Application of Enterprise Optimisation Considering Ultra High Intensity Blasting Strategies

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SUMMARY

This case study assesses the application of Mine-to-Mill integrated unit operations optimisation and Whittle Consulting's Enterprise Optimisation, for the purpose of economic value enhancement of open cut, base and precious metal operations. The study extends the application of these optimisation methods to incorporate the recent practice of Ultra High Intensity Blasting (UHIB), using a desktop approach on a copper/gold open cut porphyry deposit.

In base and precious metal mining, capital and energy are the most significant cost types. Process plant capital is typically the greatest component of initial investment. The comminution circuit is frequently the production bottleneck in a mining operation and is the largest, least-efficient energy consuming unit operation. Blasting fragmentation is usually the most energy efficient unit operation.

Mine-to-Mill optimisation typically employs increased blasting intensity to debottleneck a power constrained comminution circuit. It seeks to transfer the energy requirements from the least to most efficient component to achieve a similar result, thus saving significant costs on energy. This study assesses existing engineering research and industrial trials on the interaction between blasting fragmentation and comminution power consumption and extends its application into the higher blasting powder factor range (2 - 4 kg/m^3) that is possible with UHIB designs.

The cost and power metrics developed in this study were used as inputs to Whittle Consulting's Prober® Enterprise Optimisation software, to assess the life-of-mine impact of variable fragmentation from UHIB, on mine asset Net Present Value (NPV).

The study determined that:

- Over a blasting powder factor range of 1.2 to 4.7 kg/m^3, the total unit production cost for the case study was constant at US$12.0 ± 0.2 per tonne of ore.
- Production capacity increases of up to 40% were feasible for an enterprise that was mill power constrained.
- Increasing powder factor from a conventional value of 1.2 kg/m^3 drove growth in enterprise NPV by diminishing steps, up to a powder factor of 4.3 kg/m^3.
- **NPV increased by US$0.6 billion (26%),** through that powder factor increase.
- Additionally, Life-of-mine NPV per tonne of CO_{2e} emissions increased by 52%, driven by the difference in energy efficiency of blasting relative to comminution.

Mining businesses can create significant increases in the NPV of their operations and development projects, by employing the economic optimisation power of the Mine-to-Mill engineering philosophy and combining it with the economic optimisation utility of Whittle Consulting's Prober® software. Applying increased energy to rock breakage and surface area creation through conventional and UHIB blasting designs, can materially increase metal production, cash flow and mine NPV while concurrently reducing Life-of-Mine carbon emissions.

Future research and industrial trials on the characterisation of blasting induced microcrack formation in comminution feed ore, particularly at the elevated powder factors used in UHIB, would enable improved calibration of the data required to optimise Mine-to-Mill operations over their life. It is possible that collaboration between Coalition for Energy Efficient Comminution (CEEC), CRC Ore, Orica and Whittle Consulting may advance such research and industrial trials.

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1 INTRODUCTION

Whittle Consulting provides strategic mine planning and business optimisation services to the mining industry, with a focus on enterprise wide simultaneous technical and commercial optimisation over the operation's life. Known as Enterprise Optimisation, Whittle Consulting has applied this approach at over 150 operations and development projects, where consequent Net Present Value uplifts of at least 5-35% have been reported. Whittle Consulting actively disseminates the philosophy and methodology of its Enterprise Optimisation to a wide group of mining professionals, executives and industry financiers via regular "Money Mining and Sustainability" seminars.

Mine-to-Mill optimisation has been applied in the industry since the 1990s with the objective to integrate all mining, processing and logistics unit operations, usually with the goal of maximising metal production or minimising costs. As a commercial discipline, the Mine-to-Mill techniques are routinely applied by a minority of today's operations. In assets where Mine-to-Mill disciplines are employed, the analysis is almost universally a static assessment at a specific point in the mine's life. The complexity of seeking to simultaneously optimise multiple unit operations over an extended time, for a depleting resource is beyond the feasible capacity of most mine planning teams and their tool sets.

Mine-to-Mill methodology often employs higher blasting intensity to debottleneck a power constrained comminution circuit. This study applies engineering research and industrial trial data on the interaction between blasting fragmentation and comminution power consumption and extends its application into the higher blasting powder factor range (2 - 4 kg/m^3) that is possible with Ultra High Intensity Blasting (UHIB) designs. The cost and power metrics developed in the study were applied as inputs to Whittle Consulting's Prober® enterprise optimisation software, to assess the life-of-mine impact of variable fragmentation from UHIB, on mine Net Present Value (NPV).

1.1 PURPOSE

The purpose of this study was to employ Whittle Consulting's Enterprise Optimisation techniques, which dynamically link mining and mineral processing in a single holistic model, to evaluate the effect of UHIB design on Mine-to-Mill debottlenecking and enterprise value. This evaluation was conducted through a case study that examined the influence of variable intensity fragmentation on downstream comminution processes, using conventional blast designs and the UHIB designs that are being trialled by Orica.

