CIM Distinguished Lecturers Program 2015-2016

Smart Mining Complexes and Mineral Value Chains:

A technological perspective on risk management and sustainability

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COSMO – *Stochastic Mine Planning Laboratory* - http://cosmo.mcgill.ca/

Outline

- Introduction
- Modelling mining complexes / mineral value chains with uncertainty
- Stochastic simultaneous optimization and advantages
- Examples: Higher value for lower risk
- Conclusions

Mining Complexes and Mineral Value Chains

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

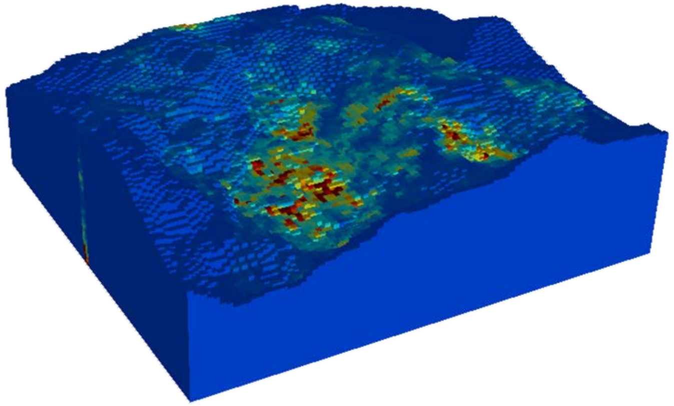
Critical facets of this integrated business are underlying uncertainties (stochasticity):

- materials produced from the mines
- metal's spot market price

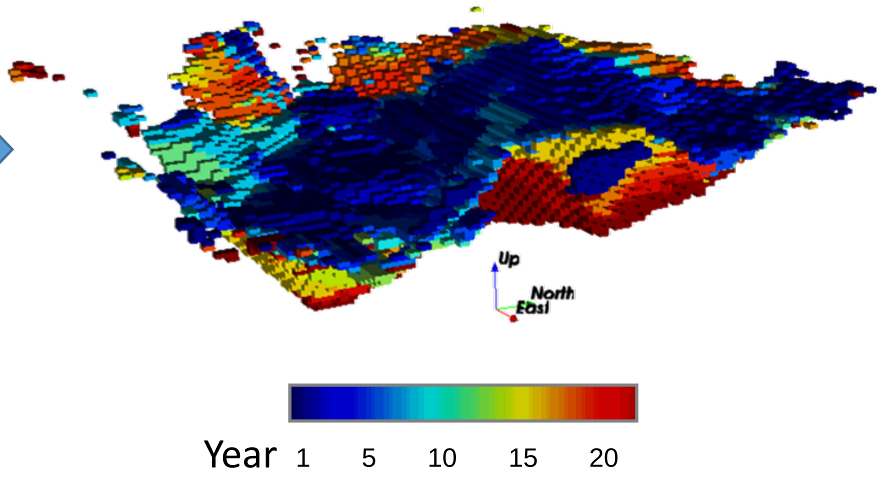
Introduction - Conventional Workflow

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

An Orebody Model

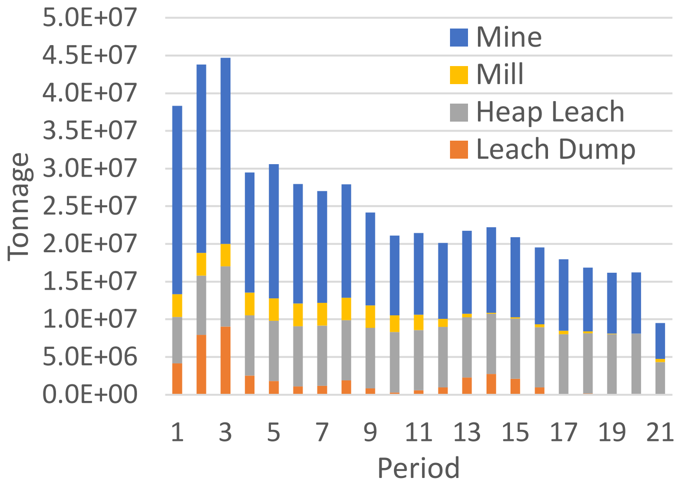


Conventional Design

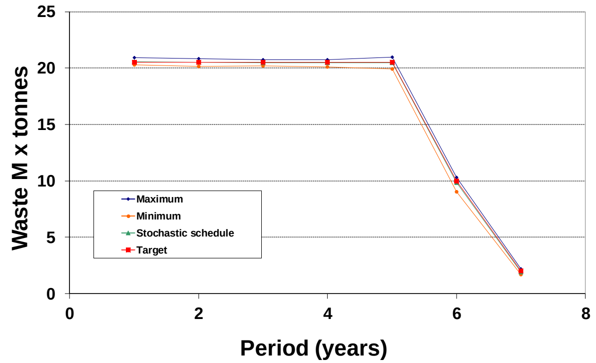


Deterministic Optimization Methods

Mine Production - Ore



Mine Production - Waste



Introduction – Deterministic Workflow

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

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).

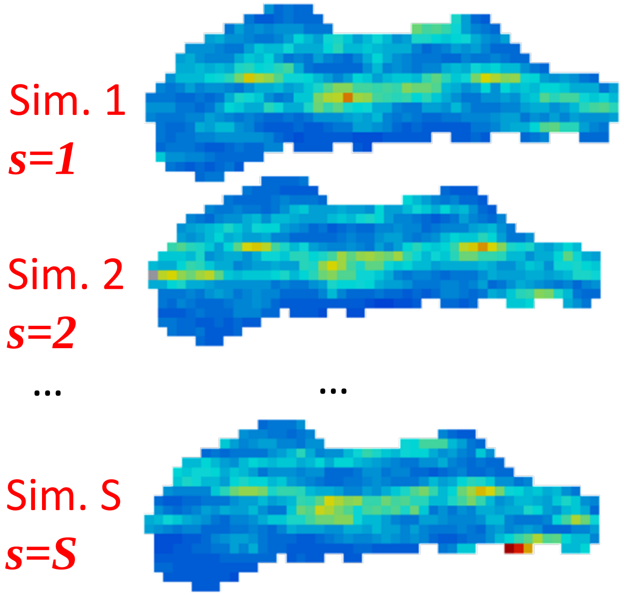
   Average in ≠ Average out

3. Can substantially undervalue the resource by ignoring the power of blending.
4. Uncertainty in material types, chemistry, grades, rock properties.

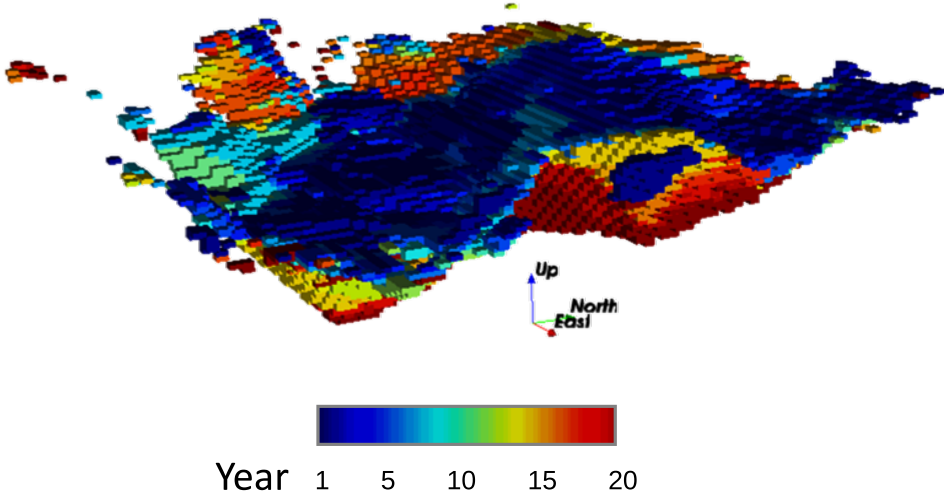
Introduction – Stochastic Workflow

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

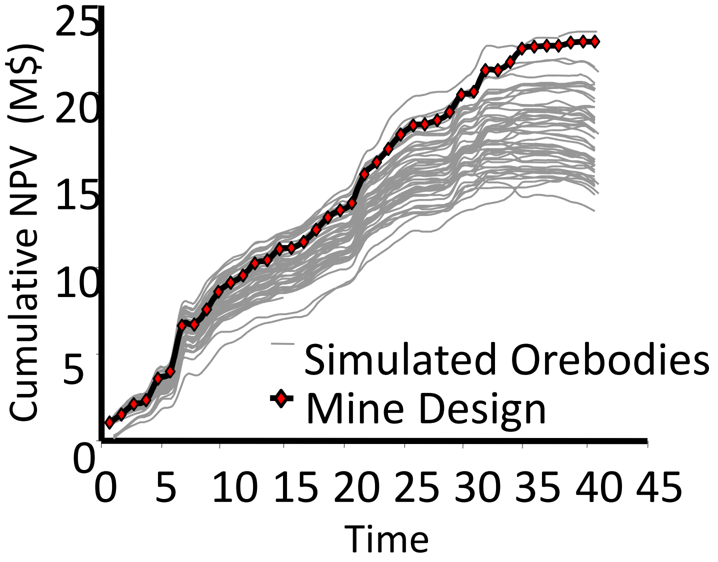
Simulated Orebody Models



Stochastic Design & Production Schedule



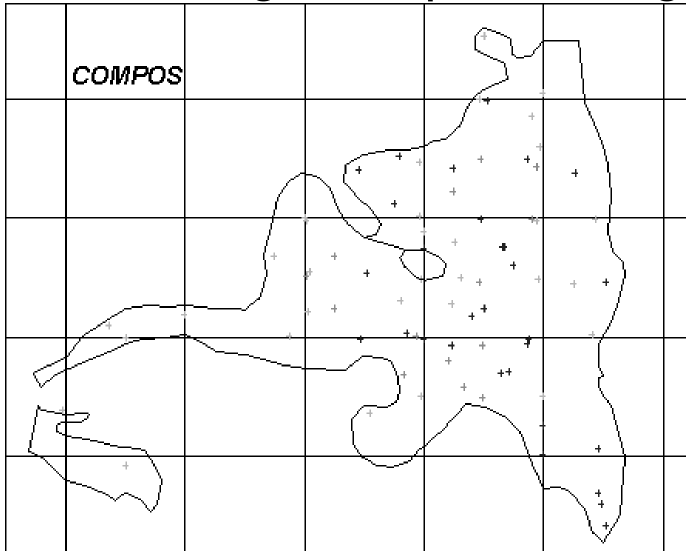
Probabilistic Reporting



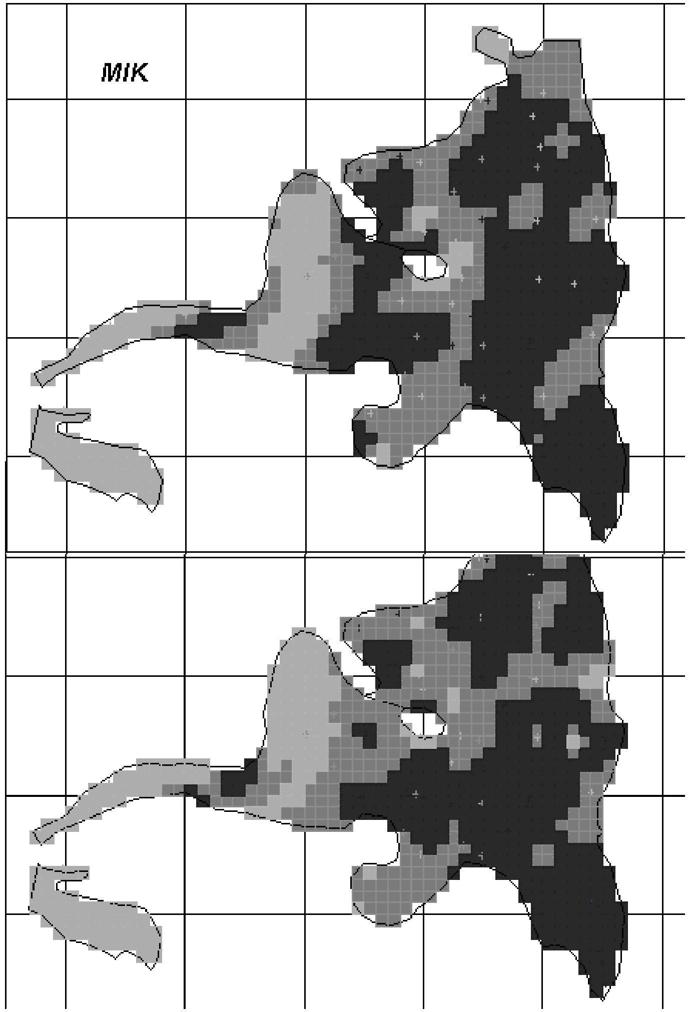
A set of the above scenarios is the quantified model of geological uncertainty

Introduction – Innovation & cross disciplinary integration

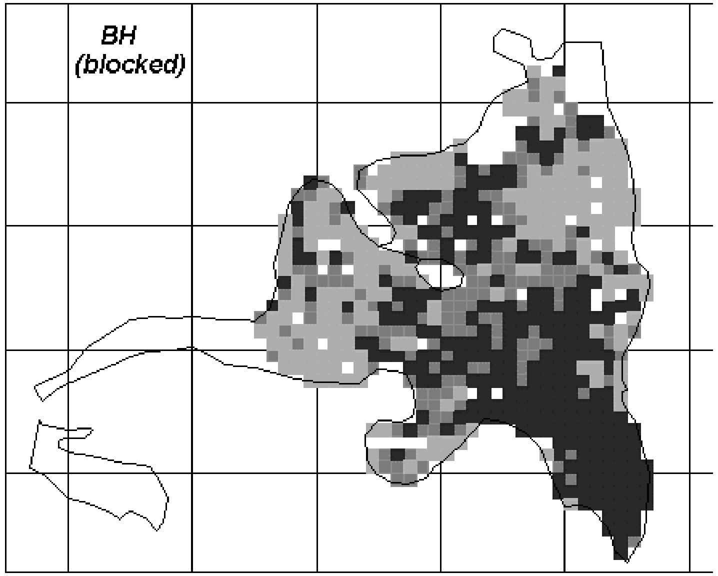
Bench in a gold deposit being mined



Estimated deposit bench, methods 1&2



Real blast hole data



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

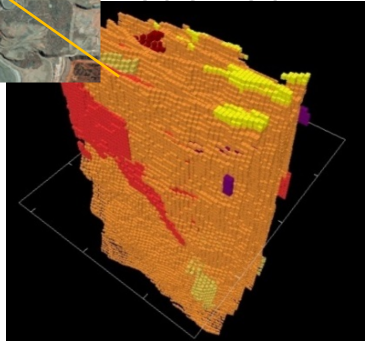
Real mineral deposits are highly variable, not smooth

10x10x5m blocks

Introduction – Stochastic Workflow

Quantified Uncertainty about a Gold Deposit

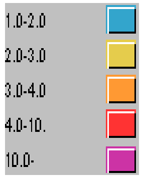
Lode 1502



A mature, well drilled and understood gold deposit

Lode 1502

3 simulated scenarios of the same section (SMU grade)

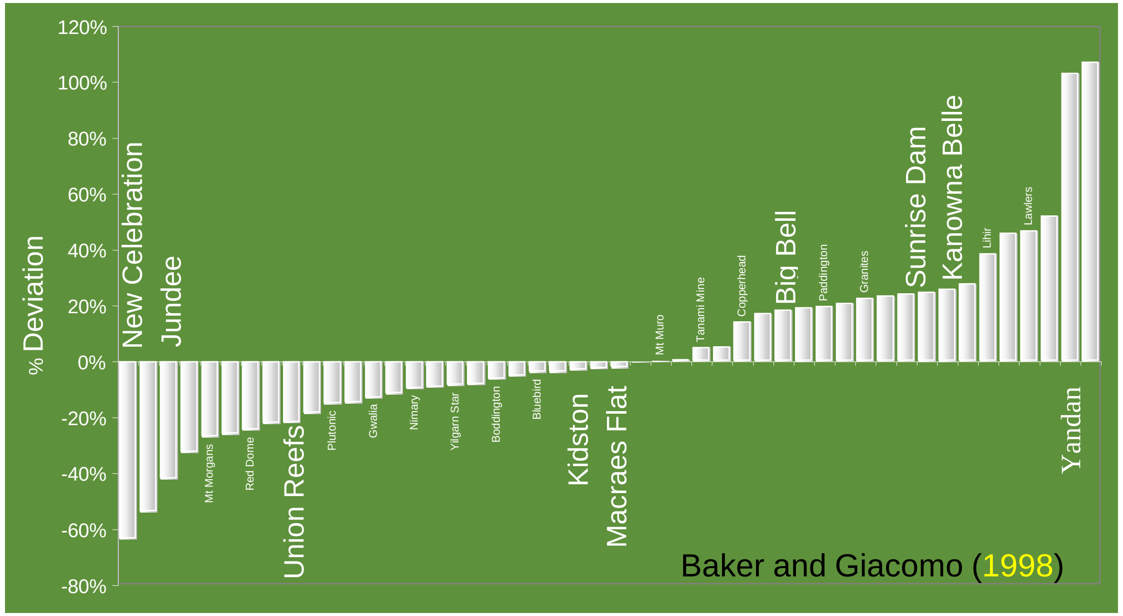


Model characteristics:

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

Introduction – Risk Management and Risk Reporting

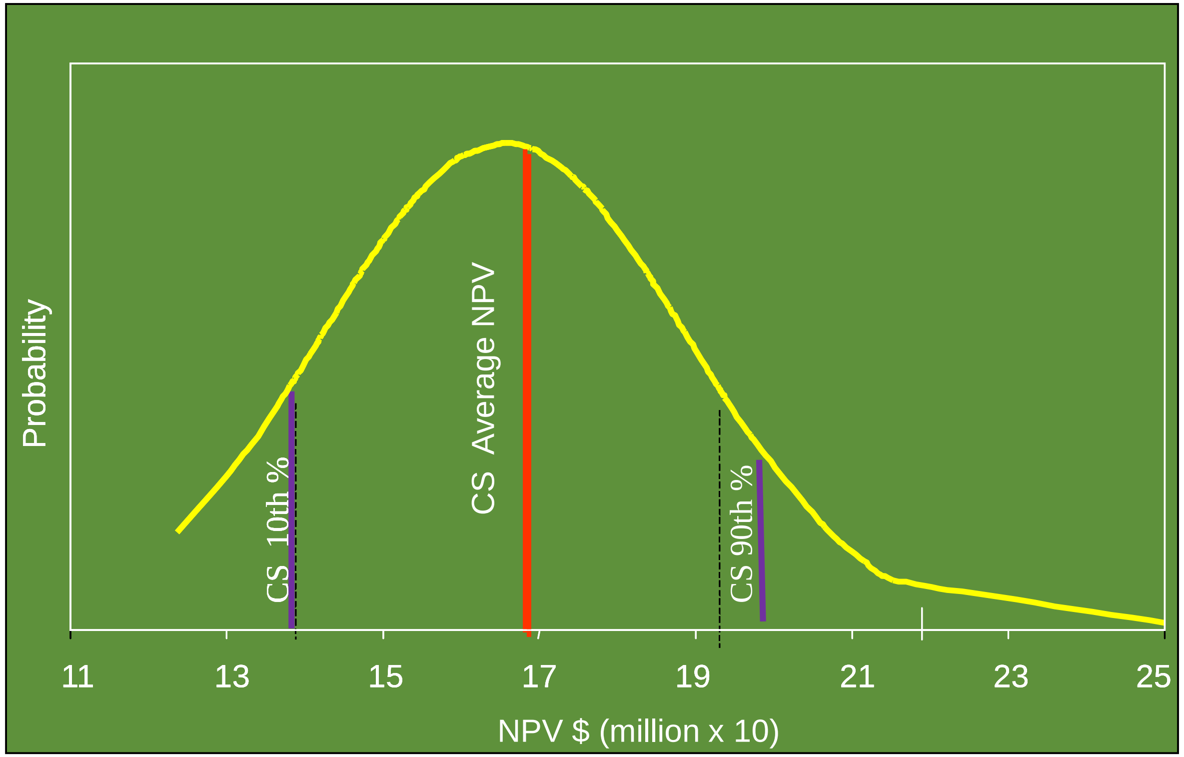
Risk in Mining
Australasian Examples



Core issue in deviations from expectations:

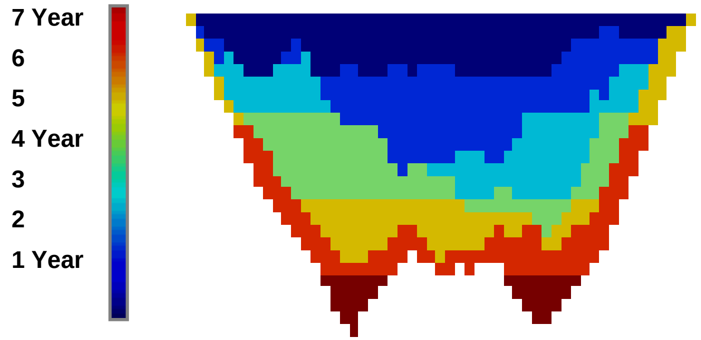
Geological uncertainty

Reporting Risk - Example: NPV Distribution

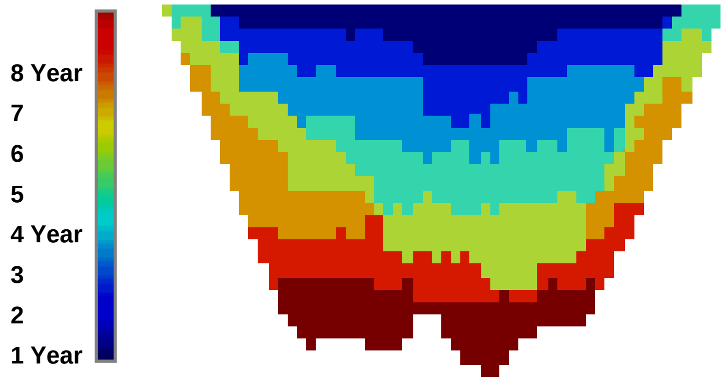


Introduction – Stochastic Mine Planning

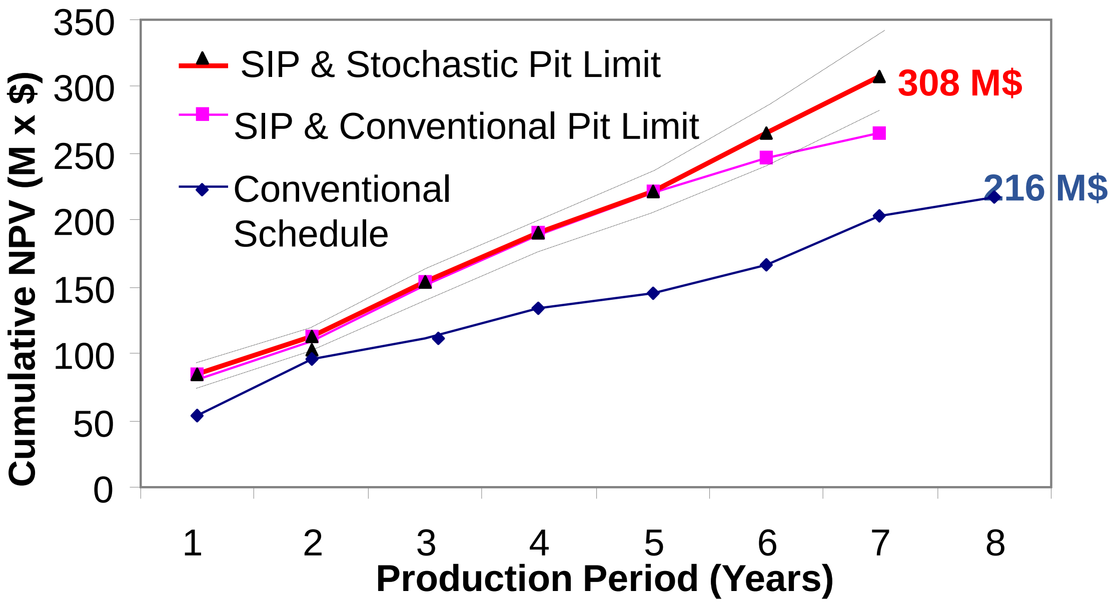
Stochastic schedule within the Deterministically optimal pit limits



Stochastically optimal pit limits

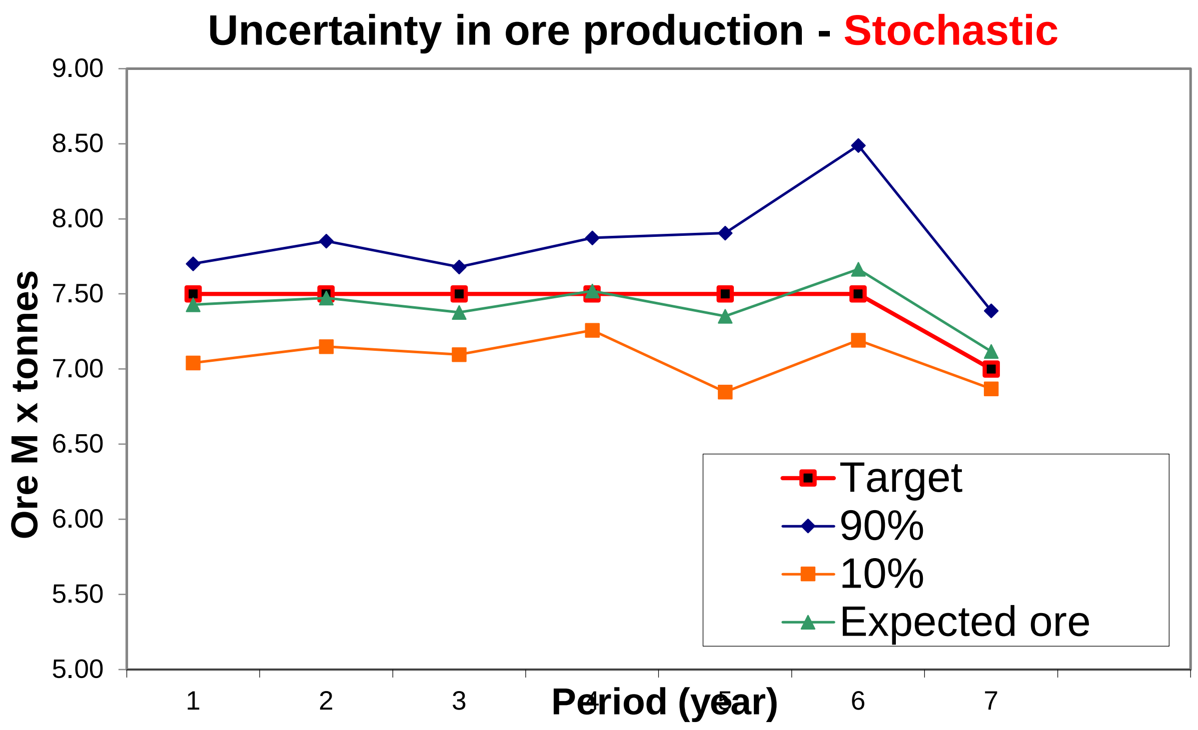


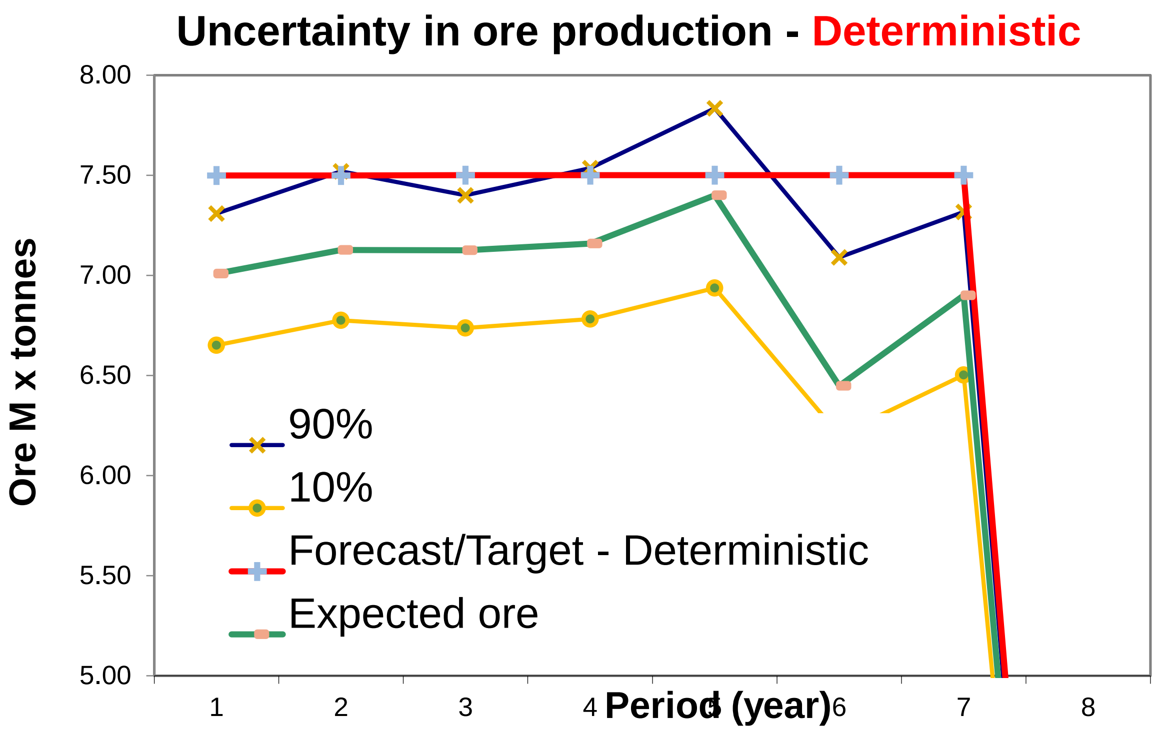
Stochastic vs Deterministic Scheduling Approaches



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

Introduction – Stochastic Mine Planning





Introduction – Stochastic Mine Planning

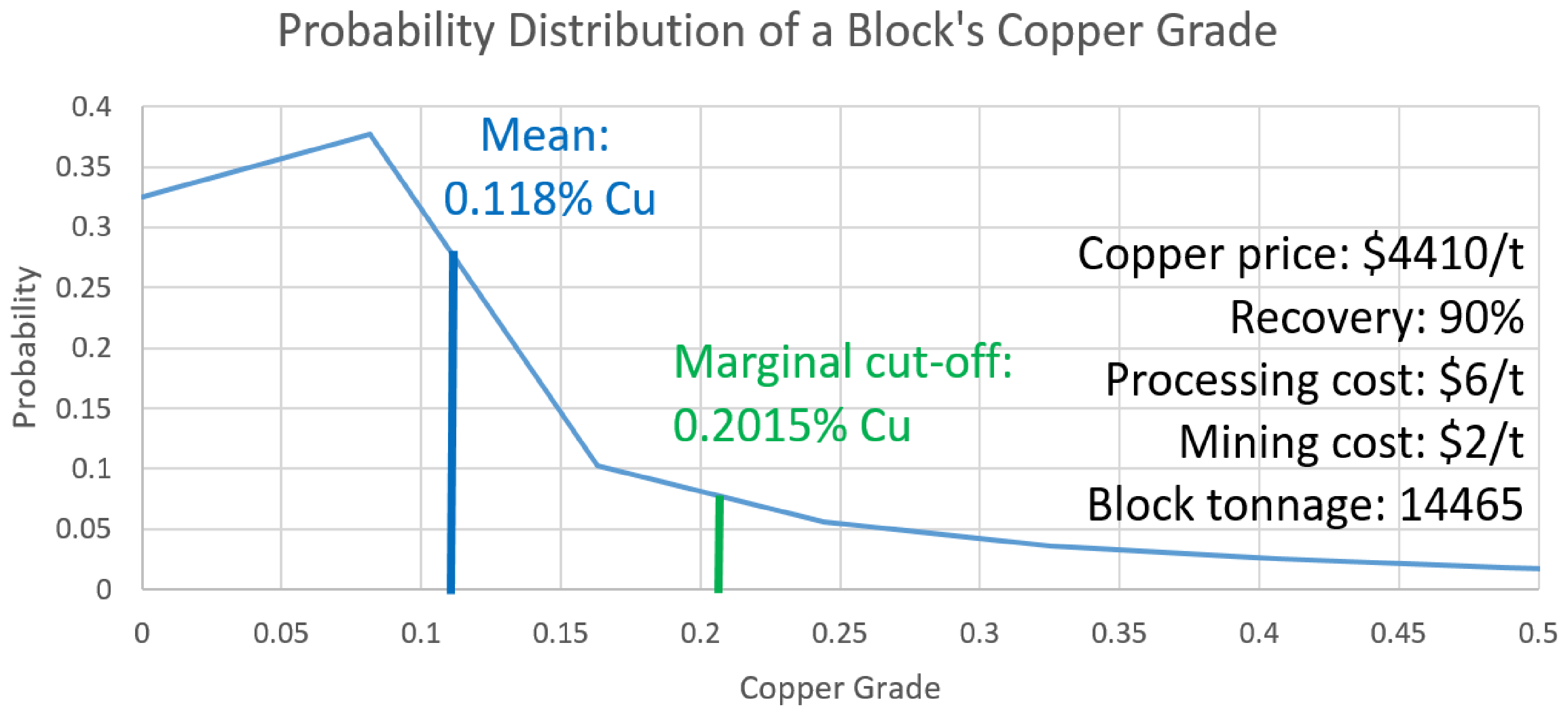
- Lower risk in meeting forecasts
- **Higher value for less risk**
- Larger pit limits
- More metal

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

Approaches to Uncertainty

- An Example:

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



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

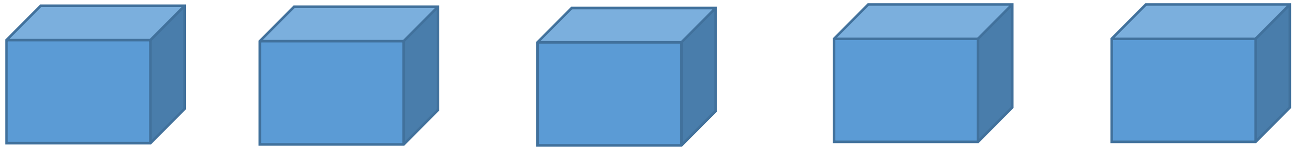
Estimated ('expected' or average) grade: 0.118% Cu

$$\$\,Value = \begin{cases} \$4410 \cdot 0.9 \cdot \dfrac{0.118}{100} \cdot 14465 - (\$2 + \$6) \cdot 14465 = \$ - 47974 & \text{if processed as ore} \\ -\$2 \cdot 14465 = \$ - 28930 & \text{if processed as waste} \end{cases}$$

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.

Stochastic Approach to Uncertainty

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



Average grade is 0.118% Cu

$$\$\,Value = \begin{cases} \$4410 \cdot 0.9 \cdot \dfrac{g}{100} \cdot 14465 - (\$2 + \$6) \cdot 14465 & \text{if processed as ore} \\ -\$2 \cdot 14465 & \text{if processed as waste} \end{cases}$$

$-28930 | $-28930 | $-28930 | $-28930 | $223008

Expected Block Value:

$$\mathbf{4 \cdot \$28930 + \$223008}$$
$$= \$\mathbf{21457}$$

A stochastic optimizer *may* choose to mine this block with an expected value of $21457. However, this is a <u>risky</u> 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 $(s_{11}x_1^1+s_{21}x_2^1+\ldots.$

$s_{12}x_1^1+s_{22}x_2^1+\ldots.)$ ... ...

Subject to

$s_{11}x_1^1+s_{21}x_2^1+\ldots. = b_1$ → Period 1

⋮

$s_{11}x_1^p+s_{21}x_2^p+\ldots. = b_1$

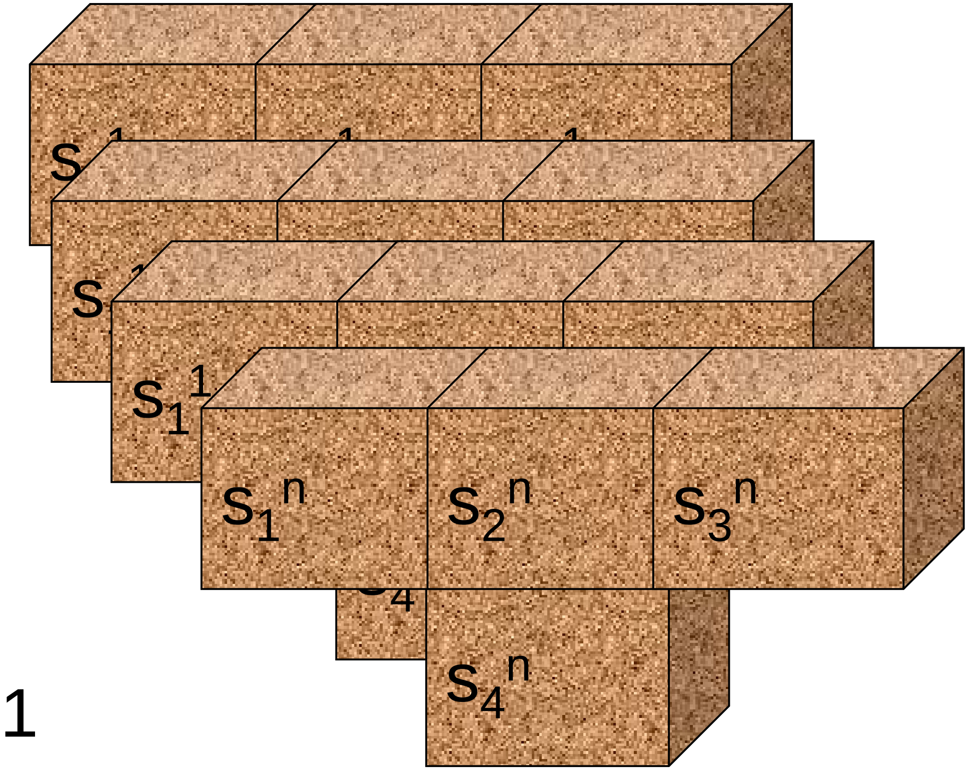
Simulated model 1

Simulated model 2

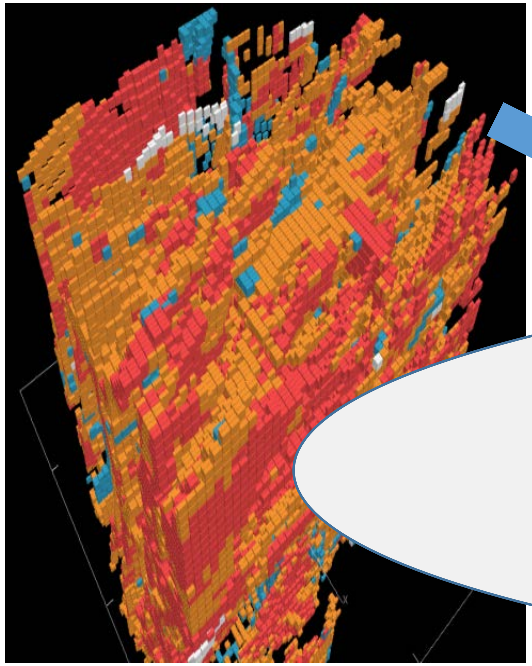
$s_{12}x_1^p+s_{22}x_2^p+\ldots. = b_1$

Simulated model r

$s_{1r}x_1^p+s_{2r}x_2^p+\ldots. = b_1$ → Period p



Introduction – Stochastic Mine Planning



Economic Mining Block Value, when optimizing, is driven by the economic values of the blocks mined rather than the products produced.

CHANGE CONTEXT and USE ONLY
geological attributes: Material Types, Grades … .

