Fast algorithm for open pit mining: tackling uncertainty, design and capacity

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Summary

• Typical planning process is a serial methods of procedures, that use geostatistics data as input and need a post hoc design and capacity correction.

• We show an idea to joint planning, geostatistics and design, considering capacity.

• Simulated annealing and floating cones is just a excuse...
Classic planning process

Final Pit → Nested pits → Lifetime → Phases → Equip, Design → Capex, Opex

Sección Vertical Mina Rajo

[Graphs and charts related to mining operations]
Houston, we've had a problem here!

- We used a “mean” block model. What about uncertainty?
- Theoretical solution is not operative.
Final Pit, as an example

• There exists efficient algorithms
• There are fast algorithms for scheduling that use Final Pits
• Divide and conquer
Lersch & Grossman

- **Translate** value maximization to a max flow in an oriented net.
- **Slope** is satisfied as a **precedence** relationship
Floating cones algorithm (Greedy)

- Accepting new cones while they add value

Remark (**representation**): in order to define the surface of final pit at left image, we need 2 points. Using Lerchs&Grossman we need 12.
Cones algorithms

Greedy
• Select a cone
• It is accepted:
  – Certainly if it adds value
  – Probably if it doesn’t destroy too much value and iteration is not too advanced (cooling down).
Stop at fixed steps.

Simulated Annealing
• Select a cone
• It is accepted:
  – Certainly if it adds value
  – Probably if it doesn’t destroy too much value and iteration is not too advanced (cooling down).
A “while” is running until system is frozen.
Why Simulated Annealing?

• There are success cases
• Planning process integrated
• Paralelized
Benchmark 1: small block model

Marvin Mine (62,220 blocks)

<table>
<thead>
<tr>
<th>Marvin</th>
<th>Value</th>
<th>Block mined</th>
<th>Representation</th>
<th>Time (secs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pseudoflux</td>
<td>8.96E+11</td>
<td>6,568</td>
<td>621</td>
<td>2</td>
</tr>
<tr>
<td>Greedy</td>
<td>8.83E+11</td>
<td>6,454</td>
<td>128</td>
<td>5</td>
</tr>
<tr>
<td>S. Annealing</td>
<td>8.81E+11</td>
<td>6,447</td>
<td>507</td>
<td>22</td>
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</tbody>
</table>

Remark: Pseudoflux is faster and achieves optimum.
Benchmark 2: strong nugget effect
Marvin + big Bernoulli noise

<table>
<thead>
<tr>
<th>Marvin+Noise</th>
<th>Value</th>
<th>Block mined</th>
<th>Representation</th>
<th>Time (secs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pseudoflux</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>24hrs</td>
</tr>
<tr>
<td>Greedy</td>
<td>1.02E+12</td>
<td>20,602</td>
<td>339</td>
<td>10</td>
</tr>
<tr>
<td>S. Annealing</td>
<td>1.03E+12</td>
<td>17,956</td>
<td>638</td>
<td>20</td>
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</tbody>
</table>

Remark: Pseudoflux does not achieve optimum after 24hrs.

\[
\tilde{V}_i = V_i \pm \max_j |V_j|
\]
Benchmark 3: big block model (Marvin refined to 1,297,770 blocks)

<table>
<thead>
<tr>
<th>Big BM</th>
<th>Value</th>
<th>Block mined</th>
<th>Representation</th>
<th>Time (secs)</th>
</tr>
</thead>
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<tr>
<td>Pseudoflux</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>24hrs</td>
</tr>
<tr>
<td>Greedy</td>
<td>1.72E+13</td>
<td>698,828</td>
<td>1197</td>
<td>90</td>
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<tr>
<td>S. Annealing</td>
<td>1.53E+13</td>
<td>619,917</td>
<td>592</td>
<td>18</td>
</tr>
</tbody>
</table>

Remark: Simulated Annealing needs short time to achieve an almost optimum point.
Conclusions for final pit

- Floating Cones with Simulated Annealing could be **more efficient** for big block models or strong nugget effect situations.
- Its **representation** is cheaper.
- It leads to try several **simulations** for block model.
- Cones is a cheap (and flexible) object to satisfy slope (and could fit mine **design**).
Remarks

