An Integrated Model for Oil Sands Long-Term Mine Planning, Tailings and Reclamation Plans

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Abstract

Different types of tailings are the main unwanted by-products of oil sands processing. Huge volume of fresh and recycled water used in bitumen extraction process results in extensive ponds that are constructed to hold tailings slurry. Since the available area for tailings dam construction is limited to the lease area and on the other hand, oil sands operators must minimize the environmental impacts of their production, the volume and contents of tailings are important from environmental and operational points of view. Oil sands operators must include site-reclamation phase in their long-term plans and most of the reclamation materials such as inter burden or tailings sand are produced in mining or processing operations. In this paper, tailings capacity and reclamation material requirement are considered as part of the integrated long term mine planning. A mixed integer linear programming (MILP) model is developed to test the performance of mine planning model on synthetic and real oil sands data sets. Moreover, a tailings model is developed based on Clark hot water extraction method to quantify the volume of total slurry and its components produced in oil sands processing. The MILP and tailings models are coded in Matlab® and verified through testing the results for synthetic and real-case data sets. Results show that the optimum production schedule meets the capacity constraint of tailings facility and guarantees production of required reclamation material. Conclusions and next steps of the research are discussed at the end.

1. Introduction

The generated economic value runs the mining industry. Net present value (NPV) is well introduced to measure the economic value of production over the mine life time. However, there are some operational, social and environmental costs that must be considered in mine planning as well. In the mining industry, limited natural resources that contain minerals are the main source of income. Mining companies are now required to minimize the land disturbance and exploit natural resources in a responsible manner. Many of current active mines are located in remote areas, where there is either no urban population, or in some cases, just some small rural communities. Mining production in such locations brings a large number of workers and facilities into the site and changes the social and demographic patterns of the region. Hence, the industry must be aware of its responsibility to consider and also minimize the social impacts of any development and control the long-term consequences of mining production.

The oil sands industry is among fast growing industries in North America. Boreal forests of Northern Alberta cover most of world's bitumen resources. An 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

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rigorous extraction treatment. According to the 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. 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 using hot water. Large volumes of added fresh and recycled water to bitumen purification cycle results in huge volume of slurry at the end point of the process. However, more than 80 percent of Alberta's bitumen is located deeper in sub-surface and needs to be extracted using an 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 for mining projects are addressed in the literature. Singh (2008) reviews some general environmental issues involved in mining projects, such as land use, socio-economic impacts, public health and safety, noise and vibrations, impacts on water quality, air and dust and impacts on the site ecology. Woynillowicz et al. (2005) and Rodriguez (2007) list the environmental issues for open-pit mining and in-situ operations for oil sands production. The impacts are classified in three categories: water-related, land-related and air-quality-related impacts.

Important water-related impacts are withdrawal from surface fresh water, issues around tailings and fresh water aquifers, and water treatment waste. 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 the addition of chemicals in the extraction process, more than 90% of this amount is not returned to the river. Reduction in the flow of water may reduce the amount of available habitat for fish and other aquatics. In addition to fresh water withdrawal, holding and treatment of tailings causes other group of environmental issues. Tailings is the slurry of water, bitumen, sand, silt and fine clay that is produced from the bitumen extraction process. It is pumped into tailings ponds, while still includes portions of bitumen that are not captured in purification process. 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 aquatic life, nearby plants and migratory birds landing on tailings ponds. Furthermore, both of oil sands operation methods influence freshwater aquifers by decreasing the water pressure in the region of mining pit (surface mining) or horizontal wells (SAGD). This may cause water to "leak down" from aquifers closer to the subsurface to operation regions. As the result, the groundwater is discharged to lakes, wetlands and streams, bringing down the level of water table (drawdown effect). Moreover, a considerable portion of water used in bitumen extraction process is the recycled water. Produced solid waste from saline water recycling is another issue in oil sands production. The solid waste is injected into disposal wells or dumped into landfills that cause other environmental issues around the proliferation of waste disposal facilities.

Land-related impacts of oil sands production include disturbing the boreal forests, landscape reclamation and erosion. 30% of Canada's land is covered by boreal forests, which contain 35% of world's wetlands and provide habitat for many important wildlife species. Most of the Alberta oil sands deposits are found under these forests. Oil sands operators have disturbed the landscape and groundwater drastically. In the case of surface mining, large land-clearings, noise and human presence are resulted in less presence of wildlife in the area. In SAGD operations, the dense network of roads, power line corridors, pipelines and seismic lines has fragmented the habitat and divided it into 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. Land peaces affected by oil sands development must be reclaimed to an "equivalent land capability" prior 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. Erosion is the other consequence of oil sands production. In order to get access to the minerals, in most cases it is necessary to remove the vegetation and thin fertile surface soil. Stripping in surface mining happens on a large scale, and in addition to construction of access roads, results in extensive vegetation loss in natural landscape. Since the plants' roots protect the soil, absence of vegetation increases the rate of erosion.

The most important air-quality-related impacts of oil sands production is the emission from purification process. Alberta has been ranked number one for air releases from industrial sources among Canadian provinces in 2003 (Pollution-watch, 2003). The main source of Alberta's industrial emissions is the oil sands industry. Criteria Air Contaminants (CACs) including sulfur dioxide (SO2), nitrogen oxides (NOx), particular 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. Pollutant emission rate is much higher in bitumen recovery process than conventional oil refinery process, because there are many more steps involved in producing synthetic crude oil from oil sands comparing conventional oil production. Dust and emission from mining operation is another source of air pollution in oil sand production. Drilling and blasting operations generate and spread dust into the air. In addition, the construction of access roads in early stages of mine-life, loading and hauling operations, emissions from mining machinery, and dried tailings are other sources for dust generation.

Sustainable mining concept is developed to include environmental aspects of mineral production in mine planning and design. Determining what environmental issues should be considered in decision making and how should they be embedded in the problem is a key point in sustainable mining practice. Environmental impacts may influence mining problem in two different - but related - categories: mine design and mine planning. Mine design includes a group of techniques that determine the overall configuration of the mine, e.g. optimal pit limit, at the end of mine life. An "environmental cost" is usually defined to include environmental aspects of the mine design (Rodriguez, 2007). On the other hand, the goal of mine planning is to optimize production schedule in such a way to extract the entire material out of the designed pit. An optimized mine planning maximizes the NPV over the mine's life time, subject to different sets of constraints, including precedence between mining blocks/cuts, mining and processing capacities and average head grade requirements for processing plant. To decide whether an environmental issue can be included in mine planning or not, it is essential to determine if there is a valid relation between that issue and the block model. As an example, extracting and processing each block generates specific amount of waste, either as waste rock or tailings. Therefore, the mine planning may include waste volume as a constraint by defining proper decision variables and coefficients to calculate the generated waste volume from extraction of each block.

Among the proposed list of environmental impacts, there are potentials for two of issues to be included in mine planning: the volume of generated tailings and the foot print of mining operation on the landscape. These two environmental impacts are considered in the integrated mine planning model in this paper. Tailings model determines the relation between tonnage of processed ore and the generated tailings volume corresponding to the processed material.

The rest of this paper is organized as follows: the problem is defined in section 2. Related literature to this problem is reviewed in section 3. The theoretical framework is discussed in section 4, including the tailings model and the mathematical formulation. A case study and its results are presented in section 5. Finally, the conclusions and next steps of the research are discussed in section 6.

2. Problem definition

Different environmental costs are considered to find the optimal pit limit in mine design phase in recent years (Odell, 2004; Rodriguez, 2007). Moreover, there have been many works addressing the maximization of NPV in mine planning(Askari-Nasab & Awuah-offei, 2009; Askari-Nasab, Pourrahimian, Ben-Awuah, & Kalantari, 2011; Askari-Nasab, Tabesh, & Badiozamani, 2010). In addition to pure mine planning and mine design, tailings plan is also included in some models (Ben-Awuah & Askari-Nasab, 2011). However, the critical aspect of mine planning is a merger between all these areas: profit maximization with respect to tailings plan and reclamation costs.

A good example of reclamation plan is what Shell Canada proposes in fulfillment of Directive 074 (McFadyen, 2008). Shell Canada has considered dedicated disposal areas (DDA) for JackPine Mine (JPM) and Muskeg River Mine (MRM) sites at Athabasca river region in Alberta. JPM includes an in-pit tailings facility, while MRM has external tailings dams. However, Shell has the same reclamation plan in both cases. Each tailings facility is consisted of multiple cells adjacent to each other. Thickened tailings (TT) is discharged into the cells consecutively, meaning that the cells receive TT in the order of their location, e.g. west to east. The cell that receives the discharge earlier is considered to be the first DDA and after a certain period of time, it changes into a dried and reclaimed landscape. Then, reclamation starts in the next cell. The drainage system is designed in such a way that any flow of surface water from DDA is discharged to the next cell. Fig. 1illustrates the layout of JPM (Shell-Canada, 2011).

