

Towards Integration of Oil Sands Mine and Tailings Plans

Mohammad Mahdi Badiozamani & Hooman Askari-Nasab
Mining Optimization Laboratory (MOL)
University of Alberta, Edmonton, Canada

Abstract

Tailings is considered to be the main by-product of oil sands processing. Due to the noticeable amount of fresh and recycled water used in the process of bitumen extraction, huge volume of slurry is produced at the end point of the process. The amount of tailings produced is also important from environmental point of view. By regulations, the oil sands companies are required to monitor and control the tailings ponds conditions and minimize the footprints of their operations when closing the mine. Tailings ponds are the most important footprint left from the mining operations. On the other hand, the available facilities for construction of tailings ponds to hold the slurry is limited and restricted to the lease areas. Therefore, the volume of tailings produced downstream is a key operational factor that affects both operation planning and environmental costs of decommissioning. In the literature, several production scheduling formulations using mixed integer liner programs (MILPs) are developed to maximize the net present value (NPV) as the main objective function. These formulations are subject to different operational constraints such as mining capacity, processing capacity, and extraction precedence. The objective of this paper is first, to calculate the amount of tailings produced as a result of extraction of each block and secondly, to revise the MILP in a way to consider the constraint of tailings pond capacity. The tailings calculation formula is retrieved from Suncor's process flow sheet. The derived formulation is verified by applying on a real mining production plan. Then, a sub-gradient algorithm is developed to solve the MILP model by Lagrangian relaxation method. Some future steps of research are mentioned at the end.

1. Introduction

The economic value that the business generates is the most important driver in the mining industry. The net present value (NPV) is well introduced to measure the economic value of the production over the active mine's life. However, apart from the economic aspects of the business, related social and environmental impacts must be considered in mine plans as well. Particularly in mining industry, limited natural resources that contain minerals are the main source that brings money into companies. Mining companies are now required to minimize the land disturbance and exploit these resources in a responsible manner. In addition, many of the mines are in remote areas, where either there is no urban population or in some cases, there are just some small rural societies in the area. As a result, large number of work force and facilities stream into the site after the start of production. It may alter the social and demographic patterns of the region. Therefore, the industry needs to be aware of its responsibility to consider and also minimize the social impacts of any development. Such social and environmental concerns have made the companies pay more attention to long term consequences of their production.

The oil sands industry is one of the fastest growing industries in North America. Most of the bitumen resources of the world are located in northern Alberta boreal forests. Oil sands deposit is a mixture of bitumen and water in sands and clay. It is a thick, sticky, heavy and viscous material and needs rigorous extraction treatment. According to Government of Alberta (2011), the proven oil reserves of Alberta are 171.3 billion barrels (more than 95% of Canadian oil reserves), making Alberta oil sands the third-largest proven crude oil reserve in the world, next to Saudi Arabia and Venezuela. Based on the depth of the resource, there are two extraction methods for oil sands' bitumen; surface mining and steam-assisted gravity drainage (SAGD) technology. Surface mining is used for near-surface reserves, requiring an open-pit mine operation. Oil sands are dug up with shovels and moved by trucks to processing facilities where the recoverable oil is separated from sand by means of hot water. On the other hand, more than 80 percent of Alberta's bitumen is located deeper in sub-surface and needs to be extracted with in-situ method. SAGD technology is used in the majority of in-situ operations. This involves pumping steam underground through the first horizontal well beneath the bitumen formation to decrease the viscosity of bitumen and then pumping the liquefied bitumen up to the surface through a second well.

Different lists of environmental impacts and their significance corresponding to mining projects are addressed in literature. Singh (2008) reviews some general environmental issues of mining projects as the land use, socio-economic impacts, public health and safety, noise and vibrations, impacts on water quality, air and dust and the impacts on environment ecology. More specific lists of impacts corresponding to the oil sands industry are presented in the literature as well. Woynillowicz et al. (2005) and Rodriguez (2007) consider the following environmental issues for open-pit mining and in-situ operations regarding oil sands industry. The impacts are classified in three categories as water related, land related and air-quality related impacts.

1. Water-related impacts

1.1. Withdrawal from surface fresh waters:

Between two to five barrels of fresh water are withdrawn from the nearby Athabasca River to extract one barrel of bitumen from Alberta oil sands. Due to added chemicals from extraction process, more than 90% of this amount is not returned to the river anymore. Reduction in the flow of water could reduce the amount of available habitat for fish.

1.2. Tailings:

The slurry of water, bitumen, sand, silt and fine clay that is produced from the extraction process is called tailings and is pumped to tailings ponds. There are a number of environmental issues associated with the tailings ponds due to the bitumen remained in the tailings. The pollutants could migrate into the groundwater system and also leak into the surface water and surrounding soil. The tailings water is also toxic to the aquatic life, nearby plants and migratory birds landing on tailings ponds.

1.3. Freshwater aquifers:

Both SAGD and oil sands mining operations could decrease the water pressure in mining pit or horizontal wells region. Then it may cause "leaking down" the water from aquifers closer to the subsurface to operation regions. Therefore, the groundwater is discharged to lakes, wetlands and streams and the level of water table goes down as a result. This phenomenon is called "the drawdown effect".

1.4. Water treatment waste:

A considerable portion of water used in bitumen extraction, whether in surface mining or SADG operations, is the saline water or produced water that is recycled. Treatment of such water results in significant amount of solid waste. This waste is injected into disposal wells

or dumped in landfills and in both cases, many other environmental issues are raised regarding proliferation of waste disposal facilities.

2. Land-related impacts

2.1. *Effect on the boreal forests:*

Canada's boreal forests cover about 30% of the country's land. This piece of land contains 35% of world's wetlands and provides habitat for many important wildlife species. Most of the Alberta oil sands deposits are found in these forests. Oil sands operations have disturbed the landscape and also groundwater drastically. In surface mining, large land-clearings, in addition to the noise and presence of human have resulted in less presence of wildlife in the area. In in-situ operations, despite the thought that the impact on the landscape is less, the dense network of roads, power line corridors, pipelines and seismic lines have fragmented the habitat and changed it to smaller patches. According to AXYS (2005) the most recently filed environmental impact assessment (EIA) shows that the currently planned oil sands development in Alberta will result in cumulative disturbance of more than 2000 square kilometers, which is a very fast growing footprint.

2.2. *Reclaimed landscapes:*

The lands affected by oil sands development are required to be reclaimed to an "equivalent land capability" to be returned to the Province of Alberta. However, the reclaimed landscapes currently proposed by the industry are very different from the original nature of boreal forests and wetlands. In fact, it is impossible to re-create the ecological diversity of the boreal ecosystem and the inter-relationships of ecosystem components.

2.3. *Erosion:*

In most cases, it is required to move the vegetation and thin fertile surface soil to get access to the minerals. In surface mining activities, stripping happens in large scales, resulting in large clearings in natural landscapes. In addition to the pit, construction of access roads also requires wiping the vegetation out. Since the plants' roots protect the soil from erosion, absence of vegetation increases the rate of erosion.

3. Air quality-related impacts

3.1. *Emission from purification processes:*

Alberta has been number one for air releases from industrial sources among Canadian provinces in 2003 (Pollution-watch, 2003). The main source for Alberta industrial emissions is the oil sands industry. Criteria Air Contaminants (CACs) including sulfur dioxide (SO₂), nitrogen oxides (NO_x), particulate matter (PM) and volatile organic compounds (VOC) are the most common air pollutants. CACs are released by burning fossil fuels in processes such as oil sands and conventional oil production. Due to the fact that many more steps are involved in producing synthetic crude oil from oil sands comparing to conventional oil, pollutant emissions are much higher in bitumen recovery processes.

3.2. *Dust and emission from mining operations:*

Apart from the bitumen extraction process that release large amounts of pollutants into the air, other production operations in open pit mining also trigger some issues related to air quality. Drilling and blasting activities generate dust and noise and spreads dust into the air. In addition, construction of the access roads in early stages of mine life, loading and hauling activities and dried tailings are other sources of dust generation. Emissions from mining machinery such as trucks are the other source of air pollution in oil sands mining.

Environmental impacts and mine planning

In response to such environmental concerns, some new concepts in mine planning and optimization are developed. *Sustainable mining* represents this new line of thinking which takes the environmental concerns of any mining project into account. Now the question is, what environmental issues should be considered in decision making and how should they be embedded in the problem. In fact, there are two related categories in which the environmental issues should be considered in; mine design and mine planning.

