Daily Blending of Large-Scale Surface Mines: A Multiple Objective Optimization Approach

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ABSTRACT

Oil sands mining contributes to the Canadian daily oil production by 1.753 million barrels per day. Processing oil sands is a complex operation with a critical sensitivity to the properties of the blended ore at the crusher that must follow the slurry pipeline and separation tank requirements. The blend optimisation in oil sands mines is a tedious work performed mostly manually by the mining engineers at the mine sites and requires fine-tuning as shovels move from one block to another in the same mining face. Miscalculations leading to deviation from the target properties cause inevitable economically and operationally expensive problems to the value chain including but not limited to sanding the pipeline, separation tank hick-ups, etc. Herein, we present a multiple objective mathematical programming model for blend optimization in oil sands mines. The model takes the processing targets as inputs and minimizes deviations from each desired target by considering material properties at mining faces, the capacity of trucks, and shovels' production rate.

1. Introduction

One major challenge of oil sands mining is the necessity of constant delivery of homogenous feed to the processing plant. This, in turns requires a proper blending of material being delivered from several mining faces with different properties. Grade, percentage of fine and d_{50} (average size of material) are three main factors that should be considered in the blending process to meet the feed target quality.

Due to the importance of proper blending, mine planning researchers have had enough attention on it in coal, cement and polymetallic ore deposits [1-4]. However, to the best of our knowledge, despite being among the largest open pit mining operations, oil sands blending have not attracted any attention. This article proposes a mixed integer linear goal programming (MILGP) model that aims to optimize the quality and quantity of the oil sands blend.

2. Methodology

A MILGP model is proposed to optimize blending in oil sands mines. The list of used symbols is represented in Tables 1 to 3. The objective function aims to minimize deviations from desired tonnage, grade, fine and d_{50} and constraints represent deviations from targets.

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Table 1. List of indices that are used in the proposed mathematical model.

Indices:	
i	Mining face
j	Crusher
k	Truck
h	Hydraulic shovel
e	Electric shovel

Table 2. List of parameters that are used in the proposed mathematical model.

Parameters:	
I	Number of mining faces
J	Number of crushers
K	Number of trucks
S_h	Number of hydraulic shovels
S_e	Number of electric shovels
T	Time of shift work
t_{ijkh}	The average cycle time of truck k if it travels between i to j path, where it is loaded by hydraulic shovel h
t_{ijke}	The average cycle time of truck k if it travels between i to j path, where it is loaded by electric shovel e
ρ_k	Capacity of truck k
η_h	Hydraulic shovel productivity in a shift work
η_e	Electric shovel productivity in a shift work
p_i	Tonnage of bitumen in face i
g_i	Grade of bitumen in face i
f_i	Fine content of bitumen in face i
d_i	d_{50} of bitumen in face i
$\breve{p}_i$	Desired tonnage for crusher j
$\breve{g}_i$	Desired grade for crusher j
$\breve{f}_i$	Desired fine for crusher j
$\breve{d}_i$	Desired d_{50} for crusher j

Objective function includes two parts: first part focuses to reach in desired tonnage by provide enough bitumen for crusher from different mining faces. Both over and under meet target tonnage leads to awful consequences. Under meet desired tonnage results in stop crusher. Over meet desired tonnage need an area for temporary stock bitumen as well as impose re-handling costs to system. Therefore, we are not interested to any deviation from desired tonnage. Providing enough bitumen for crusher guarantees the quantity of feed. Meanwhile, the quality of material could be managed by control bitumen properties. Grade, fine content and d_{50} are three main factors in oil sand blending process that define the quality of feed. Therefore, main goal in the second part of objective function is minimizing grade, fine and d_{50} deviations from target values.

Table 3. List of variables that are used in the proposed mathematical model.

Variables:	
p_j^+	Over meet target tonnage in crusher j
p_j^-	Under meet target tonnage in crusher j
G_j^+	Over meet target grade in crusher j
G_j^-	Under meet target grade in crusher j
F_j^+	Over meet target fine in crusher j
F_j^-	Under meet target fine in crusher j
D_j^+	Over meet target d_{50} in crusher j
D_j^-	Under meet target d_{50} in crusher j
x_{ih}	A binary decision variable that indicates if hydraulic shovel h is assigned to mining face i or not
x'_{ie}	A binary decision variable that indicates if electric shovel e is assigned to mining face i or not
y_{ijkh}	A binary decision variable that indicates if truck k, which is loaded by hydraulic shovel h, is used between i to j path or not
y'_{ijke}	A binary decision variable that indicates if truck k, which is loaded by electric shovel e, is used between i to j path or not
w_{ij}	A binary decision variable to show material flow between i to j path