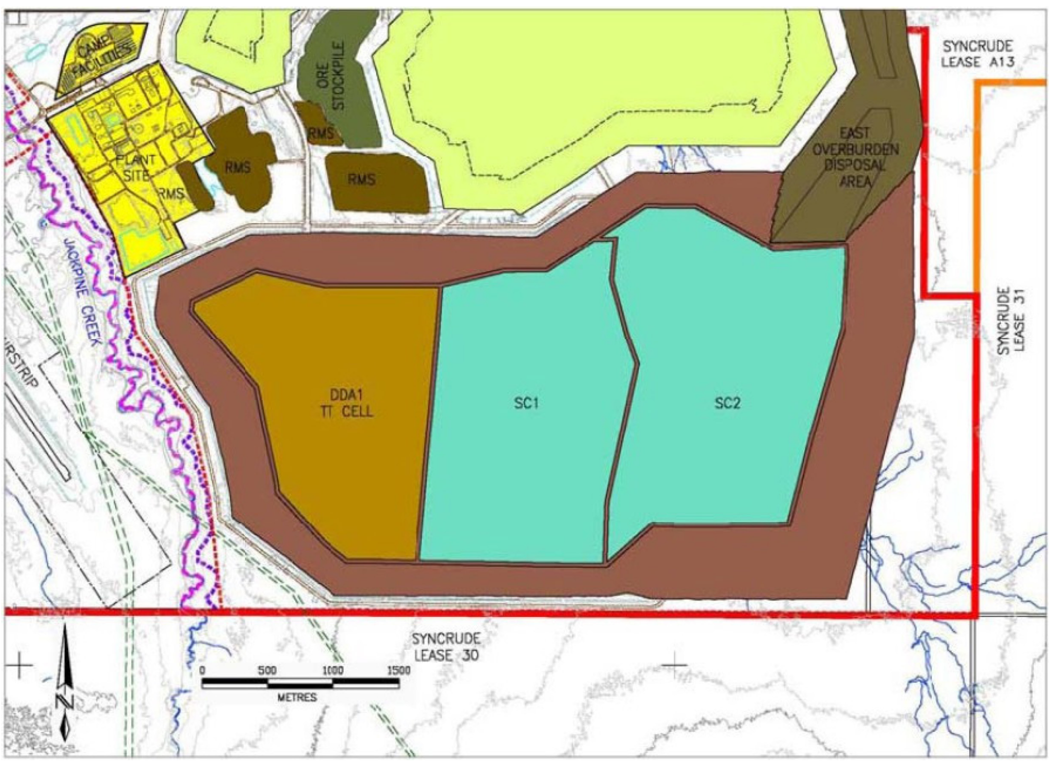

Fig. 1. Layout of dedicated disposal area 1 within the JPM ETF
(from Shell Canada report).

Shell considers three main phases in its plan for decommissioning of the external tailings facility, including construction, operations and closure. All three phases have ties to mine planning. For example, waste material that is produced in extraction operations is used for the preparation of a starter dyke, external dyke walls and upstream dyke (construction phase). Thickened tailings (TT), centrifuge cake manufacturing and coarse sand tailings (CST) are the by-products of processing and are used in filling and capping activities (operations phase). Moreover, the over burden and cover soil that is removed in pre-stripping stages is used later for capping activities (closure phase). Thus, any change to mine production plan changes the amount of produced tailings and required material for reclamation. Table 1 summarizes the steps of reclamation for an external tailings facility in JPM site (Shell-Canada, 2011).

Table 1. Summary of time line for decommissioning of an external 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

Considering that the required material for reclamation of tailings facility is produced in mining and processing operations, the problem is to develop an integrated long-term mine plan that includes the capacity of tailings facility and reclamation material requirement. In other words, the optimal production plan should not only maximize the NPV of the extracted oil sands, but it must satisfy the capacity constraints for holding the tailings and guarantee to provide the required reclamation materials for capping. Production and reclamation should be integrated because any delay in providing reclamation material or any additional shipment of material increases the costs and has a negative effect on the overall cash flow. Therefore, the integrated model should be capable to manage the stream of materials for reclamation.

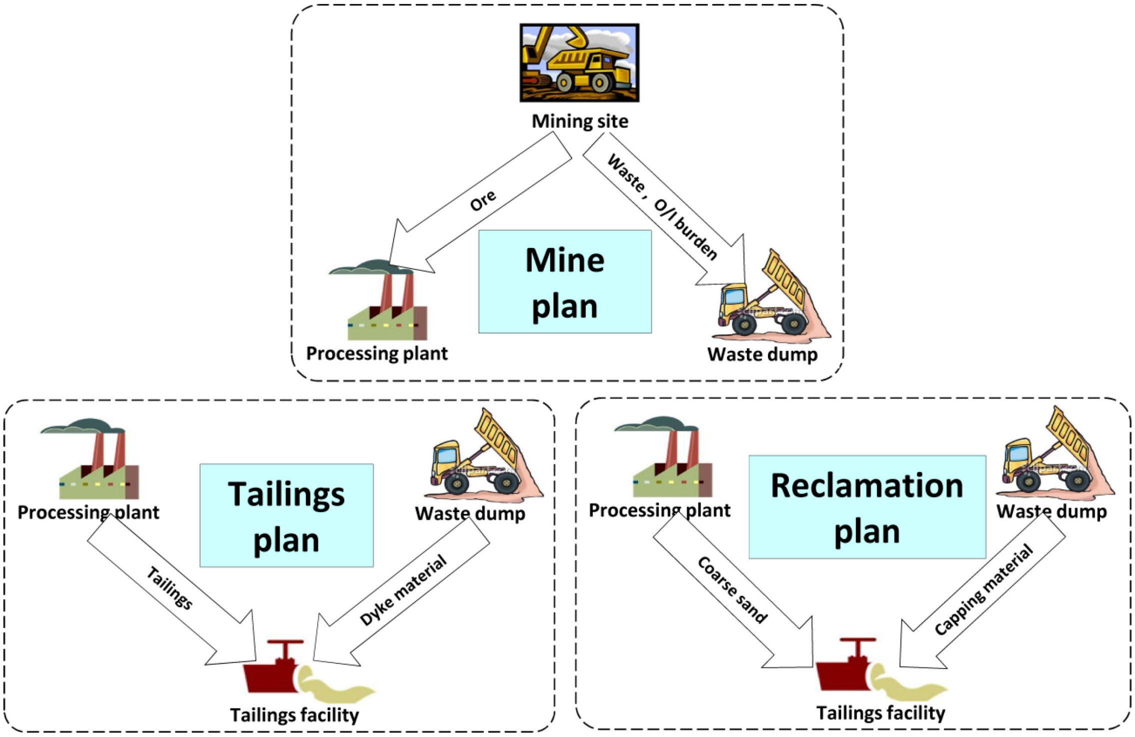

Fig. 2. An overview of traditional mine planning, tailings and reclamation plans.

Fig. 2 presents a schematic overview of conventional mine planning. The organization of a typical MILP model that maximizes the NPV with respect to mining and processing constraints is as follows:

Maximize (NPV)

Subject to:

Processing plant constraints

Mining capacity constraints

Extraction precedence constraints

In an integrated mine planning, in addition to the typical constraints, the costs and constraints for reclamation material requirements are included in the model. Decision variables are revised in such a way that sending portions of extracted material to different destinations becomes possible. Limited capacity for tailings facilities is also taken into account in the integrated model. Therefore, new objective function terms and also some constraints are added to the previous version of MILP model to include tailings capacity, reclamation material requirement and reclamation cost. The organization of the revised MILP is as follows:

Maximize (NPV – reclamation costs)

Subject to:

Processing plant constraints

Mining capacity constraints

Extraction precedence constraints

Tailings capacity constraints

Reclamation material requirement constraints

A schematic overview of integrated mine planning model is illustrated in Fig. 3.

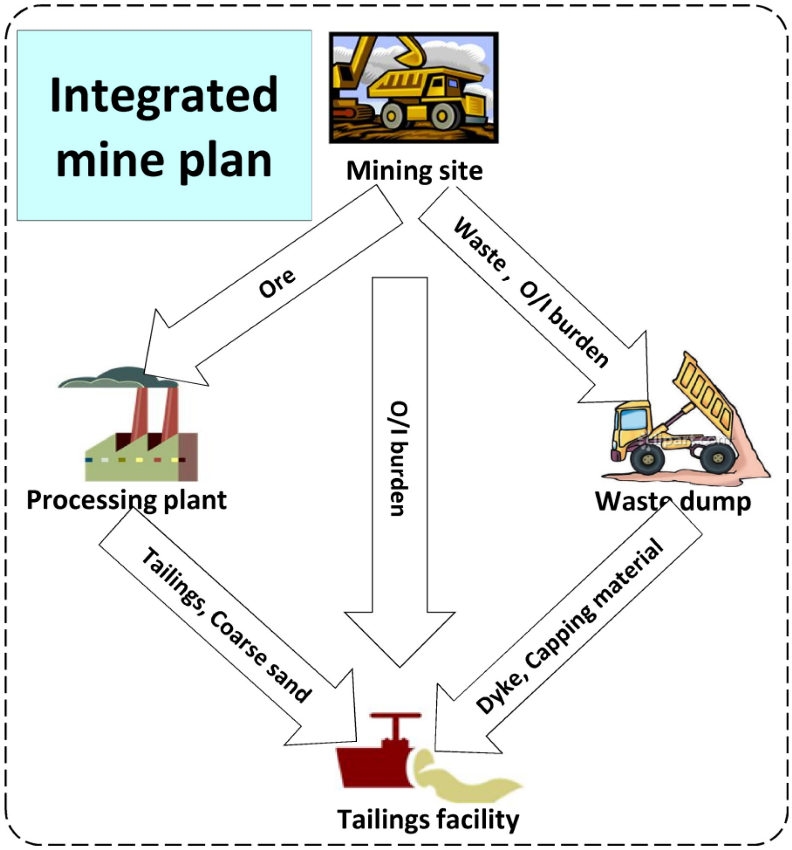

Fig. 3. An overview of integrated mine planning.

