



MasterClass

From diagnosis to debottlenecking:
How we de-constrain
underperforming circuits

Dr Rajiv Chandramohan

Global Technical Director – Operations Optimisation



Agenda

- Introductions
- Defining the Value
- Circuit Diagnosis – Where to start?
- Creating an Implementation Plan
- Case Studies
- General Commentary – What good looks like?
- Closing - Questions



Presenters



Dr Rajiv Chandramohan

**Global Technical
Director – Operations**

- SME Comminution
- Integrated Optimisation
- Process Optimisation
- Process Control
- Training



Matt Pyle

**Global Director –
Technical Solutions**

- Technical Solutions
- New Technology
- Techno-Economic Modelling



Dr Bianca Foggatto

**Regional Practice
Lead**

- SME Comminution
- Project Development
- Geo-metallurgy



Daniel Domanski

**Senior Process
Consultant**

- Flotation, Leach
- Geo-metallurgy
- Testwork development
- Training
- Process Optimisation



Logan Phillips

**Process
Consultant**

- Analytics
- Process Optimisation
- Testwork Development

Context

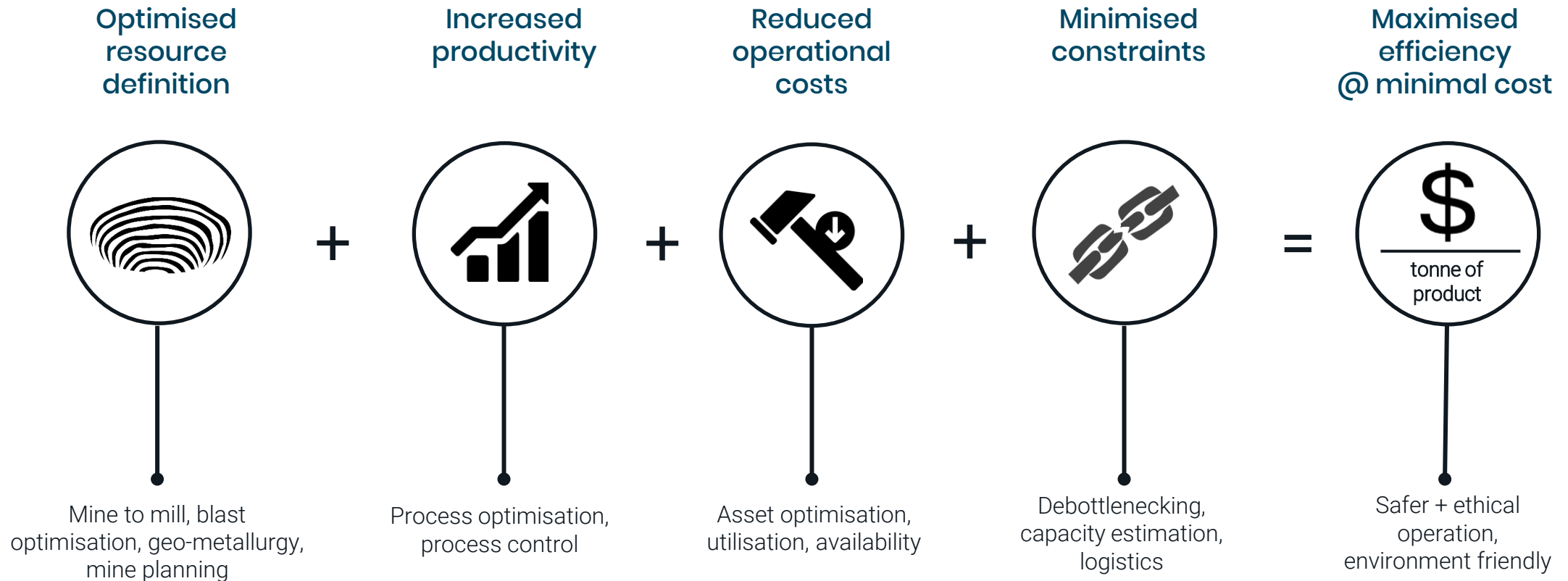
Poor plant performance is a result of:

- Lack of understanding of the process
- Poor benchmarking
- Not challenging the norm
- Poor control

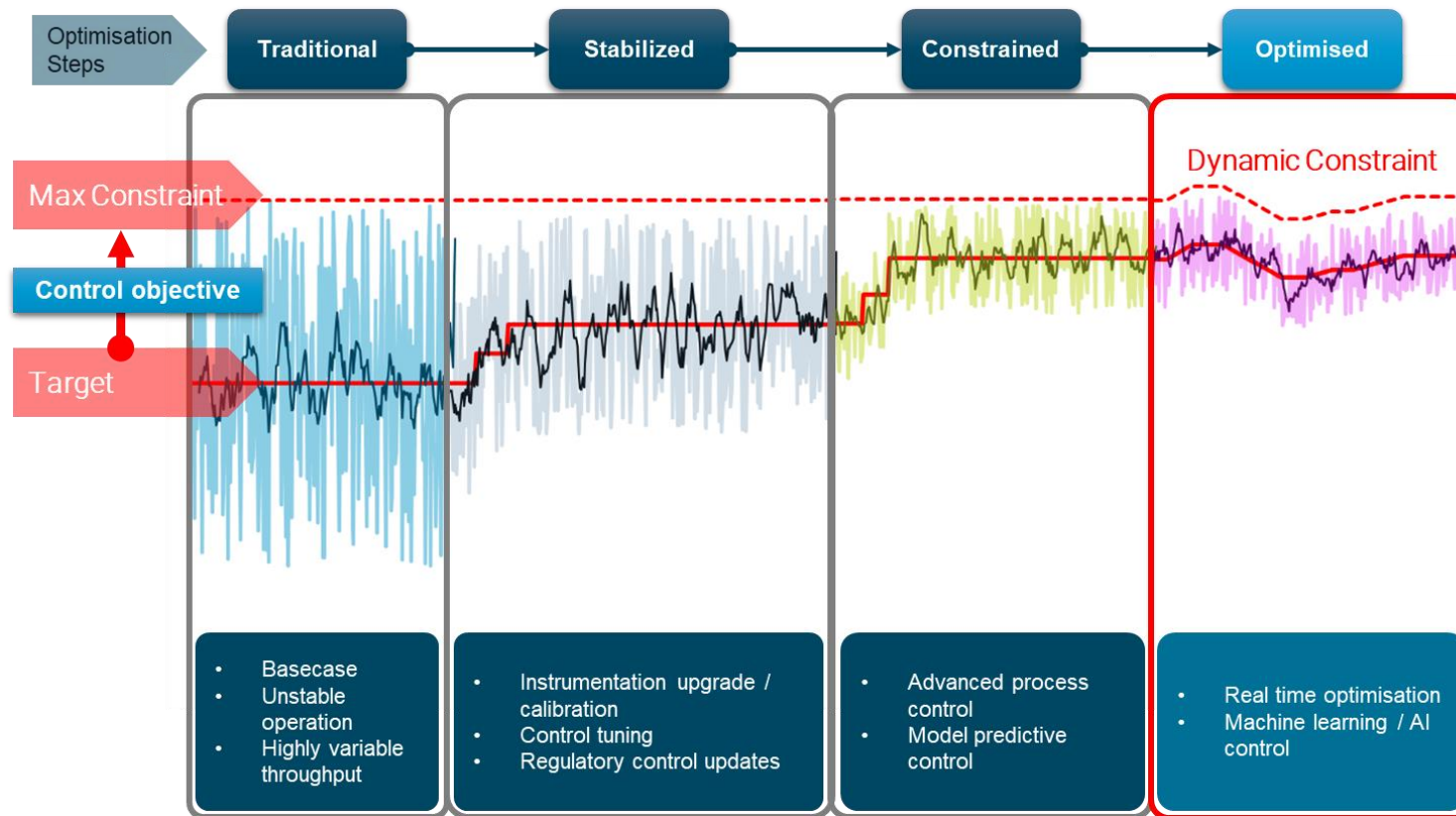
Our approach to debottlenecking and optimising operations is by:

1. Getting the basics right – i.e. control, operating conditions etc..
2. Understanding the constraints – use benchmarking to identify the opportunities
3. Focusing on stability
4. Pushing the limits of assets – i.e. power utilisation, operating parameters etc..

How we Unlock Value



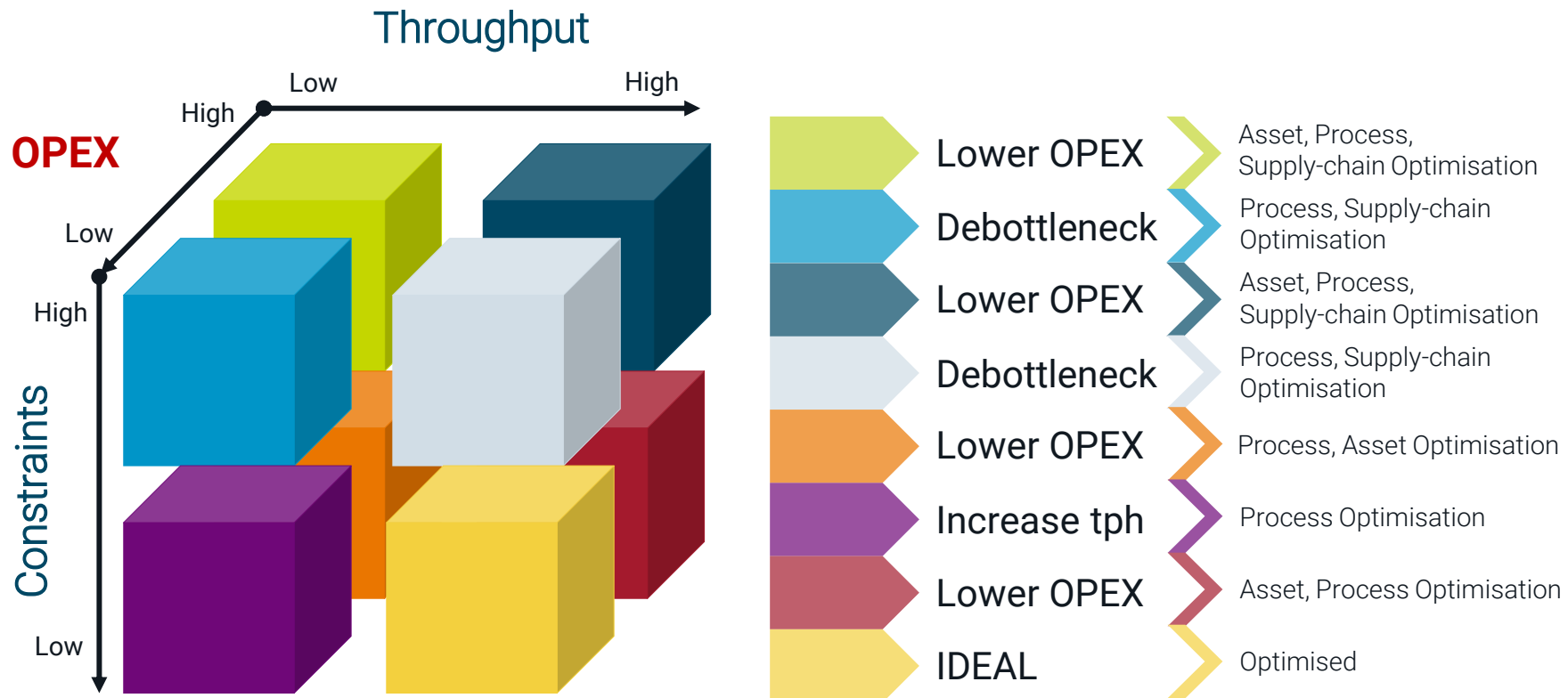
Focusing on Stability



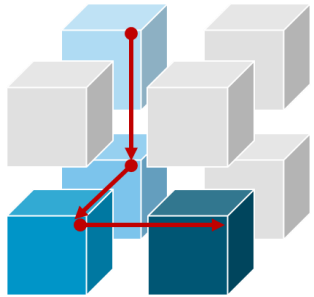
Visnovec & Chandramohan, 2020

'You cannot optimise an unstable operation. First, make it stable. Only from stability you can see a path to optimisation' - Joe Pease @ AUSIMM Delprat Lecture 2020

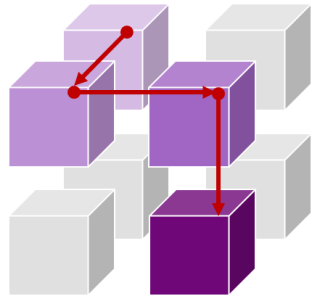
Where is the Opportunity?



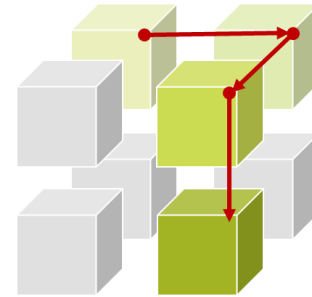
Which Optimisation Strategy?



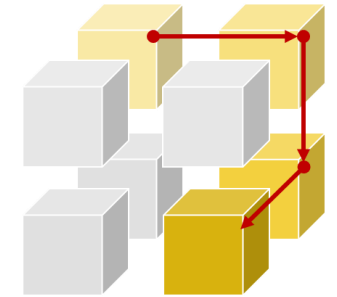
Deconstrain > optimise asset > increase throughput



Optimise asset > increase throughput > deconstrain



Increase throughput > optimise asset > deconstrain



Increase throughput > deconstrain > optimise asset

Optimum optimisation strategy is selected by managing risk and understanding the value-add – ‘The Goal’

Penasquito Optimisation



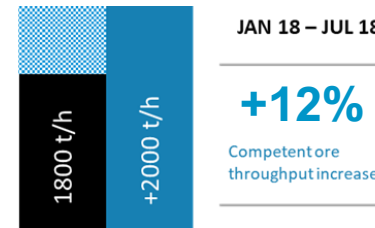
- Redesigning SAG liner system to maximise power draw
- Optimising grinding circuit control
- Revising crushing circuit operational strategy

PNG Mine



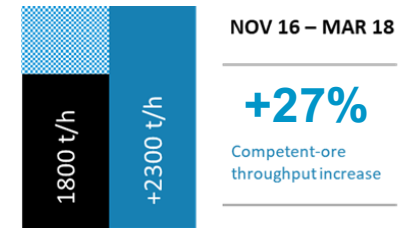
- Optimising three grinding circuits for five different ore types
- De-constraining and maximising asset utilisation
- Mine to mill approach

Chilean Mine



- Advanced process control
- Onsite training

Phu Kham Optimisation



- Redesigning SAG mill liner system to maximise power draw
- Optimising SAG mill control
- Onsite training

Focusing Questions

- What is the baseline capacity? (e.g., throughput, grind size, recovery, and availability)
- What is the impact of ore variability on the baseline based on the mine plan schedule? (e.g., ore competency and hardness)
- What does success look like for the site team? (i.e. short and long term strategy)
- What are the risks and opportunities for the proposed improvements? (i.e. SWOT analysis)

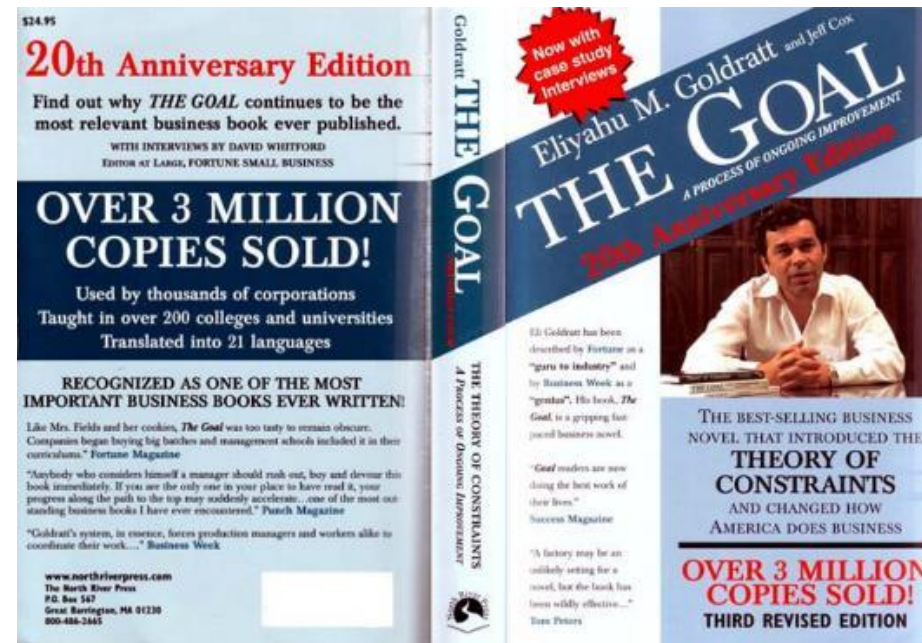
Masterclass take-away points:

- How should the opportunity/value be defined?
- How to diagnose and identify issues?
- Developing an implementation plan
- Examples

1

Defining the Value

Which optimisation route?
Which option?
At what value?
What are the risks?
What are the constraints?



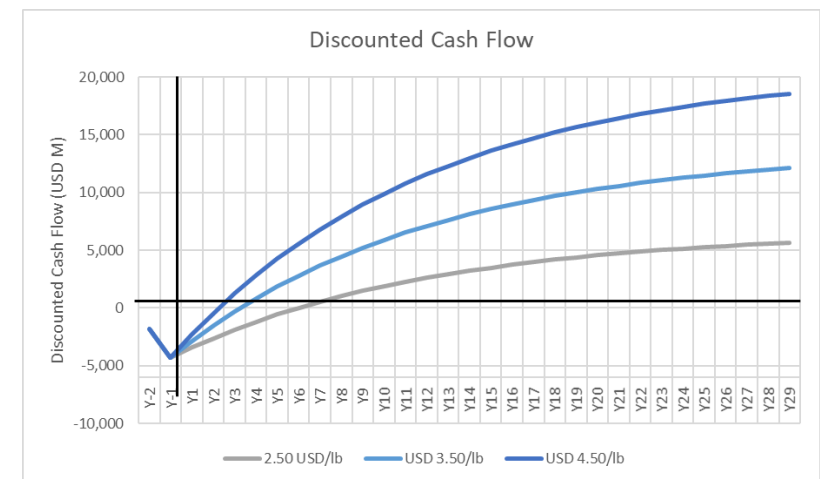
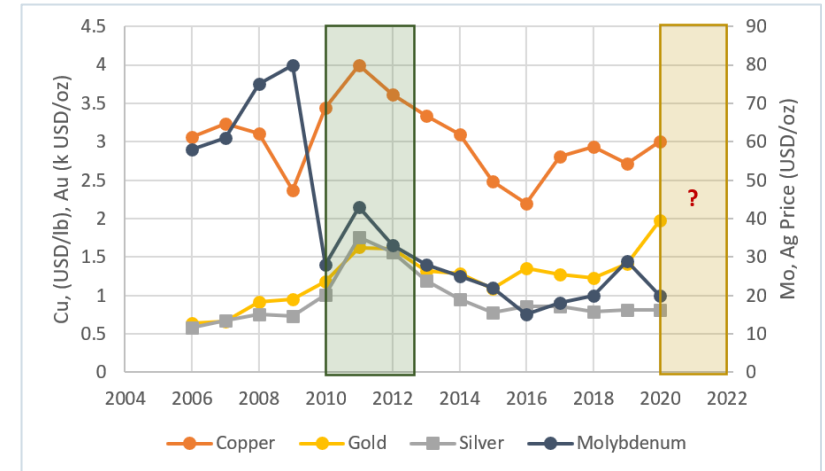
Focusing on Value – A Business framework

- In basketball, the object of the game is not to run up and down the court. **The object is to score points.**
- The object of business is not to create plans and spend money. **The object is to generate profit/value.**
- Generating value depends less on performing tasks than it does on **completing jobs effectively.**



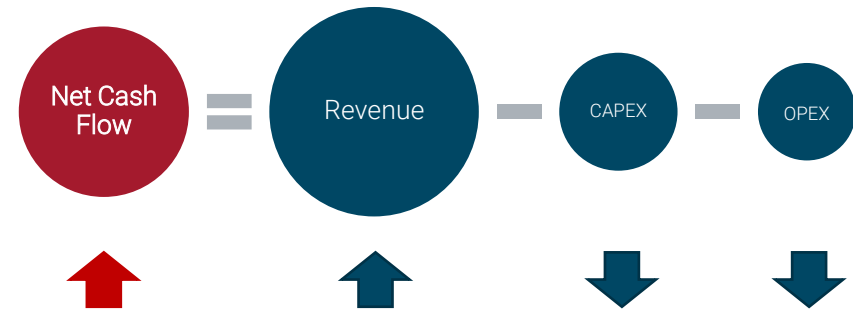
Why defining value is key to de-bottlenecking

- It informs where to focus
 - Market driven
 - Orebody characteristics
 - Mining and processing
- It is a method to define and understand the knowns and unknowns
- It informs the relative significance of risks and opportunities
- It is a tool for decision making
- It is a tool for financing
- It is a tool for communicating to business leaders