The results from this study provide a basis for potential collaborations in Mine-to-Mill strategic mine planning and operational cash flow optimisation, with the support of mine operators and blasting service providers.

1.2 ULTRA HIGH INTENSITY BLASTING

Blasting is the most energy efficient process for the creation of new surface area in the sequence that is required to sufficiently expose the target mineral, for recovery through processes such as flotation or leaching. Conversely, comminution processes are the least energy efficient in creating new surface area. Mine-to-Mill optimisation exploits this significant difference in energy efficiency, with 7-8 times leverage, by increasing blasting fragmentation to debottleneck a power draw constrained comminution circuit.

Comminution power and grinding media consumption are reasonably well understood and predicted through engineering equations relating to work. Unit energy consumption is a known function of feed size distribution, product size and the physical characteristics of the rock, defined as Bond Work Index (BWI).

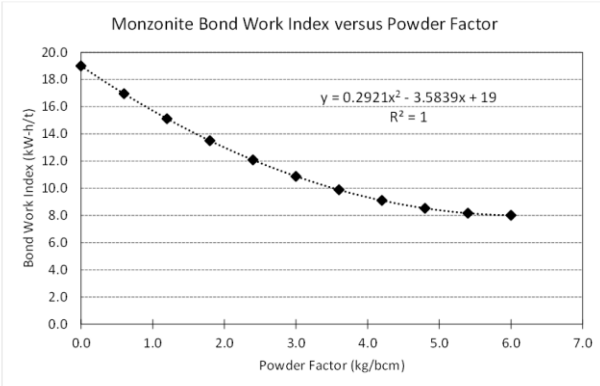

Figure 1: Monzonite Bond Work Index versus Powder Factor

The copper porphyry deposit used in this case study is monzonite with an in-situ BWI of 19 kW-h/t. Figure 1 exhibits the empirical relationship between BWI and blasting intensity (powder factor, kg/m^3).

Increasing blasting intensity "softens" the rock fragments, postulated to be via lattices of shock induced micro-cracks. Beyond 4 kg/m^3, the test data indicate diminishing returns from further energy input.

Figure 2 illustrates that most of comminution circuit unit energy reduction arises from this "softening" effect rather than size reduction.

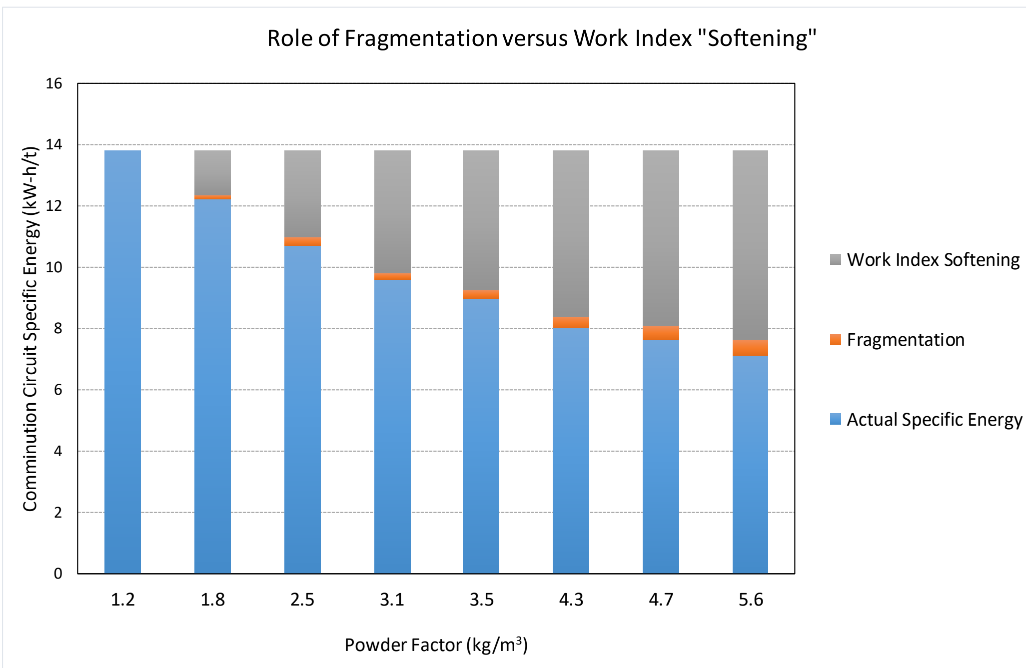

Figure 2: Contributions to comminution specific energy reduction

The leverage of blasting intensity on Mine-to-Mill optimisation is well known and commonly practiced by miners who understand its utility and are not constrained by functional silo KPIs such as minimising mining costs to the exclusion of all other considerations. Nevertheless, there are practical constraints on how far blasting intensity can be increased due to safety constraints from fly-rock and ground vibration impacts on neighbours. Conventional blasting practice does not exceed a powder factor of 2 kg/m^3 and few mines operate near that maximum. Most hard rock blasting operations would not exceed 1 kg/m^3.