3. Literature review

In the literature, two groups of methods are used to evaluate sustainability in mining industry: descriptive (qualitative) and quantitative methods. Descriptive approaches are based on various reports that point to environmental conditions and concerns in mining projects. Some of these reports are prepared voluntarily by mining companies to show differences from others in the market in terms of environmentally clean practices. However, in some cases the companies must publish a report of their practices in fulfillment of regulations imposed by governments or regional authorities. On the other hand, in quantitative approaches the target is to quantify some measures that are originally qualitative, and to provide quantitative results to assess the situation of mining companies.

As an example of qualitative work, Sinding (1999) reviews environmental management and communication tools in mining industry. The author discusses the specifications of environmental management tools, such as environmental management systems, environmental impact assessment, life cycle assessment and environmental accounting. Different phases in any typical mining production, including (1) mineral exploration, (2) mine development decision-making, (3) production phase, and (4) mine closure and decommissioning are reviewed. Then the author suggests proper tool for each phase.

Qualitative methods introduce some guidelines to follow sustainable mining practices. For instance, mining companies should consider a full range of environmental management and documentation for their activities. In addition, to be able to compare different mining products and determine “the cleanest” one, it is necessary to establish a global environmental reporting mechanism for the mining industry. Moreover, effective environmental management tools such as increased monitoring and post audit reviews should be included in new mining projects. A practical suggestion for implementation of such recommendations is to include environmental assessment as part of ISO 14001 for mining projects. Sinding (1999) introduces a comprehensive list of current environmental management tools. However, generality and not going into detailed quantitative measures are shortfalls of descriptive tools.

Manteiga and Sunyer (2000) modify the previous environmental evaluation methodologies to close one step to the practicality of the methods. The authors introduce a simplified three-step methodology for environmental evaluation assessment, including (1) establishment of an assessment framework, (2) assessment of the environmental situation and (3) environmental assessment. Indicators are defined to measure the final results of each step. However to use these indicators practically, the authors suggest that greater efforts are required. The efforts by both environmental authorities who define indicators and mining sector that is responsible for recording precise data of the indicators are critical in successfulness of the methodology.

Quantitative approaches include the second class of methods in sustainable mining literature. Social and environmental impacts in mining industry are considered quantitatively through different approaches. In some cases, environmental issues are included in the designing phase of a mining project. Rodriguez (2007) develops a heuristic algorithm and defines a new term, environmental cost (EC), that is added to other mining and processing costs. EC covers a variety of costs regarding environmental issues, such as drilling and blasting, pit excavation, waste rock dumping, tailings disposal and decommissioning. Estimations of EC and other mining and processing costs are deducted from the economic block value (EBV), and the revised EBV is used to find the pit limit for open pit mine design problem 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 include sustainability in mine design. Sustainability primer methodology is based on multi-criteria analysis (MCA), also known as multiple accounts evaluation (MAE). MCA is consisted of some distinct approaches, but the basis for all of them is the same; defining different scenarios (options) and assess each scenario through a number of explicit criteria (indicators). Assessment of scenarios is typically done in MCA tables. However, MCA approach is a good choice if (1) time and financial resources are available, (2) supporting data is available and sufficient, (3) project team is expert in analyzing tables, and (4) the number of decision options are determined (finite or infinite). MCA methodology is applied for an open pit copper mine in Peru. For this case, MCA seems to be the proper choice, since the decision context in the case study shows a high complexity and a wide range of interested stakeholder groups. Different aspects of mining projects, including social and environmental issues, are considered in assessment of multiple scenarios by employing MCA tables. The author suggests to refine new packages of holistic mine design tools to include the social and environmental impacts of the mining projects in mine designing.

MCA approach is a powerful tool and is suitable in the development of new packages for mining projects assessment (Odell, 2004). However, it is a scenario-based approach. To form MCA tables, it is essential to have (1) certain scenarios as table columns and (2) a variety of indicators representing different engineering, economic, social and environmental criteria as table rows. Therefore, MCA is a useful tool for general decision-making in feasibility study stages when there are several scenarios on the table and pre-estimations for different indicators under each scenario are available.

Fuzzy logic is another powerful tool that is used to quantify descriptive values. Many environmental impacts are described qualitatively. Moreover in many cases, it is necessary to have judgment of an expert to assess quantitative indicators. Expert judgment changes the quantitative nature of an indicator to qualitative. Fuzzy logic, membership functions and fuzzy sets are strong tools in transforming the fuzzy nature of environmental variables to crisp values. Shepard (2005) discusses the implementation of fuzzy logic in quantification of environmental impact assessment. The author reviews the traditional approach of environmental impact assessment and introduces fuzzy logic as successful approach in quantification of environmental impacts.

As the summary of environmental impact assessment literature, it turns out that in most of current literature, the focus is on qualitative approaches rather than quantitative ones. In few works, environmental impacts are discussed quantitatively. However, the scope of current quantitative approaches is mine design, not mine planning. Although current mine planning models are relatively comprehensive, but they are prepared separately from tailings and reclamation plans. The missing part in mine planning literature is the merger between conventional long term mine planning, tailings and reclamation plans. Such integrated mine planning model maximizes the NPV with respect to the amount of produced tailings as the main environmental issue in oil sands industry and at the same time, considers reclamation of the mine site to minimize the mining foot prints resulted from tailings ponds.

4. Theoretical framework

Two concepts that are investigated and developed in this research are advancement in precedence definition and tailings calculations. Therefore, prior to proposition of mathematical model, it is essential to discuss about directional mining and tailings model.

4.1. Directional mining

Vertical precedence relation between blocks is well introduced and implemented in mine planning models (Askari-Nasab, et al., 2011). Except for the very first level of blocks on top of the pit (first bench), it is assumed that there are nine blocks on top of each block in a regular grid. It is assumed that all of these nine blocks must be extracted prior to get access to the block under. Pit slope is controllable by changing the number of vertical precedence blocks on top. A schematic configuration of vertical precedence is illustrated in Fig. 4(a).

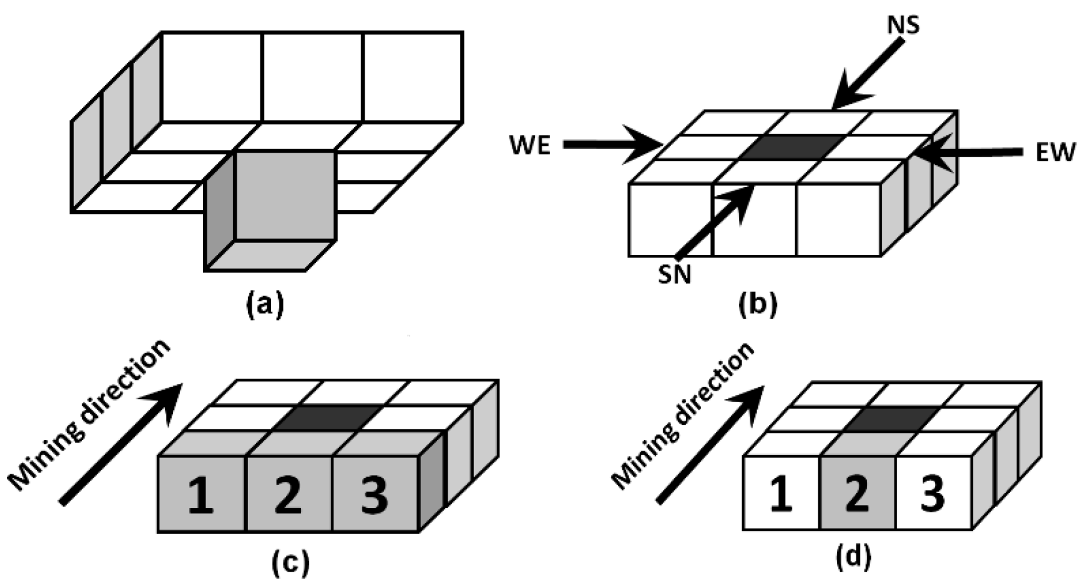

Fig. 4. Block precedence in vertical (a) and horizontal (b, c and d) directions.

In many applications such as in oil sands mining, defining vertical precedence does not guarantee a feasible practical solution from mining point of view. In addition to the vertical precedence, horizontal precedence also must be defined and introduced to the model to have a practically feasible optimal solution. In some case of oil sands surface mining, it is essential to clear the pit completely from one side and push the mining face forward in a specific direction so that after few periods, tailings can be pumped into the excavated empty pit (in-pit tailings facility). Directional mining includes group of mining problems with a specific horizontal direction. Many different horizontal directions can be defined for any problem. However, there are eight main directions, including four in east-west and north-south directions and opposites, and four in north_east-south_west and north_west-south_east directions and their opposites. Four of directions are illustrated in Fig. 4(b).

Fig. 4(c) shows an example of horizontal precedence relation in west-east direction. Block numbers 1, 2 and 3 must be extracted completely to access the shaded block in centre (block number 5). In other words, blocks 1, 2 and 3 are horizontal predecessors for block 5. However in a simplified version of horizontal precedence, block 2 is assumed to be the only horizontal predecessors for block 5, as illustrated in Fig. 4(d). This assumption decreases the number of precedence relations and hence, reduces the number of precedence constraints which means a decrease in the problem size. Despite of the fact that it seems this assumption will result in narrow mining in one direction, test results show that it does not happen to the problem. The reason is that vertical precedence is in effect at the same time, which only allows extracting those blocks whose top blocks are completely mined out. When vertical and horizontal precedence work together, the results look reasonable.