First constraint in the proposed model enforces the amount size of supplied bitumen from different mining faces be close to the target tonnage of each crusher. Hydraulic and electric shovels are two types of loading equipments in oil sand benches. Difference in bucket size of these shovels cause different loading time of trucks. Actually, different loading time result in cycle time of truck and it finally change the total number of truck cycles in a shift work. So in order to accurate calculation, the amount tonnage of arrived bitumen to each crusher depends on the type of loading equipment.

The average grade of bitumen which is arrived to crusher j is calculated by Equation (1). If w_{ij} becomes one, it means that there is a material flow between face i and crusher j. Therefore, g_i should be take account into the average grade calculation.

$$\overline{g}_j = \frac{\sum_{i=1}^{I} w_{ij} g_i}{\sum_{i=1}^{I} w_{ij}} \tag{1}$$

If $\overline{g}_j$ be the average grade of arrived bitumen to crusher j, then G_j^+ and G_j^- are tow continues decision variables which show positive and negative deviation from the desired grade of bitumen, respectively.

$$\overline{g}_j - \tilde{g}_j = \frac{\sum_{i=1}^{I} w_{ij} g_i}{\sum_{i=1}^{I} w_{ij}} - \tilde{g}_j = G_j^+ - G_j^- \tag{2}$$

In order to linearization Equation (2), both left and right hand sides are multiplied by $\sum_{i=1}^{I} w_{ij}$.

$$\sum_{i=1}^{I} \left(g_i - \tilde{g}_j \right) w_{ij} = \sum_{i=1}^{I} G_j^+ w_{ij} - \sum_{i=1}^{I} G_j^- w_{ij} \tag{3}$$

Since right hand side becomes non-linear, we replace these non-linear parts by two new decision variables. So, $\sum_{i=1}^{I} G_j^+ w_{ij}$ and $\sum_{i=1}^{I} G_j^- w_{ij}$ are replaced by g_j^+ and g_j^-, respectively.

$$\sum_{i=1}^{I} \left(g_i - \tilde{g}_j \right) w_{ij} = g_j^+ - g_j^- \tag{4}$$

The above approach is also used for fine and d_{50} factors.

$$\sum_{i=1}^{I} \left(f_i - \tilde{f}_j \right) w_{ij} = f_j^+ - f_j^- \tag{5}$$

$$\sum_{i=1}^{I} \left(d_i - \tilde{d}_j \right) w_{ij} = d_j^+ - d_j^- \tag{6}$$

By Eq. 12, trucks are fixed and they just travel between a specific path. Trucks are assigned to $i-j$ path, when there is an operating shovel (hydraulic or electric) in face i (EQs. 13 and 14). From operational view, due to working space limitations, only one shovel should be operated in a specific mining face (Eq. 15). The amount tonnage of forwarded bitumen from a specific face to different crushers by several trucks should be less than the productivity of shovel which is operated on that face (EQs. 16 and 17). If trucks are moved between $i-j$ path, then there is a material flow on this path, i.e., it means that w_{ij} value becomes one (Eq. 18). For a shift work, EQs. 19 and 20 enforce each hydraulic and electric shovel is only operated in a mining face.

$$z=\min\sum_{j=1}^{J}p_j^{+}+p_j^{-}+g_j^{+}+g_j^{-}+f_j^{+}+f_j^{-}+d_j^{+}+d_j^{-} \tag{7}$$

Subject to:

$$\sum_{i=1}^{I}\sum_{k=1}^{K}\rho_k\left(\sum_{s=1}^{S_h}\left\lfloor\frac{T}{t_{ijkh}}\right\rfloor .y_{ijkh}+\sum_{e=1}^{S_e}\left\lfloor\frac{T}{t_{ijke}}\right\rfloor .y'_{ijke}\right)-\tilde{p}_j=p_j^{+}-p_j^{-} \qquad \forall j \tag{8}$$

$$\sum_{i=1}^{I}\left(g_i-\tilde{g}_j\right)w_{ij}=g_j^{+}-g_j^{-} \qquad \forall j \tag{9}$$

$$\sum_{i=1}^{I}\left(f_i-\tilde{f}_j\right)w_{ij}=f_j^{+}-f_j^{-} \qquad \forall j \tag{10}$$