Orica Mining Services has designed two techniques for safely executing Ultra-High Intensity Blasting (UHIB) up to powder factors of 4 kg/m^3 and beyond. These UHIB designs have been tested in production trials at mines in Chile and Mexico at powder factors up to 3 kg/m^3.

The trial in Mexico employed UHIB in a design known as "Pre-conditioning" where high intensity blasts are extended into the bench below via a much deeper sub-drill, to the usual stemming depth. This pre-blasted layer acts as a blanket to contain the energy of the next bench blast and fragments the usually coarse stemming zone that occurs in conventional blast design. Basic design features of conventional and Orica's UHIB Pre-condition method are described by the diagrams below.

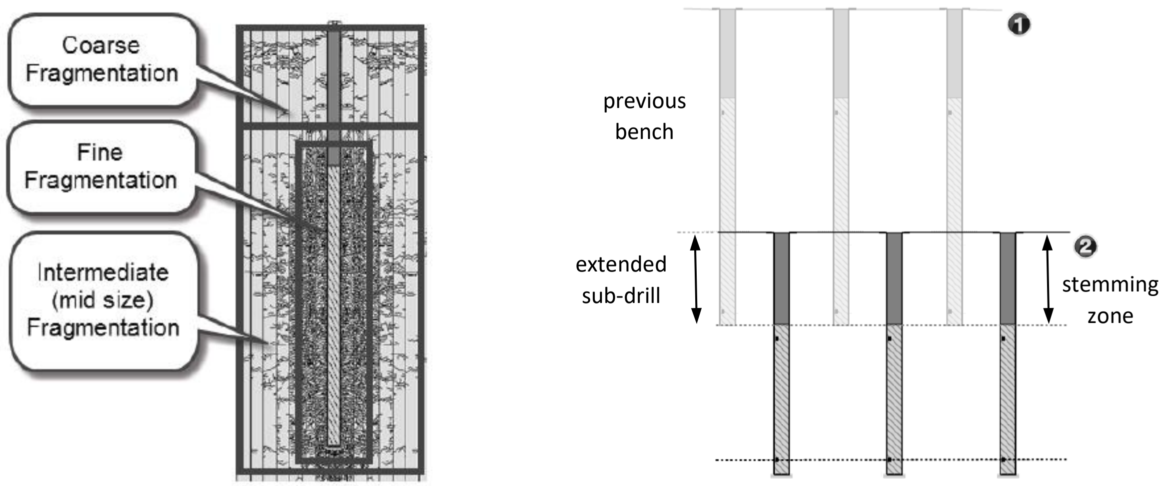

Figure 3: Conventional Blasting (left) and Pre-condition Ultra High Intensity Blast (right)

A consistent set of unit costs, labour and equipment productivity have been employed to generate Mine-to-Mill cash costs over a broad range of blasting powder factors, illustrated in Figure 4.