For the sake of practicality, blocks are aggregated to mining cuts as the input into the MILP model (Tabesh & Askari-Nasab, 2011). This means that any precedence must be defined between mining cuts, not blocks. Knowing that each block belongs to which mining cut, it is easily possible to map block precedence to cut precedence. Since all mining cuts do not have regular shapes, they are not in a regular grid. However, if a horizontal or vertical precedence can be defined between any of blocks within two cuts, then a precedence relation is defined for cuts. An example of horizontal precedence between mining cuts is presented in Fig. 5(a). Block “a” precedes block “b” in west-east mining direction. Therefore, mining cut “A” which includes block “a” is the predecessor for mining cut “B” which includes block “b”. The same precedence relation can be defined for mining cuts “A” and “D” in vertical direction, as presented in Fig. 5(b).

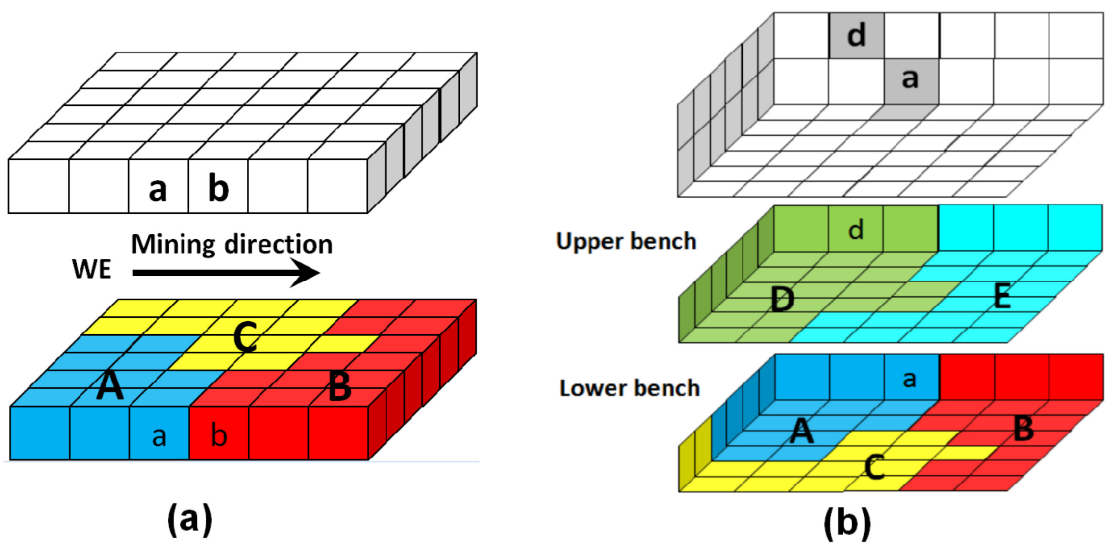

Fig. 5. Cut precedence in horizontal (a) and vertical (b) directions.

There is one more step in precedence definition; pushback precedence. Any mining pit is partitioned in a number of pushbacks. Currently, pushbacks are defined based on some increments in the revenue factor associated with selling price of the ore. In practice, these smaller pit subsets are used in mine planning. A good example that shows necessity of pushback precedence is in-pit tailings facility. In order to guarantee that the pit is completely cleared from one side and the surface is pushed in a specific horizontal direction, it is needed to define precedence between pushbacks. This precedence lets mining to start in a pushback only when its precedent pushback is completely extracted and cleared. Precedence relation between pushbacks can be defined in couple of ways. Fig. 6 shows the way that pushback precedence is defined in this paper.

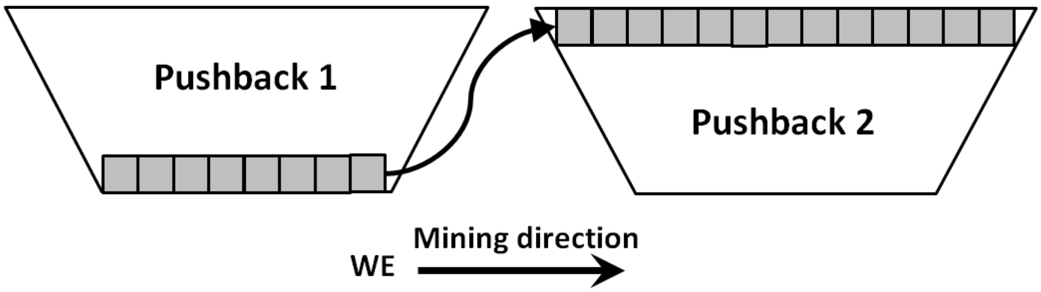

Fig. 6. Pushback precedence.

Supposing that pushback 1 is predecessor of pushback 2 in this specific mining direction, all the mining cuts at the bottom of pushback 1 are defined as predecessor for all the mining cuts at the very top bench in pushback 2. This set of new precedence is called pushback precedence and is added to the precedence list.

4.2. Tailings model

For the integrated mine planning, it is essential to have an estimate for the volume and tonnage of total tailings and its components that are produced as a result of oil sands processing in surface mining. In this paper, Suncor's flow sheet is used to find the mass-balance relationship between ore feed and tonnage of the total ponded slurry tailings, total sand, water and fine material (Suncor, 2009). Some operational assumptions are considered in this flow sheet, based on what Suncor applies for its hot water extraction process. A schematic view of a related part from Suncor's oil sands processing flow diagram is illustrated in Fig. 7.

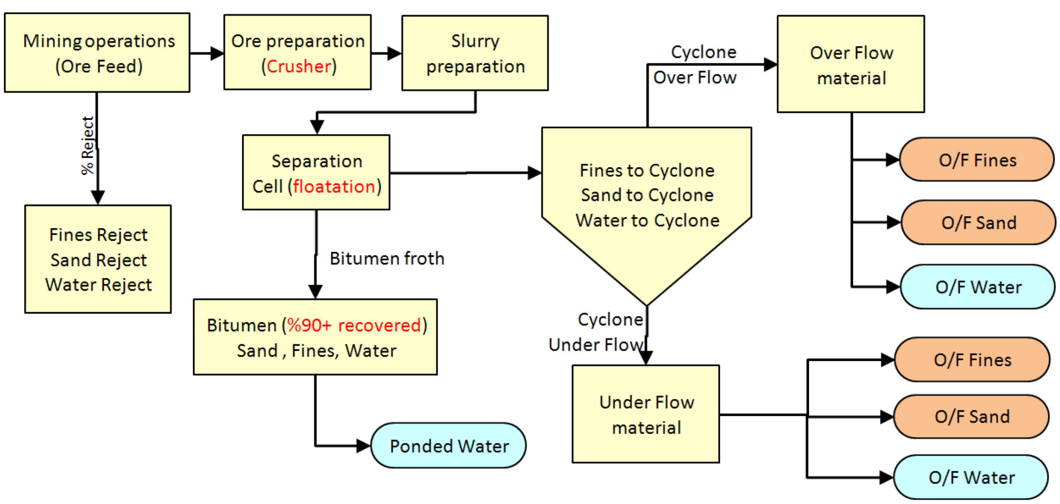

Fig. 7. Part of Suncor flow diagram for Clark hot water extraction process.

In this paper, the focus is on three main streams that produce the tailings. The first one that feeds the largest portion of the tailings material is the over flow slurry. The second and third ones are the under flow and the bitumen froth treatment streams. The tailings components for each of streams are illustrated in Fig. 7. For the sake of simplification, more details from the flow sheet, regarding composite tailings (CT) and mature fine tailings (MFT) are not included in this paper.

The total volume of produced tailings is calculated as in Eq. (1).

$$V_{Tailings} = V_{Overflow} + V_{Underflow} + V_{Bitumen\ froth} \tag{1}$$

The total volume of fines, sand and water are calculated as in Eqs. (2), (3) and (4).

$$V_{Fines} = V_{Fines}^{Overflow} + V_{Fines}^{Underflow} \tag{2}$$

$$V_{Sand} = V_{Sand}^{Overflow} + V_{Sand}^{Underflow} \tag{3}$$

$$V_{Water} = V_{Water}^{Overflow} + V_{Water}^{Underflow} + V_{Water}^{Bitumenfroth} \tag{4}$$

In this paper, the focus is on three main streams that produce slurry and water, ending in the tailings pond. The first one, which feeds the largest portion of the tailings material, is the over flow slurry. The second one is underflow slurry and finally the third one, is the pond water from bitumen froth treatment. These three parts are illustrated in Fig. 7. More detail flow sheet includes processes for preparation of composite tailings (CT) and mature fine tailings (MFT). However, at this stage CT and MFT are not considered in tailings model.

