Incorporating Cut-off Grade Optimization into Oil Sands Production Scheduling

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Abstract

In pursuance of achieving the maximum benefit in oil sands mining, the long-term production schedule should have the time and the sequence of removing the ore, dyke and waste material. In long-term production scheduling, determining the optimum cut-off grade profile is an important aspect. Based on regulatory requirements, all the material containing more than 7% Bitumen should be mined. Cut-off grade optimization is used to generate an optimum grade schedule with the purpose of specifying the cut-off grade, duration of mining of the grade and tonnage mined during the mine life. This research developed a heuristic model that generates an optimum cut-off grade policy and a schedule for ore and waste material as well as overburden, interburden and tailings coarse sand dyke material. The application of the model to a case study proves its ability to maximize the Net Present Value of the operation through cut-off grade optimization. Scenarios investigated includes: no stockpiling; stockpiling and reclaiming at the end of mine life; and stockpiling with limited reclamation duration. The first two scenarios have similar cut-off grades but the second scenario had one more year mine life because of utilization of the stockpile after the mining operation. The third scenario had the highest cut-off grade profile compared to the others. The optimum schedule can subsequently be used as input for medium and short-term production scheduling and waste management.

1. Introduction

Surface mining accounts for a considerable amount of the produced minerals to meet the increasing need of resources of the high-tech society. Extracting minerals from earth whereby the ore body is accessed by opening a large stretch of ground to expose the ore to air is known as surface mining or open pit mining (Shishvan and Sattarvand, 2015). The mine plan can be categorized as; short-term, medium-term and long-term. The long-term production plan refers to the optimized scheduling of extraction of blocks which lie in the final pit limit in a way that the Net Present Value (NPV) of the deposit is maximized. The results of the long-term production planning process are used as guides for medium and short-term planning (Ben-Awuah and Askari-Nasab, 2011).

Cut-off grade determination is an essential aspect of optimizing the mine strategy and should be an outcome of the optimization process. However, commonly in the mining industry a cut-off grade is calculated prior to mine planning and is used as an input for the strategic plan (Hall, 2014).

Determining the cut-off grade policy is one of the most important steps for optimizing the long-term production plan since it is the criterion that separates ore material from waste material. Materials with a grade value higher than the cut-off grade value are considered as ore and materials with a grade value lower than the cut-off grade value are classified as waste. The aim 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 such as mining capacity, processing capacity, refinery capacity, environmental issues and extraction sequence.

One of the simplest methods to calculate the cut-off grade is called break-even calculation. Although break-even cut-off grade is widely used in mining industry, it does not guarantee generating the maximum NPV of the deposit. The grade at which the obtained revenue is equal to the cost of generating that revenue is called break-even cut-off grade. Equation 1 shows the simple break-even calculation. The break-even calculation is only based on economic parameters and it does not include the mining, processing and refinery capacity and the geology of the deposit.

$$g_{BE} = \frac{\cos t}{(price - selling \cos t) \times \text{recovery}} \tag{1}$$

Poniewierski and Hall (2016) stated that break-even calculation is not accurate enough. They illustrated that an error of 0.1 gram per tonne in the break-even calculation for a low grade gold mine can result in 50-60 percent of the ore material being considered as waste. The main two reasons which can cause errors in the break-even calculation are the fixed recovery and the exclusion of the sustaining capital costs. The fixed recovery percentage is being used in calculating the break-even grade but as a matter of fact, low grade materials and high grade materials do not have the same recovery percentage. In addition, excluding the sustaining capital costs for maintaining the capital items during the life of the equipment will result in noticeable errors in the break-even calculation (Poniewierski and Hall, 2016).

As mentioned earlier, the break-even calculation does not include the two sets of parameters, geology and operational capacities. In 1950, Mortimer described a new cut-off grade model which included geology parameters or grade distribution and cost parameters. He targets two goals in his model: the first goal is that the minimum grade of material must pay for itself and the second goal is that a minimum profit per tonne must be provided by the average grade of material (Mortimer, 1950).A general cut-off grade model was introduced in 1964 by Lane which accounts for all the parameters including costs, grade distribution and operational capacity. The goal of Lane's model is to maximize the NPV which is the most common goal in mining industry. He defined that any mining operation has three stages: mining, processing and refinery. In his model, six potential optimum cut-off grades are calculated. The first three cut-off grades are called limiting economic cut-off grades and they are directly calculated based on economic parameters. The second three cut-off grades are called balancing cut-off grades and they are dependent on grade distribution of the deposit. Lane (1964) introduced an algorithm to find the optimum cut-off grade between the six potential grades. It has been proven that it is only by applying some optimization methods like Lane's model that the precision of cut-off grade decision can be guaranteed (Lane, 1964, 1988, 1997; Hall, 2014). Lane's model is used as the starting point of this research. This paper introduces a cut-off grade optimization model that integrates concurrent production scheduling and waste disposal planning with limited stockpiling duration.

The next section of this paper covers the literature on the application of cut-off grade optimization in mine planning. A brief overview of oil sands mining will be discussed in section 3. The problem definition will be presented in section 4. Section 5 outlines the methodology for the cut-off grade optimization model. This is followed by a section on the implementation of a cut-off grade optimization model that features production scheduling and waste disposal planning as applied in oil sands mining. In section 7, a case study presents an application of the cut-off grade optimization model and the generated production schedule. The paper concludes with a discussion of results and future research work.

2. Summary of Literature Review

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

The simple break-even calculation can generate the processing cut-off grade within the pre-defined pit limit. It has been proven that break-even calculation cannot maximize the NPV of the operation since it ignores the geology of the deposit and the operational constraints. The results of the simple break-even calculation will generate a constant cut-off grade schedule for the life of the mine (Taylor, 1972; Poniewierski and Hall, 2016). In 1964, Lane developed a cut-off grade optimization model which can consider all the required parameters such as economic parameters, grade-tonnage distribution and operational capacities. The objective function of the Lane's model is to maximize the NPV of the operation with respect to capacity of the mining, processing and refinery. He considered the concept of opportunity cost in his model. Hall (2014) 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 maximizes the NPV of the operation and generates a dynamic cut-off grade policy based on the concept of opportunity cost for the life of mine. During the early years of mining operation, Lane's model generates a higher cut-off grade and this decreases towards the end of the operation's life (Lane, 1964). The dynamic nature of the 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 (Asad et al., 2016). Many mine planning software use the Lane's theory in order to specify the optimum cut-off grade policy (Whittle, 1999).

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

During the past years many researchers such as Osanloo and Gholamnejad, tried to incorporate environmental issues and related cost in the cut-off grade calculation. Osanloo et al. (2008) modified the basic Lane's model to consider two different destinations for acid and non-acid wastes. They considered the cost of dumping different kinds of wastes in their formulation. Their case study showed an improvement of NPV compared to Lane's basic model as well as the environmental sustainability for the operation.