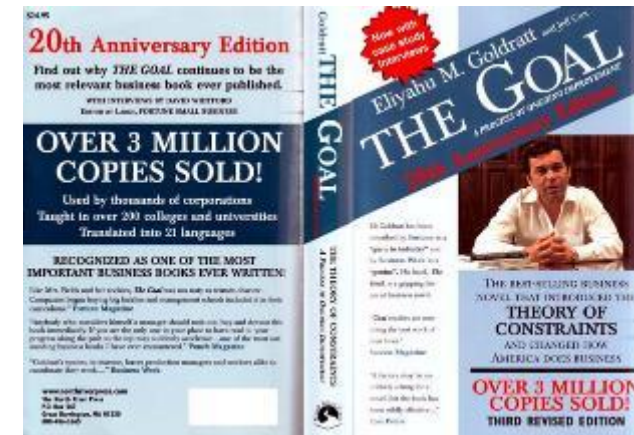
The Goal

- The goal is to increase value by;
 - Increasing metal produced
 - Reducing capital costs
 - Reducing operating expenses
- For any change **Net Cash / Cost** is the key metric
- Refer to 'The Goal' by Eli Goldratt for Theory of Constraints



$$NPV = \sum_{t=1}^{LOM} \frac{Cash\ Flow_t}{(1+i)^t} - \sum Risks \times consequences$$

i = 'discount rate' or 'cash cost'



Building a Business Case

$$\uparrow \mathbf{ROI} = \uparrow \sum \mathit{CASHFLOWS} + \uparrow \sum \mathit{VALUE} - \downarrow \sum \mathit{RISKS}$$

$$\uparrow \mathbf{ROI} = \frac{\uparrow \mathit{REVENUE} - \downarrow \mathit{OPERATING EXPENSES}}{\downarrow \mathit{INVESTMENT}} + \uparrow \sum \mathit{VALUE} - \downarrow \sum \mathit{RISKS}$$

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$$\uparrow REVENUE = \uparrow \underbrace{Product}_{\text{Throughput x Feed Grade x Recovery x Availability}} \times (\uparrow Selling Price - \downarrow Selling Costs)$$

Throughput x Feed Grade x Recovery x Availability

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$$\downarrow RISKS = \downarrow \text{Hazards} \times \downarrow \text{Consequences (what could go wrong)}$$

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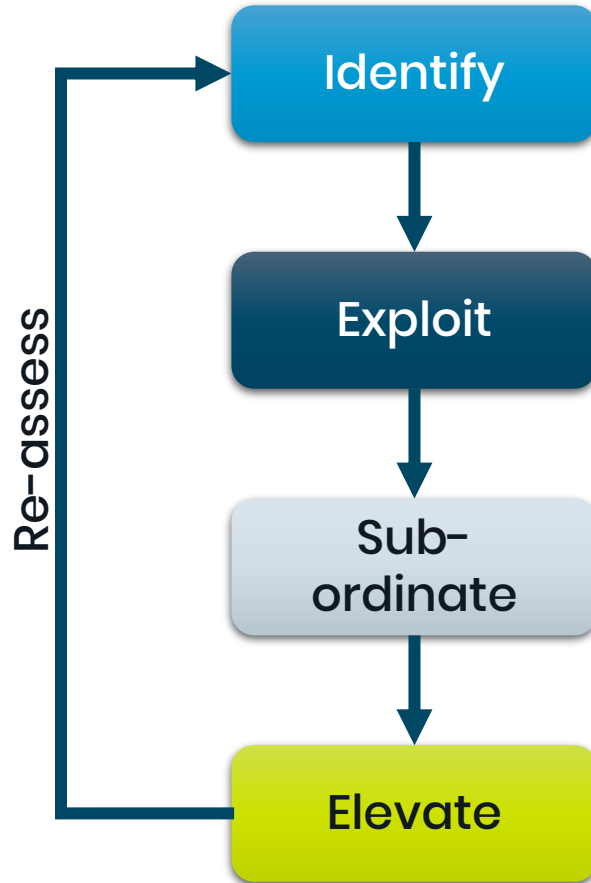
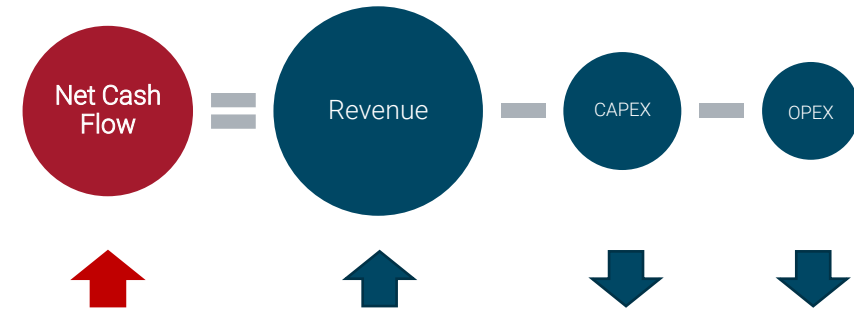
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The above approach should consider present and future values, and is not simply “accounting” past values

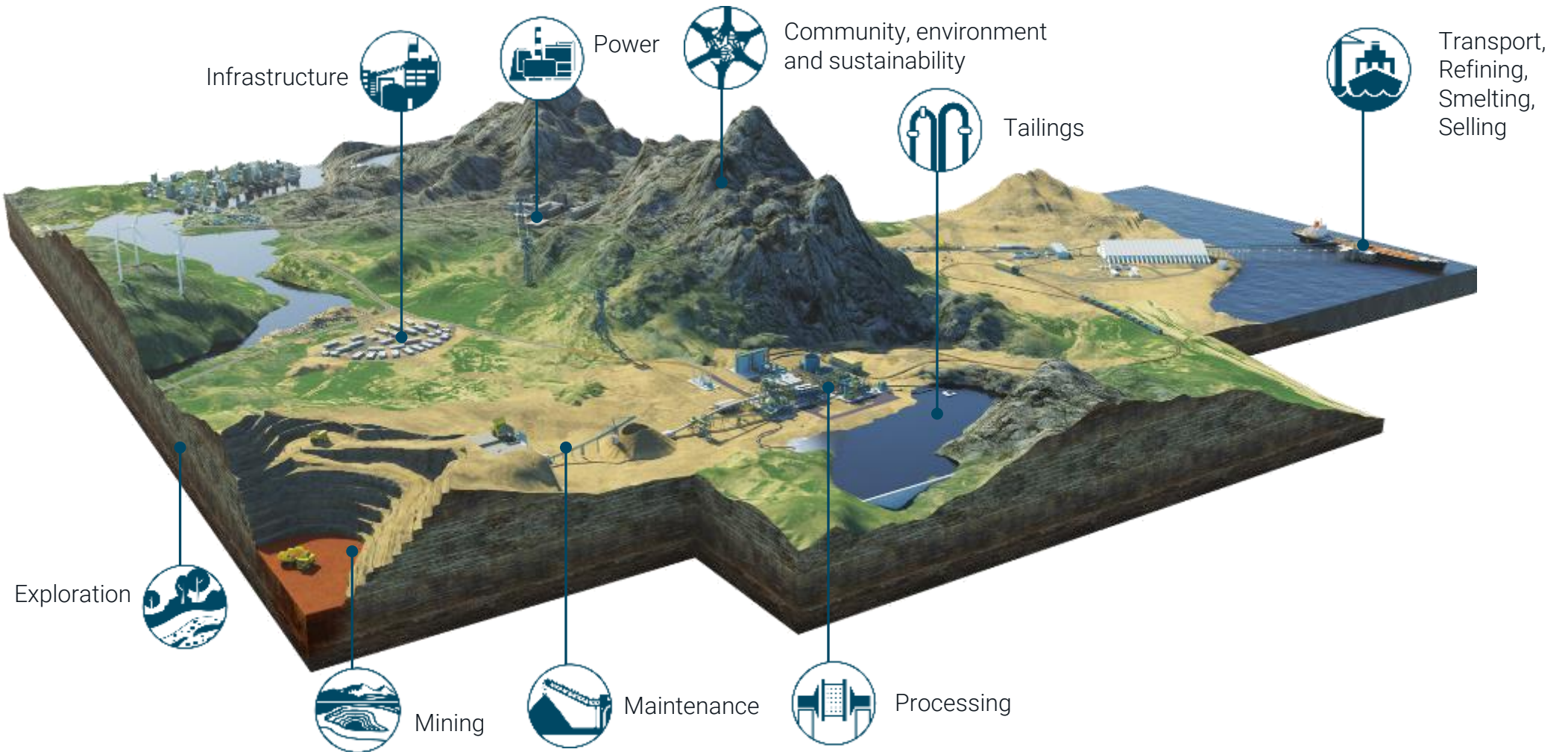
Theory of Constraints



- Identify the constraint: e.g. revenue constrained by the SAG mill throughput
- Exploit the constraint: e.g. ensure the revenue constraint is fully utilised (i.e. maximising power draw)
- Sub-ordinate the operation: e.g. subordinate upstream (finer blasting and crushing), downstream (i.e. tailings pumps) and maintenance to maximise availability and throughput of the SAG mill constraint
- Elevate the constraint: e.g. redesign liners, increase throughput, install secondary crushing etc.

Consider the Big Picture Context

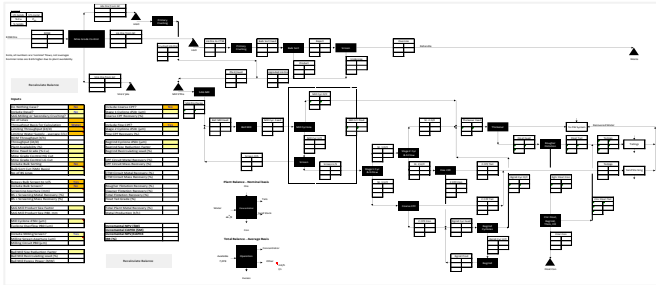
Continually apply theory of constraints across the entire value-chain



Value Assessments at Different Levels of Complexity

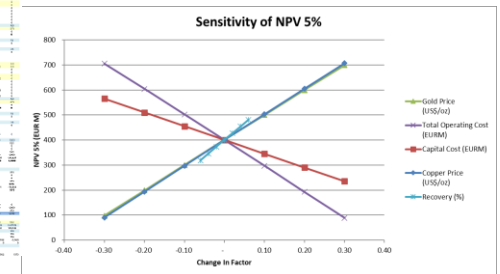
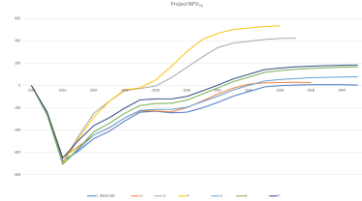
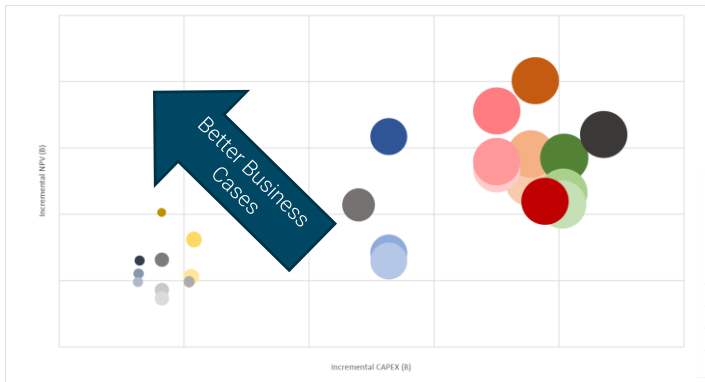
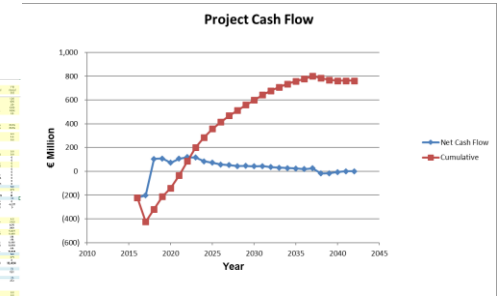
Desktop

Feasibility



A large spreadsheet table with multiple columns and rows. It appears to be a financial model or data table, with various numerical values and some text labels. The table is organized into sections, possibly representing different project components or time periods.

A detailed financial model spreadsheet. It features a summary section at the top with key metrics, followed by numerous columns and rows of data. The data is color-coded, with yellow and blue highlighting specific areas. The spreadsheet likely represents a comprehensive financial analysis of the project.

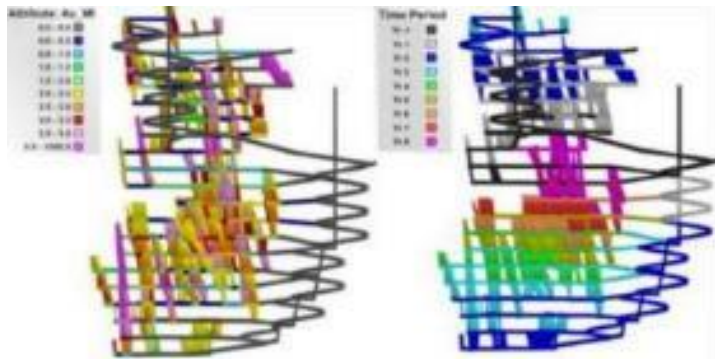


Outcomes from Value Assessments

Gives very different value levers for different optimisation / debottlenecking projects:

Higher value/t material

- Small deposits (typically U/G)
- High mining cost per tonne of ore
- Often mine limited
- Maximise recovery
- Plant CAPEX and OPEX can be less critical



Lower value/t material

- Large open pit deposits
- Low mining cost per tonne of ore
- Often plant limited
- Maximise throughput & metal prod'n
- Pre-concentrate
- Reduce OPEX and CAPEX



Routes to Value-add

$$\uparrow \text{ROI} = \frac{\uparrow \text{REVENUE} - \downarrow \text{OPERATING EXPENSES}}{\downarrow \text{INVESTMENT}} + \uparrow \sum \text{VALUE} - \downarrow \sum \text{RISKS}$$

Driver	Example	What it achieves
<p>↑ROI (↑Revenue, ↑Value, ↓Operating Expenses, ↓Investment, ↓Risks)</p>	<ul style="list-style-type: none"> • ROI dashboarding • Techno-economic modelling and optimisation • Growth Pathway Identification • Operating strategy 	<ul style="list-style-type: none"> • Transparency and real-time tracking of performance, company alignment and motivation • Model, understand and optimise the competing value drivers • Demonstrate the long term cashflows, values and risks and set strategic direction
<p>↑Revenue, ↑Value, ↓Investment</p>	<ul style="list-style-type: none"> • Process control optimisation • Mine to Market <ul style="list-style-type: none"> - Geometallurgy - Strategic mine planning and processing - Grade-recovery optimisation - Operational decision-making tools • Constraints assessment and de-bottlenecking • Technical Support 	<ul style="list-style-type: none"> • Identifies 'low-hanging' opportunities • Demonstrate high-value expansions

Routes to Value-add (cont'd)

$$\uparrow \mathbf{ROI} = \frac{\uparrow \mathbf{REVENUE} - \downarrow \mathbf{OPERATING EXPENSES}}{\downarrow \mathbf{INVESTMENT}} + \uparrow \sum \mathbf{VALUE} - \downarrow \sum \mathbf{RISKS}$$

Driver	Example	What it achieves
<ul style="list-style-type: none"> ↓ Operating Expense ↓ Risk 	<p>Asset Optimisation;</p> <ul style="list-style-type: none"> • Equipment performance vs. availability vs. risk vs. cost • RAM assessments • Maintenance strategies • Maintenance planning and execution • Root cause analysis 	<ul style="list-style-type: none"> • Increase uptime • Optimise performance vs. availability vs. risk vs. cost • Streamlined work management • Improved quality/predictability/stability • Improve planned vs. unplanned downtime
↓ Investment	Cost effective design and project execution	Maximises ROI for given investment
Execute strategy	<p>Operations (Business as usual)</p> <ul style="list-style-type: none"> • Short term operational planning • Operational execution • Maintenance execution • Operational and maintenance diligence 	<ul style="list-style-type: none"> • Achieve long term plans • Achieve 'dashboard' targets

How to drive value from economic modelling

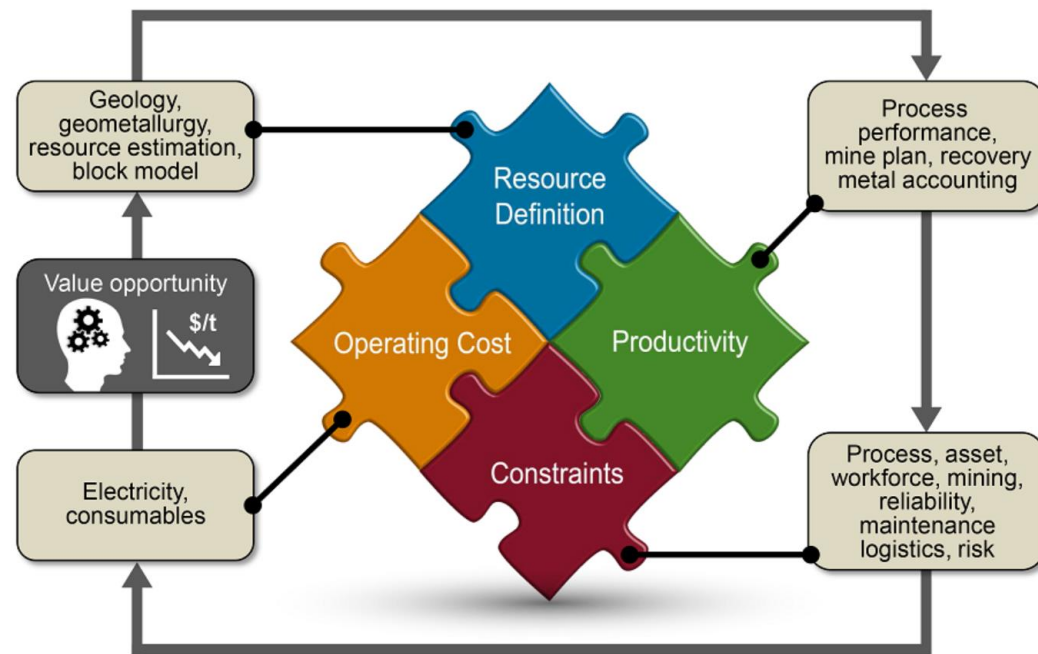
- Optimise the process and mine together;
 - Mining method
 - Value sources, ore types, processing routes, criteria, products
 - Stockpiling, blending, bring cash forward
 - Water, power, access, footprint, tailings, waste
- Challenge perceived constraints
- Look for step changes
- Combining technical & economic aspects into one model, can be incredibly powerful
- Don't overcomplicate it



2

Diagnosing Issues

What is the **Performance for LOM?**
Is it **Stable?** How do I **Benchmark?**
How do I diagnose?
What are the control Setpoints?



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Stage of Diagnosis		Focusing Questions
Identify	<ul style="list-style-type: none"> • Communicate • Collaborate • Key stakeholders and project champions assigned 	<p>What is the issue and who does it effect? How does issue effect greater strategy?</p>
Review and Approach	<ul style="list-style-type: none"> • What data/information is available? • Is available data useful? – Representative, Verified • Gap Analysis – What additional data is needed? • Path forward planning 	<p>What do we <u>already know</u>?</p> <p>How can we find out <u>what we need to know</u>?</p>
Investigate	<ul style="list-style-type: none"> • Survey, Sampling • Process Control Review • Targeted Testwork • Inspection • Trials • Data Analysis 	<p>What is the <u>cause and effect</u>?</p> <p>What is still unknown?</p> <p>What <u>other issues were identified</u> during this process?</p>
Evaluate	<ul style="list-style-type: none"> • Mass balance, Simulation • Techno-economic modelling • Prioritization – Just do or further investigation initiative 	<p>Is constraint driven by original hypothesis?</p> <p>What are the solutions and what are they worth?</p> <p>What is need to implement solution?</p>

Stage	Key Question	Stage of Diagnosis of Pb – Ag Concentrator targeting Ag improvement	
Identify	What is the goal and who does it effect?	Objective : Increase Q3 Ag recovery by 5 % <ul style="list-style-type: none"> Key stakeholders: Mill Manager, Tech Super, Chief Met, Plant Mets and Ops 	
Review and Planning	<p>What do we <u>already know</u>?</p> <p>How can we find out <u>what we need to know</u>?</p>	<p>What data we have:</p> <ul style="list-style-type: none"> Major stream assays, basic Pi data, daily bench float, daily production report <p>What we know:</p> <ul style="list-style-type: none"> OSA P80 shows meeting grind target Lab rougher yields +3% Ag recovery consistently with 1% higher mass pull. Visually coarse fraction in tails Primary mill power draw 70% of install Reagent dosing strategy based on g/t feed basis <p>Gap Analysis</p> <ul style="list-style-type: none"> What is the baseline recovery Ag department and loss mechanism Recent grinding survey, size x assay data for major streams Grade vs recovery relationship Mill and Cyclone process control response 	
Investigate	<p>What is the <u>cause and effect</u>?</p> <p>What <u>other issues</u> have been identified?</p> <p>Outdated Met models and absent GEOMET evaluation</p>	<ul style="list-style-type: none"> Data Analysis – Forensic metallurgy Grind and cyclone survey Size x assay Process Control Review Sighter testwork Ball Charge trials, Reagent trials 	<p>Next steps:</p> <ul style="list-style-type: none"> What is the Cause and Effect? Develop Plan and schedule for just do initiatives and next phase of investigation.