Mine design refers to the group of techniques that are applied to determine what the overall view of the mine will be at the end of its life. Particularly in open pit mining, the final pit limit is determined in a way that the most possible amount of the ore body can be extracted, based on the estimations of ore value and also extraction and processing costs over the mine-life. A number of environmental issues could be considered in mine design phase by defining a new cost as “environmental cost”. The new term may cover estimations of environmental costs corresponding to different stages in mine life such as exploration, excavation and reclamation (Rodriguez, 2007).

On the other hand in mine planning, the objective is to find the optimal production plan to extract all the material out of the optimal pit. A typical mine plan maximizes the NPV over the mine life subject to some technical constraints such as production and processing capacities. For sustainable mine planning, the impacts with ties to the block model should be considered in planning as well. In any block model, there are some attributes such as ore grade, ore tonnage, waste tonnage, rock type and block coordinates. If a valid relation between any of the environmental issues and corresponding blocks can be defined, then that issue could be considered at the mine planning stage. For example, extraction of each block results in generating some amount of waste, either as solid (waste) or wet (as tailings). This waste should be dumped or pumped into an appropriate waste facility and it results in landscape disturbance. Now if based on the specifications of each block, a value called disturbance factor could be assigned to that block, then the disturbance can be measured and considered in planning phase. As a result, the solution to the model maximizes the NPV and at the same time, minimizes the disturbance to the landscape.

From the presented list of environmental impacts, two important impacts are considered to have significant ties to the block model; the tailings and the land disturbance. Thus, these two environmental issues are considered in this paper. It is first required to establish a relationship between the environmental impacts of land disturbance and the block model and then revise the traditional mine planning models in a way to consider these impacts in finding the optimal solution to the problem. The new model makes it possible to take into account both NPV as the financial driver of the industry and environmental issues as the public concerns at the same time.

The rest of the paper is organized as follows: the problem definition is discussed in section 2. Section 3 covers the review of the related literature. The theoretical framework is discussed in section 4. The formulation to calculate the amount of tailings produced out of each block is presented and verified in section 5. The mathematical model for the problem is presented in section 6. Finally, the conclusions and further steps for the research are discussed in section 7.

2. Problem definition

By reviewing the literature, it turns out that already there are many works addressing the maximization of profit in mine planning. Also, there are some models that have considered different environmental costs in finding the optimal pit limits for the mine. However, the missed critical aspect in mine planning is the merger between two areas; profit maximization and environmental cost minimization.

For a better understanding of reclamation process and also the missing part in mine planning chain, revision of Shell’s plan in fulfillment of Directive 074 (ERCB, 2009) is helpful. Shell Canada has

considered some dedicated disposal areas (DDA) for its JackPine Mine (JPM) and Muskeg River Mine (MRM) sites in Athabasca river region, Alberta, Canada. The two sites are different in terms of tailings facilities; JPM has in-pit tailings facilities while MRM has external tailings facilities. However, the concept of reclamation is almost the same. In both cases, the tailings facilities are constructed with multiple cells adjacent to each other. The thickened tailing (TT) is discharged into the cells consecutively, meaning that the cells receive TT in the order of their location. The cell that receives the discharge earlier is considered as the first DDA, meaning that after a certain period of time, it changes into a dried and reclaimed landscape and reclamation continues in the next cell. The drainage system is designed in a way to discharge any flow of surface water to the adjacent cell. The layout for JPM is illustrated in Fig. 1.

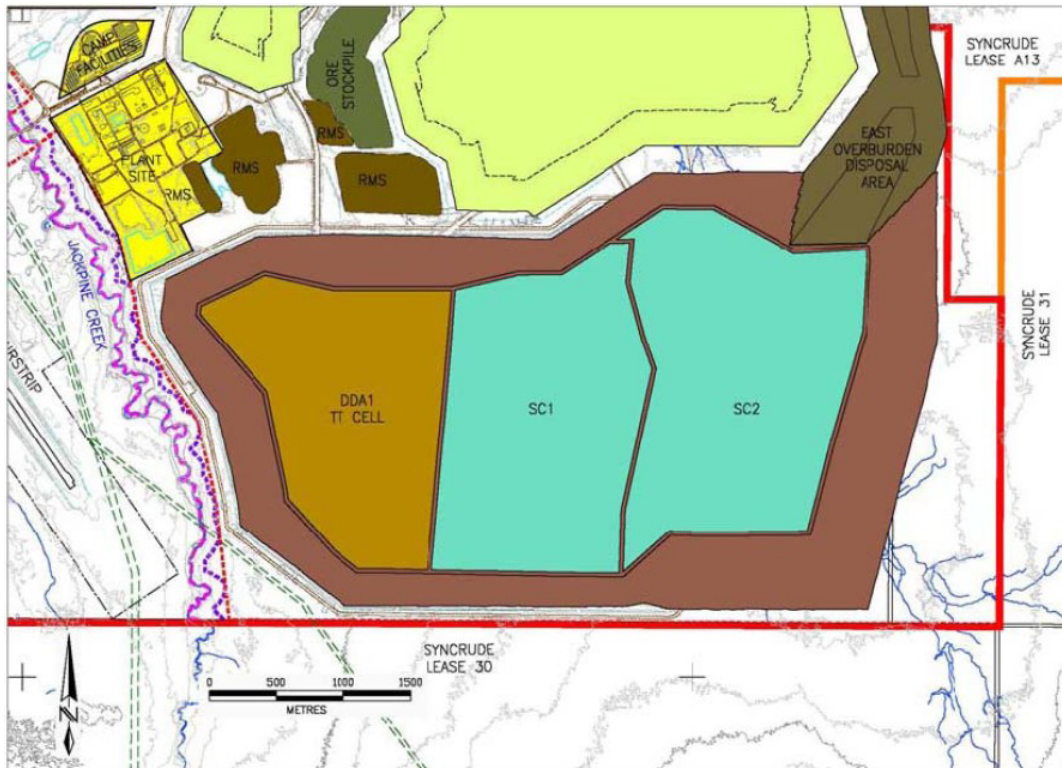


Fig. 1. Layout of dedicated disposal area 1 within the JPM external tailings facility (Shell-Canada, 2011).

Shell Canada considers three main categories in its plan for decommissioning of the external tailings facility as the DDA; (1) construction, (2) operations and (3) closure. Among these three, the construction and operations have ties to the extraction plan of the mine. The amount of waste material that is produced in extraction operations is used for the preparation of starter dyke, external dyke walls and upstream dyke. Also the thickened tailings (TT), centrifuge cake manufacturing and coarse sand tailings (CST) are the by-products of extraction and processing operations. Thus, any change to the production schedule has some impacts on the required material for decommissioning. Now, the question is “*what is the optimal extraction plan that simultaneously maximizes the NPV and minimizes the disturbance on the landscape by considering the decommissioning costs of the mine site?*” in other words, not only the production plan should maximize the NPV with respect to the technical constraints, but also providing required material for decommissioning must be considered as well. Any delay in providing the material required for decommissioning or any additional shipment of material from other stockpiles to the DDA causes extra costs. Therefore, it is important to take into account the destinations for different extracted materials so as to properly manage the stream of materials for decommissioning. As the first step towards considering decommissioning costs in the mine plan, the amount of downstream tailings

that is produced from processing oil sands is calculated (section 5) and considered as a new constraint in the mathematical model (section 6). Table 1 presents the steps involved in the decommissioning of an external tailings facility in Jackpine Mine site (Shell-Canada, 2011).

Table 1. Summary of time line for decommissioning of an external tailings facility by Shell Canada Energy in JMP site.