• **Uncertainty**: try block model simulations inside the heuristics running, and accept new cones if its value distribution pass certain criteria. *Joint planning and geostatistics.*

• **Design**: try truncated operative cones. It leads an operative final pit. *Joint planning and design.*
Context

• This ppt is a part of a PhD thesis.
• Subject: Mine Planning under geological uncertainty.
• A priori approach:
  – Simulation and design embedded in optimization, turning bands
  – Simulated annealing to solver hard problems.
  – **Strategy** instead of rigid planning solution
• Final application: long term planning for open pit to underground transition
ALGORITHMS BASED ON AGGREGATION FOR THE OPEN-PIT BLOCK SCHEDULING PROBLEM
• Scheduling

• Current techniques are based on Lerchs & Grossman algorithm (1965): It **does not consider** production and mining capacities, hence, it does not take **time** into account.
Main idea: Aggregation

- Use aggregation to reduce the complexity of the problem and heuristics to generate feasible (good) solutions:
  - Reducing number of periods
  - Relaxing constraints
  - Reblocking
Blocks in the *borders* are then refined and re-optimized.
Final solution is reported at original block level
Case study: Marvin

- Imaginary mine (but well known).
- About 12,500 blocks
- Discount rate: 10% per year
- 12 time periods
- Data blocks:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>VALUE [US$]</th>
<th>TONNAGE</th>
<th>TON. PLANT</th>
</tr>
</thead>
<tbody>
<tr>
<td>4075</td>
<td>7050</td>
<td>705</td>
<td>-10260</td>
<td>10260</td>
<td>0</td>
</tr>
<tr>
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<td>7050</td>
<td>675</td>
<td>-61587</td>
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<td>7050</td>
<td>645</td>
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<tr>
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<td>7170</td>
<td>615</td>
<td>1413201</td>
<td>72360</td>
<td>72360</td>
</tr>
</tbody>
</table>

- Two capacity constraints:
  - Mining (transportation) is 70,000 [TPD]
  - Processing (plant) is 30,000 [TPD].
- Block predecessors:
  - Slope angle of 45 degrees
Results

Each cell reports the value (MMUS$) and time (sec) to reach the solution.

- IP: Original problem (unsolvable)
- LP (upper bound) is available only for the larger blocks, and gives gaps of about 9%.
- OoM = Out of Memory

<table>
<thead>
<tr>
<th>Mine</th>
<th>M15</th>
<th>M30</th>
</tr>
</thead>
<tbody>
<tr>
<td># Blocks</td>
<td>99,744</td>
<td>12,468</td>
</tr>
<tr>
<td>IP</td>
<td>OoM</td>
<td>OoM</td>
</tr>
<tr>
<td>LP</td>
<td>OoM</td>
<td>1,246</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7,235 [s]</td>
</tr>
<tr>
<td>HInc</td>
<td>-</td>
<td>1,134</td>
</tr>
<tr>
<td></td>
<td>&gt;10,800 [s]</td>
<td>312 [s]</td>
</tr>
<tr>
<td>HInc-STW</td>
<td>-</td>
<td>998</td>
</tr>
<tr>
<td></td>
<td>&gt;10,800 [s]</td>
<td>9,324 [s]</td>
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<tr>
<td>HReb/ IP</td>
<td>OoM</td>
<td>OoM</td>
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<tr>
<td>HReb/HInc</td>
<td>1,123</td>
<td>1,134</td>
</tr>
<tr>
<td></td>
<td>2,027 [s]</td>
<td>312 [s]</td>
</tr>
</tbody>
</table>

M15 Production Plan (HReb/HInc)
Conclusions and further work

- Aggregation techniques allow to tackle instances that are “unsolvable” otherwise.
- Distribute computational effort (steps of algorithm) at multiple computers simultaneously (parallelization).
- Extend to the case where coefficients in capacity constraints may be negative (constraints on the average value of some attribute).
- Extend to the case where the model decides the destination of the block (cut ore grade not fixed).
- Stochastic case (geology, prices, operations).
Joining...
Joining: planning, geo-uncertainty, design, capacity

- Embebing uncertainty in planning with floating cones.
- Using turning bands to sampling (Stochastics Samping Aver.)
- Using operative cones to fix a design strategy
- Reblock to reduce difficulty in time.
- Parallelize sampling (turning bands), simulated annealing.
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