Example of Investigative Stage

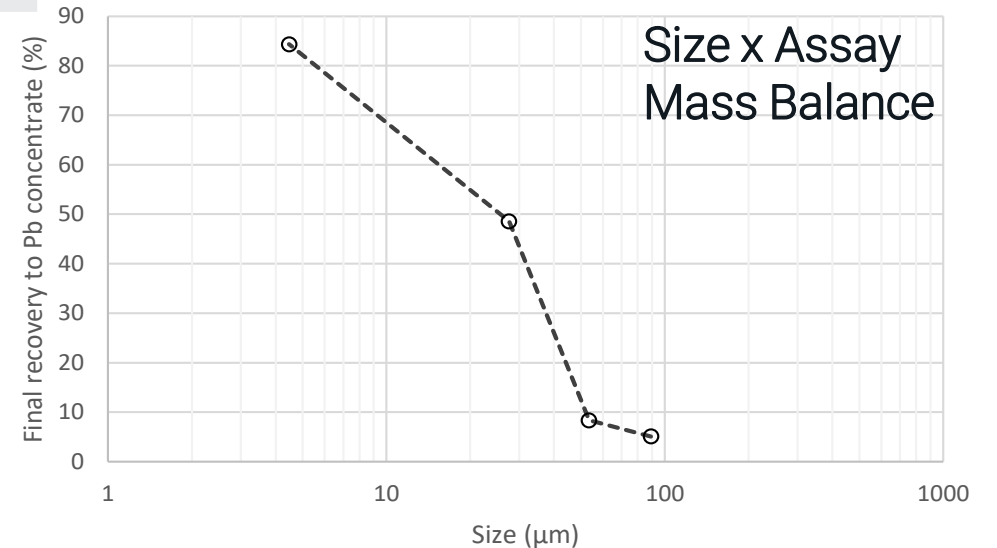
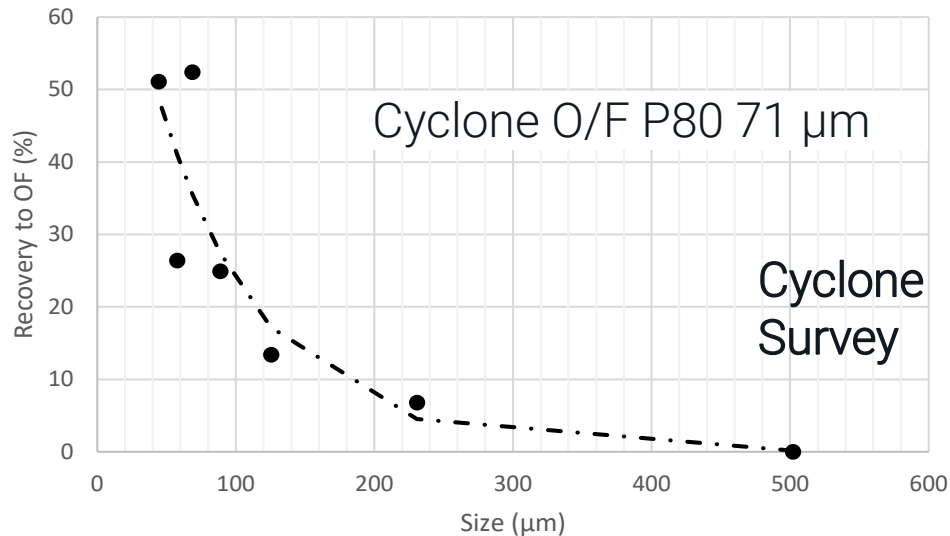
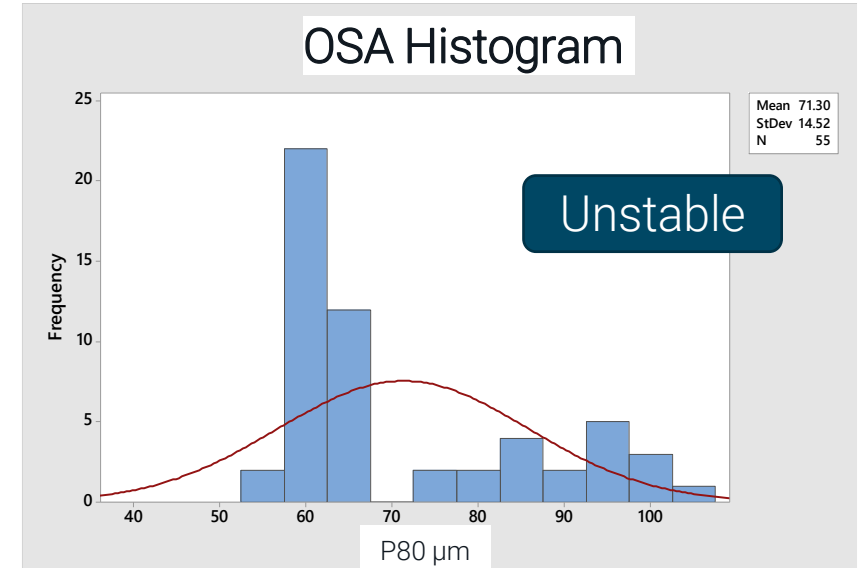
Investigative Findings

Findings

- Bi-modal product grind size, indicating unstable milling conditions
- 65-80% ball mill Power Utilization
- Inefficient cyclone – Coarse material escaping
- Poor Ag recovery from coarse fraction
- 14% of Tails Ag departs to +106 μm

Outcome

- Just Do - Trial increased ball charge and process control review and tuning of ball mill and cyclone pack
- Investigate cause of bimodal grind response and higher lab recovery – Geomet, cell bias, reagent dosing etc.



Diagnosing

Most common issues of an underperforming operation

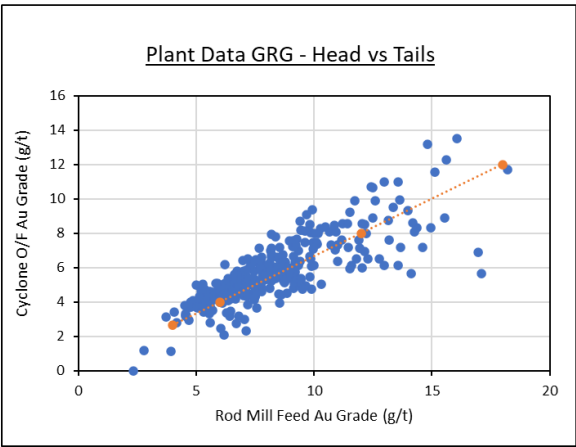
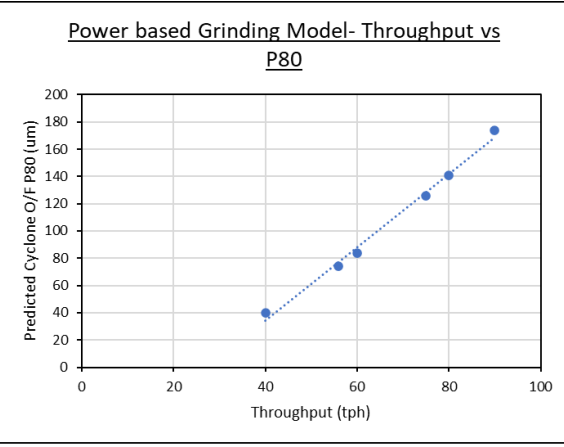
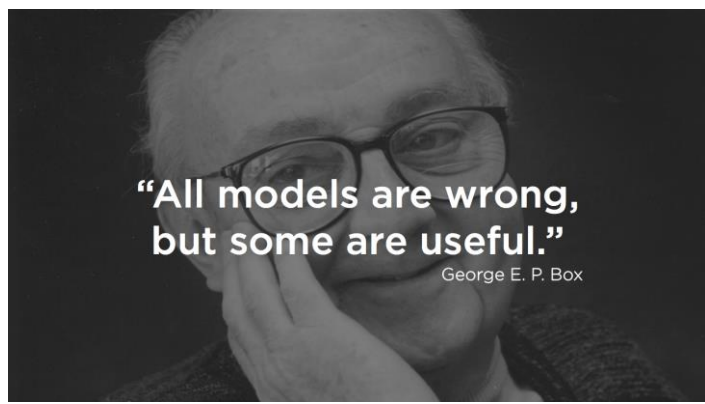
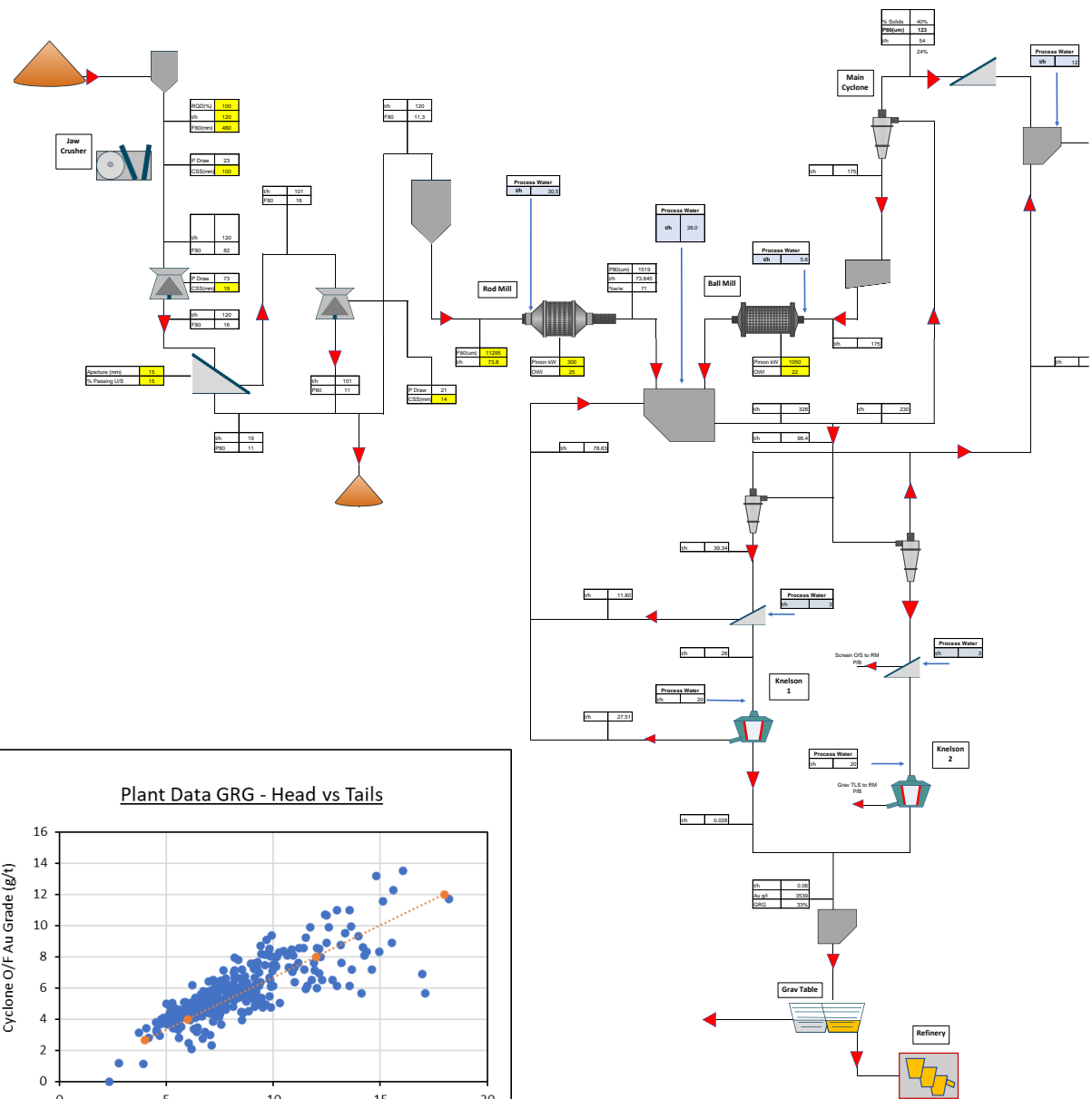
- Not doing the basics – ball charging, maintaining equipment, efficient classification, reagent dosing etc.
- Poor control tuning or preference to run in manual
- Incorrect or redundant setpoints and KPIs
- Poor or incomplete understanding of geometallurgy and its impact on plant stability

Approach :

1. Benchmark and Baseline (mass balance, control evaluation)
2. Use control diagnosis to reduce operational variability
3. Stabilize circuit response and full utilize installed assets
4. Trial operational changes
5. Re-evaluate effect of operational changes
6. Stabilise then optimize

Flowsheet Simulation

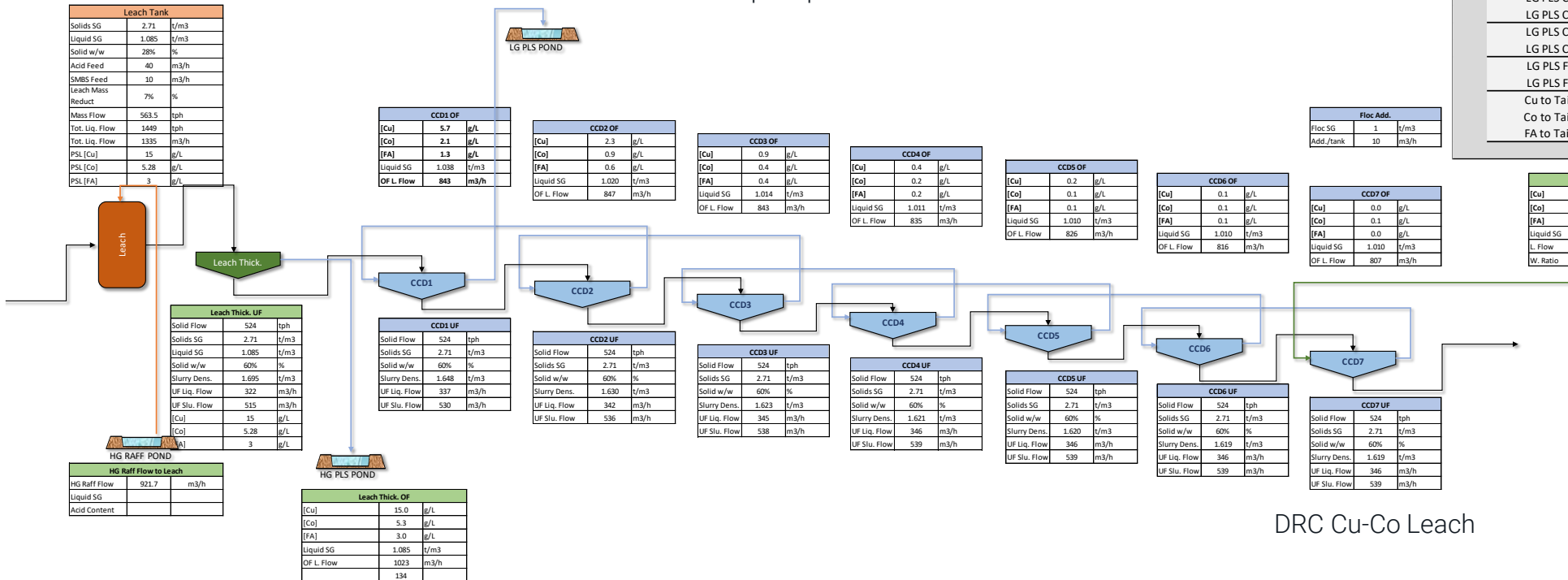
- Fully utilize mass balance through coupling with excel based flowsheet simulation
- Plant data and surveys used to develop met models to baseline circuit performance
- Use plant data to benchmark original design criteria
- Link daily plant process report for daily diagnostics and troubleshooting
- Trial operating strategies to identify constraints
- Use model to identify gaps in data and understanding – Testwork to validate outcomes and further model capabilities.



Canadian Au Mill

Technoeconomic modelling

- Benchmarked model used to explore processing scenarios to debottleneck circuit and increase revenue.
- Include metal value and OPEX within mass balance.
- Run trade off studies for expansions
- Example: CCD Evaluation
 - Trial Thickener U/F density and wash flowrates scenarios to determine impact on metal recovery
 - Identify pumping limitations
 - Predict metal tenors to feed into SX and Co precipitation isotherms



DRC Cu-Co Leach

Model	Units	Model Outputs				
		1	2	3	4	5
CCD1 OF						
TOT LG Flowrate	m ³ /h	881	1084	1284	1852	1685
Wash Ratio		1.2	1.5	1.9	2.7	2.5
[Cu]	g/L	10.46	8.77	7.48	5.22	5.74
[Co]	g/L	3.70	3.12	2.67	1.89	2.07
[Free Acid]	g/L	2.40	2.06	1.74	1.15	1.28
Liq. SG	t/m ³	1.061	1.053	1.046	1.035	1.038
Liq. Flow Rate	m ³ /h	440	542	642	926	843
CCD7 UF						
Liq. Flow Rate	m ³ /h	345.0	345.7	345.9	346.0	346.0
[Cu]	g/L	0.7	0.2	0.1	0.0	0.04
[Co]	g/L	0.3	0.2	0.1	0.1	0.10
[Free Acid]	g/L	0.4	0.2	0.1	0.0	0.0
Summary						
Cu Recovery	%	98.9%	99.6%	99.8%	100.0%	99.9%
Cu Wash Efficiency	%	95.2%	98.2%	99.2%	99.8%	99.7%
LG PLS Cu	tph	4.61	4.75	4.80	4.84	4.83
LG PLS Cu	tpd	110.6	114.1	115.3	116.1	116.0
Co Recovery	%	98.5%	99.2%	99.4%	99.5%	99.5%
Co Wash Efficiency	%	93.5%	96.5%	97.4%	97.9%	97.9%
LG PLS Cu	tph	0.14	0.09	0.08	0.09	0.09
LG PLS Cu	tpd	3.4	2.3	2.0	2.3	2.1
Both Trains						
Liq. Flow Rate	m ³ /h	881	1084	1284	1852	1685
LG PLS Cu	tph	9.2	9.5	9.6	9.7	9.7
LG PLS Cu	tpd	221.1	228.2	230.6	232.2	232.0
LG PLS Co	tph	3.3	3.4	3.4	3.5	3.5
LG PLS Co	tpd	78.2	81.1	82.4	84.1	83.7
LG PLS FA	tph	78.2	81.1	82.4	84.1	83.7
LG PLS FA	tpd	50.8	53.5	53.6	51.0	51.7
Cu to Tails	tpd	11.1	4.1	1.8	0.5	0.6
Co to Tails	tpd	5.3	2.9	2.1	1.7	1.7
FA to Tails	tpd	6.7	3.3	1.7	0.5	0.6

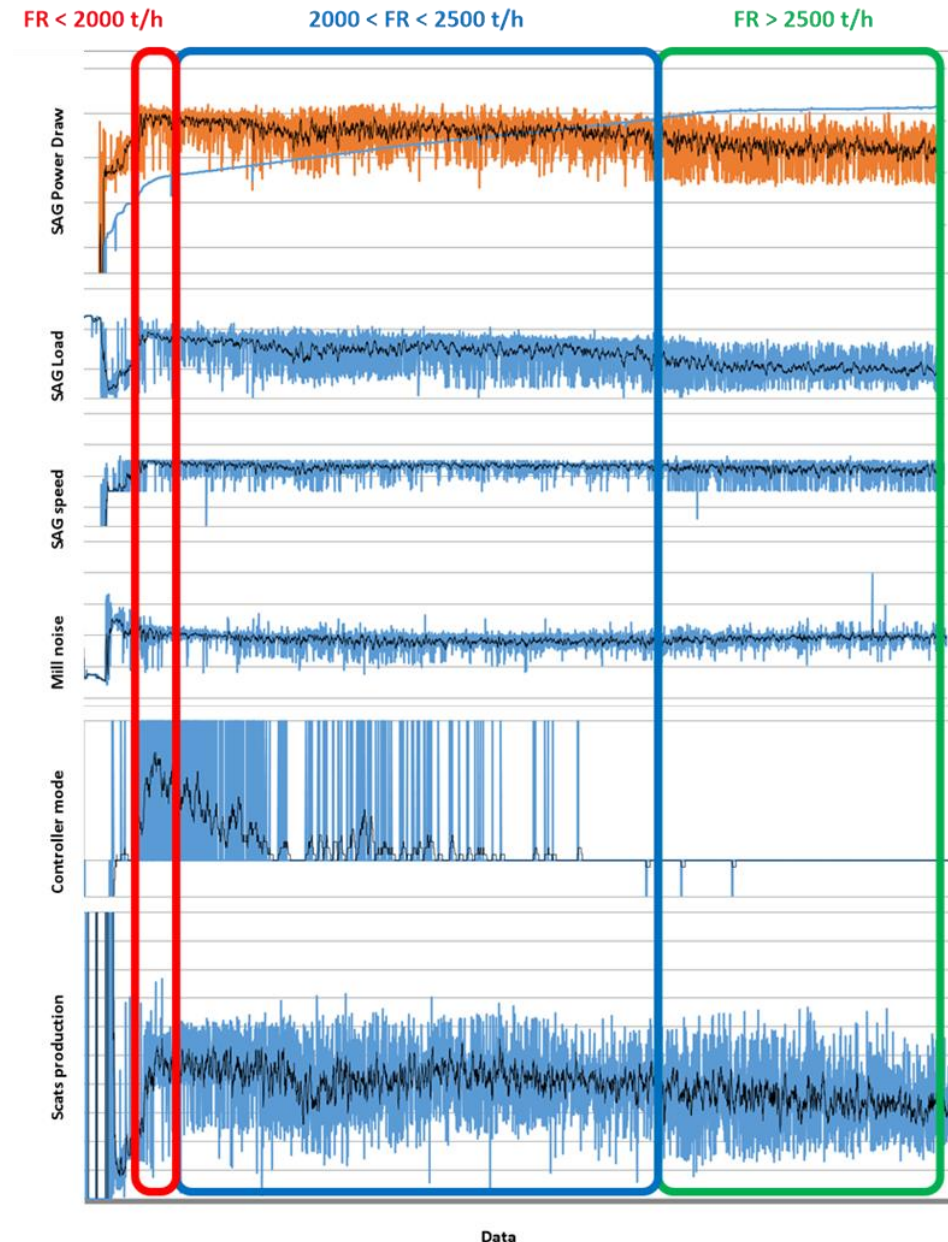
Diagnosing Control Issues

Objectives

- Understanding the 'cause and effect'
- Benchmark against setpoint and control philosophy
- Evaluate short-term and long-term trends
- Redefine the way we look at data and variable relationships
- Identify opportunities for further analysis and advanced diagnostics