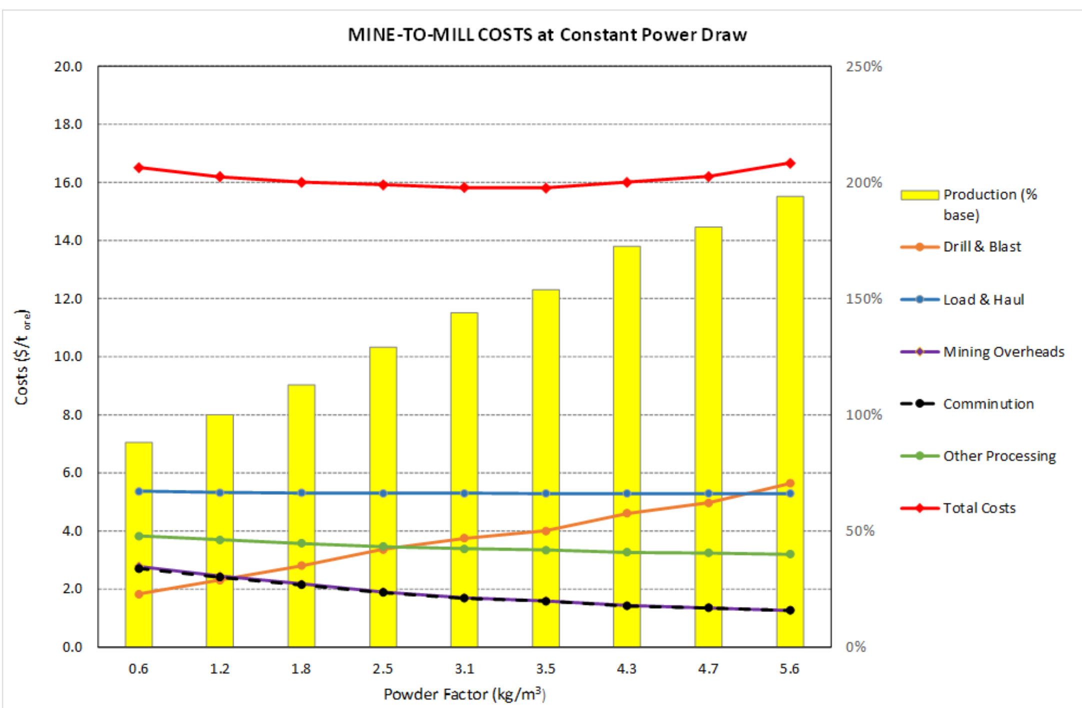

Figure 4: Mine-to-Mill cost build up at constant power draw

The cost profiles for each unit operation have been built on the assumption of operation at a constant comminution power draw limit, with blasting energy facilitating increased mill feed rate at the fixed power draw. Figure 4 highlights the trade-off between increasing drill and blast costs and decreasing unit costs of comminution and other fixed processing. The integrated operation's unit costs are quite constant at A$16.0±0.2/tonne $_{ore}$, (US$12.0/t) while debottlenecking mill ore capacity by up to 40-50%.

1.3 Whittle Consulting Optimisation Methodology

Whittle Consulting are specialists in Integrated Strategic Planning for the mining industry. A team of highly experienced industry specialists, they are dedicated to adding value to mining businesses.

With technical expertise in a range of disciplines including geology, mining engineering, metallurgy, research, mathematics, computing, finance, operational/ financial modelling and analysis, Whittle Consulting has a thorough appreciation of practical, organisational and contextual reality of mining operations. As experts in embracing and harnessing complexity, Whittle Consulting often identifies opportunities that are not readily apparent using traditional strategic mine planning methods.

Since 1999, Whittle Consulting has conducted over 150 Whittle Enterprise Optimisation (EO) studies around the world. These studies repeatedly demonstrated that the disciplined application of Whittle Integrated Strategic Planning and the concepts from the Money Mining & Sustainability Seminar, improves the economics of a mining project or operation by 15%, and in many cases substantially more. These results are achieved even when conventional mining optimisation has been completed prior.

Whittle Consulting operates worldwide and is represented in Australia, United Kingdom, United States of America, Canada, South Africa, Chile, Peru and Indonesia.

Enterprise Optimisation (EO) is a methodology for maximizing the life of mine value of mining and mineral processing assets, using net present value (NPV) as the metric that is maximized. The technique involves simultaneous optimisation of the entire mining value chain from the mineral resource through to the end product market. EO employs the economic principles of the Theory of Constraints (TOC) and Activity Based Costing (ABC), and utilizes the proprietary Prober® E software of Whittle Consulting.

EO involves simultaneously optimizing all ten steps in the value chain shown in Figure 5.

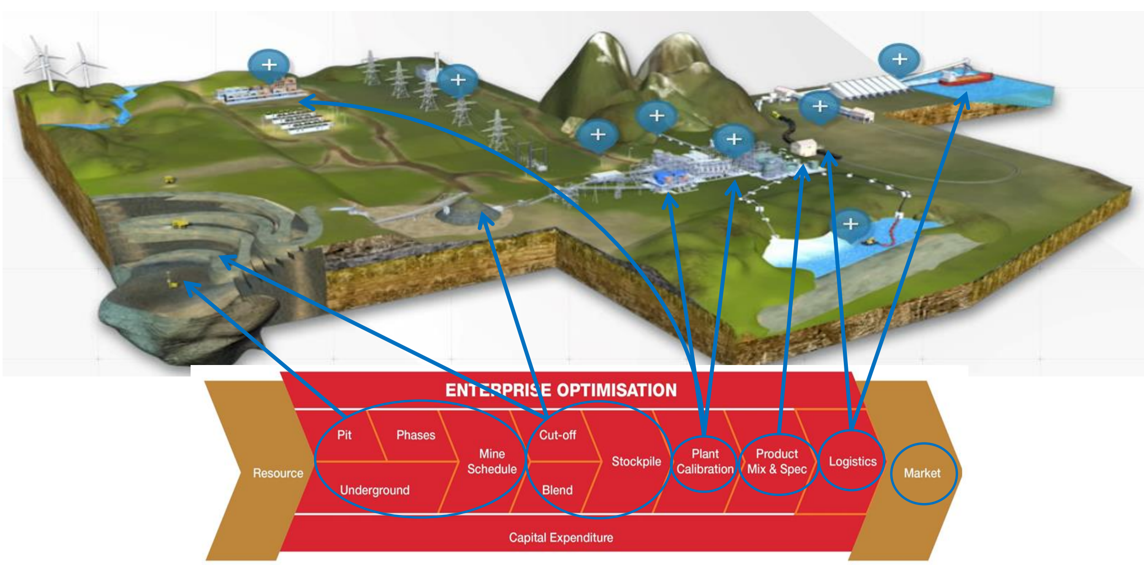

Figure 5: Mining and mineral processing value chain

An EO assessment consists of three stages;

