Ore Selection and Sequencing

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Exploration and Subsequent Drilling

Grades interpolated to form a Block Model
Kriged or Conditional Simulation
Ore Selection from the Block Model

Distinguish Ore Blocks from Waste Blocks

Ore Block
Waste Block
Ore Selection - Objectives

• For Iron Ore: Grade of interest is \{Fe, Al_2O_3, SiO_2, P\}
• Value: Fe positive, the others are contaminants of negative value.
• IDEALLY – Maximise Net Present Value
• Equivalent to: Marginal Value > 0
• Marginal Value Not Usually Known

• IN PRACTICE
• Maximise Tonnage at a Target Grade
• Target Grade Set by Marketing (in Iteration with Planning)
Ore Sequencing - Objectives

• 1) Feasible sequence (no undercutting or too steep cliffs)
• 2) Keep production grade constant
• (to avoid costly re-handling)
• 3) Minimise equipment movement.
• 4) Balance production from multiple pits or locations.

• 1) is a constraint that must be obeyed.
• 2) 3) and 4) are objectives to be traded off against each other.
Ore Selection – Cut-Off Grade Criteria

A Single Criterion - Fe Cut-Off Only

Plot showing the relationship between Al₂O₃ and Fe concentrations.
Ore Selection – Cut-Off Grade Criteria

Quadrant Cut-Off - Fe and Contaminant

Multidimensional when all contaminants considered
Ore Selection – Cut-Off Grade Criteria

Rejected blocks acceptable if combined (black)
Same Total Grade – Composite Gives More Ore
Ore Selection

Another Hypothetical Example

• Two Pits, Alpha and Beta
  • Alpha is Low Fe, but Low Al₂O₃
  • Beta is High Fe, but High Al₂O₃
    • Each block is 50 kt
  • Target \{Fe, Al₂O₃\} = \{57.5, 3.2\}
    • Find Maximum Tonnage
Block Model Data for Two Pits (hypothetical, but realistic)
Quadrant Method
Inconsistency #1.
Rejected Blocks
Acceptable if Aggregated
Pit Specific Quadrants Yield 15.55 Mt
(single quadrant gave 10.10 Mt)
Inconsistency #2.  
Same Grade, 
Different Pit, 
Different Outcome

Ore for Beta  
Waste for Alpha

Ore for Alpha  
Waste for Beta
Composite Method Yields Maximum Tonnes (20.85 Mt) at Target Grade
Composite Score = Fe - 3.76 Al₂O₃
Comparison

• Single Quadrant – Yields 10.10 Mt
  Inconsistent because it rejects individual blocks that would be acceptable if aggregated

• Pit-Specific Quadrants – Yield 15.55 Mt
  Further Inconsistency: rejects ore from one pit that would be acceptable from the other
  But still better than Single Quadrant
  – Theory of the Second Best (Lipsey and Lancaster, 1956)

• Composite Method – Yield 20.85 Mt – OPTIMAL!
Cut-Off Grades – Marginal Criterion

Accept Ore if:

- Marginal Value > Marginal Cost (MC)
- \( K_0.\text{Fe} - K_1.\text{Al}_2\text{O}_3 - K_2.\text{SiO}_2 - K_3.\text{P} > \text{MC} \)

Marginal Cost:

- Within Pit,
  - Cost of Processing, Handling, Transport
- At Pit Boundary,
  - add in the Cost of Mining
Cut-Off Grades – Target Grades

Marginal Value not usually available.

Instead:

Maximise Ore Tonnage satisfying Nominated Target Grade Vector

Select Ore if:

\[ \text{Fe} - K_1 \cdot \text{Al}_2\text{O}_3 - K_2 \cdot \text{SiO}_2 - K_3 \cdot \text{P} > X_{\text{critical}} \]

Adjust \( \{K_1, K_2, K_3, X_{\text{critical}}\} \) to Satisfy Target Grade
Grade Stress

Target Grade = $\mathbf{T} = \{T_{\text{Fe}}, T_{\text{Al}}, T_{\text{Si}}, T_P\}$