Tools

- Traditional: Time series data
- Variable ordered trends
- Histograms (1-D Visualization)
- Heat maps (2-D Visualization)

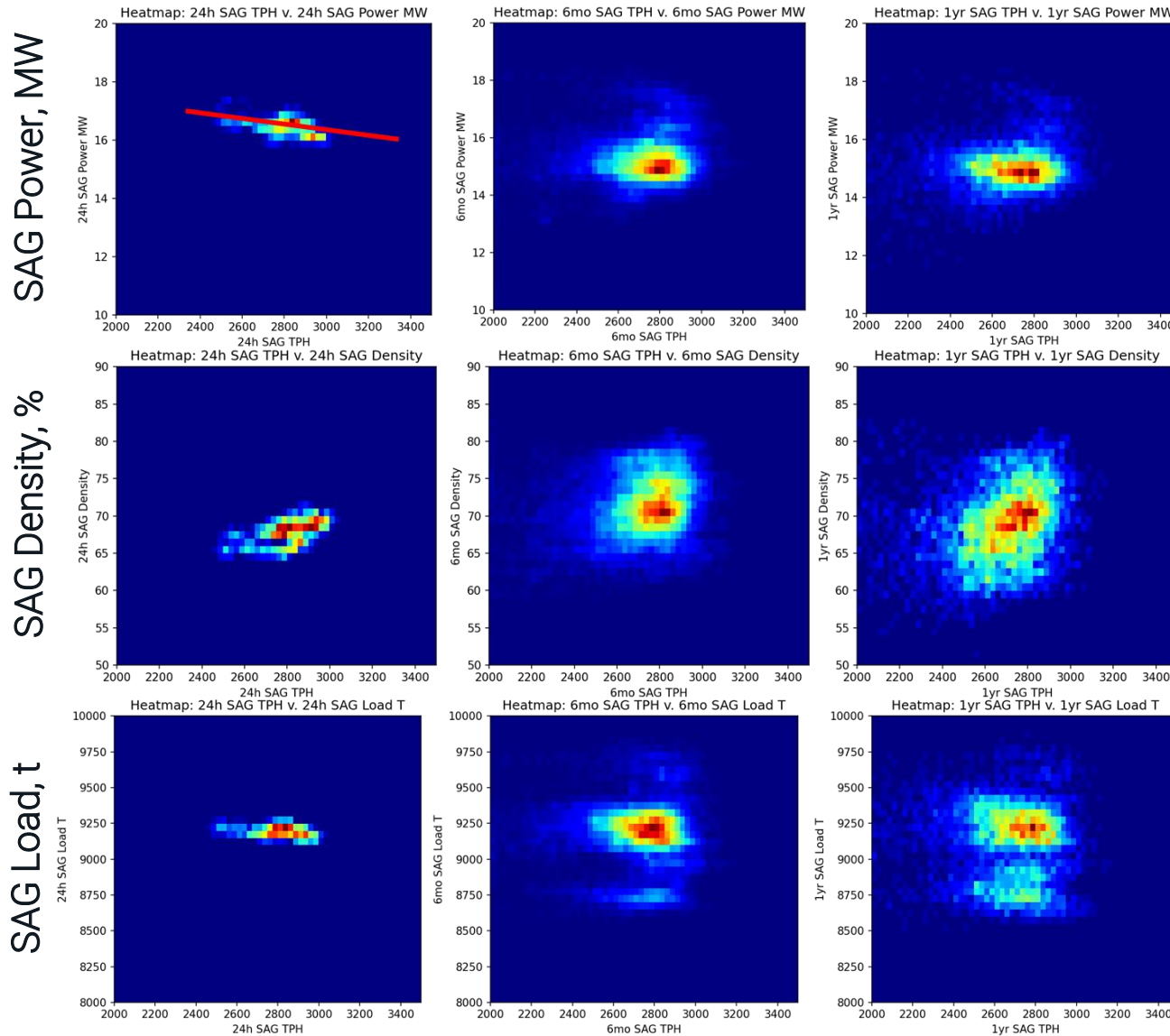


Heat Maps

24 hr

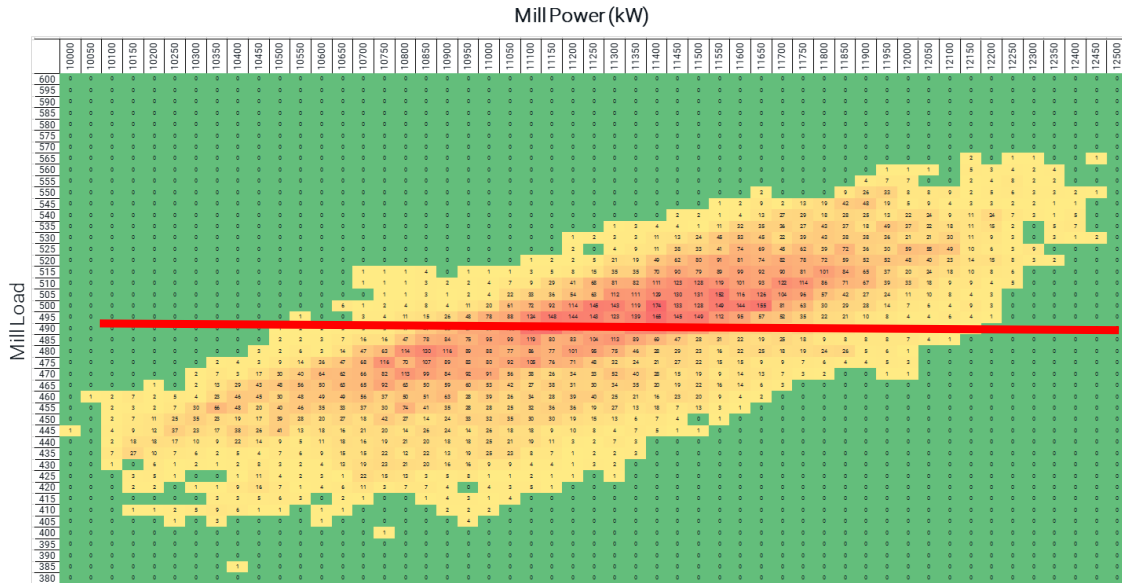
6 month

1 year

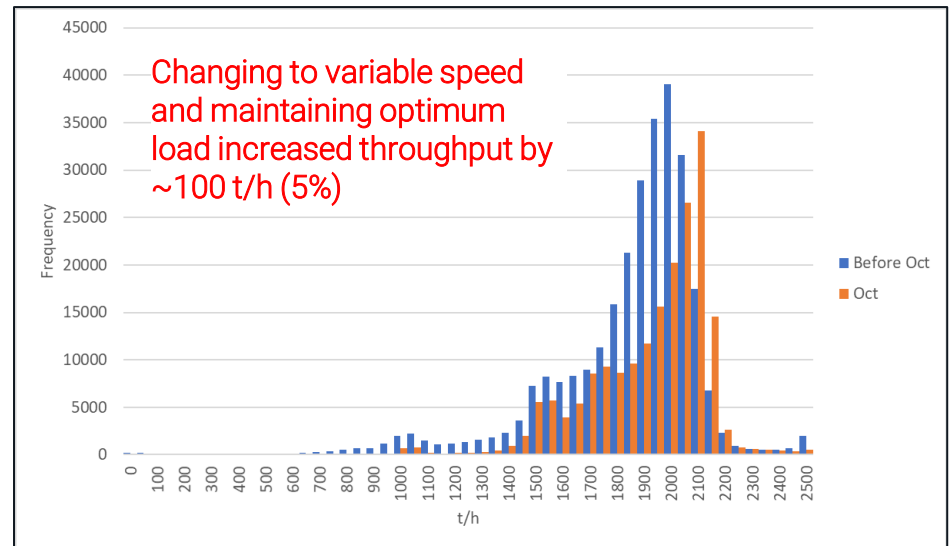
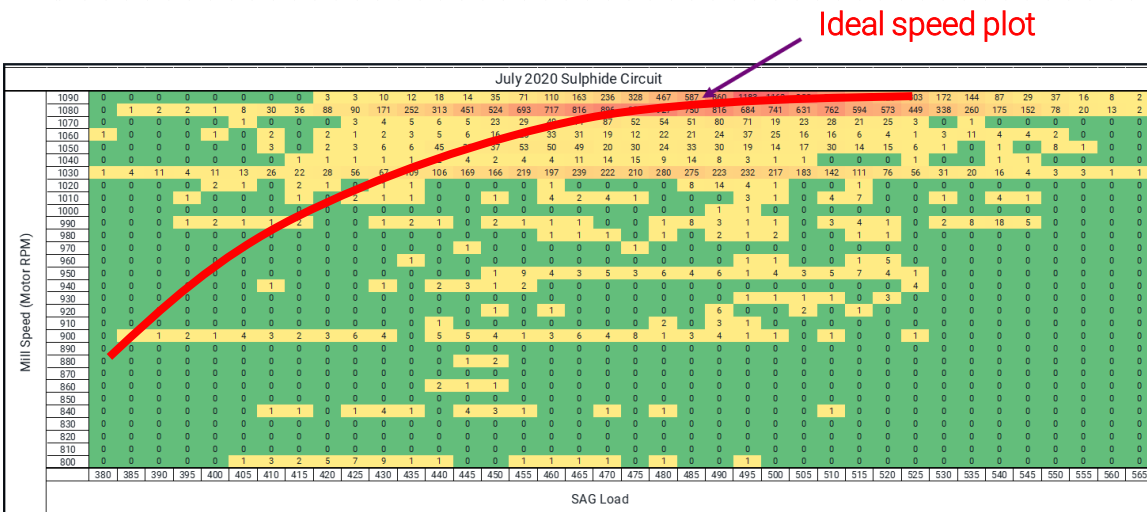
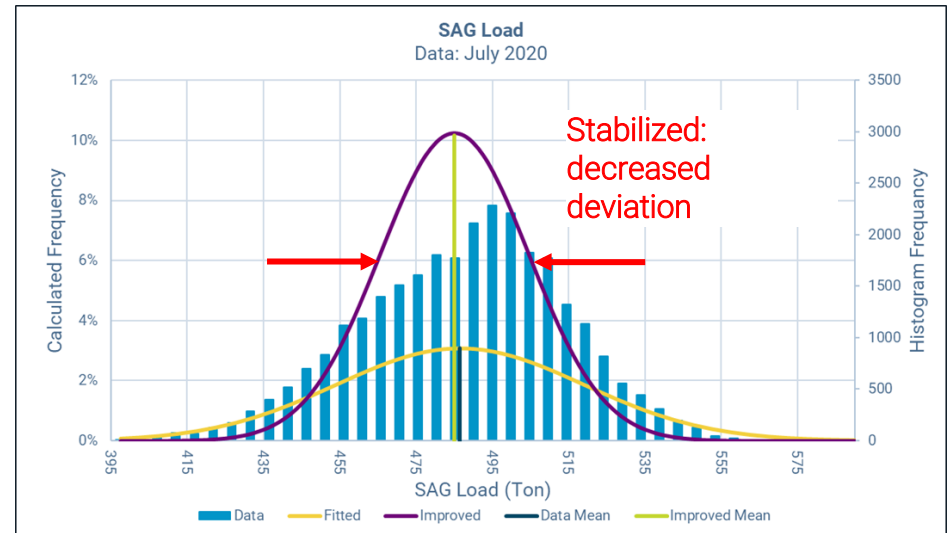


- Narrows scope for targeted analysis and identifying quick wins
- Easy to construct
- Redefine the way we look at data
- Understand the effect of sampling frequency and range on variable comparison
- Higher level diagnostics of data and model comparison
- Allows more advanced techniques (statistical regression analysis, machine vision)

Diagnosing Control Performance

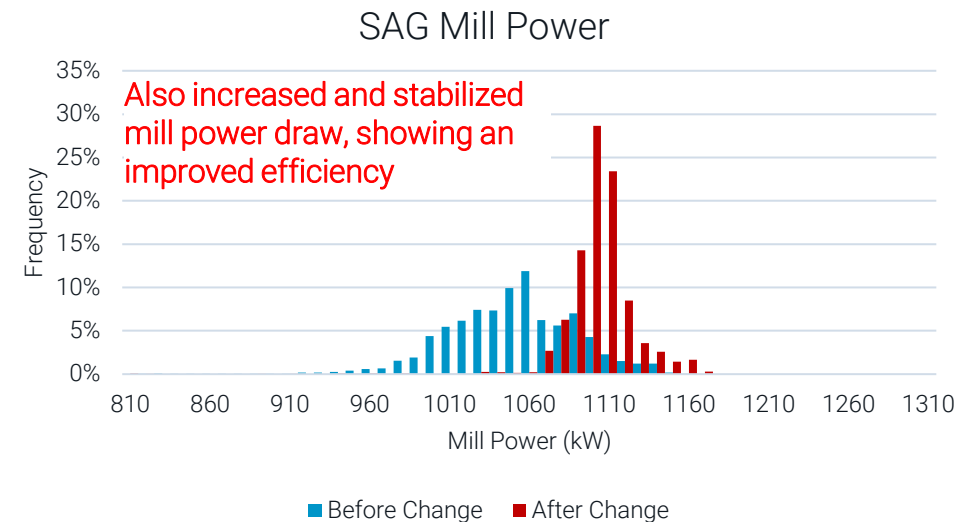
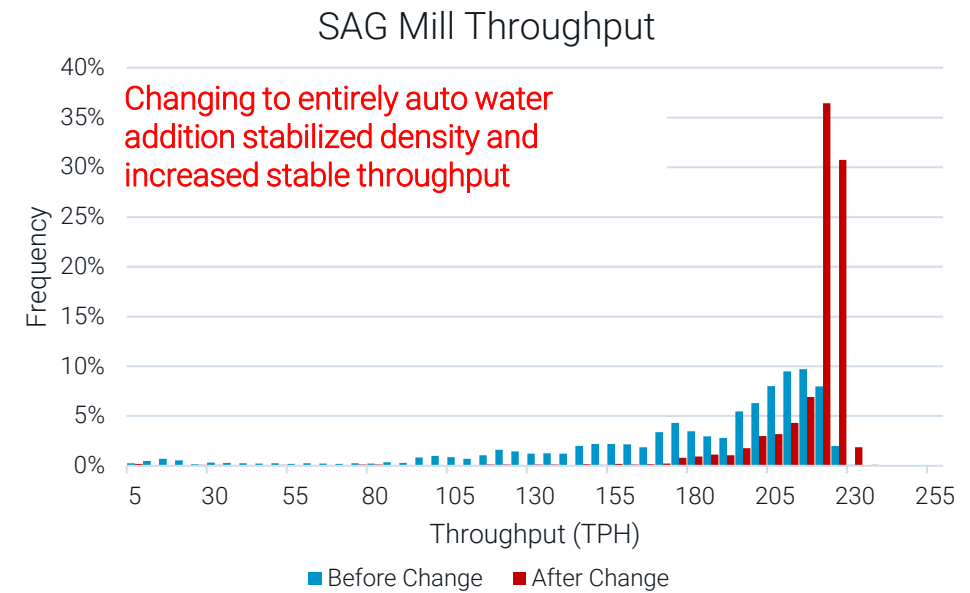
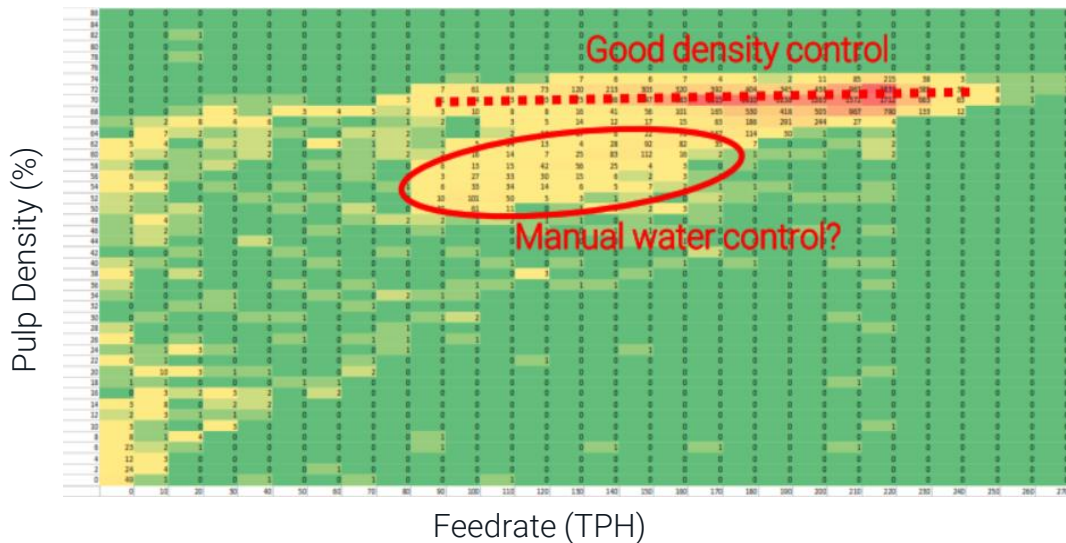


Ideal Load vs. Power for variable speed mill



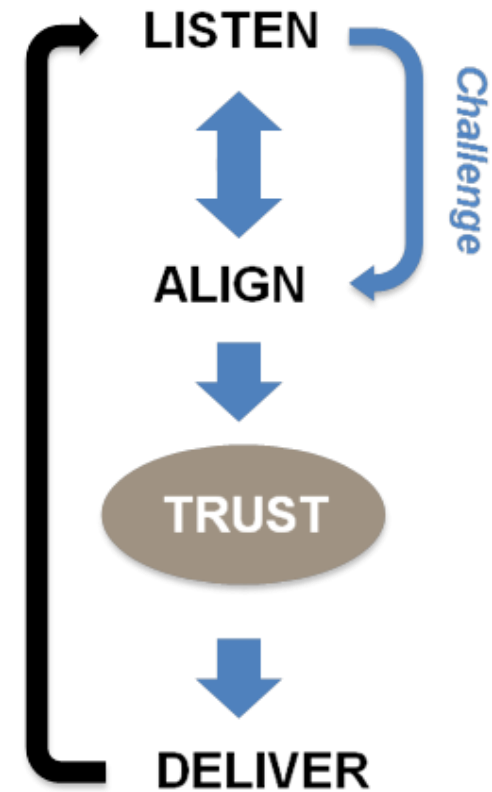
Diagnosis Results

- Quick win: Turn on automated density control in SAG mill
- Results: increased throughput and power draw (mill utilization) with reduced variability
- Overall: 2 quick wins identified with this approach raised gold recovery by 1-2% and throughput as shown



3

Developing an Implementation Plan



Greg Lane, 2007

Value is realised by...

Three core principles:

- 1** **Be proactive** — Do through action
- 2** **Reduce complexity** — Concentrate effort on basic, critical tasks... the essential things
- 3** **Seek improvement** — The essential things done better

Successful Implementation Requires

Strategic Direction

- Sound business strategy based around challenging visions and shared values
- Supported by thorough analysis and accurate data
- Sets the direction and provides the context and enthusiasm for improvement work

Rigorous Methodologies

- To understand the processes upon which the business relies
- Provide the tools necessary to monitor, analyse and improve performance
- Based on well-proven quality and statistical techniques
- The technology and processes must be understood so that the right things are being worked upon and measured.