1. The Base Case in which the existing Life-of-Mine plans and performance characteristics of the enterprise are used to calibrate the EO model;
2. The Optimised Case in which the enterprise is mathematically optimized using the same structure, limitations and parameters as the Base Case, by employing the 10 Whittle sequential optimisation steps:
    1) Whittle pit optimisation using Geovia Whittle software
    2) Phase (pushback) optimisation for early access to high grade ore while maximizing deferral of waste movement
    3) Mine schedule sequence and rate of production optimisation
    4) Application of variable cut-off "grade" using Ken Lane's theory applied to cut-off defined as Net Value per Bottleneck Unit, rather than metal grade
    5) Use of stockpiles for lower grade ore mined early in life, processed later
    6) Simultaneous optimisation of Steps (1) to (5), and subsequent steps
    7) Blending and processing optimisation of ore types and process options
    8) Product grade, throughput, grind size and recovery optimisation of payable metal production through the available process options
    9) Logistics optimisation in circumstances where downstream logistics may be the constraint on cash flow and project value.
    10) Capital to de-constrain the enterprise economic bottleneck (not used in this study's model runs)
3. Assessment of Scenarios in which other potential degrees of freedom are tested.

In this case study where the model does not require calibration to existing mine plans and facility performance, the Optimized Base Case forms the foundation for assessing the effects of variation in blasting intensity. EO runs that were conducted to develop the Optimized Base Case are not reported in this document. Only the Optimized Base Case (designated Case 8A) is reported and discussed together with the scenario cases that progressively tested increased blasting intensity. The final scenario that was assessed (designated Case 9B) represents the optimized enterprise employing variable high intensity blasting.

Enterprise Optimisation methodology is anchored in the following principles;

1.3.1 Time Value of Money

A mining operation will typically have a life of decades. A methodology for optimizing the operation's value must take account of the time value of money. Cash today is more valuable than the same quantity of received cash in ten years' time. Whittle's optimisation algorithm discounts future cash flows to generate a Net Present Value (NPV) that is used to directly compare alternate scenarios.

1.3.2 Theory of Constraints

The Theory of Constraints (TOC) is a management philosophy originated by Eliyahu M. Goldratt in the 1980s, that has been widely applied in the manufacturing industries. It draws upon methodologies such as the Critical Path Method, System Dynamics and Program Evaluation and Review Technique. TOC's primary tenet is that an enterprise which is managed to a goal, such as maximizing cash flow, is limited by constraints. A very small number of the system constraints, often just one, act as the bottleneck that limits overall output, such as cash flow. Relaxation of that constraint can debottleneck the system's output until another bottleneck is encountered.

In mining enterprises, the common constraints are process plant capacity, mining tonnage, processing concentration, vertical rate of advance, stockpile or dump size, power or water supply limits, and product specification or environmental emission limits. In a system that has been optimized the primary bottleneck ought to be the constraint that has least ability to change. In mining, this is usually the most capital-intensive part of the operation such as the SAG/Ball mill or the shaft in underground mines. In some circumstances it can be externally imposed, for example the total emissions into an airshed. Frequently mining rate is one of the easiest constraints to debottleneck, because discrete units of mining capacity (mobile equipment) can be obtained by leasing or for relatively small capital compared to new plant expansions. In some cases, downstream markets can impose a constraint on output of commodity products for an individual mine.

1.3.3 Activity Based Costing

Enterprise optimisation has an essential requirement that all resource consumption costs are allocated to the physical activity that drives that resource being consumed. Only cash costs are considered with accounting considerations of depreciation and amortization being excluded, as they are in all NPV cash flow analysis.

All costs must be segregated into variable (attributable) costs that are incurred per unit of resource consumed, and period costs which are absolute amounts incurred as a fixed cost for a certain time period to keep an activity operating. For example, typical variable costs are consumption of diesel fuel and routine maintenance spares per tonne (or bcm) of waste rock or ore loaded, or consumption of diesel and tyres per tonne-kilometre of material hauled.

If a permanent workforce is employed and a mining rate of say 60Mt p.a. is planned for the coming year, then the A$30 million annual cost of operating labour required to man the 60Mt p.a. mining fleet, is a period cost. The period cost would change if an 80Mt p.a. mining rate and fleet were planned in a subsequent period of time. Period costs are "consumed" by time, rather than by mineral resource consumption.