	Start date	End date
Construction		
Preparation of Starter Dyke	2008	2010
Preparation of External Dyke Walls (centerline)	2015	2029
Preparation of Upstream Dyke	2010	2011
Operations		
TT deposition – initial filling period(1)	2010	2027
Centrifuge Cake Manufacture / Deposition	2014	2027
TT deposition – in-pit tailings CST capping activities(2)	2035	2036
TT deposition – in-pit tailings CST capping activities	2049	2050
TT deposition – in-pit tailings CST capping activities	2054	2055
TFT transfer to SC1	2010	2055
Closure, Capping and Final Landform Design		
Completion of TT deposition	n/a	2055
Trafficable tailings surface	2055	2057
Overburden capping and drainage contouring	2057	2059
Reclamation cover soil placement	2060	2061
Nurse crop coverage and cap settlement	2060	2062
Re-vegetation	2062	2063
Monitoring	2063	TBD
Completion of TT deposition	n/a	2055

Already, the mathematical model that maximizes the NPV corresponding to the mining and processing constraints is well proposed as MILP models in the literature. The overview of such models is as follows:

Maximize (NPV)

Subject to:

Processing plant constraints

Mining capacity constraints

Extraction precedence

In this new model, the costs and constraints corresponding to decommissioning operations is considered as well. Decision variables are revised in a way that facilitates sending of each extracted block or its fractions to different destinations. New objective function terms and constraints are added to the original MILP model to quantify the costs regarding decommissioning. The overview of the revised MILP is as follows:

Maximize (NPV – decommissioning costs)

Subject to:

Processing plant constraints

Mining capacity constraints

Extraction precedence
Capacity constraints for each destination
Capacity constraints for tailings facilities
Providing required material for decommissioning purposes

3. Literature review

During the recent decades, many papers have been published around different aspects of environmental impacts in the mining industry and sustainable mining. In the literature, two groups of tools are used to evaluate sustainability in the mining industry, the descriptive tools and the quantitative ones. Descriptive approaches mostly are based on some reports, for example about the environmental conditions and concerns in mining projects. These reports are either mandatory, obliged by governments or regional authorities, or voluntarily with which the company aims to show its differences from others in the market in terms of environmentally clean practices. On the other hand, quantitative approaches try to quantify the qualitative measures and provide quantitative assessment results for mining operations.

As a descriptive work, Sinding (1999) reviews the environmental management and communication tools for mining industry and discusses the specifications for some of them such as environmental impact assessment, environmental management systems, environmental accounting and life cycle assessment. Sinding (1999) focuses on different stages in a typical mining production as (1) mineral exploration, (2) mine development decision-making, (3) production phase, and (4) mine closure and decommissioning. Then the proper tools for each stage are suggested. Some general recommendations about sustainable mining practices are found in this group of descriptive papers. For instance, the mining companies should consider full range of environmental management and documentation for their activities. Also, it is necessary to establish a global environmental reporting mechanism for the mining industry so that in general, different mining products can be comparable and "the cleanest" can be determined. Furthermore, there should be more emphasis on the effective environmental management in new projects and for effective environmental assessment, increased monitoring and post audit reviews are essential. As a more practical step towards the implementation of these remedies, some have recommended the environmental assessment of projects to be considered as per ISO 14001.

Descriptive works have discussed relatively a complete list of environmental issues tied to mining activities. A comprehensive list of environmental management tools that are in-hand and essential to be implemented are available (Sinding, 1999). However, most of descriptive tools are very general and provide qualitative suggestions rather than explicit quantitative and practical solutions for the problem.

Some other works take a step towards more practical recommendations on environmental aspects of mining projects. Manteiga and Sunyer (2000) modify the recently developed environmental evaluation methodologies in order to make them more practical. A simplified three-step methodology for environmental evaluation assessment is proposed in their work, consisting of; (1) establishment of an assessment framework, (2) assessment of the environmental situation and (3) environmental assessment. Then, these steps are elaborated in details and some indicators to quantify the final results of each step are defined. However, greater efforts are required to achieve the operational implementation of these indicators, both by the environmental authorities who define the indicators and by the mining sector who implement the projects and is responsible for recording precise data corresponding to the indicators.

Quantitative approaches can be classified as the second category of sustainable mining works. Several quantitative approaches are used to take into account the social and environmental impacts of mining industry. In some cases, the environmental impacts are quantified in the designing phase of a mining project. Rodriguez (2007) develops a heuristic algorithm that considers the

environmental cost and adds it up to the other mining costs to find the pit limit for an open pit mining problem. The focus in this work is on the technical issues regarding environmental impacts, rather than social impacts. A new term known as environmental cost (EC) is defined that covers a variety of costs regarding environmental issues such as land clearing, construction of access roads, drilling and blasting, pit excavation, waste rock dumping, tailings disposal and decommissioning. EC is deducted from the economic block value (EBV) and the revised EBV is used to find the pit limit in an iterative algorithm.

Odell (2004) uses the sustainability primer methodology proposed by the association of professional engineers and geoscientists of British Columbia (APEGBC) to integrate sustainability into the mine design process. The basis for APEGBC process is the multi criteria analysis (MCA), also known as multiple accounts evaluation (MAE) and multiple attribute analysis (MAA). MCA consists of a number of distinct approaches, but the basis for all of them is to define different options (scenarios) and assess each option with respect to series of explicit criteria, which is typically done through MCA tables. Some important factors in selecting the proper MCA are (1) availability of time and financial resources, (2) availability and the amount of supporting data, (3) analytical expertise of the project team, (4) administrative culture of decision-making body and (5) the number of decision options (finite or infinite). Odell (2004) applies the methodology for an open pit copper deposit in Peru. Since the decision context in the case study shows a high complexity and a wide range of interested stakeholder groups, the MCA seems to be the proper choice for the problem. It turns out that with MCA approach, it is strongly possible to take into account the different aspects of mining projects, including social and environmental issues, in order to assess different scenarios. New packages of holistic mine design tools should be refined and prepared so as to consider the social and environmental impacts of the mining projects in advance, not just mitigating the environmental consequences afterward.

Odell (2004) shows that MCA is a strong tool that can be used in the development of new packages for assessment of mining projects. However, some pre-determined options (scenarios) should be defined to be used in MCA matrices. In other words, the MCA approach requires two major building blocks to form the MCA matrices; these are some scenarios (as matrix columns) and a variety of indicators representing different engineering, economical, social and environmental criteria (as matrix rows). Therefore, MCA is more suitable for general decision-making in feasibility study stages when several scenarios can be defined and there are some pre-estimations for different indicators under each scenario. MCA is considered as a powerful tool for mine design, but is not that handy when it is intended to optimize production scheduling problem, because optimization requires more detail and numerical values to be used in mathematical programming. At that stage, the idea of defining scenarios fails. Therefore, MCA does not work for mine planning purpose.

Fuzzy logic is the other tool that can be used in quantification of descriptive and qualitative values. Many of environmental impacts are either described qualitatively or there are some quantitative indicators but still the judgment of an expert is required to assess them. Thus, fuzzy sets and fuzzy logic are strong tools to capture the uncertainty and fuzzy nature of environmental variables. Shepard (2005) makes an introduction to the fuzzy logic and discusses its implementation in quantification of environmental impact assessment. The traditional approach in environmental impact assessment is reviewed and fuzzy logic is introduced as the modern approach in the field.

The focus in the current literature is mostly on qualitative approaches for assessment of environmental impacts. There are few works that have considered the impacts quantitatively. However, the scope of the current quantitative approaches is mine design, not mine planning. Therefore, this paper aims at integrating the mine and decommissioning long term plans for the case of oil sands.

4. Theoretical framework

In a typical mine planning problem, the number of variables is directly related to the number of blocks and the number of time periods considered in planning. Since in real world problems, usually hundreds of thousands to millions of blocks are considered in the optimum pit and for long-term planning, multiple periods are taken into account, a typical mine planning problem has millions of variables, among them some integers and others continuous. This makes the problem NP-hard and non solvable with current software, or solvable with a very long solution time. In a brief review, the literature regarding the methodology used in finding the solution can be classified into two main categories; (1) those based on the exact methods, mainly relying on linear programming (LP) to find the exact optimal solution with a long CPU time, and (2) those based on the approximation of optimal solution by applying heuristic algorithms. Applying the heuristic approach may result in quality solution in reasonable time, but the solution may not be necessarily optimal.

In many of the works focusing on exact methods, the binary nature of integer variables is relaxed. For instance, Tan and Romani (1992) consider the equipment capacity constraints and find the optimal extraction schedule over multiple periods, using both linear programming (LP) and dynamic programming (DP). Since the integer nature of decision variables is relaxed, the block sequencing constraints are not satisfied. Fytas et al. (1993) use different approaches for long-term and short-term decision making problems. As the first phase, the simulation is used to find those blocks that should be extracted in long-term. At this phase, the precedence constraints, the minimum and maximum production and processing capacity constraints and also the bounds on the grade of entering material to the processing plant are considered. Then for the second phase, the LP is used for the short-term planning, subject to the same constraints of long-term, but with the assumption that the partial extraction of blocks is permitted. Finally, an iterative approach is proposed to deliver a practical mining sequence.