Managerial Leadership

- Take advantage of all skills in the business
- Improve the processes rather than fighting fires
- Constantly talking with their people

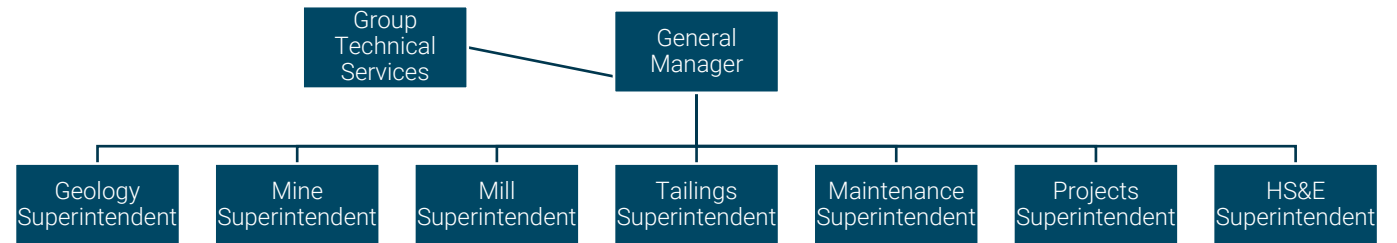
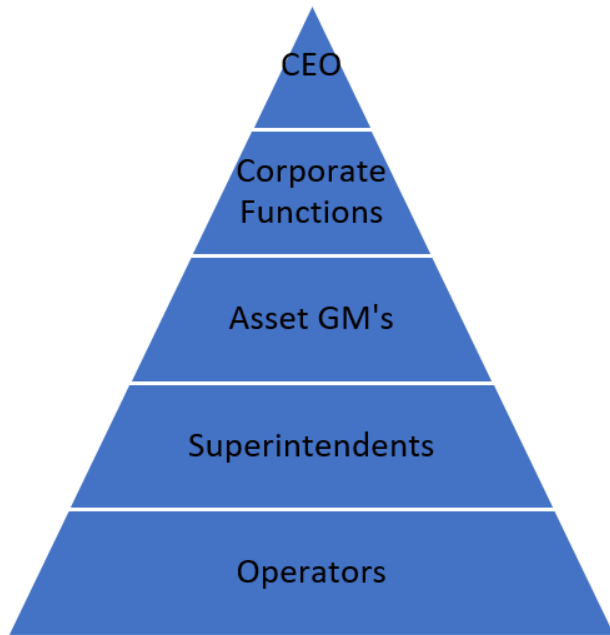
Systems & Infrastructure

- Supporting systems and infrastructure to actively encourage desired behaviours and attitudes.
- Aligned resources and policies that build and maintain an improvement mindset.
- Consistently reinforce the commitment for excellence in all aspects of the business.

Successful Implementation Requires



People and Management







Few are skilled in the whole art

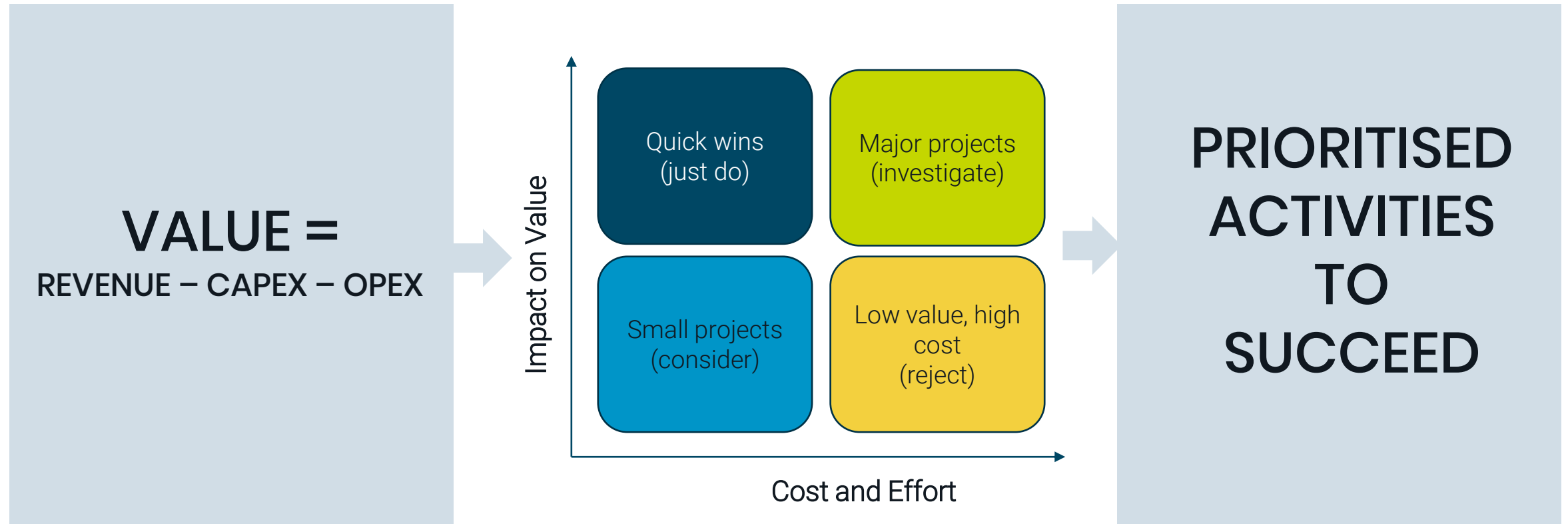
People, communication and management can be a constraint

Link Strategy to Implementation

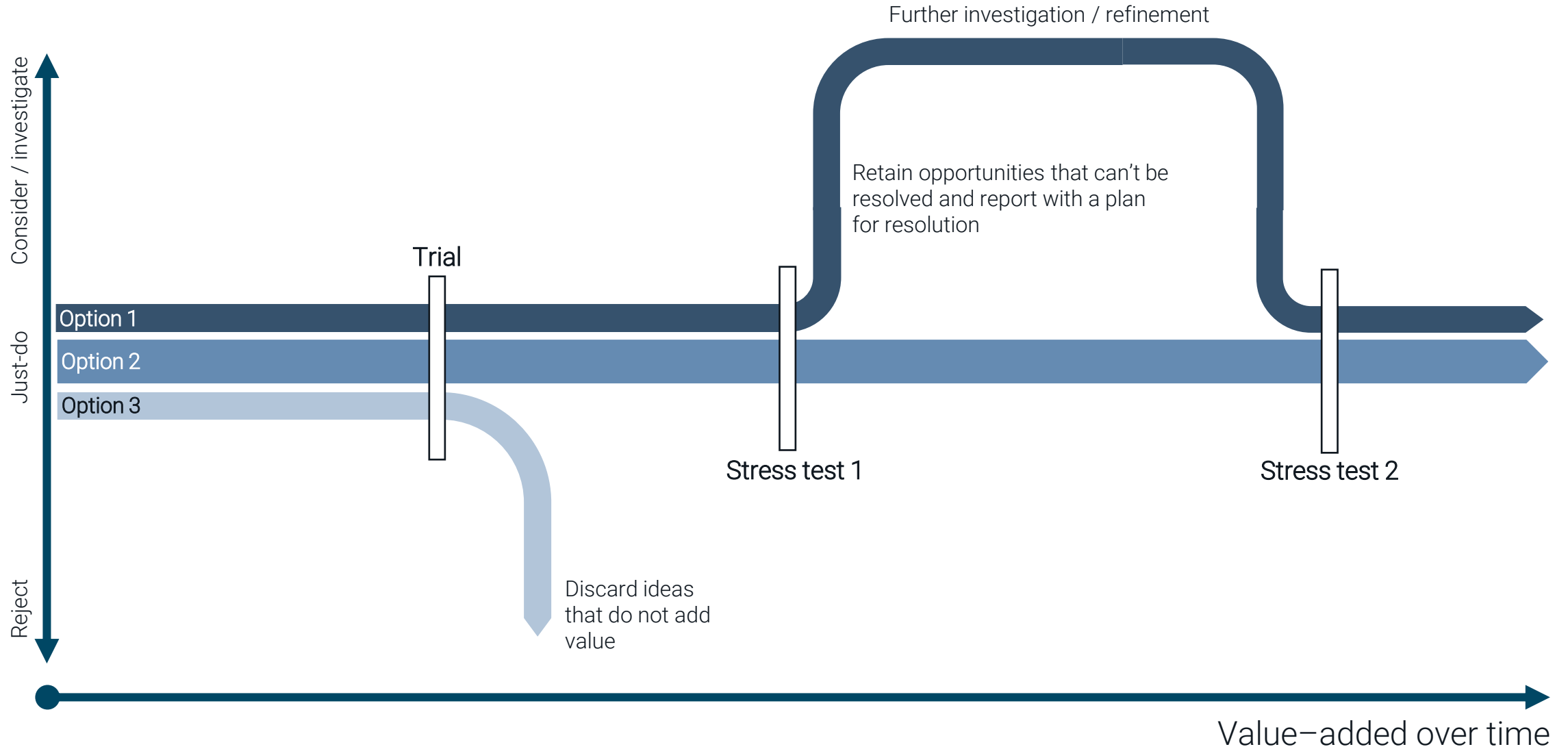
Value drivers

					
		Optimised resource definition	Increased productivity	Minimised constraints	Reduced operating costs
Strategy	Mine to mill, process & process control optimisation	✓	✓		
	Growth pathways, debottlenecking		✓	✓	
	Capacity estimation, risk assessments, maintenance optimisation			✓	✓
Implementation	Techno-economic / project evaluation / pit to port simulations	✓	✓	✓	✓
	Change & operations management	✓	✓		✓
	Mine planning	✓			
	Supply chain & maintenance management			✓	✓
	Training		✓		✓

Prioritise Implementation



Find the Optimum Solution



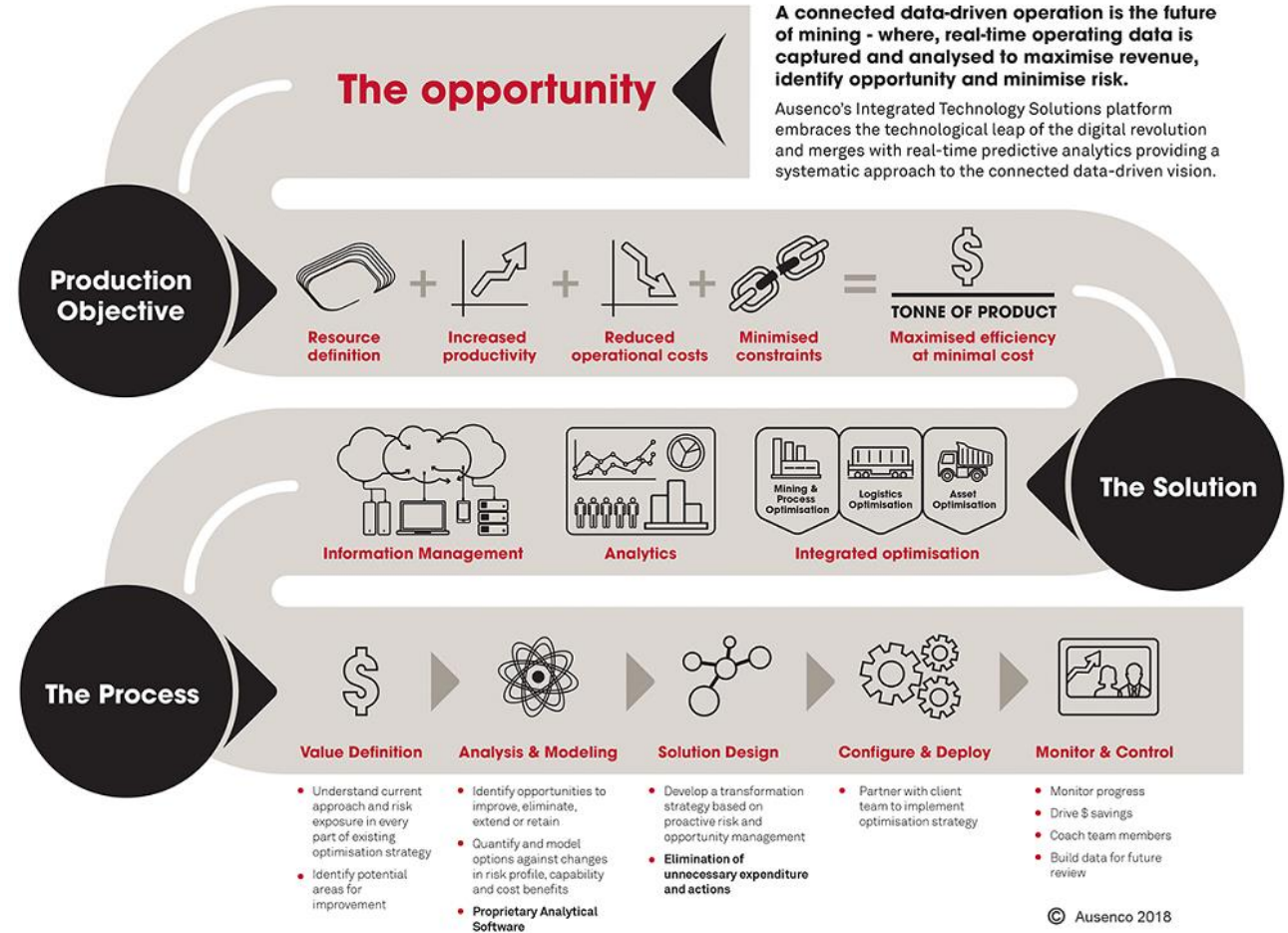
Implementation Plan

1. **Workshops** – problem identification + align with key stakeholders
2. **Develop a plan** – with an end-goal in mind
3. **Rank the options** – from low-cost initiatives to capital intensive initiatives
4. **Track the changes** – follow through and be accountable
5. Build trust and **deliver**



A connected data-driven operation is the future of mining - where, real-time operating data is captured and analysed to maximise revenue, identify opportunity and minimise risk.

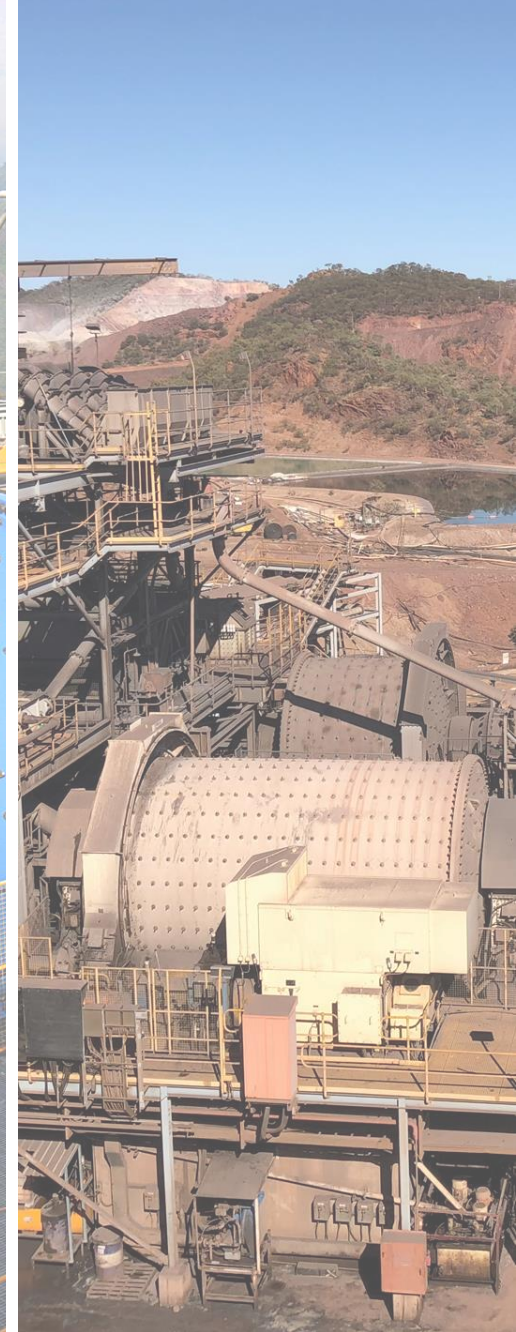
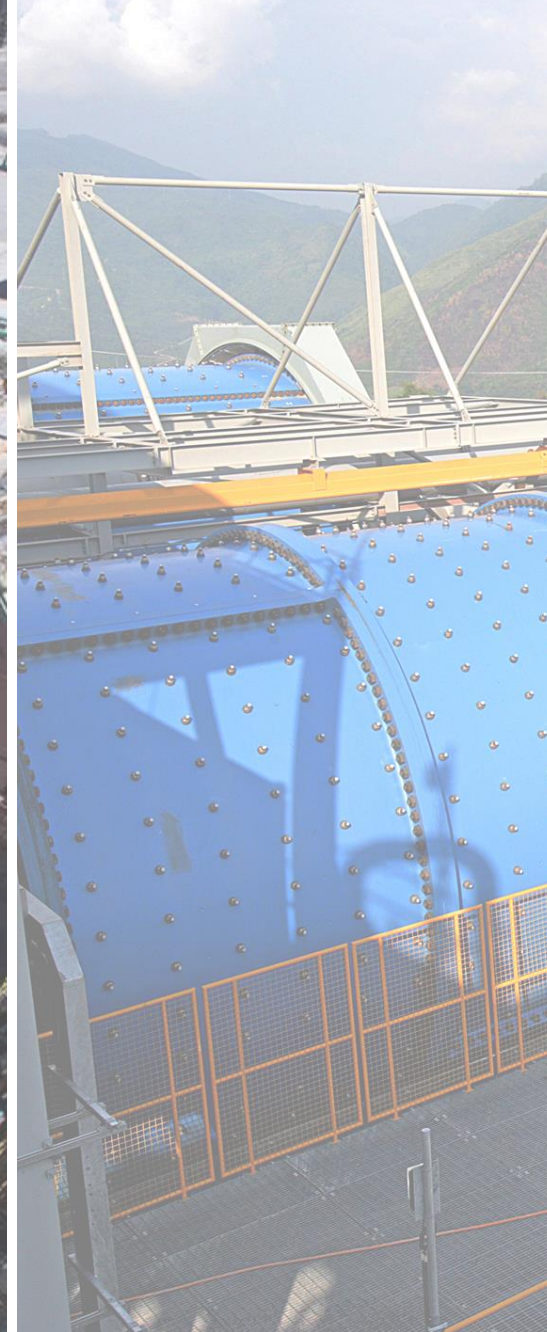
Ausenco's Integrated Technology Solutions platform embraces the technological leap of the digital revolution and merges with real-time predictive analytics providing a systematic approach to the connected data-driven vision.