1.3.4 Optimisation Software – *Prober®*

Whittle Consulting utilizes its proprietary Prober software to implement modelling and optimisation of a myriad of complex elements and inter-relationships in a mining business. Prober models the mining and processing operations from inputs through to end markets, with the modelled solution optimized to maximize NPV, produced by a schedule that demonstrates the cash flow and material paths through the system over the mine's life. The enterprise may be comprised of multiple mines and processing plants in dispersed geographies that inter-relate through physical assets or markets.

As it is not practical to provide entire block models as direct Prober inputs, aggregation into parcels of like materials by rock type (oxide/sulphide, domain, geometallurgy) of similar net values (including period cost allocation for use of a bottleneck) occurs upstream of input. In open-pit mines, the mining shape selection (pits and phases) are sized using Geovia Whittle pit optimisation software by a skilled mine planning engineer based on the assumption of probable outcome (in particular for this model, of what powder factor and grind size is most likely used). Initially some iteration between the two optimizers is necessary as Prober® is used to explore probable outcomes which is then used to inform pit design. Underground stope designs, shapes and sequences employ a similar approach with other software.

2 METHODOLOGY

Whittle Consulting's Enterprise Optimisation has the ability to model and mathematically optimise a mining enterprise with all the above drivers, to support the development of a strategic business planning and scenario based assessment of Ultra High Intensity Blasting. The Enterprise Optimisation follows a 10 step methodology as shown in Figure 6.

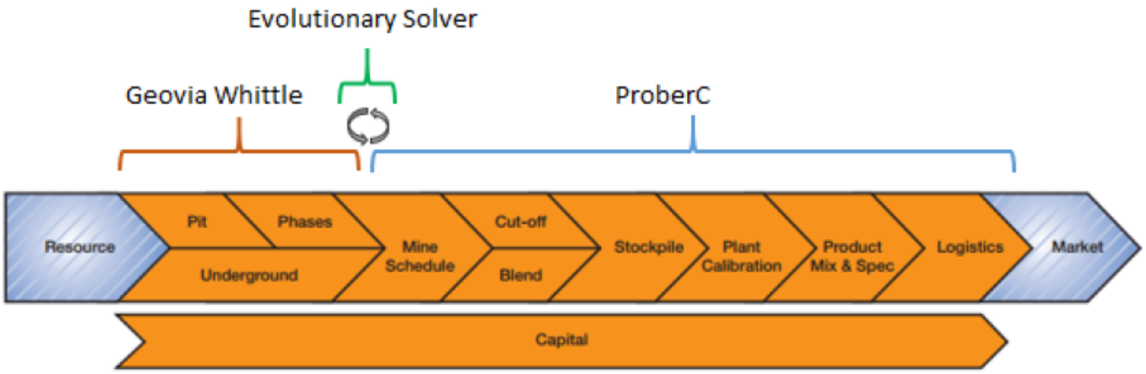

Figure 6: Enterprise Optimisation methodology 10 steps

2.1 BUSINESS OPTIMISATION MODEL

The Whittle Enterprise Optimisation process starts with the construction of a Business Optimisation Model document and file. The purpose of the Business Optimisation Model is threefold;

The first objective is to document the structure and specifics of a mining operation in a way that fits with Prober®'s conceptualisation of a mining operation. A flow diagram showing material movements through the operation is drawn. The Business Model is a spreadsheet representation of that flow diagram.

The second purpose of the Business Model is to model the flow of material through the system such that the material data (e.g. rock mass, mineral masses, rock type) can be entered and the output materials and monetary flows through all procedures are calculated. In this respect the Business Model is not only a descriptive document but also a functional component of the system model's design.

The Business Model has a third purpose which is to present the process of how an operation has been modelled, so as to facilitate validation and troubleshooting.

2.2 PITS AND PHASES

Geovia Whittle takes as input a block model representing the physical ore body. While the software package provides some capability to specify a business model through a user interface, Whittle Consulting instead pre-calculate the mining costs, processing costs and revenues for each block in the block model. This is done by inputting, via an automated process, each block into the Business Optimisation Model with a single specified processing path chosen for that block based on a set of rules and likely operating conditions and constraints at the time the block is to be extracted.

Geovia Whittle is then invoked, with some additional parameters such as maximum slopes and minimum mining widths if necessary, to size the pit. Other functions produce outcomes that are purely optimal when taking into account multi-path processing systems, multi-pit mines and discounted cash flows. An experienced Mine Planning Engineer may use manual techniques to try to further improve the outcome.

The pit and phases created are then exported from Geovia Whittle as pit-list and shape files.

