Smart Mining Complexes and Mineral Value Chains:

A technological perspective on risk management and sustainability

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Outline

• Introduction

• Modelling mining complexes / mineral value chains with uncertainty

• Stochastic simultaneous optimization and advantages

• Examples: Higher value for lower risk

• Conclusions
A mining complex may be seen as an *integrated business* starting from the extraction of materials to a set of sellable products delivered to various customers and/or spot market.

Critical facets of this integrated business are underlying uncertainties (stochasticity):

- materials produced from the mines
- metal’s spot market price
Introduction - Conventional Workflow

Orebody Modelling → Mine Design & Production Scheduling → Financial & Production Forecasts

An Orebody Model

Conventional Design

Deterministic Optimization Methods
Introduction – Deterministic Workflow

Limits of current-generation optimizers:

1. Evaluating the $ value of the block independently of others.

2. Ignore **non-linear transformations** in the processing stream that act on the blend of materials (e.g. non-linear grade-recovery). **Average in ≠ Average out**

3. Can substantially undervalue the resource by ignoring the power of blending.

4. Uncertainty in material types, chemistry, grades, rock properties.
Introduction – Stochastic Workflow

Stochastic Orebody Modelling — Stochastic Mine Design & Production Scheduling — Financial & Production Forecasts

Simulated Orebody Models

Stochastic Design & Production Schedule

A set of the above scenarios is the quantified model of geological uncertainty
Introduction – Innovation & cross disciplinary integration

Bench in a gold deposit being mined

Black indicates DDH grade above 1.3 g/t and grey between 0.7 and 1.3 g/t

Estimated deposit bench, methods 1&2

Real blast hole data

Real mineral deposits are highly variable, not smooth

10x10x5m blocks
Introduction – Stochastic Workflow

Quantified Uncertainty about a Gold Deposit

A mature, well drilled and understood gold deposit

Model characteristics:
- Large number of blocks
- Multiple domains
- 20 simulations: 557 million nodes
- 27 million mining blocks

Lode 1502

3 simulated scenarios of the same section (SMU grade)
Introduction – Risk Management and Risk Reporting

Risk in Mining
Australasian Examples

Core issue in deviations from expectations:
Geological uncertainty

Reporting Risk - Example:
NPV Distribution

Baker and Giacomo (1998)
Introduction – Stochastic Mine Planning

Stochastic schedule within the Deterministically optimal pit limits

Stochastically optimal pit limits

Stochastic vs Deterministic Scheduling Approaches

- Lower risk in meeting forecasts
- Higher value for less risk
- Larger pit limits
- More metal
Introduction – Stochastic Mine Planning

Uncertainty in ore production - Stochastic

Uncertainty in ore production - Deterministic

Introduction – Stochastic Mine Planning

Uncertainty in ore production - Stochastic

Uncertainty in ore production - Deterministic

90%
10%
Forecast/Target - Deterministic
Expected ore
Introduction – Stochastic Mine Planning

- Lower risk in meeting forecasts
- Higher value for less risk
- Larger pit limits
- More metal

Stochastic schedule within the deterministically optimal pit limits

Stochastic vs Deterministic Scheduling Approaches

- Lower risk in meeting forecasts
- Higher value for less risk
- Larger pit limits
- More metal

Cumulative NPV (M x $) vs Production Period (Years)
Approaches to Uncertainty

• An Example:

Calculating the economic value of a block using a marginal cut-off grade

Probability Distribution of a Block's Copper Grade

Mean: 0.118% Cu
Marginal cut-off: 0.2015% Cu

Copper price: $4410/t
Recovery: 90%
Processing cost: $6/t
Mining cost: $2/t
Block tonnage: 14465
Deterministic Approach to Uncertainty

A block’s economic value, according to a deterministic optimizer

Copper price: $4410/t  ($2/lb Cu)
Recovery: 90%
Processing cost: $6/t
Mining cost: $2/t
Block tonnage: 14465 t

\[
\text{Value} = \left\{ \begin{array}{ll}
\$4410 \cdot 0.9 \cdot \frac{0.118}{100} \cdot 14465 - (\$2 + \$6) \cdot 14465 & \text{if processed as ore} \\
-\$2 \cdot 14465 & \text{if processed as waste}
\end{array} \right.
\]

\$ -47974  \quad \text{if processed as ore}
\$ -28930  \quad \text{if processed as waste}

This block’s estimated grade lies below the marginal cut-off grade. A deterministic optimizer will only mine this block as waste, with a value of $-28930.
A stochastic optimizer *may* choose to mine this block with an expected value of $21457. However, this is a risky block if we wish to feed a mill up to its capacity.