The following notation is used in tailings calculation:

4.2.1. Parameters

$Sd\%_{UF}$: Sand content of the underflow

$Sl_{solid\%}$: Solid percent of slurry 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 fine 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 (%)

4.2.2. Input variables

M^{O}_{Feed} : 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 (%)

4.2.3. Outputs

$M^{Overflow}_{ponded}$: Mass of total overflow ponded material

$M^{Underflow}_{ponded}$: Mass of total underflow ponded material

M^{W}_{ponded} : Mass of total ponded water from bitumen froth treatment

M^{slurry}_{ponded} : Mass of total ponded slurry

Eq. (5) is used to calculate the water content of the processing plant feed (Masliyah, 2010).

$$W_{Feed} = 0.75 \times F_{Feed} + 2.3 \tag{5}$$

The total tonnage of ponded slurry is calculated as in Eq. (6) and consists of three parts, the overflow slurry, the underflow slurry and the ponded water as the downstream product of bitumen froth treatment.

$$M^{Slurry}_{ponded} = M^{Overflow}_{ponded} + M^{Underflow}_{ponded} + M^{W}_{ponded} \tag{6}$$

As an example of tailings formulation, the overflow slurry, M^{W}_{ponded} , and the ponded water from bitumen froth treatment, $M^{Overflow}_{ponded}$, are presented as Eqs. (7) and (8), respectively.

$$M^{W}_{ponded} = \left(\frac{\left(B_{Feed} - Rj\% \times Rj\%_{B} \right) \times M^{O}_{Feed} \times R}{B\%_{SET}} \right) \times \left(\begin{array}{l} W\%_{SET} - \dfrac{Sd\%_{SET}}{\left(1 - F\%_{Beach}\right) \times BDD} \\ + \dfrac{Sd\%_{SET}}{SG_{s}} + \dfrac{Sd\%_{SET} \times F\%_{Beach}}{\left(1 - F\%_{Beach}\right) \times SG_{f}} \\ + \left(\dfrac{S\%_{MFT} - 1}{S\%_{MFT}} \right) \\ \times \left(\dfrac{F\%_{SET} \times \left(1 - F\%_{Beach}\right) - Sd\%_{SET} \times F\%_{Beach}}{\left(1 - F\%_{Beach}\right)} \right) \end{array} \right) \tag{7}$$

$$M_{ponded}^{Overflow} = M_{Feed}^{O} \times \left(\begin{array}{l} \left(1 - B_{Feed} - W_{Feed}\right) \times \left(\begin{array}{l} -\dfrac{1 - F_{Feed}}{UF_{Sd\%}} \times \left(UF_{F\%} + UF_{W\%}\right) \\ \times Sd\%_{UF} \\ -\left(1 - F_{Feed}\right) \times Sd\%_{UF} \\ +\dfrac{1}{Sl_{solid\%}} \end{array} \right) \\ +\left(B_{Feed} - Rj\% \times Rj\%_{B}\right) \times \dfrac{R}{B\%_{SET}} \\ \times \left(\begin{array}{l} \dfrac{Sd\%_{SET} \times Sd\%_{UF}}{UF_{Sd\%}} \times \left(UF_{F\%} + UF_{W\%}\right) \\ +Sd\%_{SET} \times Sd\%_{UF} - \dfrac{F\%_{SET}}{Sl_{solid\%}} - \dfrac{Sd\%_{SET}}{Sl_{solid\%}} \end{array} \right) \\ +Rj\% \times \left(\begin{array}{l} \dfrac{Rj\%_{Sd} \times Sd\%_{UF}}{UF_{Sd\%}} \times \left(UF_{F\%} + UF_{W\%}\right) \\ +Rj\%_{Sd} \times Sd\%_{UF} - \dfrac{Rj\%_{F}}{Sl_{solid\%}} - \dfrac{Rj\%_{Sd}}{Sl_{solid\%}} \end{array} \right) \end{array} \right) \quad (8)$$

4.2.4. Verification of tailings model

In order to check the results from the formulations, the tailings tonnage is calculated for an optimized long-term mining production case. The final pit limit for the case contains 61,490 blocks of 50 by 50 by 15 meters and the production is scheduled for 19 periods. Blocks are aggregated into 302 mining cuts. According to the presented formulation, four main input variables are required to calculate the tailings tonnage: (1) percentage of bitumen content, (2) percentage of fines content, (3) tonnage of ore in extracted portion, and (4) percentage of water content of each block. The first two inputs already exist 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. Finally, water content of the feed comes from Eq. (5).

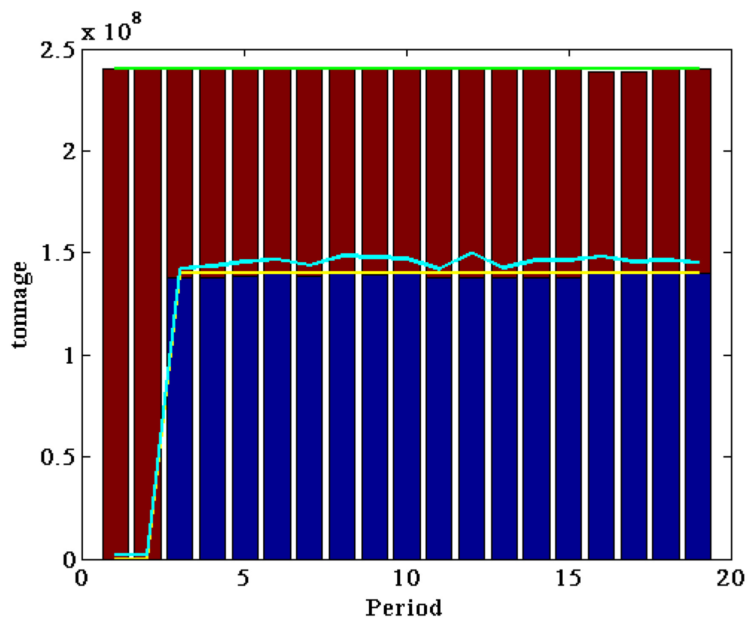

Fig. 8. Mining, processing and tailings tonnages in periods.

The tonnage 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. 8.

The horizontal lines in Fig. 8 represent the processing and mining capacities. Based on the optimal schedule, all of the extracted material in the first two periods is waste, and is sent to the waste dump (two years of pre-stripping). The bright curve represents the amount of tailings that is produced in each period. The presented formulation is used to determine 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 find the total amount of tailings in each period.

To double-check the result of the formulation, the tailings tonnage is also calculated using a second method. In this method, the tailings tonnage is calculated for one sample block with an ore tonnage of 1000 tonnes. 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 tailings tonnages resulting from the two methods are 1.25%, 1.40% and 1.32%, respectively. This shows that the two methods result in almost the same tailings tonnages and formulation are working well. The differences between the results from the first and the second methods for the 17 periods are compared in Fig. 9.

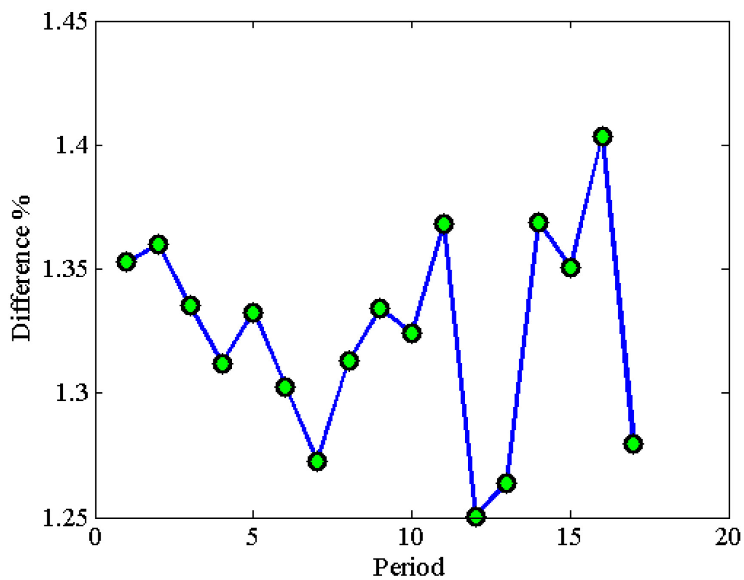

Fig. 9. Difference percentage for two tailings calculation methods.

4.3. The mixed integer linear programming (MILP) model

The long-term mine production scheduling problem is formulated using mixed integer linear programming. The formulated model for the strategic production and operational reclamation material scheduling problem has an objective function and number of constraints. The materials used for reclamation purposes in oil sands surface mining - overburden, inter burden and coarse sand material - are all from the block model. However, the cost relating to each portion is different. In reality, due to the different activities associated with dumping, reloading and hauling of each type of material, there are different costs for each portion. Therefore, different decision variables and cost coefficients are defined in the mathematical model to differentiate portions of each block.

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

4.3.1. Sets

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

$J = \{1,...,J\}$ Set of all phases (push-backs) in the model.

$U = \{1,...,U\}$ Set of all material destinations in the model.

$C_k(L)$ For each mining-cut *k*, there is a set $C_k(L) \subset \boldsymbol{K}$ 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 $M_k(P) \subset \boldsymbol{K}$ 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 $B_j(H)$.

4.3.2. Indices, subscripts and superscript

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

$t \in \{1,......,T\}$ Index for periods.

$k \in \{1,......,K\}$ Index for mining-cuts.

$e \in \{1,......,E\}$ Index for elements of interest in each mining-cut.

$j \in \{1,......,J\}$ Index for phases (pushbacks).

$u \in \{1,......,U\}$ Index for material destinations.

D,S,M,P subscripts and superscripts for overburden and inter burden material, tailings sand, mining and processing respectively..

4.3.3. Parameters

$d_k^{u,t}$ Discounted profit obtained by extracting mining-cut *k* and sending it to destination *u* in period *t*.

$r_k^{u,t}$ 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*.

$n_k^{u,t}$	Extra discounted cost of mining the over/inter burden material of the mining-cut k in period t and sending it for reclamation in destination u.
$m_k^{u,t}$	Extra discounted cost of producing tailings sand from mining-cut k in period t and sending it for reclamation in destination u.
$q_k^{u,t}$	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	Average grade of element e in the ore portion of mining-cut k.
$\underline{g}^{u,t,e}$	Lower bound on the required average head grade of element e in period t at processing destination u.
$\overline{g}^{u,t,e}$	Upper bound on the required average head grade of element e in period t at processing destination u.
f_k^o	Average percentage of fines in the ore portion of mining-cut k.
$\underline{f}^{u,t,o}$	Lower bound on the required average fines percentage of ore in period t at processing destination u.
$\overline{f}^{u,t,o}$	Upper bound on the required average fines percentage of ore in period t at processing destination u.
f_k^c	Average percentage of fines in the over/inter burden reclamation material portion of mining-cut k.
$\underline{f}^{u,t,c}$	Lower bound on the required average fines percentage of over/inter burden material in period t at reclamation destination u.
$\overline{f}^{u,t,c}$	Upper bound on the required average fines percentage of over/inter burden material in period t at reclamation destination u.
o_k	Ore tonnage in mining-cut k.
w_k	Waste tonnage in mining-cut k.
d_k	Over/inter burden material tonnage in mining-cut k.
l_k	Tailings sand material tonnage in mining-cut k.
t_k	Tailings tonnage produced downstream from extracting all of the ore from mining-cut k.
T_{Mu}^t	Upper bound on mining capacity (tonnes) in period t.
T_{Ml}^t	Lower bound on mining capacity (tonnes) in period t.
$T_{Pu}^{u,t}$	Upper bound on processing capacity (tonnes) in period t at destination u.
$T_{Pl}^{u,t}$	Lower bound on processing capacity (tonnes) in period t at destination u.
$T_{Cu}^{u,t}$	Upper bound on over/inter burden reclamation material requirement (tonnes) in period t at destination u.
$T_{Cl}^{u,t}$	Lower bound on over/inter burden reclamation material requirement (tonnes) in period t at destination u.