Gholamnejad used the Lane's theory in order to determine the optimum cut-off grade in the presence of rehabilitation cost. He stated that, by considering the rehabilitation cost, the optimum cut-off grade will be reduced. He showed that the amount of ore will increase and the amount of waste will decrease by considering the rehabilitation cost. Gholamnejad claimed that the total NPV of the project will be increased. He mentioned that the rehabilitation cost should be determined prior to optimization, so it can be used to generate more realistic results (Gholamnejad, 2008, 2009).

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

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

In 1984, Lane introduced an important extension to the original model. The new model was capable of calculating the cut-off grades for multiple economic mineral deposits. For instance, a deposit with two economic minerals requires refinery detail for two minerals and so the formulation needs some modifications. In order to provide solution for such kind of problems, Lane used the grid search technique and provided a case study to illustrate the implementation of the approach (Lane, 1984, 1988).

Asad (2005) also developed a model as an extension to Lane's original theory for cut-off grade optimization for deposits considering two economic minerals with stockpiling option. The stockpile acts as an additional push back when the mining operation is finished. The material with grade between break-even grade and optimum cut-off grade is sent to the stockpile in each year. He mentioned that long-term stockpiling can cause series of problems such as leaching, deterioration of material and oxidation which can cause poor recoveries in the treatment process. He showed that his model can increase the NPV of the mining operation in the hypothetical case study (Asad, 2005). He used the concept of varying the annual commodity price and the operating costs. He presented the effects of these modifications on the NPV of the mining operation by applying the model to a hypothetical copper deposit (Asad, 2007). Asad and Topal (2011) completed the Asad's 2007 model by adding the stockpiling scenario. They used the stockpile after finishing the mining operation. They demonstrated the advantages of the model by comparing the cut-off grade policy with and without stockpiling option and the improved NPV of the operation.

Many studies have been undertaken with improvements to Lane's model for deposits with single and multiple economic minerals. In the case of oil sands mining, the planning engineer is required to schedule both ore, overburden and interburden; and the stockpiled material must be processed within a limited timeframe due to oxidation that affects processing recovery efficiency. This paper presents an extension of Lane's model that features concurrent production scheduling and waste management with limited stockpile duration.

3. Oil sands mining

For open pit design and scheduling, the material in the orebody is divided into a three-dimensional array of cubical blocks called a block model. The block model has some attributes such as rock type, economic data, densities and grade which can be represented numerically (Askari-Nasab et al., 2011). The block model dimensions are selected based on deposit geology and equipment size. An oil sands deposit contains five main rock types namely: 1) Muskeg/peat, 2) Pleistocene unit, 3) Clear water formation, 4) McMurray formation and 5) Devonian carbonates. The desired mineral is bitumen which is contained in the McMurray formation. In order to get access and mine the McMurray formation, the overburden material which includes muskeg, pleistocene unit and clear water formation should be removed. After mining and processing the oil sands ore, more than 80% of the ore are deposited in tailing dams (Masliyah, 2010). The significant amount of tailings material has caused several environmental issues. The regulatory requirement by Alberta Energy Regulator (AER) Directive 082 (formerly interim directive ID 2001-7) requires oil sands mining companies to integrate their waste management strategy into their long-term production plans. It also requires mining companies not to leave behind any material containing more than 7% bitumen (Ellis, 2016). In order to reduce the environmental footprints, dyke construction should take place simultaneously as the mine advances and the area of each push back become available for dyke construction. The material required for the dyke construction mainly comes from mining operation. The dyke material includes overburden (OB), interburden (IB) and tailings coarse sand material (TCS) (Ben-Awuah and Askari-Nasab, 2011; Ben-Awuah et al., 2012). The above mentioned regulatory requirement and environmental issues make the waste management strategy as a necessary part of the long-term production planning.

Figure 1 illustrates the strategic production planning for an oil sands deposit containing K mining-cuts and M push backs. Mining-cuts are made up of blocks within the same level that are grouped together based on their attributes; location, rock type and grade using an agglomerative hierarchical clustering algorithm by Tabesh and Askari-Nasab (2011).

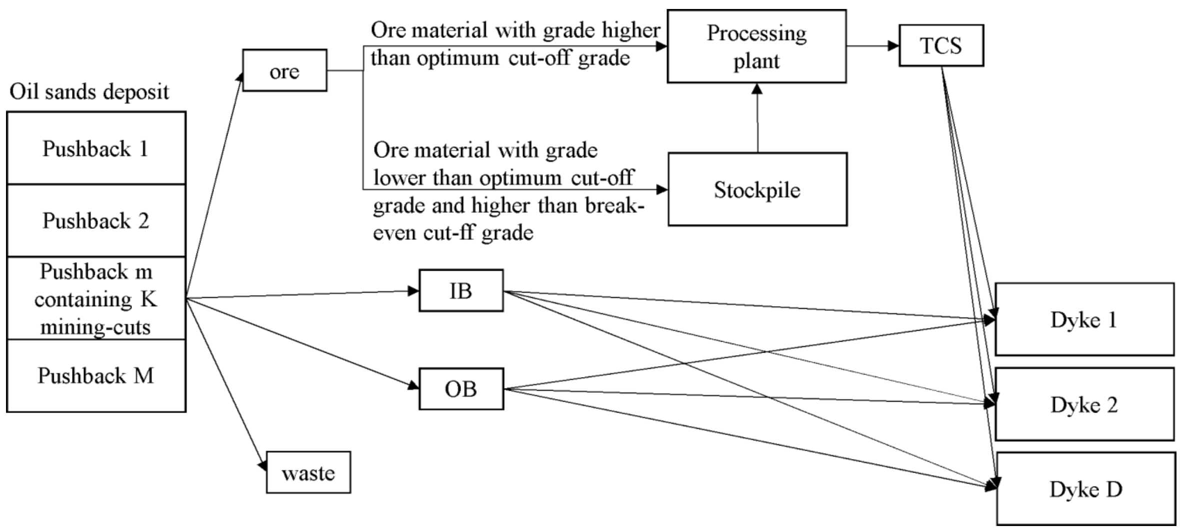

Figure 1 - Material flow for oil sands production planning and waste management modified after Ben-Awuah and Askari-Nasab (2013)

Lowest acceptable grade is the break-even grade of the oil sands operation taking into consideration the grade-recovery relationship. Initial scheduling analysis with Whittle Milawa Balanced (Gemcom Software, 2013) generates a lowest acceptable cut-off bitumen grade of 6%. Figure 2 shows the processing plant recovery factor based on average weight percent bitumen content according to Directive 082 (Ellis, 2016). Material with bitumen grade less than 6%, have recovery less than 31% and hence are not economic for processing. Each mining-cut contains: 1) ore which is the material with bitumen grade higher than 6%, 2) TCS which is the dyke material from processed ore, 3) OB and IB which are the material with bitumen grade less than 6% and meet the dyke construction material requirements and 4) waste.