There are some techniques to reduce the problem size and make large problems solvable using exact methods. Block aggregation is one of these techniques. The idea is to merge the blocks to create “*mining-cuts*” and hence, reduce the number of MILP variables (Askari-Nasab et al., 2010). However in the 1980s, a new approach emerged, aiming to reduce the problem size, not by reducing the number of variables, but by relaxing some of the constraints. The Lagrangian relaxation is used to relax some of the constraints and help to find the exact solution of the relaxed problem. The main idea in the Lagrangian relaxation approach is to relax some of the constraints and instead, add penalty terms into the objective function. The constraints of the MILP can be classified into two categories: (1) hard constraints, including those that define the precedence of blocks extraction and (2) soft constraints, including those constraints that are defined to satisfy the limited production and processing capacities and grade bounds for the material entering the processing plant. In most of the papers, the soft constraints are relaxed and corresponding terms are added into the objective function with a penalty multiplier. This relaxation triggers another question: to what extent the objective function should be penalized if the corresponding constraint is not satisfied? In other words, what are the proper values for Lagrangian multipliers? Some algorithms are developed to find the answer to such questions. Among them, one of non-heuristic algorithms is the sub-gradient method.

Dagdelen and Johnson (1986) use the Lagrangian relaxation to relax constraints on the maximum production in each period. The sub-gradient method is applied to update the multipliers in some small examples. This is one of the first papers in the field of Lagrangian relaxation, using the sub-gradient method. Akaike and Dagdelen (1999) extend the previous work by changing the value of the Lagrangian multipliers in an iterative procedure. The procedure continues until the relaxed problem reaches the optimal solution that is feasible for the original problem.

Kawahata (2006) expands the idea of Dagdelen and Johnson (1986) by defining a variable cut-off grade that specifies the destination of extracted material, i.e. whether to go to the processing plant, to be stockpiled or to be dumped as waste. Then two Lagrangian relaxation sub problems are used to find the bounds of the original problem; one for the most conservative case of mine sequencing and the other for the most aggressive case. Since the solution for the relaxed problem is not necessarily feasible for the original problem, some bounds are adjusted on capacities to guarantee the feasibility of Lagrangian solution for the original problem.

To develop the theoretical concept of Lagrangian relaxation, it is assumed that there is a maximization problem with some constraints. This original problem is called the *primal* problem. In addition, it is assumed that the constraints have made the primal problem so complicated that it takes a long run-time to find the optimal solution. One practical way to tackle the complexity of the problem is to relax some of the constraints and consider the relaxed version of the primal problem as the *dual* problem. It is proved that the optimal solution to the dual problem always equals, or is greater than the optimal solution to the primal problem (Fisher, 2004). In other words, the dual optimal solution is always considered as an upper bound to the primal optimal solution.

On the other hand, we assume that just a feasible solution to the primal problem can be found. Since by definition, the optimal solution to any maximization problem is greater than, or equal to any point in the feasible space of the problem, any feasible solution is considered as a lower bound for the optimal solution of the primal problem. The idea of upper bound and lower bound works for any minimization problem as well, just in reverse order for lower and upper bounds. The concept of lower and upper bounds in a maximization problem is illustrated in Fig. 2.

To avoid the violations from relaxed constraints, proper penalty terms are added to the objective function to penalize any violation from the corresponding constraints. For any penalty term, a penalty multiplier called the Lagrangian multiplier, is considered and multiplied to the penalty term. One of the most well known and typical approaches used to find the multiplier values is the sub-gradient method.

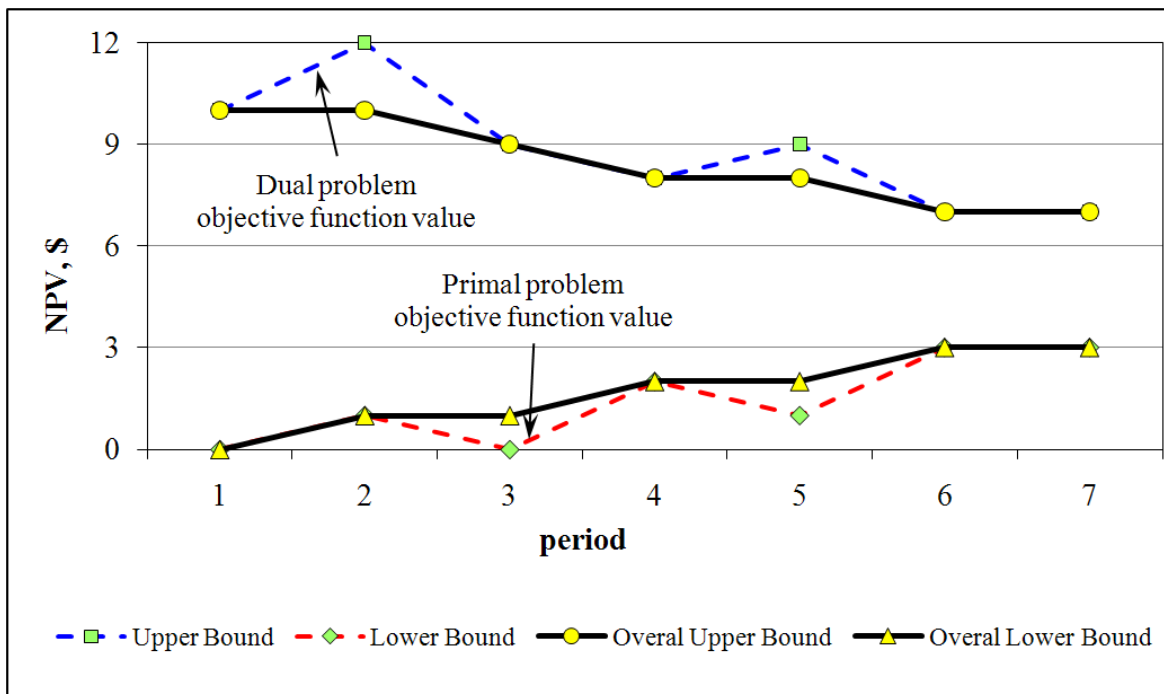


Fig. 2. Upper and lower bounds for a typical maximization problem.

The sub-gradient method

Fisher (1985) provides an application oriented guide to Lagrangian relaxation and presents the following formulation for typical primal and dual problems and the sub-gradient method.

The integer programming problem, called the primal is formulated as Eqs. (1) and (2).

$$Z = \max cx \quad (1)$$

Subject to:

$$Ax \leq b$$

$$Dx \leq e \quad (2)$$

$$x \geq 0, \text{int}$$

Where x is $n \times 1$, b is $m \times 1$, e is $k \times 1$ and all other matrices have conformable dimensions. In this formulation, the constraints are partitioned into two sets, $Ax \leq b$ and $Dx \leq e$. It is assumed that it is easy to solve the primal problem, if the set of constraints $Ax \leq b$ are relaxed. This relaxation produces the dual problem LR_u^k , using an m vector of non-negative multipliers u . (Eqs. (3) and (4))

$$Z_D(u) = \max cx + u(b - Ax) \quad (3)$$

Subject to:

$$Dx \leq e$$

$$x \geq 0, \text{int} \quad (4)$$

Since the dual problem provides an upper bound for the primal maximization problem, ideally the vector u should be found in a way that $Z_D(u)$ be minimized. This is formulated with Eq. (5).

$$Z_D = \min Z_D(u) \quad (5)$$

Eq. (5) is considered as the basis of the sub-gradient method. The goal is to find the proper set of Lagrangian multipliers that minimizes $Z_D(u)$. Multiplier values are updated, considering the initial value of u^0 and according to Eq. (6).

$$u^{k+1} = \max \{0, u^k - t_k(b - Ax^k)\} \quad (6)$$

Where x^k is the optimal solution to LR_u^k , the Lagrangian problem with dual variables set to u^k , and t_k is a scalar step size value. According to Fisher (1985), a formula for t_k that has been proven to be effective in practice is given by Eq. (7).

$$t_k = \frac{\lambda_k(Z_D(u^k) - Z^*)}{\sum_{i=1}^m (b_i - \sum_{j=1}^n a_{ij}x_j^k)^2} \quad (7)$$

In this formula, Z^* is the objective value of the best known feasible solution to (P) and λ_k is a scalar chosen between 0 and 2. Frequently, the sequence λ_k is determined by starting with $\lambda_k = 2$ and reducing it by a factor of two whenever $Z_D(u^k)$ has failed to decrease in a specific number of iterations.

