities for the ICOGO model.

Table 4.13: Grade-Tonnage distribution of the oil sands deposit (second case study)

Bitumen Grade (%)	Tonnage (Mt)		
	Pushback 1	Pushback 2	Pushback 3
0 – 6	1293.9	1418.8	1517.9
6 – 7	47.6	47.3	78.7
7 – 8	57.6	96.2	88.4
8 – 9	59.5	120.3	108
9 – 10	158.9	143.1	168
10 – 11	179.6	160.9	139.7
11 – 12	117.1	140.4	28.1
12 – 13	42.5	75.4	62.4
13 – 14	26.7	65.3	43.6
Above 14	5.9	26.9	11.5

Table 4.14: Operational capacities for second case study

Description	Value		
	Pushback 1	Pushback 2	Pushback 3
Ratio of TCS dyke material (R_{TCS})	0.6846	0.6650	0.7874
Ratio of OB dyke material (R_{OB})	0.4643	0.4770	0.3921
Ratio of IB dyke material (R_{IB})	0.3465	0.4083	0.3958
Mining capacity (Mt/year)	Unlimited	Unlimited	Unlimited
Processing capacity (Mt/year)	110	110	110
Refinery capacity (Mt/year)	Unlimited	Unlimited	Unlimited

The processing weighted average recovery of the final pit limit was determined to be 82%. The model was implemented based on three stockpiling management scenarios: 1) without stockpile, 2) reclaiming stockpile simultaneously with the mining operation after one year duration, and 3) reclaiming stockpile simultaneously with the mining operation after two years duration. Based on the results from the first case study, the scenario of reclaiming the stockpile at the end of mine life was not evaluated due to significant oxidation of the ore affecting processing recovery. The mine life for the second case study was estimated to be 22 years. The termination criterion for the cut-off grade heuristic optimization algorithm is a NPV tolerance of $5 M.

The results for each of the production schedule scenarios after cut-off grade optimization are presented in Table 4.15 to Table 4.17.

Table 4.15: Scenario 1 - Production schedule with optimum cut-off grade policy without stockpile

			Pushback 1		Pushback 2		Pushback 3	
Year	Cut-off grade (%)	Average head grade (%)	Material mined (Mt/year)	Material processed (Mt/year)	Material mined (Mt/year)	Material processed (Mt/year)	Material mined (Mt/year)	Material processed (Mt/year)
1	0	0	275.2	0	-	-	-	-
2	6.76	10.22	286.1	110	-	-	-	-
3	6.59	10.17	282.6	110	-	-	-	-
4	6.4	10.12	278.7	110	-	-	-	-
5	6.17	10.06	274.4	110	-	-	-	-
6	6	10.02	271.1	110	-	-	-	-
7	6	10.02	271.1	110	301.8	-	-	-
8	6	10.02	50.1	20.3	-	-	-	-
8	7.14	10.46	-	-	219.3	89.7	-	-
9	7.06	10.43	-	-	266.4	110	-	-
10	6.88	10.38	-	-	262.8	110	-	-
11	6.68	10.34	-	-	259.8	110	-	-
12	6.45	10.29	-	-	256.5	110	-	-
13	6.19	10.24	-	-	252.9	110	-	-
14	6	10.20	-	-	250.3	110	322.9	-
15	6	10.20	-	-	224.8	98.8	-	-
15	6.35	9.77	-	-	-	-	30.7	11.2
16	6.49	9.82	-	-	-	-	306.6	110
17	6.36	9.77	-	-	-	-	302.4	110
18	6.22	9.72	-	-	-	-	297.6	110
19	6.06	9.65	-	-	-	-	292.4	110
20	6	9.63	-	-	-	-	290.5	110
21	6	9.63	-	-	-	-	290.5	110
22	6	9.63	-	-	-	-	112.7	42.7

Table 4.16: Scenario 2 - Production schedule with optimum cut-off grade policy and simultaneous stockpile reclamation after one year duration

			Pushback 1		Pushback 2		Pushback 3	
Year	Cut-off grade (%)	Average head grade (%)	Material mined (Mt/year)	Material processed (Mt/year)	Material mined (Mt/year)	Material processed (Mt/year)	Material mined (Mt/year)	Material processed (Mt/year)
1	0	0	275.2	0	-	-	-	-
2	6.81	10.23	287.1	110	-	-	-	-
3	6.65	10.19	267	110	-	-	-	-
4	6.44	10.14	267.4	110	-	-	-	-
5	6.22	10.08	266.9	110	-	-	-	-
6	6	10.02	267.2	110	-	-	-	-
7	6	10.02	271.1	110	301.8	-	-	-
8	6	10.02	87.3	35.4	-	-	-	-
8	7.19	10.48	-	-	183.4	74.6	-	-
9	7.17	10.47	-	-	255.3	110	-	-
10	6.99	10.41	-	-	244.8	110	-	-
11	6.79	10.37	-	-	247.7	110	-	-
12	6.56	10.32	-	-	247.2	110	-	-
13	6.3	10.26	-	-	246.9	110	-	-
14	6.02	10.2	-	-	246.5	110	-	-
15	6	10.2	-	-	250.1	110	322.9	-
16	6	10.2	-	-	71.1	31.2	-	-
16	6.5	9.82	-	-	-	-	219.9	78.8
17	6.46	9.81	-	-	-	-	293.2	110
18	6.31	9.75	-	-	-	-	285.5	110
19	6.14	9.69	-	-	-	-	285.2	110
20	6	9.63	-	-	-	-	286.1	110
21	6	9.63	-	-	-	-	290.5	110
22	6	9.63	-	-	-	-	262.9	99.6

Table 4.17: Scenario 3 - Production schedule with optimum cut-off grade policy and simultaneous stockpile reclamation after two years duration

			Pushback 1		Pushback 2		Pushback 3	
Year	Cut-off grade (%)	Average head grade (%)	Material mined (Mt/year)	Material processed (Mt/year)	Material mined (Mt/year)	Material processed (Mt/year)	Material mined (Mt/year)	Material processed (Mt/year)
1	0	0	275.2	0	-	-	-	-
2	6.81	10.23	287.1	110	-	-	-	-
3	6.64	10.19	283.6	110	-	-	-	-
4	6.45	10.14	263.4	110	-	-	-	-
5	6.22	10.08	262.6	110	-	-	-	-
6	6	10.02	263	110	-	-	-	-
7	6	10.02	267.1	110	301.8	-	-	-
8	6	10.02	87.3	35.4	-	-	-	-
8	7.18	10.48	-	-	183.3	74.6	-	-
9	7.16	10.47	-	-	269.7	110	-	-
10	7	10.41	-	-	250.4	110	-	-
11	6.8	10.37	-	-	241.4	110	-	-
12	6.57	10.32	-	-	244.3	110	-	-
13	6.31	10.26	-	-	244	110	-	-
14	6.02	10.2	-	-	243.1	110	-	-
15	6	10.2	-	-	246.2	110	322.9	-
16	6	10.2	-	-	70.5	31.1	-	-
16	6.55	10.2	-	-	-	-	220.1	78.9
17	6.46	9.81	-	-	-	-	305.5	110
18	6.32	9.75	-	-	-	-	288.6	110
19	6.15	9.69	-	-	-	-	280.1	110
20	6	9.63	-	-	-	-	280.5	110
21	6	9.63	-	-	-	-	285.9	110
22	6	9.63	-	-	-	-	262.6	99.6

Discussion of results

It was assumed that since the mining capacity required for pre-striping operations is temporal, it could be secured through contract mining. Hence, before starting the ore mining operation for each pushback, one year of pre-striping waste was planned in order to provide a uniform ore production rate when ore mining starts. The periods of moving from one pushback to another are referred to as transition years and are highlighted in Table 4.15 to Table 4.17. During the transition years, the mining and processing capacities are shared across pushbacks in order to complete extraction in the current pushback and start extraction in the next pushback. The pre-striping of pushbacks 2 and 3 happens a year before of transition years to provide exposed ore in the subsequent pushback to be mined.

In the production schedule generated by the ICOGO model (Figure 4.21), extra mining capacity is required for pre-striping operations in years 7 and 14 for pushbacks 2 and 3 respectively. The ICOGO model generated a uniform ore production rate and ensured complete extraction of all other available material in the final pit limit. In Scenario 1, the total NPV generated together with the waste management cost is $4,731.1 M. Figure 4.21 shows the schedule for the material mined and produced TCS dyke material.

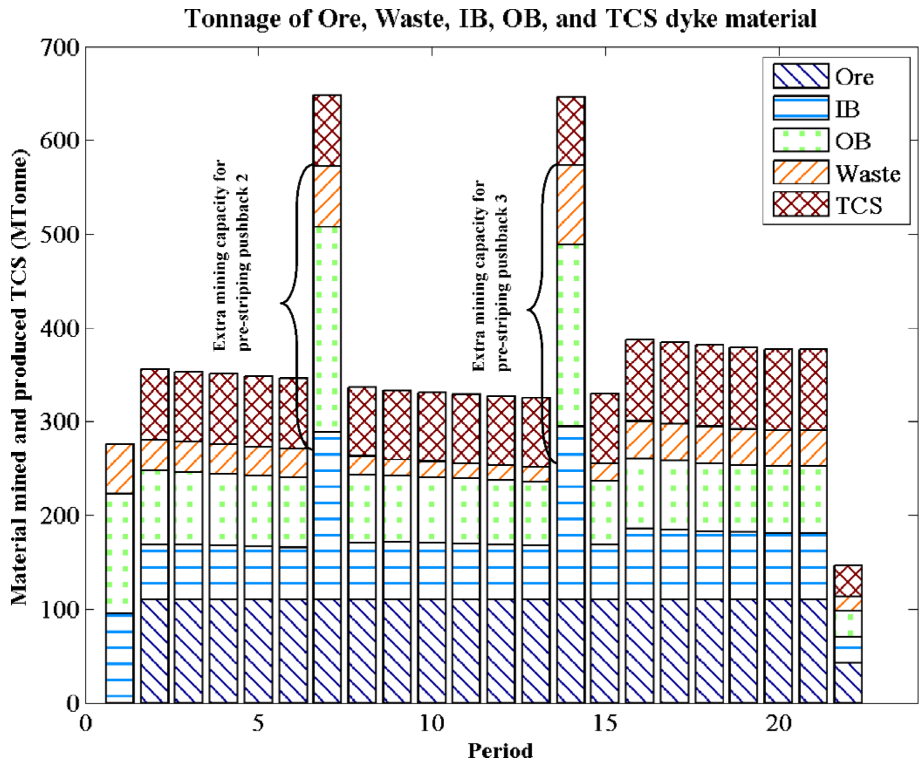

Figure 4.21: Scenario 1 - Schedule for material mined and produced TCS

In Scenario 2, reclamation of the stockpile is conducted simultaneously with the mining operations after one year duration. The quantity of material reclaimed in a given year is equal to the amount of material that was sent to the stockpile in the previous year. Since some of the processing capacity is filled with stockpile material, less material with grade above cut-off grade will be mined each time. This results in a reduction in the mining capacity during the years when stockpile material is available for reclamation.

Utilizing the stockpile material simultaneously during the mining operation provided a blending opportunity, maintained the average head grade for plant feed, and prevented the high reduction in processing recovery. Scenario 2 generated an overall NPV of $4,845.9 M. In comparison with the first scenario, Scenario 2 enhanced the NPV of the operation by $114.8 M. This improvement was caused by stockpiling the low grade material and processing them in later years. In the first scenario, 56.9 Mt of low grade ore was sent to waste. Figure 4.22 shows the schedule for the material mined, reclaimed and produced TCS dyke material for Scenario 2 and Figure 4.23 shows the associated schedule for stockpile material movement. In Scenario 2, 61.3 Mt of ore was sent to the stockpile and reclaimed in later years throughout the mine life.

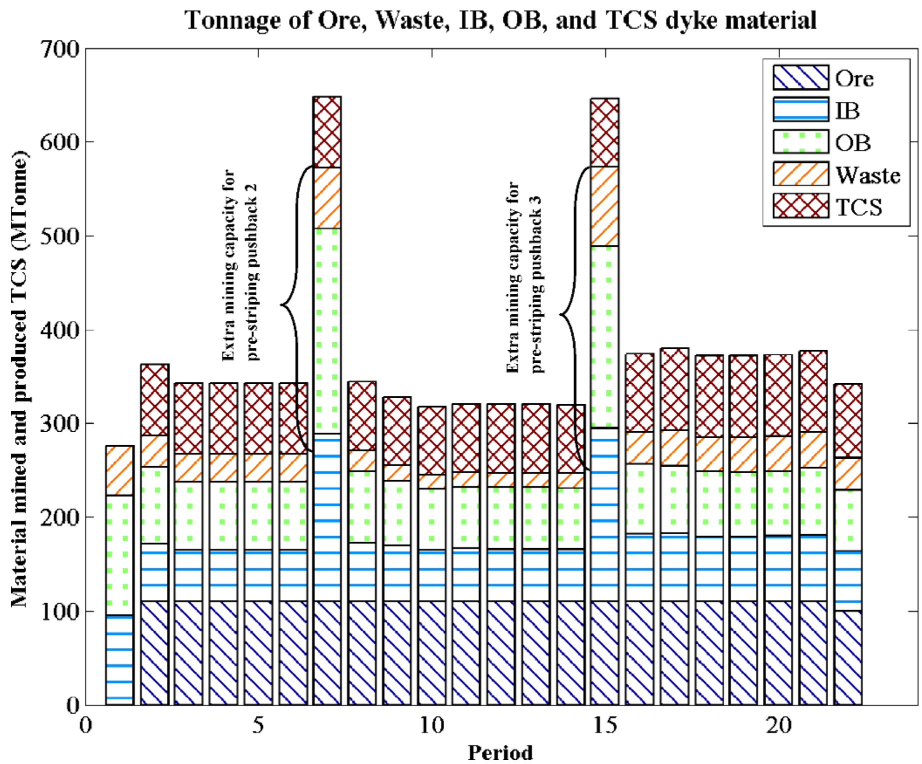

Figure 4.22: Scenario 2 - Schedule for material mined, reclaimed and produced TCS

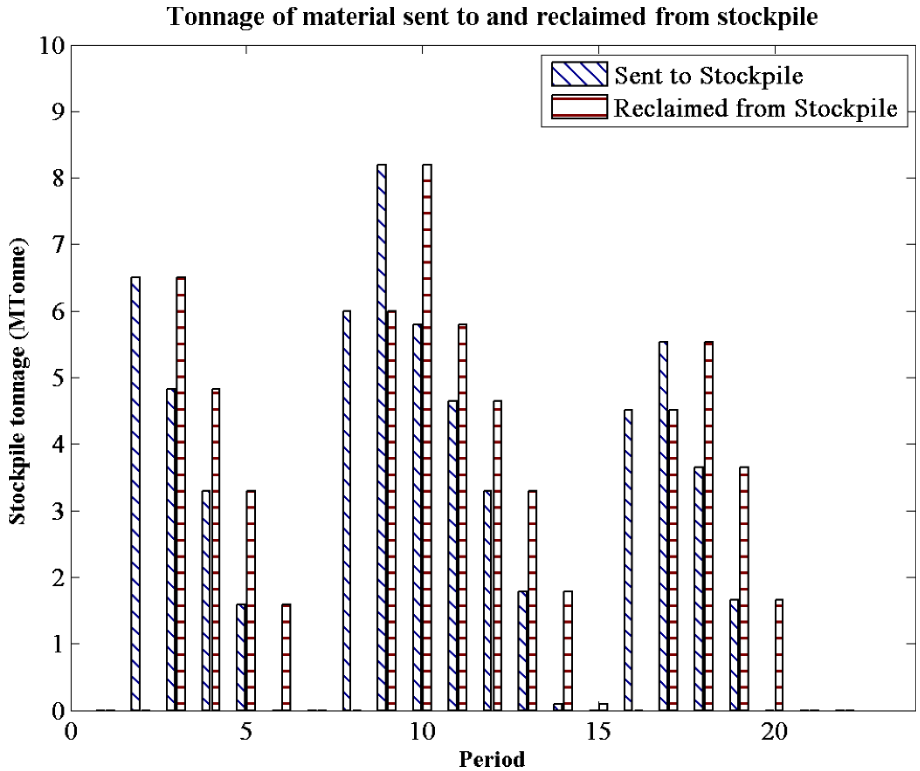

Figure 4.23: Scenario 2 - Schedule for material stockpiled and reclaimed after one year duration

In Scenario 3, the stockpile reclamation happens after two years. Stockpiling the material for a longer time will reduce the processing recovery which affects the generated NPV of the operation. However, the average head grade will be maintained for plant feed similar to the one year stockpile scenario (Scenario 2). The ICOGO model generates a uniform ore production rate for processing throughout the mine life while the overall mining capacity varied depending on the material available in each pushback. The NPV generated by Scenario 3 was $4,822.7 M, which is 0.4% less than the NPV generated by the one year stockpile scenario (Scenario 2). Scenario 3 improved the NPV by $91.6 M compared to Scenario 1 that makes no use of stockpiling. Figure 4.24 shows the schedule for the material mined, reclaimed and produced TCS dyke material for Scenario 3 and Figure 4.25 shows the schedule for stockpile material movement.