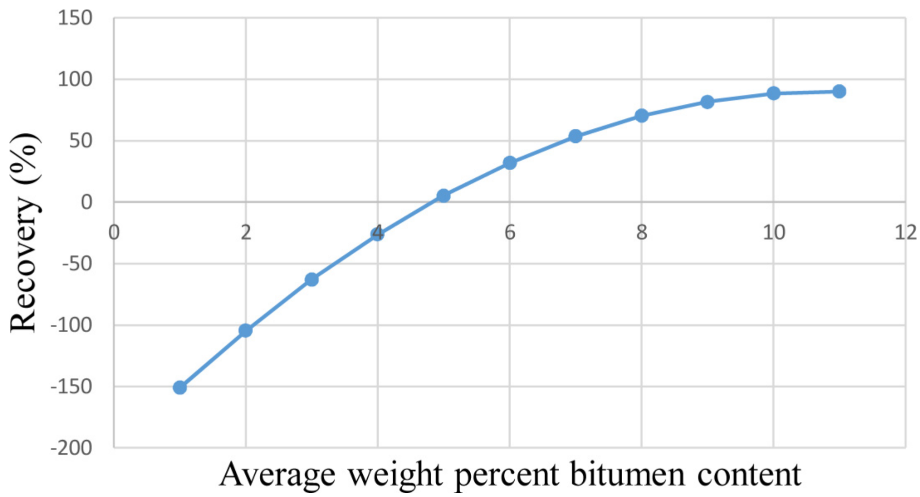

Figure 2 - Processing plant recovery factor

4. Problem definition

The main problems in oil sands mining that this paper is addressing can be classified into three categories:

1- Determining the life of mine optimum cut-off grade profile and corresponding ore tonnages to maximize the NPV of the operation.
2- Determining the dyke material schedule for dyke construction.
3- Assessing the impacts of stockpiling and stockpile reclamation with limited duration.

In order to maximize the NPV of the oil sands mining operation with respect to processing capacity, an extension of the Lane's model will be developed to determine the optimum cut-off grade policy in presence of waste management for dyke construction and stockpiling with limited duration. The cut-off grade optimization model developed in this work considers stockpile rehandling 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.

The result from the cut-off grade optimization can be used as guidance for defining the input parameters in oil sands production scheduling and waste management for medium and short-term mine planning.

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

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 is dependent on the economic parameters, the limiting operational capacities and the grade distribution of the deposit. Using stockpiling can improve the NPV of the operation significantly. The stockpiled material can be reclaimed in two ways (Ali and Khan, 2004):

1. The stockpile is reclaimed after pit mining is finished;
2. The stockpile is reclaimed simultaneously during active pit mining.

We are going to present the modified version of Lane's model 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 duration during the cut-off grade optimization process. The two stockpiling scenarios outlined will be presented in addition to a no stockpiling scenario. Since oil sands ore has grade dependent processing recovery characteristics, the ICOGO framework features the use of a weighted average recovery factor.

5.1. Notations

The following are the details of notation used in the formulation of the ICOGO model.

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

d the discount rate.

F the annual fixed cost.

n the index of scheduling period.

f_n the opportunity cost of the year n.

g_{avg_n} the average head grade of the year n.

g_{BE} the break-even cut-off grade.

g_l the minimum acceptable cut-off grade.

g_m the mining limited cut-off grade.

g_p the processing limited cut-off grade.

g_r the refinery limited cut-off grade.

ic the cost per tonne of interburden dyke material for dyke construction.

kc the cost of mining a tonne of ore from stockpile.

kd the duration of stockpiling the material.

kt_n the amount of material (tonnes) send to the stockpile in period n.

kt_{n-kd} the amount of material (tonnes) reclaimed from the stockpile in period n.

mc the cost of mining a tonne of waste.

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

pr_n the annual profit.

qk the amount of reclaimed material from stockpile

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.

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

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

R_{TCS} the ratio of the TCS dyke material to the total amount of ore.

sp the selling price per unit of product.

sc the refinery and selling cost per unit of product.

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

5.2. Optimum Cut-Off Grade

Using the lowest acceptable cut-off grade of 6%, material in the final pit limit is classified as 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 costs of waste management into the cut-off grade optimization process, we need to relate the ratio of the amount of dyke construction material to the total amount of ore and waste. Equation (2) shows the ratio of the TCS dyke material to the total amount of ore; Equation (3) and (4) show the ratio of the OB and IB dyke material to the total amount of waste, respectively.

$$R_{TCS} = \frac{Total\ amount\ of\ TCS\ dyke\ materail}{Total\ amount\ of\ ore} \tag{2}$$

$$R_{OB} = \frac{Total\ amount\ of\ OB\ dyke\ materail}{Total\ amount\ of\ waste} \tag{3}$$

$$R_{IB} = \frac{Total\ amount\ of\ IB\ dyke\ materail}{Total\ amount\ of\ waste} \tag{4}$$

A mining operation is made up of three stages: 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. These are modified in the ICOGO model for oil sands mining.

5.3. ICOGO Limiting Cut-off Grade

These cut-offs are calculated based on the economic parameters. Each of the mining, processing and refinery stages can be the limiting factor for mine production. Equation (5) shows the profit expression for mining and waste management operations.

Profit = Revenue - Processing Cost - Mining Cost - TCS Cost - OB Cost - IB Cost - Annual Cost

$$pr = (sp - sc)qr - pc.qp - mc.qm - tc.R_{TCS}.qp - bc.R_{OB}.(qm - qp) - ic.R_{IB}.(qm - qp) - FT \tag{5}$$

- If maximum mining rate is the overall constraint:

  The time (mine life) required to mine the total amount of material when the mining rate is the main constraint is calculated by Equation (6). The amount of product is determined based on the amount of ore that is sent to the processing plant. Equation (7) shows the relation between the amount of ore and the amount of product.

$$T_m = \frac{qm}{QM} \tag{6}$$

$$qr = g_{avg}.r_{avg}.qp \tag{7}$$

For mining limited cut-off grade, Equation (11), can be calculated by substituting Equations (6) and (7) into Equation (5); and take the derivative of Equation (8) with respect to the grade and set it to zero for optimum cut-off grade.

$$pr = \left(\left(sp - sc\right).g_{avg}.r_{avg} - pc - tc.R_{TCS} + bc.R_{OB} + ic.R_{IB}\right).qp - \left(mc + bc.R_{OB} + ic.R_{IB} + \frac{F}{QM}\right).qm \quad (8)$$

$$\frac{dpr}{dg} = \left(\left(sp - sc\right).g_{avg}.r_{avg} - pc - tc.R_{TCS} + bc.R_{OB} + ic.R_{IB}\right).\frac{dqp}{dg} - \left(mc + bc.R_{OB} + ic.R_{IB} + \frac{F}{QM}\right).\frac{dqm}{dg} = 0 \quad (9)$$

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 $\frac{dqm}{dg} = 0$, so to make the Equation (9) equal to zero, Equation (10) should be zero, which gives us the mining limited cut-off grade.