5. Tailings calculation

The volume and tonnage of tailings that is produced as a result of oil sands processing is required in surface mine planning. In this paper, Suncor's flow sheet is used to find the mass-balance relationship between ore feed and tonnage of the total pond slurry tailings (Suncor, 2009). Suncor

has applied some assumptions in its flow sheet. These assumptions are based on Suncor's operational factors and are implied here as well. A schematic view of a related part from Suncor's oil sand processing flow diagram is presented in Fig. 3.

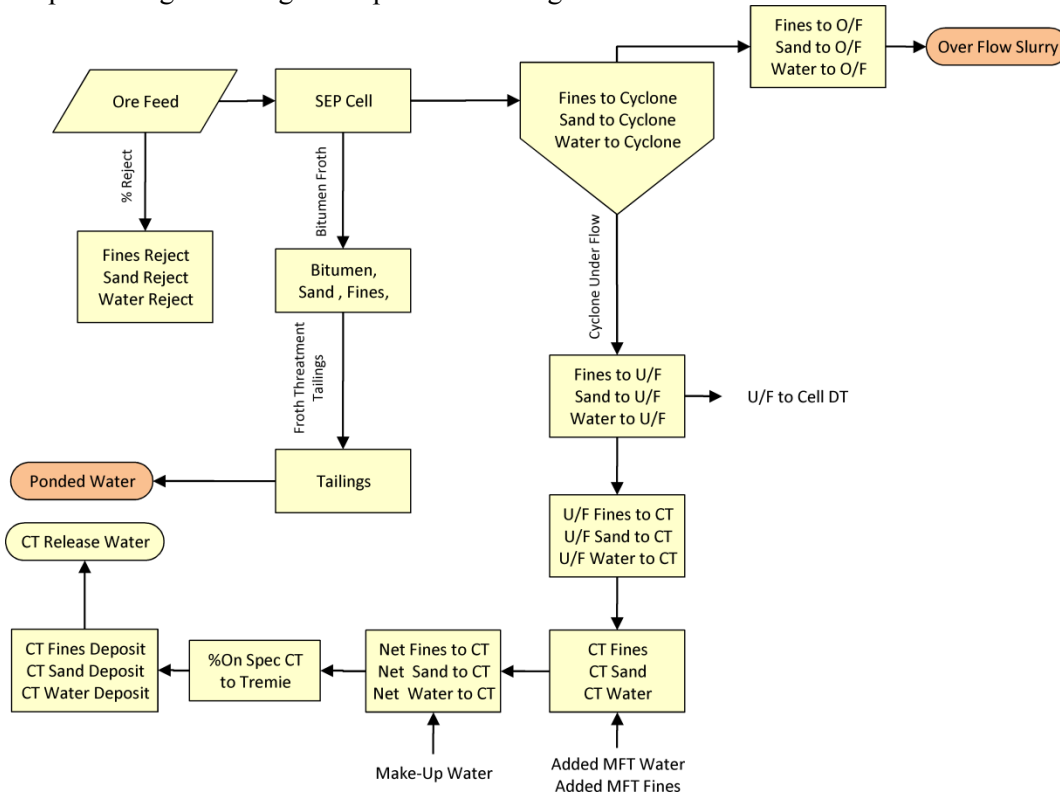


Fig. 3. Suncor processing flow diagram.

In this paper, the focus is on two main streams that make slurry and water, ending in the tailings pond. The first one feeding the greatest portion of the tailings material is the over flow slurry. The second one is the pond water from bitumen froth treatment. These two parts are highlighted in Fig. 3. In addition to these streams, there are two other streams in the process. These two streams (that result in producing CT and MFT) come from cyclone under flow. Since it is assumed that these two products are held in different cells, they are not considered in calculating the total amount of ponded tailings.

The following notations are used in the tailings calculation:

Parameters

$Sd_{UF}^{\%}$: Sand content of the underflow

$Sl_{solid}^{\%}$: Slurry solid percent sent to cyclone

$UF_{Sd}^{\%}$: Sand percent in cyclone underflow

$UF_{F}^{\%}$: Fine percent in cyclone underflow

$UF_{W}^{\%}$: Water percent in cyclone underflow

- R : SET recovery percent
- $B\%_{SET}$: SET bitumen percent
- $F\%_{SET}$: SET fines percent
- $Sd\%_{SET}$: SET sand percent
- $W\%_{SET}$: SET water percent
- $Rj\%$: Reject percent
- $Rj\%_F$: Fines reject percent
- $Rj\%_{Sd}$: Sand reject percent
- $Rj\%_W$: Water reject percent
- $Rj\%_B$: Bitumen reject percent
- HPW : HPW
- SG_f : Fines specific gravity
- SG_s : Sand specific gravity
- $F\%_{Beach}$: Fines content in beach solids (%)
- BDD : Beach dry density
- $S\%_{MFT}$: MFT solid content (%)

Input variables

- M_{Feed}^O : Mass of ore in the feed
- B_{Feed} : Bitumen content of the feed (%)
- F_{Feed} : Fines content of the feed (%)
- W_{Feed} : Water content of the feed (%)

Outputs

$M_{Ponded}^{Overflow}$ Mass of total overflow ponded material

M_{Ponded}^W Mass of total ponded water from froth treatment

M_{Ponded}^{Slurry} Mass of total ponded material

The total tonnage of ponded slurry is calculated as in Eq. (8) and consists of two parts, the overflow slurry and the ponded water as the downstream product from bitumen froth treatment.

$$M_{Ponded}^{Slurry} = M_{Ponded}^{Overflow} + M_{Ponded}^W \quad (8)$$

The overflow slurry, $M_{Ponded}^{Overflow}$, is the summation of total fines, sand and water that is the overflow material produced by the cyclone and is calculated as Eq. (9).

$$M_{Ponded}^{Overflow} = M_{Feed}^O \times \left(\begin{array}{l} \left((1 - B_{Feed} - W_{Feed}) \times \left(\begin{array}{l} -\frac{1 - F_{Feed}}{UF_{Sd\%}} \times (UF_{F\%} + UF_{W\%}) \\ \times Sd\%_{UF} \\ -(1 - F_{Feed}) \times Sd\%_{UF} \\ + \frac{1}{Sl_{solid\%}} \end{array} \right) \right) \\ + (B_{Feed} - Rj\% \times Rj\%_B) \times \frac{R}{B\%_{SET}} \\ \times \left(\begin{array}{l} \frac{Sd\%_{SET} \times Sd\%_{UF} \times (UF_{F\%} + UF_{W\%})}{UF_{Sd\%}} \\ + Sd\%_{SET} \times Sd\%_{UF} - \frac{F\%_{SET}}{Sl_{solid\%}} - \frac{Sd\%_{SET}}{Sl_{solid\%}} \end{array} \right) \\ + Rj\% \times \left(\begin{array}{l} \frac{Rj\%_{Sd} \times Sd\%_{UF} \times (UF_{F\%} + UF_{W\%})}{UF_{Sd\%}} \\ + Rj\%_{Sd} \times Sd\%_{UF} - \frac{Rj\%_F}{Sl_{solid\%}} - \frac{Rj\%_{Sd}}{Sl_{solid\%}} \end{array} \right) \end{array} \right) \quad (9)$$

Finally, the ponded water from bitumen froth treatment is calculated through Eq. (10).

$$M_{Ponded}^W = \left(\begin{array}{l} \frac{(B_{Feed} - Rj\% \times Rj\%_B) \times M_{Feed}^O \times R}{B\%_{SET}} \\ + \frac{W\%_{SET} - \frac{Sd\%_{SET}}{(1 - F\%_{Beach}) \times BDD}}{SG_s} + \frac{Sd\%_{SET} \times F\%_{Beach}}{(1 - F\%_{Beach}) \times SG_f} \\ + \left(\frac{S\%_{MFT} - 1}{S\%_{MFT}} \right) \\ \times \left(\frac{F\%_{SET} \times (1 - F\%_{Beach}) - Sd\%_{SET} \times F\%_{Beach}}{(1 - F\%_{Beach})} \right) \end{array} \right) \quad (10)$$

