Smart Industrial Mining Complexes - Mineral Value Chains, Present and Future

New Digital Technologies, Artificial Intelligence and Self-Learning, Advances and Challenges

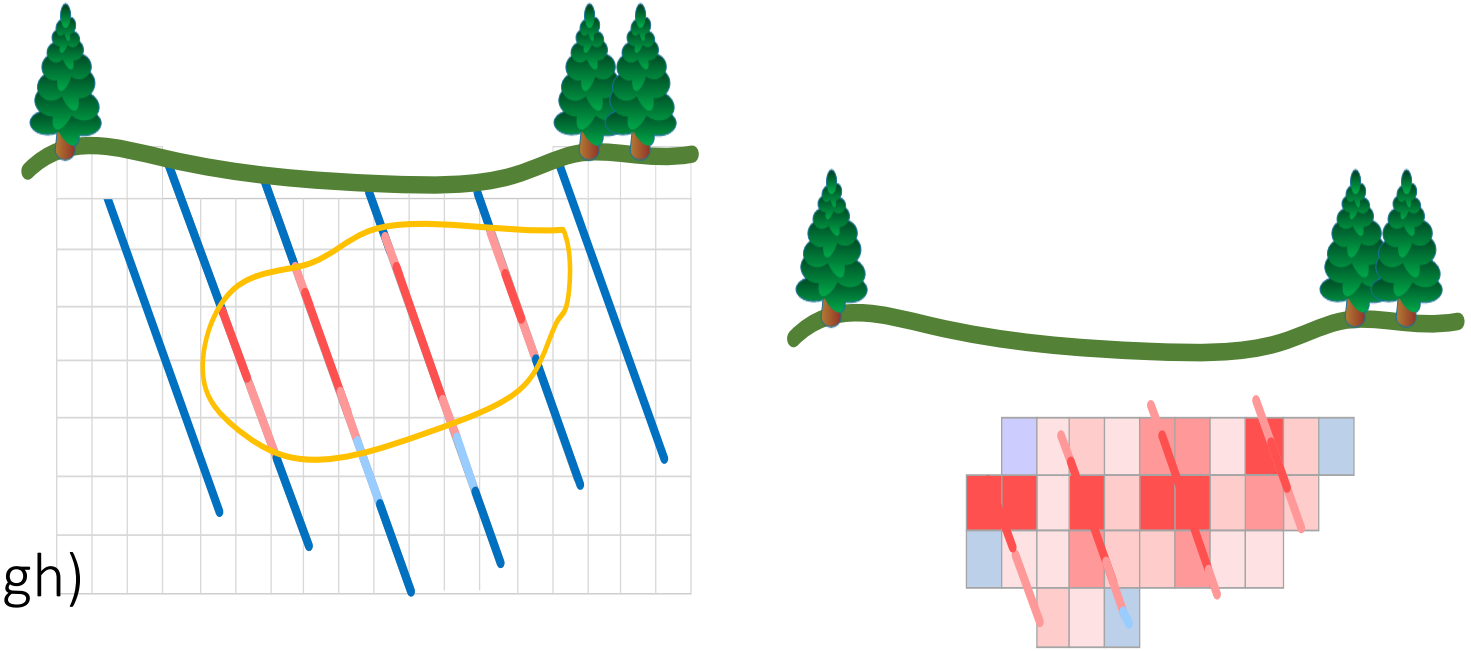
Roussos Dimitrakopoulos

Content

- Mining complexes - Mineral value chains
- Simultaneous stochastic optimization and example from a gold mining complex
- Production planning and new information
- Artificial intelligence - Reinforcement learning
- Example from a copper mining complex
- Conclusions

Introduction

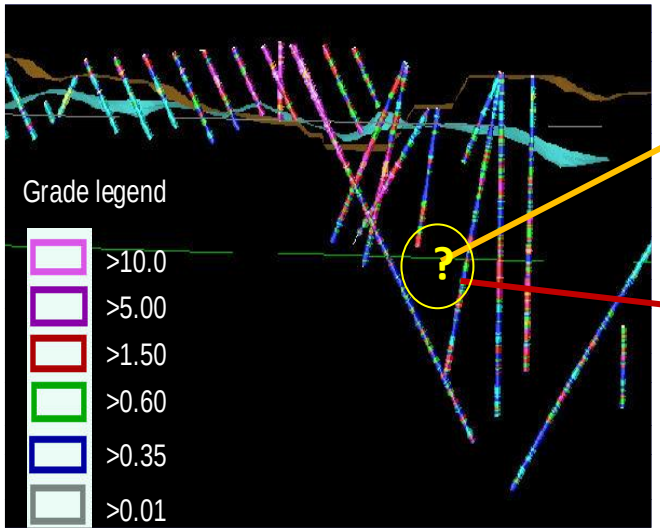
- From drill holes to mines: discretize the model into 3D volumes (mining blocks), create models for the metal content, material types… for each block in the orebody



Traditional Orebody Models:

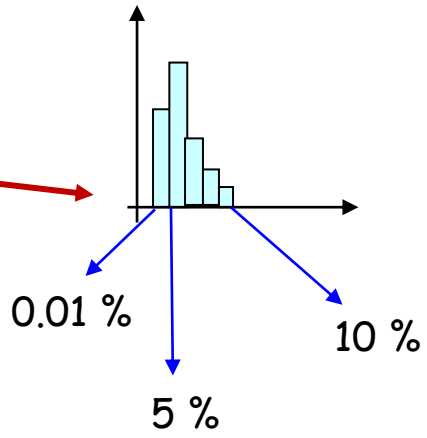
Some Limitations and *Shortcomings*

Conventional models **DO NOT account for uncertainty….**

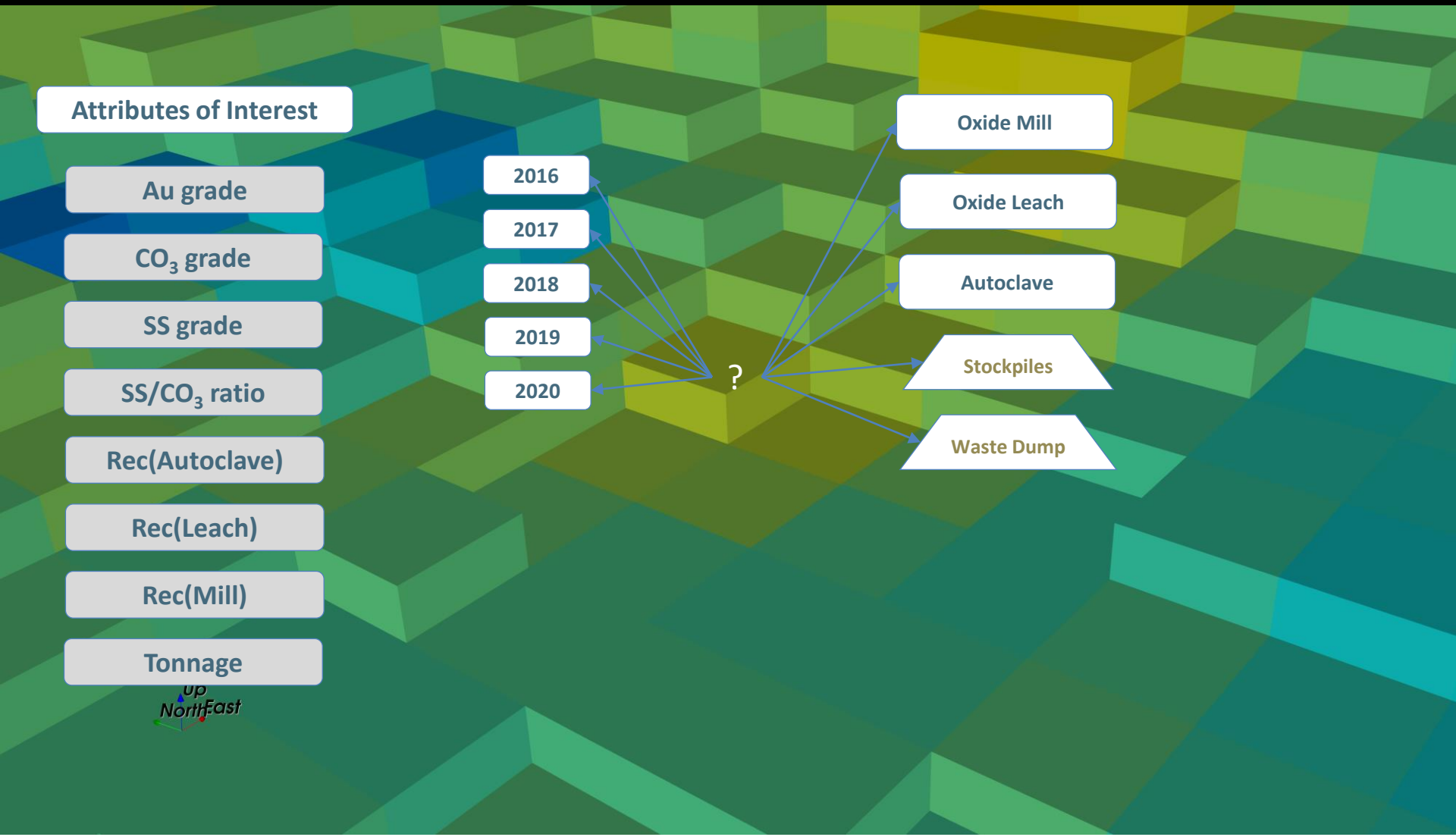


5 % ?

Estimation methods try to approximate some average grade value ... not the actual one



Mining Decisions



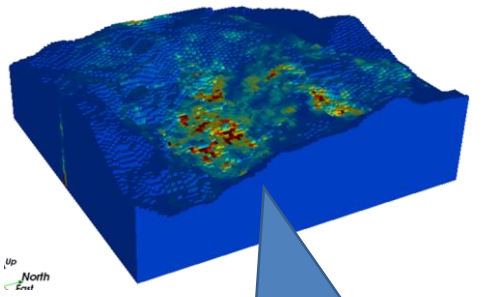
Traditional production scheduling methodologies neglect uncertainty and variability!

Source: M.Godoy, Newmont Gold, SME 2016

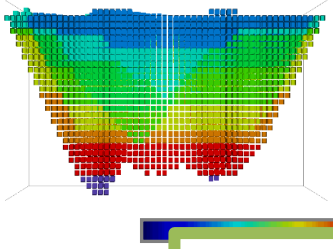
Conventional Mine Planning Workflow

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

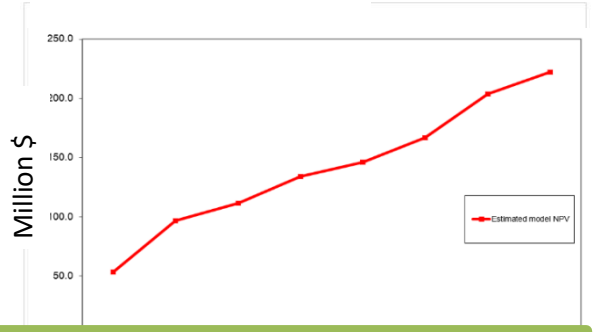
Estimated Orebody Model



Deterministic Design



Production Forecast



Can a single estimated model represent a mineral deposit? (Grade variability, uncertainty)