$$\left(\left(sp - sc\right).g_{avg}.r_{avg} - pc - tc.R_{TCS} + bc.R_{OB} + ic.R_{IB}\right) = 0 \quad (10)$$

$$g_m = \frac{pc + tc.R_{TCS} - bc.R_{OB} - ic.R_{IB}}{\left(sp - sc\right).r_{avg}} \quad (11)$$

- If maximum processing rate is the overall constraint:

  The time (mine life) is determined by the processing rate using Equation (12). For processing limited cut-off grade, Equation (15), can be calculated by substituting Equations (7) and (12) into Equation (5); and take the derivative of Equation (13) with respect to the grade and set it zero for optimum cut-off grade.

$$T_p = \frac{qp}{QP} \quad (12)$$

$$pr = \left(\left(sp - sc\right).g_{avg}.r_{avg} - pc - tc.R_{TCS} + bc.R_{OB} + ic.R_{IB} - \frac{F}{QP}\right).qp - \left(mc + bc.R_{OB} + ic.R_{IB}\right).qm \quad (13)$$

Similarly, for $\frac{dpr}{dg} = 0$, Equation (14) should be zero which gives us the processing limited cut-off grade.

$$\left(\left(sp - sc\right).g_{avg}.r_{avg} - pc - tc.R_{TCS} + bc.R_{OB} + ic.R_{IB} - \frac{F}{QP}\right) = 0 \quad (14)$$

$$g_p = \frac{pc + tc.R_{TCS} - bc.R_{OB} - ic.R_{IB} + \frac{F}{QP}}{\left(sp - sc\right).r_{avg}} \quad (15)$$

- If maximum refinery rate is the overall constraint:

  The time (mine life) is determined by the refinery rate calculated by Equation (16). For refinery limited cut-off grade, Equation (19), can be calculated by substituting Equations (7) and (16) into Equation (5); and take the derivative of Equation (17) with respect to the grade and set it zero for optimum cut-off grade.

$$T_r = \frac{qr}{QR} \tag{16}$$

$$pr = \left(\left(sp - sc - \frac{F}{QP}\right).g_{avg}.r_{avg} - pc - tc.R_{TCS} + bc.R_{OB} + ic.R_{IB}\right).qp - \left(mc + bc.R_{OB} + ic.R_{IB}\right).qm \tag{17}$$

Similarly, for $\frac{dpr}{dg} = 0$, Equation (18) should be zero which gives us the refinery limited cut-off grade.

$$\left(\left(sp - sc - \frac{F}{QP}\right).g_{avg}.r_{avg} - pc - tc.R_{TCS} + bc.R_{OB} + ic.R_{IB}\right) = 0 \tag{18}$$

$$g_r = \frac{pc + tc.R_{TCS} - bc.R_{OB} - ic.R_{IB}}{\left(sp - sc - \frac{F}{QR}\right).r_{avg}} \tag{19}$$

The optimal production and waste disposal schedule with optimum cut-off grade policy can be generated with an iterative algorithm which is presented in the section 6.1 using an oil sands case study.

6. Implementation of the ICOGO Model

In the case of oil sands mining, mine production is mainly limited by the processing plant capacity. Dadgelen (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 (SME, 2011). Using Lane's model, we present a modified version of Dagdelen's algorithm in the ICOGO model. The ICOGO model generates an optimum production schedule for oil sands mining considering waste management for dyke construction and stockpiling with limited duration.

6.1. Steps of Iterative Algorithm

1. Take the input parameters including: economic parameters, operational capacities and grade-tonnage curve.

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

2. Determine the lowest acceptable grade, g_l .
3. Calculate the opportunity cost (f_n) by Equation (20). 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.
4. Determine processing cut-off grade in the year n by Equation (21).

$$f_n = \frac{d \times NPV_n}{QP} \tag{20}$$

$$g_{p_n} = \frac{pc + tc.R_{TCS} - bc.R_{OB} - ic.R_{IB} + f_n + \frac{F}{QP}}{(sp - sc).r_{avg}} \tag{21}$$

5. If the calculated g_{p_n} is less than g_l , set the $g_{p_n} = g_l$

6. From the most recent grade-tonnage curve determine:
- q_o : The amount of ore tonnage above the cut-off grade g_{p_n}
- g_{avg_n} : The weighted average ore grade above the cut-off grade g_{p_n}
- q_w : The amount of waste tonnage below the cut-off grade g_{p_n}
- $R_{sr} = \dfrac{q_w}{q_o}$: The stripping ratio

7. In this step the stockpile option should be decided; 1) without stockpile, 2) utilizing the stockpile after the mine is exhausted or 3) utilizing the stockpile simultaneously with the mining operation.

7.1) 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 year n by Equation (22)

$$qm = qp.\left(1 + R_{sr}\right) \tag{22}$$

- Adjusting the grade-tonnage curve without changing it's shape: subtract the proportionate amount of qp from the ore tonnes and the proportionate amount of $\left(qm - qp\right)$ from the current waste tonnes of the grade-tonnage curve.
- Calculate the annual profit for the mining operation by Equation (23)

$$pr_n = \left(\left(\left(sp - sc\right).g_{avg_n}.r_{avg}\right) - pc - tc.R_{TCS} + bc.R_{OB} + ic.R_{IB} - \frac{F}{QP}\right)qp - \left(mc + bc.R_{OB} + ic.R_{IB}\right)qm \tag{23}$$

7.2) Utilizing the stockpile after the mine is exhausted:
We will consider the stockpile as an extra pushback, when the mine is exhausted.
- 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 year n by Equation (22)
- Adjusting the grade-tonnage curve without changing it's shape: subtract the proportionate amount of qp from the ore tonnes and the proportionate amount of $\left(qm - qp\right)$ with grades between g_{p_n} and g_l, 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 $\left(qm - qp\right)$ 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 (24)

$$pr_n = \left(\left(\left(sp - sc\right).g_{avg_n}.r_{avg}\right) - pc - tc.R_{TCS} + bc.R_{OB} + ic.R_{IB} - \frac{F}{QP}\right)qp - \left(mc + bc.R_{OB} + ic.R_{IB}\right)qm \tag{24}$$

- After depletion of pit reserves, start reclaiming stockpile. If total stockpile tonnage is more than QP, repeat the algorithm from step 1 for the cut-off grade optimization of stockpile reclamation; otherwise proceed.
- Calculate the annual profit for stockpile reclamation by Equation (25)

$$pr_n = \left(\left((sp - sc).g_{avg_n}.r_{avg} \right) - pc - tc.R_{TCS} + bc.R_{OB} + ic.R_{IB} - \frac{F}{QP} \right) qp - (kc) qk \tag{25}$$

7.3) Utilizing 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 enters the stockpile should be used in 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 (22)
- Adjusting the grade-tonnage curve without changing it's 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, 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 (26)

$$pr_n = \left(\left((sp - sc).g_{avg_n}.r_{avg} \right) - pc - tc.R_{TCS} + bc.R_{OB} + ic.R_{IB} - \frac{F}{QP} \right) (qp + kt_{n-kd}) - (mc + bc.R_{OB} + ic.R_{IB}) qm - (kc).kt_{n-kd} \tag{26}$$

8. If qp is less than processing capacity QP

   Set $T = n$ and go to next step,

   Otherwise set $n = n + 1$ and go to step 3.
9. Calculate the incremental NPV_n from year n to T by using equation (28)

$$NPV_n = \sum_{k=n}^{T} \frac{pr_k}{(1+d)^{k-n+1}} \tag{28}$$

10. If the calculated NPV_1 is not in a specific tolerance from the previous iteration, update the opportunity costs and go to step 1. Otherwise, stop the process, the NPV of the whole deposit is maximized and the g_{p_n} for the years 1 to T (life of mine) is the optimum cut-off grade policy.