(METAL*RECOVERY*PRICE - ORE*COSTP)

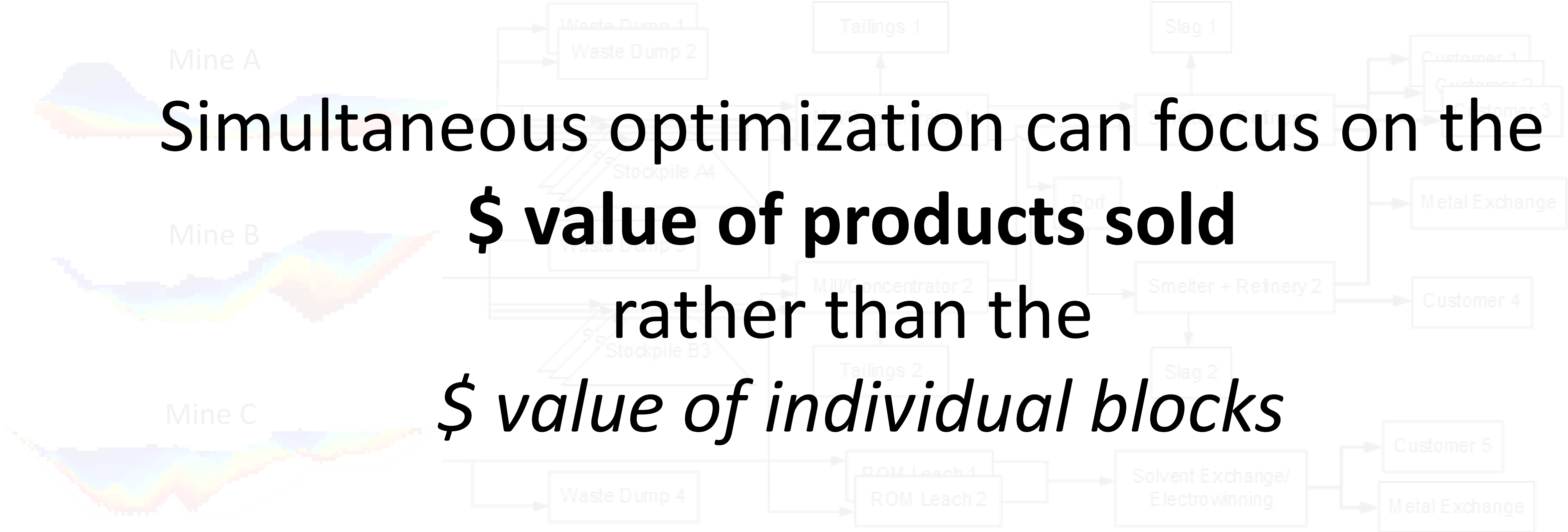
- ROCK*COSTM

Simultaneous Optimization of Mining Complexes - Mineral Value Chains for Decision Support

Extending models

Simultaneous Optimization of Mining Complexes

Stochastic Production Scheduling & Value Chain Optimization → Financial & Production Forecasts



Simultaneous optimization can focus on the

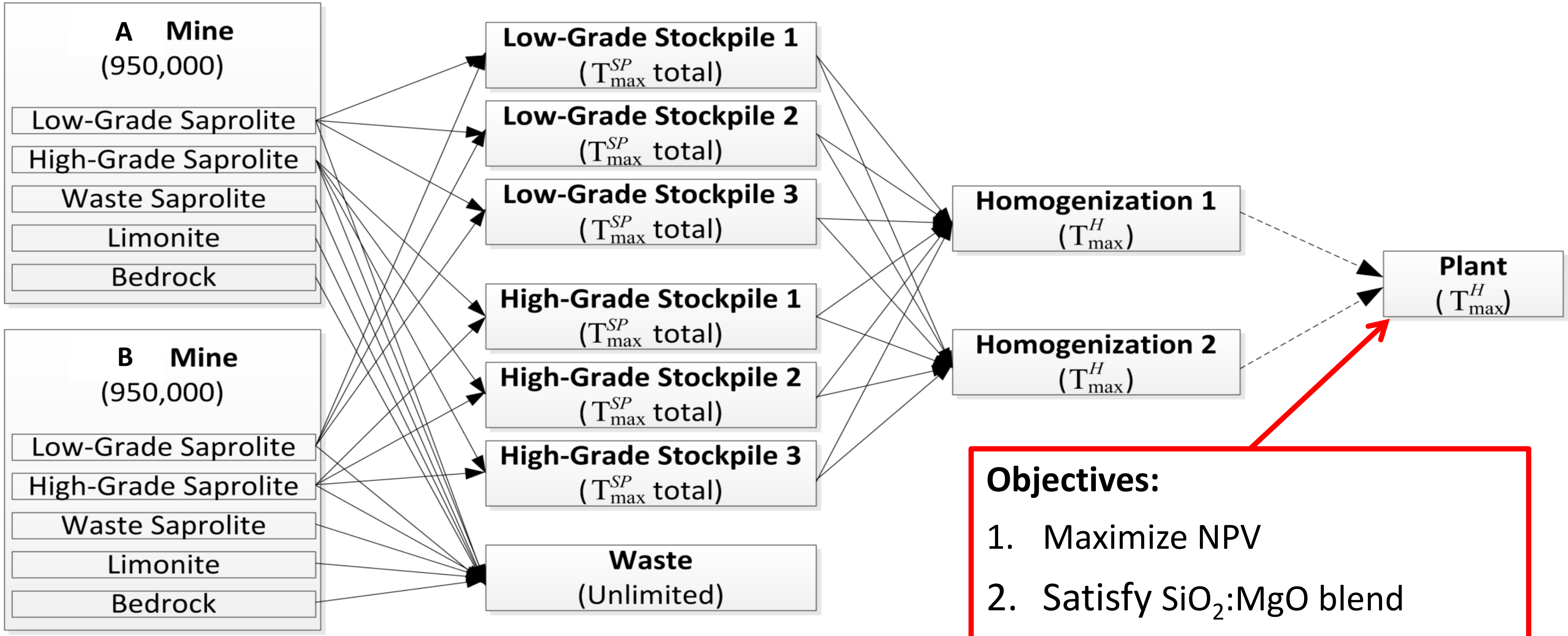
$ value of products sold

rather than the

$ value of individual blocks

Simultaneous Optimization

Example: Nickel laterite mineral value chain - Blending policy optimization



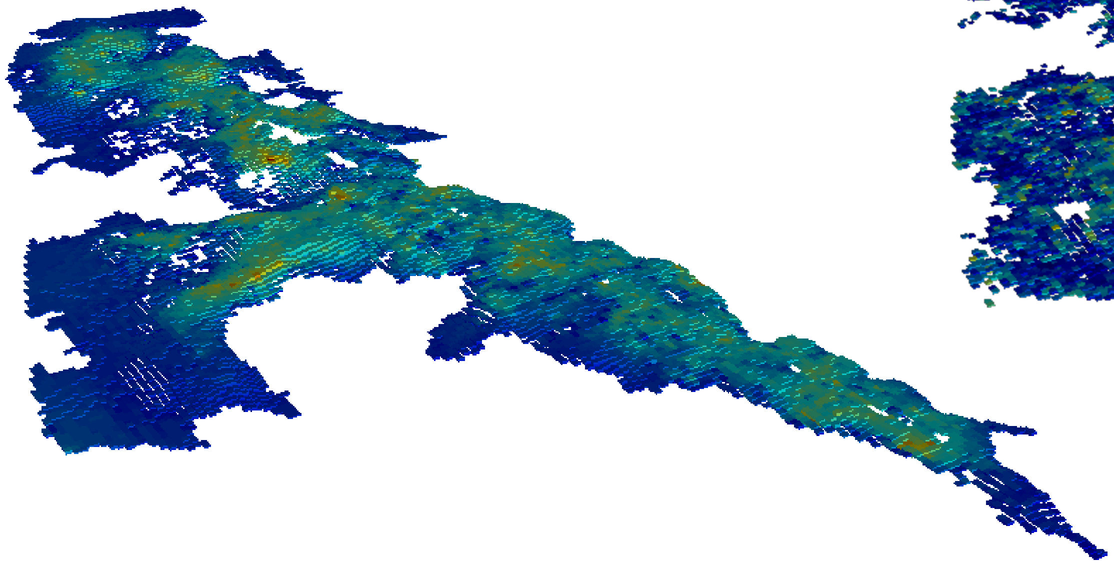
Objectives:

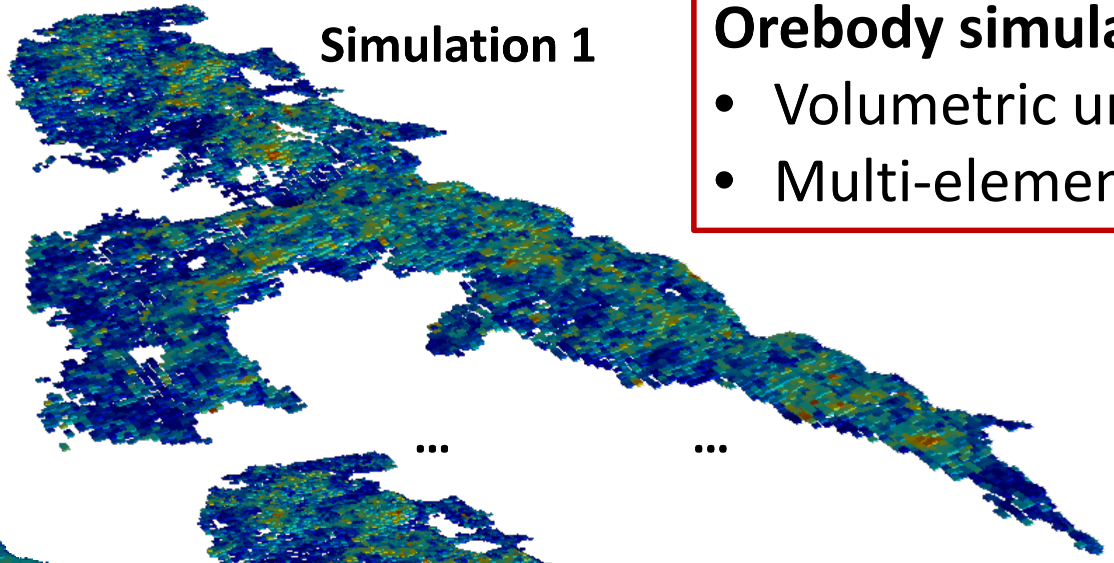
1. Maximize NPV
2. Satisfy SiO_2:MgO blend
3. Minimize deviations from plant capacity target

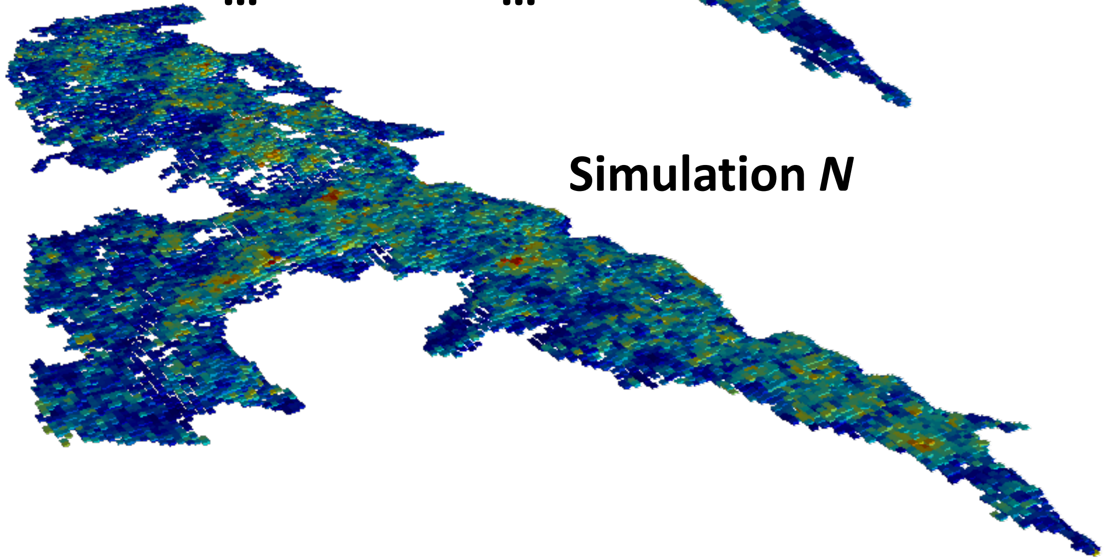
*T_{max} is the maximum plant feed tonnage

Simultaneous Optimization

Nickel Laterite Complex – Risk Analysis of Deterministic Design





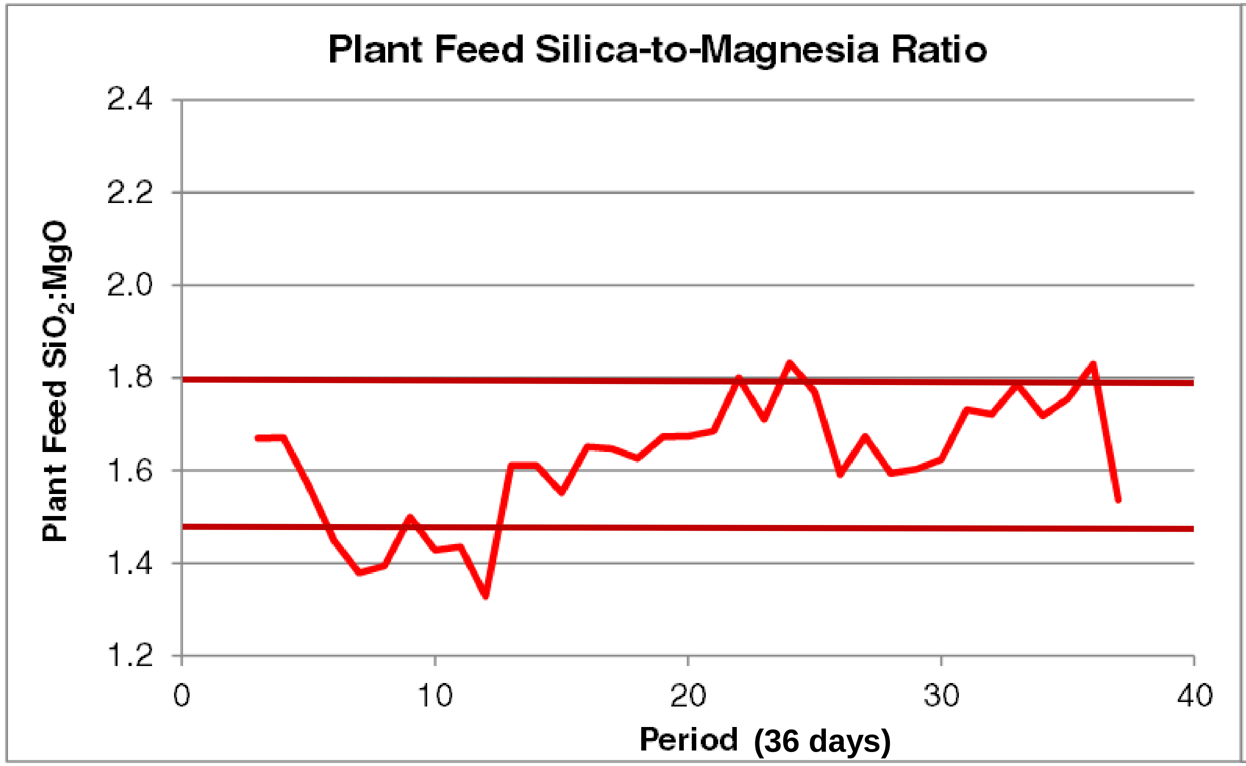


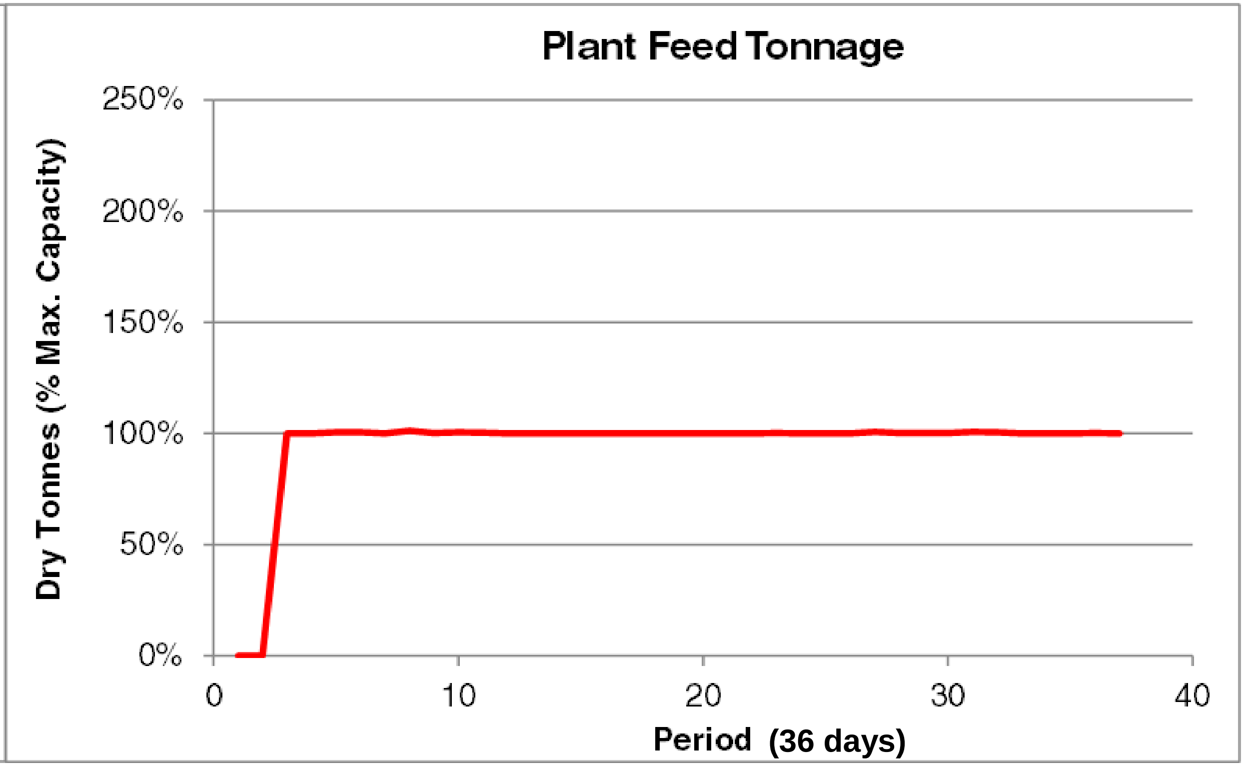
Orebody simulations quantify:

- Volumetric uncertainty
- Multi-element uncertainty

Simultaneous Optimization

Nickel Laterite Complex – Deterministic Simultaneous Optimization

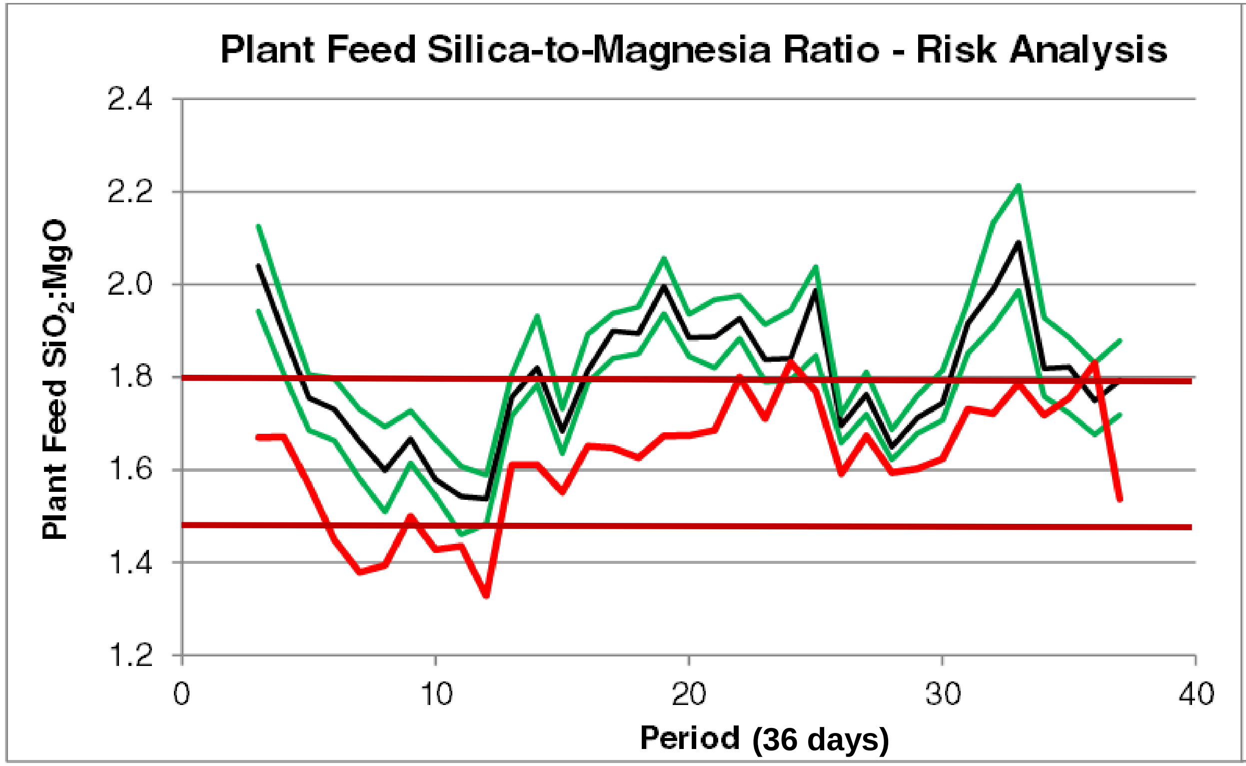


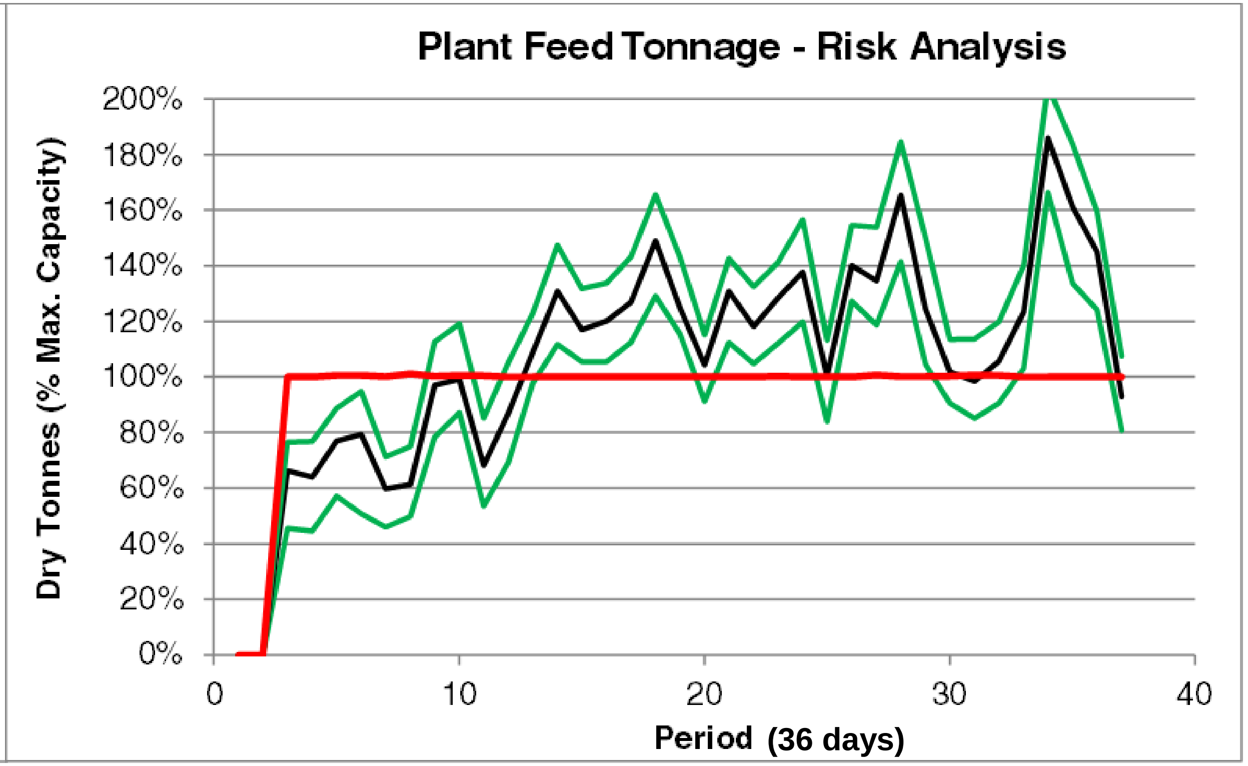


P-10 & P-90 P-50 Deterministic

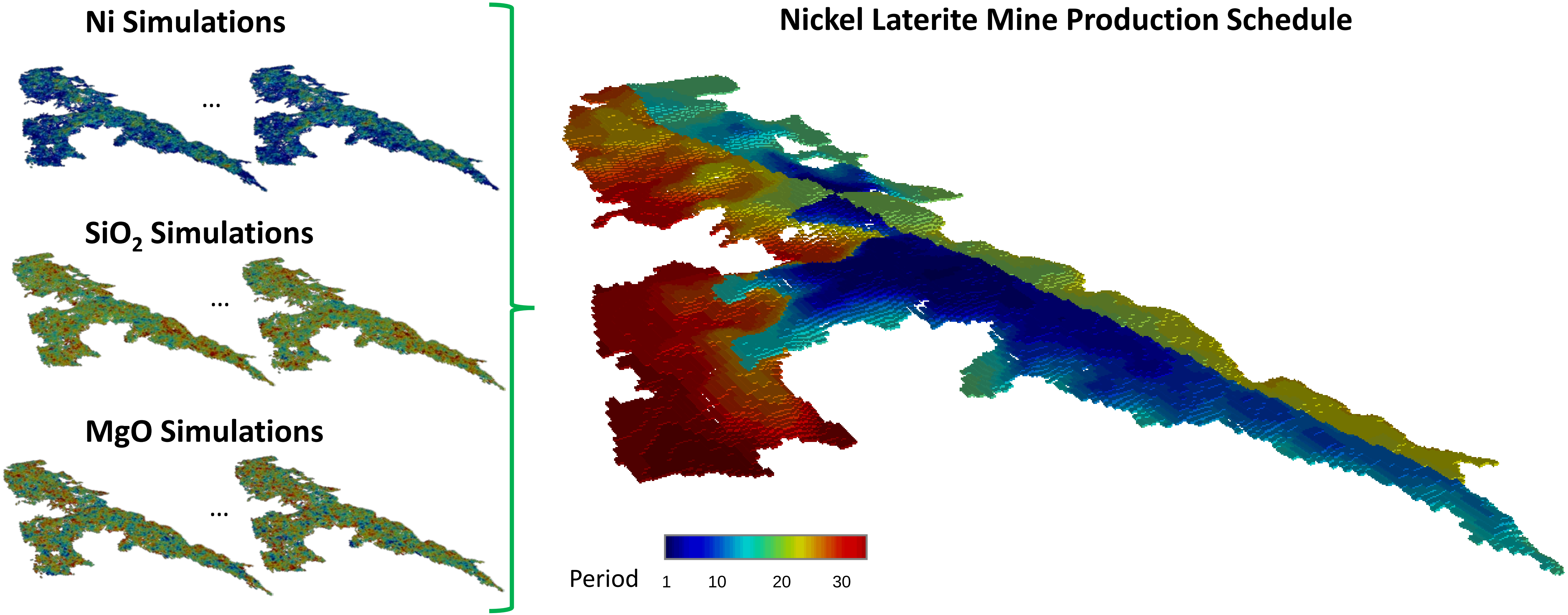
Simultaneous Optimization

Nickel Laterite Complex – Risk Analysis of Deterministic Design



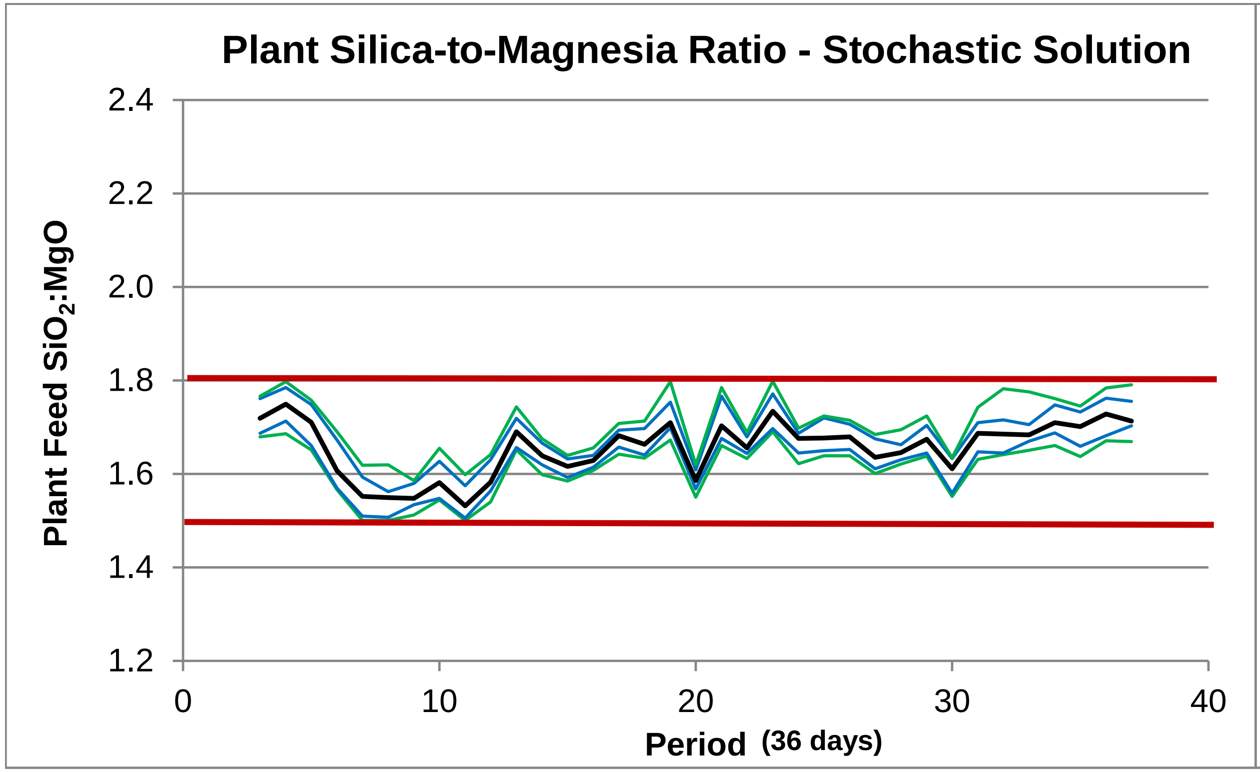


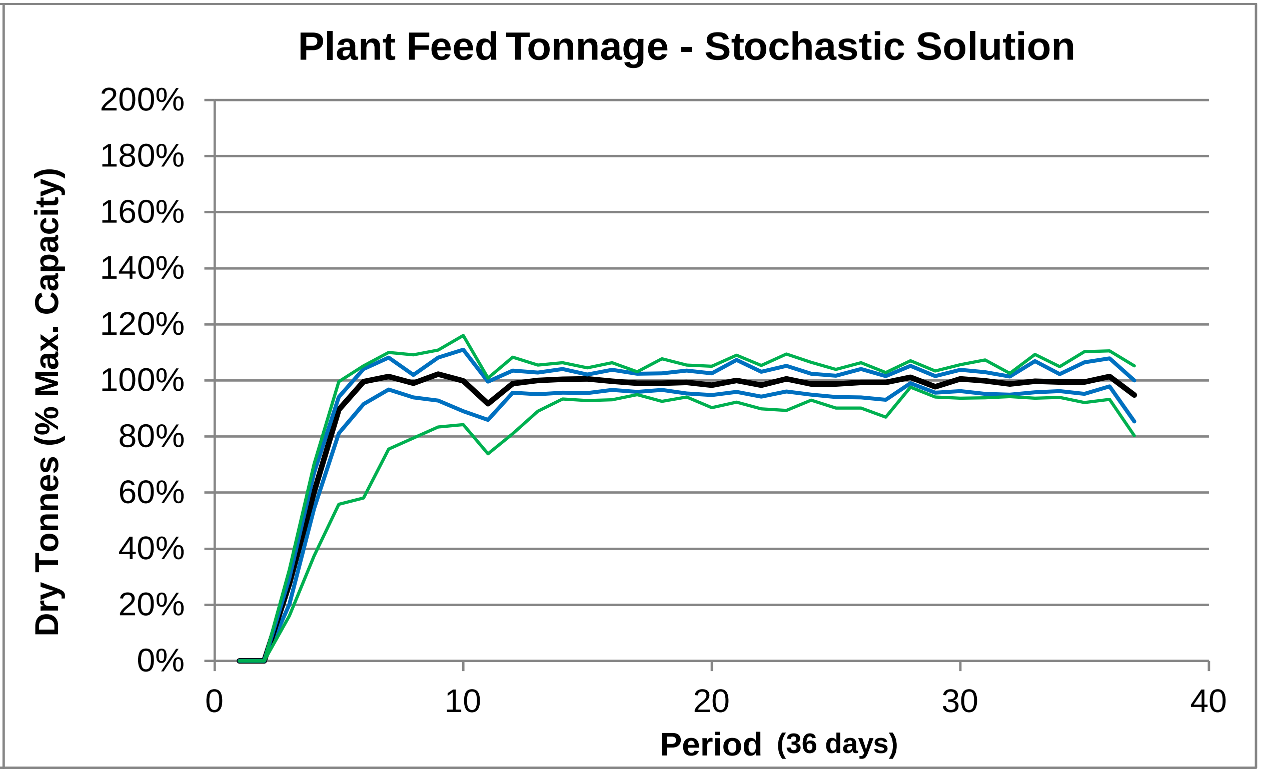
Stochastic Simultaneous Optimization



Stochastic Simultaneous Optimization

Nickel Laterite Complex - Stochastic Simultaneous Optimization





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:

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

Attributes of interest:

- Revenues from metal sale
- Mining, processing & stockpiling costs

Penalties for deviations from targets

- Mining, stockpile, processing capacities
- Blending constraints
- Deleterious elements

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

$$v_{a,t,s} + l_{a,t,s} \geq L_{a,t} \quad \forall a \in \mathbb{A}, s \in \mathbb{S}, t \in \mathbb{T}$$

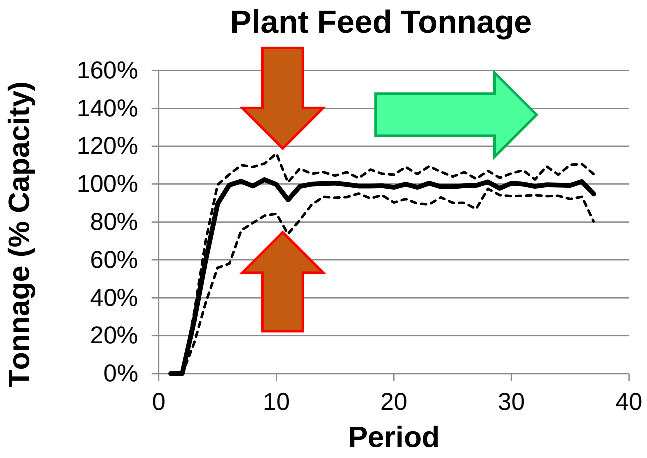
Stochastic Simultaneous Optimization Formulation

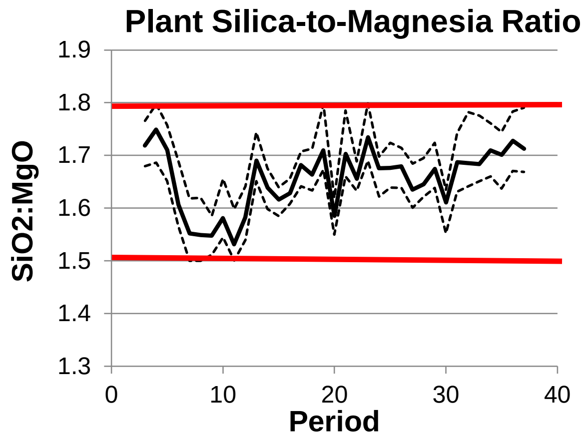
- Adaptable two-stage stochastic integer programming model:

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

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:

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

$$- \sum_{t\in\mathbb{T}} \sum_{k\in\mathbb{K}} p_{k,t} \cdot w_{k,t}$$

CAPEX discounted cash flow

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

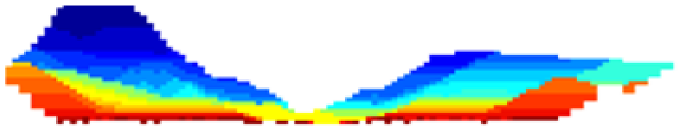
$$v_{a,t,s} - l_{a,t,s} \ge L_{a,t} + \sum_{t'=t-\lambda_k+\tau_k} \kappa_{a,k} \cdot w_{k,t'}$$

Change of capacities depends on:

- Quantity purchased ($w_{k,t'}$)
- Constraint increase ($\kappa_{a,k}$)
- Life of equipment (λ_k)
- Lead time (τ_k)

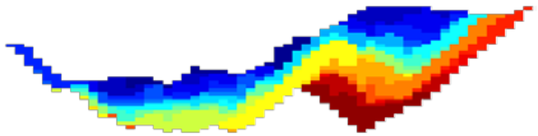
Modelling Mining Complexes with Uncertainty

Production schedule



Sulfides - Mine 1
- Metal tonnes
- Total tonnes

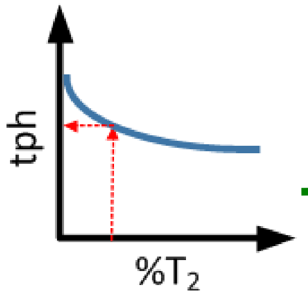
Sulfides - Mine 2
- Metal tonnes
- Total tonnes