4

Case Studies

- Penasquito
- Phu Kham
- Capricorn Copper



Penasquito Optimisation

Major Constraints

- Low throughput due to competent ore
- Under utilised comminution equipment
- Incorrect operating parameters
- Bulk ore handling challenges

Optimisation Period

Dec 2018 to-date

Value realised to-date

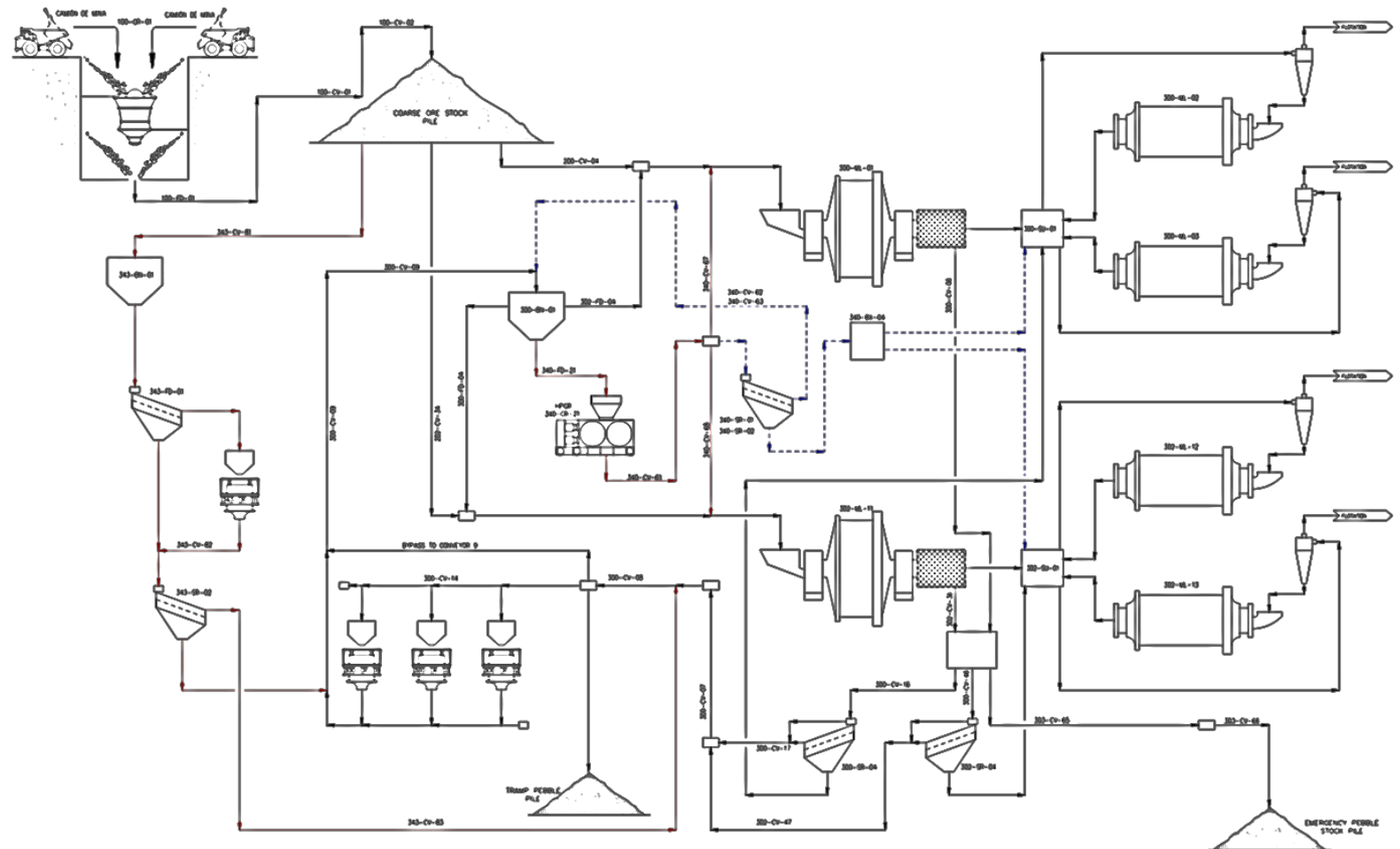
+15% increase in throughput for high competence feed

Reference:

Chandramohan et al – SAG Conference 2019

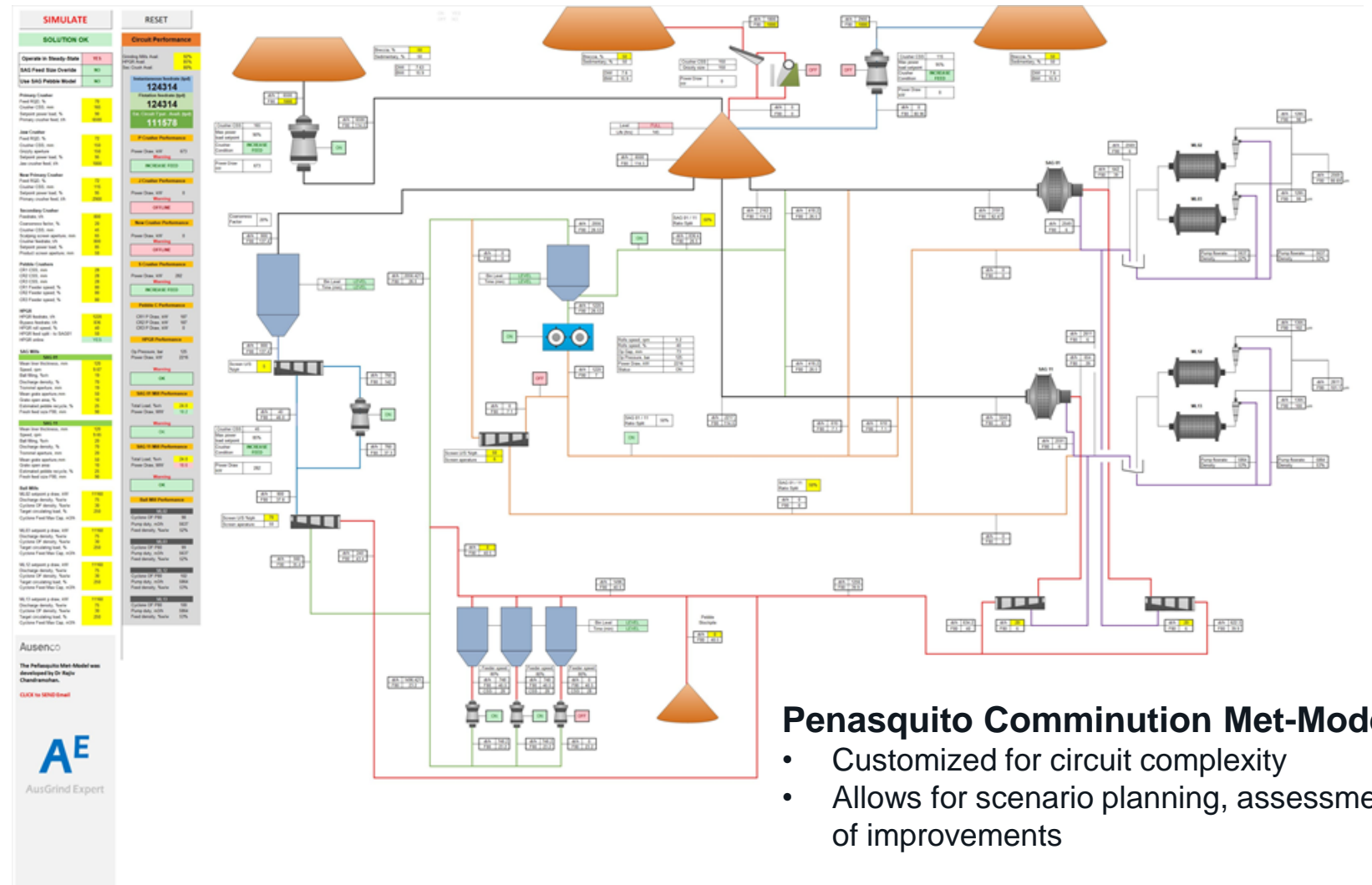
Peñasquito Comminution Flowsheet

- Open pit mine (Penasco & Chili Colorado)
- Polymetallic orebody – Au, Ag, Zn and Pb
- 125 ktpd circuit design capacity
- Future ore sources are more competent and harder



Optimisation Objectives

- Determine circuit limiting bottlenecks
- Reconfigure circuit for future competent ore source
- Provide operational training and strategy



Penasquito Comminution Met-Model

- Customized for circuit complexity
- Allows for scenario planning, assessment of improvements

Key Bottlenecks & Opportunities

Secondary Crusher (Raptor XL1100, 750 kW)

- Under-utilization of installed power
- Challenges to operate at high throughput with low COS height

HPGR (Thyssenkrupp Polycom, 5.0 MW)

- HPGR power draw not maximised – feeder design limitations
- HPGR control strategy limited full potential use of power draw

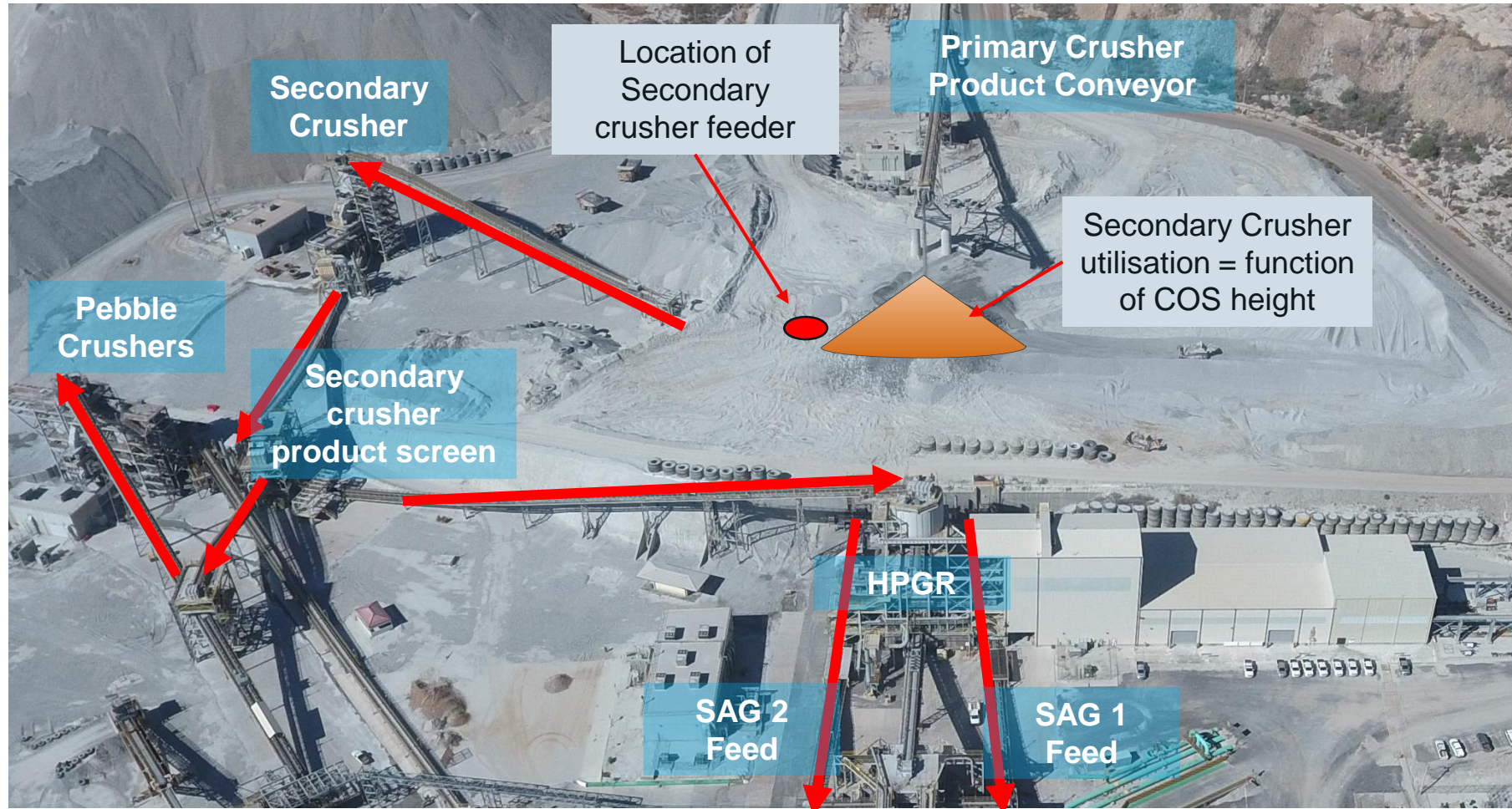
SAG Mills (two 38' x 22.5', 19.4 MW)

- High operating mill total load
- Ineffective process control strategy – mill protection and power draw
- Inappropriate liner design – attributing to poor control strategy and operation

Pebble crushers (three, Sandvik H8800, 600 kW)

- Secondary crusher product screen size limiting pebble crusher operation
- Feeder constraint and bin level control

Crushing Circuit



Crushing Circuit Operating Strategy

Maximise feed rate to augmented feed circuit

- Maintain high COS level
- Sustain and improve feed rate from 800 t/h (average) to 1800 t/h (sustained target secondary crusher throughput)

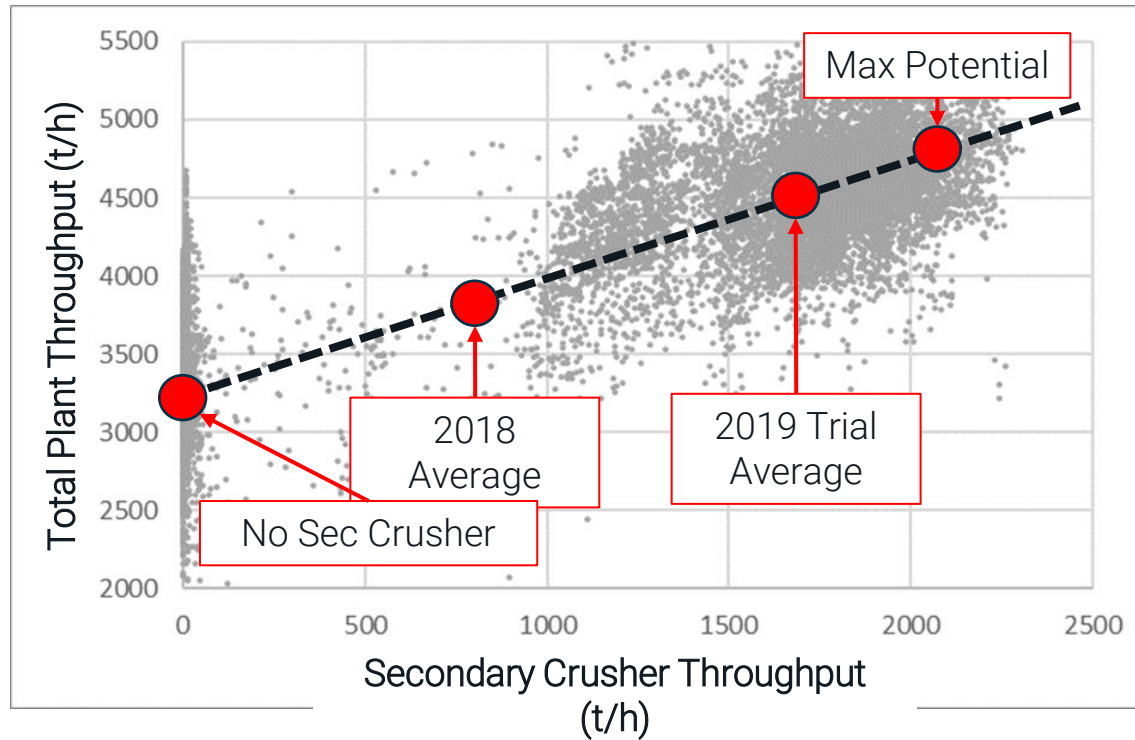
Increase pebble crusher feeder capacity

- From 700 t/h to 1000 t/h
- Operate three pebble crushers (instead of 2 + 1)

Maximise feed rate through HPGR

- Maximum at 2500 t/h
- Only bypass crushed pebbles to SAG mills when HPGR bin is full

Secondary Crusher & HPGR Optimisation



No Secondary operation

~ 3300 t/h Total Plant Feed Rate

2018 Average tph @ 800 t/h

~ 3800 t/h Total Plant Feed Rate

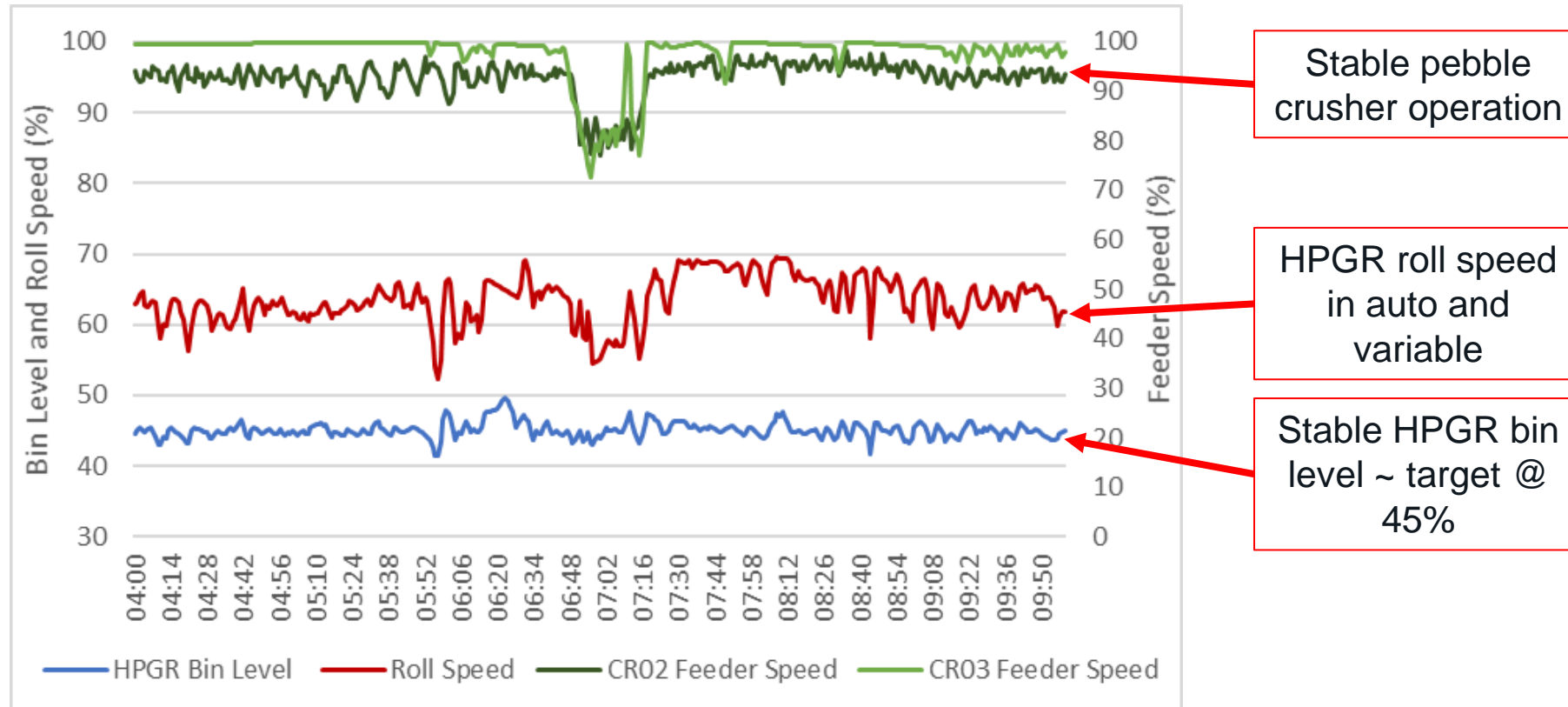
2019 Trial tph @ 1700 t/h

~ 4500 t/h Total Plant Feed Rate

Max Potential tph @ 2100 t/h

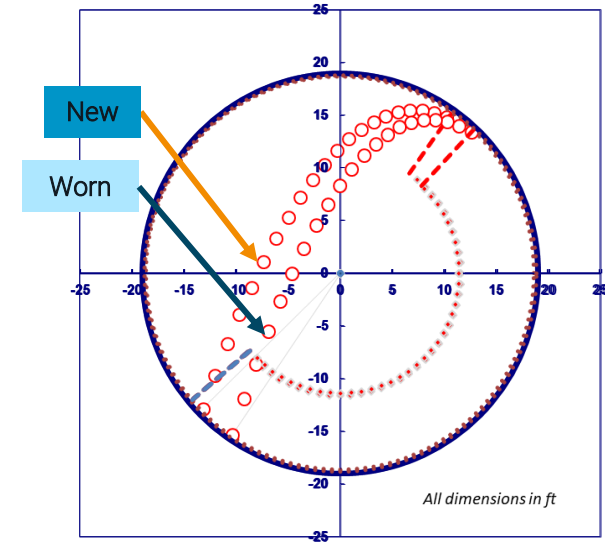
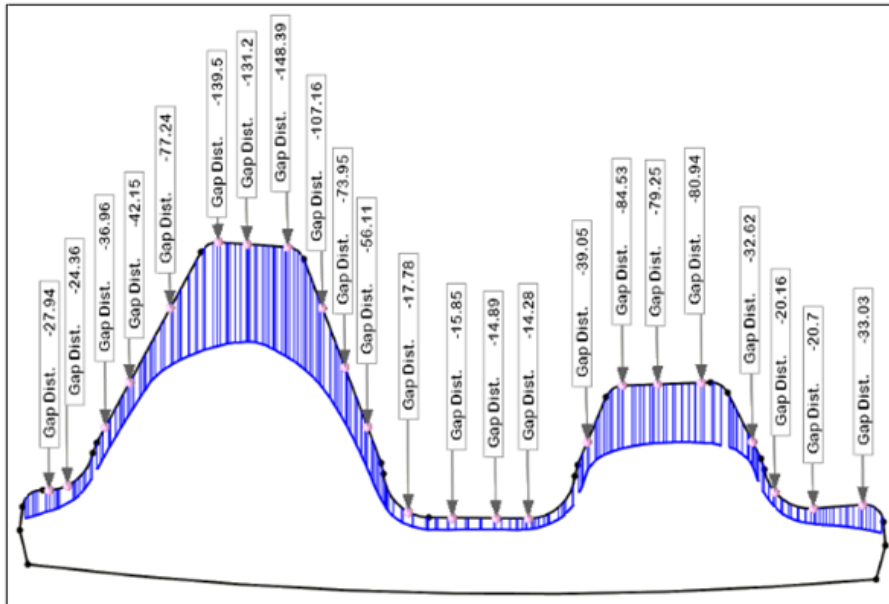
~ 4800 t/h Total Plant Feed Rate

HPGR Optimisation



After

SAG Mill Optimisation



- Steep lifter design
- SAG throughput congested by high total filling
- Liner damage when operating at high mill speeds