7. Case Study

The final pit limit for the case study was generated with Whittle (Gemcom Software International, 2013) software using the LG algorithm (Lerchs and Grossman, 1965). Table 1 shows information about the oil sands deposit for the case study and Table 2 contains economic parameters and operational capacities for our model oil sands mine which is processing limited. The economic data are extracted and compiled based on Ben-Awuah (2013) and Burt et al. (2012). Figure 3 represents the cumulative grade-tonnage distribution of the deposit and Figure 4 shows the bitumen grade distribution in the case study area at level 300m.

Table 1: Oil sands deposit final pit characteristics

Description	Value
Total tonnage of material (Mt)	1340.5
Total ore tonnage (Mt)	452.1
Total TCS dyke material tonnage (Mt)	341.9
Total OB dyke material tonnage (Mt)	426.9
Total IB dyke material tonnage (Mt)	167.8
Total waste tonnage (Mt)	293.7

Table 2: Economic parameters and operational capacities

Parameter (unit)	Value	Parameter (unit)	Value
Mining cost ($/tonne)	2.3	R_{TCS}	0.7563
Processing cost ($/tonne)	5.03	R_{OB}	0.4805
Selling cost ($/bitumen %mass)	0	R_{IB}	0.1889
Stockpiling cost($/tonne)	0.5	Mining capacity (Mt/year)	Unlimited
Selling price ($/bitumen %mass)	4.5	Processing capacity (Mt/year)	40
Annual fixed cost (M$/year)	480	Refinery capacity (Mt/year)	Unlimited
TCS dyke material cost ($/tonne)	0.92	Mining recovery fraction (%)	100
OB dyke material cost ($/tonne)	1.38	Processing weighted average recovery (%)	84
IB dyke material cost ($/tonne)	1.38	Discount rate (%)	15

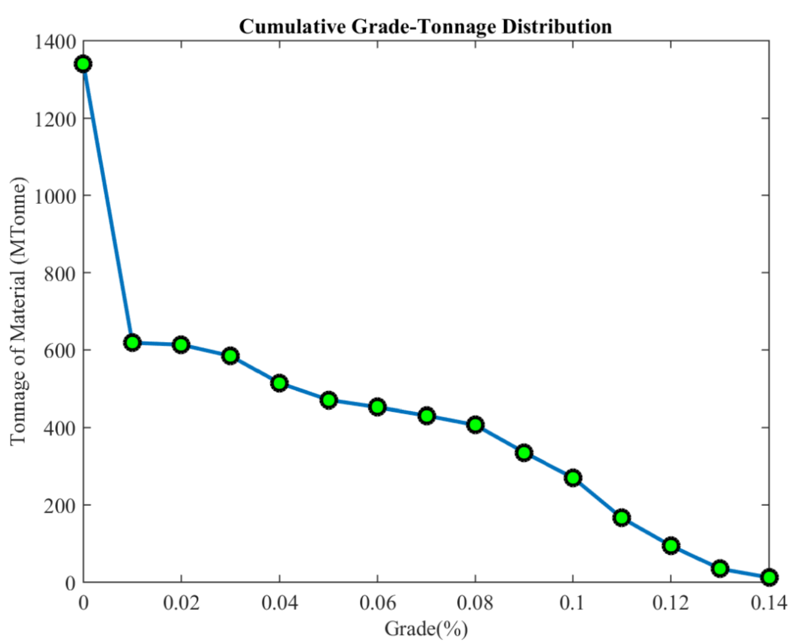

Figure 3 - Cumulative grade-tonnage distribution of the oil sands deposit

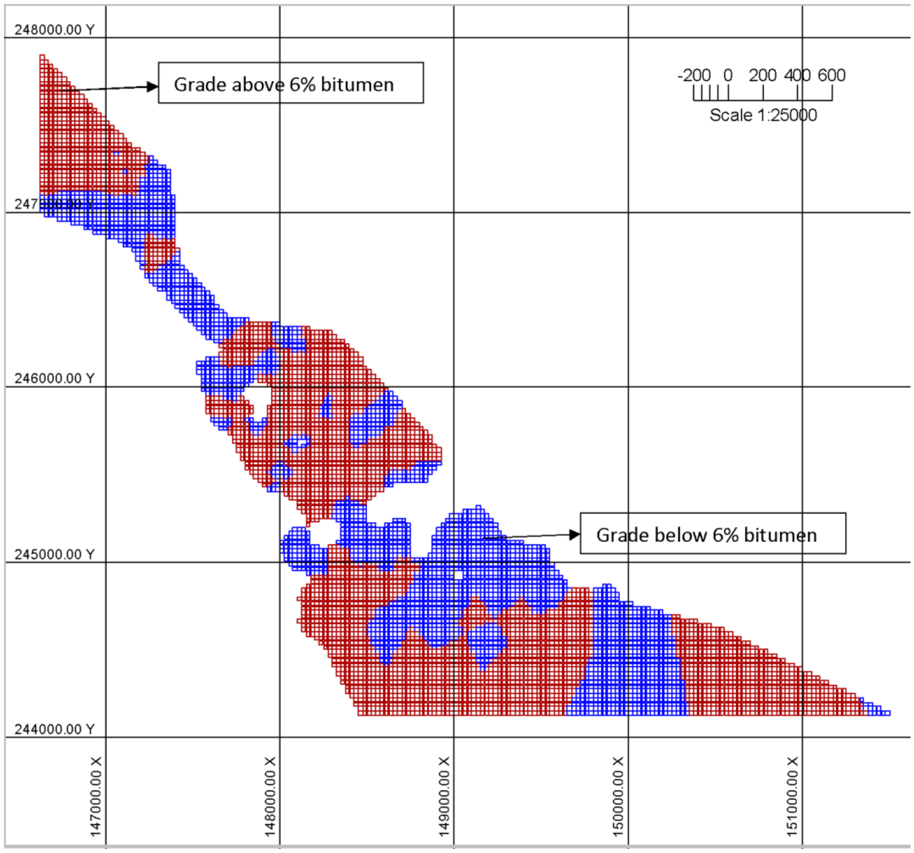

Figure 4 - Bitumen grade distribution in the case study area at level 300m

The ICOGO model was coded in Matlab (Mathworks, 2015) and implemented on the oil sands deposit. The grade-tonnage distribution of the deposit which is needed for the ICOGO model is presented in Table 3. We have implemented the model with three stockpile scenarios: 1) without stockpile, 2) reclaiming stockpile at the end of the mine life and 3) reclaiming stockpile simultaneously with the mining operation. The termination criterion for heuristic optimization algorithm is NPV tolerance of $5M. The results for each of the production schedule scenarios after cut-off grade optimization are presented in

Table 4 to

Table 6, respectively.