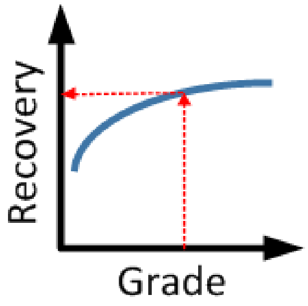


Destination policies

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

Processing streams

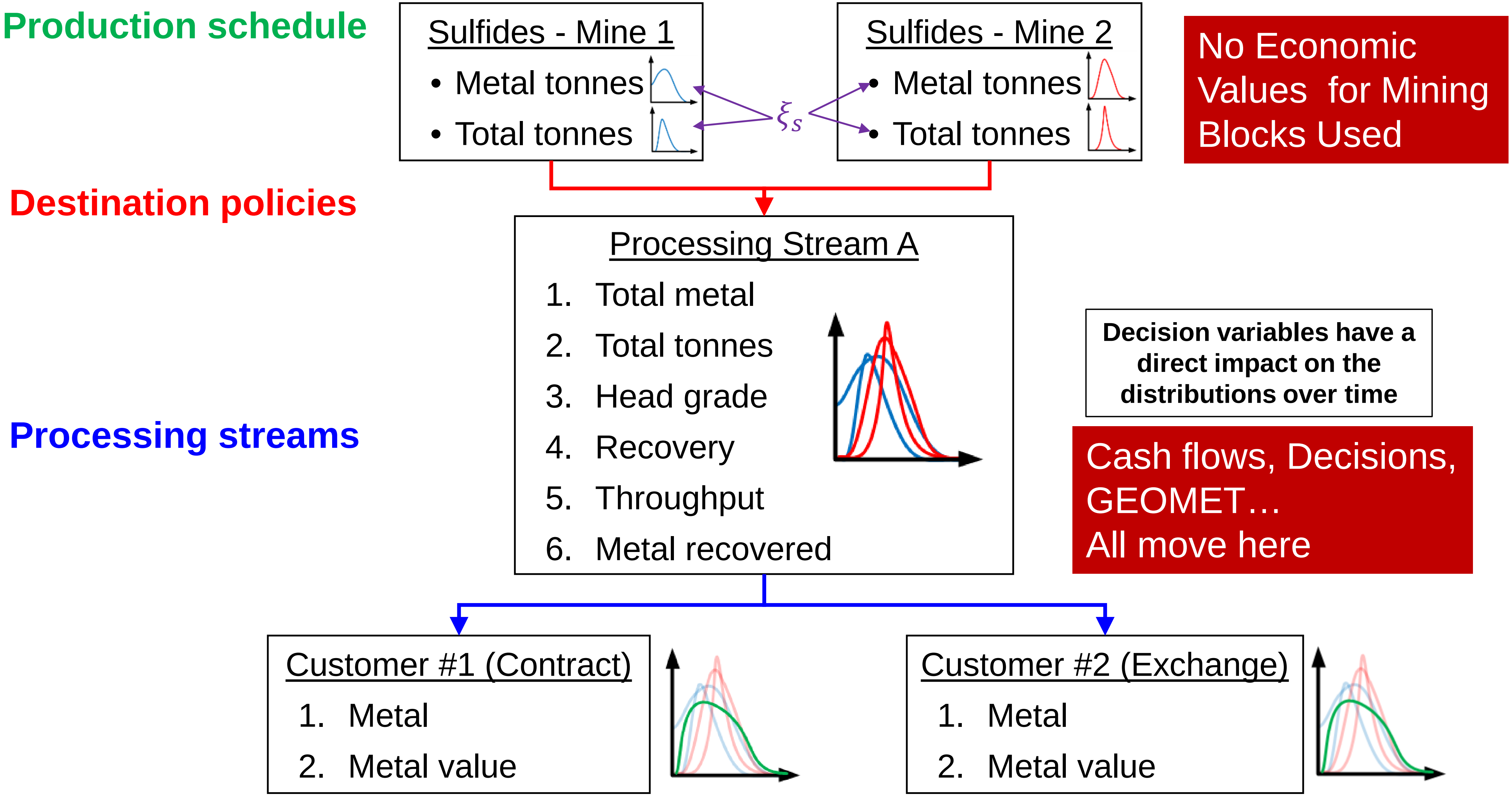




Customer #1 (Contract)
1. Metal
2. Metal value

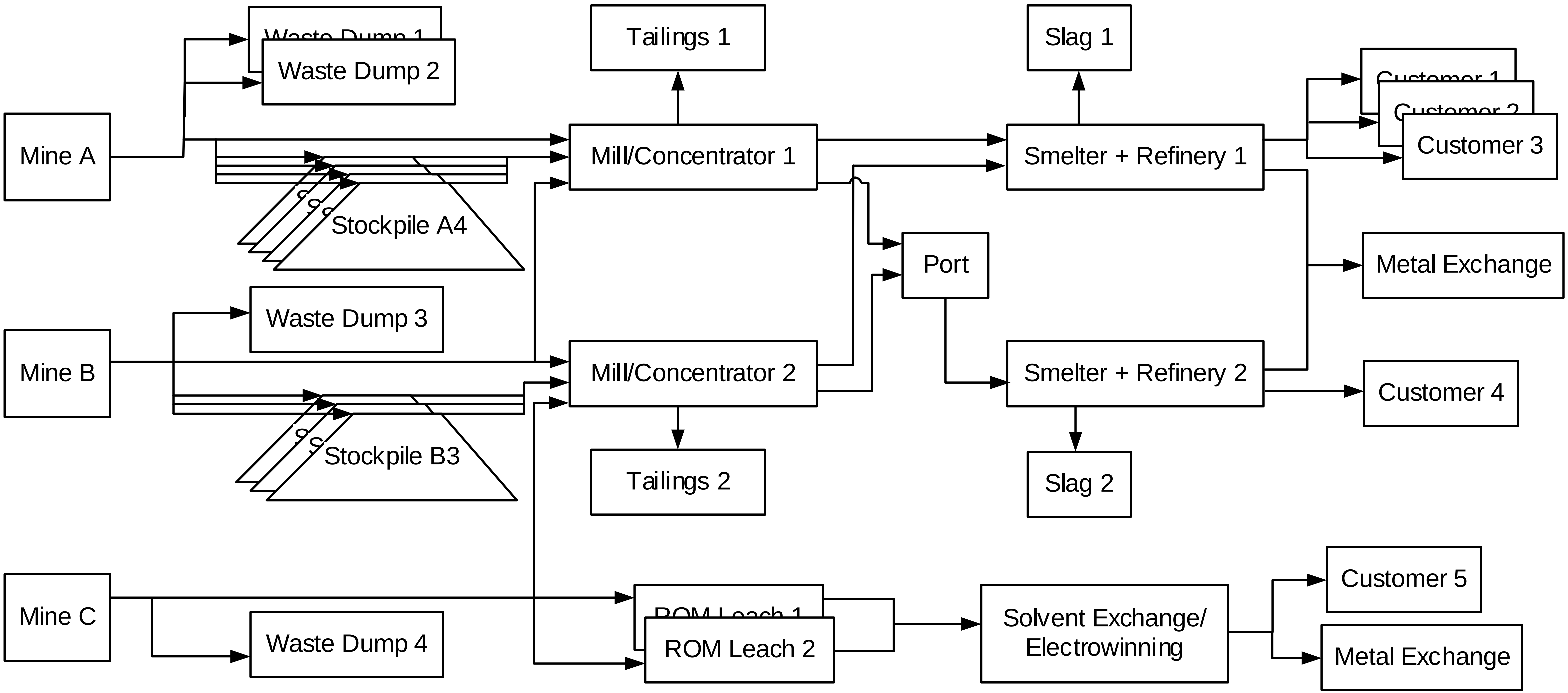
Customer #2 (Exchange)
1. Metal
2. Metal value

Modelling Mining Complexes with Uncertainty



Modelling Mining Complexes with Uncertainty

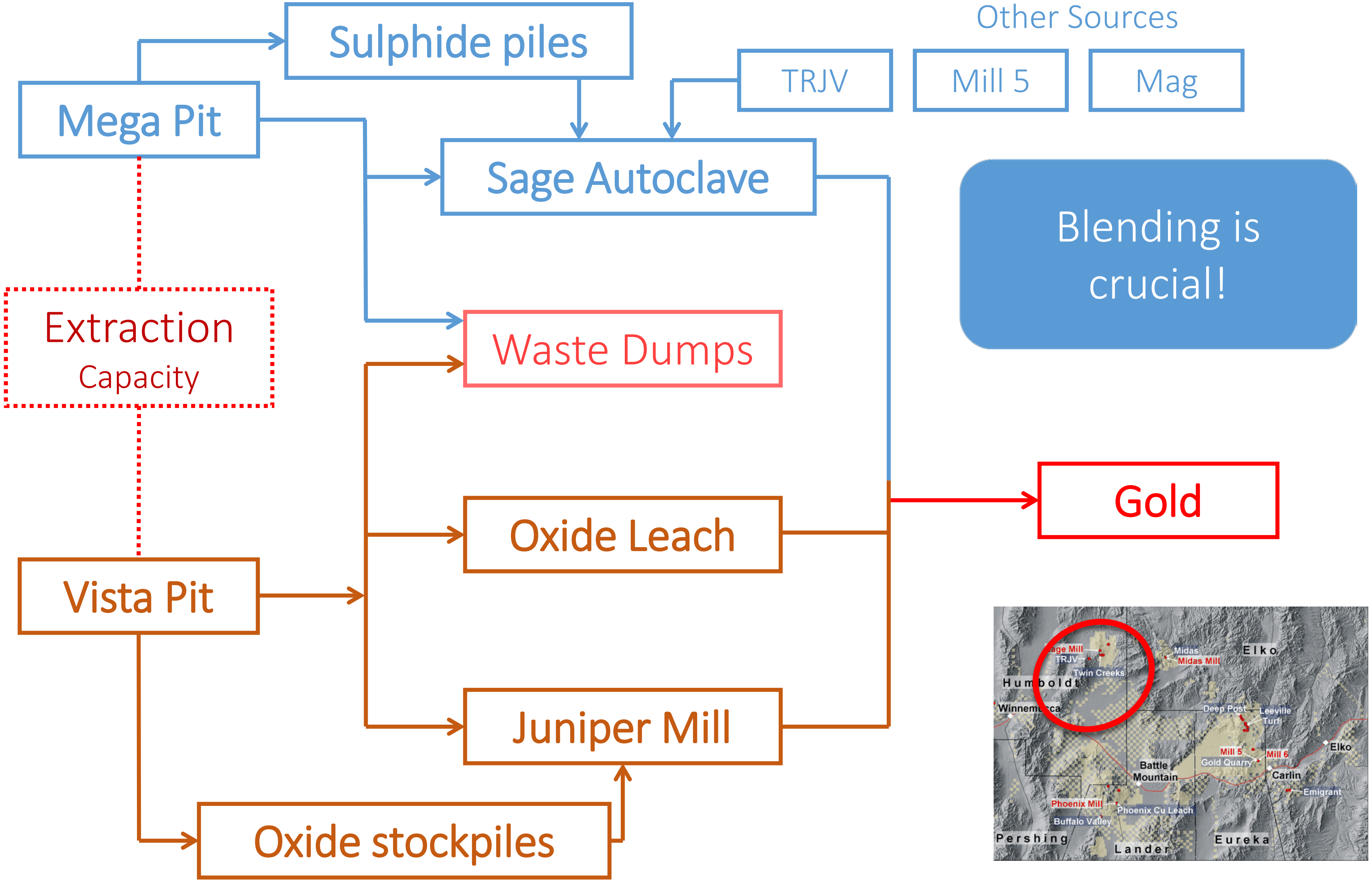
There is no need to simplify our models of the value chain



The Twin Creeks

Gold Mining Complex, Nevada

Twin Creeks (TC) gold mining complex

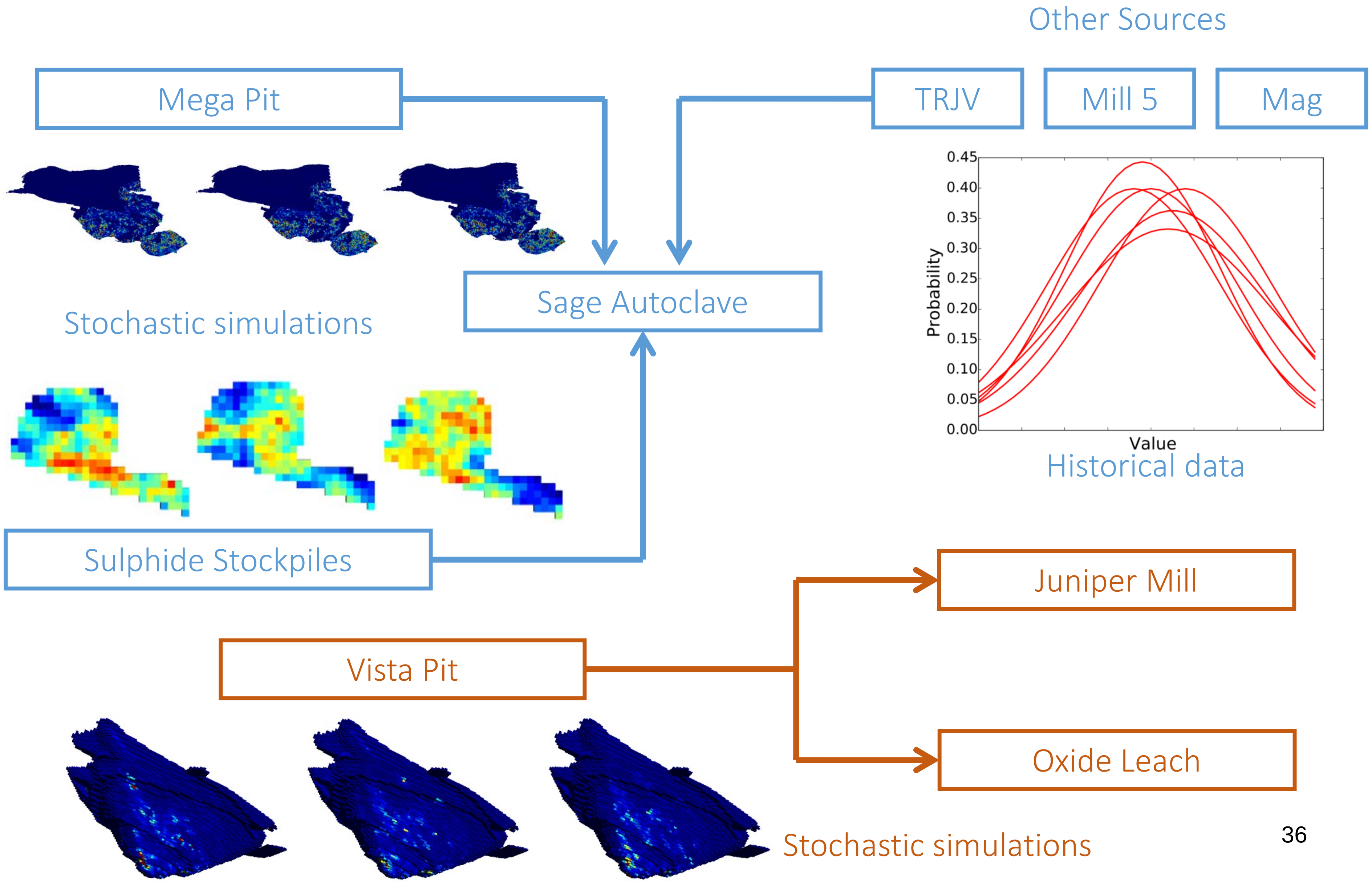


Base Case

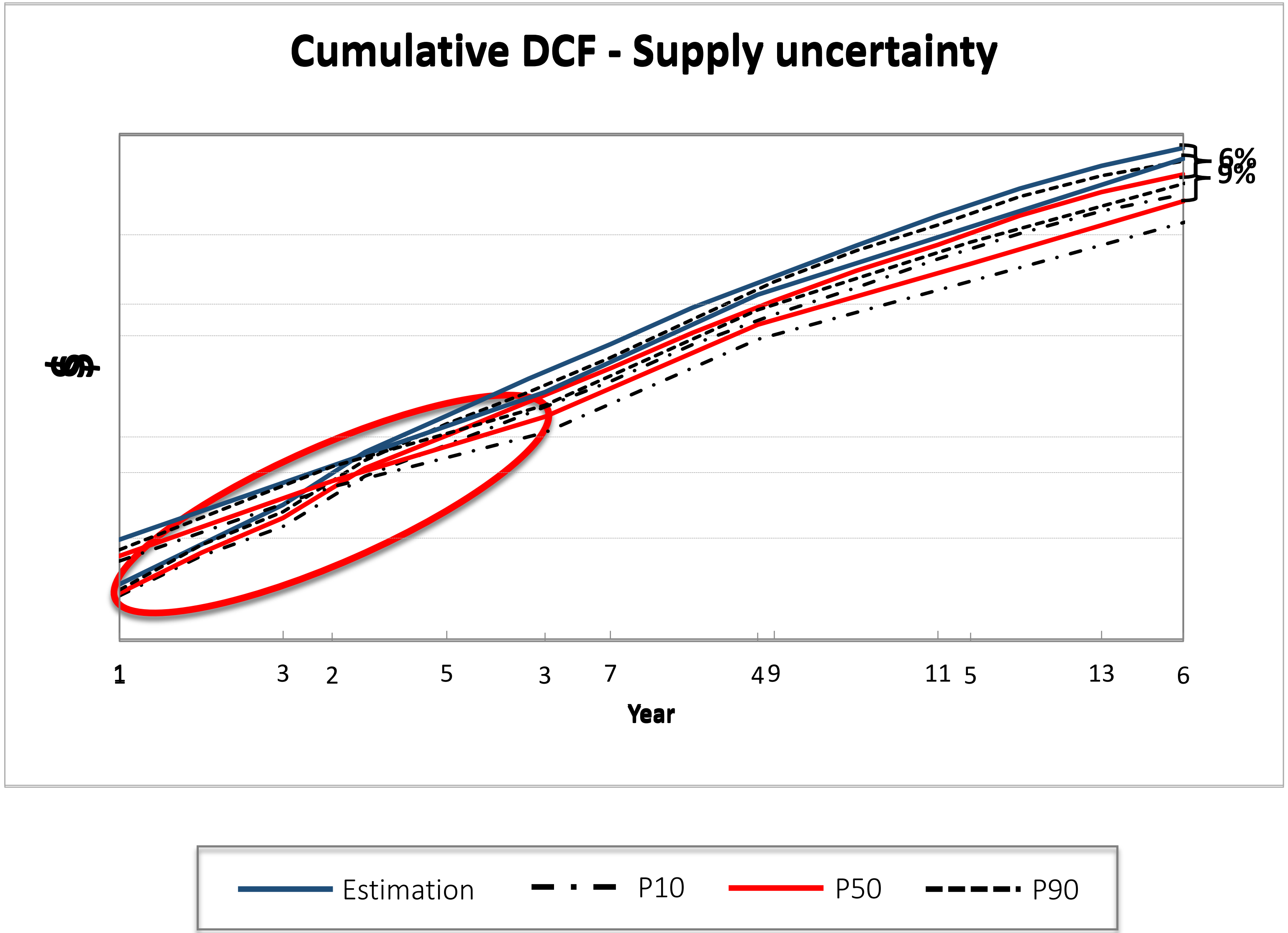
Long-term Production Schedule

& Risk Analysis

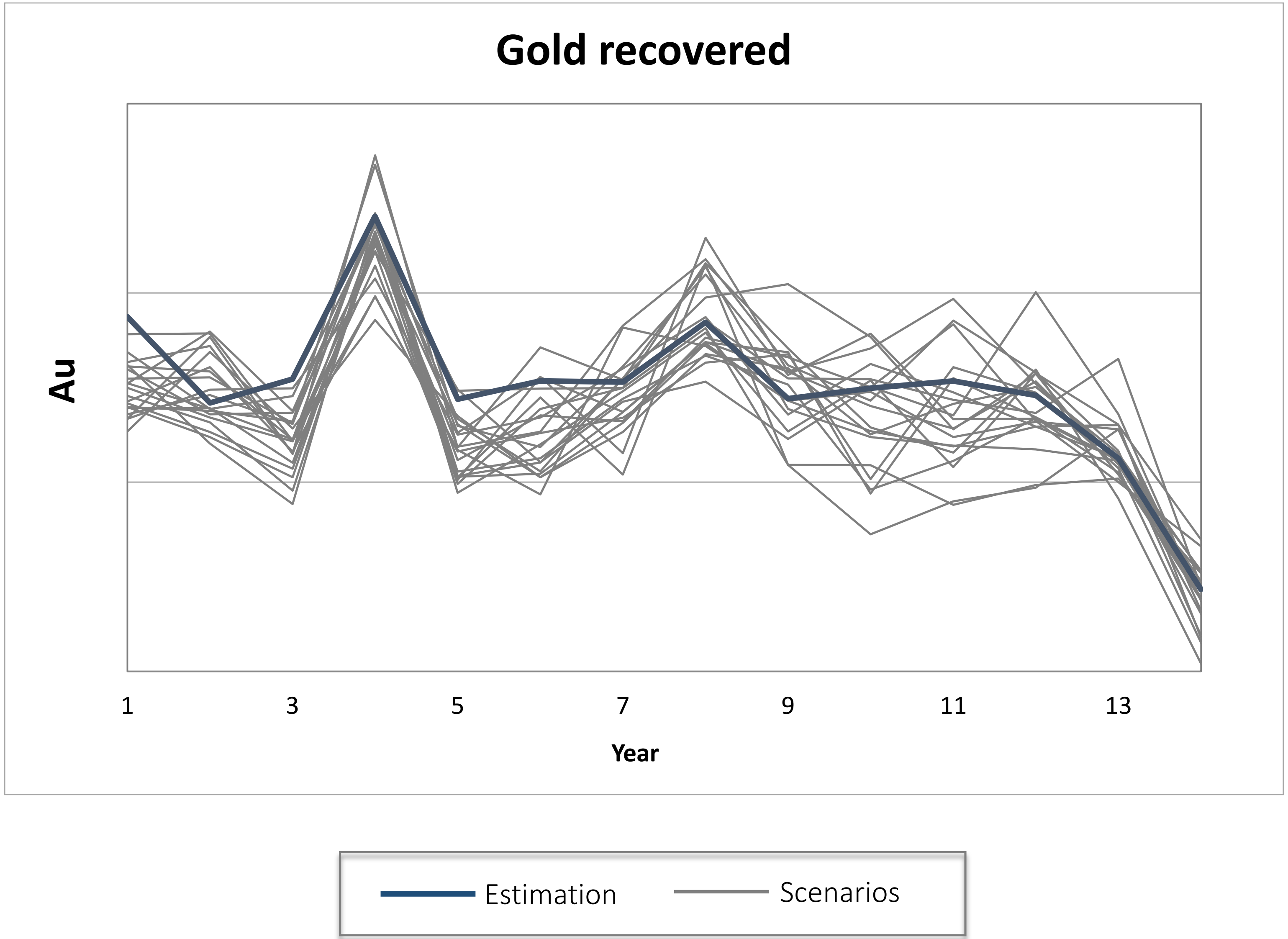
Base case - Sources of supply uncertainty