Is
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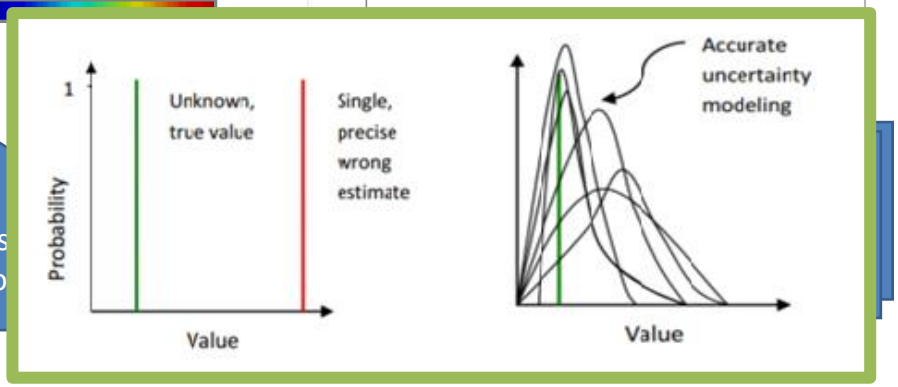
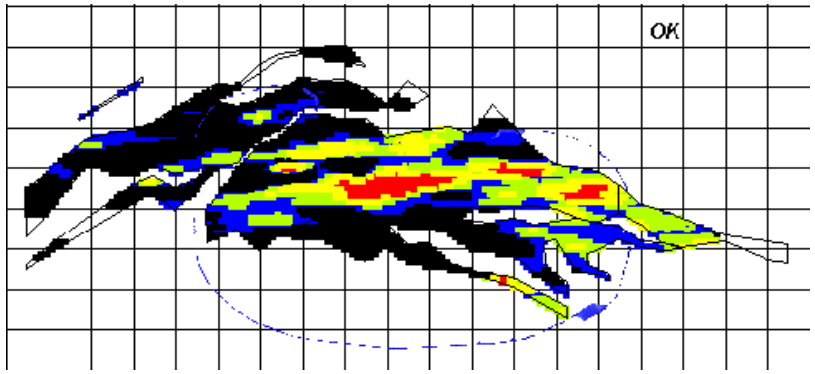
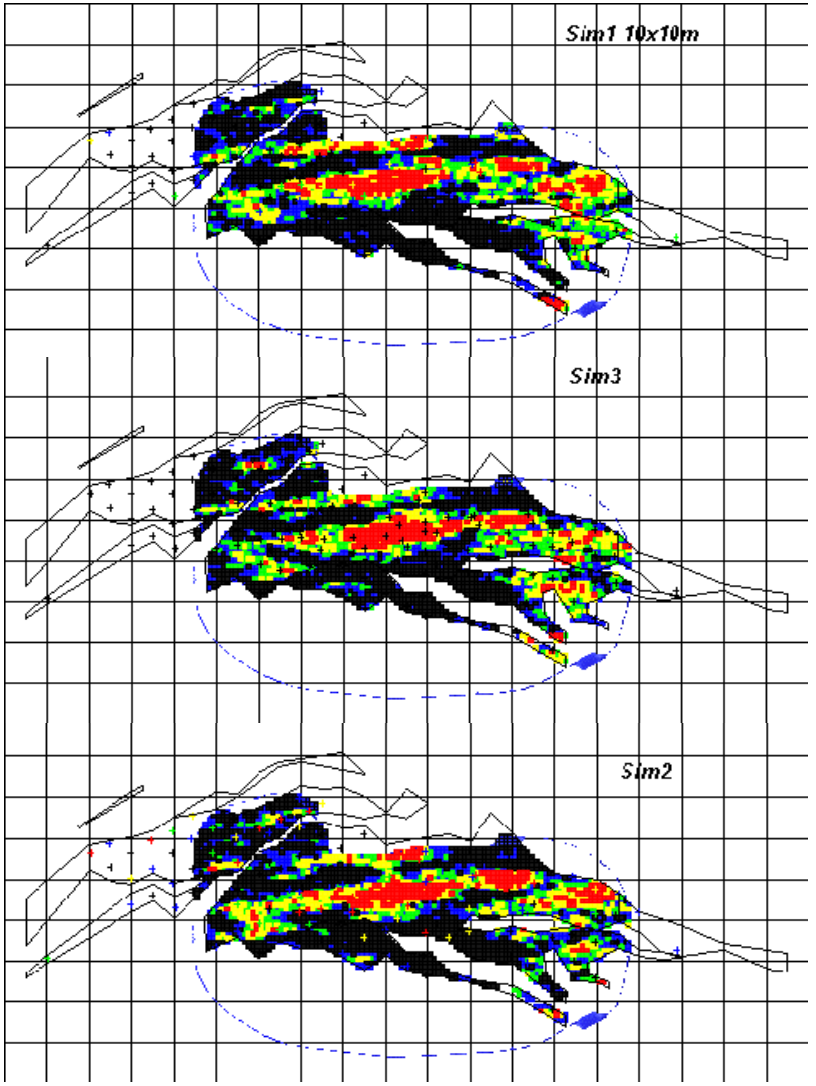


Estimation vs Simulation does it Matter?

Estimation



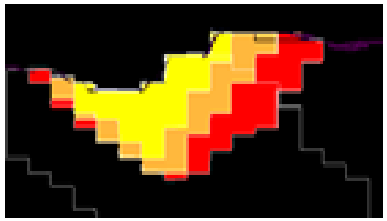
Simulation



A Copper Deposit

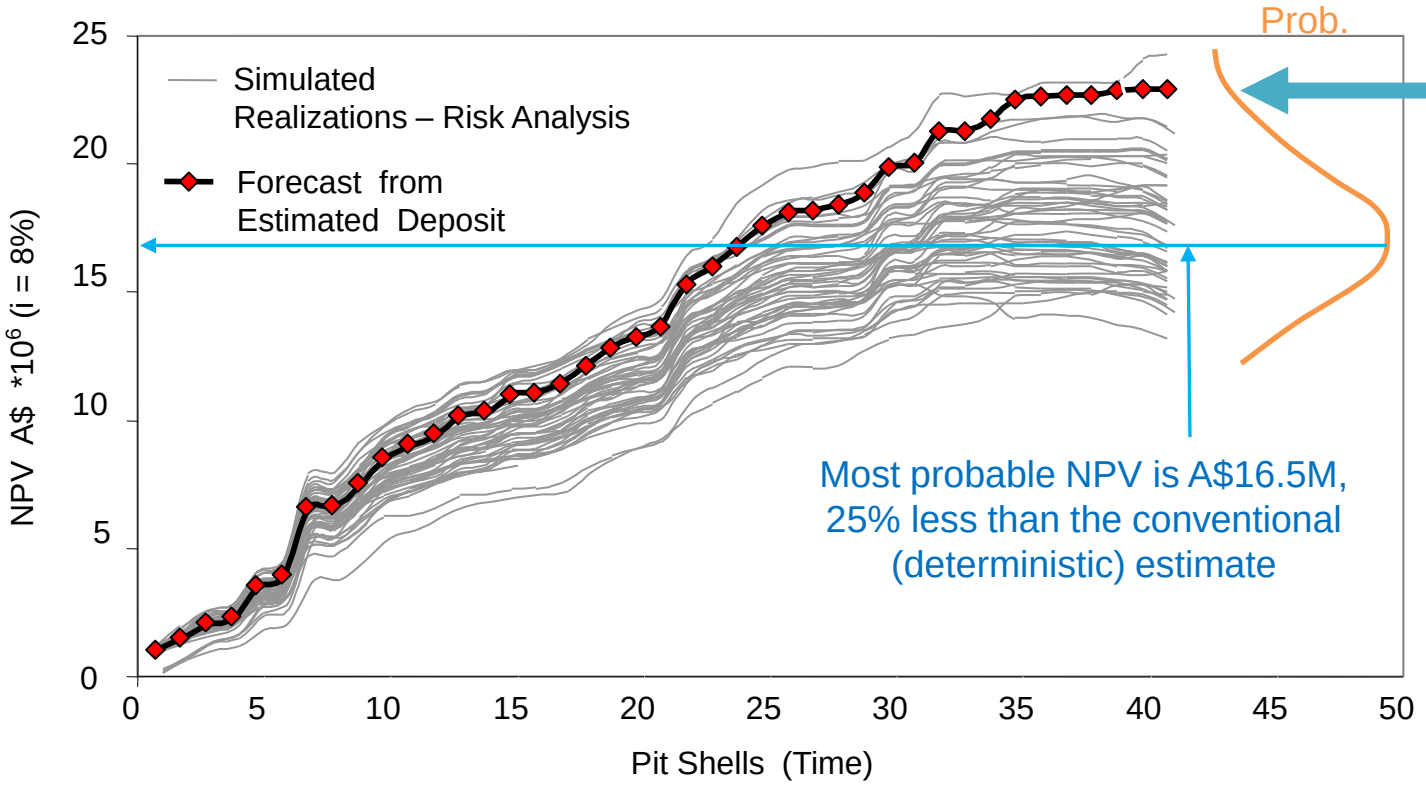
Colors are Cu% (read is highest)

Estimation vs Simulation does it Matter?



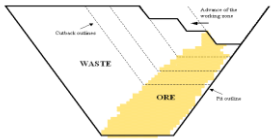
A recall from 1998

Testing the conventional plan against simulated scenarios …



The expected project NPV has only 2-4% probability to be realized

Most probable NPV is A$16.5M, 25% less than the conventional (deterministic) estimate



Why? Estimation methods misrepresent volumes of different grade ranges … and more …

PUBLISHED SUNDAY, OCTOBER 8, 2000, IN THE *SAN JOSE MERCURY NEWS*

The Flaw of Averages

IF YOU COUNT ON THE STOCK MARKET'S AVERAGE RETURN TO SUPPORT YOU IN RETIREMENT, YOU COULD WIND UP PENNILESS

By Sam Savage

"The only certainty is that nothing is certain."

So said the Roman scholar Pliny the Elder. And some 2000 years later, it's a safe bet he would still be right. The Information Age, despite its promise, also delivers a dizzying array of technological, economic and political uncertainties. This often results in an error I call the Flaw of Averages, a fallacy as fundamental as the belief that the earth is flat.

The Flaw of Averages states that: Plans based on the assumption that average conditions will occur are usually wrong.

A humorous example involves the statistician who

Wrong! Given typical levels of stock market volatility there are only slim odds that the fund will survive the full time. The following charts simulate this retirement strategy with actual S&P 500 returns starting in various years.

Notice that the level of average returns over any par-

The Flaw of Averages distorts everyday decisions in many other areas. Consider the hypothetical case of a Silicon Valley product manager who has just been asked by his boss to forecast demand for a new-generation microchip.

thousands of scenarios covering all conceivable real world contingencies in proportion to their likelihood.

In the 1950s, Harry Markowitz, a brash young gradu-

Conventional / Deterministic Workflows

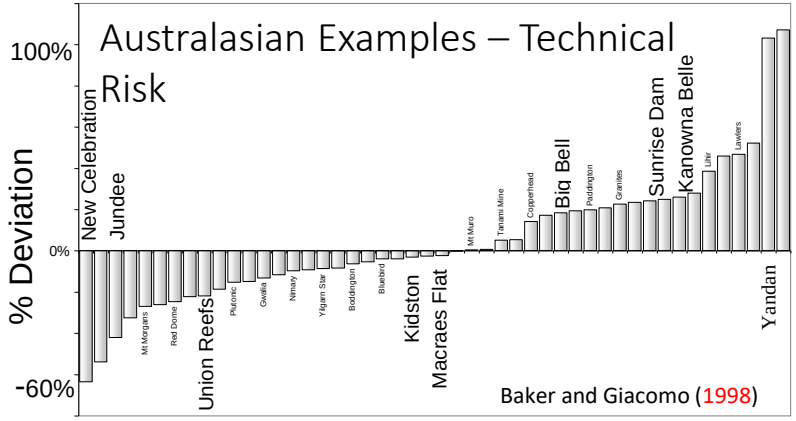
Mine

Processing streams

Customers & Markets …

Waste dumps…. Tailings… Rehab …

80% of Failures Due to Geological Risk



Stochastic Workflows

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

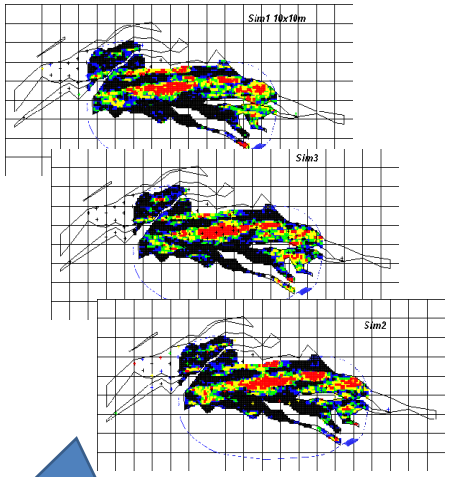
Simulated Orebody Models

Sim. 1 *s=1*

Sim. 2 *s=2*

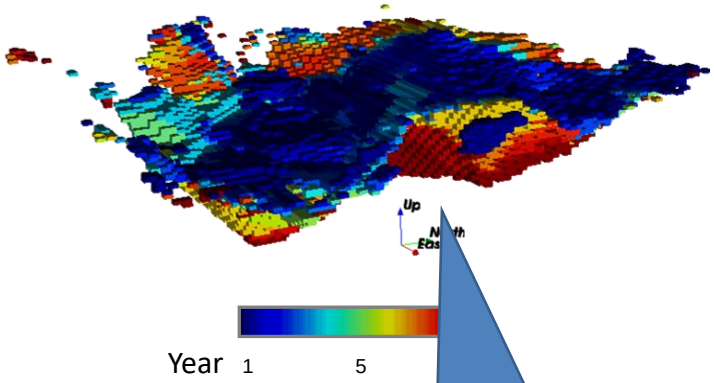
...