Table 3: Grade-Tonnage distribution of the oil sands deposit

Grade (%)	Tonnage (Mt)
0 – 6	888.4
6 – 7	21.2
7 – 8	24.2
8 – 9	70.9
9 – 10	65.2
10 – 11	104.3
11 – 12	71.8

12 – 13	59.8
13 – 14	22.4
Above 14	12.3

Table 4: 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)	Incremental NPVs ($M)
1	6.96	10.56	124.2	40	2539.1
2	6.86	10.54	123.5	40	2433.2
3	6.75	10.52	122.9	40	2312.1
4	6.62	10.50	122.1	40	2173.4
5	6.47	10.47	121.3	40	2015.1
6	6.30	10.43	120.3	40	1833.9
7	6.10	10.39	119.2	40	1627.3
8	6.00	10.37	118.6	40	1391.7
9	6.00	10.37	118.6	40	1121.8
10	6.00	10.37	118.6	40	811.4
11	6.00	10.37	118.6	40	454.5
12	6.00	10.37	12.6	4.2	44.1

Table 5: Production schedule with optimum cut-off grade policy and stockpile reclamation after the mine 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)	Incremental NPVs ($M)
1	6.96	10.56	124.2	1.9	0	40	2548.2
2	6.86	10.54	123.5	1.7	0	40	2443.5
3	6.75	10.52	122.9	1.4	0	40	2323.9
4	6.62	10.50	122.1	1.2	0	40	2187.1
5	6.47	10.47	121.3	0.9	0	40	2030.9
6	6.30	10.43	120.3	0.6	0	40	1851.9
7	6.10	10.39	119.2	0.2	0	40	1648.1
8	6.00	10.37	118.6	0	0	40	1415.5
9	6.00	10.37	118.6	0	0	40	1149.2
10	6.00	10.37	118.6	0	0	40	842.9
11	6.00	10.37	118.6	0	0	40	490.7
12	6.00	10.37	12.6	0	0	4.2	85.7
13	6.00	6.5	0	0	7.9	7.9	47.9

Table 6: Production schedule with optimum cut-off grade policy and simultaneous stockpile reclamation during mining

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)	Incremental NPVs ($M)
1	7.03	10.57	124.6	2.1	0	40	2607.3
2	6.93	10.55	117.7	1.7	2.1	40	2511.4
3	6.80	10.53	117.9	1.4	1.7	40	2380.4
4	6.66	10.50	117.8	1.2	1.4	40	2233.8
5	6.50	10.47	117.7	0.9	1.2	40	2068.6
6	6.31	10.44	117.6	0.5	0.9	40	1883.1
7	6.11	10.40	117.5	0.1	0.5	40	1674.3
8	6.00	10.37	118.1	0	0.1	40	1439.9
9	6.00	10.37	118.6	0	0	40	1175.3
10	6.00	10.37	118.6	0	0	40	872.9
11	6.00	10.37	118.6	0	0	40	525.3
12	6.00	10.37	35.8	0	0	12.1	125.5

7.1. Discussion

In this case study, the mining operation is only limited by the processing capacity. In the first scenario, the total NPV generated including the waste management cost is $2539.1M. The mine operates at the maximum processing capacity until the last year when the material in the final pit limit is finished. Figure 5 shows the schedule for material mined and the amount of produced TCS dyke material. The model generates a uniform production schedule for ore, IB, OB, TCS and waste material over the life of mine.

In the second scenario, the life of mine is increased by one year and the generated NPV shows $9.1M improvement in the total NPV of the operation. This increase results from reclamation of the stockpile after the mining operation. Here, the total amount of ore that has been processed increases by 7.9 Mt compared to the first scenario which sends the 7.9 Mt of material below the optimum cut-off grade to the waste dump. Figure 6 shows the schedule for material mined, reclaimed and the amount of produced TCS dyke material for Scenario 2. Figure 7 shows the amount of material sent to the stockpile.

In oil sands mining, maintaining a uniform average head grade is one of the most important issues. Due to the fact that we only stockpile the low grade ore material, we will miss the opportunity of blending the low grade and high grade materials when we want to reclaim the stockpile material.

Table 5 shows that, when we start reclaiming the stockpile material after the mine is exhausted, the average head grade will have a significant drop which directly reduces the generated profit.