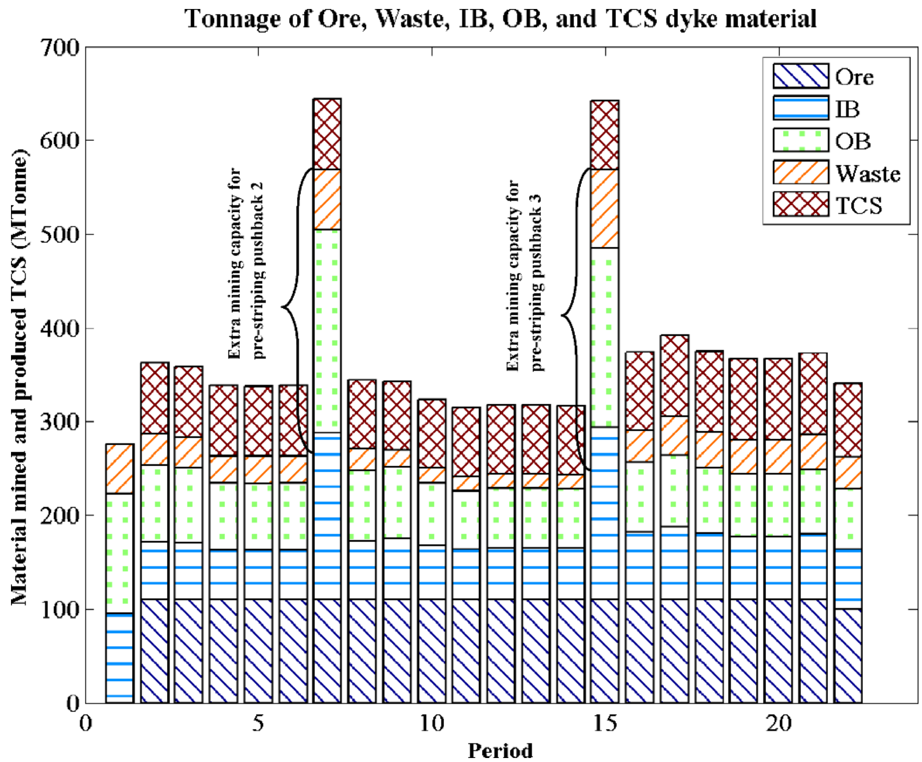

Figure 4.24: Scenario 3 - Schedule for material mined, reclaimed and produced TCS

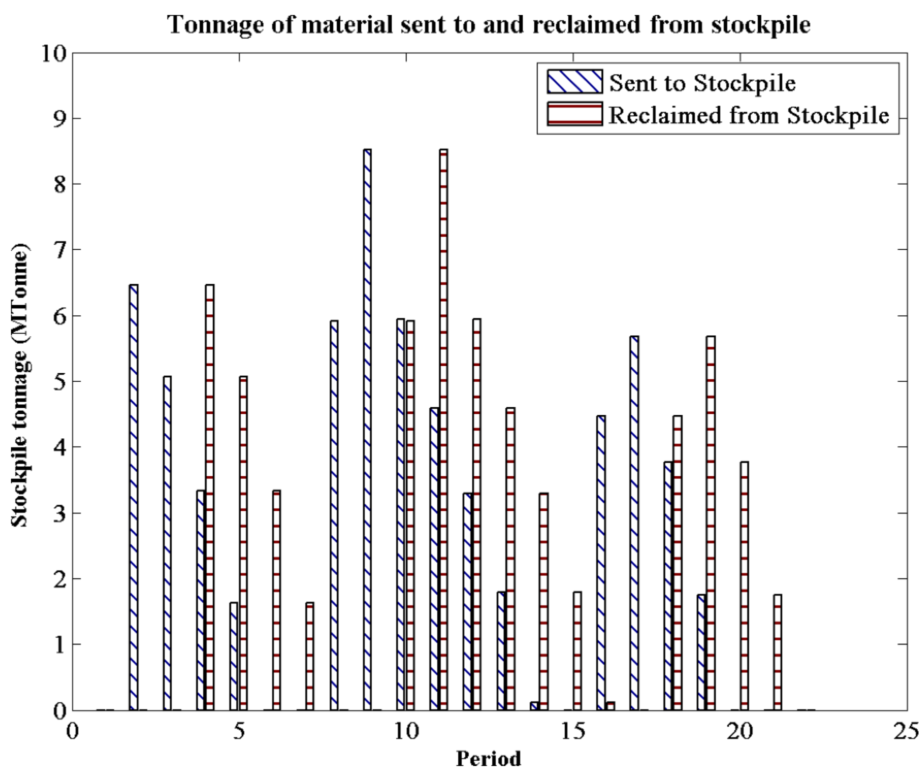

Figure 4.25: Scenario 3 - Schedule for material stockpiled and reclaimed after two years duration

Figure 4.26 shows the cut-off grade profiles for all three scenarios in the three pushbacks. The cut-off grades calculated for Scenarios 2 and 3 are very similar; however, Scenario 2 has the highest cut-off grade profile compared to the others.

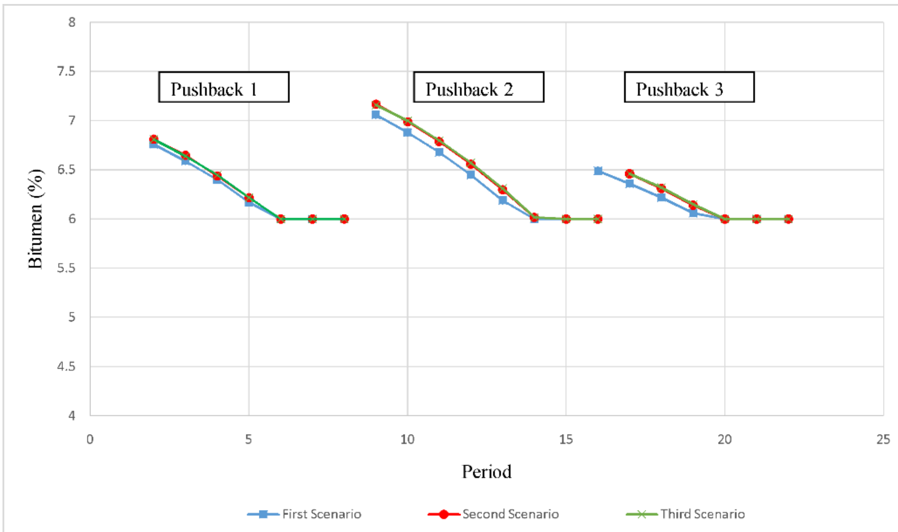

Figure 4.26: Case study 2 - Cut-off grades profile for the three scenarios

4.3.2. Application of MILGP Model

The production schedule generated by the ICOGO model is used as a guide for setting up the MILGP mine planning model. The MILGP model was coded in Matlab (Mathworks, 2015) and IBM CPLEX (IBM ILOG, 2012) was used as the optimization solver. An EPGAP of 10% was set as the termination criterion for the optimization process. The MILGP model was implemented on a Core i7 Alienware R3 computer at 2.6 GHz with 16 GB of RAM. The optimization problem was solved in 90.2 hours for the scenario with one year stockpile duration (referred to here as Scenario 2b) and 84.5 hours for the scenario with two years stockpile duration (referred to here as Scenario 3b).

Table 4.18 shows the material quality requirements for scheduling. The results from the ICOGO model were used to define the production tonnages. The average head grade goal function and the cut-off grade boundaries were also defined from the ICOGO model results. The cut-off grade boundaries and average head grade target for Scenarios 2b and 3b are reported in Table 4.16 and Table 4.17 respectively.

Table 4.18: Material quality requirements for second case study

Parameter	Value
Ore fines percent upper/lower bounds (wt%)	40/0
IB dyke material fines percent upper/lower bounds (wt%)	50/0

In this case study, one of the main objectives is to get a uniform ore production rate for the processing plant. Taking advantage of the prioritized penalty parameters we can set different goals based on mine management requirements. In this experiment, the prioritized penalty parameters for dyke material were set to higher values to ensure we can achieve most of the dyke material goals while ensuring a feasible near-optimal production schedule.

Figure 4.27 shows the schedule for material mined, reclaimed, processed, and OB, IB and TCS dyke material for different dyke construction destinations.

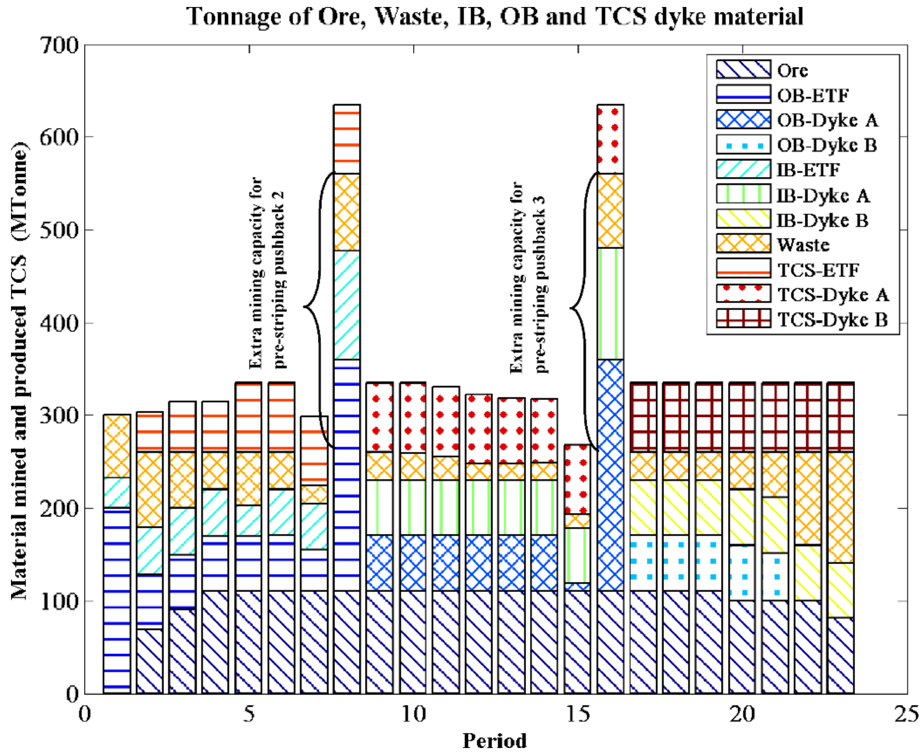

Figure 4.27: Scenario 2b - Schedule for material mined, reclaimed and produced TCS

Figure 4.28 shows the production schedule for ore material. The processing target (red line) could not be achieved in year two. This was due to the location of ore material in the pit and mining precedence of the mining-cuts. The ICOGO model does not take into consideration the actual mining precedence of mining-cuts and hence generated a production target which was unachievable in year two. In the remaining years, all processing targets were achieved until the last year when the ore material was finished. The ore production target starts with 90 Mt for the first two years due to pre-stripping of the ore material. The target is then ramped up to a maximum capacity of 110 Mt. In the last four years, the target is reduced to 100 Mt. The life of mine was increased by one year in the MILGP model compared to the ICOGO model because of ore production rate in the early years of mine life. Figure 4.29 shows the stockpile material scheduled for processing.

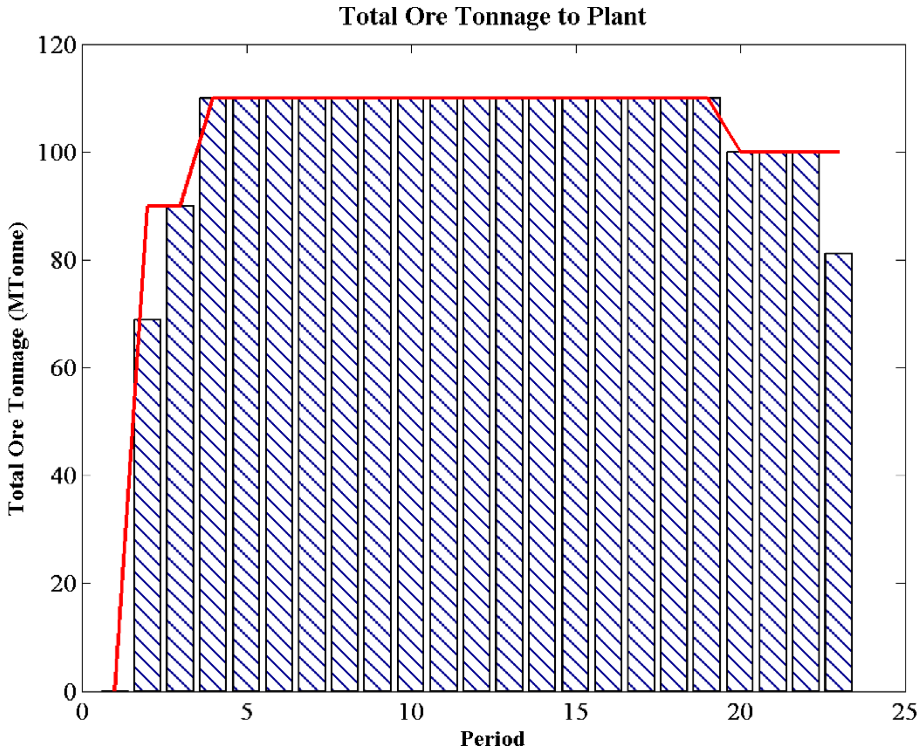

Figure 4.28: Scenario 2b - Schedule for ore material

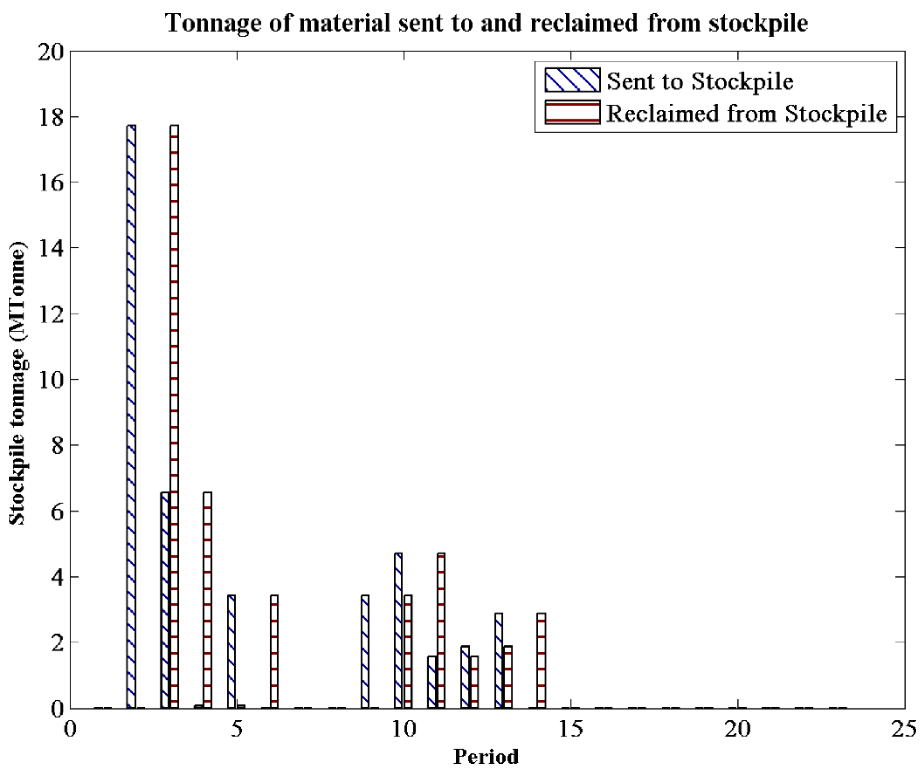

Figure 4.29: Scenario 2b - Schedule for material stockpiled and reclaimed after one year duration

The MILGP model generated a NPV of $5,951.1 M for the life of mine for Scenario 2b (production with one year stockpile duration) including the waste management cost. Figure 4.30 illustrates the mining sequence on level 302.5m.

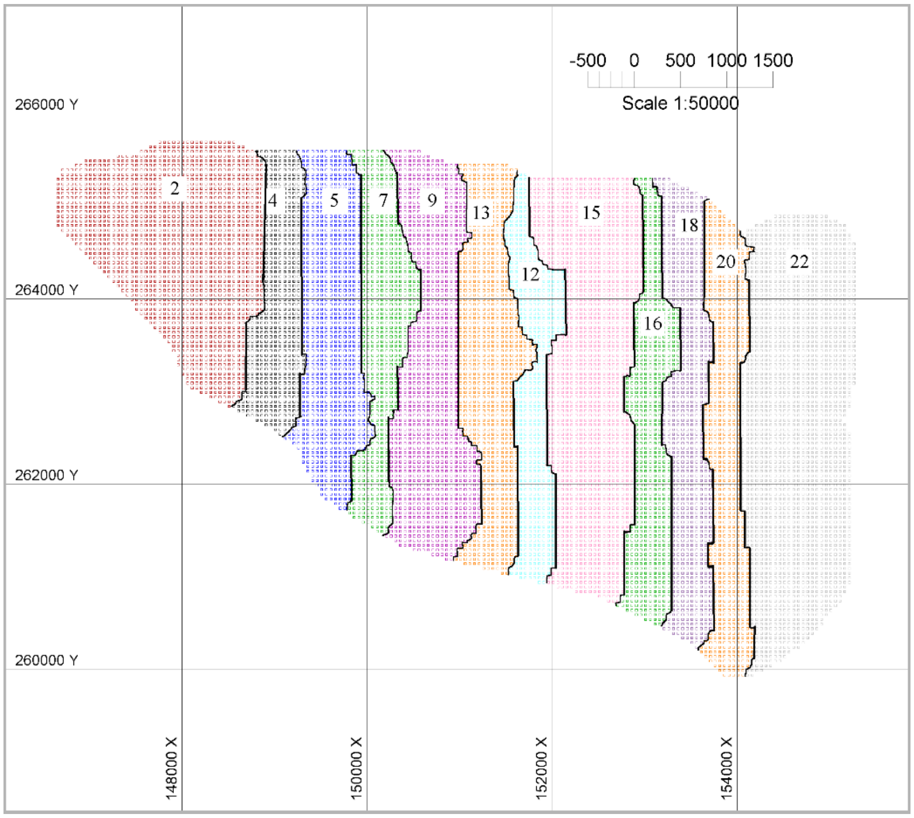

Figure 4.30: Scenario 2b - Mining sequence on level 302.5m

In the MILGP model, the average bitumen head grade was calculated based on the mining-cuts that are extracted in each period and reclaimed stockpile material, while the average bitumen head grade achieved with the ICOGO model was based on a weighted average of the overall available ore tonnage above the cut-off grade and reclaimed stockpile material. Figure 4.31 shows the average bitumen head grade target for each period and the scheduled average bitumen head grade with the MILGP model. It can be seen that the MILGP average bitumen head grade in the early years of mine life is less than the target whereas subsequent years are higher than the target. Figure 4.32 shows the average ore fines percent for the material delivered to the processing destination. Details of the production schedules generated by the MILGP model for Scenario 2b are presented in figures in Appendix B.