Validation of the formula

In order to check the results from the formulations, the tailings tonnage is calculated based on the derived formulation for an optimized long term mining production case. The final pit limit for the case contains 61490 blocks of 50 by 50 by 15 meters and the production is planned for 19 periods. In order to reduce the number of variables and make the selective mining units more practical, the blocks are aggregated into 302 mining cuts. According to the presented formulation and notation, four main input variables are required to calculate the tailings amount; (1) percentage of bitumen content of the block, (2) percentage of fines content of the block, (3) tonnage of ore in extracted portion of each block and (4) percentage of water content of the block. The first two inputs already exists in the block model for the case study. The ore tonnage of the block is multiplied by the portion of the block that is extracted as ore in each period to calculate the ore tonnage of the processing plant feed. Eq. (11) is used to calculate the water content (Masliyah, 2010) of the processing plant feed.

$$W_{Feed} = 0.75 \times F_{Feed} + 2.3 \quad (11)$$

The amount of mined material, processing material sent to the mill and the produced tailings sent to the tailings pond for 19 periods is illustrated in Fig. 4.

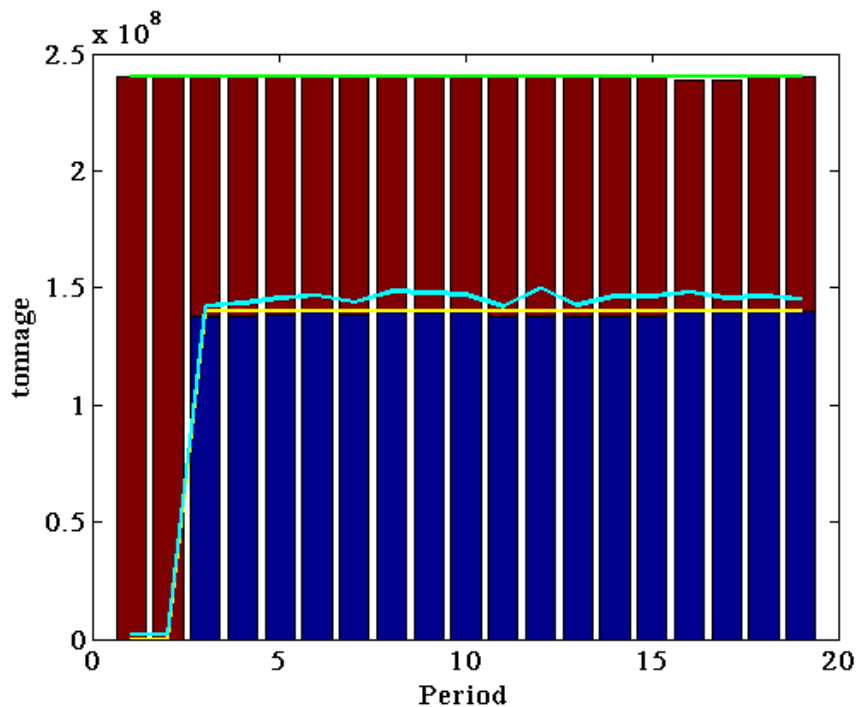


Fig. 4. Mining, processing and tailings amount per period.

The horizontal lines in Fig. 4 represent the processing and mining capacities. Based on the optimal mine production schedule, all the extracted material in the first two periods are waste and sent to the waste dump (two years of pre-stripping). As a result, the amount of processing material is zero in periods one and two. The bright curve represents the amount of tailings that is produced in each period. The presented formulation is used to figure out the total tonnage of tailings in each period. Initially the tailings amount corresponding to the processed portion of each block in a period is calculated. Then, the calculated tailings tonnages are aggregated to build the total amount of tailings in the period.

To double check the result of the formulation, the tailings tonnage is also calculated in another method. In the second method, the tailings tonnage is calculated for a block with the ore tonnage of 1000 tonne. For each period, the average values for bitumen content, fines content and water content of the blocks that are going to be extracted in the period are considered in calculations. Then the result for tailings tonnage in each period is multiplied by the total tonnage of the material that is processed in that period. The minimum, maximum and average differences between the amounts of tailings resulting from the two methods are 1.25%, 1.40% and 1.32%, respectively. It shows that the two methods result in almost the same amounts of tailings and the derived formulation works well. The differences between the results from the first method and the second one for the 17 periods with non-zero values for the tailings are compared in Fig. 5.

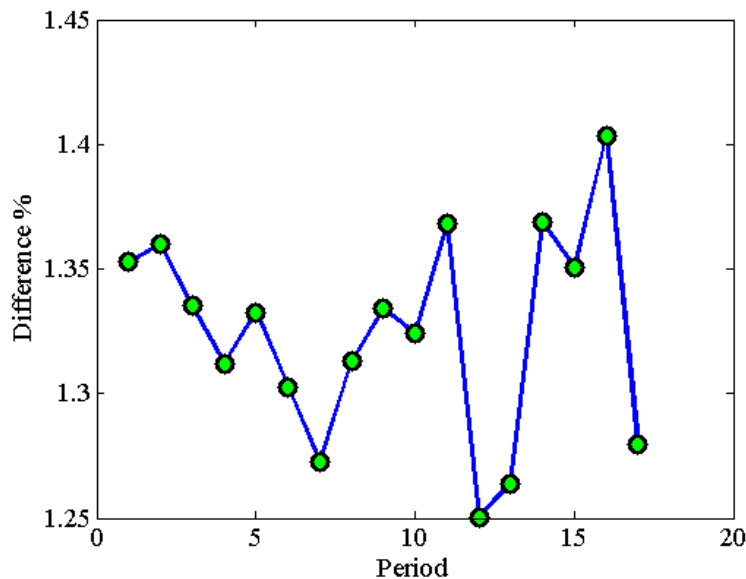


Fig. 5. Percent of difference between two methods for tailings calculation.

6. Mathematical model

The long-term mine production scheduling problem is formulated using mixed integer linear programming. The formulated model for the strategic production and operational decommissioning (capping) material scheduling problem has an objective function and number of constraints. The material used for capping purposes in oil sands surface mining, which are overburden, interburden and coarse sands tailings, are all from the block model. However, the costs regarding to each portion are different. In reality, due to the different activities associated with dumping, reloading and hauling of each type of material, the costs are different. Thus, different decision variables and cost coefficients are defined in the mathematical model to differentiate between different portions of each block.

The notation used in the formulation of the problem has been classified as sets, indices, subscripts, superscripts, parameters, and decision variables. Multiple material types and destinations are taken into account in the MILP formulation. Finally, the MILP formulation framework is developed based on mining-cuts.

Sets

$K = \{1, \dots, K\}$ set of all the mining-cuts in the model.

$J = \{1, \dots, J\}$	set of all the phases (push-backs) in the model.
$U = \{1, \dots, U\}$	set of all possible destinations for materials in the model.
$C_k(L)$	For each mining-cut k , there is a set $C_k(L) \subset K$ defining the immediate predecessor mining-cuts above mining-cut k that must be extracted prior to extraction of mining-cut k , where L is the total number of mining-cuts in the set $C_k(L)$.
$M_k(P)$	For each mining-cut k , there is a set $M_k(P) \subset K$ defining the immediate predecessor mining-cuts in a specified horizontal mining direction that must be extracted prior to extraction of mining-cut k at the specified level, where P is the total number of mining-cuts in the set $M_k(P)$.
$B_j(H)$	For each phase j , there is a set $B_j(H) \subset K$ defining the mining-cuts within the immediate predecessor pit phases (push-backs) that must be extracted prior to extracting phase j , where H is an integer number representing the total number of mining-cuts in the set $B_j(H)$.

Indices, subscripts and superscript

A parameter, f , can take indices, subscripts, and superscripts in the format $f_{k,j}^{u,e,t}$. Where:

$t \in \{1, \dots, T\}$	index for scheduling periods.
$k \in \{1, \dots, K\}$	index for mining-cuts.
$e \in \{1, \dots, E\}$	index for element of interest in each mining-cut.
$j \in \{1, \dots, J\}$	index for phases.
$u \in \{1, \dots, U\}$	index for possible destinations for materials.
D, S, M, P	subscripts and superscripts for overburden and interburden material, tailings sand, mining and processing respectively.