Sim. S *s=S*



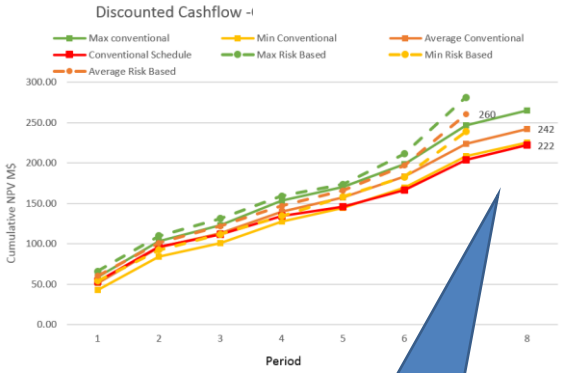
A set of simulations describe geological uncertainty and *grade variability*

Stochastic Design & Production Schedule



A single mine design and production schedule accounting for uncertainty and managing risk

Probabilistic Reporting



A better NPV is always obtained through the use of stochastic mine planning in comparison with conventional methods

Simultaneous Optimization

Mines

Processing streams

Customers & Markets …

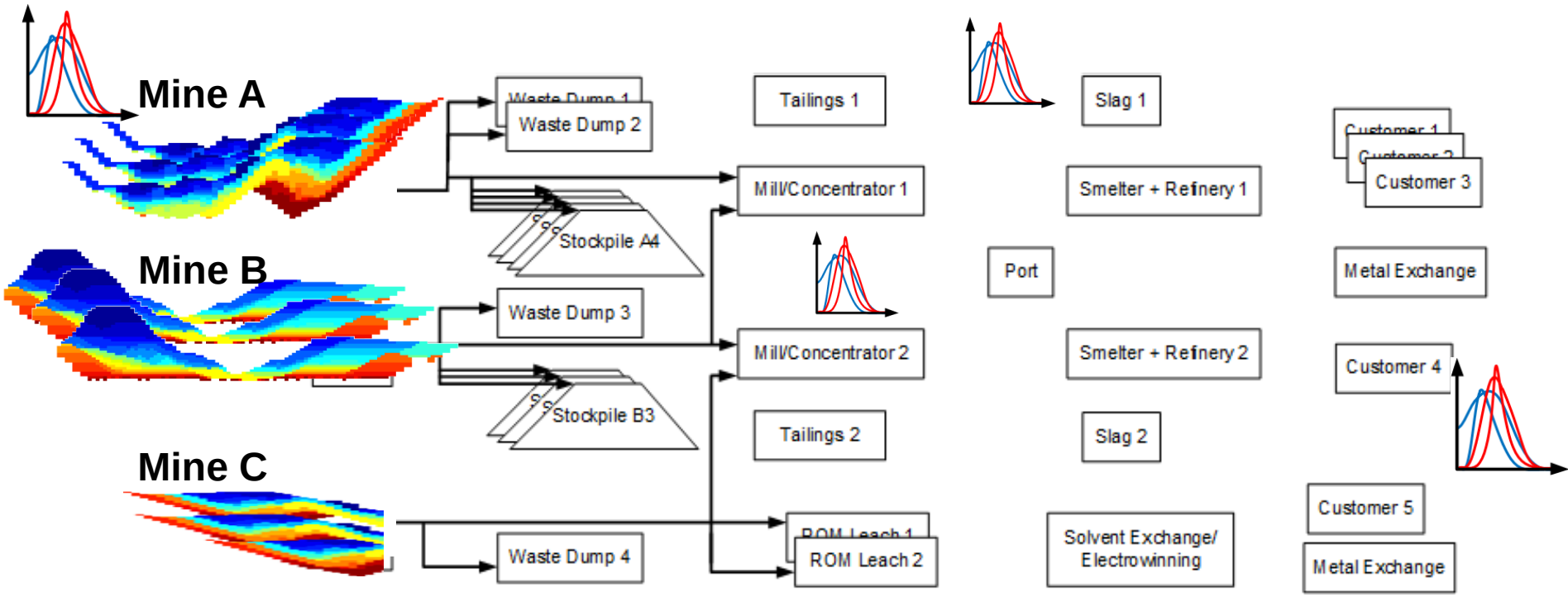
Waste dumps…. Tailings… Rehab …

***One* Stochastic Mathematical Programming Formulation for the whole Mineral Value Chain**

Mining Complexes - 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

Simultaneous stochastic optimization of the mining complex/value chain



Simultaneous:

a. One optimization model to *capitalize on synergies*,
b. $ value of products sold no *$ value of individual blocks*

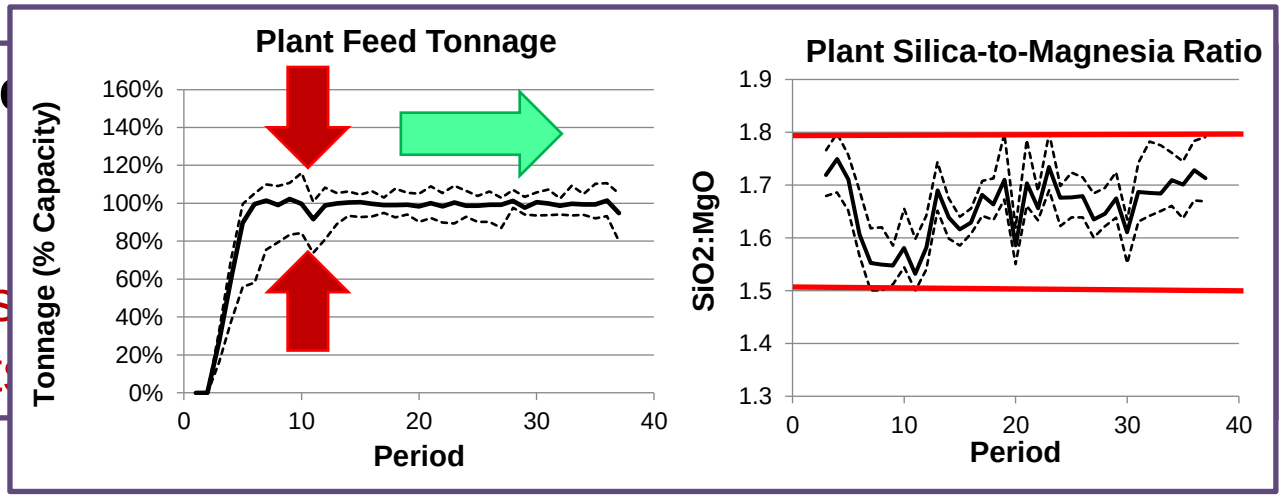
Simultaneous Stochastic Optimization

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

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

Attributes of int

- Revenues from metal sale
- Mining, process stockpiling cost

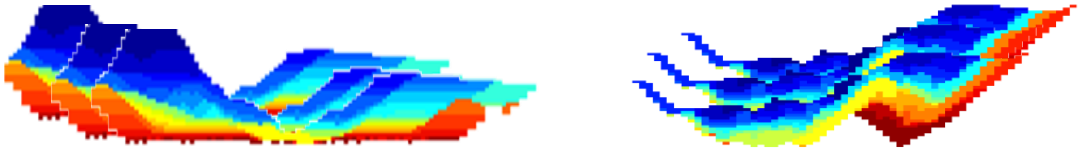


$$-\sum_{t\in\mathbb{T}} \sum_{k\in\mathbb{K}} p_{k,t} \cdot w_{k,t}$$

CAPEX

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

Mining Complexes with Risk Management



Production schedule

Sulfides - Mine 1
- Metal tonnes
- Total tonnes

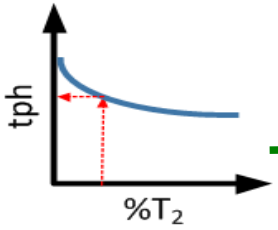
ξ_s

Sulfides - Mine 2
- Metal tonnes
- Total tonnes

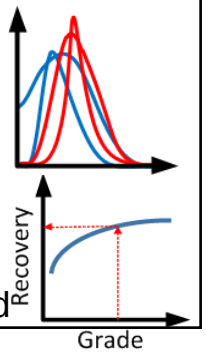
No Economic Values for Mining Blocks Used

Destination policies

Processing streams



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

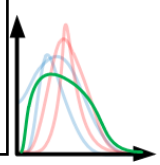


Decisions, Blending, GEOMET… ….. ….. All topics related to materials mined move here

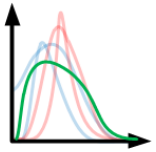
Uncertainty can be quantified at any stage