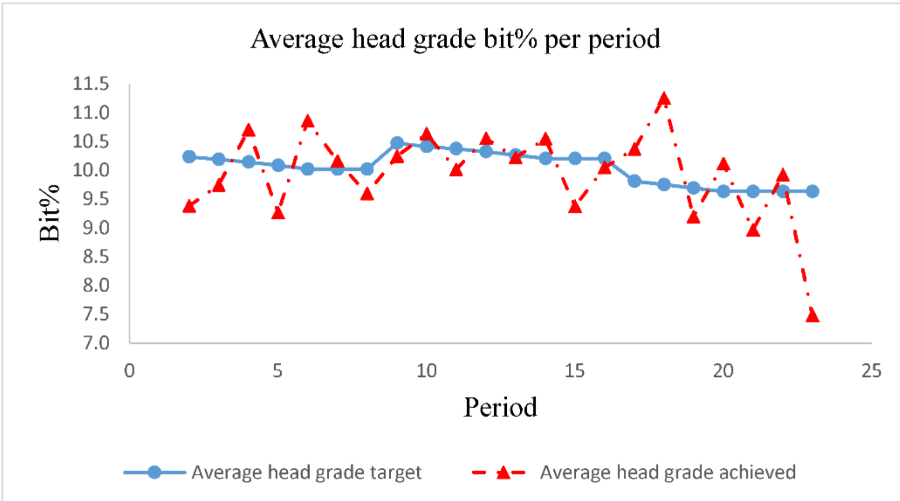

Figure 4.31: Scenario 2b - Average bitumen head grade target and scheduled

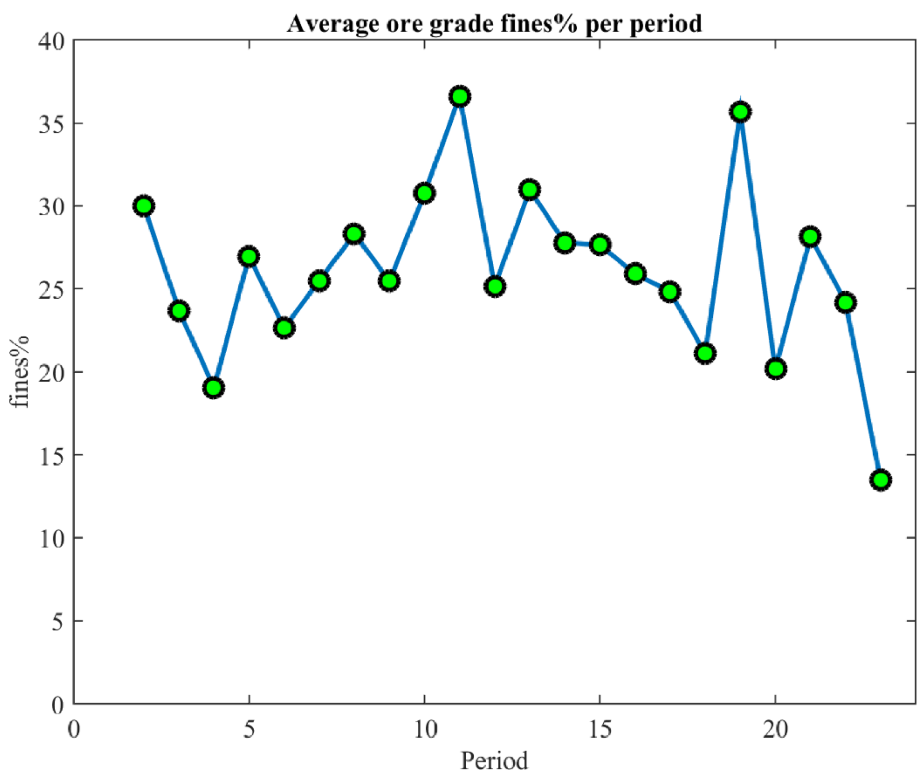

Figure 4.32: Scenario 2b - Average ore fines%

In order to make a comparison of the NPV generated by the ICOGO and MILGP models, the dyke construction cost was excluded from each model due to different waste management tonnage extracted. The ICOGO model generated NPV of $6,337.7 M for scenario of one year stockpile duration while the MILGP model generated NPV of $7,156 M. The MILGP model generated 13% higher NPV than the ICOGO model. This improvement is due to the fact that the MILGP model scheduled higher bitumen grades for processing in the second half of the mine life (Figure 4.31). In addition, the MILGP model did not extract all the material in the final pit limit. The MILGP model left some of the dyke and waste material in the pit since they do not prevent the extraction of the ore material. This resulted in improvement of the profitability of the operation.

Subsequently, the MILGP model was applied to Scenario 3b (production with two year stockpile duration). The NPV generated was 0.1% less than the one year stockpile duration scenario (Scenario 2b). This reduction happens because Scenario 3b mined more waste material than Scenario 2b. As shown in case study 1, if the optimization problem is solved to a tighter EPGAP boundary, the NPV of Scenario 3b will be higher than Scenario 2b due to more flexibility in stockpiling and reclamation allowing the optimizer to send higher grades for processing in the early years to generate more revenue. Figure 4.33 shows the comparison between the average bitumen head grade target and the achieved average bitumen head grade for Scenarios 2b and 3b. Details of the production schedules generated by the MILGP model for Scenario 3b are presented in Appendix C.

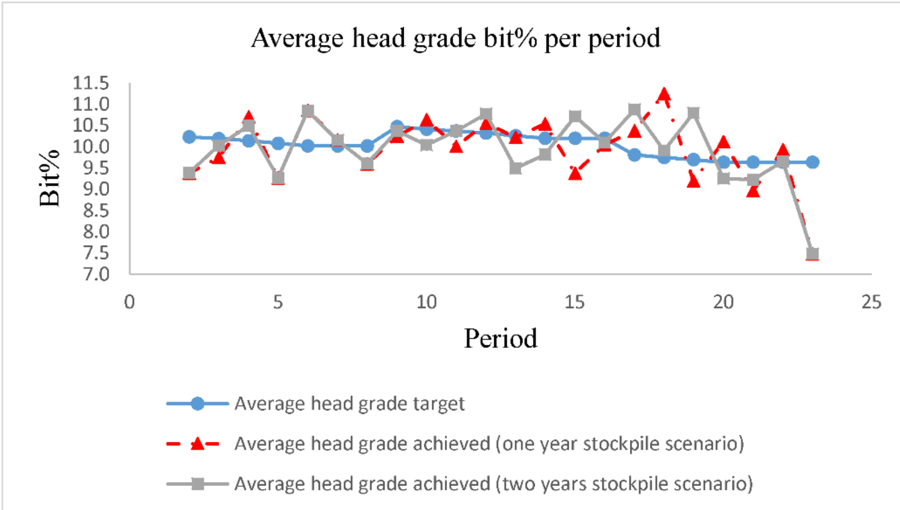

Figure 4.33: Average bitumen head grade for Scenarios 2b and 3b

4.4. Summary

The main focus of this research is to provide a workflow for generating an optimum cut-off grade policy and a strategic production plan for integrated oil sands mining and waste management. The ICOGO model generated an optimum cut-off grade policy. It also generated a uniform production schedule for ore mining and dyke material mining to be extracted from the final pit limit. The advantages of using stockpiling with cut-off grade optimization were evaluated with the ICOGO model. Utilizing stockpile reclamation simultaneously with the mining operation maintained the average head grade and prevented a high reduction in processing recovery due to oxidation of stockpiled material over time. In general, the NPV generated by the scenarios that utilized stockpiling were higher than the scenario without stockpile reclamation. The MILGP model used the bitumen cut-off grade profile and average head grade profile generated by the ICOGO model to define the bitumen grade boundaries and average head grade targets for the mine life. The production schedule targets generated by the ICOGO model were used as a guide to define the production schedule goals in the MILGP model.

The NPV generated with the ICOGO model for the two year stockpiling scenario was less than the NPV generated for the one year stockpiling scenario due to reduction in processing recovery. The NPV generated with the MILGP model for the two year stockpiling scenario was higher than the NPV generated with the one year stockpiling scenario. This increase in NPV is due to more flexibility in stockpiling and reclamation allowing the optimizer to send higher grades for processing in the early years to generate more profit. Table 4.19 shows a summary of the results for both models on two case studies. Despite the ICOGO model not taking into consideration the level of mining-cut extraction detail associated with the MILGP model, it is able to generate solutions for cut-off grade optimization faster. Apart from the MILGP model, the results from the ICOGO model can be used as a guide for medium and short-term planning with any production scheduling optimization framework.

Table 4.19: Summary of the results

	Model	Stockpile management scenario	Total material mined (Mt)	Total material processed (Mt)	Material processed from stockpile (Mt)	Total dyke material (Mt)	NPV (M$)	NPV without waste management cost (M$)
Case 1	ICOGO	Without stockpile	1338.7	432.9	-	936.1	1,411.5	1,819.2
		Reclamation at end of the mine life	1338.7	451.8	18.9	936.1	1,451.3	1,862.9
		Reclamation after 1 year	1338.7	451.8	20.5	936.1	1,543.5	1,975.2
		Reclamation after 2 years	1338.7	451.8	20.7	936.1	1,532.8	1,962.1
	MILGP	Reclamation after 1 year	1338.7	451.8	24.6	899.9	1,354.5	1,767.0
		Reclamation after 2 years	1338.7	451.8	22.3	906.6	1,357.5	1,771.0
Case 2	ICOGO	Without stockpile	6530.2	2242.7	-	5133.1	4,731.1	6,087.9
		Reclamation after 1 year	6530.2	2299.6	61.3	5133.1	4,845.9	6,337.7
		Reclamation after 2 years	6530.2	2299.6	62.4	5133.1	4,822.7	6,303.5
	MILGP	Reclamation after 1 year	6475.8	2299.6	42.2	4665.9	5,951.1	7,156.0
		Reclamation after 2 years	6503.8	2299.6	40.5	4585.3	5,950.5	7,143.7

CHAPTER 5

5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1. Summary of Research

Long-term production scheduling optimization is one of the important aspects of mine planning. In achieving the maximum benefit from a mining operation, the long-term production schedule should consider the time and sequence of removing ore and waste material from the final pit limit. Improving the efficiency of production scheduling optimization tools' performance in the mining industry is a high priority task since the economic gains are considerably high.

The mine planning process is affected by several factors. The most important of these factors is the cut-off grade since it defines the amount of available ore and waste to be mined in the final pit limit. In the case of oil sands mining, the waste management strategy drives the sustainability and profitability of the mining operation. It makes it necessary to consider the waste management cost and it constraints in the cut-off grade optimization process for integrated long-term production scheduling. On this basis the Integrated Cut-Off Grade Optimization (ICOGO) framework, which is a heuristic optimization model, was developed in this research. The ICOGO model determines the optimum cut-off grade policy taking into consideration stockpiling with limited duration, and waste management for dyke construction and tailings deposition. The developed model is a modified version of Lane (1964) cut-off grade optimization models. A limitation of the ICOGO model is that it cannot handle detailed mining-cut extraction precedence. In order to resolve this challenge, a Mixed Integer Linear Goal Programming (MILGP) framework was developed to determine the time and sequence for removal of ore, dyke material and waste mining-cuts. The model developed here is a modified version of the

Ben-Awuah et al. (2012) models. The MILGP framework uses the cut-off grade profile generated by the ICOGO model as a guide in determining the grade of material that can be sent to the plant or to the stockpile. The production schedule generated by the ICOGO model was also used in setting up the goal functions to be achieved by the MILGP model. The developed models were applied to two oil sands case studies to ensure their practicality and reliability.

5.2. Conclusions

The heuristic cut-off grade optimization model developed in this research considers waste management cost and stockpiling with limited duration in generating an optimum cut-off grade policy that ensures maximum NPV for an oil sands mining operation. The following are specific concluding statements listing the features of the ICOGO model:

1. The ICOGO model generates an optimum cut-off grade policy and a uniform production schedule for ore, OB, IB, TCS and waste material over the life of mine; and maximizes the NPV of the oil sands mining operation.
2. The waste management strategy required for oil sands mining operation based on the Alberta Energy Regulator (AER) Directive 082, was achieved by providing OB, IB and TCS dyke material required for ex-pit and in-pit dyke construction.
3. An evaluation of stockpiling with varying reclamation strategies was discussed for oil sands mining. Reclaiming the stockpiled material after pit mining is complete results in an increase of the processed ore tonnage. Alternatively, reclaiming stockpiled material simultaneously during active pit mining increases the available ore tonnage and maintains the average head grade required by the processing plant. By maintaining the

average head grade, the NPV generated in the scenario with simultaneous stockpile reclamation was higher than other stockpile management scenarios.

Subsequently, the cut-off grade profile and production schedule generated by the ICOGO model were used as guides in setting up the input for the MILGP model. The following are the concluding statements listing the features of the MILGP model:

1. The MILGP model generates a more practical schedule for extracting ore, waste and dyke material from the final pit limit.
2. The MILGP model provides simultaneous stockpile reclamation with a specific stockpiling duration taking into consideration processing recovery changes resulting from oxidation of stockpiled ore. The MILGP model provides a framework consistent for sustainable oil sands mining with respect to regulatory requirements of the Alberta Energy Regulator (AER) Directive 082.
3. By applying clustering algorithm, the MILGP model was able to solve large scale long-term production planning problems.

Although the level of mining-cut extraction detail of the ICOGO model is not similar to the MILGP model, it provides an initial production schedule for life of mine planning. In both case studies, the NPV generated by the ICOGO model for one year stockpiling scenario was higher than other stockpiling scenarios. For the MILGP the NPV generated for the two year stockpiling scenario was higher than the one year stockpiling scenario. It should be mentioned that the main advantage of the ICOGO model over the MILGP model is that it is capable of solving the long-term optimization problem in less than 3 seconds with a Core i5 Lenovo E550 computer at 2.2

GHz and 8 GB of RAM, while the MILGP model requires a longer time (4.4 minutes) to run on the same computer. Table 5.1 shows the numerical results for the MILGP model.

Table 5.1: Numerical results for the MILGP model

	Stockpile management scenario	Number of constrains	Number of continuous variables	Number of binary variables	EPGAP	Solution time (hrs)
Case 1	Reclamation after 1 year	38,380	222,726	952	1%	0.1
	Reclamation after 2 years	38,380	222,726	952	1%	0.1
Case 2	Reclamation after 1 year	152,764	845,710	8,372	10%	90.2
	Reclamation after 2 years	152,764	845,710	8,372	10%	84.5

The results from the ICOGO model can be used as a guide in determining the inputs for any integrated production scheduling and waste management optimization framework. In comparison, whereas the ICOGO model solved the optimization problem faster, the MILGP model results provide detailed mining-cut extraction sequencing for mining.

5.3. Contributions of M.A.Sc Research

In summary, the major contributions of this research work on oil sands production scheduling are as follows:

1. Developed an integrated cut-off grade optimization (ICOGO) model that allows the incorporation of waste management costs into the cut-off grade optimization framework.
2. The ICOGO model incorporates stockpiling with limited duration in the long-term production scheduling for an oil sands operation. The ICOGO model can generate fast solution for long-term production scheduling problems for large mining projects.

3. Developed a mixed integer linear goal programming (MILGP) model that features stockpiling with limited duration for detailed integrated long-term production and waste management planning.
4. Provided a workflow that uses the ICOGO model to generate initial life of mine planning targets which are subsequently used as guides in setting up production goals for detailed medium and short-term production planning.
5. The ICOGO and MILGP models and workflow seek to support the oil sands mining industry in integrating mine planning and waste management in accordance with Directive 085 issued by the Alberta Energy Regulator (AER) on Fluid Tailing Management for Oil Sands Mining Projects.

5.4. Recommendations for Future Work

The author of this thesis believes that the proposed integrated cut-off grade optimization model and the mathematical programming model still have room for further improvements. The following two areas are enumeration of the author’s recommendations for future work:

1. In the development of the ICOGO and MILGP models, it was assumed that all of the input data were deterministic. However, there are uncertainties related to mine planning parameters such as grade, cost and price. Consideration of uncertainties related to grade and mine economics will result in a risk-based evaluation of the life of mine plan.
2. The main limitation in using the MILGP formulation for integrated oil sands mine planning and waste management optimization with stockpiling is the long runtime required to generate solutions. This is primarily due to the problem size – optimizing decades of mining schedules. Working towards improving the computational efficiency

of the MILGP model would add great value in terms of ease and frequency of use by mine planners.

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6. APPENDIX A: Case Study 1 - Scenario 4b

Figure 6.1 to Figure 6.9 show the production schedules generated for different material types with the MILGP model for two year stockpiling scenario.