Tolerance = $\mathbf{t} = \{t_{\text{Fe}}, t_{\text{Al}}, t_{\text{Si}}, t_P\}$

Ore Grade = $\mathbf{Y} = \{Y_{\text{Fe}}, Y_{\text{Al}}, Y_{\text{Si}}, Y_P\}$

Then Grade Stress = $\mathbf{S} = \{S_{\text{Fe}}, S_{\text{Al}}, S_{\text{Si}}, S_P\}$

where $S_{\text{Fe}} = (Y_{\text{Fe}} - T_{\text{Fe}})/t_{\text{Fe}}$

Total Grade Stress = $S_T^2 = S_{\text{Fe}}^2 + S_{\text{Al}}^2 + S_{\text{Si}}^2 + S_P^2$

convenient single non-dimensional measure of fit
Iterative Procedure

\[ X = Fe - K_1 \cdot Al_2O_3 - K_2 \cdot SiO_2 - K_3 \cdot P \]

Make initial estimate of \( \{K_1, K_2, K_3\} \)

- Compute \( X \) for each block
- Sort in descending \( X \)
- From top down to each block:
  - Compute cumulative grade
  - Compute Total Stress = \( \sum_i S_i^2 \)
  for \( i^{th} \) analyte, \( S_i = (\text{Grade-Target})/\text{Tolerance} \)
- Select Cut-Off with minimum Total Stress

Revise \( \{K_1, K_2, K_3\} \) and repeat the procedure
Cumulative Grade – Sorted by Fe or by Al₂O₃

Fe

Decreasing Fe

Increasing Al₂O₃

Al₂O₃

Decreasing Fe

Increasing Al₂O₃

Max Fe
Min Al₂O₃
Target
Finding the Composite Cut-Off Function

- Max Fe, \( X = Fe \), cumulated by descending Fe
- Min Al\(_2\)O\(_3\), \( X = - Al\(_2\)O\(_3\) \), cumulated by ascending Al\(_2\)O\(_3\)
- Fitted \( X = Fe - 3.76 \text{ Al}_2\text{O}_3 \)

More generally: \( X = Fe - K_1 \text{ Al}_2\text{O}_3 - K_2 \text{ SiO}_2 - K_3 \text{ P} \)

cumulated by descending \( X \), with \( K_1, K_2, K_3 \) optimised
Cumulative Grade – Sorted by $X = \text{Fe} - 3.76 \text{Al}_2\text{O}_3$
Ore Selection - Conclusions I

- Quadrant Cut-Off – Commonly used
  - Inconsistent, therefore sub-optimal
  - Different cut-offs for different pits
    - Also inconsistent
  - But increases yield for Quadrant Method
    - “Theory of the Second Best”
Ore Selection - Conclusions II

• The Composite Cut-Off Grade model
• Preferable to Quadrant Cut-Off
• Optimal Ore Selection

  • Operationally:
    • Iterative adjustment to meet target grade

  Composite Cut-Off consistent with using Marginal Value to Maximise Net Present Value
Having Selected the Ore Blocks
they now need to be Sequenced
Ore Sequencing – Live Ore and Dead Ore

Portion of a Block Model

- **Before a Block is Mined**

<table>
<thead>
<tr>
<th>Waste</th>
<th>Live Ore</th>
<th>Waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leave</td>
<td>Live Ore</td>
<td>Dead Ore</td>
</tr>
</tbody>
</table>

- **After the Block is Mined**

<table>
<thead>
<tr>
<th>Waste</th>
<th>Live Ore</th>
<th>Live Ore</th>
<th>Live Ore</th>
<th>Leave</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leave</td>
<td>Live Ore</td>
<td>Live Ore</td>
<td>Mined</td>
<td>Leave</td>
</tr>
</tbody>
</table>
Ore Sequencing – The Available Block List

<table>
<thead>
<tr>
<th>Moved</th>
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<th>Moved</th>
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</tr>
<tr>
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<td>Moved</td>
<td>Moved</td>
<td>Live Ore</td>
<td>Waste</td>
</tr>
<tr>
<td>Leave</td>
<td>Live Ore</td>
<td>Dead Ore</td>
<td>Dead Ore</td>
<td>Leave</td>
</tr>
</tbody>
</table>

Waste blocks removed as encountered

Live Ore Blocks
- Do not underlie other blocks
- Do not create walls above a specified height

The Available Block List (ABL)
- The ABL is all current Live Ore blocks
**Grade Stress - Again**

Target Grade = $\mathbf{T} = \{T_{\text{Fe}}, T_{\text{Al}}, T_{\text{Si}}, T_{\text{P}}\}$