Product Value

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



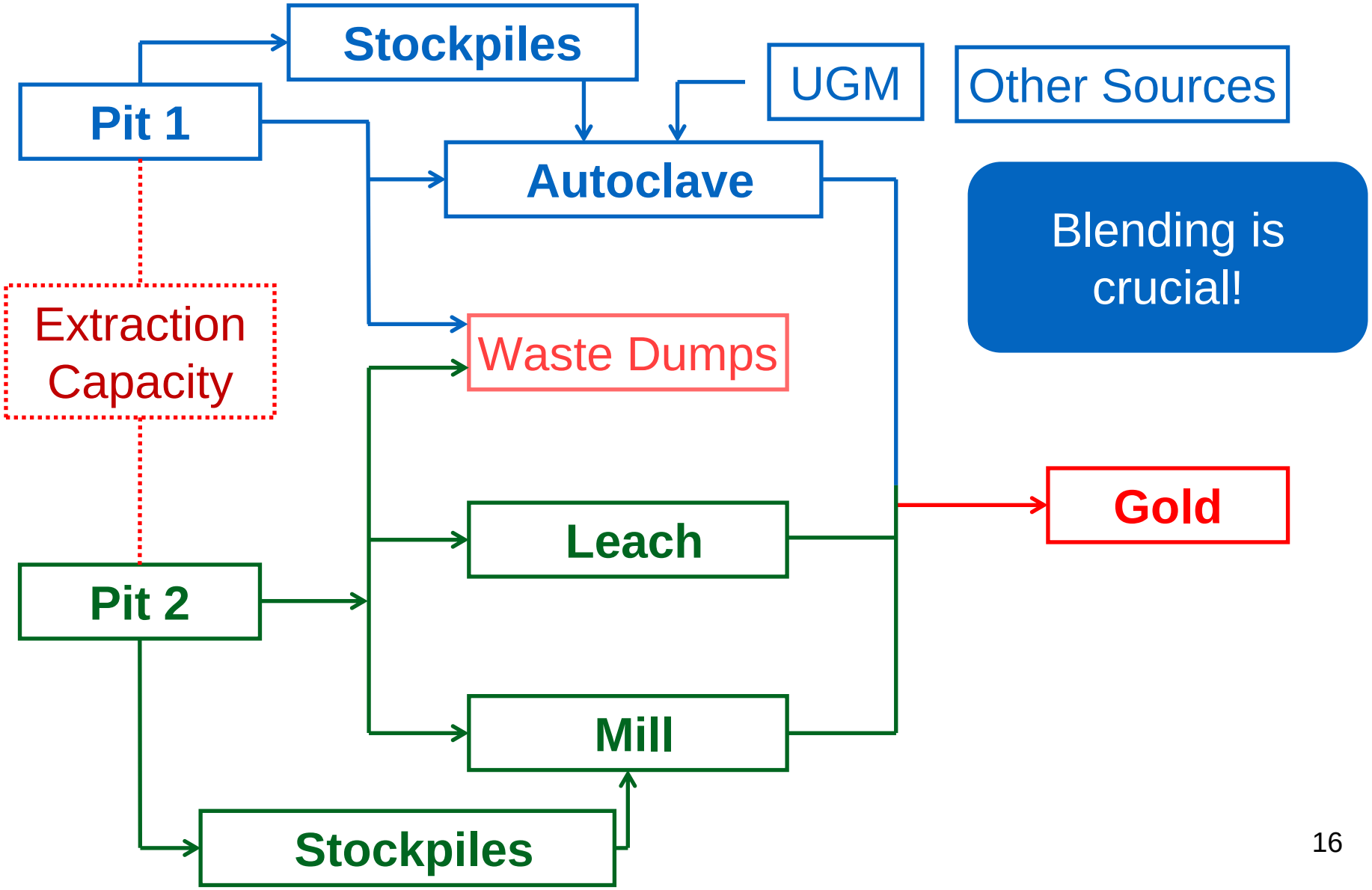
Customer #2
1. Metal
2. Metal value



Cash flows are calculated here using products

The life-of-asset(s) strategic plan is the output of the optimization

A Gold Mining Complex



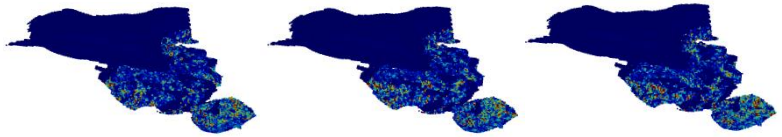
Sources of Supply Uncertainty

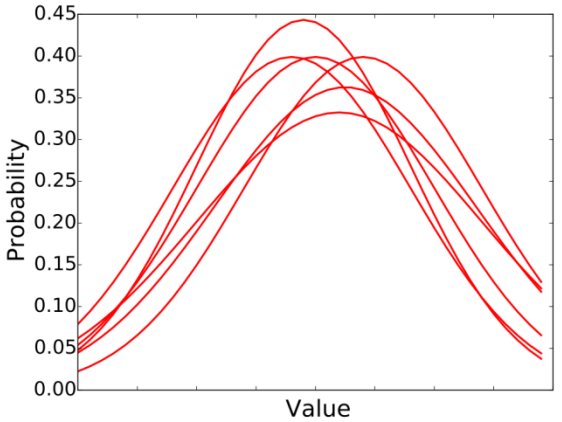
Other Sources

Pit 1

A

B

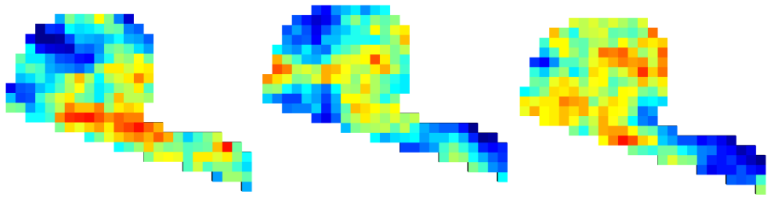




Historical data

Stochastic simulations

Autoclave

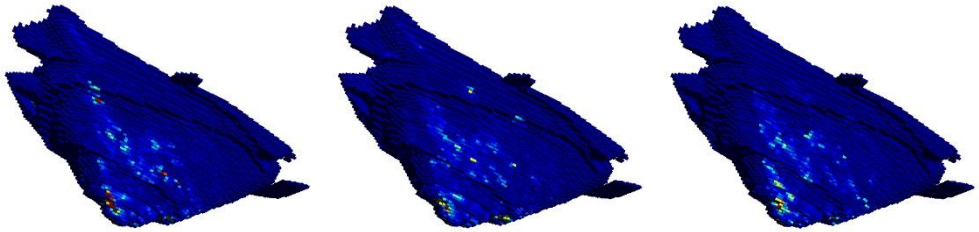


Simulated Sulphide Stockpiles

Mill

Pit 2

Leach

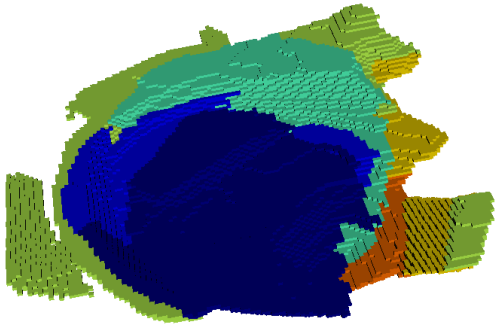


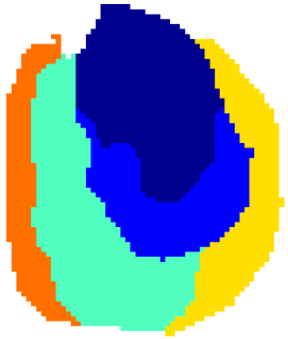
Stochastic simulations

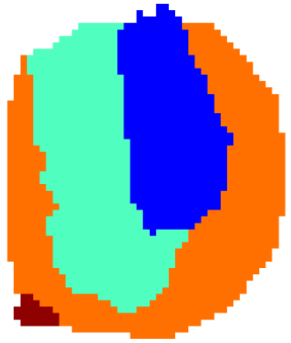
Practical Stochastic Schedule - Example

Full View | **Bench A** | **Bench B**

Practical Stochastic plan

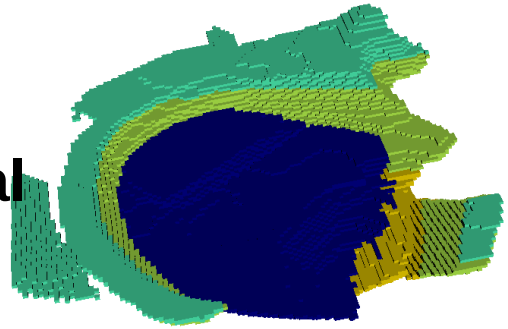






Colours represent *production years*

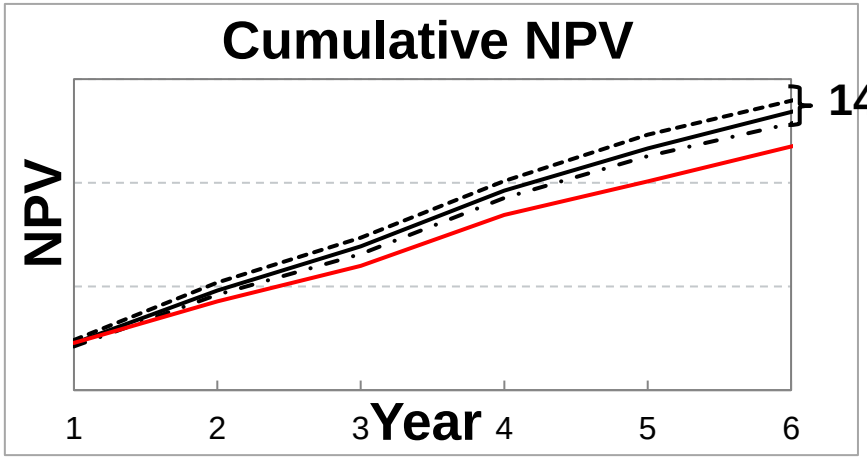
The Mine's Practical Conventional plan

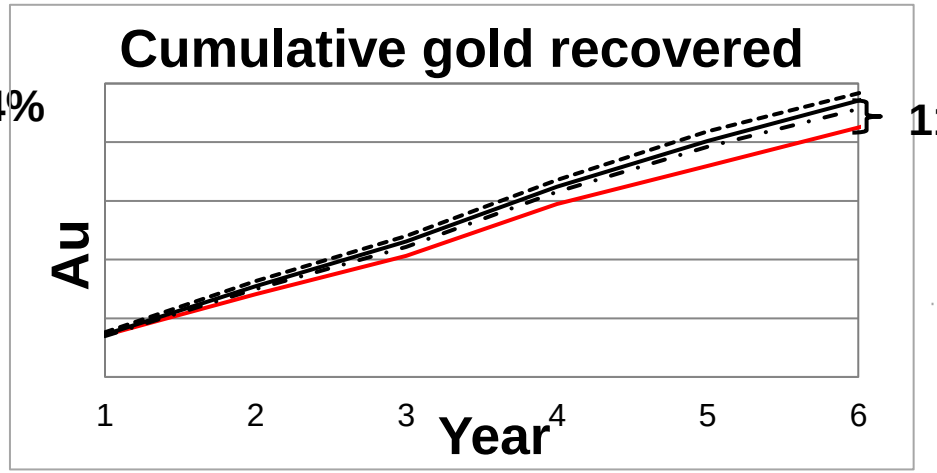


Stochastic vs conventional schedules:

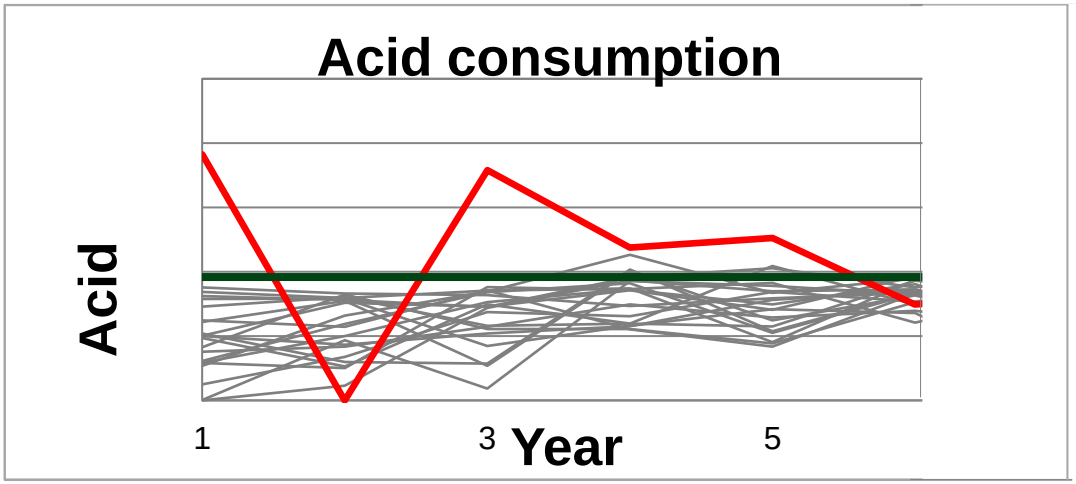
Substantially different parts of the pit are mined at the same year

Stochastic Optimization in a Mining Complex





Mine's schedule — P10 — P50 - - - - P90 of Stochastic schedule



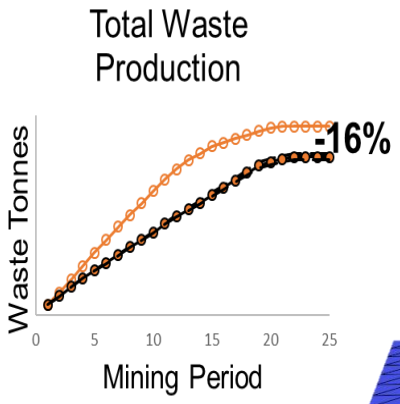
Mine's — Stochastic — Limit

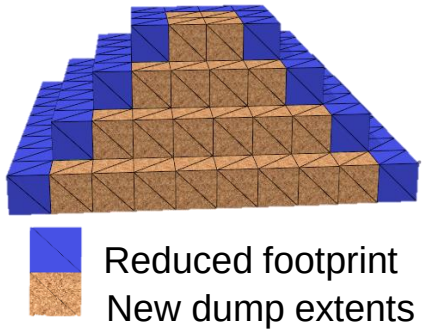
Environmental & social impacts

- Waste management and

  Rehabilitation

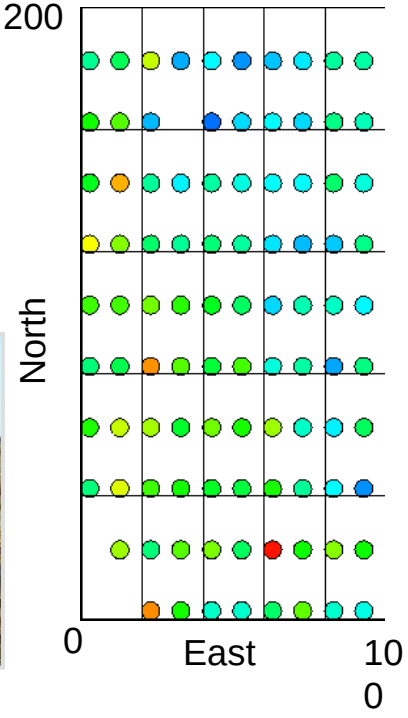
- Acid rock drainage
  - Result of oxidation of sulfidic rock
- Decreased environmental footprint
- ….