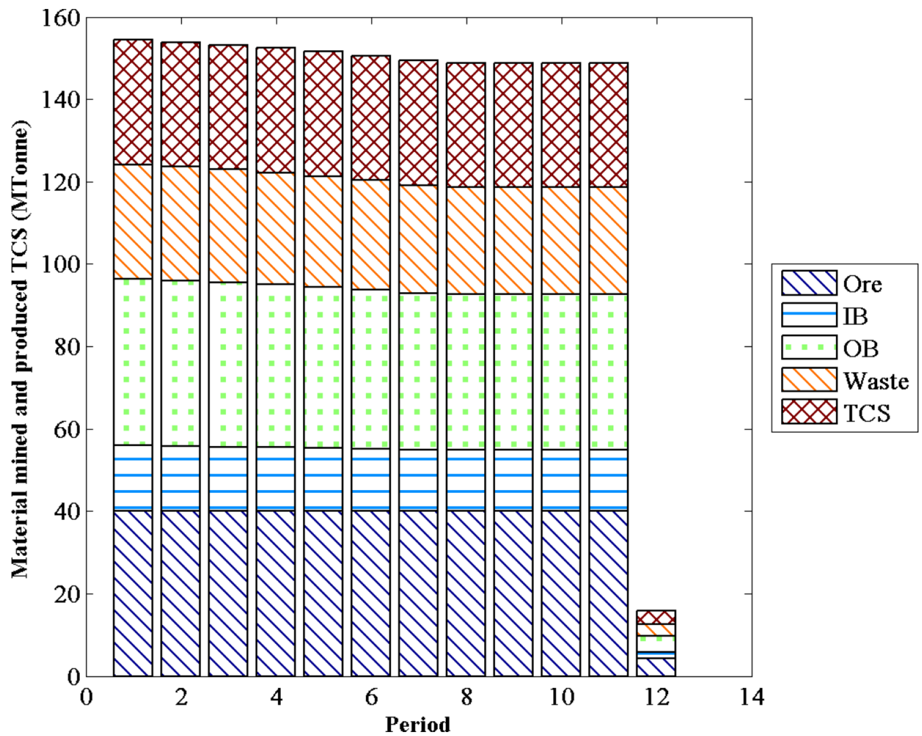

Figure 5 - Scenario 1: Schedule for material mined and produced TCS

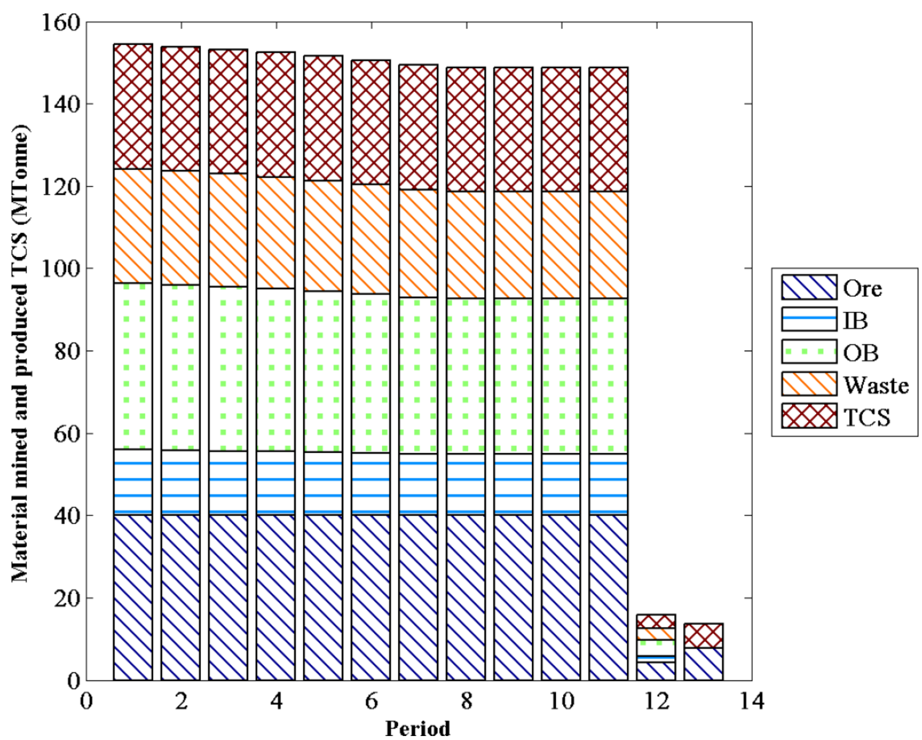

Figure 6 - Scenario 2: Schedule for material mined, reclaimed and produced TCS

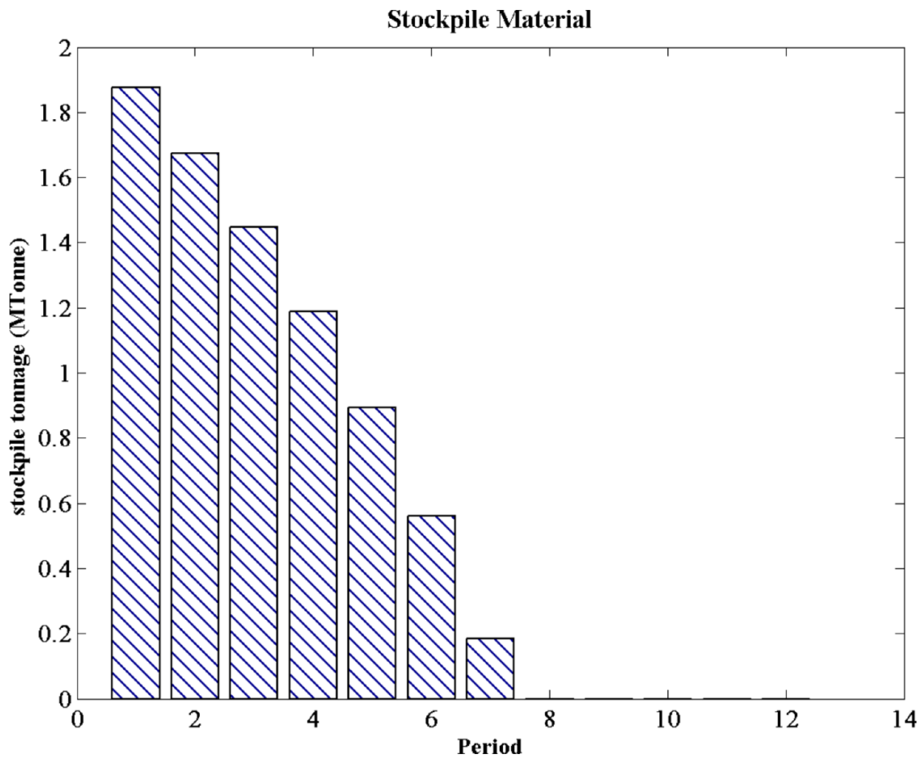

Figure 7 - Scenario 2: Schedule for material stockpiled

In order to prevent this problem, we can utilize the stockpile parallel to the mining operation. Based on material characteristics, any limitations on stockpiling duration such as processing recovery can be determined. In the case of this oil sands mining case study, to prevent oxidation of ore material that affects processing recovery, one year stockpiling duration is chosen. In the third scenario, production schedule with optimum cut-off grade policy and utilization of the stockpile simultaneously with mining operation is presented. In this scenario, the amount of material that is sent to the stockpile in a given year must be used in the following year. Since some portion of processing capacity is filled with the stockpile material, less material above cut-off grade will be mined each time. It can be seen in

Table 4 and

Table 5 that the mining capacity for the first and second scenarios have a decreasing gradient from the first year to the last year due to dynamic nature of optimum cut-off grade policy. However, in the third scenario as a consequence of using the stockpile material during the first 8 years, the mining capacity is less than the other scenarios in those years. Also, after the year 8 the mining capacity is increased since there is no more material from the stockpile. Figure 8 represents the schedule for material mined, reclaimed and the produced TCS dyke material for the third scenario and Figure 9 shows the schedule of material sent to the stockpile.

Utilizing the stockpile material parallel to the mining operation provides blending opportunity and maintains the average head grade for plant feed. The third scenario generated an overall NPV of \$2607.3M. It improved the NPV of the operation by \$68.2M compared to the first scenario and \$59.1M compared to the second scenario.

Figure 10 shows the cut-off grades profile for three scenarios. The first two scenarios have similar cut-off grades, but the second scenario has one more year mine life because of utilization of the stockpile after the mining operation. It should be noted that the stockpiled material can be used in year 12 since the processing capacity is not at the maximum. The third scenario has the highest cut-off grade profile compared to the others.