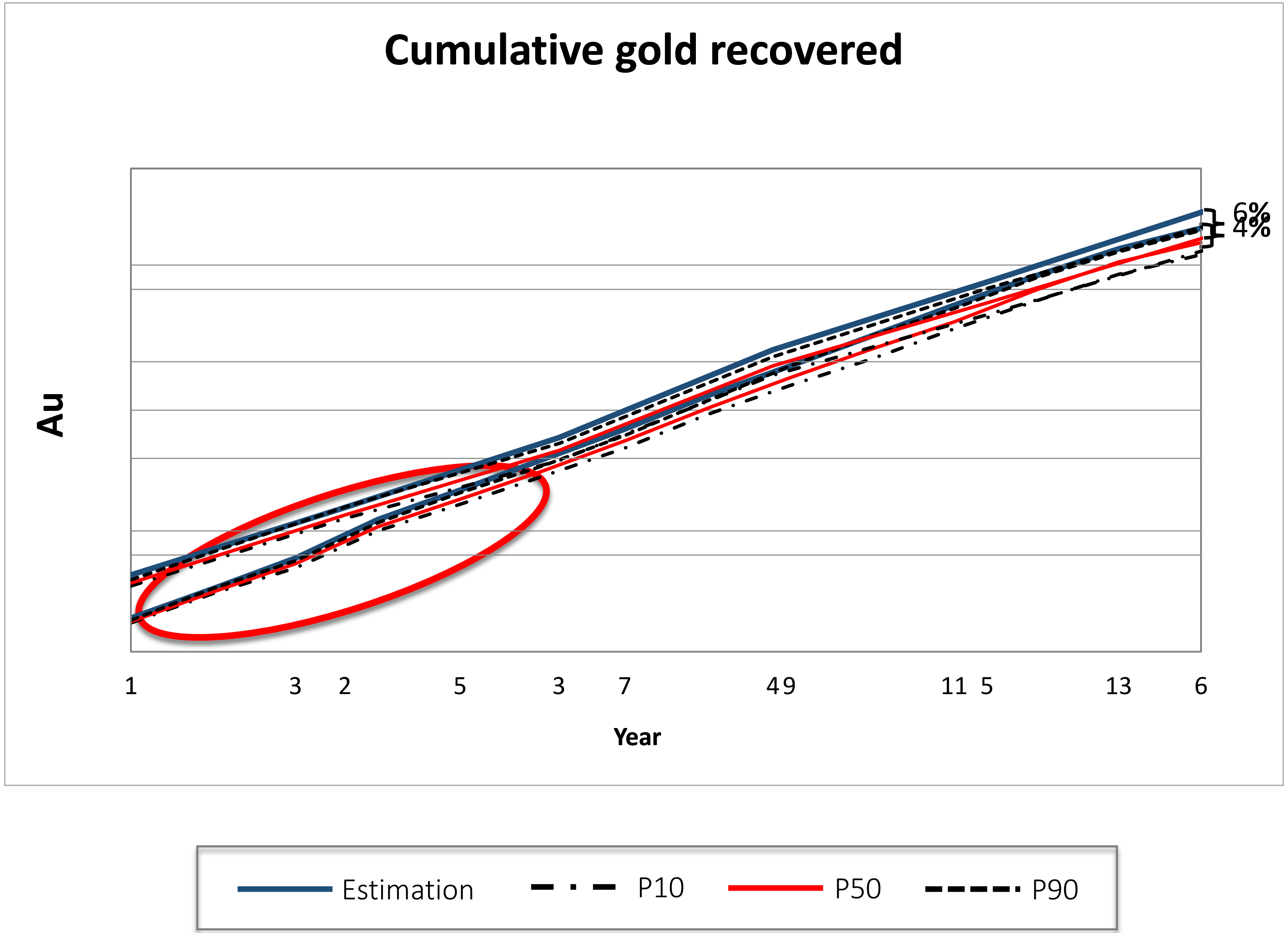
Base case - DCF & Risk analysis



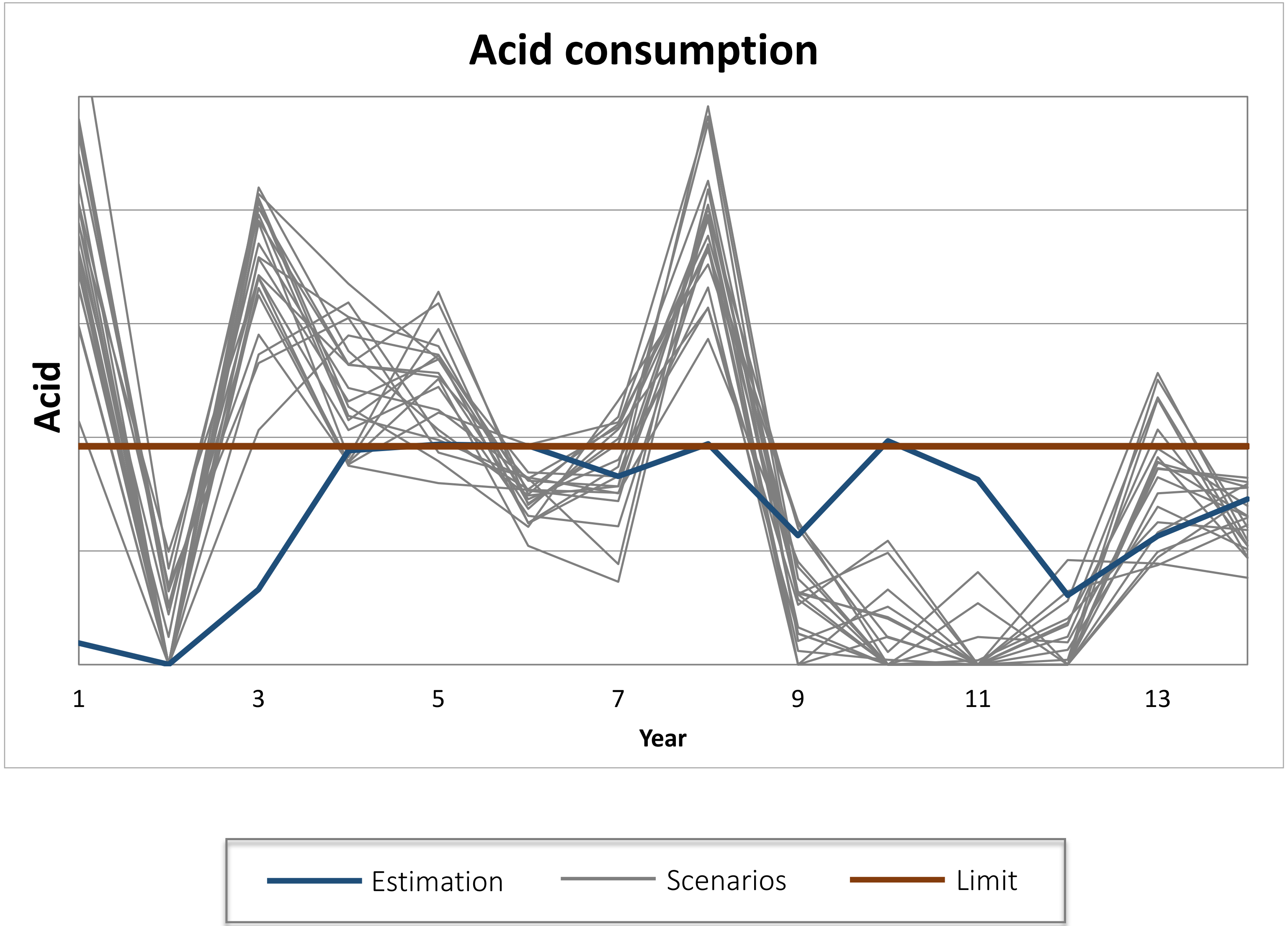
Base case - Gold recovered & Risk analysis



Base case - Gold recovered & Risk analysis



Base case - Blending: Acid consumption



Stochastic
Long-term Production Schedule

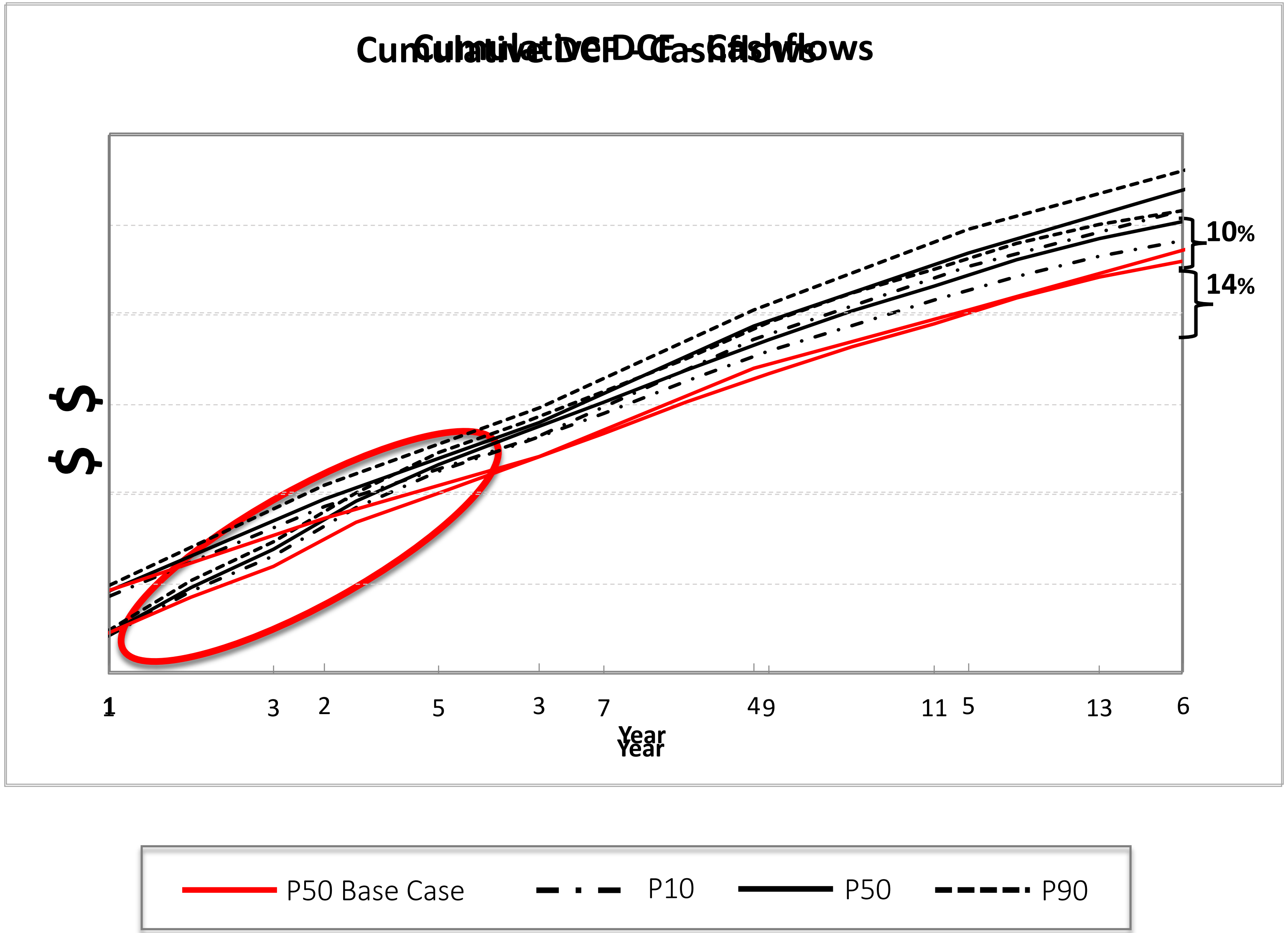
Production schedule (I):

within the conventionally ‘optimal’ pit

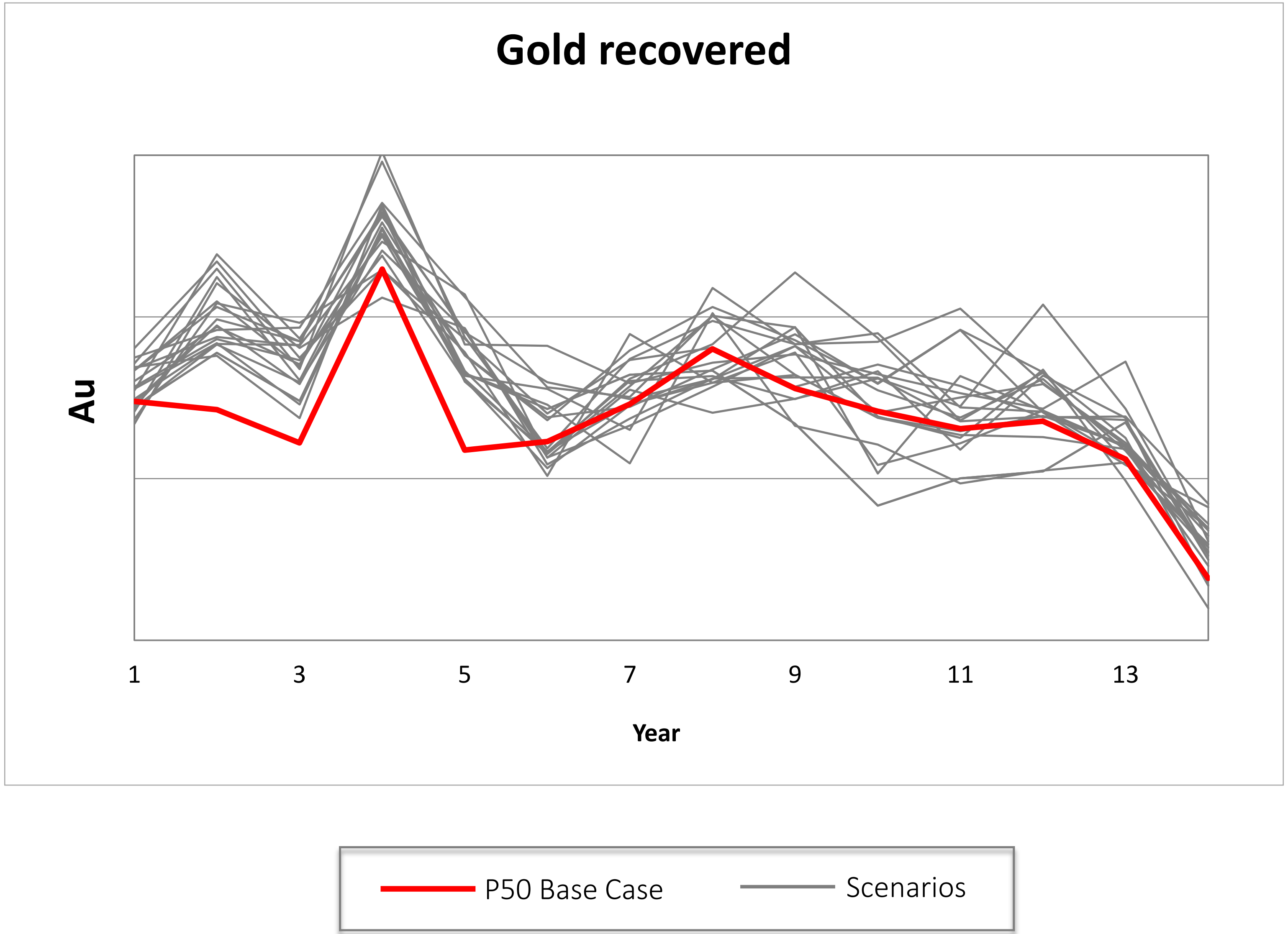
Production schedule (II):