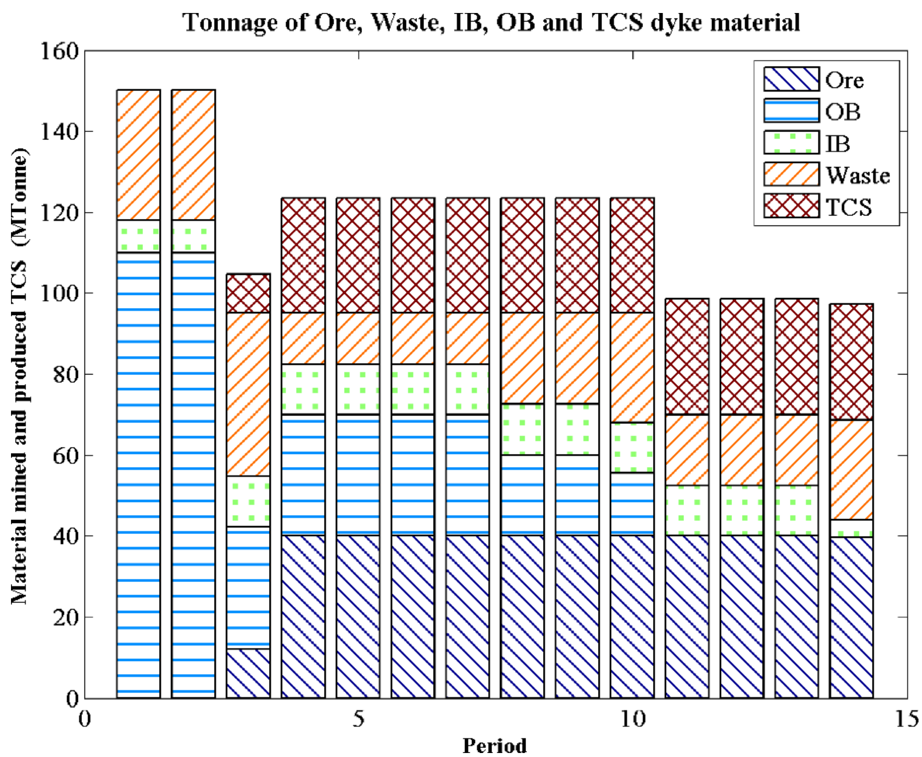

Figure 6.1: Scenario 4b - Schedule for material mined, reclaimed and produced TCS

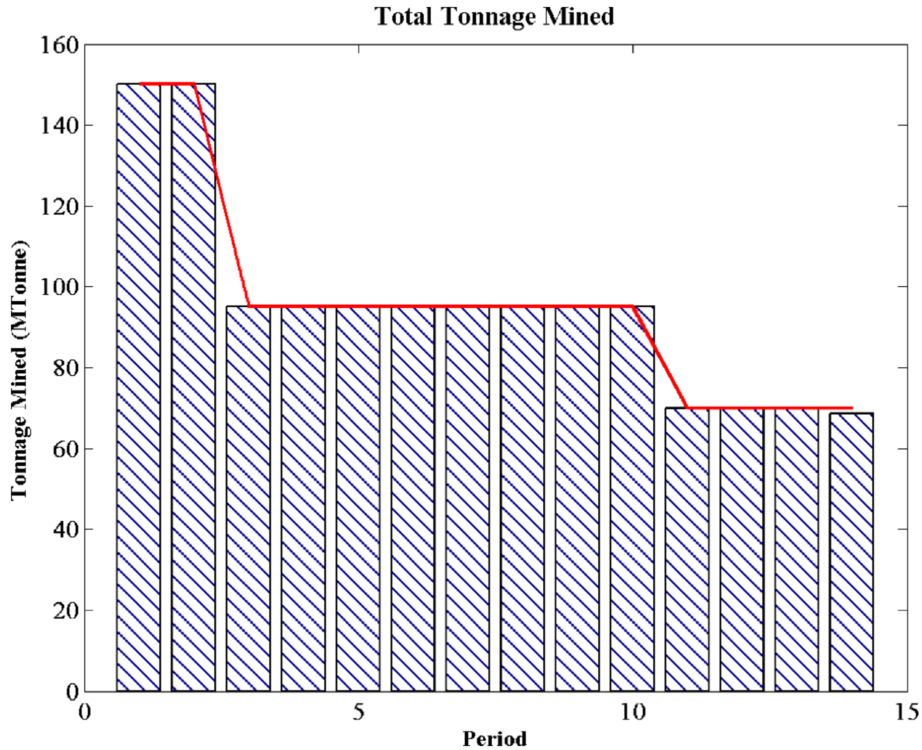

Figure 6.2: Scenario 4b - Mining goal schedule

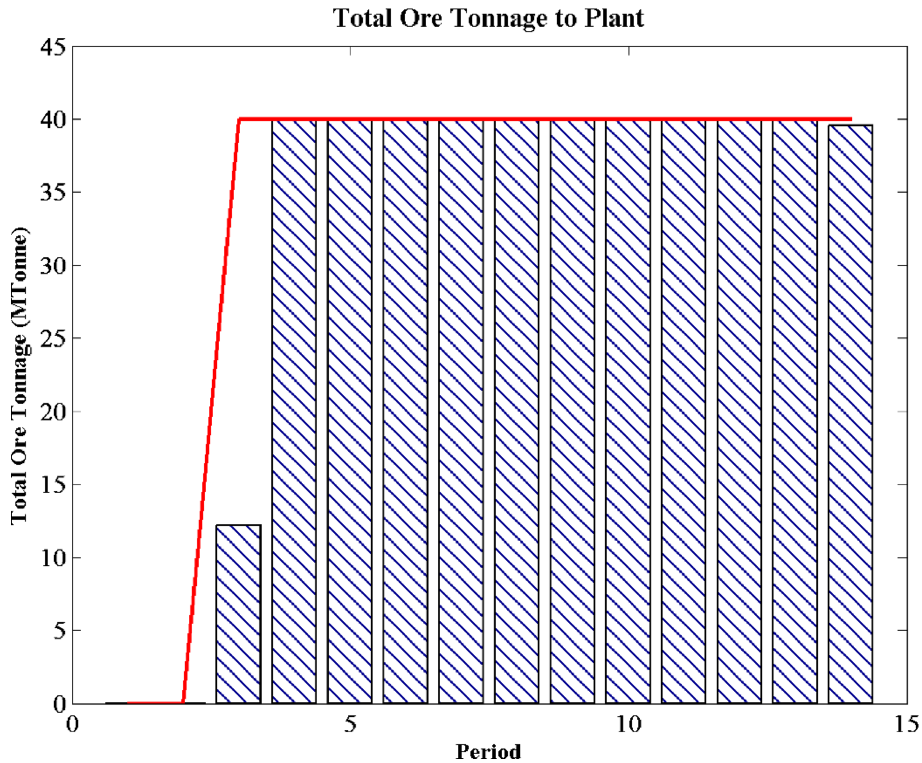

Figure 6.3: Scenario 4b - Processing goal schedule

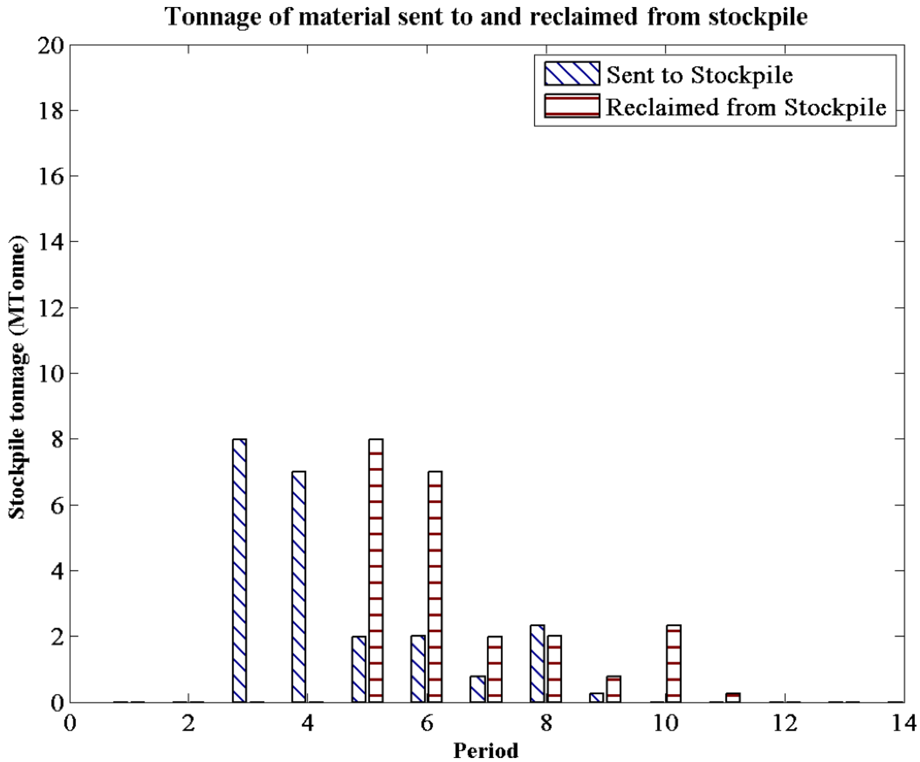

Figure 6.4: Scenario 4b - Stockpiled material schedule

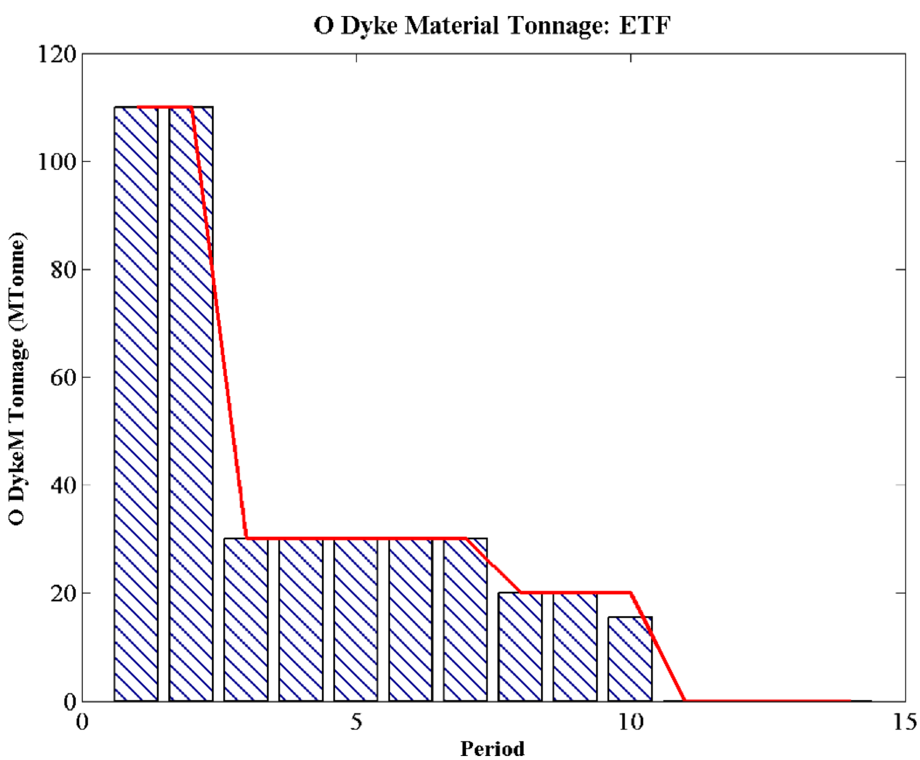

Figure 6.5: Scenario 4b - OB dyke material schedule

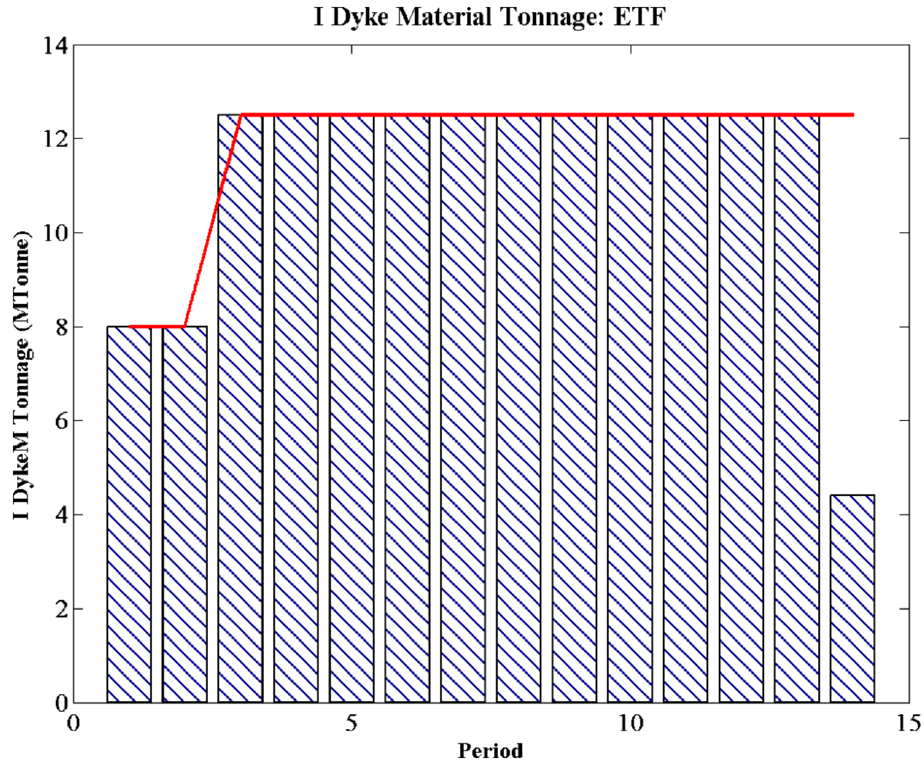

Figure 6.6: Scenario 4b - IB dyke material schedule

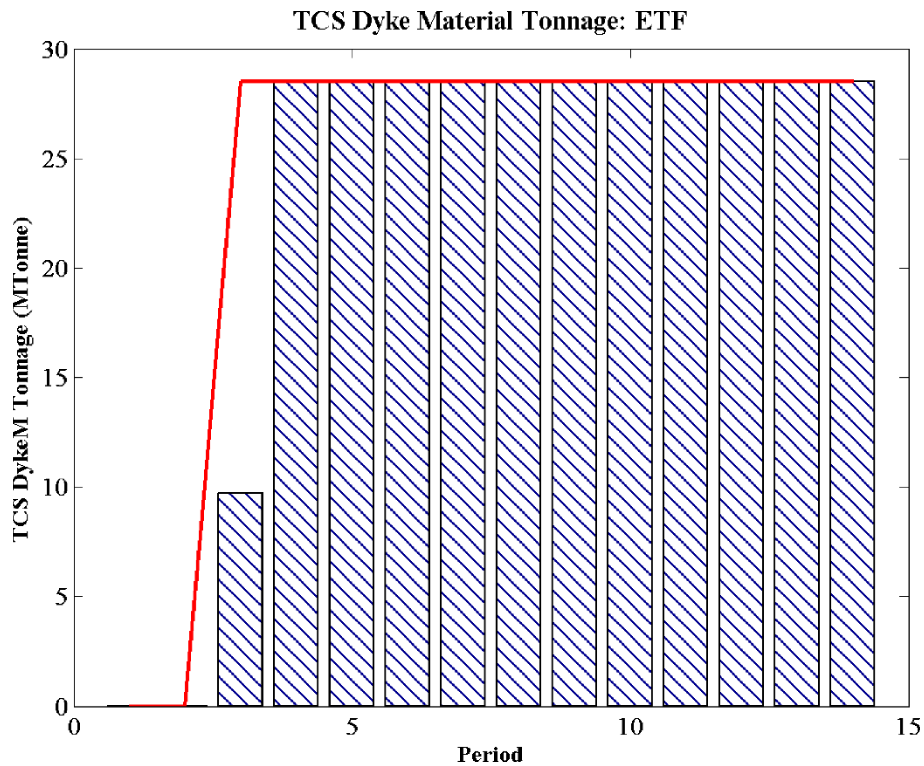

Figure 6.7: Scenario 4b - TCS dyke material schedule

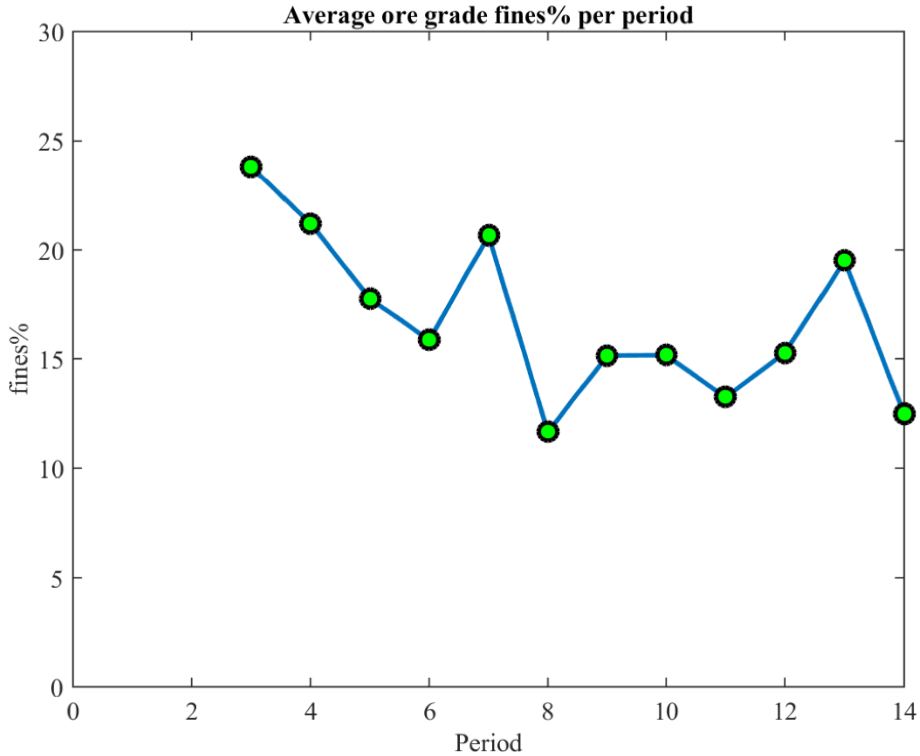

Figure 6.8: Scenario 4b - Average ore fines%

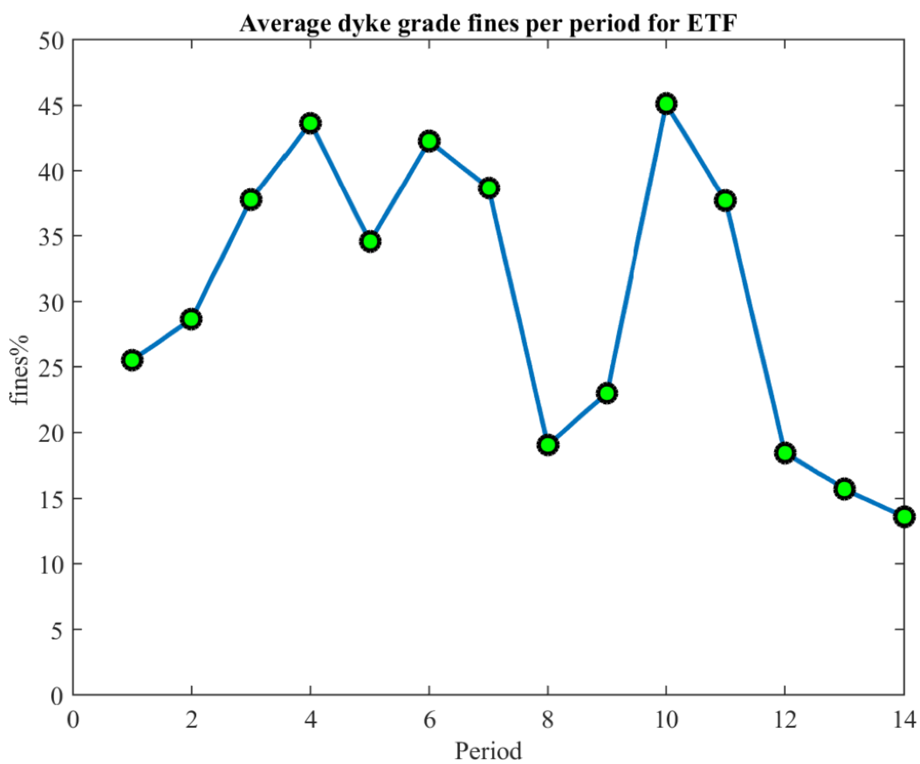

Figure 6.9: Scenario 4b - Average IB dyke material fines%

7. APPENDIX B: Case Study 2 - Scenario 2b

Figure 7.1 to Figure 7.13 show the production schedules generated for different material types with the MILGP model for one year stockpiling scenario.