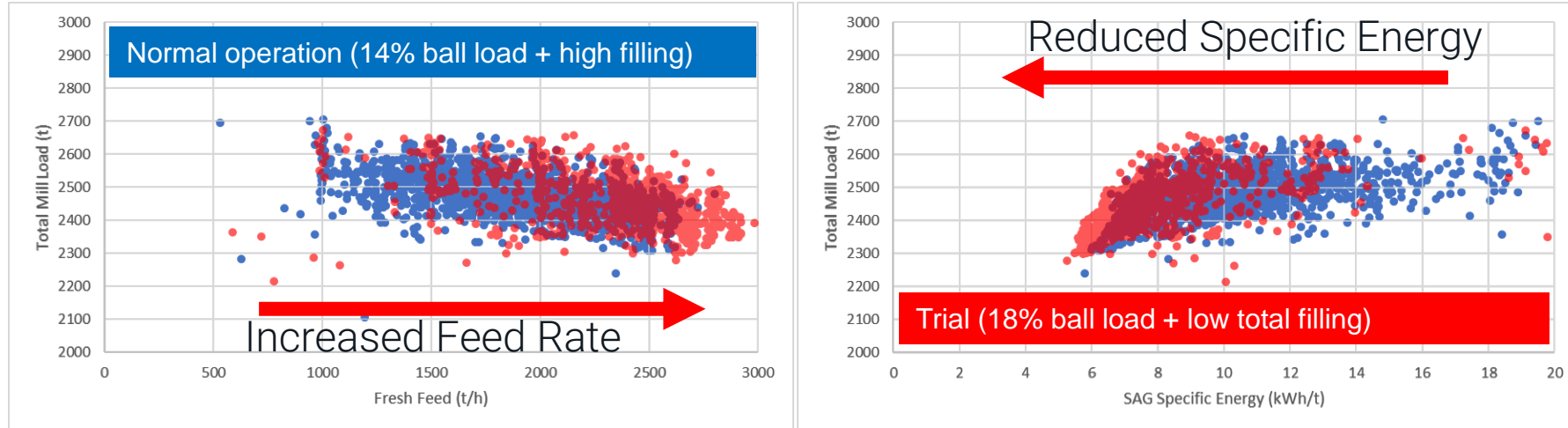
High total filling

- Total charge = 38% v/v
- Ball charge = 15% v/v
- Speed = 75% Nc
- New liners power draw = 17.3 MW
- Worn liners power draw = 17.9 MW

SAG Mill Optimisation

- Minimise pebble crusher product bypass directly to SAG mill
 - Maximise HPGR utilisation
- Optimise process control to maximise power draw
 - Fully utilise the mill speed (instantaneous power draw for varying load conditions)
 - Optimise mill load (reduced rock-ball ratio – higher ball load~ 18% v/v)
- Minimise shell impact
 - Ensure mill protection systems are functional and fully utilized
 - Optimise liner / lifter design - function of lifter face angle and design

SAG Mill Load Trials



	Normal Operation	Trial
Average feedrate (t/h)	2100	2350
Average mill load (t)	2550	2400
Pinion power draw (MW)	18.5	17.2
Mill speed (rpm)	9.2	8.8

Phu Kham Optimisation

Major Constraints

- Low throughput due to competent ore
- Unsuitable SAG mill liner design
- Restrictive controller operation
- Incorrect operating parameters

Optimisation Period

Jan 2017 to Dec 2018

Value realised to-date

+27% increase in throughput for high competent feed

Reference:

Chandramohan et al – Mill Ops 2018

Phu Kham Copper Gold Operation

- Located in Laos (Laos People's Democratic Republic)
- Operated by Phu Bia Mining Ltd: 90% owned by PanAust Limited and 10% owned by Laos Government
- Commissioned in 2008 – nameplate production of 12Mt/y
- currently 19M/y with the addition of second ball mill

- SAG mill throughput limited by:
 - High diorite and skarn feed (future ores)
- Evaluate six liner designs
- Optimise operation for competent feed



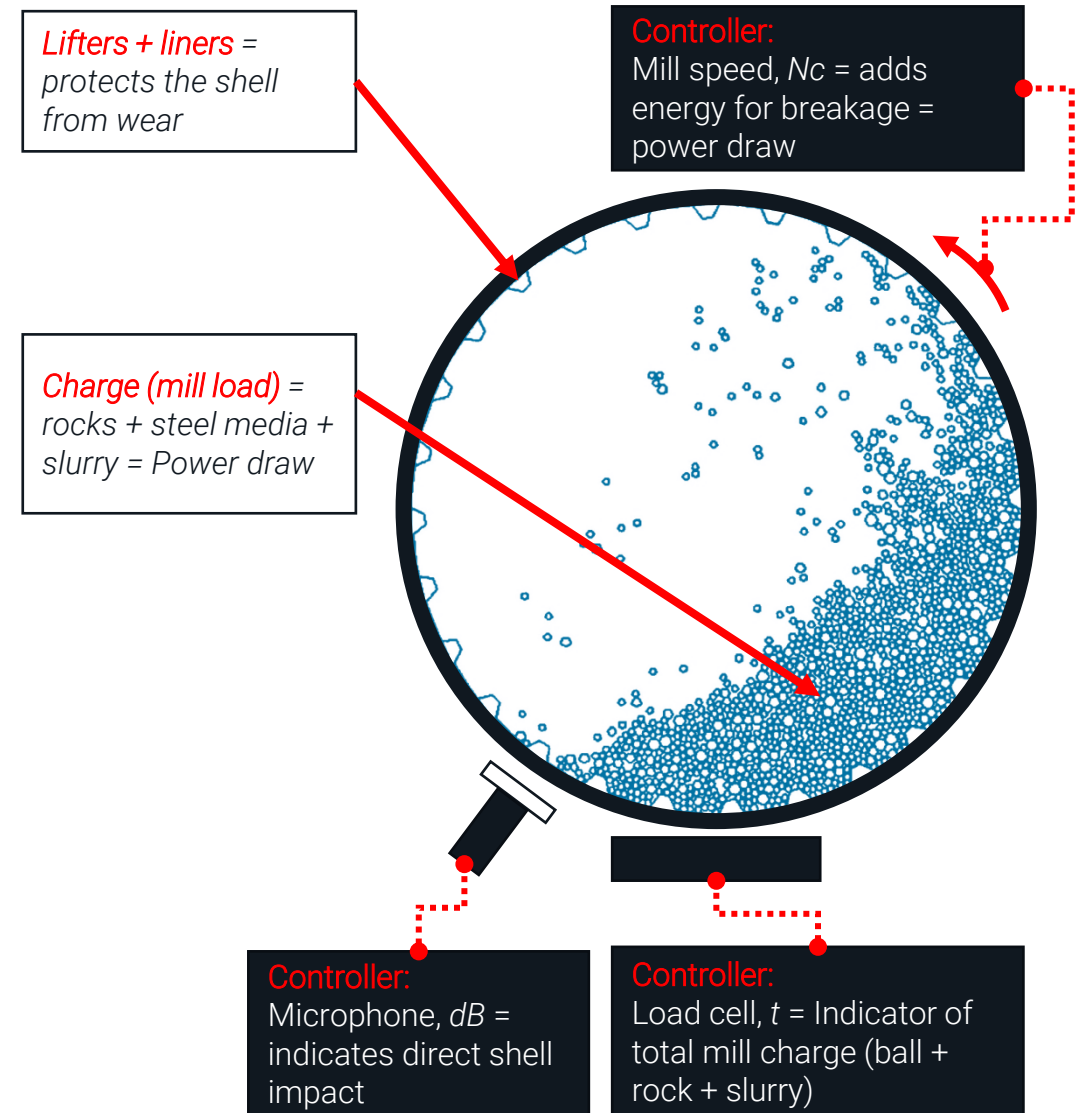
SAG Mill Liners

Design objective

- Increase instantaneous throughput at start-up (75%Nc, 15% v/v ball load, 28% v/v total charge) – operate at or above synchronous speed (SER)
- Increase liner life
- Increase volumetric slurry flow for greater than 2500 t/h ore feed rate
- Maximise power draw = increase in throughput

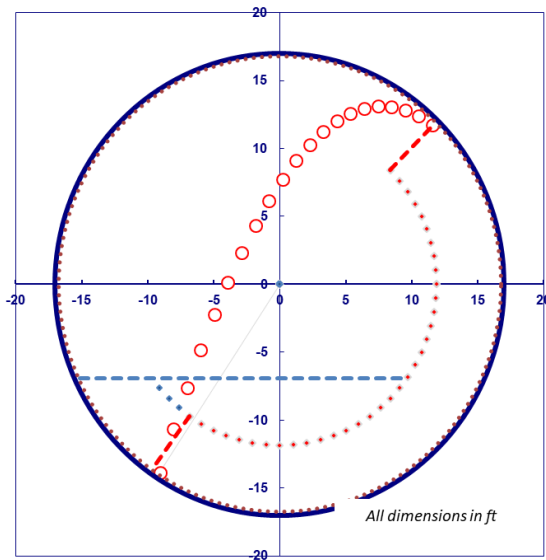
Design Limitation

- Max bearing pressure reading 75 bar / total liner + charge mass = 1200 t
- Must not exceed operational sound level of 55 dB



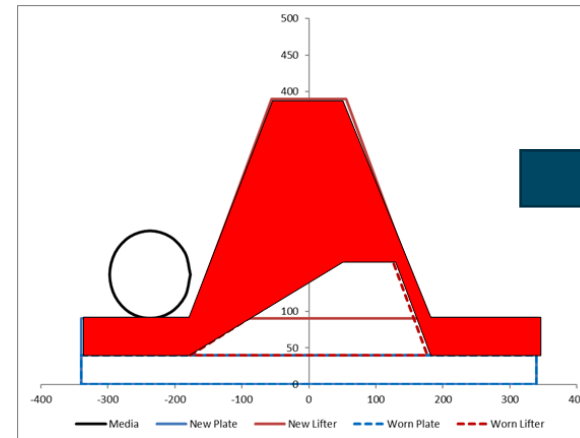
Ausgrind SAG Mill Optimisation Tool

Developed for rapid diagnosis of SAG mill performance

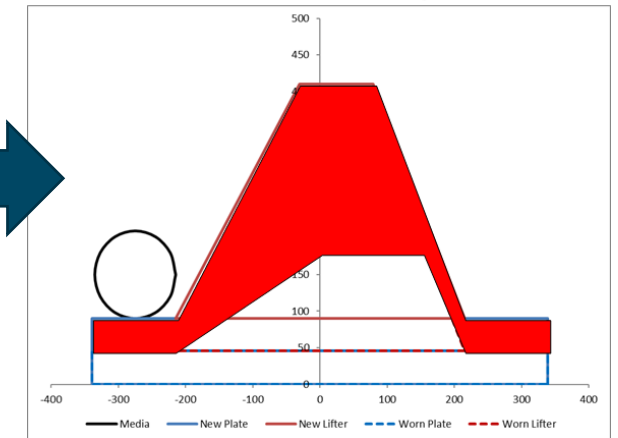


- Trajectory calculation
- Power Model calculation (Charge profile)
- Slurry Pool calculation (discharge capacity)

Base case liner design



Test liner design



- Parametric liner wear model
- Use basecase liner design to predict the wear of new liners
- Validated using Cadia + Phu Kham data

Liner Wear Predictions

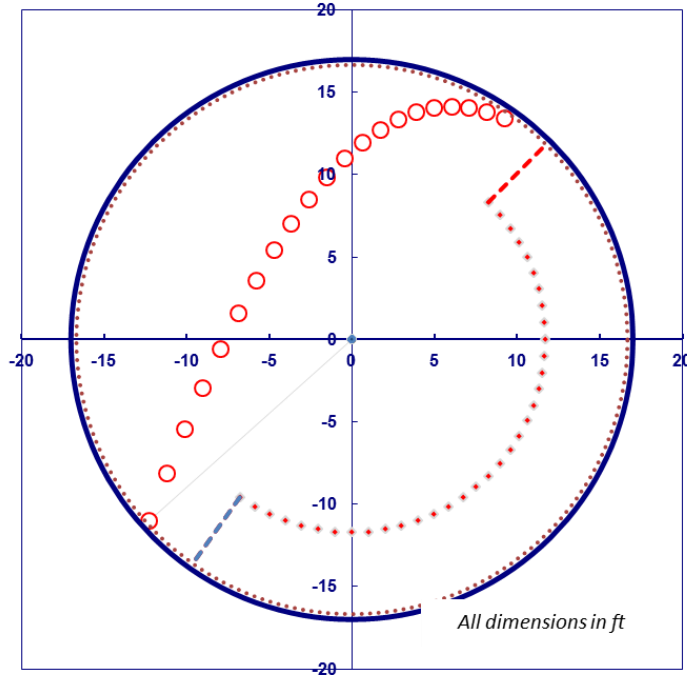
Shell Profile	Base case	Design 1	Design 2
Trial dates	2008 - 2017	2017 (Mar - Sept)	2017 (Sept onwards)
Face angle (deg)	22	35	30
Rear angle (deg)	22	10	23
Lifter height (mm)	300	340	320
Plate thickness (mm)	90	130	90
Life at change out (days)	161	177	158
Predicted liner life days (Ausgrind)	-	173	155

Wear Prediction Assumption:

- Same tonnes processed
- Similar rate of mass loss
- Similar type of ore processed
- Based on baseline 96 % availability
- Minimum plate thickness = 40 mm
- Minimum worn lifter face angle = 60 deg

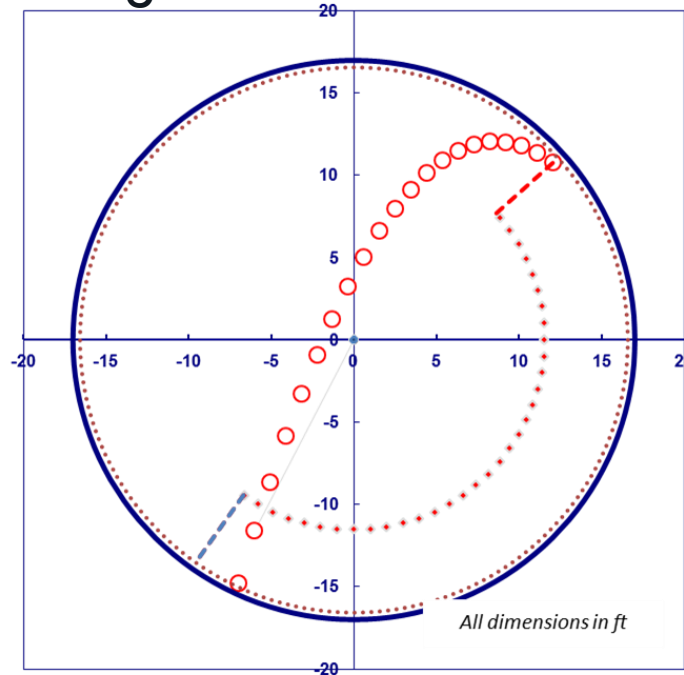
Start-up Comparison

Base Case



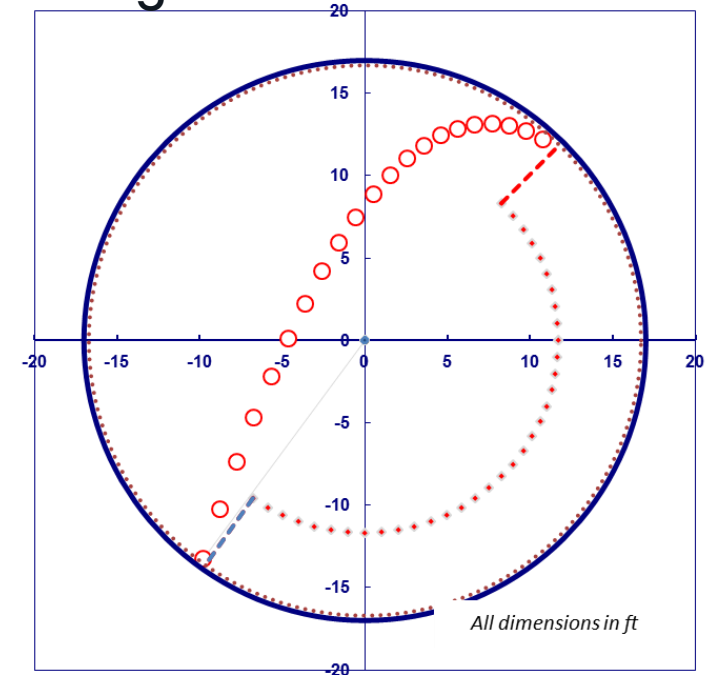
- Face angle = 22 deg
- Mill speed = 75 % critical (**shell impact**)
- Total charge = 28 %v/v
- Ball charge = 15 % v/v
- **Power draw = 11.8 MW**

Design 1



- Face angle = 35 deg
- Mill speed = 75 % critical (impact within charge)
- Total charge = 28 %v/v
- Ball charge = 15 % v/v
- **Power draw = 11.6 MW**

Design 2

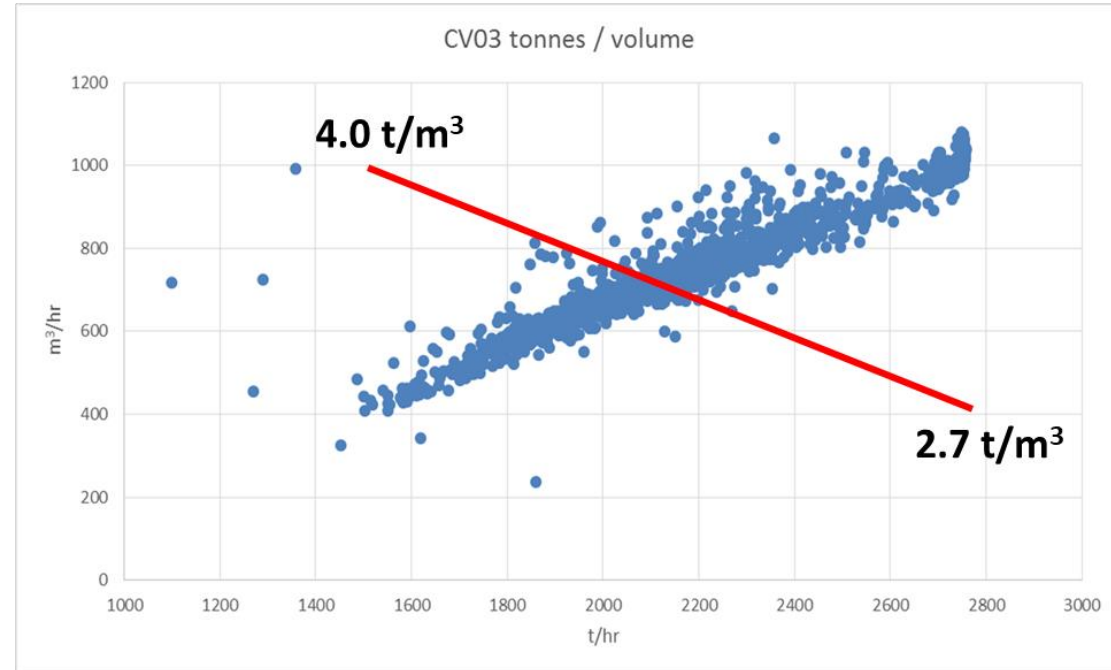


- Face angle = 30 deg
- Mill speed = 75 % critical (toe impact)
- Total charge = 28 %v/v
- Ball charge = 15 % v/v
- **Power draw = 11.9 MW**

Performance Overview

Shell liner performance summary	Base case	Design 2	Design 3
Face angle, deg (vertical)	22	35	30
Liner / Lifter thickness, mm	100 / 300	130 / 340	90 / 320
Discharge system type	Radial	Curved	Radial
Grate Open Area / aperture, %/mm	14.5 % / 25 mm	14.5 % / 25 mm	15.6% / 30 mm
Total mass limit, t	1200		
Total liner package mass, t	485	610	480
Theoretical max filling based on 15% ball charge load, %v/v	34	31	38
Max speed for new install, % Nc	68	77	75
Ball charge at start up, % v/v	15	15	17
Available power for new install, MW	10.6	12.0	12.4
Operational limit	High lifter face angle = shell impact	High liner mass = constrained mill load and operational speed	None
Instantaneous throughput for hard ore (@ S.E = 6.0 kWh/t), t/h	1770	2000	2100

Control Optimisation



Remarks

- Transitioning from friable low SG ore to competent high SG feed caused frequent disturbances
- Advanced mill control was not adequate to resolve sudden changes in feed composition
- Inclusion of inferred ore SG measurement improved overall response of the controller

Capricorn Copper Optimisation

Major Constraints

- Shifting constraint between mine and concentrator
- Low SAG mill availability due to poor liner design
- Low Ball mill power draw
- Low circuit stability

Optimisation Period

Jan 2018 to-date

Value realised to-date

+35% increase in throughput and +4% increase in Cu recovery +50% increase in nameplate capacity

Reference:

Ausenco Website – Capricorn Copper Project

Background

- Capricorn Copper Mine (CCM) is located in a range of hills approximately 125km by road northwest of Mt Isa in North West Queensland
- Mineralization was first discovered in 1882, with multiple processing methods used throughout its history.
- The existing operating infrastructure includes:
 - Processing plant
 - 3 underground mines (ESS, MAM and GST)
 - Water treatment plant for acid water treatment and sulphate removal
 - Workshops and stores
 - Concentrate storage shed
 - Tailings storage facility (old open pit)
 - Raw water and power supply
 - Utilities
- In January 2019, Ausenco was awarded a five-year contract to operate and maintain the Capricorn Copper processing facility.



Improvements to Date

In 2018, Ausenco was awarded a five-year contract to operate and maintain the Capricorn Copper processing facility.