**Stochastic optimizers account for this risk, in addition to its potential value.**
Introduction – Stochastic Mine Planning

Stochastic Integer Programming

The objective function is ....

Maximize \((s_{11}x_1^1+s_{21}x_2^1+... \quad s_{12}x_1^2+s_{22}x_2^2+... \quad ) \quad ...

Subject to

\[ s_{11}x_1^1+s_{21}x_2^1+... = b_1 \]
\[ s_{11}x_1^p+s_{21}x_2^p+... = b_1 \]
\[ s_{12}x_1^p+s_{22}x_2^p+... = b_1 \]
\[ s_{1r}x_1^p+s_{2r}x_2^p+... = b_1 \]

\rightarrow \text{Period 1}
\text{Simulated model 1}
\rightarrow \text{Simulated model 2}
\rightarrow \text{Simulated model r}
\rightarrow \text{Period p}
Economic Mining Block Value, when optimizing, is driven by the economic values of the blocks mined rather than the products produced.

\[
\text{VALUE for A MINING BLOCK} = (\text{METAL} \times \text{RECOVERY} \times \text{PRICE} - \text{ORE} \times \text{COSTP}) - \text{ROCK} \times \text{COSTM}
\]

**CHANGE CONTEXT and USE ONLY geological attributes: Material Types, Grades ....**
Simultaneous Optimization of Mining Complexes - Mineral Value Chains for Decision Support Extending models
Simultaneous optimization can focus on the $ value of products sold rather than the $ value of individual blocks.
Simultaneous Optimization

Example: Nickel laterite mineral value chain - Blending policy optimization

Objectives:
1. Maximize NPV
2. Satisfy SiO₂:MgO blend
3. Minimize deviations from plant capacity target

*Tₘₐₓ is the maximum plant feed tonnage
Simultaneous Optimization

Nickel Laterite Complex – Risk Analysis of Deterministic Design

Orebody simulations quantify:
- Volumetric uncertainty
- Multi-element uncertainty
Simultaneous Optimization

Nickel Laterite Complex – Deterministic Simultaneous Optimization

Plant Feed Silica-to-Magnesia Ratio

Plant Feed Tonnage

- P-10 & P-90
- P-50
- Deterministic
Simultaneous Optimization

Nickel Laterite Complex – Risk Analysis of Deterministic Design

Plant Feed Silica-to-Magnesia Ratio - Risk Analysis

Plant Feed Tonnage - Risk Analysis

- P-10 & P-90
- P-50
- Deterministic
Stochastic Simultaneous Optimization

Ni Simulations
SiO₂ Simulations
MgO Simulations

Nickel Laterite Mine Production Schedule

Period: 1 10 20 30
Stochastic Simultaneous Optimization

Nickel Laterite Complex - Stochastic Simultaneous Optimization

Plant Silica-to-Magnesia Ratio - Stochastic Solution

Plant Feed Tonnage - Stochastic Solution

- P-10 & P-90
- P-20 & P-80
- P-50
- Deterministic
Modelling Mining Complexes with Uncertainty

New mathematical models
Stochastic Optimisation Formulation

• Adaptable two-stage stochastic integer programming model with CAPEXs:

\[
\max \frac{1}{||S||} \sum_{t \in T} \sum_{s \in S} \sum_{a \in A} p_{a,t} \cdot v_{a,t,s} - \frac{1}{||S||} \sum_{t \in T} \sum_{s \in S} \sum_{a \in A} (c^+_{a,t} \cdot u_{a,t,s} + c^-_{a,t} \cdot l_{a,t,s})
\]

Attributes of interest:
• Revenues from metal sale
• Mining, processing & stockpiling costs

Penalties for deviations from targets
• Mining, stockpile, processing capacities
• Blending constraints
• Deleterious elements

\[
v_{a,t,s} - u_{a,t,s} \leq U_{a,t} \quad \forall a \in A, s \in S, t \in T
\]

\[
v_{a,t,s} + l_{a,t,s} \geq L_{a,t} \quad \forall a \in A, s \in S, t \in T
\]
Stochastic Simultaneous Optimization Formulation

- Adaptable two-stage stochastic integer programming model:

\[
\max \frac{1}{|S|} \sum_{t \in T} \sum_{s \in S} \sum_{a \in A} p_{a,t} \cdot v_{a,t,s} - \frac{1}{|S|} \sum_{t \in T} \sum_{s \in S} \sum_{a \in A} (c_{a,t}^+ \cdot u_{a,t,s} + c_{a,t}^- \cdot l_{a,t,s})
\]