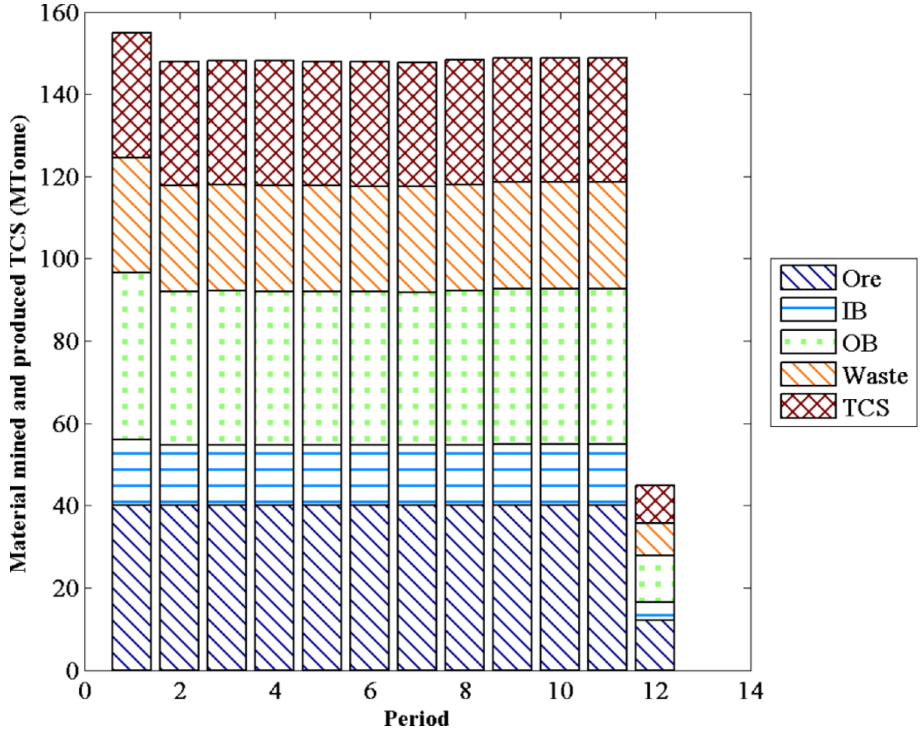

Figure 8 - Scenario 3: Schedule for material mined, reclaimed and produced TCS

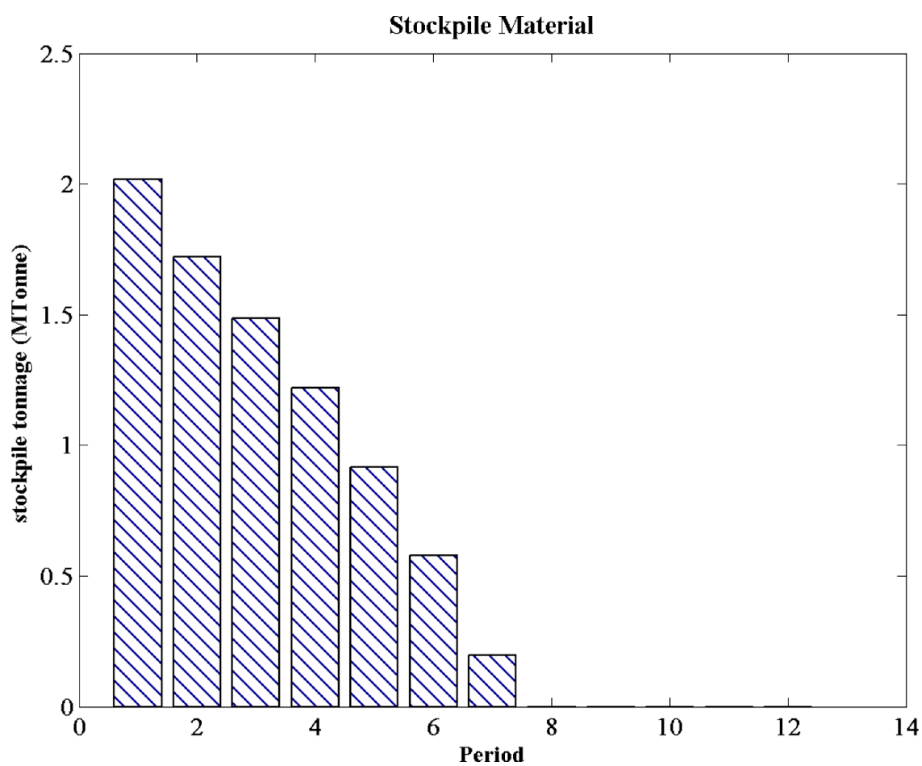

Figure 9 - Scenario 3: Schedule for material stockpiled

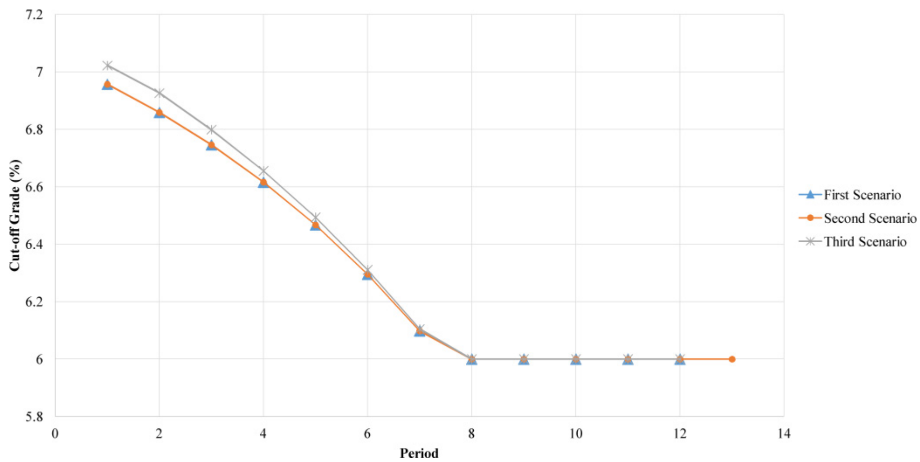

Figure 10 - Cut-off grades profile for the three scenarios

8. Conclusion and Future Work

In this paper, we developed, implemented and tested a cut-off grade optimization model to incorporate waste management cost and limited stockpiling duration for oil sands long-term production scheduling. A real data set of an oil sands deposit was used to verify the model. The model generates an optimum cut-off grade policy and a uniform production schedule for ore, OB, IB, TCS and waste material over the mine life. The OB, IB and TCS dyke material are required for dyke construction. The benefit of using the stockpile with two reclamation methods was presented. Reclaiming the stockpiled material after the mining operation results in increasing the total ore tonnage. Also, utilizing the reclamation of stockpiled material simultaneously with the mining operation increased the total ore tonnage as well as maintaining the average head grade required by the processing plant. By maintaining the average head grade, the total NPV generated in the third scenario was higher than the second scenario.

The optimum cut-off grade policy and the production schedule generated by the ICOGO model can be used as guidance for the input parameters for medium and short-term production scheduling. The authors are developing a comprehensive Mixed Integer Linear Goal Programming (MILGP) model which features mining, processing, stockpiling, IB, OB, TCS and grade goal functions for medium and short-term planning. The initial targets of these goal functions in the MILGP model will be defined based on the results from the ICOGO model.

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