Increase 2018 to 2020 YTD

↑ **40%**
Increase in revenue

↑ **4%**
Recovery

↑ **10%**
Mill operating time

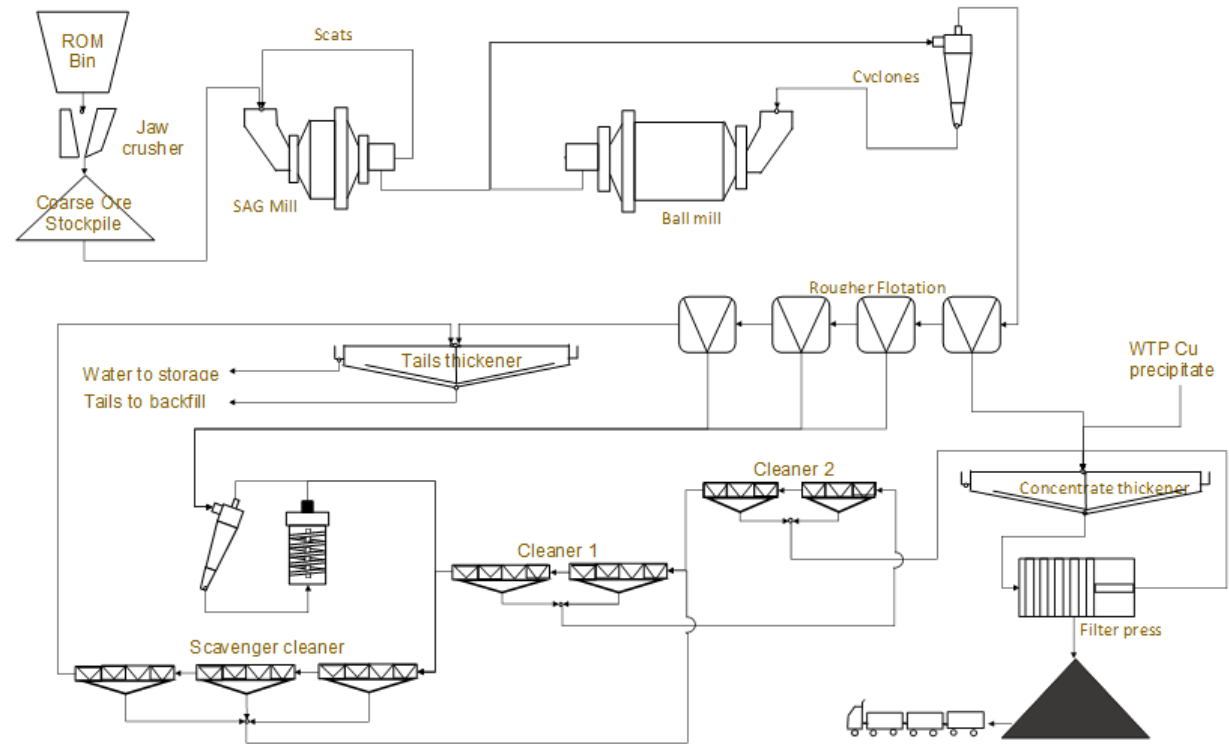
↑ **50%**
Nameplate Capacity

↑ **7%**
Concentrate grade

↑ **35%**
Ore milled year on year

Baseline challenges

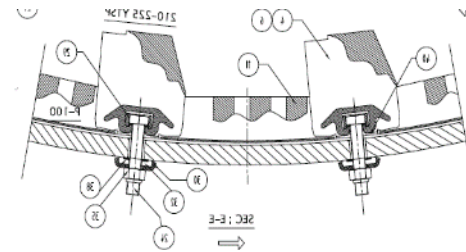
- Constraints changing from concentrator to mine and back again
 - Priorities flip between throughput and recovery and cost
- Low mill availability
- Short SAG mill liner life – 8 weeks
- SAG mill media loss
- Ball mill scats and media discharge
- Ball mill power under-utilized
- Ultra-fine particle generation
- Poor circuit stability and high amounts of time generating spillage in the flotation circuit



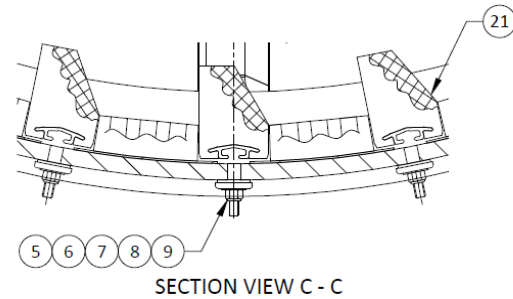
Grinding improvements

SAG lifters and liners re-design

Previous supplier Lifters

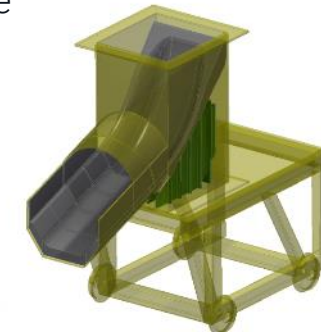


Current Lifters



SAG feed chute re-design

Current SAG feed chute



Media charge adjustments



High Intensity Blasting & Pre-Crushing of Harder Ores



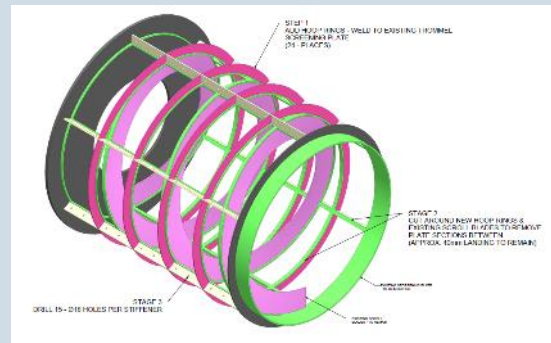
Grinding improvements (cont.)

- SAG trommel re-design
- Ball mill retaining ring
- SAG mill weight control
- Cyclone pressure control
- SAG mill density control
- Operating Strategy improvements

Pegged trommel



Re-designed trommel



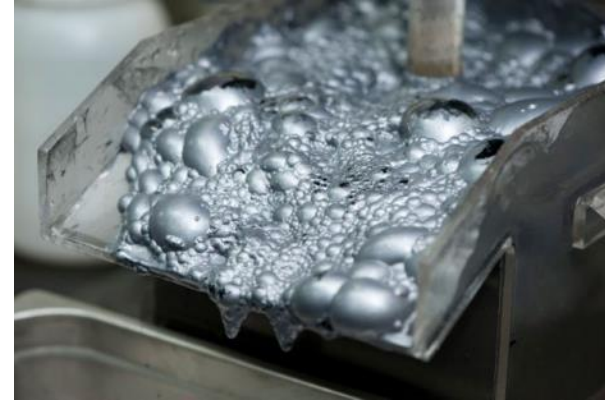
Ball mill retaining ring



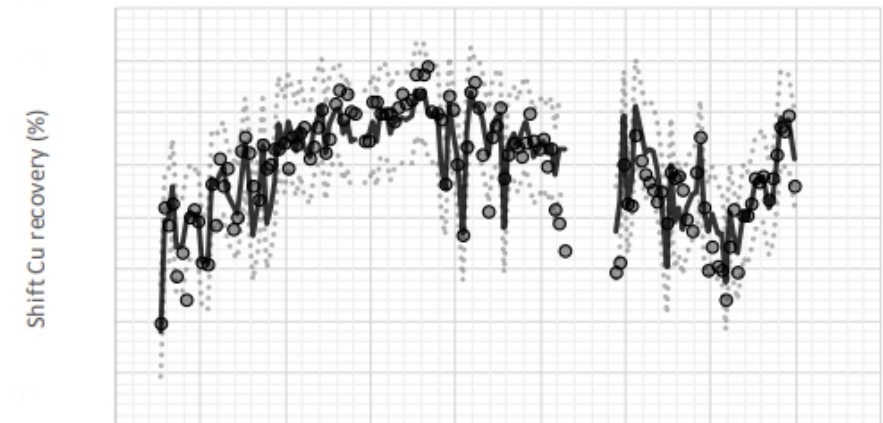
Flotation improvements

- Mine to market
 - Geomet meetings
 - Blending of ore sources
 - Recovery modelling using a S/Cu proxy
- Testwork and optimisation
 - Collector selectivity
 - Water chemistry
 - Regrind
- Operating strategies and TARPs
- Control improvements
 - Flotation circuit level control tuning
 - OSA performance
 - Automated reagent system
- Engineering projects
 - Sprays upgrades

Testwork



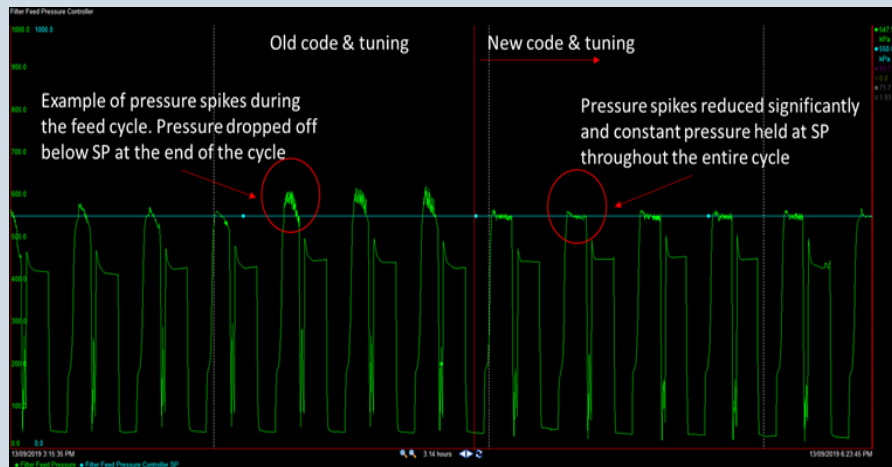
Recovery modelling



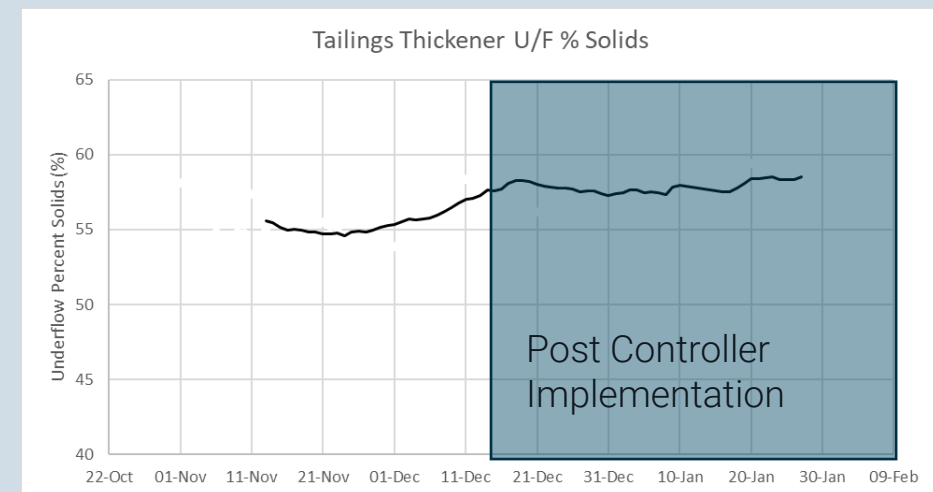
Concentrate handling and tailings management

- Improved Pressure Control for Filter Feed Cycle
- Upgrade of Concentrate Thickener Underflow Pumps
- Recommissioning of Concentrate Storage Tank
- Tailings thickener density controller
- Upgrade of Tails Thickener Pumps and Tailings Discharge Line

Concentrate filter feed pressure controller



Tailings density control



Opportunities and next steps

- Ore segregation on ROM pad and geometallurgical domaining
- Flotation optimisation
- Testwork and optimisation of the HIG mill regrind circuit
- Primary cyclones optimisation
- Instrumentation installation and data collection for plant optimisation
- OSA upgrades
- Plant reliability and spare parts stocks level on site review
- Structural refurbishment works

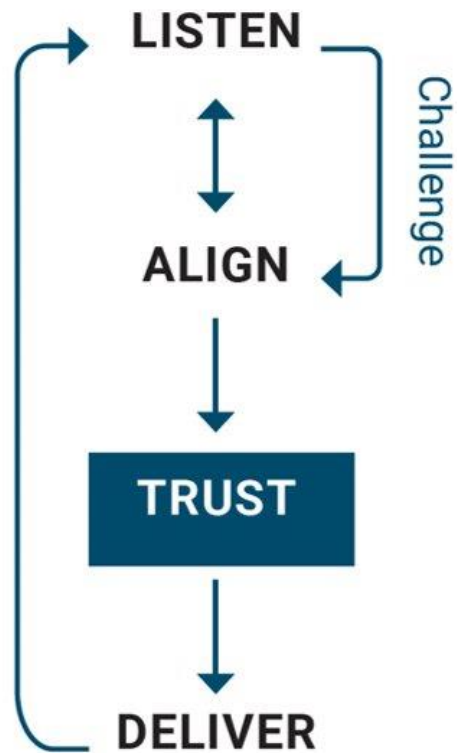


5

What good looks like



Success is driven by...



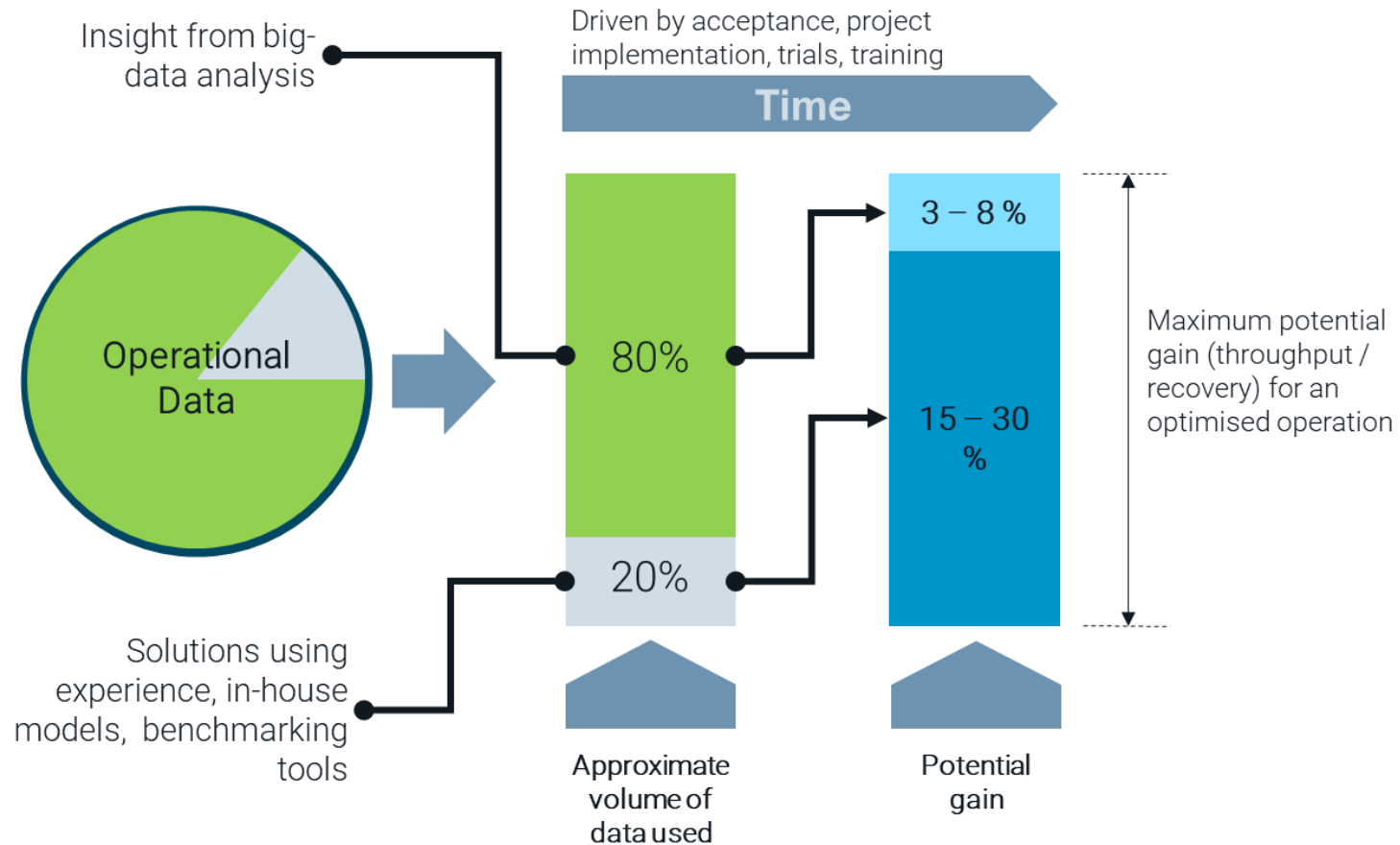
Greg Lane, 2007

- Focusing on alignment and building trust through effective communications
- Engaging people who know what good looks like
- All stakeholders working to achieve the same goal – **VALUE**

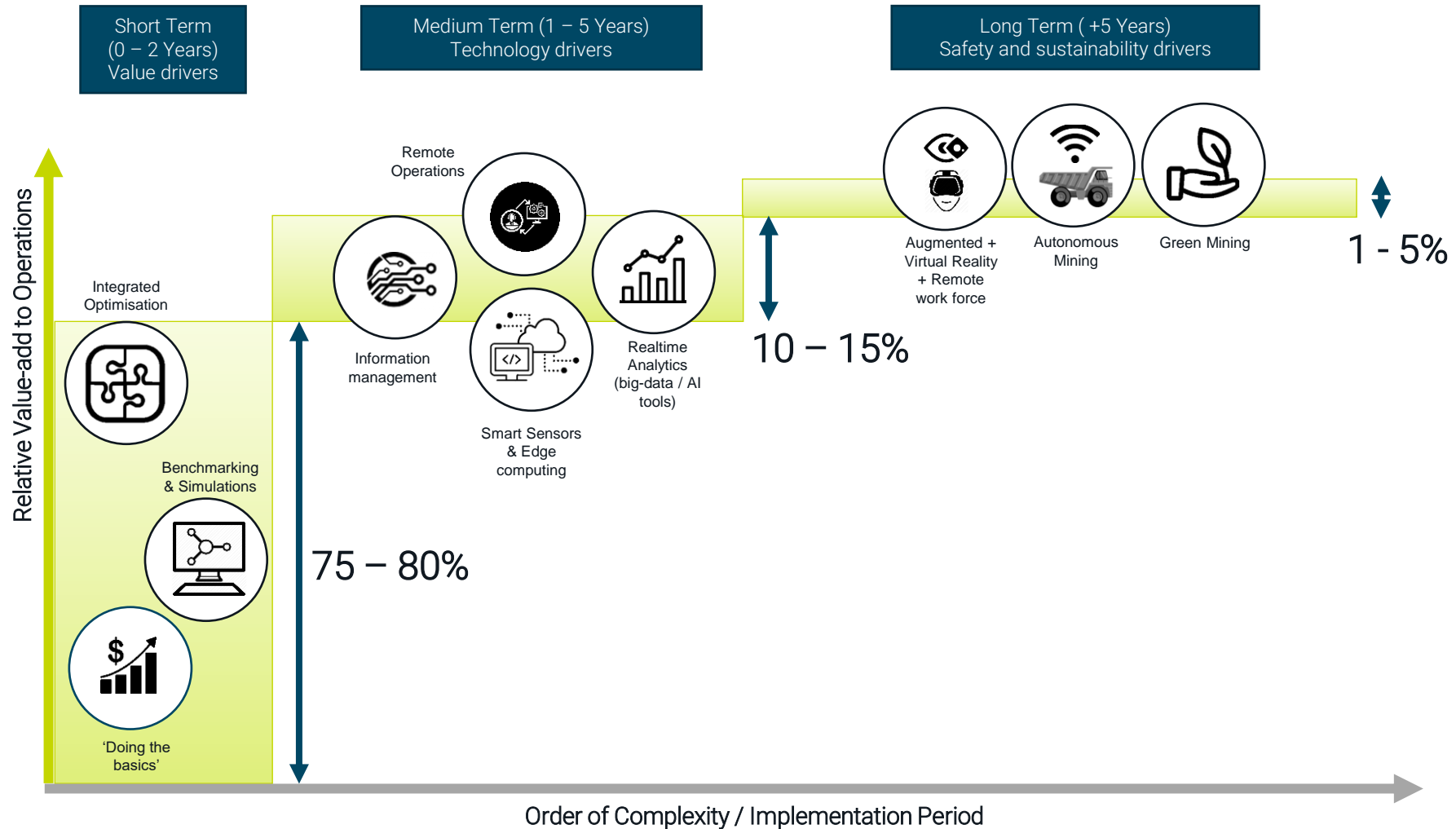


Sensible use of Data

Insights gained from data can turn 20% of the data into 80% of the value



Linking Technology to Value-add



We can Operate Smarter by...



Focusing on the value

- Get the basics right
- Understand the constraints
- Focus on stability
- Push the limits of assets



Gaining insight using good data

- Think about the integrated approach
- 80% of the value can be gained from 20% of the data



Adopting future technologies

- Drive value analysis
- Be sensible about data usage and application
- Enabler to push the limits of asset utilisation

Final thoughts

- 1 Operations outperform their competitors by aiming to **be different**, not better
- 2 New problems call for **new methods**
- 3 Success is motivated more by **meeting a need than a target**
- 4 The true strategist more resembles an **experimental scientist** than a clairvoyant planner
- 5 Everything important happens “at the edge of chaos”





Thank you – Questions?

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