$$\sum_{i=1}^{I}\left(d_i-\tilde{d}_j\right)w_{ij}=d_j^{+}-d_j^{-} \qquad \forall j \tag{11}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\left(\sum_{h=1}^{S_h}y_{ijkh}+\sum_{e=1}^{S_e}y'_{ijke}\right)\le 1 \qquad \forall k \tag{12}$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K}y_{ijkh}\le M.x_{ih} \qquad \forall i,h \tag{13}$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K}y'_{ijke}\le M.x_{ie} \qquad \forall i,e \tag{14}$$

$$\sum_{h=1}^{S_h}x_{ih}+\sum_{e=1}^{S_e}x'_{ie}\le 1 \qquad \forall i \tag{15}$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K}\left\lfloor \frac{T}{t_{ijkh}} \right\rfloor \rho_k y_{ijkh} \le \eta_h \qquad \forall i,h \qquad (16)$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K}\left\lfloor \frac{T}{t_{ijke}} \right\rfloor \rho_k y'_{ijke} \le \eta_e \qquad \forall i,e \qquad (17)$$

$$\sum_{k=1}^{K}\sum_{h=1}^{S_h} y_{ijkh} + \sum_{k=1}^{K}\sum_{e=1}^{S_e} y'_{ijke} \le M.w_{ij} \qquad \forall i,j \qquad (18)$$

$$\sum_{i=1}^{I} x_{ih} \le 1 \qquad \forall h \qquad (19)$$

$$\sum_{i=1}^{I} x'_{ie} \le 1 \qquad \forall e \qquad (20)$$

$$x_{ih} \in \{0,1\} \qquad \forall i,h \qquad (21)$$

$$x'_{ie} \in \{0,1\} \qquad \forall i,e \qquad (22)$$

$$y_{ijkh} \in \{0,1\} \qquad \forall i,j,k,h \qquad (23)$$

$$y'_{ijke} \in \{0,1\} \qquad \forall i,j,k,e \qquad (24)$$

$$w_{ij} \in \{0,1\} \qquad \forall i,j \qquad (25)$$

$$p_j^+, p_j^-, g_j^+, g_j^-, f_j^+, f_j^-, d_j^+, d_j^- \ge 0 \qquad \forall j \qquad (26)$$

3. Results

The proposed model was implemented on a real data set from an oil sand mine in Canada. Mine includes one crusher and it works 12 hours per shift. The information of operating equipments in ore mining faces is listed in Table 4. There are three mining faces on this case study with different grade, fine and d_{50} properties (See Table 5). A computer program was designed and implemented on C# (WPF) programming language and it uses CPLEX 12.4 as solver. It facilities input data, solving process and save solution. Target values and obtained solution revealed by the computer program are documented in Table 6. Since the proposed model aims to satisfy all factors, there is a minor deviation between desired parameters and obtained results.

Table 4. The information of working time, hauling and loading equipments.

Parameters	**Value**	**Unit**
Time (shift work)	12	hour
Truck capacity	370	tonne
Hydraulic shovel productivity	38400	tonne per shift
Electric shovel productivity	50400	tonne per shift
Number of trucks	12	
Number of hydraulic shovel	1	
Number of electric shovels	2	

Table 5. Properties of bitumen in three existing mining faces.

Mining face	Grade (%)	Fine (%)	$d_{50}\left(\mu m\right)$
1	8	16	300
2	11	13	180
3	14	10	110

Table 6. Input data and obtained solution.

Factor	Target	Solution	Deviation
(Tonnage (tonne	144,000	116,920	27,080
(%) Grade	12	11	1
(%) Fine	14	13	1
$d_{50}\left(\mu m\right)$	260	196.67	63.33

4. Conclusions

By producing 1.753 million barrels per day, oil sand mining is an important and critical industry for Canada government. Providing enough materials with good properties for oil sand crushers guarantees the quantity and quality of feed. Blending procedure is a complex problem in oil sand mining with significant consequences on downstream processes. However currently, this problem is solved manually and there is not a guarantee to produce an optimal solution. In this article, a multi objective programming model is proposed and it aims to minimize any deviations from tonnage, grade, fine and d_{50} target values, as well as, it is looking for the best scheduling program for trucks and shovels in a shift work. The proposed model was successfully implemented on a real case study from north Alberta province and the obtained results were good enough.

5. References

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