Parameters

$d_k^{u,t}$	the discounted profit obtained by extracting mining-cut k and sending it to destination u in period t .
$r_k^{u,t}$	the discounted revenue obtained by selling the final products within mining-cut k in period t if it is sent to destination u , minus the extra discounted cost of mining all the material in mining-cut k as ore and processing at destination u .
$n_k^{u,t}$	the extra discounted cost of mining all the material in mining-cut k in period t as overburden and interburden material for capping at destination u .
$m_k^{u,t}$	the extra discounted cost of mining all the material in mining-cut k in period t as tailings sand material for capping at destination u .

$q_k^{u,t}$	the discounted cost of mining all the material in mining-cut k in period t as waste and sending it to destination u .
g_k^e	the average grade of element e in ore portion of mining-cut k .
$\underline{g}^{u,t,e}$	the lower bound on the required average head grade of element e in period t at processing destination u .
$\overline{g}^{u,t,e}$	the upper bound on the required average head grade of element e in period t at processing destination u .
f_k^o	the average percent of fines in ore portion of mining-cut k .
$\underline{f}^{u,t,o}$	the lower bound on the required average fines percent of ore in period t at processing destination u .
$\overline{f}^{u,t,o}$	the upper bound on the required average fines percent of ore in period t at processing destination u .
f_k^c	the average percent of fines in overburden and interburden capping material portion of mining-cut k .
$\underline{f}^{u,t,c}$	the lower bound on the required average fines percent of overburden and interburden capping material in period t at capping destination u .
$\overline{f}^{u,t,c}$	the upper bound on the required average fines percent of overburden and interburden capping material in period t at capping destination u .
o_k	the ore tonnage in mining-cut k .
w_k	the waste tonnage in mining-cut k .
d_k	the overburden and interburden material tonnage in mining-cut k .
l_k	the tailings sand material tonnage in mining-cut k .
t_k	the tailings tonnage produced downstream from extraction of ore from mining-cut k .
$T_{Mu}^{m,t}$	the upper bound on mining capacity (tonnes) in period t .
$T_{Ml}^{m,t}$	the lower bound on mining capacity (tonnes) in period t .
$T_{Pu}^{u,t}$	the upper bound on processing capacity (tonnes) in period t at destination u .
$T_{Pl}^{u,t}$	the lower bound on processing capacity (tonnes) in period t at destination u .
$T_{Cu}^{u,t}$	the upper bound on overburden and interburden capping material requirement (tonnes) in period t at destination u .
$T_{Cl}^{u,t}$	the lower bound on overburden and interburden capping material requirement (tonnes) in period t at destination u .
$T_{Nu}^{u,t}$	the upper bound on tailings sand capping material requirement (tonnes) in period t at destination u .

$T_{NI}^{u,t}$	the lower bound on tailings sand capping material requirement (tones) in period t at destination u .
$T_{Tu}^{u,t}$	the upper bound on capacity of tailings pond (tones) in period t at destination u .
$T_{Tl}^{u,t}$	the lower bound on capacity of tailings pond (tones) in period t at destination u .
$r^{u,e}$	the proportion of element e recovered (processing recovery) if it is processed at destination u .
$p^{e,t}$	the price of element e in present value terms per unit of product.
$cs^{e,t}$	the selling cost of element e in present value terms per unit of product.
$cp^{u,e,t}$	the extra cost in present value terms per tonne of ore for mining and processing at destination u .
$cl^{u,t}$	the cost in present value terms per tonne of overburden and interburden dyke material for capping at destination u .
$cu^{u,t}$	the cost in present value terms per tonne of tailings sand dyke material for capping at destination u .
$cm^{u,t}$	the cost in present value terms of mining a tonne of waste in period t and sending it to destination u .

Decision variables

$x_k^{u,t} \in [0,1]$	a continuous variable representing the portion of ore from mining-cut k to be extracted and processed at destination u in period t .
$w_k^{u,t} \in [0,1]$	a continuous variable representing the portion of overburden and interburden material from mining-cut k to be extracted and used for capping purposes at destination u in period t .
$v_k^{u,t} \in [0,1]$	a continuous variable representing the portion of tailings sand material from mining-cut k to be extracted and used for capping purposes at destination u in period t .
$y_k^t \in [0,1]$	a continuous variable representing the portion of mining-cut k to be mined in period t , which includes ore, overburden and interburden capping material, tailings sand capping material and waste.
$b_k^t \in [0,1]$	a binary integer variable controlling the precedence of extraction of mining-cuts. b_k^t is equal to one if the extraction of mining-cut k has started by or in period t , otherwise it is zero.
$c_j^t \in [0,1]$	a binary integer variable controlling the precedence of mining phases. c_j^t is equal to one if the extraction of phase j has started by or in period t , otherwise it is zero.

Modeling of economic mining-cut value

The objective function of the MILP model is to maximize the net present value of the mining operations, including operation-related portion of the decommissioning costs. The concept of economic mining-cut value is based on ore parcels within mining-cuts which could be mined selectively. The profit from mining a mining-cut is a function of the value of the mining-cut based

on the processing destination and the costs incurred in mining, processing and cell decommissioning at a specified destination. The cost of cell decommissioning is also a function of the location of the tailings facility being constructed and the type and quantity of used dyke and tailings sand material. The discounted profit from mining-cut k is equal to the discounted revenue obtained by selling the final product contained in mining-cut k minus the discounted cost involved in mining mining-cut k as waste (Askari-Nasab and Awuah-offei, 2009). In this paper, in addition to the previous terms, two new terms are considered in calculation of economic mining cut value; the extra discounted cost of mining overburden/interburden (OI) and tailings sand (TS) material for capping purposes. This has been simplified into Eqs. (12) to (16).

$$d_k^{u,t} = r_k^{u,t} - q_k^{u,t} - n_k^{u,t} - m_k^{u,t} \quad \forall t \in \{1, \dots, T\}, u \in \{1, \dots, U\}, k \in \{1, \dots, K\} \quad (12)$$

Where:

$$r_k^{u,t} = \sum_{e=1}^E o_k \times g_k^e \times r^{u,e} \times (p^{e,t} - cs^{e,t}) - \sum_{e=1}^E o_k \times cp^{u,e,t} \quad \forall t \in \{1, \dots, T\}, u \in \{1, \dots, U\}, k \in \{1, \dots, K\} \quad (13)$$

$$q_k^{u,t} = (o_k + d_k + w_k) \times cm^{u,t} \quad \forall t \in \{1, \dots, T\}, u \in \{1, \dots, U\}, k \in \{1, \dots, K\} \quad (14)$$

$$n_k^{u,t} = d_k \times cl^{u,t} \quad \forall t \in \{1, \dots, T\}, u \in \{1, \dots, U\}, k \in \{1, \dots, K\} \quad (15)$$

$$m_k^{u,t} = l_k \times cu^{u,t} \quad \forall t \in \{1, \dots, T\}, u \in \{1, \dots, U\}, k \in \{1, \dots, K\} \quad (16)$$

The mixed integer linear programming model

The objective functions of the MILP model for strategic and operational production plan for oil sands mining can be formulated as: i) maximizing the NPV and ii) minimizing the decommissioning (capping) cost. These are represented by Eqs. (17) and (18), respectively.

$$Max \sum_{u=1}^U \sum_{t=1}^T \sum_{j=1}^J \left(\sum_{k \in B_j} (r_k^{u,t} \times x_k^{u,t} - q_k^{u,t} \times y_k^t) \right) \quad (17)$$

$$Min \sum_{u=1}^U \sum_{t=1}^T \sum_{j=1}^J \left(\sum_{k \in B_j} (n_k^{u,t} \times w_k^{u,t} + m_k^{u,t} \times v_k^{u,t}) \right) \quad (18)$$

Eqs. (17) and (18) can be combined as a single objective function, formulated as in Eq. (19).

$$Max \sum_{u=1}^U \sum_{t=1}^T \sum_{j=1}^J \left(\sum_{k \in B_j} \left[(r_k^{u,t} \times x_k^{u,t} - q_k^{u,t} \times y_k^t) - (n_k^{u,t} \times w_k^{u,t} + m_k^{u,t} \times v_k^{u,t}) \right] \right) \quad (19)$$