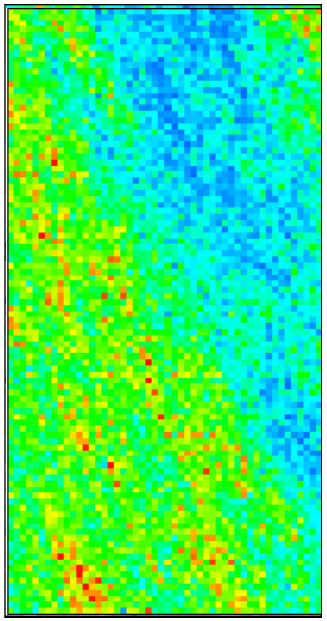


Waste Characterization and Rehabilitation

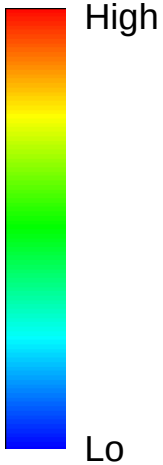
Waste dump

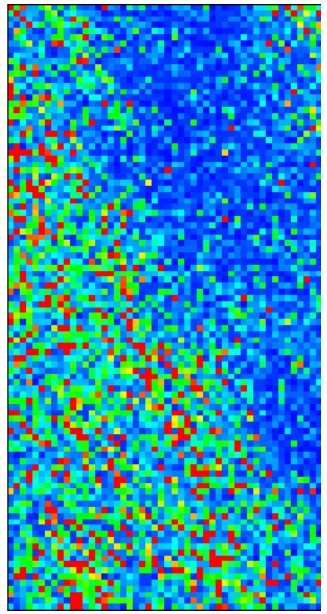


Electric Conductivity

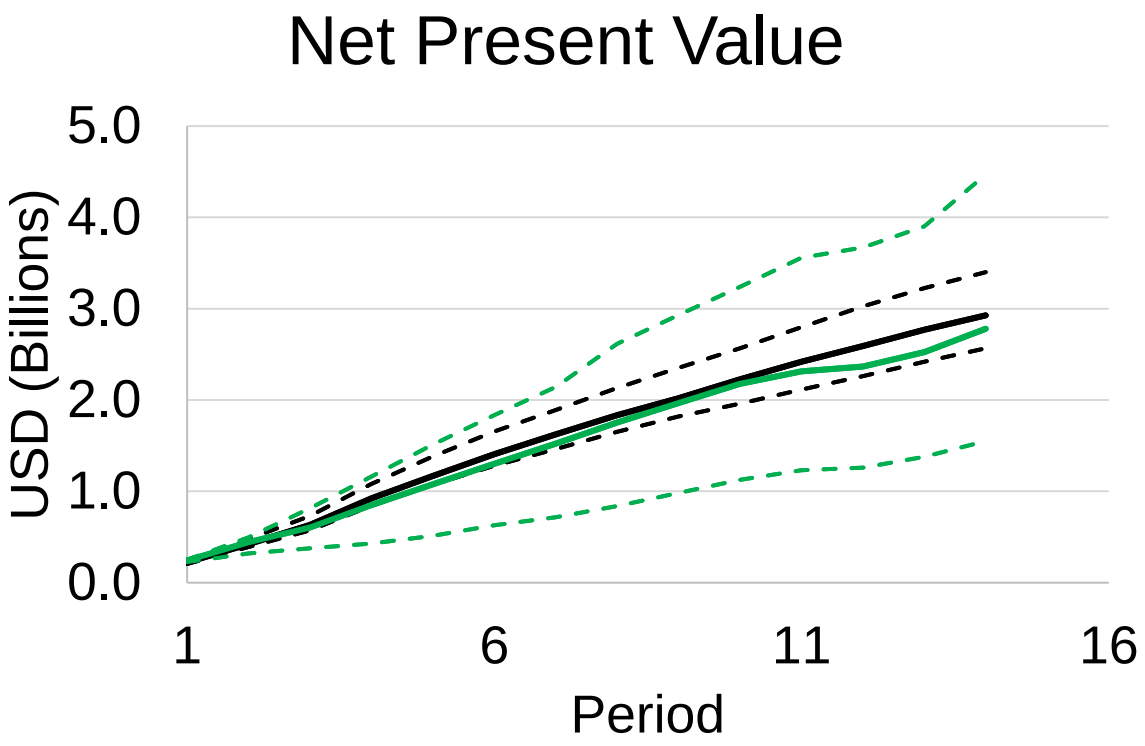


Concentration $[H^+]$





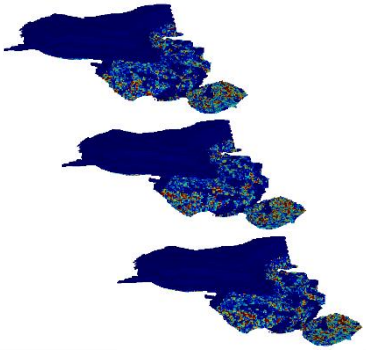
Joint Supply and Market Uncertainty

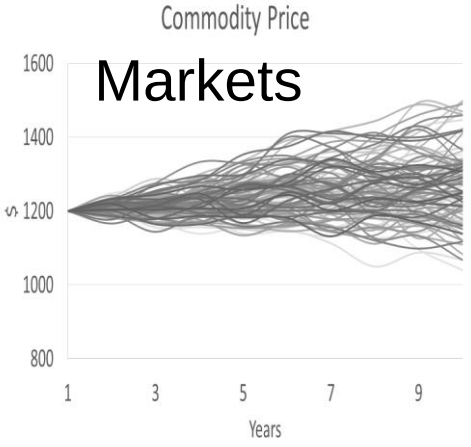


P10/P90 ---- P50 ——

Joint Supply and Market Uncertainty Supply Uncertainty

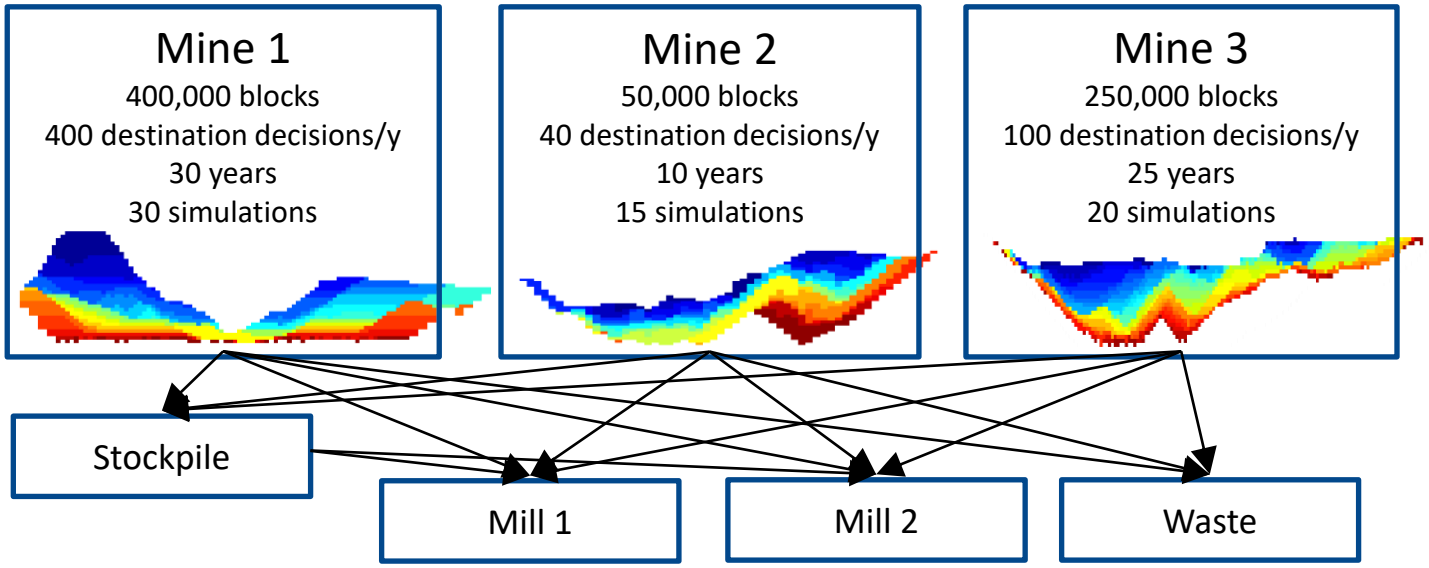
Mineral Deposits





Optimization with Metaheuristics

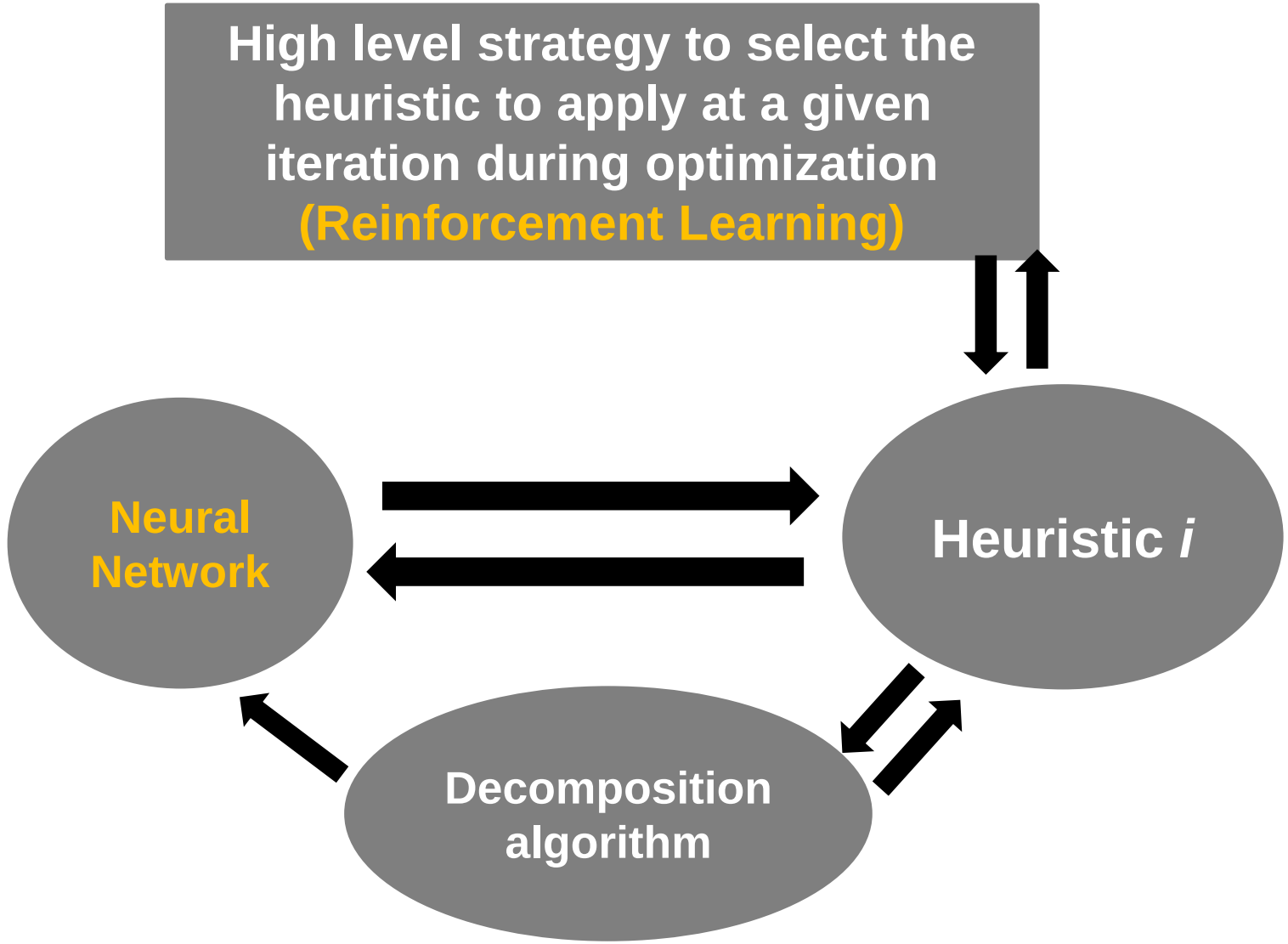
- Computationally prohibitive optimization models, IN THE PAST.



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

New Research - AI based Optimization Solutions

For Mineral Value Chain optimization formulations



Mining Complexes - Mineral Value Chains

The Self-learning Mining Complex

and

Updating Short-term Production Plans

and .....

New Information - Mining Complexes

- Sensor generated information
  - Equipment (Truck, Shovel)
  - Crushers
  - Conveyor belt
  - Processing plant
- Blasthole data
- New exploration data

Sensor Information

Trucks

Crusher

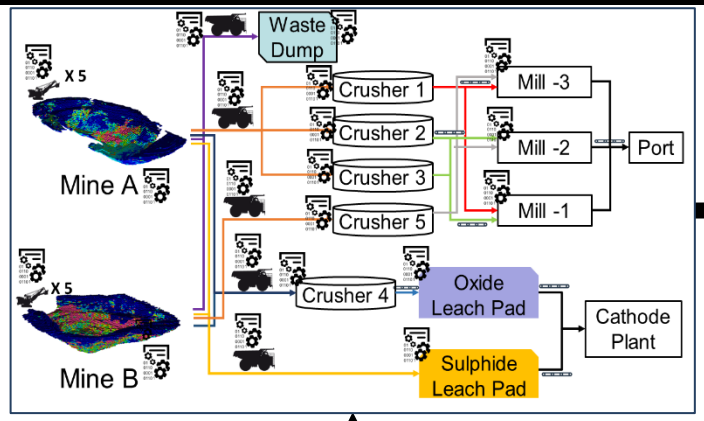
Shovels

Conveyor Belt

Exploration

Blasthole

New Information: Workflow

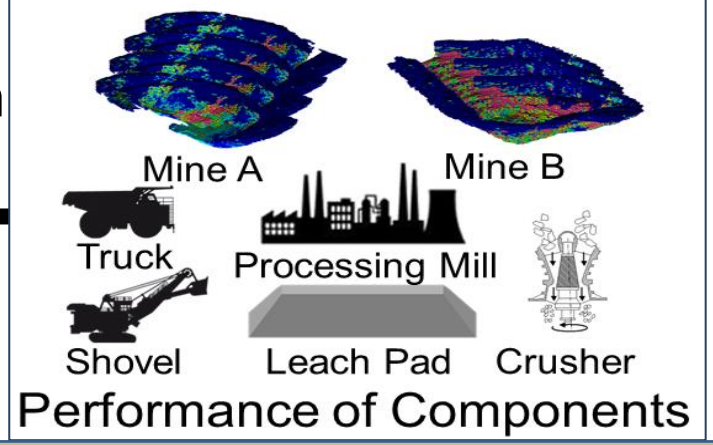


New Information Collected

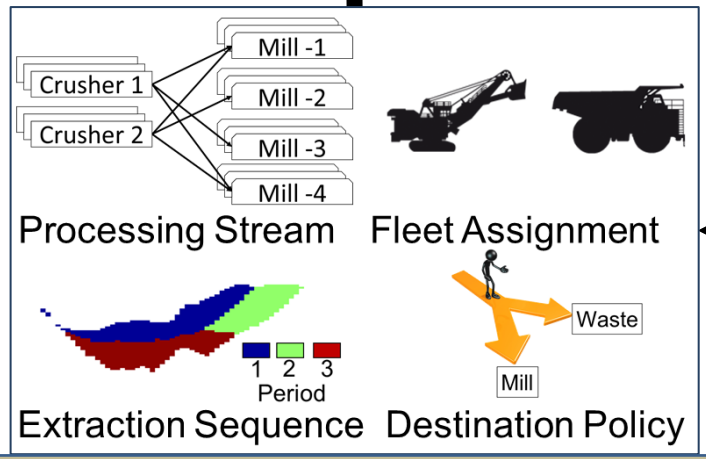
New Information

Material extracted	Material hauled
Deleterious elements	Material leached
Shovel performance	Leach performance
Material loaded	Crusher performance
Truck performance	Material processed
Material crushed	Plant performance

Update Uncertainty Models



Update Short-term Production Plan



Feedback to Mining Complex

Big Data → Machine Learning Methods → Update Short-Term Production Decisions

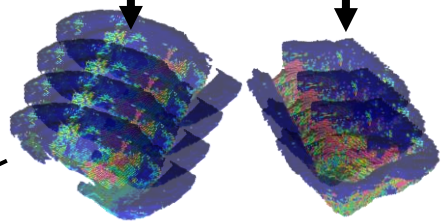
The Self-Learning Mining Complex

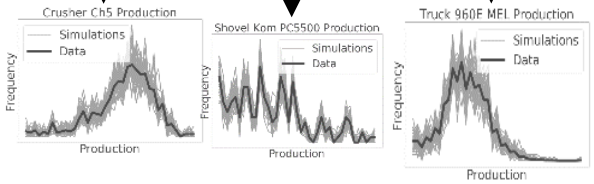
Digital Information Database

Quantity of material	Quality of material	Production
Extracted	Extracted	Shovels
Hauled	Hauled	Trucks
Crushed	Crushed	Crushers
Leached	Leached	Mills
Processed	Processed	Leaches