$T_{Nu}^{u,t}$	Upper bound on tailings sand reclamation material requirement (tones) in period t at destination u.
$T_{Nl}^{u,t}$	Lower bound on tailings sand reclamation material requirement (tones) in period t at destination u.
$T_{Tu}^{u,t}$	Upper bound on capacity of tailings facility (tones) in period t at destination u.
$T_{Tl}^{u,t}$	Lower bound on capacity of tailings facility (tones) in period t at destination u.
$r^{u,e}$	Proportion of element e recovered (processing recovery) if it is processed at destination u.
$p^{e,t}$	Price of element e in present value terms per unit of product.
$cs^{e,t}$	Selling cost of element e in present value terms per unit of product.
$cp^{u,e,t}$	Extra cost in present value terms per tonne of ore for mining and processing at destination u.
$cl^{u,t}$	Extra cost in present value terms for mining and shipping a tonne of over/inter burden material for reclamation at destination u.
$cu^{u,t}$	Extra cost in present value terms for mining and shipping a tonne of tailings sand material for reclamation at destination u.
cm^{t}	Cost in present value terms of mining a tonne of waste in period t.

4.3.4. 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 over/inter burden material from mining-cut k to be extracted and used for reclamation 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 reclamation 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, over/inter burden material, tailings sand 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.

4.3.5. Modeling of economic mining-cut value

The objective function of the MILP model is to maximize the net present value of the mined bitumen, including the operation-related portion of the reclamation costs. The concept of economic mining-cut value is based on ore parcels within mining-cuts that 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 reclamation at a specified destination. The cost of reclamation is also a function of the location of the tailings facility being constructed and the type and quantity of over/inter burden and tailings sand material that is used. 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, et al., 2011). In this paper, two new terms are considered in calculation of economic mining cut value in addition to the previous terms; the extra discounted cost of mining over/inter burden (OI) and tailings sand (TS) material for reclamation. This has been simplified into Eqs. (9) to (13).

$$d_k^{u,t} = r_k^{u,t} - q_k^{u,t} - n_k^{u,t} - m_k^{u,t} \qquad \forall t \in \{1,...,T\},\ u \in \{1,...,U\},\ k \in \{1,...,K\} \tag{9}$$

Where:

$$r_k^{u,t} = \sum_{e=1}^{E} o_k \times g_k^e \times r^{u,e} \times \left(p^{e,t} - cs^{e,t}\right) - \sum_{e=1}^{E} o_k \times cp^{u,e,t} \qquad \forall t \in \{1,..,T\}, u \in \{1,..,U\}, k \in \{1,..,K\} \tag{10}$$

$$q_k^t = \left(o_k + d_k + w_k\right) \times cm^t \qquad \forall t \in \{1,..,T\}, k \in \{1,..,K\} \tag{11}$$

$$n_k^{u,t} = d_k \times cl^{u,t} \qquad \forall t \in \{1,..,T\}, u \in \{1,..,U\}, k \in \{1,..,K\} \tag{12}$$

$$m_k^{u,t} = l_k \times cu^{u,t} \qquad \forall t \in \{1,..,T\}, u \in \{1,..,U\}, k \in \{1,..,K\} \tag{13}$$

4.3.6. The MILP formulation

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 reclamation cost. These are represented by Eqs. (14) and (15), respectively.

$$Max \sum_{u=1}^{U} \sum_{t=1}^{T} \sum_{j=1}^{J} \left(\sum_{k \in B_j} \left(r_k^{u,t} \times x_k^{u,t} - q_k^t \times y_k^t \right) \right) \tag{14}$$

$$Min \sum_{u=1}^{U} \sum_{t=1}^{T} \sum_{j=1}^{J} \left(\sum_{k \in B_j} \left(n_k^{u,t} \times w_k^{u,t} + m_k^{u,t} \times v_k^{u,t} \right) \right) \tag{15}$$

Eqs. (14) and (15) can be combined as a single objective function, formulated as in Eq. (16).

$$Max \sum_{u=1}^{U} \sum_{t=1}^{T} \sum_{j=1}^{J} \left(\sum_{k \in B_j} \left[\left(r_k^{u,t} \times x_k^{u,t} - q_k^t \times y_k^t \right) - \left(n_k^{u,t} \times w_k^{u,t} + m_k^{u,t} \times v_k^{u,t} \right) \right] \right) \tag{16}$$

The complete MILP model comprising of the combined objective function and constraints is formulated as:

Objective function:

$$Max \sum_{u=1}^{U} \sum_{t=1}^{T} \sum_{j=1}^{J} \left(\sum_{k \in B_j} \left[\left(r_k^{u,t} \times x_k^{u,t} - q_k^t \times y_k^t \right) - \left(n_k^{u,t} \times w_k^{u,t} + m_k^{u,t} \times v_k^{u,t} \right) \right] \right) \tag{17}$$

Constraints:

$$T_{Ml}^{t} \le \sum_{j=1}^{J}\left(\sum_{k\in B_j}\left(o_k + w_k + d_k\right)\times y_k^t\right) \le T_{Mu}^{t} \qquad \forall t \in \{1,...,T\} \tag{18}$$

$$T_{Pl}^{u,t} \le \sum_{j=1}^{J}\left(\sum_{k\in B_j}\left(o_k \times x_k^{u,t}\right)\right) \le T_{Pu}^{u,t} \qquad \forall t \in \{1,...,T\},\ u \in \{1,...,U\} \tag{19}$$

$$T_{Cl}^{u,t} \le \sum_{j=1}^{J}\left(\sum_{k\in B_j}\left(d_k \times w_k^{u,t}\right)\right) \le T_{Cu}^{u,t} \qquad \forall t \in \{1,...,T\},\ u \in \{1,...,U\} \tag{20}$$

$$T_{Nl}^{u,t} \le \sum_{j=1}^{J}\left(\sum_{k\in B_j}\left(l_k \times v_k^{u,t}\right)\right) \le T_{Nu}^{u,t} \qquad \forall t \in \{1,...,T\},\ u \in \{1,...,U\} \tag{21}$$

$$\sum_{j=1}^{J}\sum_{k\in B_j} g_k^e \times o_k \times x_k^{u,t} - \overline{g}^{u,t,e}\sum_{j=1}^{J}\sum_{k\in B_j} o_k \times x_k^{u,t} \le 0 \qquad \forall t \in \{1,..,T\}, u \in \{1,..,U\}, e \in \{1,..,E\} \tag{22}$$

$$\underline{g}^{u,t,e}\sum_{j=1}^{J}\sum_{k\in B_j} o_k \times x_k^{u,t} - \sum_{j=1}^{J}\sum_{k\in B_j} g_k^e \times o_k \times x_k^{u,t} \le 0 \qquad \forall t \in \{1,..,T\}, u \in \{1,..,U\}, e \in \{1,..,E\} \tag{23}$$

$$\sum_{j=1}^{J}\sum_{k\in B_j} f_k^o \times o_k \times x_k^{u,t} - \overline{f}^{u,t,o}\sum_{j=1}^{J}\sum_{k\in B_j} o_k \times x_k^{u,t} \le 0 \qquad \forall t \in \{1,..,T\}, u \in \{1,..,U\} \tag{24}$$

$$\underline{f}^{u,t,o}\sum_{j=1}^{J}\sum_{k\in B_j} o_k \times x_k^{u,t} - \sum_{j=1}^{J}\sum_{k\in B_j} f_k^o \times o_k \times x_k^{u,t} \le 0 \qquad \forall t \in \{1,..,T\}, u \in \{1,..,U\} \tag{25}$$

$$\sum_{j=1}^{J}\sum_{k\in B_j} f_k^c \times d_k \times w_k^{u,t} - \overline{f}^{u,t,c}\sum_{j=1}^{J}\sum_{k\in B_j} d_k \times w_k^{u,t} \le 0 \qquad \forall t \in \{1,..,T\}, u \in \{1,..,U\} \tag{26}$$

$$\underline{f}^{u,t,c}\sum_{j=1}^{J}\sum_{k\in B_j} d_k \times w_k^{u,t} - \sum_{j=1}^{J}\sum_{k\in B_j} f_k^c \times d_k \times w_k^{u,t} \le 0 \qquad \forall t \in \{1,..,T\}, u \in \{1,..,U\} \tag{27}$$