**Attributes of interest:**
- Revenues from metal sale
- Mining, processing & stockpiling costs

**1. Risk reduction.**
**2. Risk deferral (geological risk discounting).**
Stochastic Optimisation Formulation

- Adaptable two-stage stochastic integer programming model with CAPEXs:

\[
\max \frac{1}{|S|} \sum_{t \in T} \sum_{s \in S} \sum_{a \in A} p_{a,t} \cdot v_{a,t,s} - \frac{1}{|S|} \sum_{t \in T} \sum_{s \in S} \sum_{a \in A} \left( c_{a,t}^+ \cdot u_{a,t,s} + c_{a,t}^- \cdot l_{a,t,s} \right) \\
- \sum_{t \in T} \sum_{k \in K} p_{k,t} \cdot w_{k,t}
\]

\[
v_{a,t,s} - u_{a,t,s} \leq U_{a,t} + \sum_{t' = t - \lambda_k + \tau_k}^t \kappa_{a,k} \cdot w_{k,t'}
\]

\[
v_{a,t,s} - l_{a,t,s} \geq L_{a,t} + \sum_{t' = t - \lambda_k + \tau_k}^t \kappa_{a,k} \cdot w_{k,t'}
\]

Change of capacities depends on:
- Quantity purchased \((w_{k,t'})\)
- Constraint increase \((\kappa_{a,k})\)
- Life of equipment \((\lambda_k)\)
- Lead time \((\tau_k)\)
Modelling Mining Complexes with Uncertainty

Sulfides - Mine 1
- Metal tonnes
- Total tonnes

Sulfides - Mine 2
- Metal tonnes
- Total tonnes

Processing Stream A
1. Total metal
2. Total tonnes
3. Head grade
4. Recovery
5. Throughput
6. Metal recovered

Customer #1 (Contract)
1. Metal
2. Metal value

Customer #2 (Exchange)
1. Metal
2. Metal value
Modelling Mining Complexes with Uncertainty

Production schedule

Sulfides - Mine 1
- Metal tonnes
- Total tonnes

Sulfides - Mine 2
- Metal tonnes
- Total tonnes

Destination policies

Processing Stream A
1. Total metal
2. Total tonnes
3. Head grade
4. Recovery
5. Throughput
6. Metal recovered

Cash flows, Decisions, GEOMET... All move here

Decision variables have a direct impact on the distributions over time

No Economic Values for Mining Blocks Used

Customer #1 (Contract)
1. Metal
2. Metal value

Customer #2 (Exchange)
1. Metal
2. Metal value
There is no need to simplify our models of the value chain.
The Twin Creeks Gold Mining Complex, Nevada
Twin Creeks (TC) gold mining complex

- Mega Pit
  - Extraction Capacity
    - Sulphide piles
      - TRJV
      - Mill 5
      - Mag
    - Sage Autoclave
    - Waste Dumps
    - Oxide Leach
    - Juniper Mill
    - Oxide stockpiles
  - Vista Pit

- Other Sources
  - Blending is crucial!

- Gold
Base Case

Long-term Production Schedule

& Risk Analysis

Twin Creeks Gold Mining Complex, Nevada
Base case - Sources of supply uncertainty

Mega Pit
Sulphide Stockpiles
Sage Autoclave
Vista Pit

Other Sources
TRJV
Mill 5
Mag

Stochastic simulations
Historical data

Juniper Mill
Oxide Leach

Stochastic simulations
Base case - DCF & Risk analysis
Base case - Gold recovered & Risk analysis

![Gold recovered graph](image)

**Gold recovered**

- **Year**: 1, 3, 5, 7, 9, 11, 13
- **Au**: Estimation, Scenarios
Base case - Gold recovered & Risk analysis

Cumulative gold recovered

Year

Cumulative gold recovered

Estimation  P10  P50  P90
## Base case - Blending: Acid consumption

<table>
<thead>
<tr>
<th>Year</th>
<th>Acid consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
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<tr>
<td>5</td>
<td>5</td>
</tr>
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<td>9</td>
<td>9</td>
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<tr>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>13</td>
<td>13</td>
</tr>
</tbody>
</table>

![Acid consumption chart](image)

Legend:
- **Blue** - Estimation
- **Gray** - Scenarios
- **Brown** - Limit
Stochastic
Long-term Production Schedule

Production schedule (I):
within the conventionally ‘optimal’ pit

Production schedule (II):
without imposed pit limits
Stochastic schedule I - Cumulative DCF