BIG DATA

Updating





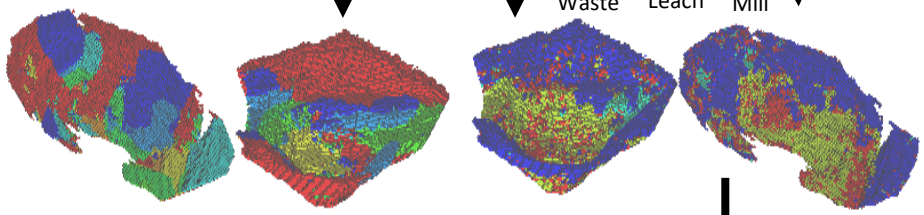
Ai

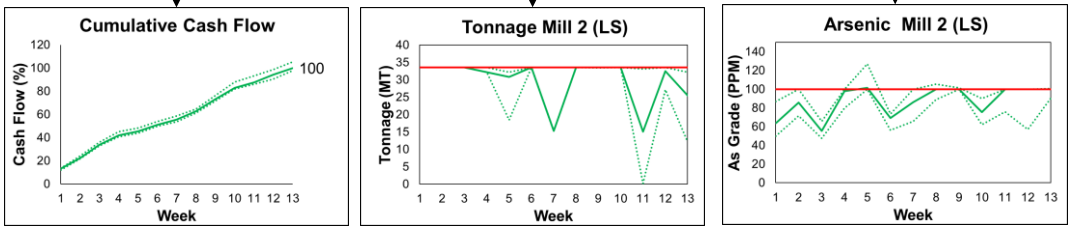
Mining Periods

1 2 3

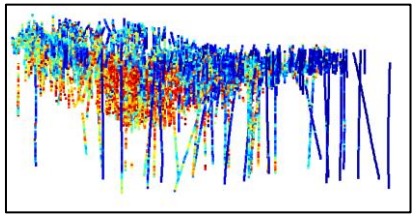
Destinations

Waste Leach Mill



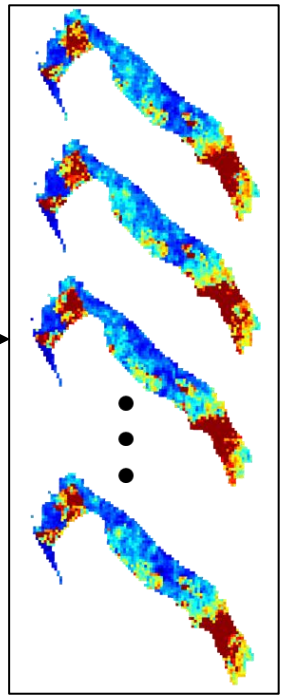


Updating Uncertainty Models



Drillhole Information

Stochastic Simulations



New Information

Material extracted	Material hauled
Deleterious elements	Material leached
Shovel performance	Leach performance
Material loaded	Crusher performance
Truck performance	Material processed
Material crushed	Plant performance

Ensemble Kalman Filter

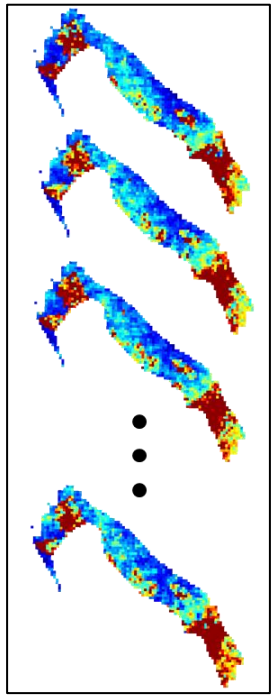
1. Prediction Step

$$AZ^t(x)$$

2. Correction Step

$$Z^{t+1}(x) = Z^t(x) + K(l + w^r - AZ^t(x))$$

Updated Stochastic Simulations

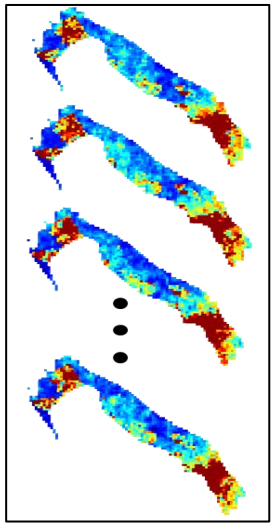


New Research - Updating Uncertainty Models

Feedback
Continuous Learning

Conventional Information

Initial Simulations

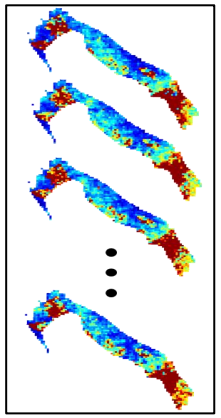


Sensor Information

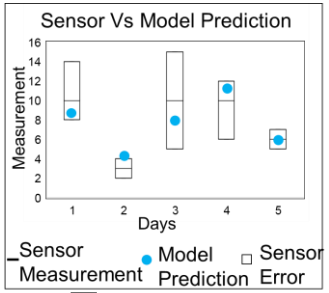
Artificial Intelligence (AI)

(Actor-Critic Reinforcement Learning)

1. Actor proposes updated value of mineral deposit (Proposal)
2. Critic evaluates if the proposed action is better/worse (Criticism)
3. Critic and actor adjust themselves to generate better proposal and criticism (Learn)



Updated Simulations



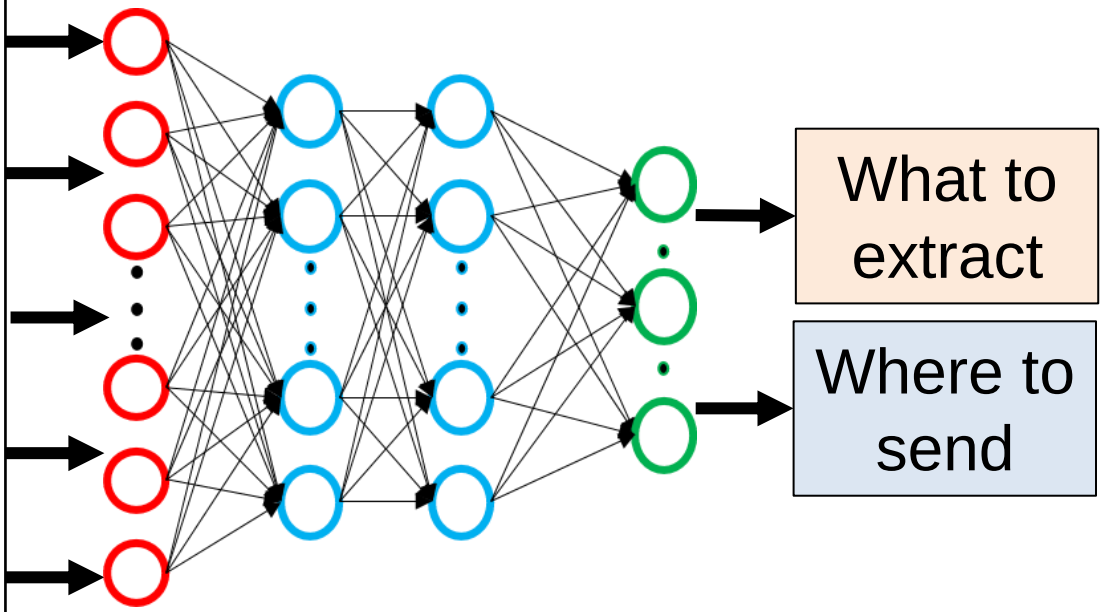
Forecast

Updating Short-term Production Plan

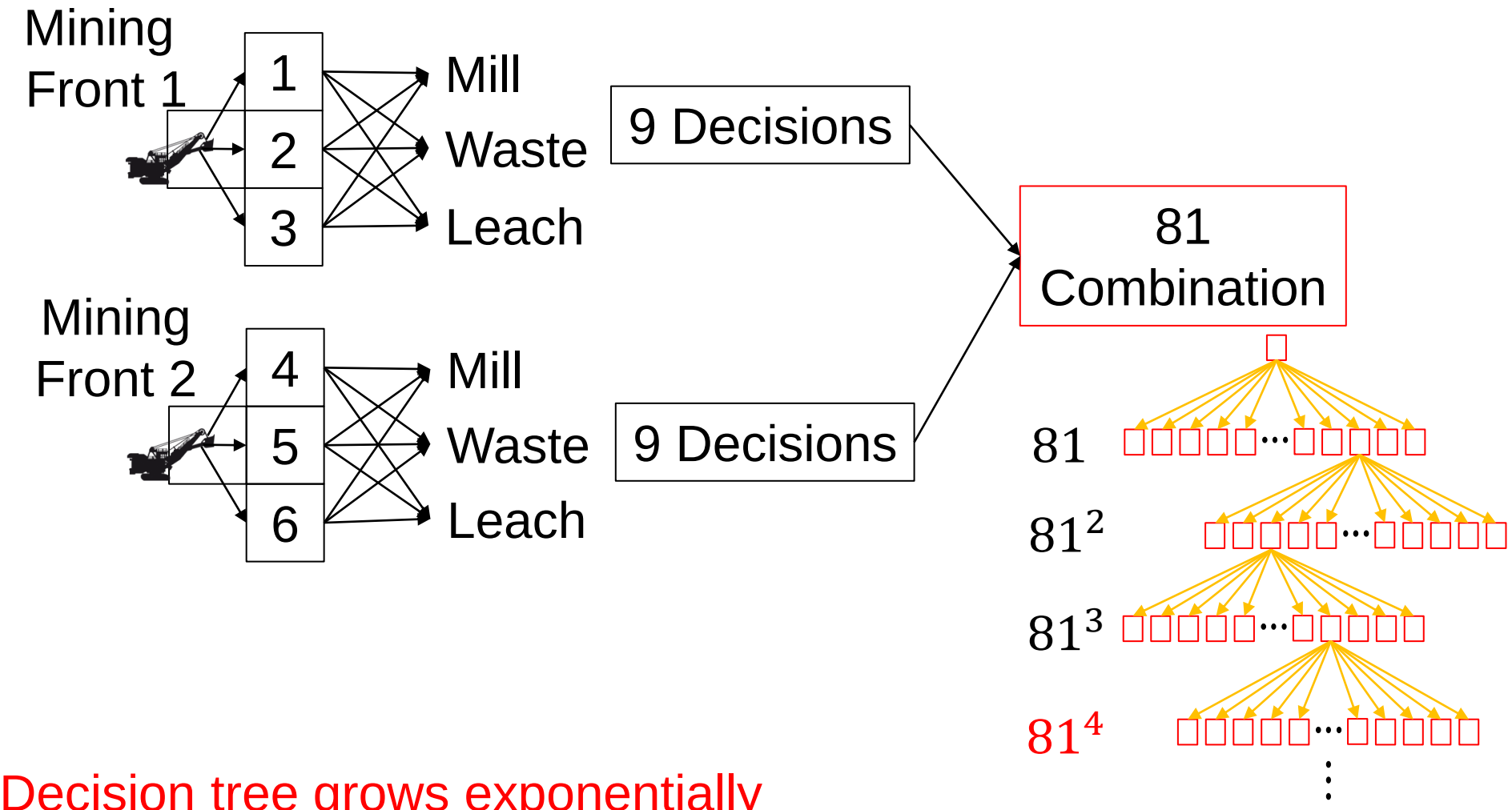
Performance of Components

Supply Uncertainty
- Block properties
- Block tonnage
- Deleterious elements
- Material crushed
- Material leached

Equipment Uncertainty
- Shovel performance
- Truck performance
- Crusher performance
- Plant performance
- Leach performance