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

$$\sum_{u=1}^{U}\left(o_k \times x_k^{u,t} + d_k \times w_k^{u,t}\right) \le \left(o_k + d_k\right)\times y_k^t \qquad \forall t \in \{1,..,T\}, k \in \{1,..,K\} \tag{29}$$

$$\sum_{u=1}^{U}\left(l_k \times v_k^{u,t}\right) \le \sum_{u=1}^{U}\left(o_k \times x_k^{u,t}\right) \qquad \forall t \in \{1,..,T\}, k \in \{1,..,K\} \tag{30}$$

$$\sum_{u=1}^{U}\sum_{t=1}^{T} x_k^{u,t} \leq 1 \qquad \forall k \in \{1,..,K\} \tag{31}$$

$$\sum_{u=1}^{U}\sum_{t=1}^{T} w_k^{u,t} \leq 1 \qquad \forall k \in \{1,..,K\} \tag{32}$$

$$\sum_{u=1}^{U}\sum_{t=1}^{T} v_k^{u,t} \leq 1 \qquad \forall k \in \{1,..,K\} \tag{33}$$

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

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

$$\sum_{i=1}^{t} y_k^i - b_k^t \leq 0 \qquad \forall t \in \{1,...,T\},\ k \in \{1,...,K\} \tag{36}$$

$$b_k^t - b_k^{t+1} \leq 0 \qquad \forall t \in \{1,...,T-1\},\quad k \in \{1,...,K\} \tag{37}$$

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

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

$$c_j^t - c_j^{t+1} \leq 0 \qquad \forall t \in \{1,...,T-1\},\ j \in \{1,...,J\} \tag{40}$$

$$\sum_{t=1}^{T} y_k^t = 1 \qquad \forall k \in \{1,...,K\} \tag{41}$$

Eq. (17) is the objective function of the formulation, which seeks to i) maximize the NPV and ii) minimize capping costs. Eq. (18) is the total mining capacity constraint. Eqs. (19), (20) and (21) are the capacity constraints for processing, OI and TS for capping requirements, respectively. Eqs. (22) , (23), (24), (25), (26) and (27) specify the upper and lower limit of 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 reclamation in each period does not exceed from the tonnage of extracted ore material 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) control 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 within the optimal pit are completely extracted.

5. Case study

A real oil sands data set is used to check the results of running the MILP and tailings models. The data set includes 45,648 blocks of 50 by 50 by 15 meters, aggregated into 980 mining cuts. There are two pushbacks in the case, separating by a river in between. Two destinations are considered for extracted material; processing plant and waste dump at tailings pond. The problem is solved for four horizontal mining directions and ten periods. Two sample plan views of resulted schedule for east-west and south-north directions are illustrated in Figs. 10 and 11, respectively.

Different periods are represented by colors and also period numbers in plan views. Figs. 10 and Fig. 11 show that the schedule follows pushback precedence (PB1-PB2) and mining direction in each pushback.

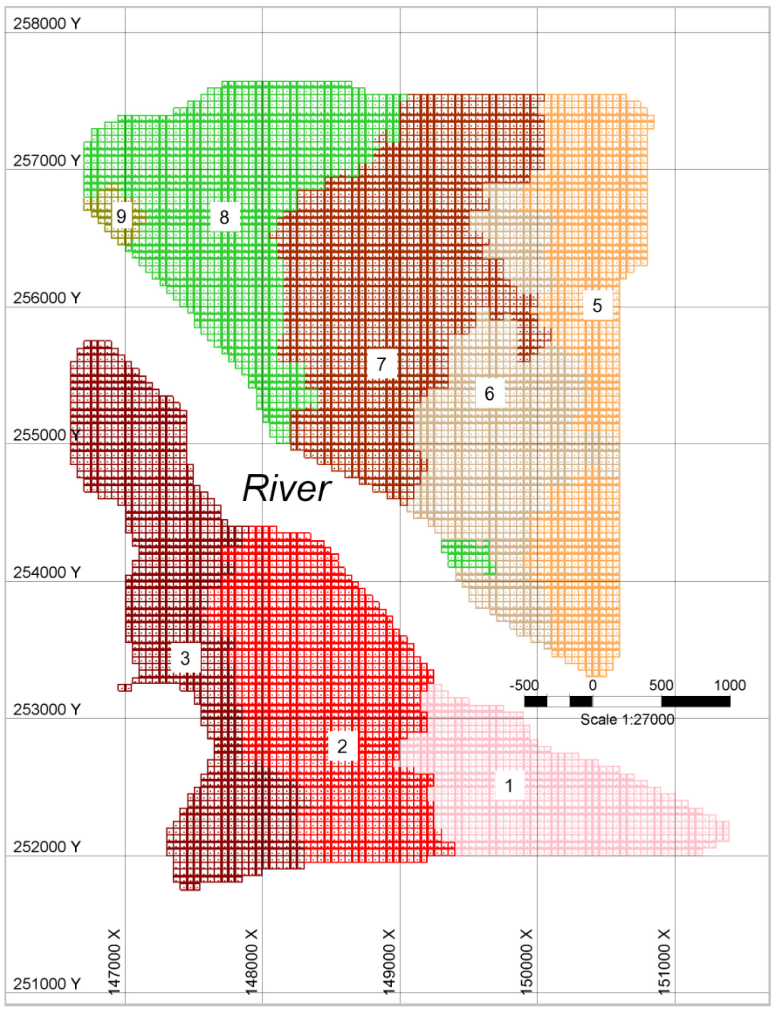

Fig. 10. Sample plan view for east-west mining direction.

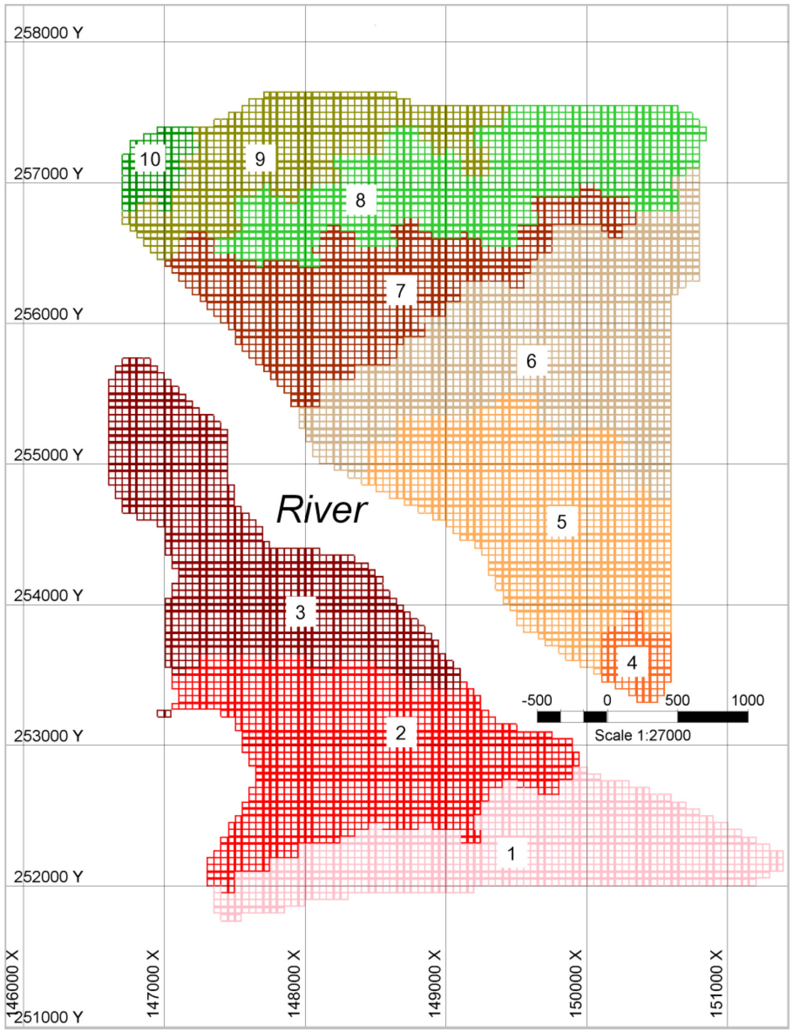

Fig. 11. Sample plan view for south-north mining direction.

To run the model for the presented case study, a MATLAB program (MathWorksInc., 2011) is developed. The code calls the TOMLAB/CPLEX (Holmström, 2009) (Holmström, 2009) to solve the MILP model. The code is executed on an Octa-core Dell Precision T7500 computer at 2.8 GHz, with 24GB of RAM. The results for four mining directions are reported in Table 2.

Table 2. Comparing model results for mining direction.

Direction	Solution gap (%)	Run time (min)	Objective function (M$)
West - East	1.86	194	23109
East – West	1.00	7	26256
South - North	1.99	5	24487
North - South	1.15	18	23998

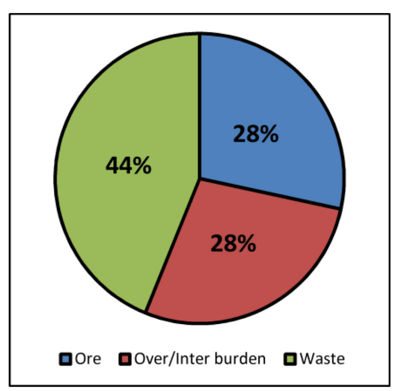

Fig. 12. Distribution of mined material for east-west direction.

Comparing the results shows that mining direction with the highest value of objective function is east-west, with the value of $26256 M. Fig. 12 shows distribution of ore, waste and over/inter burden material that is mined in east-west mining direction.

Total tonnage of mined material, including ore, waste and over/inter burden (red bars), together with total tonnage of material that is sent to processing plant (blue bars) for east-west and south-north directions are illustrated in Figs. 13 and 14, respectively. Horizontal lines represent mining and processing capacities.