without imposed pit limits

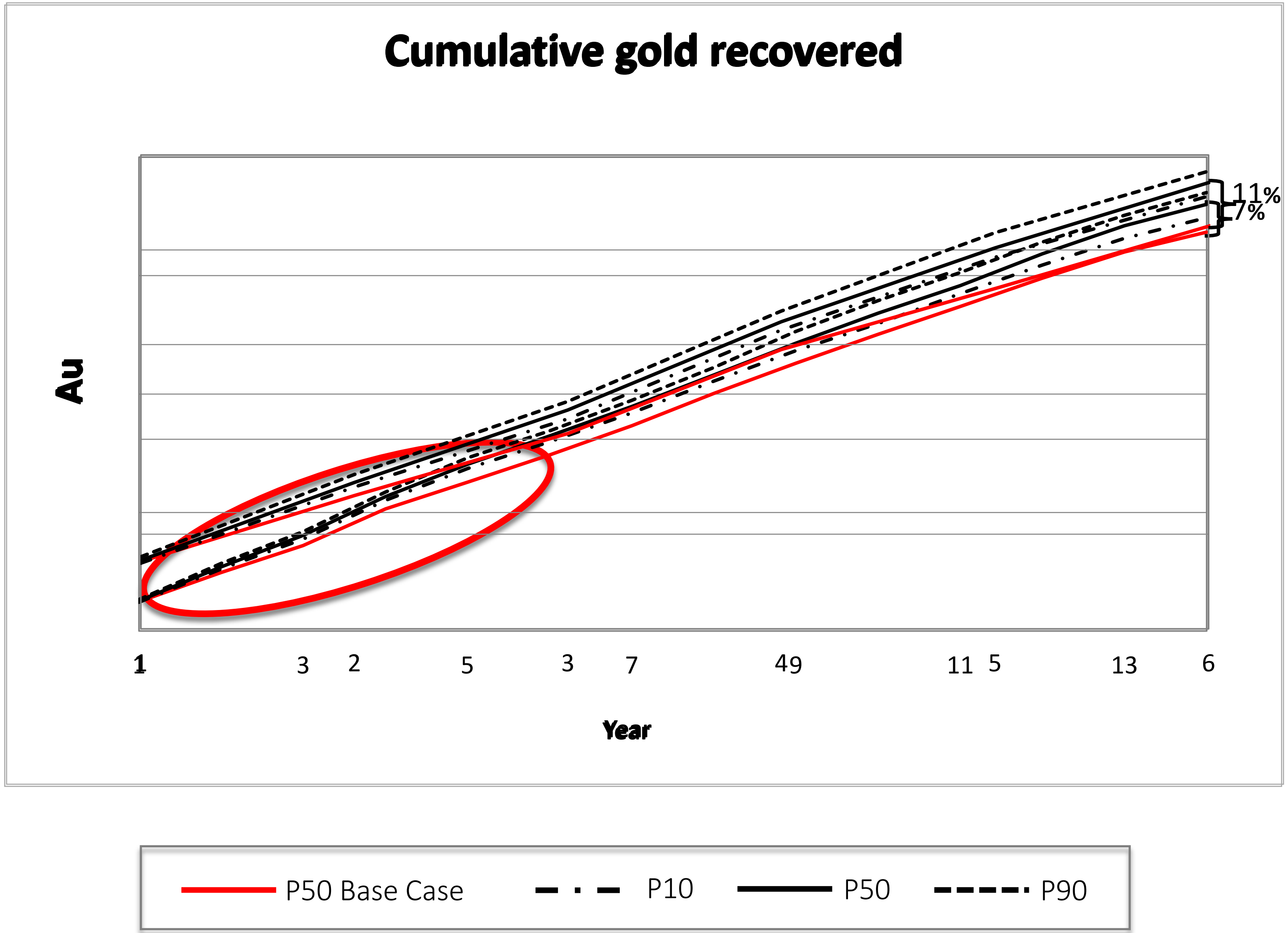
Stochastic schedule I - Cumulative DCF



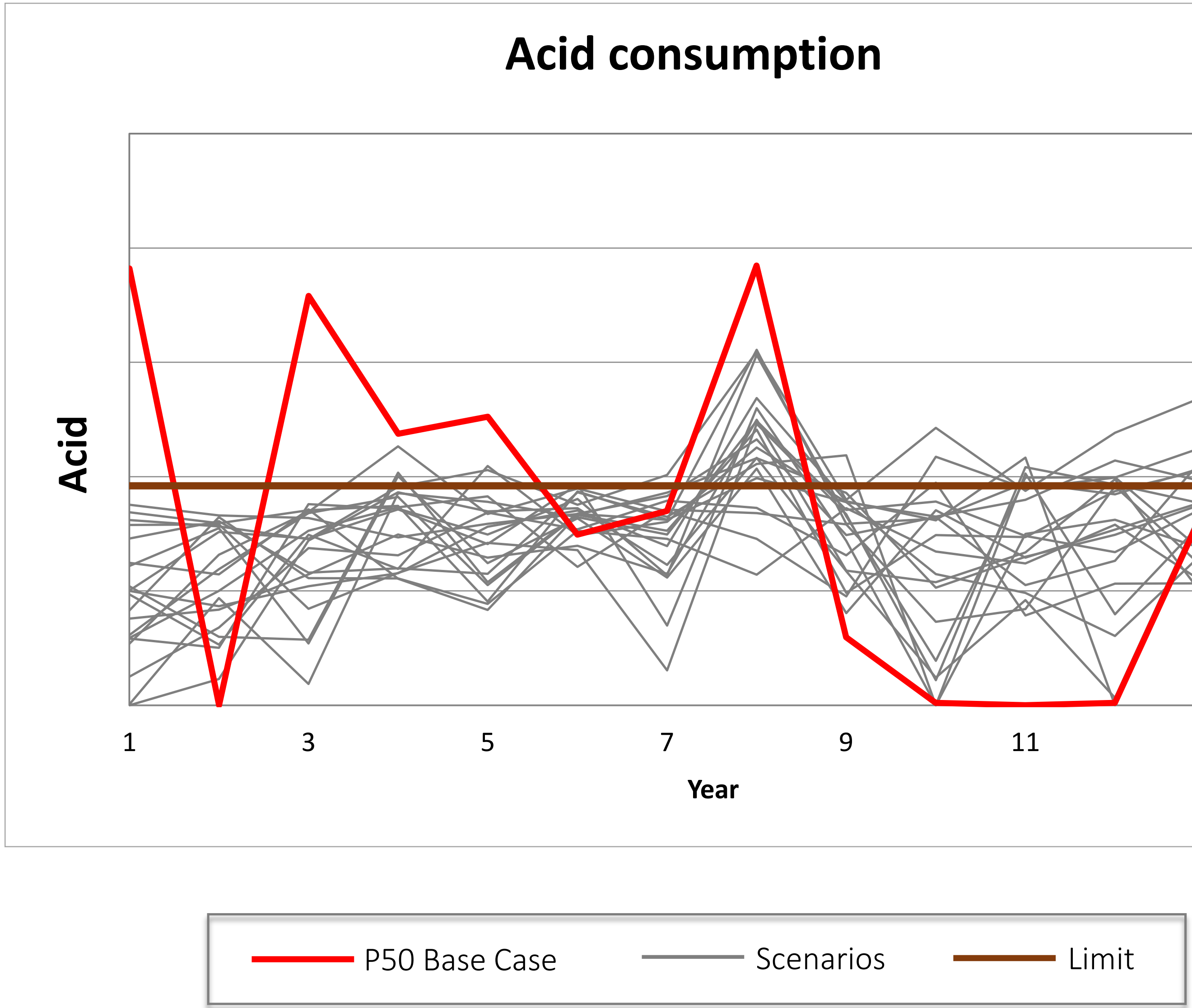
Stochastic schedule I - Recovered gold



Stochastic schedule I - Recovered gold



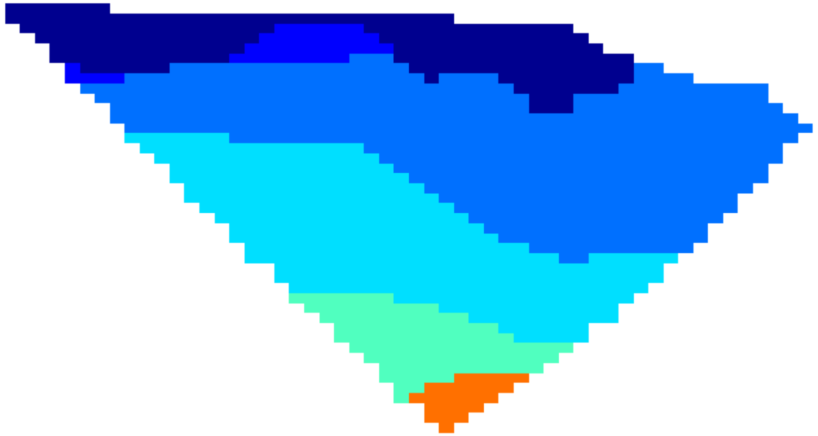
Stochastic schedule I – Blending: Acid consumption



Stochastic schedule I - Sections

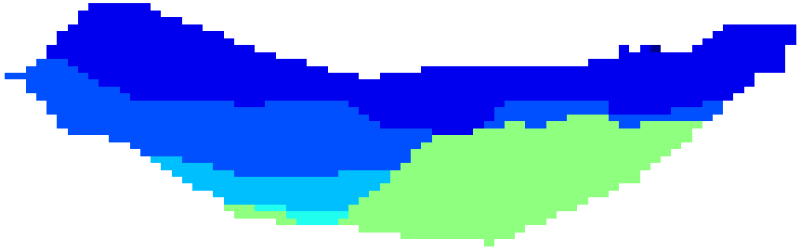
Base Case: Mega

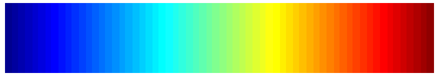
Stochastic: Mega



Base Case: Vista

Stochastic: Vista





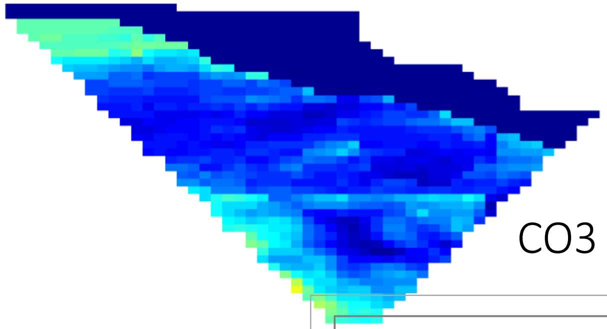
1 Period 10

Stochastic schedule II - More ore, larger pit

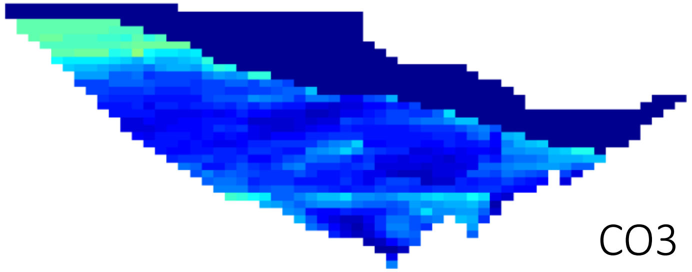
Simultaneous optimization of the mining complex decides the pit limits:

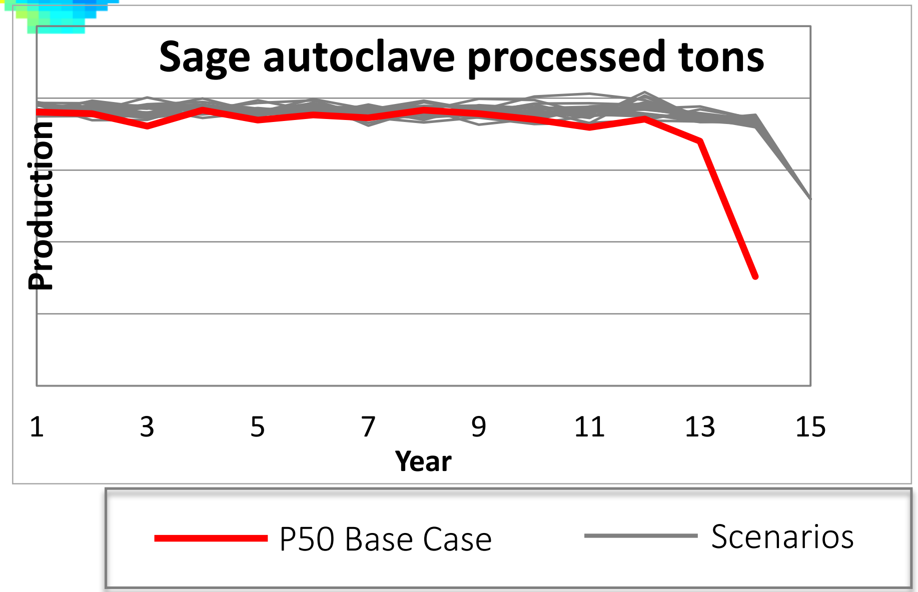
1 extra year of ore to the autoclave (Pit 11% larger)

Conventional pit limit



Stochastic pit limit



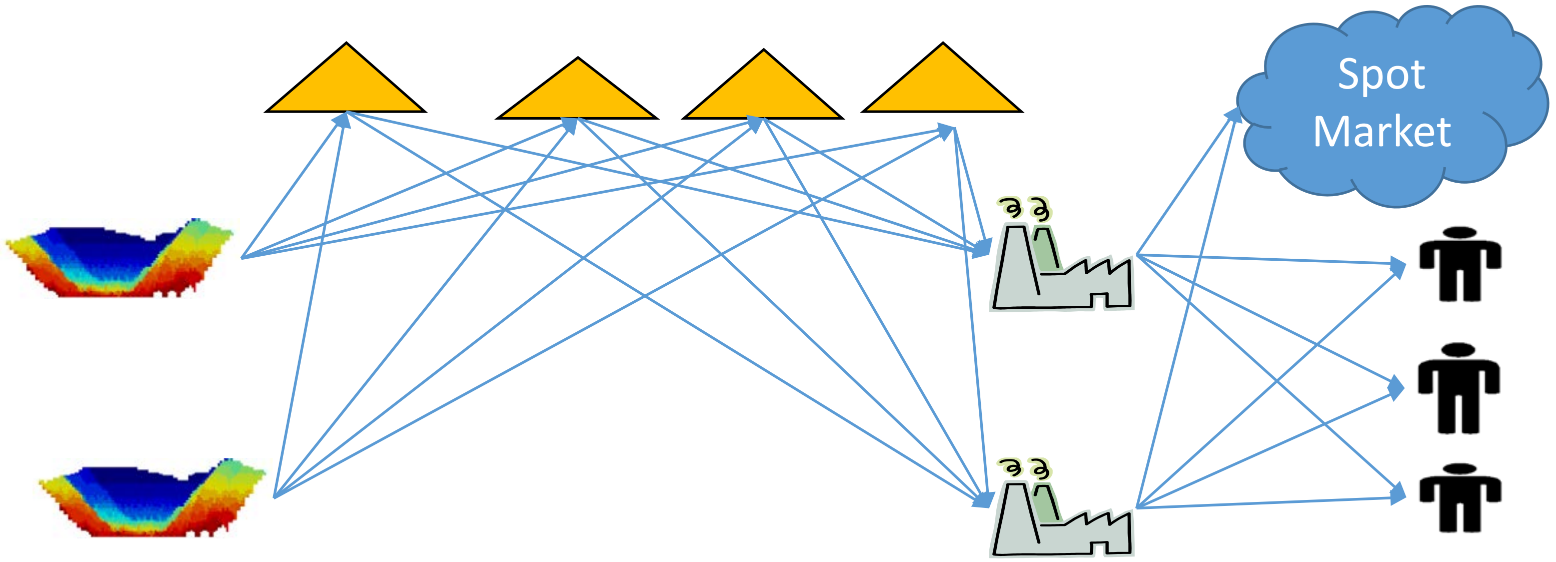


Optimizing with Joint

Supply (metal)
and
Demand (commodity price) Uncertainty

Contracts & Value Chain Optimizers

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

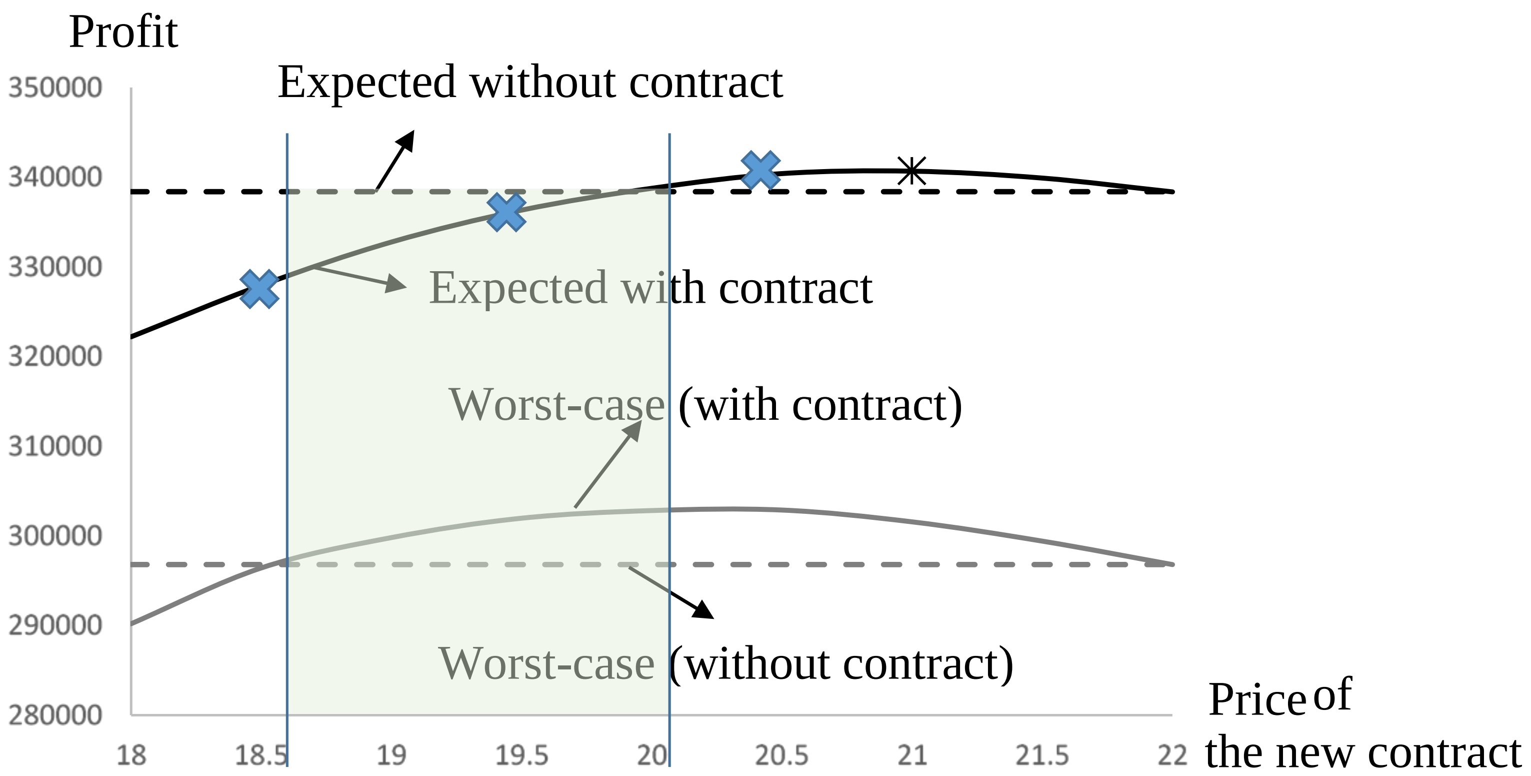


- Objective function

$$\text{Maximize} \sum_{SxS'} \sum_t \frac{1}{[1+\gamma]^t} \left[Revenue_{t,s} - ProductionCost_{t,s} - TransCost_{t,s} \right] - TransCapInvst$$

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

AngloGold Ashanti

Barrick

bhpbilliton

De Beers
A Diamond is Forever

Kinross

Newmont
The Gold Company

Vale

Canada Research Chairs
Chaires de recherche du Canada

NSERC
CRSNG

Canada Foundation for Innovation
Fondation canadienne pour l'innovation

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/

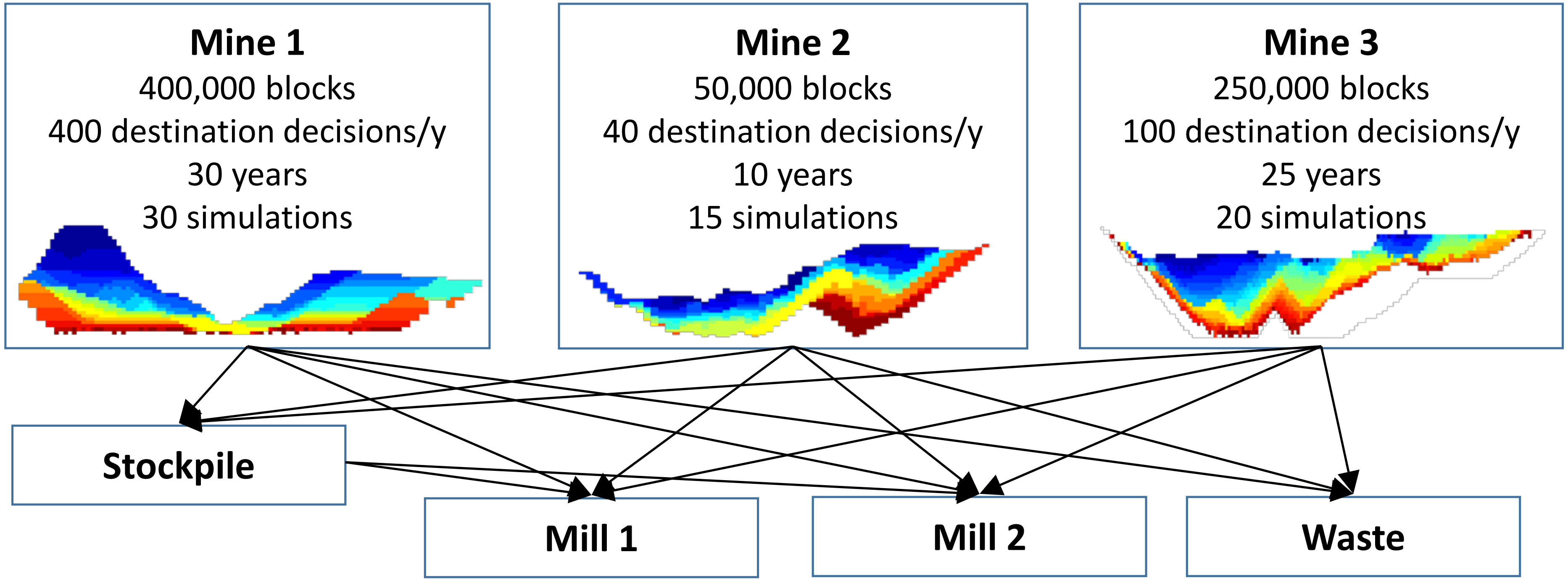
COSMO Mining Industry Consortium &

Management & Economics Society of CIM

AngloGold Ashanti
BARRICK
bhpbilliton
De Beers A DIAMOND IS FOREVER
NEWMONT The Gold Company
COSMO Lab
VALE
KINROSS
MES

Algorithmic Optimization with Metaheuristics

- Computationally prohibitive optimization models, in the past.



