INTEGRATION OF MINE-TO-MILL PRODUCTION PLANNING STRATEGY FOR OIL SANDS MINING AND WASTE DISPOSAL

Authors: Ahlam R. Maremi and Eugene Ben-Awuah

December 10, 2018

Laurentian University

BHARTI SCHOOL OF ENGINEERING
ÉCOLE DE GÉNIE

Mining Optimization Laboratory
Outline

- Oil sands mining and waste management;
- Problem definition;
- Objectives;
- Methodology – MILGP model;
- Implementation of the MILGP model with two case studies;
- Conclusions and recommendations.
Oil sands mining and waste management

Fig (1): Schematic view of McMurray deposit

- **Muskeg**
  - **Pleistocene Unit**
  - **Clear Water Formation**
  - **McMurray Formation**
  - **Devonian Carbonate**

- **Reclamation material**
- **Overburden (OB)** → For dyke construction
- **Contains the bitumen** → Tailings slurry, by product of HWEP
- **Marks the end of the deposit**
Oil sands mining and waste management

• Dykes are constructed in-pit to contain the tailings and most of the materials used to construct the dykes come from the mining operation.

• Currently, waste management is handled as a post-production scheduling optimization activity.

• Improper practices can lead to major production losses or early mine closure.
Problem definition

- Optimize the size and location of the tailing-cells
- Modify the recovery
- Topsoil scheduling
- Beginner mining engineer ???

Fig (2): Conceptual model for mining and waste management strategy modified after Ben-Awuah and Askari-Nasab, (2013)
Objectives of this research are:

– Determining the extraction sequence of the blocks that maximizes the NPV.

– Determining the destination of dyke material based on dyke requirements that minimizes construction costs.

– Controlling the annual tonnage fluctuations.

– Modify the recovery of the bitumen.

– Optimize the size and location of the tailing-cells for waste management.
Objective function of the Mixed Integer Linear Goal Programming (MILGP) model:

Maximize: $\text{NPV} - (\text{Minimize reclamation material stockpiling cost} + \text{Minimize the dyke construction cost} + \text{Minimize the deviations from the production goals})$

Subject to:

– constraints for mining and processing.
– stockpiling capacity constraints.
– bitumen grade and fines blending constraints.
– mining-panels extraction precedence constraints.
– variables controlling constraints.
– non-negativity constraints.
Objective function of the Mixed Integer Linear Goal Programming (MILGP) model:

\[
\text{Max} \sum_{l=1}^{L} \sum_{j=1}^{J} \sum_{d=1}^{D} \sum_{sp=1}^{SP} \sum_{a=1}^{A} \sum_{e=1}^{E} \sum_{t=1}^{T} \sum_{k \in MK_p}^{d} \sum_{p \in Mp_j}^{d} \left[
\left( r_m^{a,c,t} \times x^{a,t} + r_s^{a,c,t} \times c^{a,t}_{k,sp} + r_v^t \times c w^t_M - (d w^t_{l} \times y^t_{l}) - \right)
- \left( d m u^d_k \times y^d_k \right) - \left( d o b^d_k \times z^d_k + d i t^d_k \times u^d_k + d t^d_k \times q^d_k \right)
- \left( P_1 (P N_1 \times d v^{-,l,t}_1) - P_2 (P N_2 \times d v^{-,a,t}_2) - P_3 (P N_3 \times d v^{-,d,t}_3) \right)
- \left( P_4 (P N_4 \times d v^{-,d,t}_4) - P_5 (P N_5 \times d v^{-,d,t}_5) - P_6 (P N_6 \times d v^{-,d,t}_6) \right)\right]
\]

Mining-cut value: mine to plant
Mining-cut value: stockpile to plant
Extra RM material cost
Extra OB, IB and TCS dyke material costs
Cost of mining all material as waste
Waste-panel pseudo value per a cubic unit
Priority level
Penalty paid per tonne
Deviation decision variable
Methodology – MILGP model

Tonnage fluctuation constraints

- **Mining Tonnage Fluctuation:**
  \[
  \sum_{t=1}^{T} \left( \sum_{p \in MP_j} \left( o_p + mu_p + ob_p + ib_p + w_p \right) \times \left( y_{p,t}^{l+1} - y_{p,t}^l \right) \right) \leq D_m
  \]

- **Processing Tonnage Fluctuation:**
  \[
  \sum_{t=1}^{T} \left( \sum_{k \in MP_p} \left( \sum_{p \in MK_j} x_{k,t+1}^a + \sum_{sp=1}^{SP} c_{k,sp}^a(t-ts)+1 \right) - \left( x_{k,t}^a + \sum_{sp=1}^{SP} c_{k,sp}^a(t-ts) \right) \right) \times o_k \leq D_p
  \]

- **Reclamation Material Goal Function:**
  \[
  \sum_{p=1}^{P} \left( \sum_{k \in MP_p} \left( mu_k \times v_{k,d,t}^d \right) \right) + dV_{3,-d,t} = MUg_{d,t}
  \]