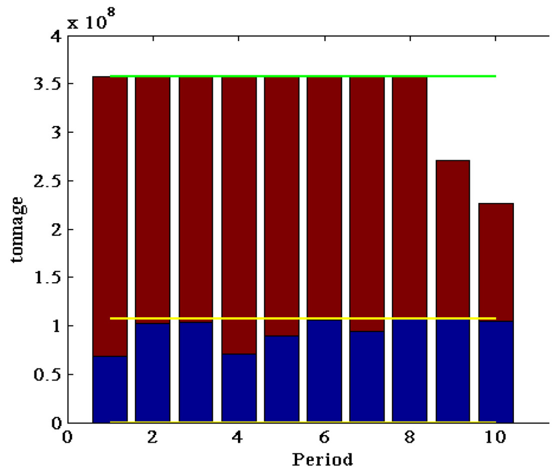

Fig. 13.Mining and processing tonnages for east-west direction.

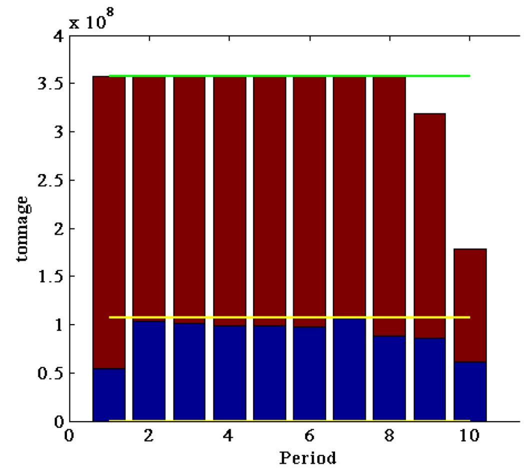

Fig. 14. Mining and processing tonnages for south-north direction.

Fig. 13 shows that mining production is almost uniform that is practically a good solution. However, ore feed to the processing plant is not as uniform as mining production. This is because of the fact that in east- west direction, the ore (bitumen) is not accessible with a smooth rate, while mining in south-north direction results in a more smooth ore feed (Fig. 14).

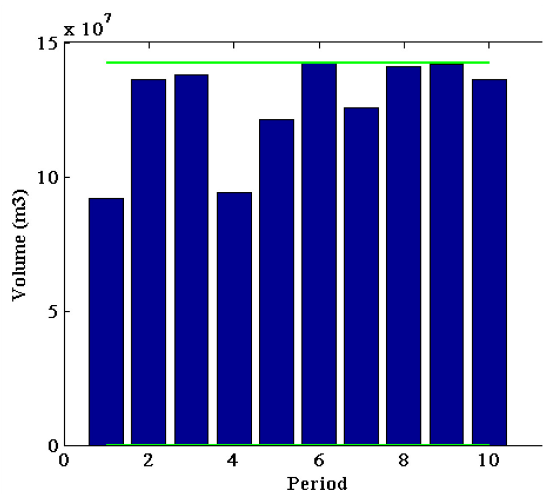

Fig. 15. Tailings volume for south-north direction.

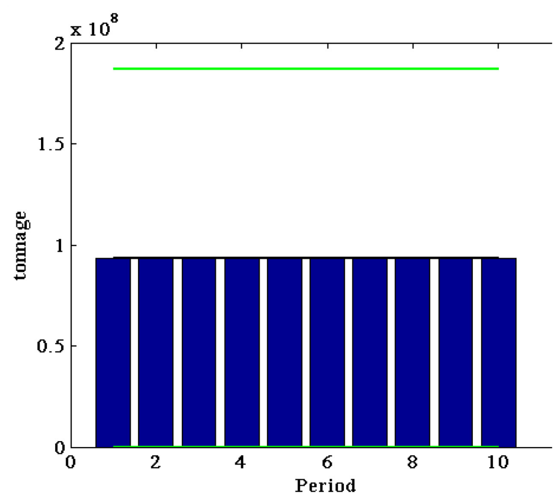

Fig. 16. Over/Inter burden material for reclamation in south-north direction.

Total volume of tailings in periods for east-west direction is compared in Fig. 15. In addition to the total volume of tailings, the quality of tailings is practically important. The results show that all tailings components including water, fine material and tailings coarse sand are within the specified input ranges. Finally, reclamation material that is produced in south-north mining direction is reported in Fig. 16. Since over/inter burden material does not have any value added to the NPV, the model keeps it in its minimum possible level, only to provide required material for reclamation. Moreover, Fig. 16 shows that reclamation material requirement constraints are binding constraints and therefore, optimization model is sensitive to material requirement bounds.

6. Conclusions

Processing of oil sands produces a huge volume of tailings, which is pumped into tailings ponds and kept there for a long period of time. Keeping the tailings in its conventional form in tailings ponds results in some severe environmental impacts. Thus, oil sand operators are responsible for monitoring their tailings facility environmental situation and decommissioning of mining site and tailings facility prior to leave the mine site. For decades in oil sands industry, tailings and reclamation plans have been developed separately from mine production plan. However, production plans directly affect the amount of tailings produced, as well as available material for site reclamation. In this paper, a new MILP model is developed that maximizes the NPV and at the same time considers material handling costs associated with reclamation operations as the new term in its objective function. Furthermore, the proposed MILP result ensures that the required material for site reclamation is available. Suncor's bitumen extraction process flow sheet is used to capture the mass balance relation in bitumen extraction process. The formulation that is used to calculate the tailings volume is verified by testing the formulation on real data from an oil sands surface mining case. Performance of the proposed MILP model is tested on real case oil sands data sets. The results show that the optimal production schedule meets material requirements for reclamation and also the produced tailings volume is within tailings capacity range in all periods. Moreover, the mining pattern follows certain horizontal direction. The integer optimal solution is found with %1.21 from problem's optimal solution. The next step in this research is to investigate some methods for problem size reduction. One way for reducing problem size is using of larger mining units, by aggregating mining cuts to mining panels. Although the block model resolution is lost with the new mining unit, but the solution closes more to what happens in real mining operations, where in real operations there is not that much selectivity in mining. Reducing the number of decision variables by eliminating irrelevant periods for extraction of near surface or deep mining blocks is the other method for problem size reduction. Another potential improvement in solving the MILP model is to use more efficient solution methods, such as Lagrangian relaxation algorithm, to find the solution in a reasonable time for large-scale problems.

7. References

[1] Askari-Nasab, H., & Awuah-offei, K. (2009). *Mixed integer linear programming formulations for open pit production scheduling*. Edmonton: University of Alberta, Mining Optimization Laboratory (MOL) report one.

[2] Askari-Nasab, H., Pourrahimian, Y., Ben-Awuah, E., & Kalantari, S. (2011). Mixed integer linear programming formulations for open pit production scheduling. *Journal of Mining Science, 47*(3), 338-359.

[3] Askari-Nasab, H., Tabesh, M., & Badiozamani, M.M. (2010). *Creating mining cuts using hierarchical clustering and tabu search algorithms*. Paper presented at the International conference on mining innovation (MININ), Santiago, Chile.

[4] AXYS, environmental consulting Ltd. (2005). *Historical resources, traditional land use and resource use environmental setting report*. Calgary, AB, Canada: Albian sands energy Inc.

[5] Ben-Awuah, E., & Askari-Nasab, H. (2011). Oil Sands Mine Planning And Waste Management Using Mixed Integer Goal Programming. *International Journal of Mining, Reclamation and Environment, 25*(3), 226 - 247.

[6] Government-of-Alberta. (2011). Alberta's oil sands.

[7] Holmström, K. (2009). TOMLAB / CPLEX (Version 11.2). Pullman, WA, USA.

[8] Manteiga, L., & Sunyer, C. (2000, September 2000). *Quantification for environmental impact: methodology and practical aspects.* Paper presented at the 4th European conference on evaluation of the structural funds, Edinburgh.

[9] Masliyah, J. (2010). *Course notes: Fundamentals of oil sands extraction, University of Alberta*. Edmonton.

[10] MathWorksInc. (2011). MATLAB Software (Version 7.13 (R2011b)).

[11] McFadyen, D. (2008). *Directive 074*. Calgary: Energy Resources Conservation Board.

[12] Odell, C. J. (2004). *Integration of sustainability into the mine design process.* Unpublished Master of applied science, University of British Colombia, Vancouver.

[13] Pollution-watch. (2003). *Pollution watch fact sheet: Alberta pollution highlights*: Environmental deffence and Canadian environmental law association.

[14] Rodriguez, G.D.R. (2007). *Evaluating the impact of the environmental considerations in open pit mine design.* Unpublished PhD., Golden, Colorado.

[15] Shell-Canada. (2011). *Jackpine Mine: Dedicated disposal area (DDA) plan for DDA1 (TT Cell)*. Fort McMurray, Alberta: Shell Canada Energy.

[16] Shepard, R.B. (2005). *Quantifying environmental impact assessments using fuzzy logic*: Springer.

[17] Sinding, K. (1999). Environmental impact assessment and management in the mining industry. *Natural resources forum, 23*, 57-63.

[18] Singh, G. (2008, November 2008). *Environmental impact assessment of mining projects.* Paper presented at the Proceedings of international conference on TREIA-2008, Nagpur.

[19] Tabesh, M., & Askari-Nasab, H. (2011). A Two Stage Clustering Algorithm for Block Aggregation in Open Pit Mines. *Transactions of the Institution of Mining and Metallurgy, SectionA, Mining Industry*.

[20] Woynillowicz, D., Severson-Baker, C., & Raynolds, M. (2005). *Oil sands fever: the environmental implications of Canada's oil sands rush*: The Pembina institute.

8. Appendix

MATLAB and TOMLAB/CPLEX documentation for the integrated mine planning model