Decision Space Complexity

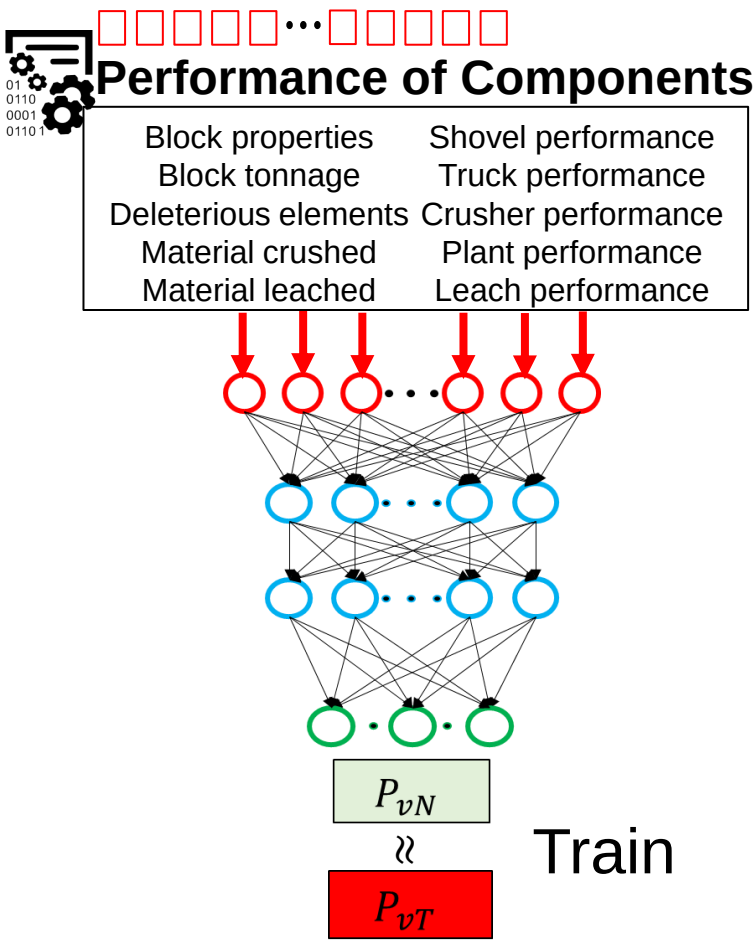


Decision tree grows exponentially

Solution: Reinforcement Learning using Monte Carlo Tree Search

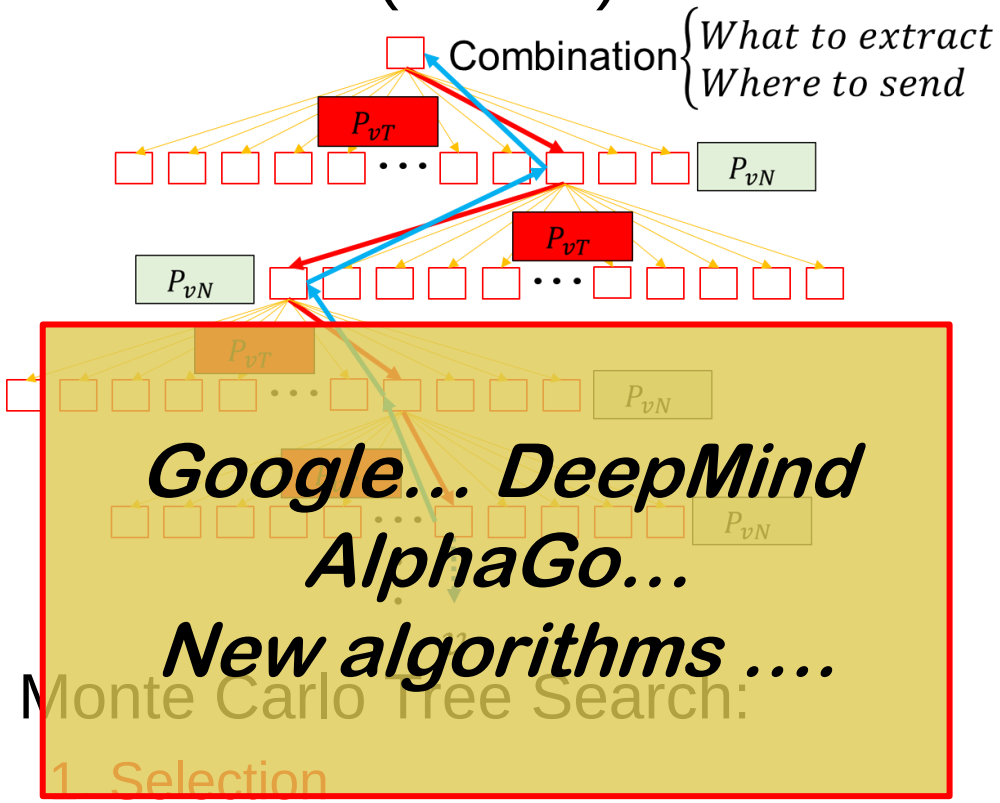
Reinforcement Learning using MCTS

Deep Neural Network



Reinforcement Learning using MCTS

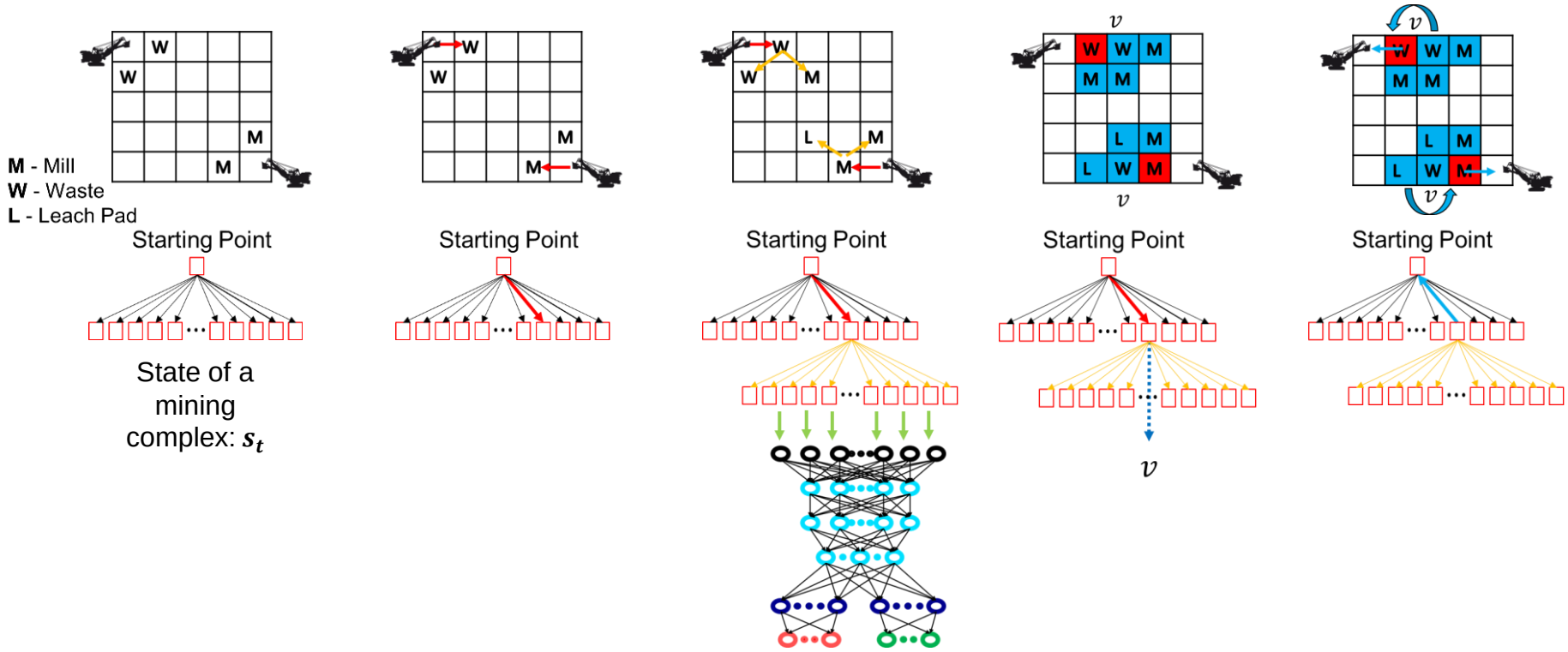
Monte Carlo Tree Search (MCTS)



Monte Carlo Tree Search:

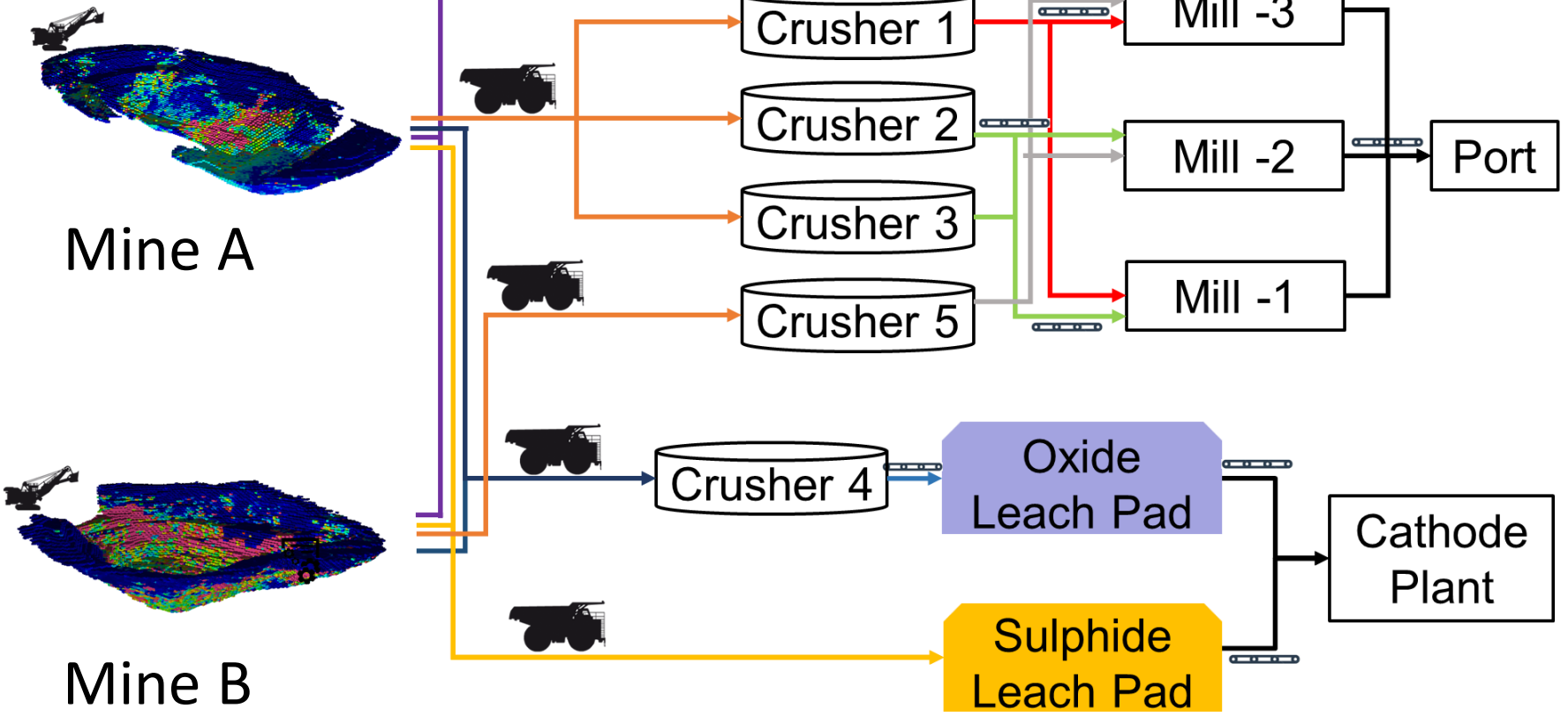
1. Selection
2. Expansion
3. Evaluation
4. Simulation
5. Backup

Deep Reinforcement Learning



$$v = \frac{1}{\left\| \mathbb{S}_I^{\mathbb{J}}(T) \right\|} \sum_{s \in \mathbb{S}_I^{\mathbb{J}}(T)} \sum_{p \in \mathcal{P}} \sum_{a \in \mathbb{P}_{\mathbb{R}}} P_{a,p} \cdot v_{a,p,T,s} \cdot r_{a,p} - \sum_{s \in \mathbb{S}_I^{\mathbb{J}}(T)} \sum_{i \in \mathcal{P} \cup \mathcal{D} \cup M} \sum_{a \in \mathbb{P}_{\mathbb{M}}} C_{a,i} \cdot v_{a,i,T,s} - \sum_{s \in \mathbb{S}_I^{\mathbb{J}}(T)} \sum_{i \in \mathcal{P} \cup \mathcal{D}} \sum_{a \in \mathbb{P}_{\mathbb{D}} \cup \mathbb{P}_{\mathbb{M}}} \left(c_{a,i}^{+} \cdot d_{a,i,T,s}^{+} + c_{a,i}^{-} \cdot d_{a,i,T,s}^{-} \right)$$