- **9,000 joint scenarios**
- **18,750,000 scheduling decision variables**
- **62,500 destination policy variables**
- **540,000 processing stream variables**

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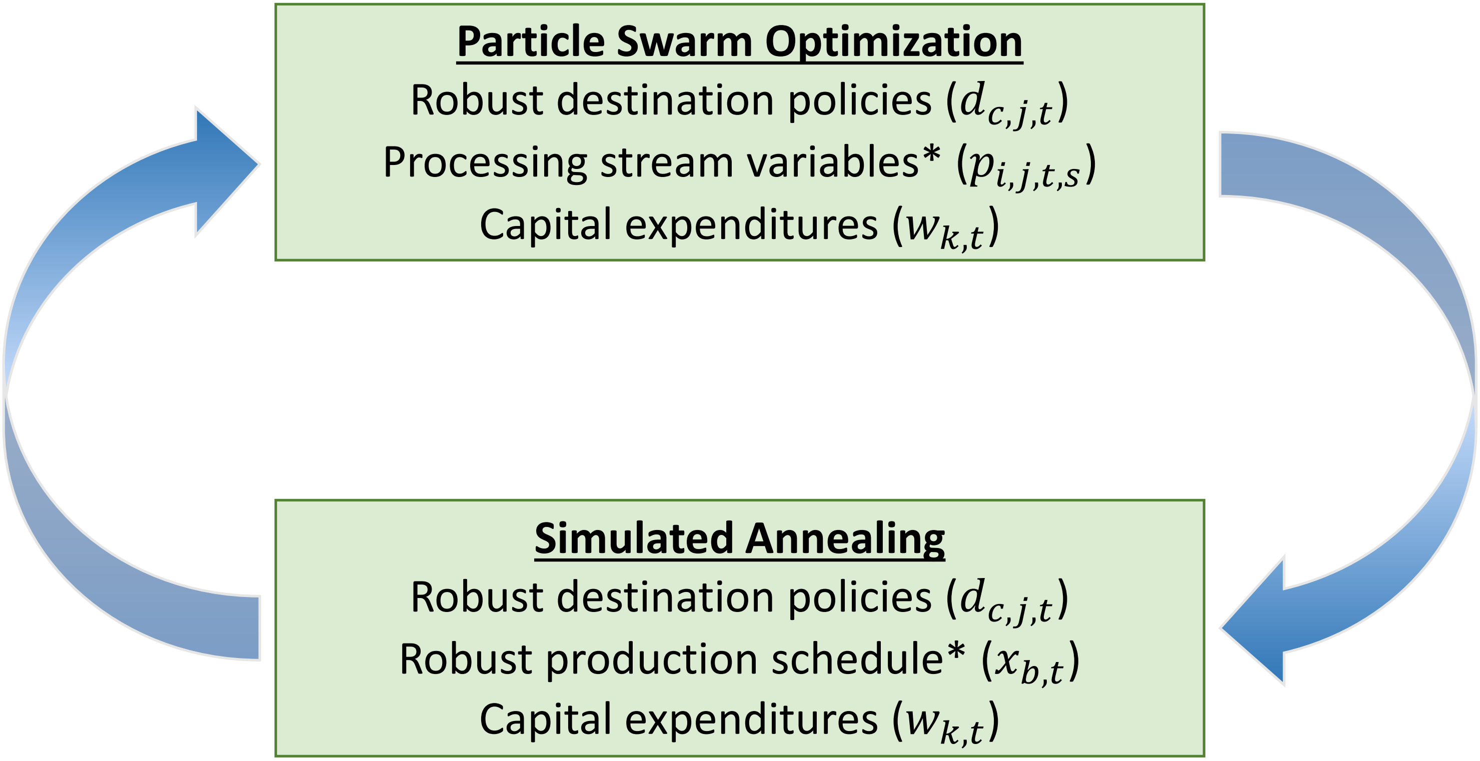
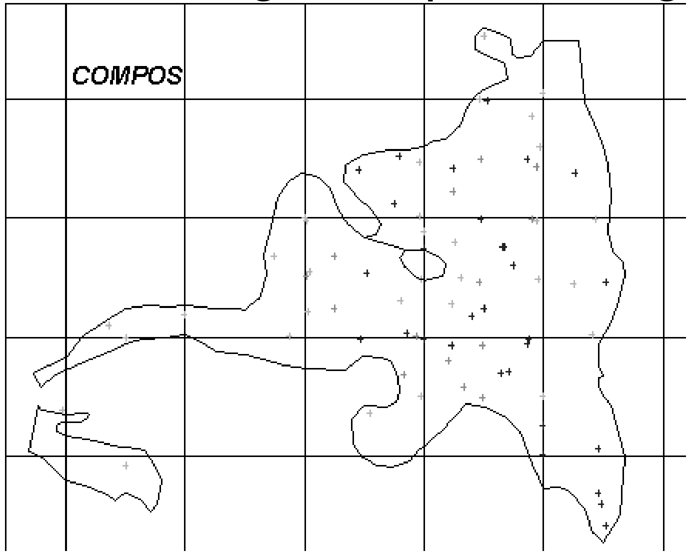
Algorithmic Optimization with Metaheuristics

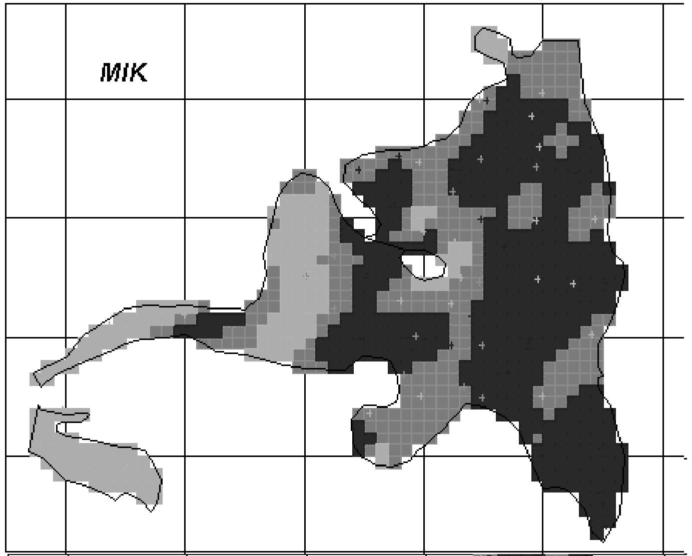


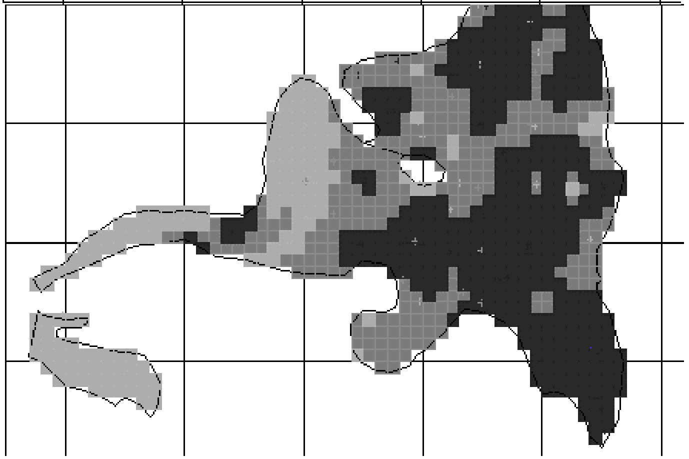
Introduction – Innovation & cross disciplinary integration

Bench in a gold deposit being mined

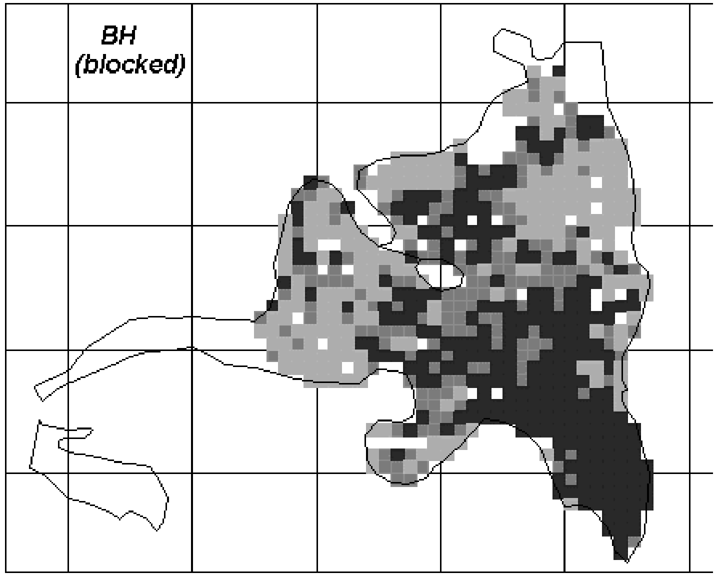


Estimated deposit bench, 2 methods





Real blast hole data

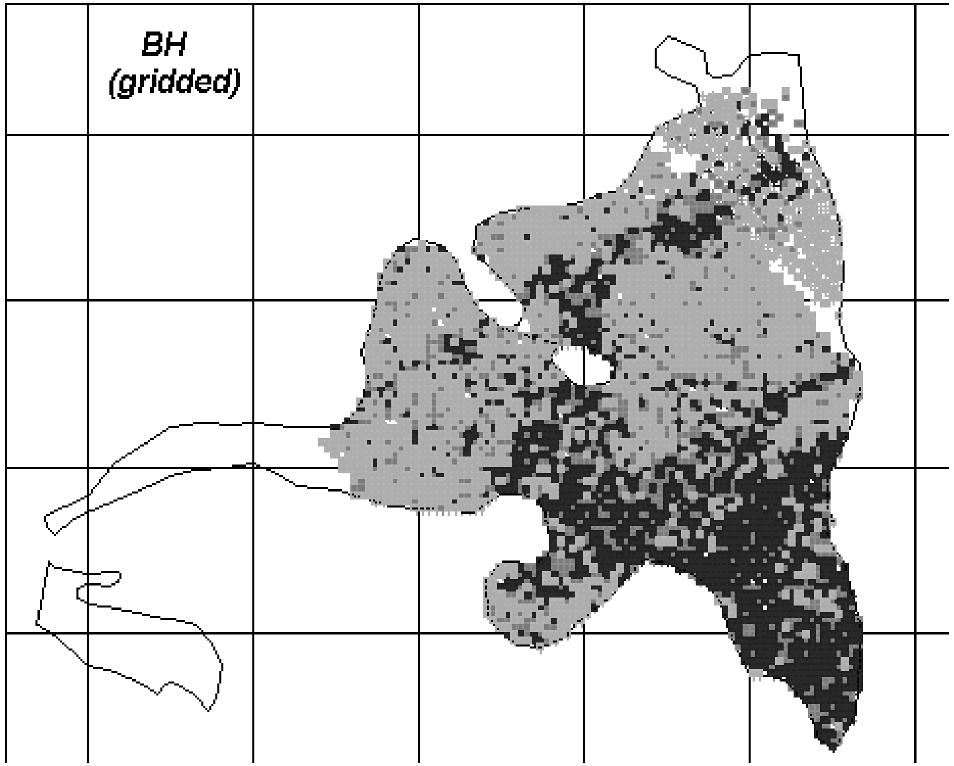


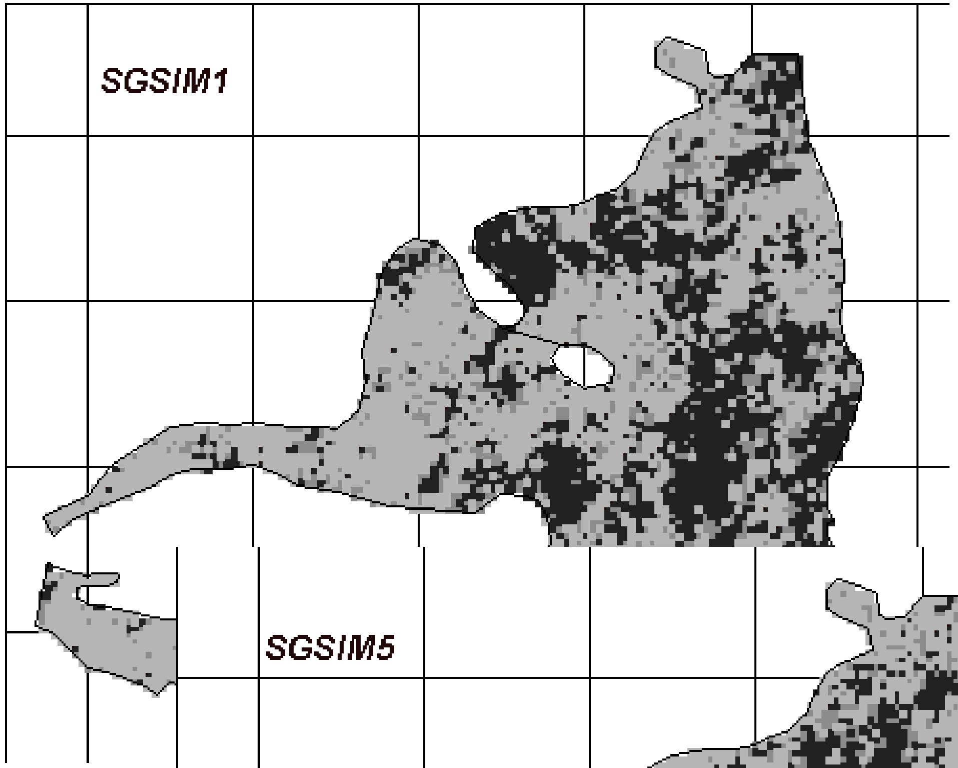
Black indicates DDH grade above 1.3 g/t and grey between 0.7 and 1.3 g/t

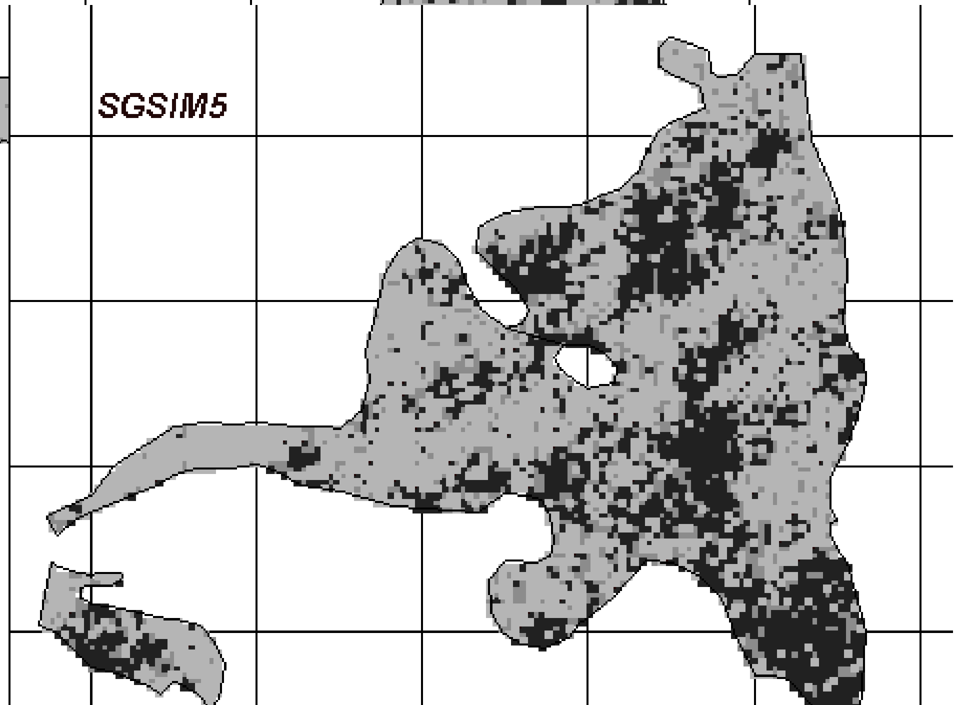
Real mineral deposits are not smooth

10x10x5m blocks

Blastholes grades and simulated blasthole grades from exploration data



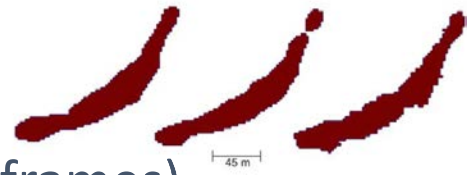




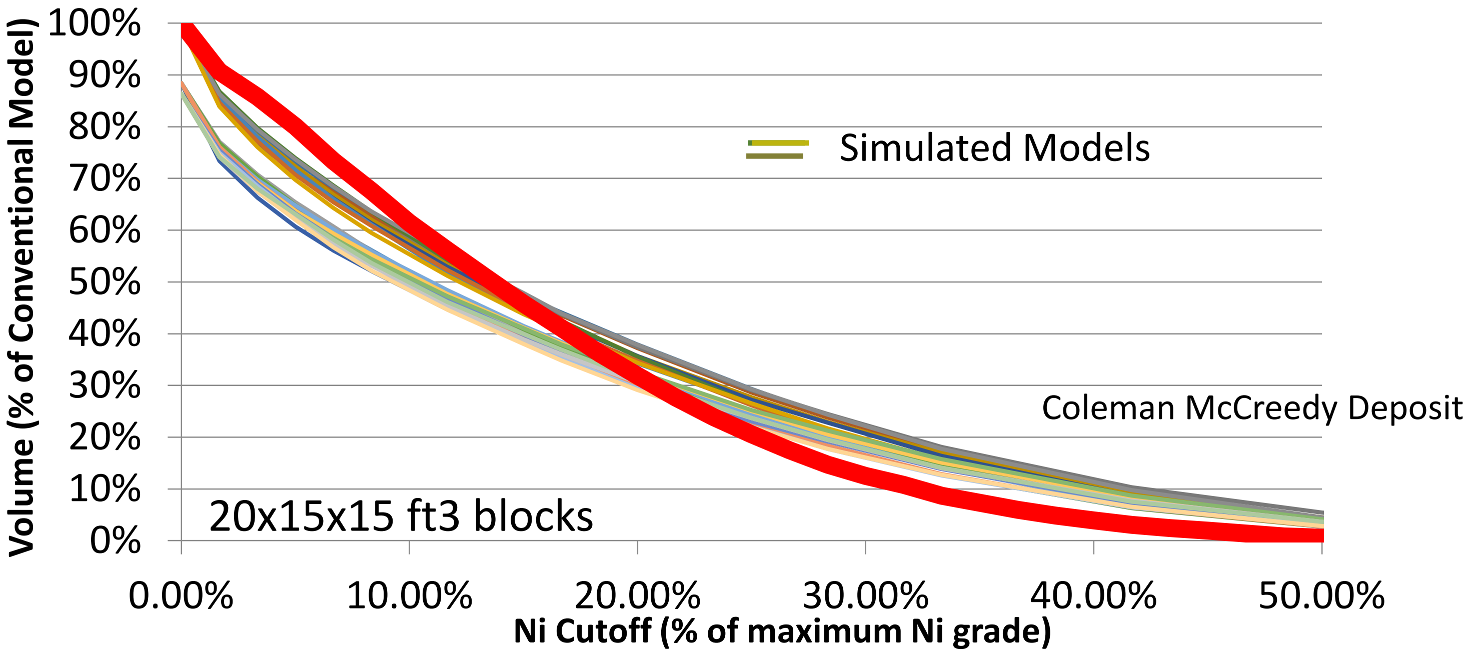
Introduction – Innovation & building blocks

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

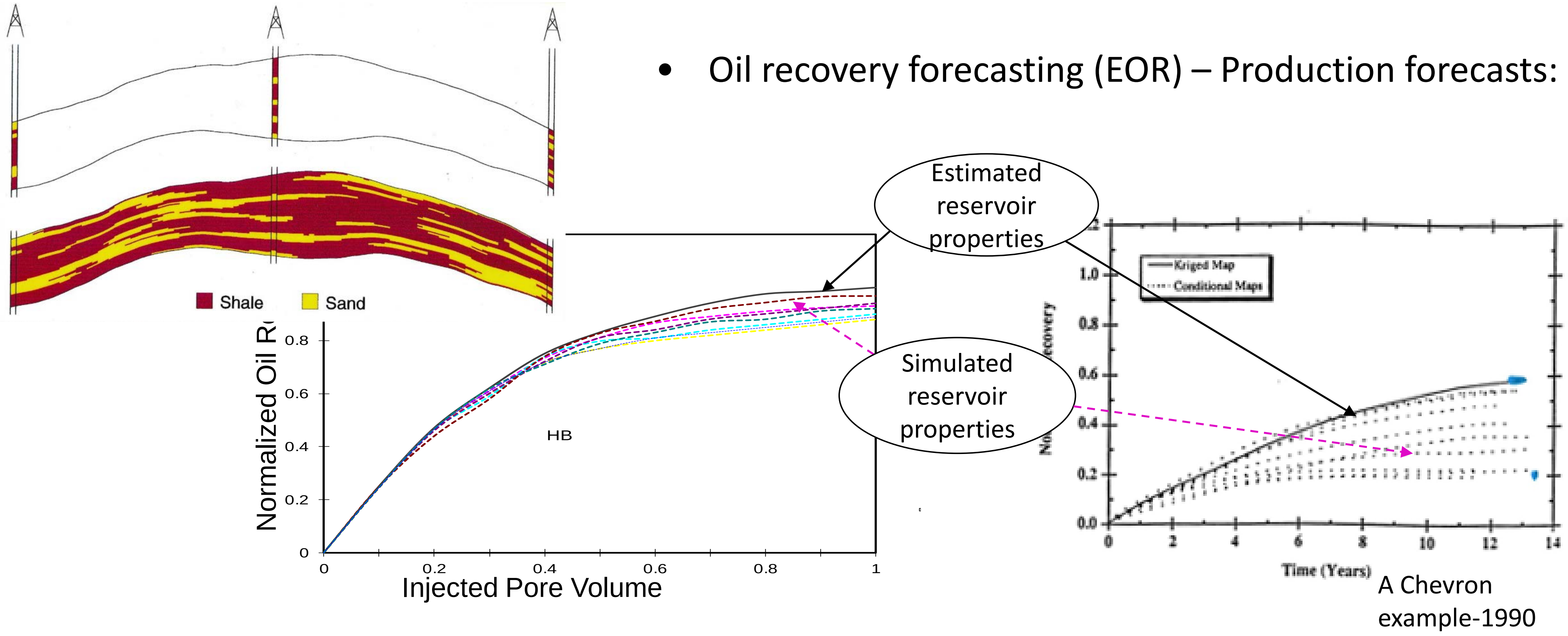


Misrepresentation from smoothing seen above in grade-tonnage curves (from any estimation method, including the “averages” from simulated realizations), *has adverse effects on the deterministic optimization conventionally utilized in mine planning.*

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