Tolerance = $\mathbf{t} = \{t_{\text{Fe}}, t_{\text{Al}}, t_{\text{Si}}, t_{\text{P}}\}$

Ore Grade = $\mathbf{Y} = \{Y_{\text{Fe}}, Y_{\text{Al}}, Y_{\text{Si}}, Y_{\text{P}}\}$

Then Grade Stress = $\mathbf{S} = \{S_{\text{Fe}}, S_{\text{Al}}, S_{\text{Si}}, S_{\text{P}}\}$

where $S_{\text{Fe}} = (Y_{\text{Fe}} - T_{\text{Fe}})/t_{\text{Fe}}$

Total Grade Stress = $S_T^2 = S_{\text{Fe}}^2 + S_{\text{Al}}^2 + S_{\text{Si}}^2 + S_{\text{P}}^2$

convenient single non-dimensional measure of fit

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If we can keep $S_T < 1.0$, then all analytes within tolerance
Mining Complete ABLs

Total Stress, Complete ABLs Mined

Ore Mined, Mt
Ore Sequencing – The Trimmed Block List

Any of the blocks in the ABL could be mined, in any order

The Trimmed Block List (TBL) is a subset of the ABL

The TBL is selected to:

• Mine in one period (such as one week)
• Match target grade (as closely as possible)
• Satisfy mining constraints, such as
  - Minimise equipment movement
  - Maintain set proportions from each pit, etc.
Trimming the ABL – Stage 1

Each TBL is selected by trimming the current ABL

In Stage 1

Blocks are successively rejected to improve the grade

$S_T$ is the combined Stress of blocks remaining in the TBL

$S_k$ is the Stress of the k$^{th}$ block

Remove the block with largest $S_k.S_T^T > S_T.S_T^T$

• Repeat until $S_T$ is down to an acceptable level
Trimming the ABL – Stage 1

Total Stress of a Available Block List, successively Trimmed

Successively Reduce Blocks to Mine

Blocks Mined

Total Stress

0  20  40  60  80  100
Blocks Mined

0  1  2  3
Total Stress
Mining Trimmed Block Lists

Total Stress, ABLs Trimmed to Target of 1.1

Mt

Ore Mined, Mt

0  50  100  150  200
Trimming the ABL – Stage 2

In Stage 2

- Blocks are rejected to reduce the span
- The block furthest from the centroid is removed
- This is repeated, unless $S_T$ has grown too large
  - If so, the grade criterion of Stage 1 is applied

Stage 2 continues until tonnage reaches target
Trimming the ABL – Stage 3

In Stage 3

The remaining TBL is examined

Any enclosed blocks not selected are added

Any blocks too deep are removed from the TBL

The TBL is complete, so extracted from the data

Then the next ABL is found, its TBL extracted

- And so on, through the mine
Extracting the TBL from the ABL

kt Remaining

Span, Metres

Total Stress
A Typical TBL
Simulated Mine Life Grade Control
Span for the Simulated TBLs
Conclusions

Ore Selection
• Discussed the Composite Cut-Off Grade model
• Shown it to be preferable to Quadrant Cut-Off
• Iterative adjustment to meet target grade

Ore Sequencing
• Discussed the ABL and TBL selection
• Shown how to sequence a mining schedule
  - To meet grade target
  - To satisfy mining constraints
The End

Power Corrupts
(Lord Acton)

Powerpoint Corrupts Absolutely
(Edward Tufte)

So for a fuller discussion please read the paper
The End

Any Questions
Thank You

ANY QUESTIONS?
Grade Stress

Target Grade = \( T = \{ T_{Fe}, T_{Al}, T_{Si}, T_{P} \} \)

Tolerance = \( t = \{ t_{Fe}, t_{Al}, t_{Si}, t_{P} \} \)

Ore Grade = \( Y = \{ Y_{Fe}, Y_{Al}, Y_{Si}, Y_{P} \} \)

Then Grade Stress = \( S = \{ S_{Fe}, S_{Al}, S_{Si}, S_{P} \} \)

where \( S_{Fe} = (Y_{Fe} - T_{Fe})/t_{Fe} \)

Total Grade Stress = \( S_{T}^2 = S_{Fe}^2 + S_{Al}^2 + S_{Si}^2 + S_{P}^2 \)

convenient single non-dimensional measure of fit