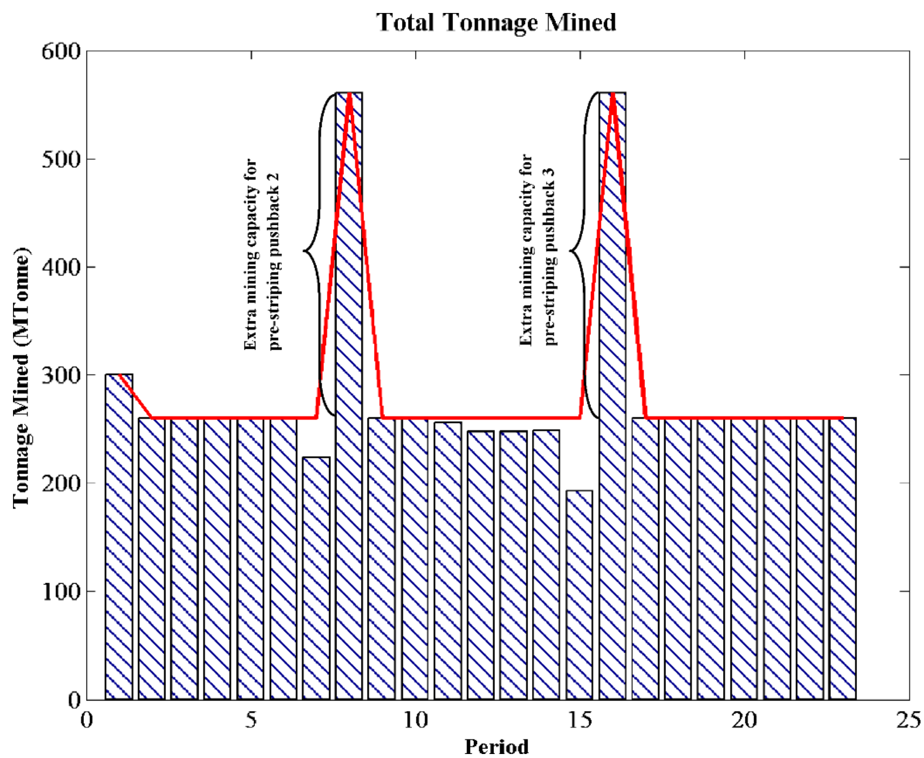

Figure 7.1: Scenario 2b - Mining goal schedule

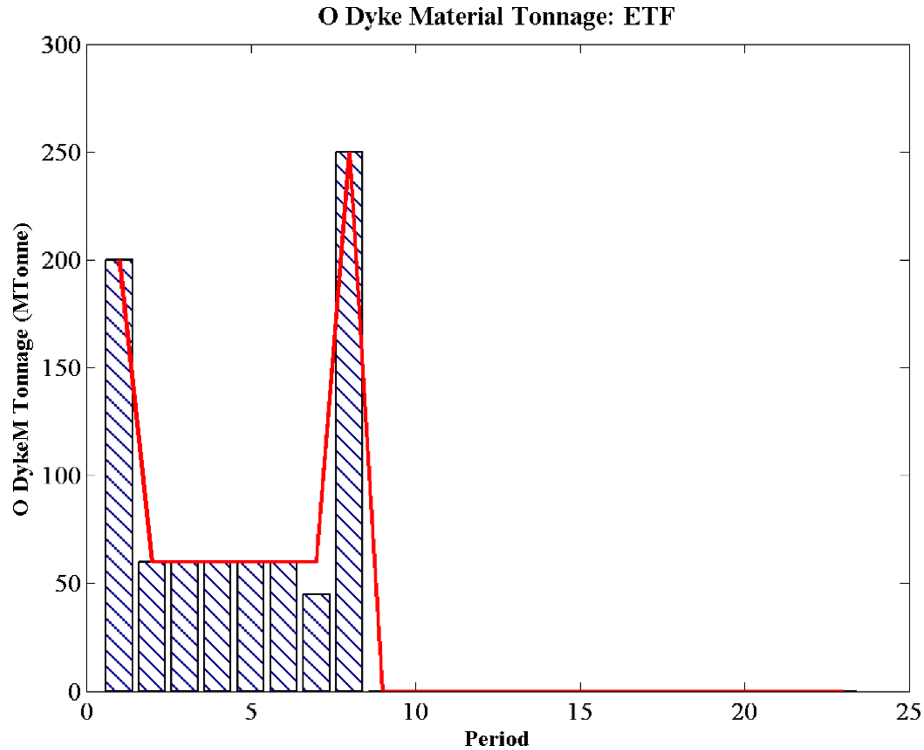

Figure 7.2: Scenario 2b - OB dyke material schedule for ETF

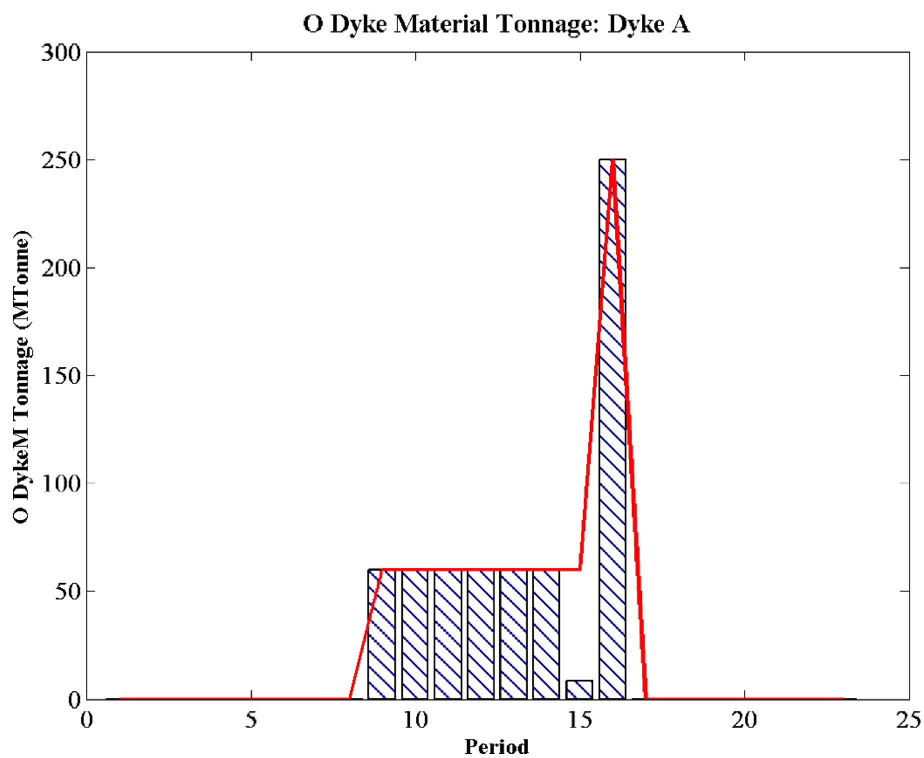

Figure 7.3: Scenario 2b - OB dyke material schedule for dyke A

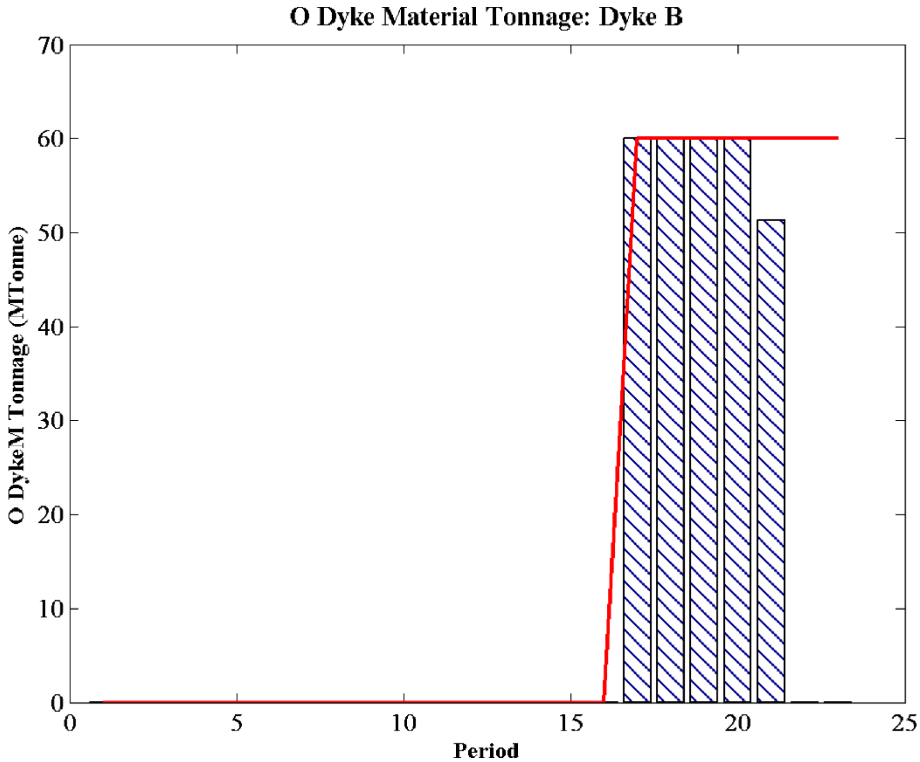

Figure 7.4: Scenario 2b - OB dyke material schedule for dyke B

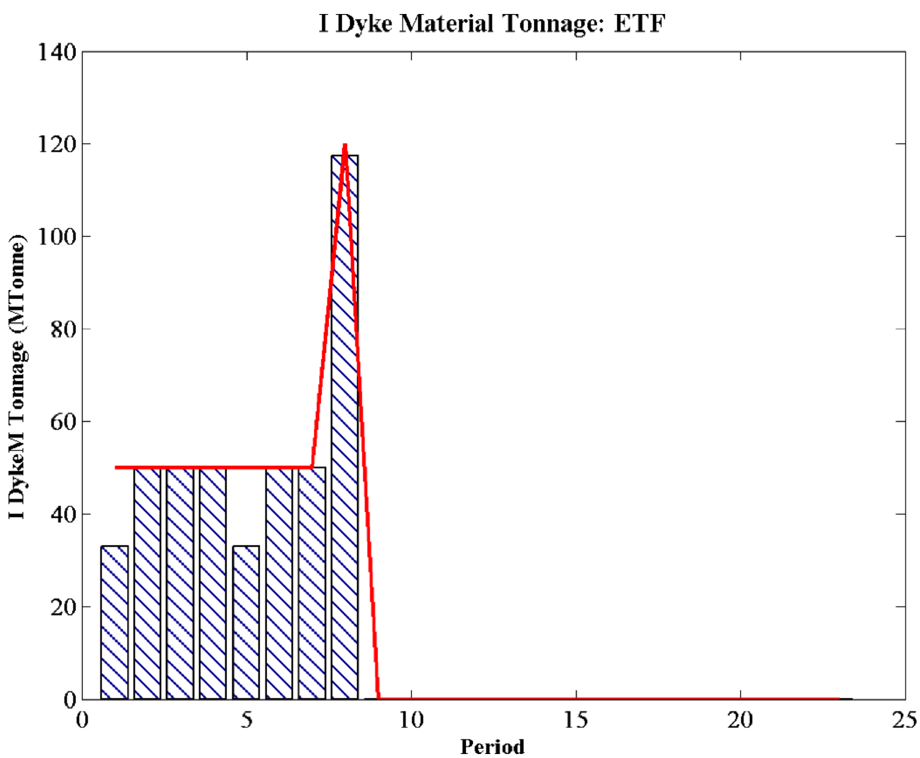

Figure 7.5: Scenario 2b - IB dyke material schedule for ETF

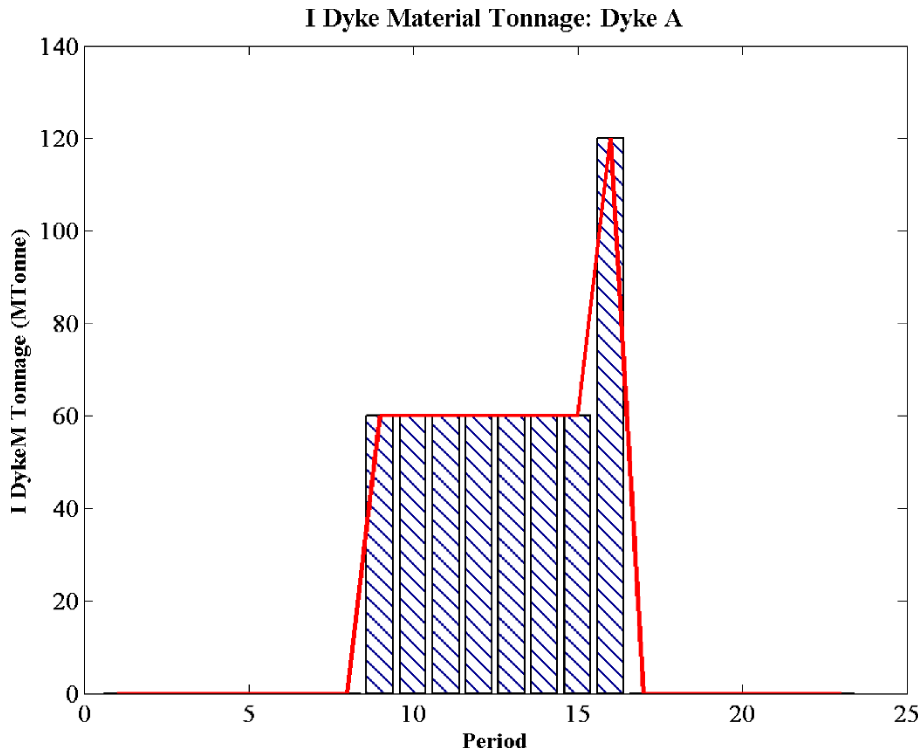

Figure 7.6: Scenario 2b - IB dyke material schedule for dyke A

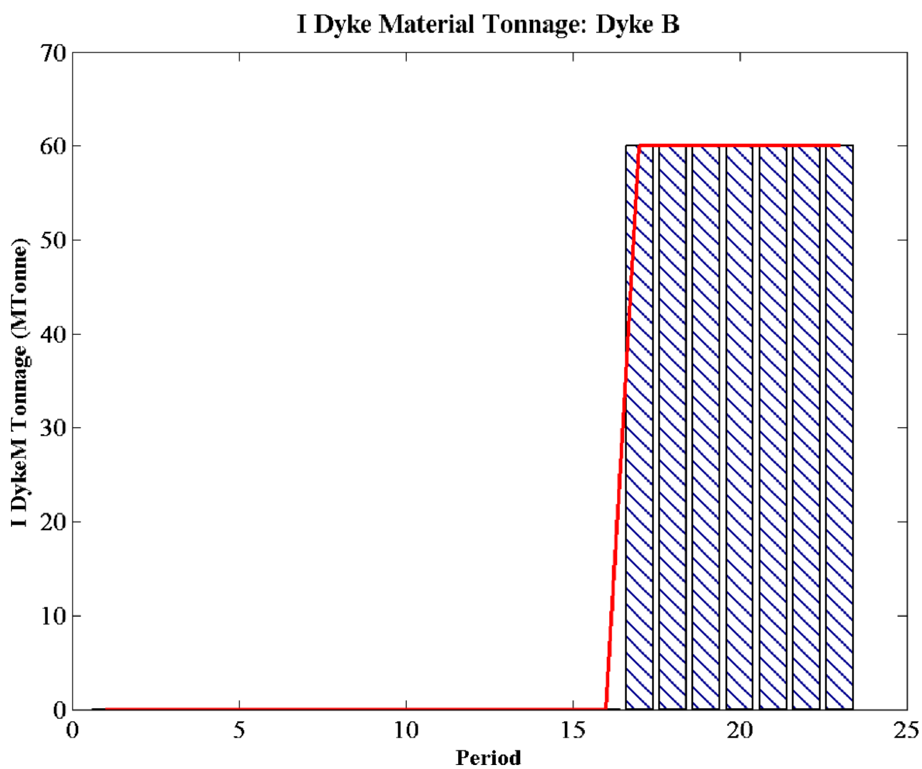

Figure 7.7: Scenario 2b - IB dyke material schedule for dyke B

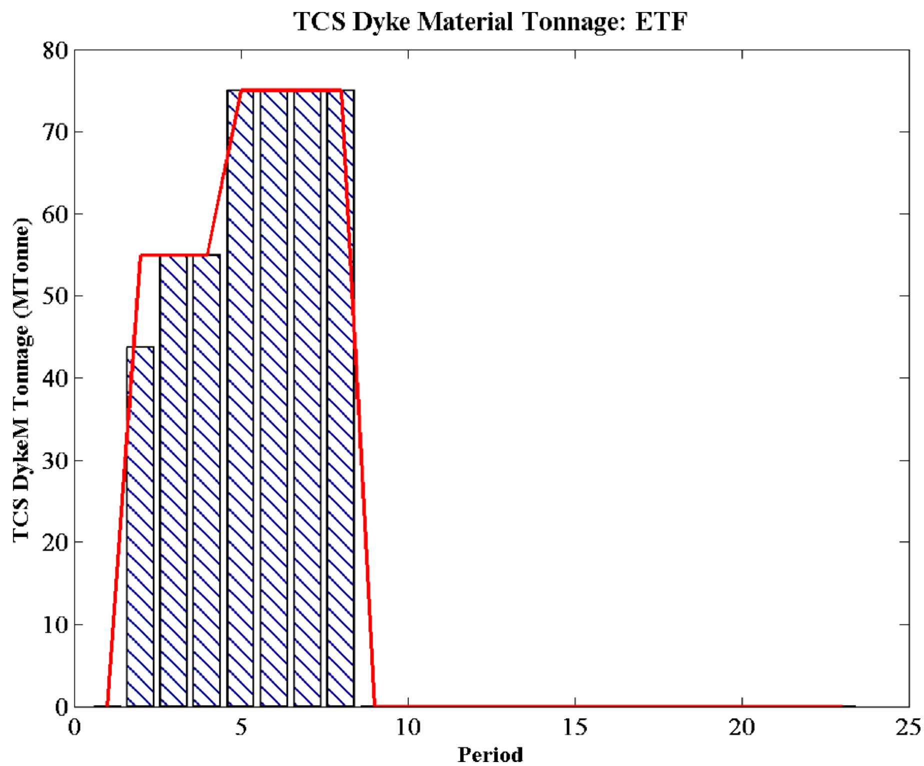

Figure 7.8: Scenario 2b - TCS dyke material schedule for ETF

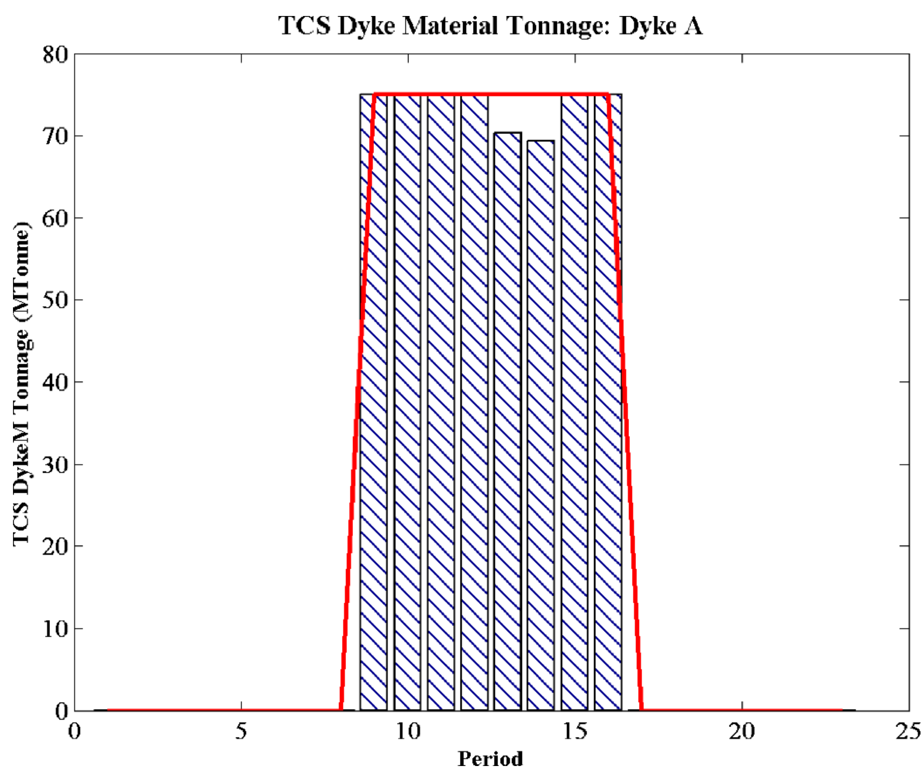