- **Dyke material Goal Functions:**
  \[
  \sum_{p=1}^{P} \left( \sum_{k \in MP_p} \left( ob_k \times z_{k,d,t}^d \right) \right) + dV_{4,-d,t} = OBg_{d,t}
  \]
  \[
  \sum_{p=1}^{P} \left( \sum_{k \in MP_p} \left( ib_k \times u_{k,d,t}^d \right) \right) + dV_{5,-d,t} = IBg_{d,t}
  \]
  \[
  \sum_{p=1}^{P} \left( \sum_{k \in MP_p} \left( cs_k \times q_{k,d,t}^d \right) \right) + dV_{6,-d,t} = CSg_{d,t}
  \]
## Thee ultimate pit characteristics

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total tonnage of material (Mt)</td>
<td>182.23</td>
</tr>
<tr>
<td>Total ore tonnage (Mt)</td>
<td>88.44</td>
</tr>
<tr>
<td>Total TCS dyke material tonnage (Mt)</td>
<td>66.33</td>
</tr>
<tr>
<td>Total OB dyke material tonnage (Mt)</td>
<td>18.02</td>
</tr>
<tr>
<td>Total IB dyke material tonnage (Mt)</td>
<td>20.05</td>
</tr>
<tr>
<td>Total reclamation material tonnage (Mt)</td>
<td>7.05</td>
</tr>
<tr>
<td>Number of blocks</td>
<td>2,523</td>
</tr>
<tr>
<td>Number of mining-cuts (clusters)</td>
<td>155</td>
</tr>
<tr>
<td>Number of mining-panels</td>
<td>22</td>
</tr>
<tr>
<td>Number of benches</td>
<td>6</td>
</tr>
</tbody>
</table>
### Economic parameters and operational capacities

<table>
<thead>
<tr>
<th>Parameter (unit)</th>
<th>Value</th>
<th>Parameter (unit)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mining cost ($/tonne)</td>
<td>4.60</td>
<td>Mining recovery fraction (%)</td>
<td>100.00</td>
</tr>
<tr>
<td>Processing cost ($/tonne)</td>
<td>5.03</td>
<td>Discount rate (%)</td>
<td>10.00</td>
</tr>
<tr>
<td>Ore stockpiling cost ($/tonne)</td>
<td>0.50</td>
<td>Cumulative periodic mining tonnage fluctuation (Mt)</td>
<td>50.0</td>
</tr>
<tr>
<td>Selling price ($/bitumen %mass)</td>
<td>4.50</td>
<td>Cumulative periodic processing tonnage fluctuation (Mt)</td>
<td>30.0</td>
</tr>
<tr>
<td>TCS dyke material cost ($/tonne)</td>
<td>0.92</td>
<td>RM capacity (MT/year)</td>
<td>1.42</td>
</tr>
<tr>
<td>OB dyke material cost ($/tonne)</td>
<td>1.38</td>
<td>OB capacity (MT/year)</td>
<td>2.5</td>
</tr>
<tr>
<td>IB dyke material cost ($/tonne)</td>
<td>1.38</td>
<td>IB capacity (MT/year)</td>
<td>2.4</td>
</tr>
<tr>
<td>RM extra mining cost ($/tonne)</td>
<td>0.50</td>
<td>TCS capacity (MT/year)</td>
<td>9.0</td>
</tr>
</tbody>
</table>
Methodology – MILGP model

In literature, Organic Rich Solids (ORS) are active solid fractions comprising about 5% of the total ore. ORS and bitumen are the main controlling factors that influence liberated and unliberated bitumen.

Recovery calculations:

1. Based on Directive 082: Alberta Energy Regulator

\[
RECOV_{AER} = -2.5 \times (BIT)^2 + 54.1 \times (BIT) - 202.7
\]

2. Based on Organic Rich Solids (ORS)

\[
RECOV_{ORS} = -0.0219 \times \left( \frac{BIT}{ORS} \right)^2 + 0.3335 \times \left( \frac{BIT}{ORS} \right) - 0.3789
\]

➢ The recovery for each block is modeled from O’Carroll, 2002 (with \( R^2 \) of 99.8%)

It is noted that the recovery calculated based on AER requirements is greater than or equal to the recovery calculated based on ORS. The recovery difference ranges between 0.0 and 4.0% for lower bitumen grades (<11%).