The complete MILP model comprising of the combined objective function and constraints can be formulated as;

Objective function:

$$Max \sum_{u=1}^U \sum_{t=1}^T \sum_{j=1}^J \left(\sum_{k \in B_j} \left[(r_k^{u,t} \times x_k^{u,t} - q_k^{u,t} \times y_k^t) - (n_k^{u,t} \times w_k^{u,t} + m_k^{u,t} \times v_k^{u,t}) \right] \right) \quad (20)$$

Constraints:

$$T_{Ml}^t \leq \sum_{j=1}^J \left(\sum_{k \in B_j} (o_k + w_k + d_k) \times y_k^t \right) \leq T_{Mu}^t \quad \forall t \in \{1, \dots, T\} \quad (21)$$

$$T_{Pl}^{u,t} \leq \sum_{j=1}^J \left(\sum_{k \in B_j} (o_k \times x_k^{u,t}) \right) \leq T_{Pu}^{u,t} \quad \forall t \in \{1, \dots, T\}, u \in \{1, \dots, U\} \quad (22)$$

$$T_{Cl}^{u,t} \leq \sum_{j=1}^J \left(\sum_{k \in B_j} (d_k \times w_k^{u,t}) \right) \leq T_{Cu}^{u,t} \quad \forall t \in \{1, \dots, T\}, u \in \{1, \dots, U\} \quad (23)$$

$$T_{Nl}^{u,t} \leq \sum_{j=1}^J \left(\sum_{k \in B_j} (l_k \times v_k^{u,t}) \right) \leq T_{Nu}^{u,t} \quad \forall t \in \{1, \dots, T\}, u \in \{1, \dots, U\} \quad (24)$$

$$\underline{g}^{u,t,e} \leq \sum_{j=1}^J \left(\sum_{k \in B_j} g_k^e \times o_k \times x_k^{u,t} / \sum_{k \in B_j} o_k \times x_k^{u,t} \right) \leq \bar{g}^{-u,t,e} \quad \forall t \in \{1, \dots, T\}, u \in \{1, \dots, U\}, e \in \{1, \dots, E\} \quad (25)$$

$$\underline{f}^{u,t,o} \leq \sum_{j=1}^J \left(\sum_{k \in B_j} f_k^o \times o_k \times x_k^{u,t} / \sum_{k \in B_j} o_k \times x_k^{u,t} \right) \leq \bar{f}^{-u,t,o} \quad \forall t \in \{1, \dots, T\}, u \in \{1, \dots, U\} \quad (26)$$

$$\underline{f}^{u,t,c} \leq \sum_{j=1}^J \left(\sum_{k \in B_j} f_k^c \times d_k \times w_k^{u,t} / \sum_{k \in B_j} d_k \times w_k^{u,t} \right) \leq \bar{f}^{-u,t,c} \quad \forall t \in \{1, \dots, T\}, u \in \{1, \dots, U\} \quad (27)$$

$$T_{Tl}^{u,t} \leq \sum_{j=1}^J \left(\sum_{k \in B_j} (t_k \times x_k^{u,t}) \right) \leq T_{Tu}^{u,t} \quad \forall t \in \{1, \dots, T\}, u \in \{1, \dots, U\} \quad (28)$$

$$\sum_{u=1}^U (o_k \times x_k^{u,t} + d_k \times w_k^{u,t}) \leq (o_k + d_k) \times y_k^t \quad \forall t \in \{1, \dots, T\}, k \in \{1, \dots, K\} \quad (29)$$

$$\sum_{u=1}^U (l_k \times v_k^{u,t}) \leq \sum_{u=1}^U (o_k \times x_k^{u,t}) \quad \forall t \in \{1, \dots, T\}, k \in \{1, \dots, K\} \quad (30)$$

$$\sum_{u=1}^U \sum_{t=1}^T x_k^{u,t} \leq 1 \quad \forall k \in \{1, \dots, K\} \quad (31)$$

$$\sum_{u=1}^U \sum_{t=1}^T w_k^{u,t} \leq 1 \quad \forall k \in \{1, \dots, K\} \quad (32)$$

$$\sum_{u=1}^U \sum_{t=1}^T v_k^{u,t} \leq 1 \quad \forall k \in \{1, \dots, K\} \quad (33)$$

$$b_k^t - \sum_{i=1}^t y_s^i \leq 0 \quad \forall t \in \{1, \dots, T\}, k \in \{1, \dots, K\}, s \in C_k(L) \quad (34)$$

$$b_k^t - \sum_{i=1}^t y_r^i \leq 0 \quad \forall t \in \{1, \dots, T\}, k \in \{1, \dots, K\}, r \in M_k(P) \quad (35)$$

$$\sum_{i=1}^t y_k^i - b_k^t \leq 0 \quad \forall t \in \{1, \dots, T\}, k \in \{1, \dots, K\} \quad (36)$$

$$b_k^t - b_k^{t+1} \leq 0 \quad \forall t \in \{1, \dots, T-1\}, k \in \{1, \dots, K\} \quad (37)$$

$$c_j^t - \sum_{i=1}^t y_h^i \leq 0 \quad \forall t \in \{1, \dots, T\}, j \in \{1, \dots, J\}, h \in B_j(H) \quad (38)$$

$$\sum_{i=1}^t y_h^i - H \times c_j^t \leq 0 \quad \forall t \in \{1, \dots, T\}, j \in \{1, \dots, J\}, h \in B_{j+1}(H) \quad (39)$$

$$c_j^t - c_j^{t+1} \leq 0 \quad \forall t \in \{1, \dots, T-1\}, j \in \{1, \dots, J\} \quad (40)$$

$$\sum_{t=1}^T y_k^t = 1 \quad \forall k \in \{1, \dots, K\} \quad (41)$$

Eq. (20) is the objective function of the formulation which seeks to i) maximize the NPV and ii) minimize capping costs. Eq. (21) is the total mining capacity constraint. Eqs. (22), (23) and (24) are the capacity constraints for processing, OI and TS for capping requirements, respectively. Eqs. (25), (26) and (27) specify the limiting requirements for bitumen in ore, fines in ore and fines in OI capping material for all destinations. Eq. (28) represents the upper and lower bounds on the capacity of each tailings facility in each period. Eq. (29) ensures that the total material that is mined in each period for all destinations does not exceed the sum of the ore and OI material that is mined. Eq. (30) states that the tonnage of TS that is mined for capping in each period should be less than or equal to the tonnage of ore material that is mined for all destinations. Any unscheduled TS material becomes available for preparation of mature fine tailings (MFT). Eqs. (31), (32) and (33) ensure that the total fractions of mining-cut k sent to all destinations in all periods are less than or equal to one. Eqs. (34), (35), (36) and (37) check the set of immediate predecessor mining-cuts that must be mined prior to mining mining-cut k for all periods and destinations. Eqs. (38), (39) and (40) check the set of immediate predecessor pit phase that must be mined prior to mining phase j in all periods for all destinations. Eq. (41) ensures that the whole blocks in the optimized pit are completely extracted.

7. Conclusions and future work

Processing of oil sands produces huge volume of tailings, pumped to the tailings ponds and being kept there for long periods of time. Keeping the tailings in their conventional form in tailings ponds

results in many severe environmental issues. Thus, mining companies are required to take care of their tailings ponds and take the responsibility for site decommissioning before leaving the mine site. For decades in the oil sands industry, the mine plans have been scheduled independently from tailings plans. Production planning directly affects the amount of produced tailings and also the availability of material that is required for decommissioning. In this paper, a new MILP model is developed that maximizes the NPV and at the same time considers the decommissioning costs as the new term in its objective function. In addition, the result from the proposed MILP model ensures that the required material for site decommissioning is available. Suncor processing flow sheet is used to capture the mass balance relation in oil sands processing. The derived formulation to calculate the amount of tailings is verified by testing the formulation on a real data from an oil sands surface mining case. Some steps toward solving the MILP model with Lagrangian relaxation method are passed. As the future work, it is required to develop an efficient Lagrangian relaxation method to solve the proposed MILP model and validate the results. In addition to decommissioning operations, dyke construction can also be added to the model. Finally, the model can be upgraded by considering multiple pits and finding the mine production, dyke construction and decommissioning schedules accordingly for multiple pits.

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9. Appendix

[HTML documentation of the MATLAB code for tailings formulation](#)