Cumulative DCF Cashflows

Year

$\$

P50 Base Case  P10  P50  P90
Stochastic schedule I - Recovered gold

Gold recovered

Au

Year

1 3 5 7 9 11 13

P50 Base Case Scenarios
Stochastic schedule I - Recovered gold

Cumulative gold recovered

Year

Cumulative gold recovered

P50 Base Case
P10
P50
P90
Stochastic schedule I – Blending: Acid consumption

Acid consumption

Year

P50 Base Case  Scenarios  Limit
Stochastic schedule I - Sections

Base Case: Mega

Stochastic: Mega

Base Case: Vista

Stochastic: Vista

Period 1 to 10
Stochastic schedule II - More ore, larger pit

Simultaneous optimization of the mining complex decides the pit limits:
1 extra year of ore to the autoclave  (Pit 11% larger)

Conventional pit limit

Stochastic pit limit

Sage autoclave processed tons

Production

Year

1 3 5 7 9 11 13 15

P50 Base Case  Scenarios
Optimizing with Joint Supply (metal) and Demand (commodity price) Uncertainty
Contracts & Value Chain Optimizers

Joint metal ($S$) and commodity price ($S'$) uncertainty

- Objective function

\[
\text{Maximize } \sum_{sxs'} \sum_t \frac{1}{[1+\gamma]^t} \left[ \text{Revenue}_{t,s} - \text{ProductionCost}_{t,s} - \text{TransCost}_{t,s} \right] - \text{TransCapInvest}
\]
Contract Design: Numerical Results

• Optimal contract price – for a given mining complex under joint metal and commodity price uncertainty
Conclusions

• Stochastic simultaneous optimization coordinates LOM production schedules, destination policies and processing streams.

• Focus on value of products sold rather than materials mined.

• Decentralized approach for evaluating processing streams permits detailed modelling, including geometallurgical responses.

• Nickel laterite example shows ability to create multi-element blending policies while considering uncertainty.

• Copper mining complex demonstrates ability to simultaneously optimize production rates, with less risk and higher NPV.
Thanks are in order to our
Cosmo Industry Members and
Government Research Funding Agencies
New Scholarship: MES-COSMO Scholarship 2016-2020 (3,000$/year)

For undergraduate students working on projects related to:

Strategic mine planning optimization under uncertainty and related risk management

Details to appear shortly on: http://www.cimmes.org/

COSMO Mining Industry Consortium & Management & Economics Society of CIM

[Logos of AngloGold Ashanti, BARRICK, bhp billiton, De Beers, Newmont, COSMO Lab, VALE, and Kinross]
Algorithmic Optimization with Metaheuristics

• Computationally prohibitive optimization models, in the past.

Mine 1
400,000 blocks
400 destination decisions/y
30 years
30 simulations

Mine 2
50,000 blocks
40 destination decisions/y
10 years
15 simulations

Mine 3
250,000 blocks
100 destination decisions/y
25 years
20 simulations

Stockpile
Mill 1
Mill 2
Waste

• 9,000 joint scenarios
• 18,750,000 scheduling decision variables
• 62,500 destination policy variables
• 540,000 processing stream variables
Algorithmic Optimization with Metaheuristics

**Particle Swarm Optimization**
- Robust destination policies ($d_{c,j,t}$)
- Processing stream variables* ($p_{i,j,t,s}$)
- Capital expenditures ($w_{k,t}$)

**Simulated Annealing**
- Robust destination policies ($d_{c,j,t}$)
- Robust production schedule* ($x_{b,t}$)
- Capital expenditures ($w_{k,t}$)
Introduction – Innovation & cross disciplinary integration

Bench in a gold deposit being mined

Black indicates DDH grade above 1.3 g/t and grey between 0.7 and 1.3 g/t

Estimated deposit bench, 2 methods

Real blast hole data

Real mineral deposits are not smooth

10x10x5m blocks
Blastholes grades and simulated blasthole grades from exploration data
The Representation of Mineral Deposit and Attributes MATTERS to Mine Planning Optimization: *Estimated* (●) vs *simulated* models (—) as inputs ...

A Nickel Deposit:
Volume above Ni Cutoff
Grade for all Min, Med and Max orebody simulated boundaries

(wireframes)

VS conventional

*Misrepresentation from smoothing* seen above in grade-tonnage curves (from any estimation method, including the “averages” from simulated realizations), has adverse effects on the deterministic optimization conventionally utilized in mine planning.
Sources of Uncertainty

**Other fields of Engineering:** Petroleum Reservoir Engineering has moved away from Estimation models since the late 1980’s (from the Stanford U related research)

- Oil recovery forecasting (EOR) – Production forecasts: Examples

Forecasts above come from multiphase flow simulation

**THE CORE REASON WE USE SIMULATED DEPOSITS IN RESERVOIR FORECASTING**