2.3 Prober Optimisations

Prober® accepts an input text file that follows a specific syntax and grammar. Whittle Consulting build this file using the automation of another spreadsheet termed the Prober® Input sheet. This contains a more formal definition of the structure of the model than the Business Model spreadsheet. However, it typically references the Business Model sheets directly for material input/output calculations.

Prober® accepts the input file, checks validity and then proceeds with the simultaneous optimisation of schedule, cut-off, stockpiles, logistics and product mix. Prober® is implemented as a combination hill-climbing algorithm to find solutions obeying the sequencing rules, with calls to a nested linear programming package for all downstream systems.

Prober® runs not as a single optimisation but as multiple samples that each return their own schedule and resultant NPV. Each sample starts with a different initial random seed and completes when a local optimal point is reached. A local optimum is no guarantee of global optimality, so hundreds or thousands of samples may be run for each specific set of parameters until an acceptable level of convergence between results is achieved. An example, showing for Case 9C the gross NPV in Prober before manual adjustments such as period cost addition for each sample, sorted in ascending gross NPV order, is shown in Figure 7.

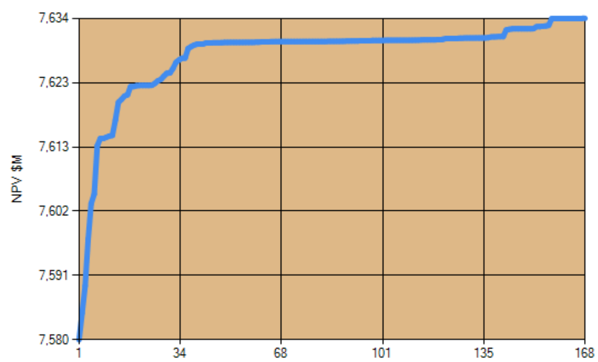

Figure 7: Sample convergence of 168 samples run in Prober for Case 9C

The output from Prober® is a text file that specifies all movements of material and cash over the life of mine. This information is imported to a data base which is then used to create spreadsheet reports.

3 MODEL & CASES

All mining operations differ in their geological character, cost structure and constraints. The potential benefits from employing variable blasting powder factor including in the UHIB range, will vary from case to case. Limited industrial operating trials of mine-to-mill optimisation have been reported in detail and the early UHIB trials were similarly brief on integrated performance benefits. This report examined the role of UHIB and mine-to-mill techniques through a series of case studies within Whittle Consulting's Enterprise Optimisation methodology using its Prober® optimiser software.

A hypothetical, yet realistic case study model of an open cut copper porphyry was built in which the effects of variable blasting intensity could be evaluated. The case study deposit, known as *Marvin*, is a well-known hypothetical deposit that has been employed by Whittle Consulting and others for such studies. The deposit and its geographical context are similar to the Cadia Hill mine in western NSW. The components of the model are an ore body (as a block model), a mining model, a processing model, and a financial model. The Prober® model was built and then fully optimised using the full suite of 10 optimisation steps (other than incremental capex). That Base Case (Run 8A) was then provided with the opportunity to employ variable blasting over steps in powder factor from 1.2 kg/m^3 to 4.7 kg/m^3.

3.1 GLOBAL SETTINGS

Global economic and unit operations settings are contained in Appendix 2.

3.2 CASES

A series of preliminary runs were conducted to test the Prober® model, validate the inputs and complete assurance on the outputs using the full Enterprise Optimisation 10 step process. Following the satisfactory completion of those preliminary runs, the following matrix of cases was run:

<table>
<tr><th>Powder Factor (kg/m^3)</th><th rowspan="2">1.2</th><th rowspan="2">1.8</th><th rowspan="2">2.5</th><th rowspan="2">3.1</th><th rowspan="2">3.5</th><th rowspan="2">4.3</th><th rowspan="2">4.7</th></tr>
<tr><th><u>Mining Rate</u></th></tr>
<tr><td>60Mt</td><td>Run 8A</td><td colspan="6">Higher PFs not available</td></tr>
<tr><td>60Mt</td><td colspan="3">Run 8B</td><td colspan="4">Higher PFs not available</td></tr>
<tr><td>60Mt</td><td colspan="5">Run 8C</td><td colspan="2">PFs not available</td></tr>
<tr><td>60Mt</td><td colspan="7">Run 8D</td></tr>
<tr><td>70Mt</td><td colspan="7">Run 9A</td></tr>
<tr><td>80Mt</td><td colspan="7">Run 9B</td></tr>
<tr><td>90Mt</td><td colspan="7">Run 9C</td></tr>
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Table 1: Prober optimisation run matrix

3.3 Ore Body

The *Marvin* ore body used in this assessment is a realistic copper-gold porphyry created by geologist Norm Hanson over a decade ago for the purposes of case studies. *Marvin* exhibits higher gold grades at shallow elevations and higher copper grades at deeper elevations, as displayed in Figure 9. Resource block model grade/tonnage semi-log curves versus cut-off grade are provided in Figure 8 for copper and gold.

