Stochastic Mine Planning Concepts, Applications and Contributions: From past developments to production scheduling with ‘future data’

Roussos Dimitrakopoulos
Overview

• The economic side of uncertainty
• Models of geological uncertainly
• Limits of traditional mine design optimization
• Shifting the paradigm: Stochastic mine planning
• Using uncertainty to improve project performance
• Uncertainty is great!
Risk in Mining: A World Bank Survey

• 60% of mines had an average rate of production LESS THAN 70% of planned rate

• In the first year after start up, 70% of mills or concentrators had an average rate of production LESS THAN 70% of design capacity

• Key contributor to mining risk felt in all downstream phases: Geology and reserves
Mining Project Valuation

Traditional view

Risk oriented view

Mining Process or Transfer Function

Orebody Model

Single estimated model

Multiple probable models

Financial and Production Forecasts

Mine Design

Production Scheduling

Single, often precise, wrong answer

Unknown, true answer

Accurate uncertainty estimation

Probabilities
Quantitative Models of Geological Uncertainty:

Stochastic or geostatistical conditional simulations
Describing the Uncertainty about a Gold Deposit

Model characteristics:

- Large number of blocks
- Multiple domains
- Resource classes with specific sample selection criteria
Describing the Uncertainty about a Gold Deposit
Uncertainty is not a “Bad Thing”

Many managers believe that uncertainty is a problem and should be avoided…..

… you can take advantage of uncertainty. Your strategic investments will be sheltered from its adverse effects while remaining exposed to its upside potential. Uncertainty will create opportunities and value.

Once your way of thinking explicitly includes uncertainty, the whole decision-making framework changes.

Martha Amram and Nalin Kulatilaka in “Real Options”
Moving Forward in Optimization

Limits of traditional mine design

Using models of uncertainty
Open Pit Mine Design and Production Scheduling

pushbacks

Pit Limit
Risk Analysis in a Mine Design

Limits of Traditional Modelling

The expected project NPV has only 2 – 4% probability to be realised.
Moving Forward ….. Step 1

Exploring existing technologies
## Past Work – Open Pit Mine Design

<table>
<thead>
<tr>
<th>Pit Design</th>
<th>Upside Potential (m$)</th>
<th>Downside Potential (m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CB-1</td>
<td>CB-2</td>
</tr>
<tr>
<td>CB-1</td>
<td>2.3</td>
<td>2.41</td>
</tr>
<tr>
<td>CB-2</td>
<td>1.3</td>
<td>2.1</td>
</tr>
<tr>
<td>CB-3</td>
<td>2.4</td>
<td>2.43</td>
</tr>
<tr>
<td>CB-4</td>
<td>2.9</td>
<td>2.40</td>
</tr>
</tbody>
</table>
Moving Forward ..... Step 2

Re-writing optimizers
Models of Uncertainty in Optimization

Integer Programming

An objective function

Maximise \((c_1x_1^1 + c_2x_2^1 + \ldots )\) ...

Subject to

\[c_1x_1^1 + c_2x_2^1 + \ldots \geq b_1\]
\[
\vdots \\
\vdots \\
\vdots \\
\]

\[c_1x_1^p + c_2x_2^p + \ldots \geq b_p\]

\(c = \text{constant}\)

\(X_1^1 = \text{binary variable}\)

Period 1

Period p
The objective function now…..

Maximise \((s_{11}x_1^1+s_{21}x_2^1+\ldots s_{12}x_1^1+s_{22}x_2^1+\ldots)\).

Subject to

\[ s_{11}x_1^1+s_{21}x_2^1+\ldots \geq b_1 \]

\[ s_{1r}x_1^p+s_{2r}x_2^p+\ldots \geq b_1 \]

Period 1
Simulated model 1

Simulated model 2

Period p
Simulated model r
Higher NPV for Less Risk

“Uncertainty will create opportunities and value”
Uncertainty is Good: “Base case” vs “Risk-based”

Difference 28%
Discounting Geological Risk

The discounting goes along with production sequencing
SIP - Production Scheduling Model

Objective function

\[
\text{Max } \sum_{t=1}^{P} \left[ \sum_{i=1}^{N} E\{(NPV)_i^t\} b_i^t \right]
- \sum_{s=1}^{M} (c_{u}^{ty} d_{su}^{ty} + c_{1}^{ty} d_{sl}^{ty})
- \sum_{i=1}^{U} E\{(NPV)_i^t + MC_i^t\} * s_i^t
+ \sum_{s=1}^{M} (SV)_{s}^{t} (P) q_{s}^{t}
\]
Stochastic Integer Programming - SIP

A production schedule

- Orebody Model 1
  - Ore Grade 1 Metal
  - Deviation 1
    - TARGET [ ]

- Orebody Model 2
  - Ore Grade 2 Metal
  - Deviation 2
    - TARGET [ ]

- Orebody Model R
  - Ore Grade R Metal
  - Deviation R
    - TARGET [ ]
Managing Risk Between Periods

Deviations from metal production target

Metal quantity (1000 Kg)

Periods

$C_t = C_{t-1} \times RDF_{t-1}$

$RDF_t = \frac{1}{(1+r)^t}$

RDF – risk discounting factor

$r$ – orebody risk discount rate
Uncertainty is Good: Traditional vs Risk-Based

Cumulative NPV values
- SIP model
- WFX

Average NPV values
- SIP model
- WFX

Geological Risk Discounting = 20%

Difference = 17%

Risk Based $723 M
Traditional $609 M
Future Drilling Data

Production sequencing with simulated grade control drilling
‘Future’ Grade Control Data

Bench/Section of pit already mined out

- Exploration data
- Grade control data

Define relationship

Bench/Section of pit NOT yet mined out

- Exploration data
  - Simulate grade control data
Scheduling and Simulated Future Data

**Step 1**
Simulation of orebody models from exploration data

- SIP formulation
- Derive production schedule using SIP formulation

**Step 2**
Simulation of high density future grade control data

- Updating of the existing orebody models with the future data
- SIP formulation
- Derive production schedule using SIP formulation

**Step 3**
Schedules:
- SIP schedule derived from simulations based on exploration data
- SIP schedule derived from simulations based on simulated grade control information (updated models)
- Risk analysis of mine’s schedule with the updated models
Scheduling and Simulated Future Data

SIP and Simulated Orebody

SIP and Simulated Future Data
Scheduling and Simulated Future Data

Mine’s Schedule

SIP & Simulated Orebody

SIP & Future data

Period (years)
1. 2005
2. 2006
3. 2007
4. 2008
5. 2009
## Scheduling and Simulated Future Data

<table>
<thead>
<tr>
<th></th>
<th>Simulations (exploration data)</th>
<th>Updated simulations (future data)</th>
<th>Mine’s schedule (future data)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore Tonnes (Mt)</td>
<td>14</td>
<td>18</td>
<td>10</td>
</tr>
<tr>
<td>Metal Tonnes (Mt)</td>
<td>52</td>
<td>55</td>
<td>38</td>
</tr>
<tr>
<td>NPV ($ Mil.)</td>
<td>552</td>
<td>560</td>
<td>330</td>
</tr>
</tbody>
</table>
Uncertainty is Great

And we will eventually find out