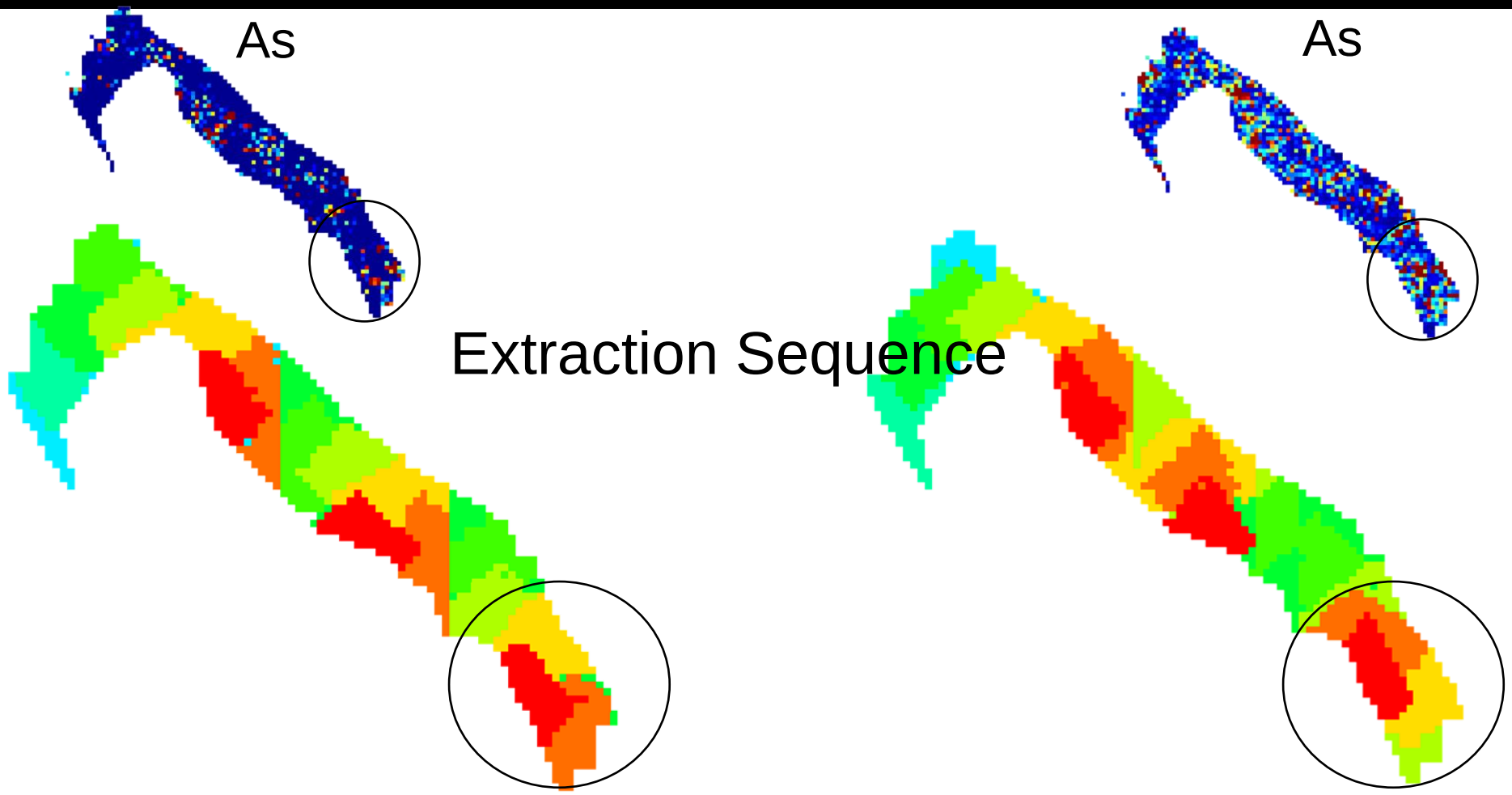
Results – A Copper Mining Complex



Parameters

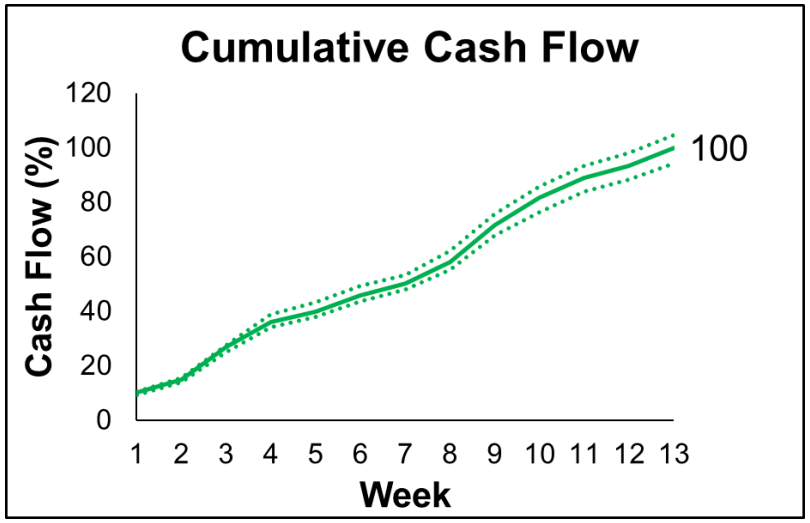
- Weekly time scale - 13 weeks of production plan updated
- Supply of materials and equipment uncertainty are considered
- Extraction and destination decisions for each block
- Elements considered: Cu, As, Au, Ag, and Mo
- 25 stochastic simulations for each mine (15 for training and 10 for testing the performance)

Updated Production Plan

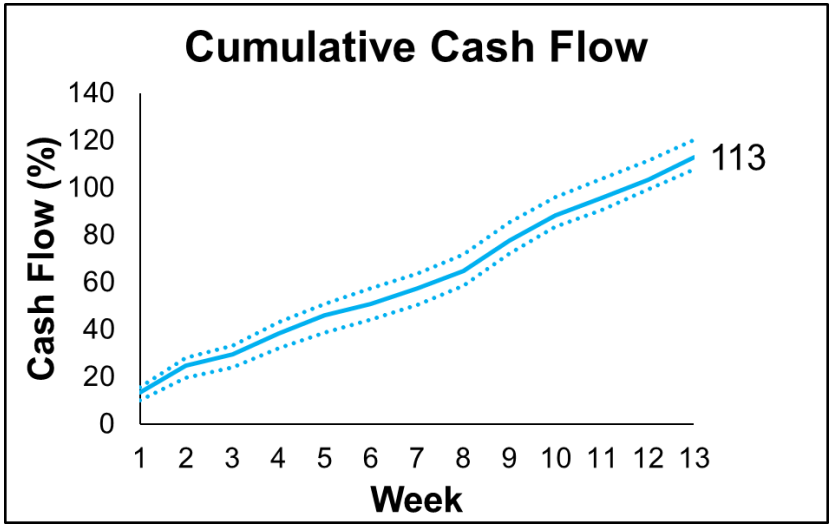


Updated Production Plan

Cumulative Cash Flows



Initial Production Plan

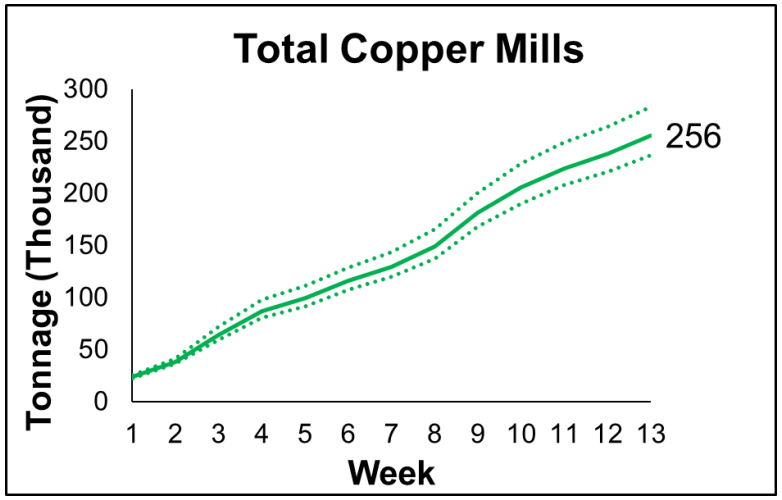


Updated Production Plan

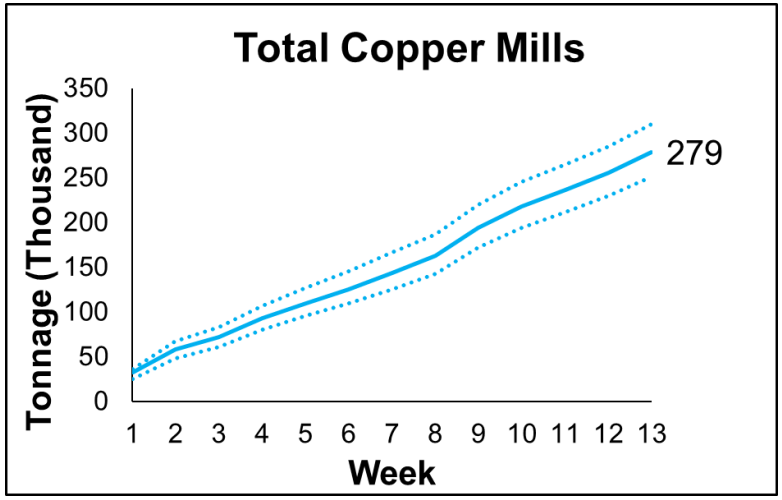
P90
P50
P10

Updated Production Plan

Copper Production



Initial Production Plan

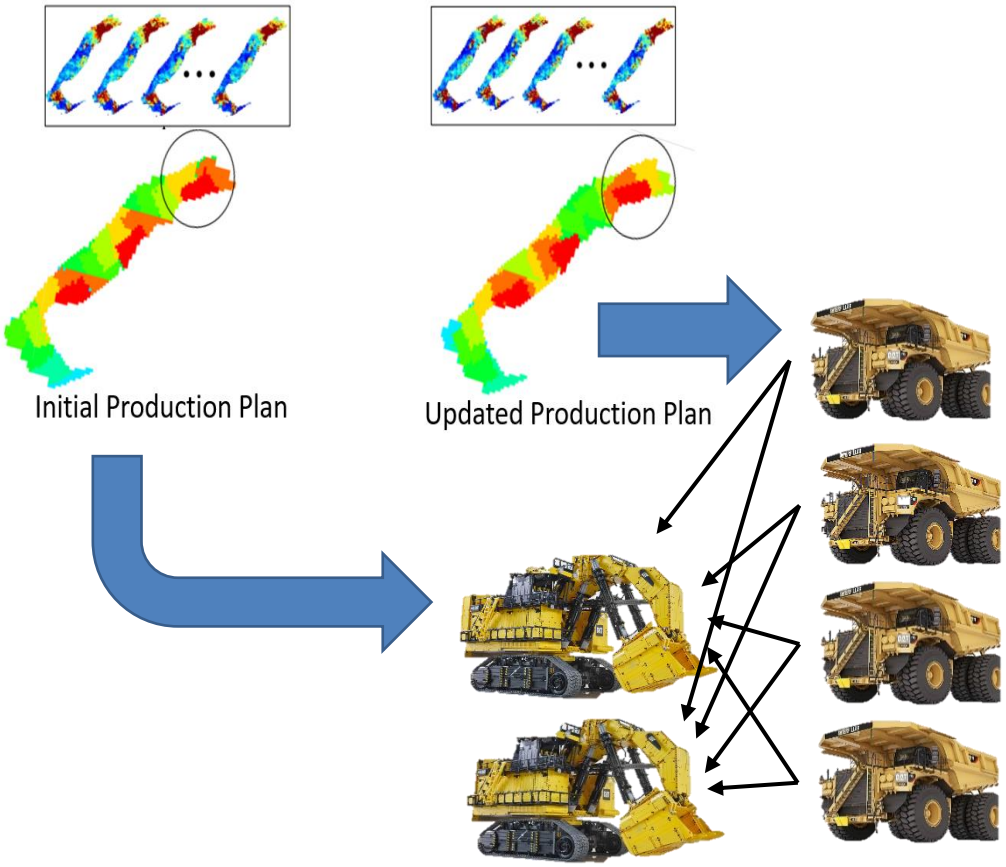


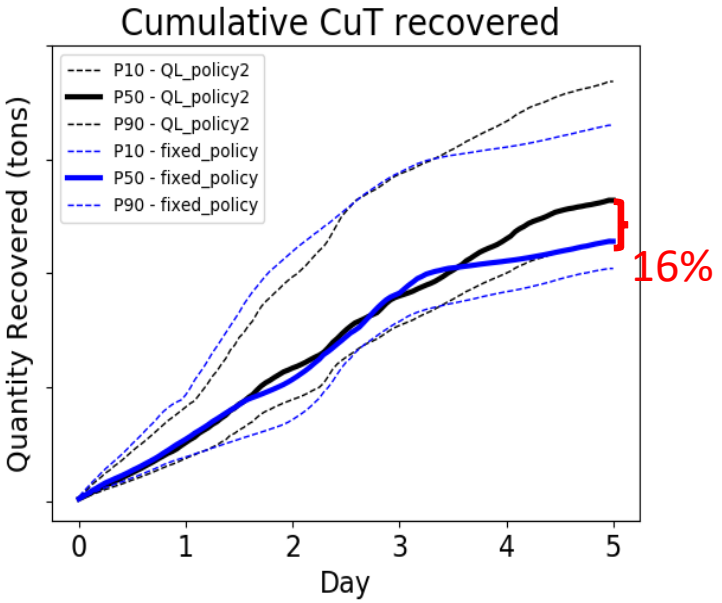
Updated Production Plan

P90
P50
P10

New Research - Reinforcement Learning for Truck Dispatching

- Adapting truck dispatching policies





Conclusions

- Simultaneous Optimization of a Mining Complex with Uncertainty (Stochastic)
- Example at a Gold Mining Complex
  - Major increase (>10%) in cash flows and gold
- Artificial Intelligence – Self-learning for Short-term Production Plans
- Example at a Copper Mining Complex
  - 13% increase in cash flow and 9% in coper from the updated production plan over 13 weeks
  - A Continuous and Fast Updating Framework (<4 min for updating 13 weeks of production plan)
- More to Expect and Much More Research Needed

WE ARE INTERESTED IN

Graduate Students and Collaborations

Please contact us for information

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http://cosmo.mcgill.ca/

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