Figure 7.9: Scenario 2b - TCS dyke material schedule for dyke A

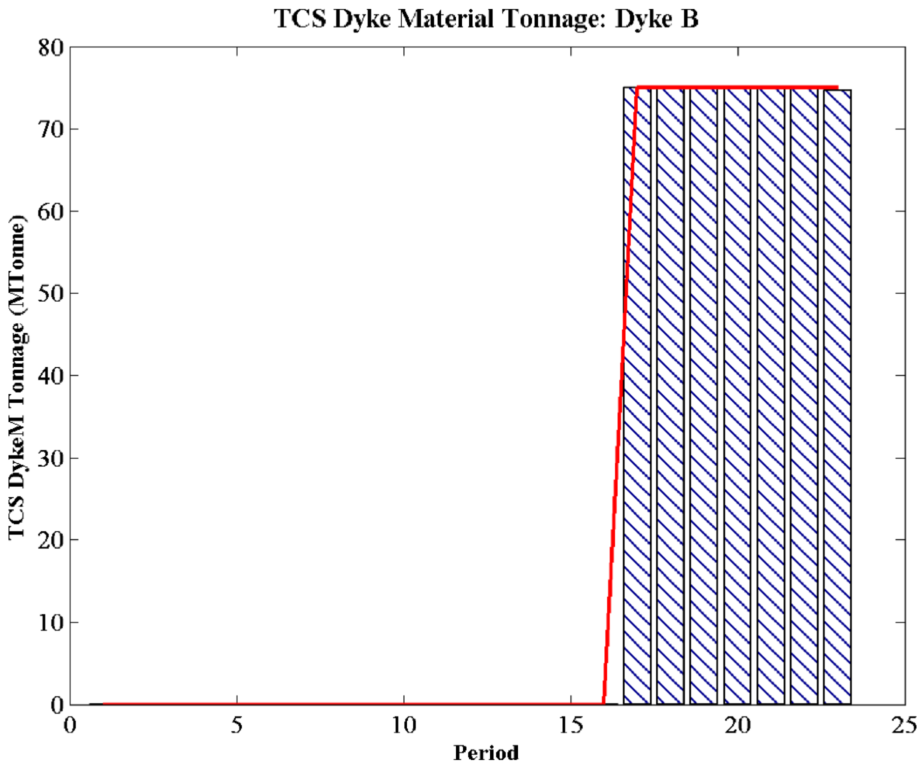

Figure 7.10: Scenario 2b - TCS dyke material schedule for dyke B

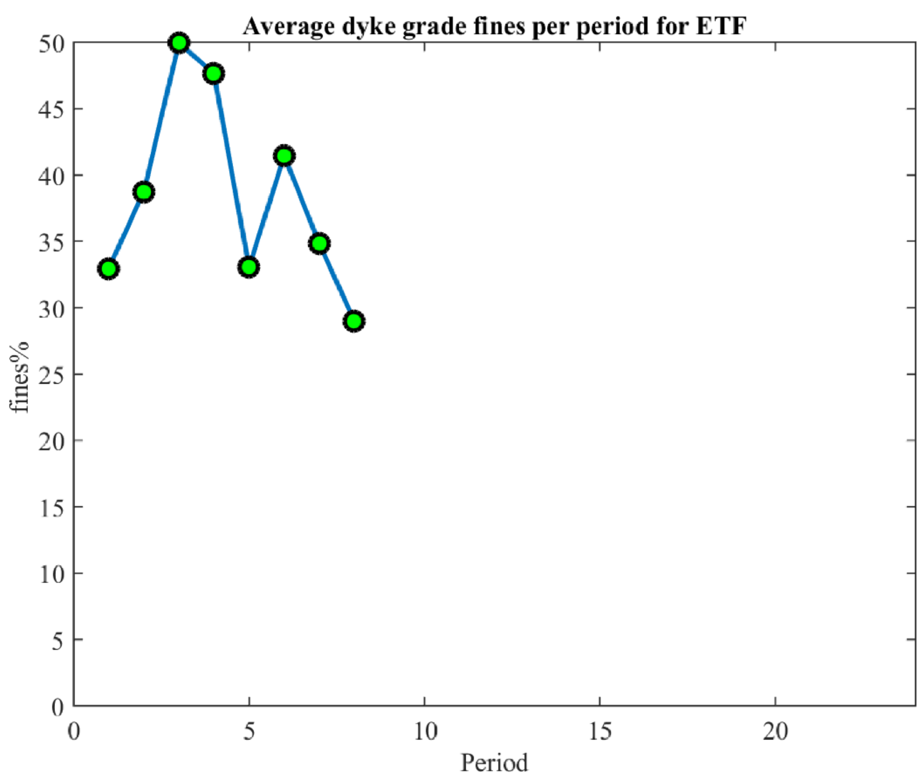

Figure 7.11: Scenario 2b - Average IB dyke material fines% for ETF

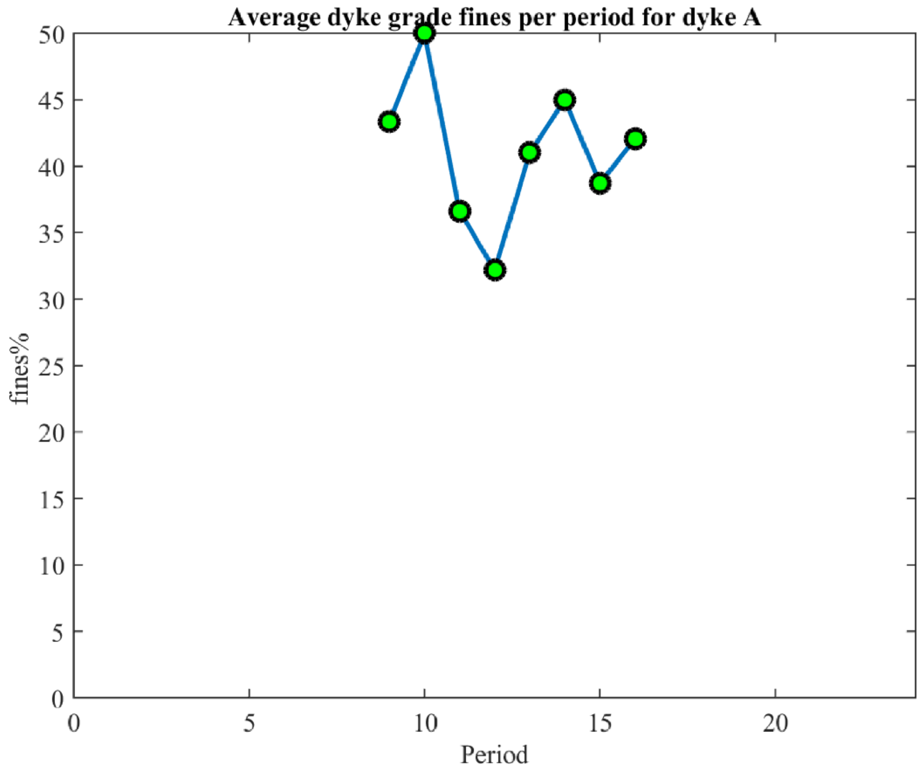

Figure 7.12: Scenario 2b - Average IB dyke material fines% for Dyke A

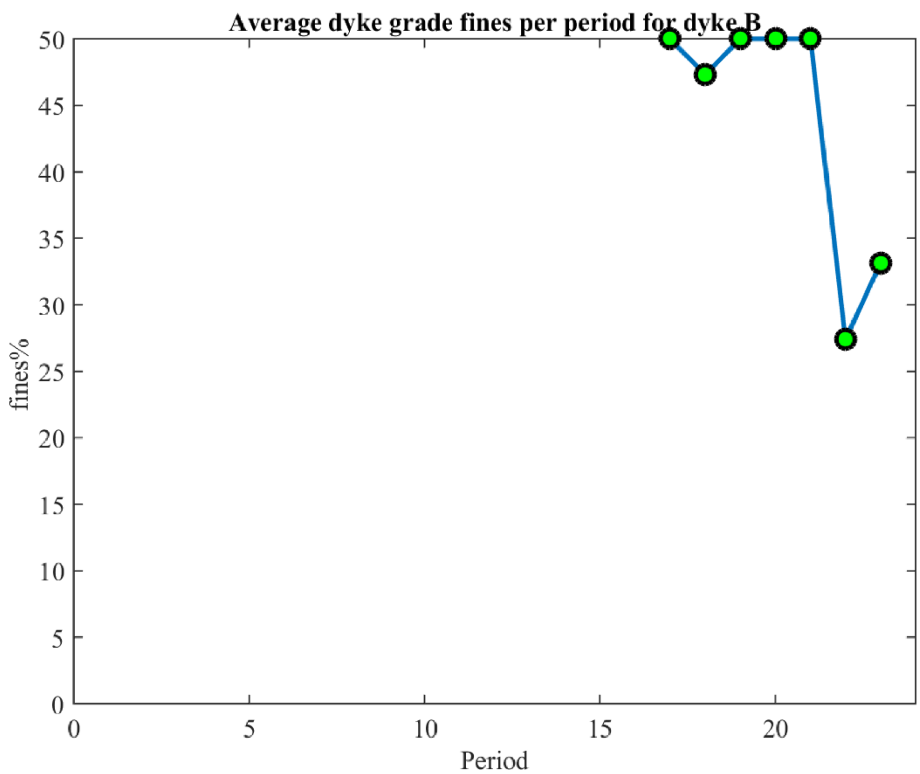

Figure 7.13: Scenario 2b - Average IB dyke material fines% for Dyke B

8. APPENDIX C: Case Study 2 - Scenario 3b

Figure 8.1 to Figure 8.17 show the production schedules generated for different material types with the MILGP model for two year stockpiling scenario.

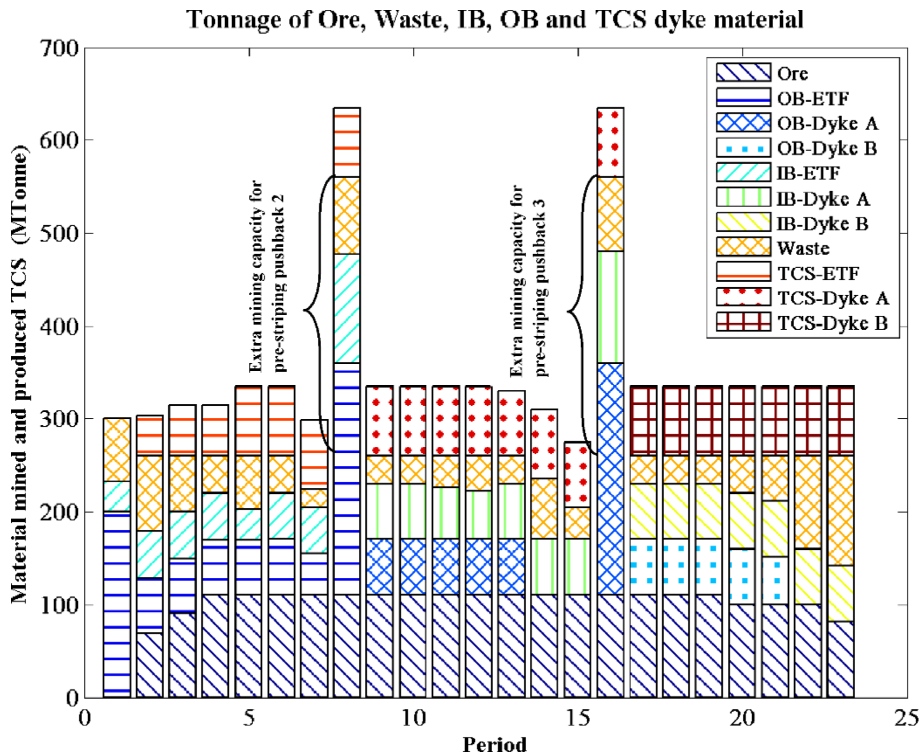

Figure 8.1: Scenario 3b - Schedule for material mined, reclaimed and produced TCS