Fig. (3) Recoveries vs bitumen grade
**Case study-1 : Scenarios 1 & 2 – Results**

**Scenario 1**: based on Directive 082: Alberta Energy Regulator  
**Scenario 2**: based on Organic Rich Solids (ORS)

<table>
<thead>
<tr>
<th>Periods</th>
<th>Material mined (MT)</th>
<th>Material processed (MT)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scenario 1</td>
<td>Scenario 2</td>
</tr>
<tr>
<td>1</td>
<td>25.00</td>
<td>24.78</td>
</tr>
<tr>
<td>2</td>
<td>25.00</td>
<td>24.78</td>
</tr>
<tr>
<td>3</td>
<td>25.00</td>
<td>24.78</td>
</tr>
<tr>
<td>4</td>
<td>25.00</td>
<td>24.78</td>
</tr>
<tr>
<td>5</td>
<td>25.00</td>
<td>24.78</td>
</tr>
<tr>
<td>6</td>
<td>25.00</td>
<td>24.78</td>
</tr>
<tr>
<td>7</td>
<td>25.00</td>
<td>24.78</td>
</tr>
<tr>
<td>8</td>
<td>6.90</td>
<td>8.43</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>181.90</strong></td>
<td><strong>181.89</strong></td>
</tr>
</tbody>
</table>
Case study-1

Scenario 1

(NPV = $1,499.3 M)

Fig (4): Processing production schedule 1-year ramping up is allowed at the beginning of mine life and 1-year ramping down at the end

Scenario 2

(NPV = $1,468.2 M)

about 2% less NPV
Case study-1 / Scenarios 1 & 2 - Results

Fig (5): Mining production schedule
Case study-2

Objective function of the Mixed Integer Linear Goal Programming (MILGP) model:

\[
\text{Max} \sum_{l=1}^{L} \sum_{j=1}^{J} \sum_{d=1}^{D} \sum_{sp=1}^{SP} \sum_{a=1}^{A} \sum_{e=1}^{E} \sum_{t=1}^{T} \left( \sum_{k \in \text{MK}_p} \sum_{p \in \text{Mp}_j} \left[ \left( rm^{a,e,t}_{k} \times x^{a,t}_{k} \right) + rs^{a,e,t}_{k,sp} \times c^{a,t}_{k,sp} + rv^{t}_{M} \times cW^{t}_{M} - (dw^{l,t}_{p})y^{l,t}_{p} \right) \right)
\]

- Mining-cut value: mine to plant
- Mining-cut value: stockpile to plant
- Extra RM material cost
- Extra OB, IB and TCS dyke material costs
- Cost of mining all material as waste
- Waste-panel pseudo value per a cubic unit
- Priority level
- Penalty paid per tonne
- Deviation decision variable
Case study-2

Optimize the size and the location of the tailing-cells for waste management

• Eq. (1) defines the horizontal mining precedence.

\[
pb_M^t - \sum_{t=1}^{T} \sum_{d=1}^{D} cw_v^{t,d} \leq 0, \quad v \in H_M(VOL) \quad (1)
\]

• Eq. (2 & 3) control the tailing-cell volume.

\[
\sum_{t=1}^{T} (v_M \times cw_M) + \sum_{t=1}^{T} \sum_{d=1}^{D} (v_i \times cw_i) \leq UP \quad (2) \\
\sum_{t=1}^{T} (v_M \times cw_M) + \sum_{t=1}^{T} \sum_{d=1}^{D} (v_i \times cw_i) \geq LW \quad (3)
\]

• Eq. (4) ensures that waste-panel can only be extracted if it has not been extracted before.

\[
\sum_{t=1}^{T} \sum_{d=1}^{D} cw_M - pb_M^t \leq 0 \quad (4)
\]
Assume: $5 per cubic unit. A Pseudo revenue = $154.2M from improved waste management.

Fig (6): Grouping waste panels into tailing-cells

<table>
<thead>
<tr>
<th>Tailing-cells</th>
<th>Waste-panels</th>
<th>Volume (* 10^6 m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1-2-3-7-8</td>
<td>17.10</td>
</tr>
<tr>
<td>B</td>
<td>4-9-10-14-15-16</td>
<td>13.69</td>
</tr>
<tr>
<td>C</td>
<td>5-6-12-13</td>
<td>17.36</td>
</tr>
<tr>
<td>D</td>
<td>11-17-18-19-23</td>
<td>15.45</td>
</tr>
<tr>
<td>E</td>
<td>20-21-22-26-27-28-33</td>
<td>16.95</td>
</tr>
<tr>
<td>F</td>
<td>24-25-29-30-31-32</td>
<td>13.73</td>
</tr>
</tbody>
</table>
Conclusions and recommendations - 1

• The MILGP model integrates the waste management into mine planning optimization problem that leads to a reduction in the environmental footprints of oil sands mining operations.

• The model schedules the topsoil for reclamation purposes.

• The stockpiling strategy is well integrated into the optimization problem for limited duration to prevent the oxidation of ore.

• The ORS have significant impact on the ore processability. If considered we can generate realistic processing plant recoveries for mine planning and might be a better predictor of ore processability.
Conclusions and recommendations - 2

• The model generates value and smooth production schedules using mining and processing tonnage fluctuation constraints.

• The model is able to optimize the size and location of the tailing-cells for waste management.

• The recommendations are:

  • To improve the model to refine the shape of the tailing-cells during the optimization.

  • To use another factor to calculate the pseudo revenue; and to apply the model on a large dataset.
Thank you …

Questions?