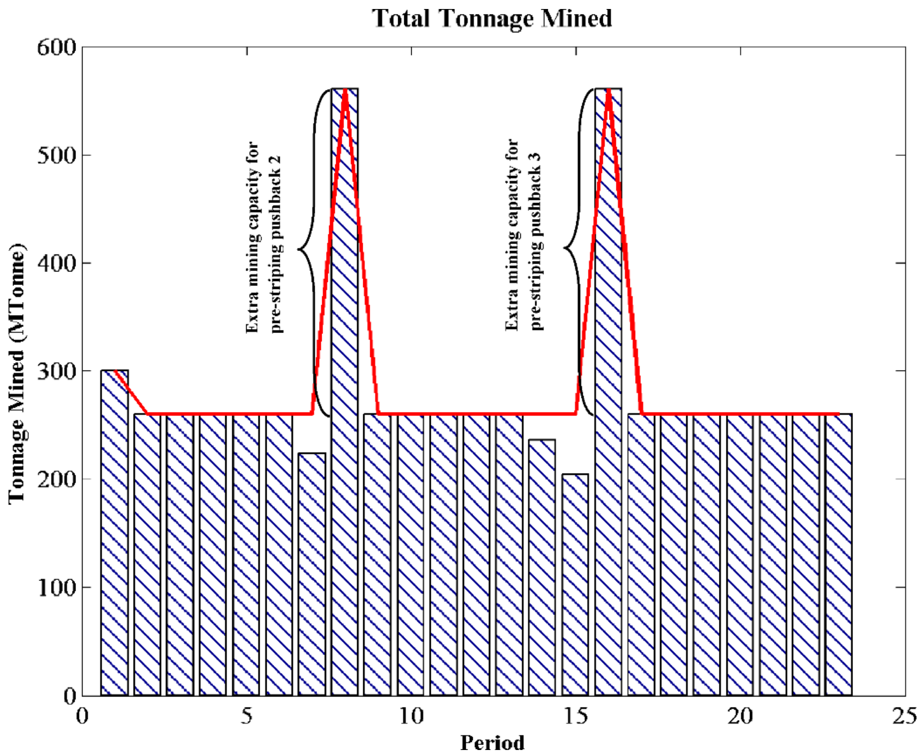

Figure 8.2: Scenario 3b - Mining goal schedule

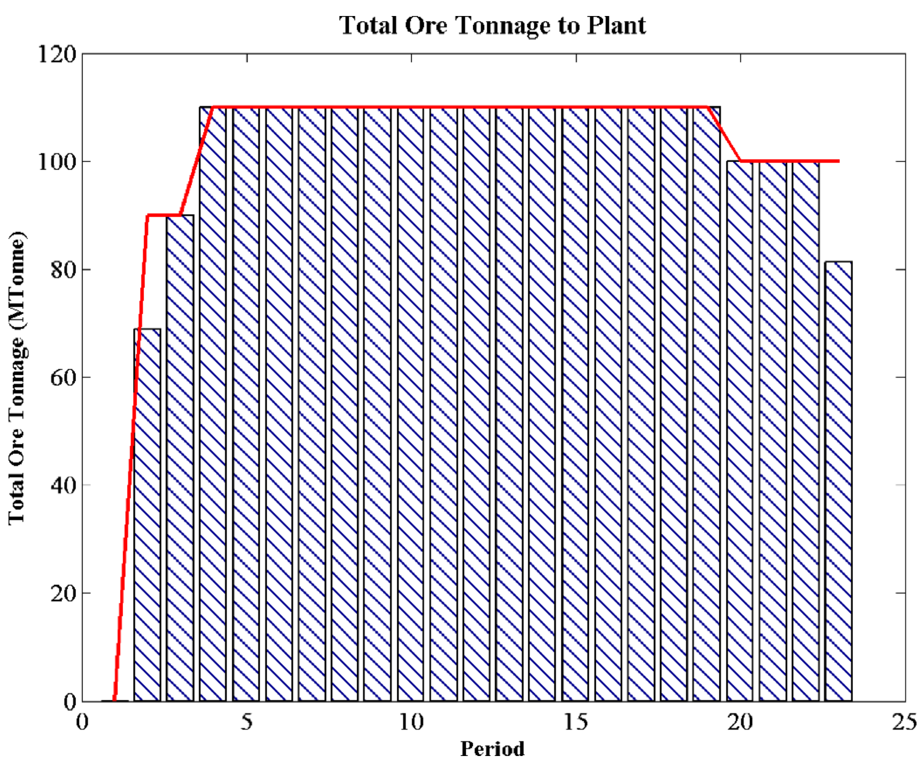

Figure 8.3: Scenario 3b - Schedule for ore material

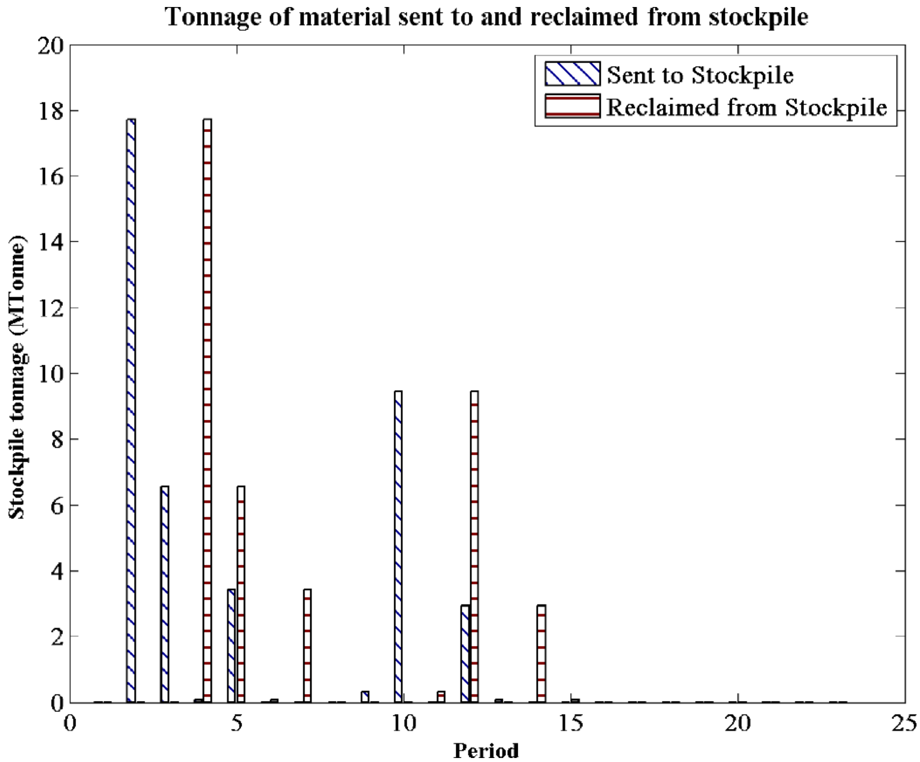

Figure 8.4: Scenario 3b - Schedule for material stockpiled and reclaimed after two year duration

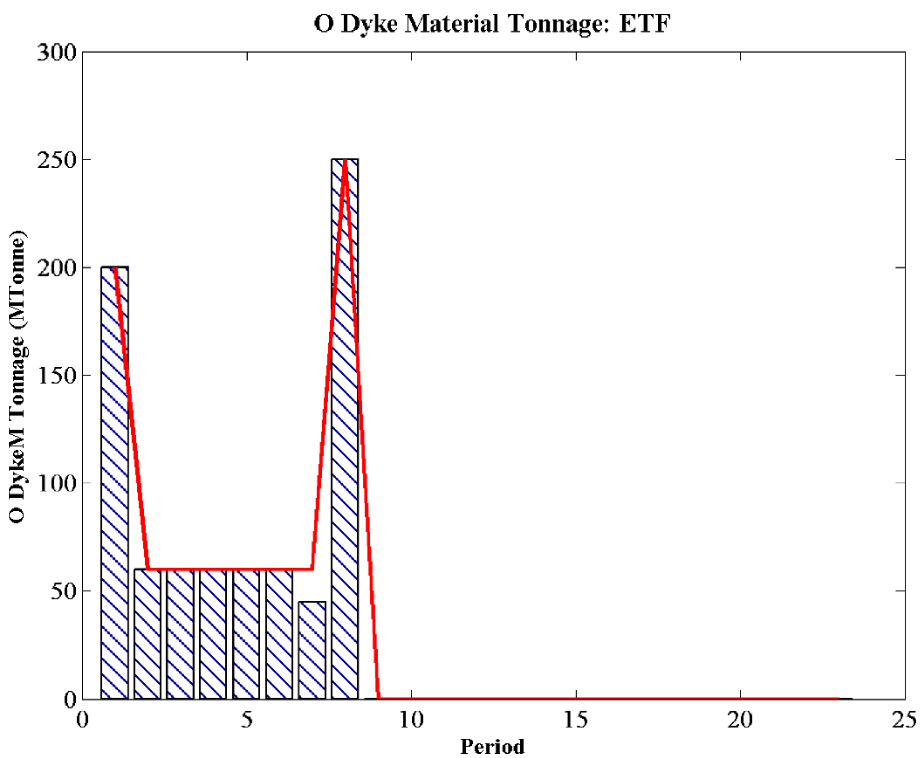

Figure 8.5: Scenario 3b - OB dyke material schedule for ETF

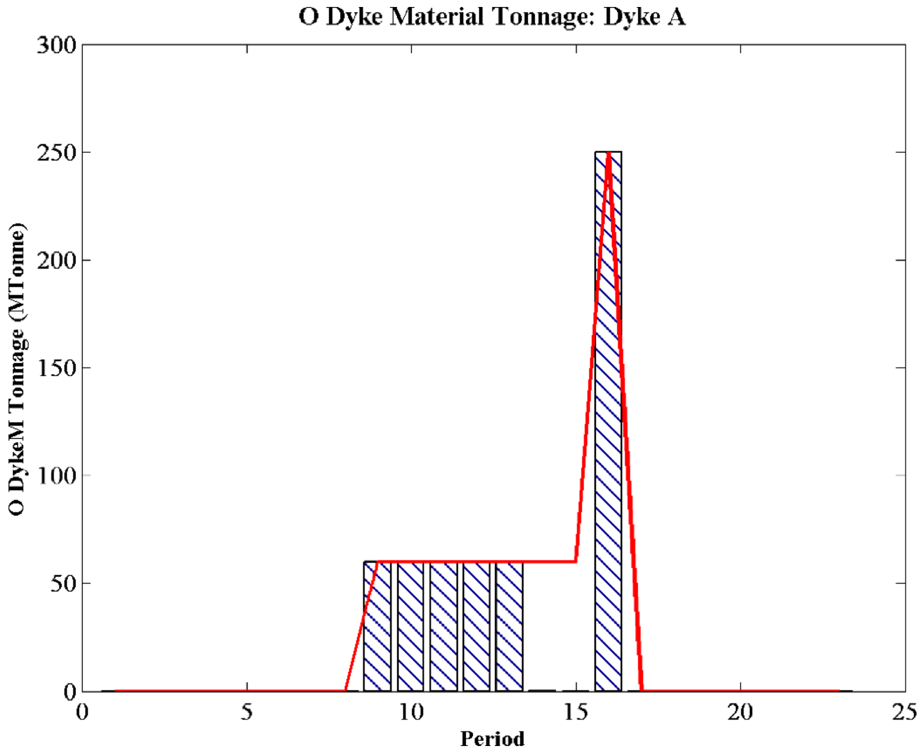

Figure 8.6: Scenario 3b - OB dyke material schedule for dyke A

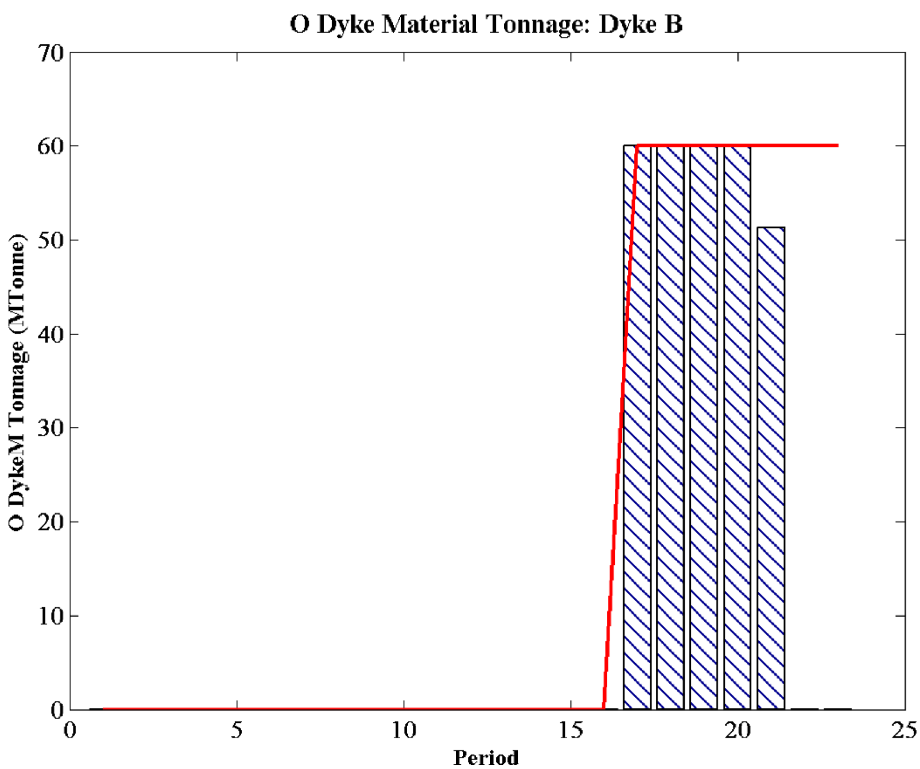

Figure 8.7: Scenario 3b - OB dyke material schedule for dyke B

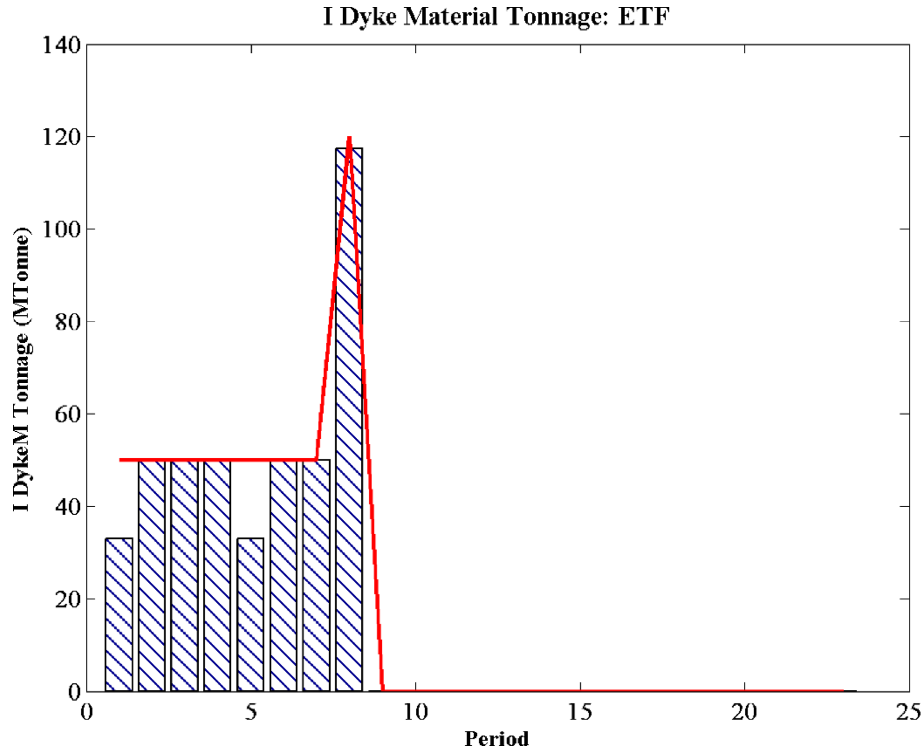

Figure 8.8: Scenario 3b - IB dyke material schedule for ETF

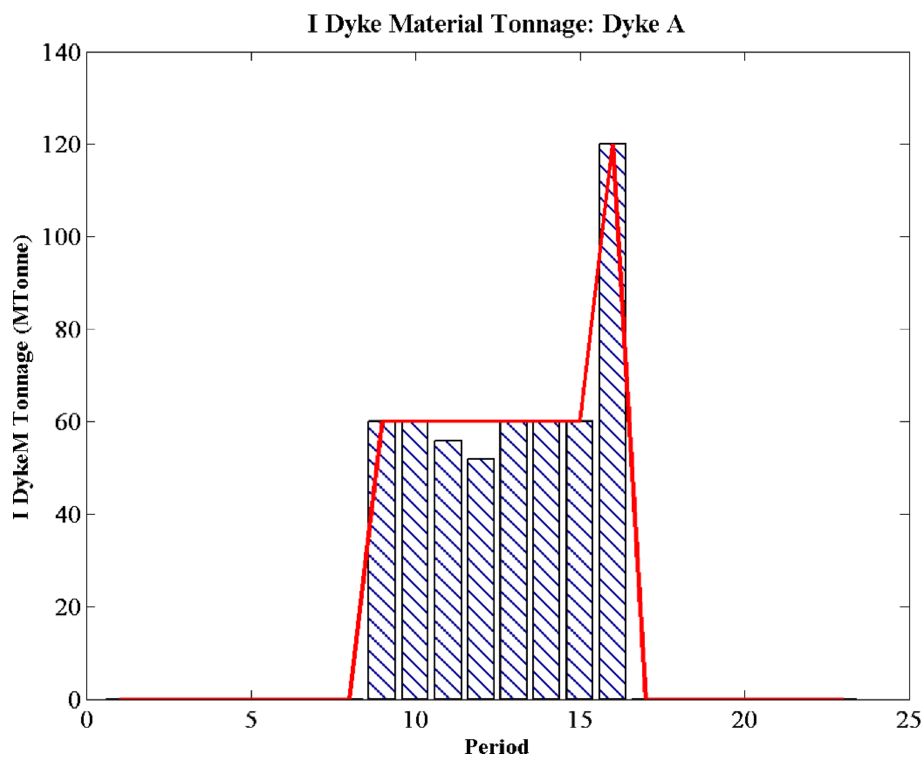

Figure 8.9: Scenario 3b - IB dyke material schedule for dyke A

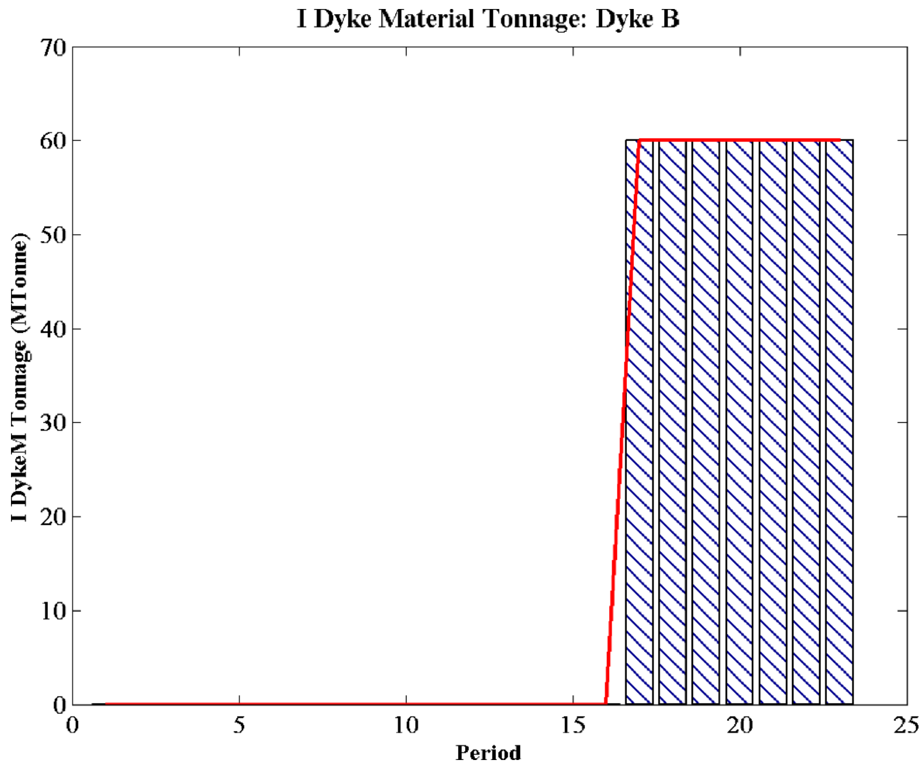

Figure 8.10: Scenario 3b - IB dyke material schedule for dyke B

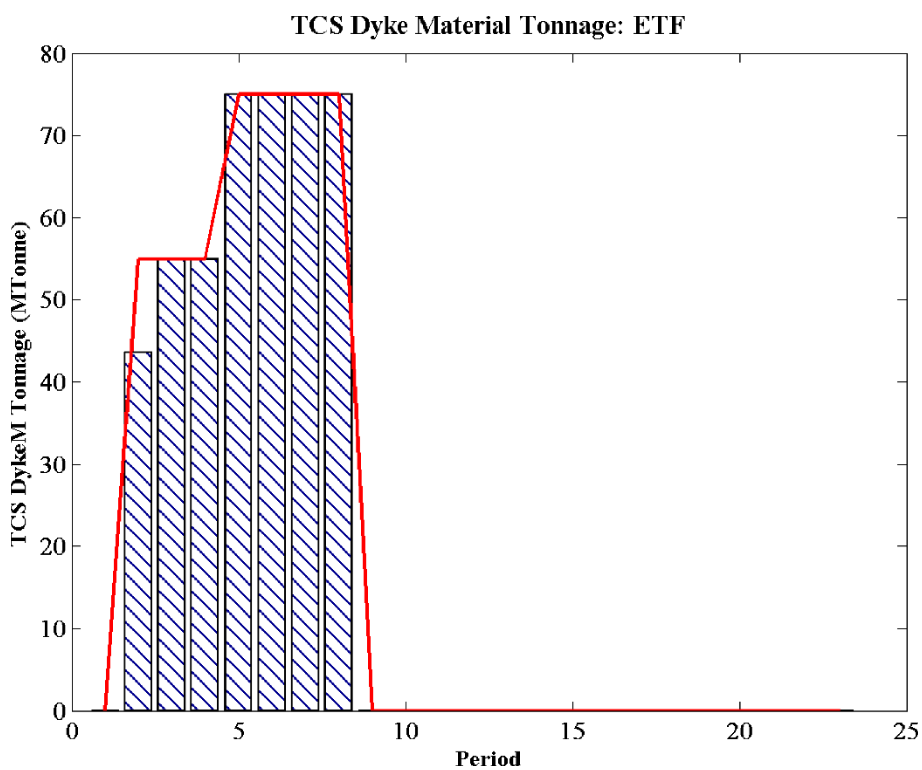

Figure 8.11: Scenario 3b - TCS dyke material schedule for ETF

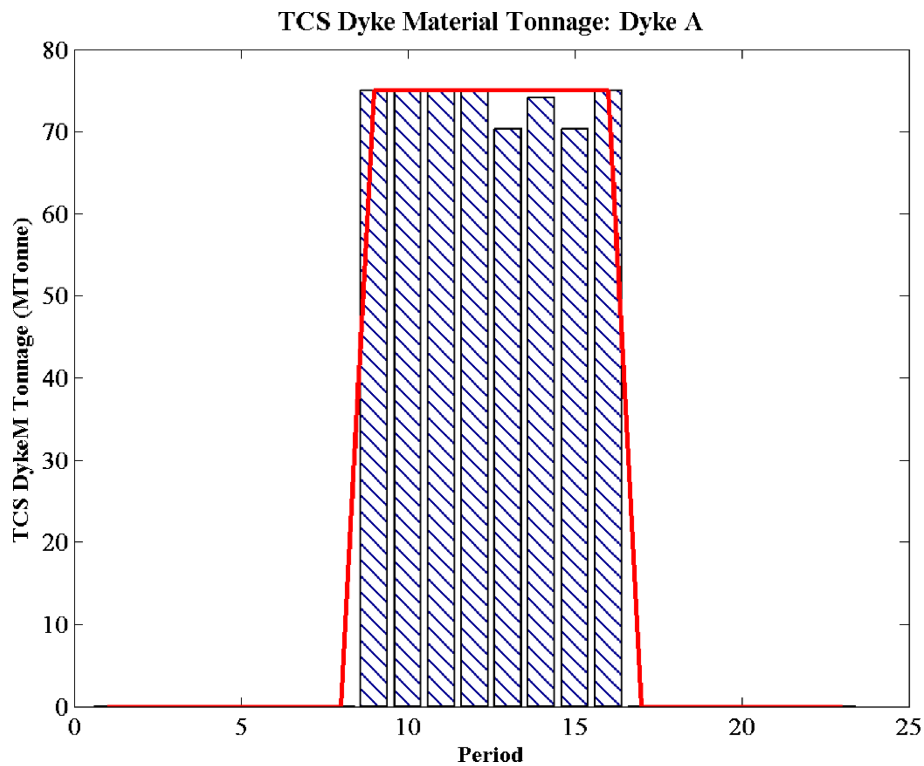

Figure 8.12: Scenario 3b - TCS dyke material schedule for dyke A

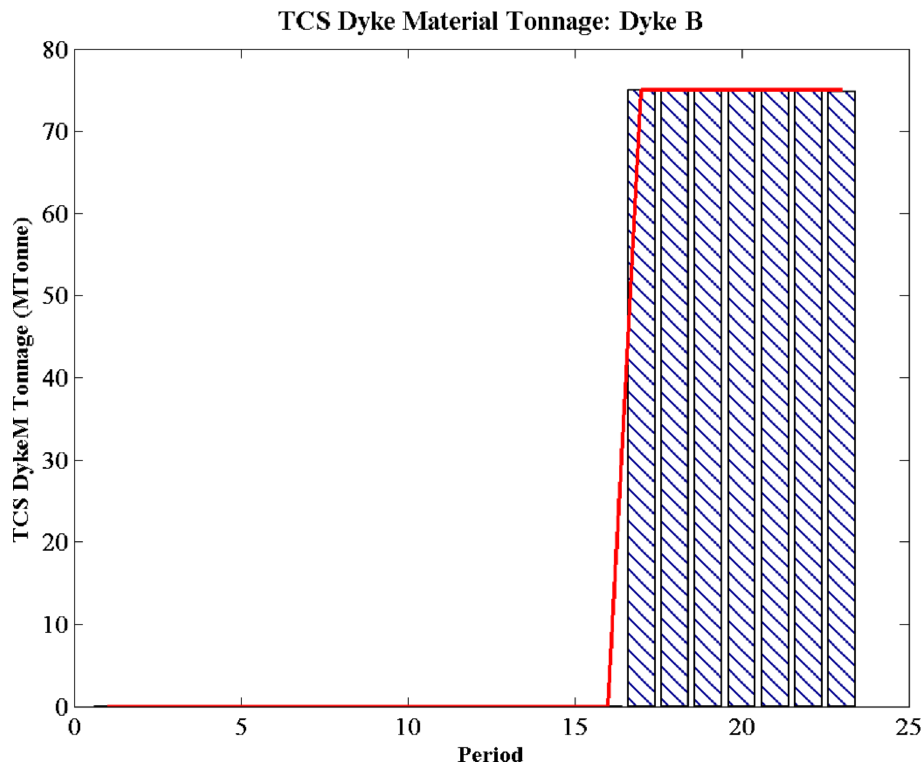

Figure 8.13: Scenario 3b - TCS dyke material schedule for dyke B

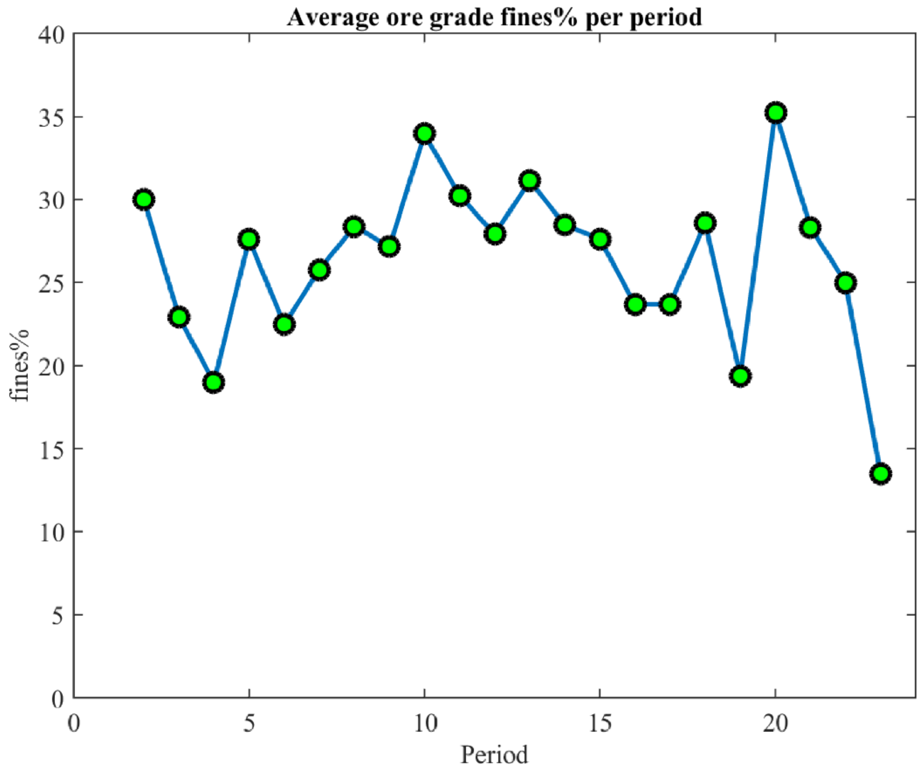

Figure 8.14: Scenario 3b - Average ore fines%

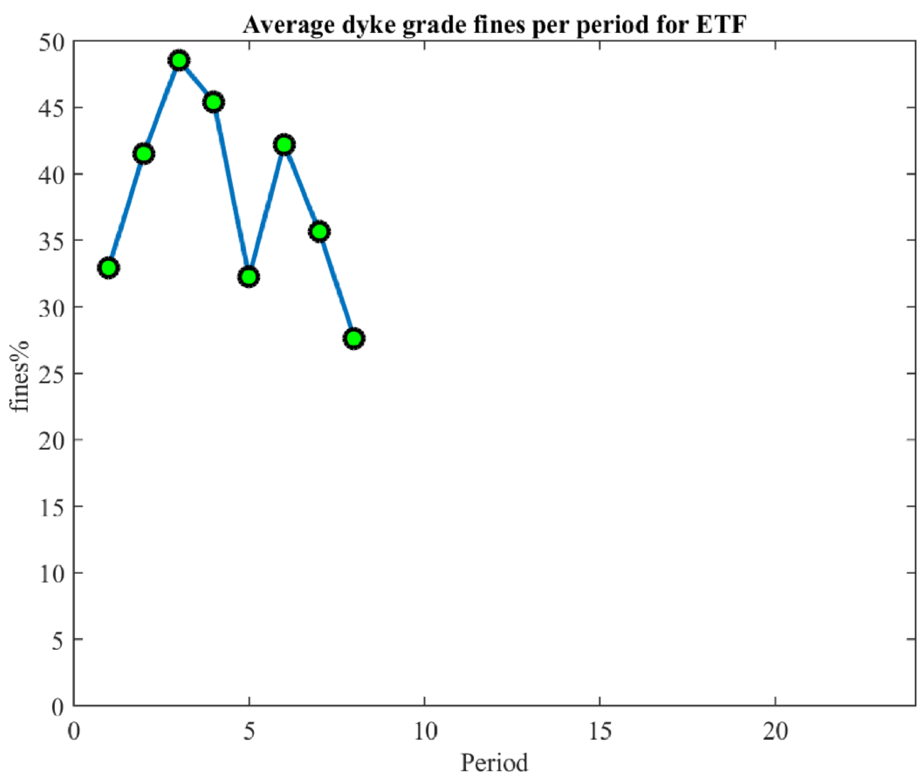

Figure 8.15: Scenario 3b - Average IB dyke material fines% for ETF

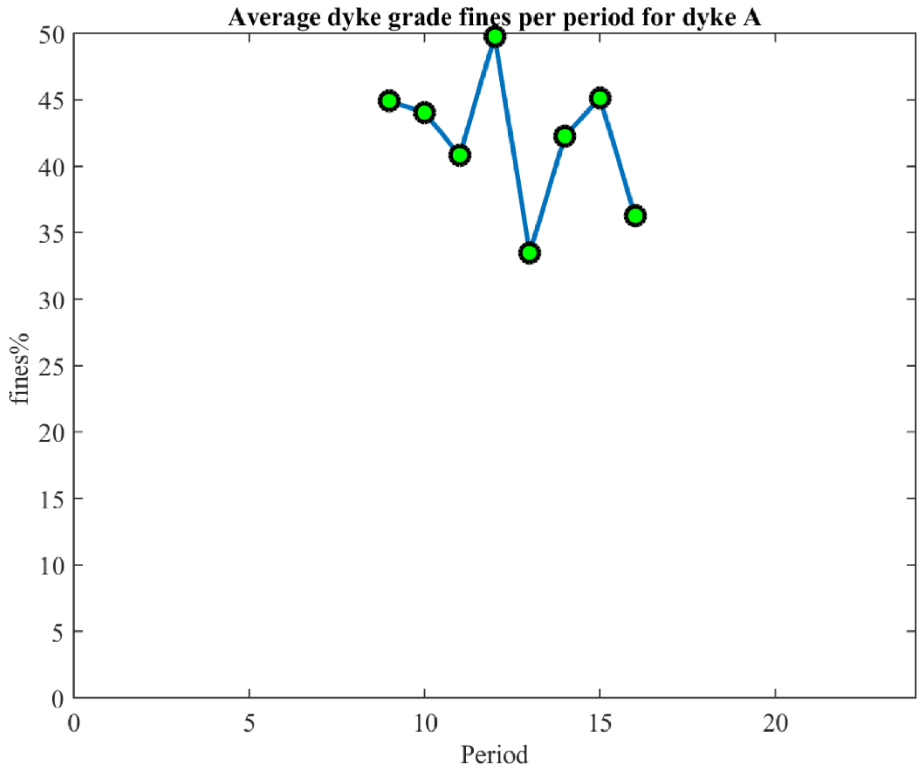

Figure 8.16: Scenario 3b - Average IB dyke material fines% for Dyke A

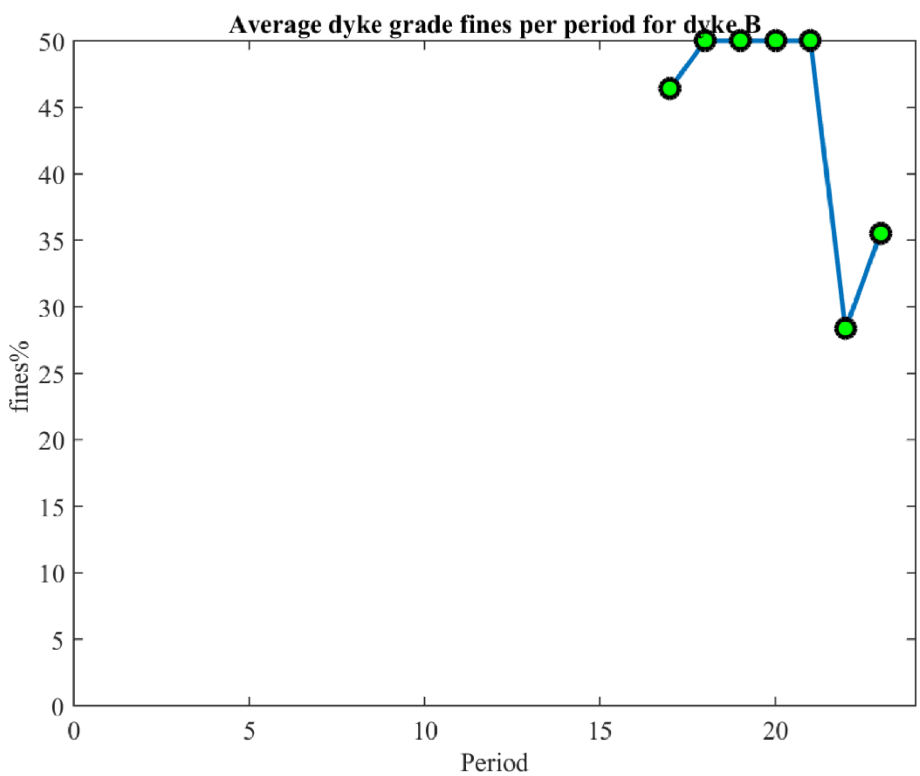

Figure 8.17: Scenario 3b - Average IB dyke material fines% for Dyke B