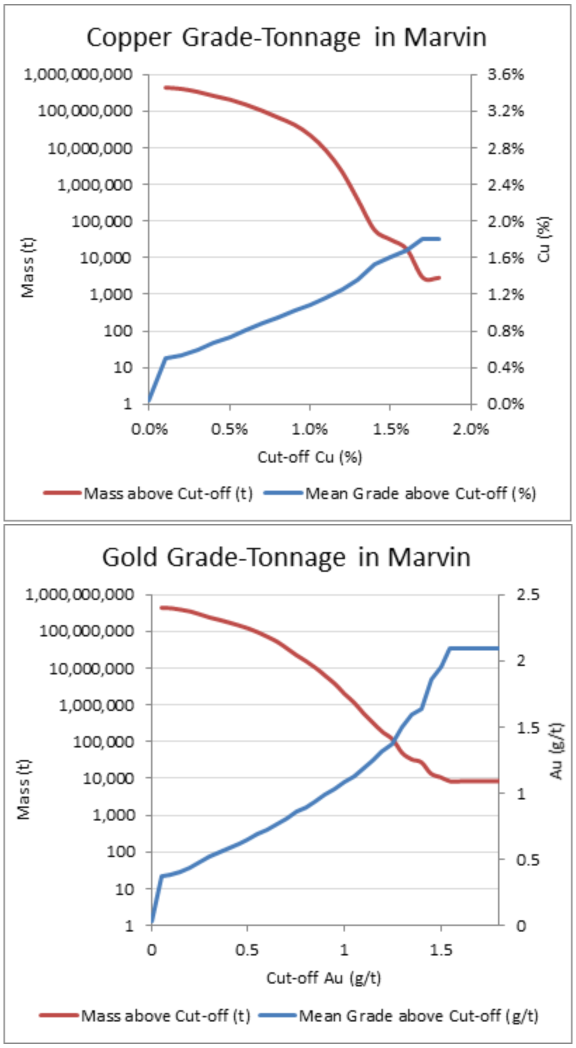


Figure 8: Grade Tonnage Curves

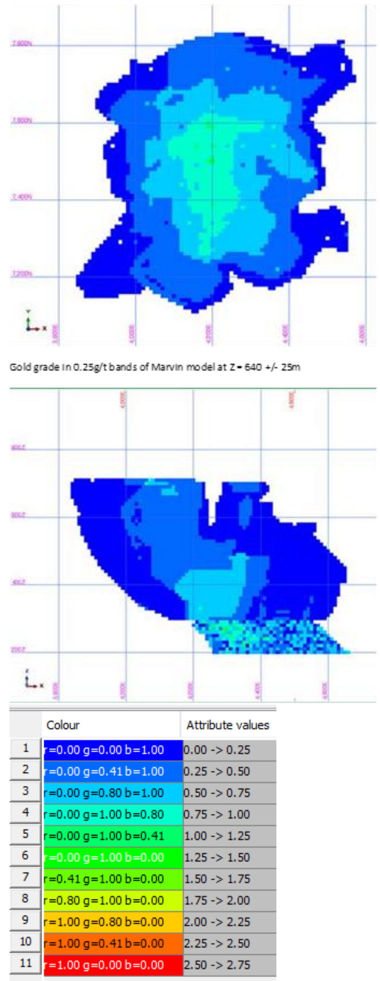


Figure 9: Marvin Ore Body Grade Plots

"Cut-off grades" presented in isolation in each grade/tonnage curve above are in practice optimized together during Enterprise Optimisation.

The ore body contains oxide, transition and fresh (sulphide) zones that behave differently in terms of their metallurgical and physical (hardness) characteristics. The entire resource block model tonnes and grade by ore type are summarised in Table 2 below. Only a portion of the ore body that is described by the block model, is mined as ore or waste.

Rock Type	**Mineral Type**	**Quantity** (Mt)	**Contained Cu** (kt)	**Contained Au** (k oz)	**Cu grade** (%)	**Au Grade** (g/t)
Waste	waste	4,139	-	-	-	-
Ore	sulphide	45	199	388	0.44	0.27
Ore	sulphide	192	900	1,962	0.47	0.32
Ore	transition	88	546	1,387	0.62	0.49
Ore	transition	85	505	1,114	0.59	0.41
Ore	oxide	9	25	151	0.28	0.52
Ore	oxide	17	44	215	0.26	0.40

Table 2: Marvin Ore Body Resource Block Model Summary

3.4 Optimised Base Case

The Base Case model consists of the ore body, a mining procedure, stockpiles, a Heap Leach and a Processing Plant consisting of a SAG Mill, Ball Mill and Flotation Circuit. Crushing occurs upstream of the Heap Leach and Processing Plant. Figure 10 describes the model flowsheet.

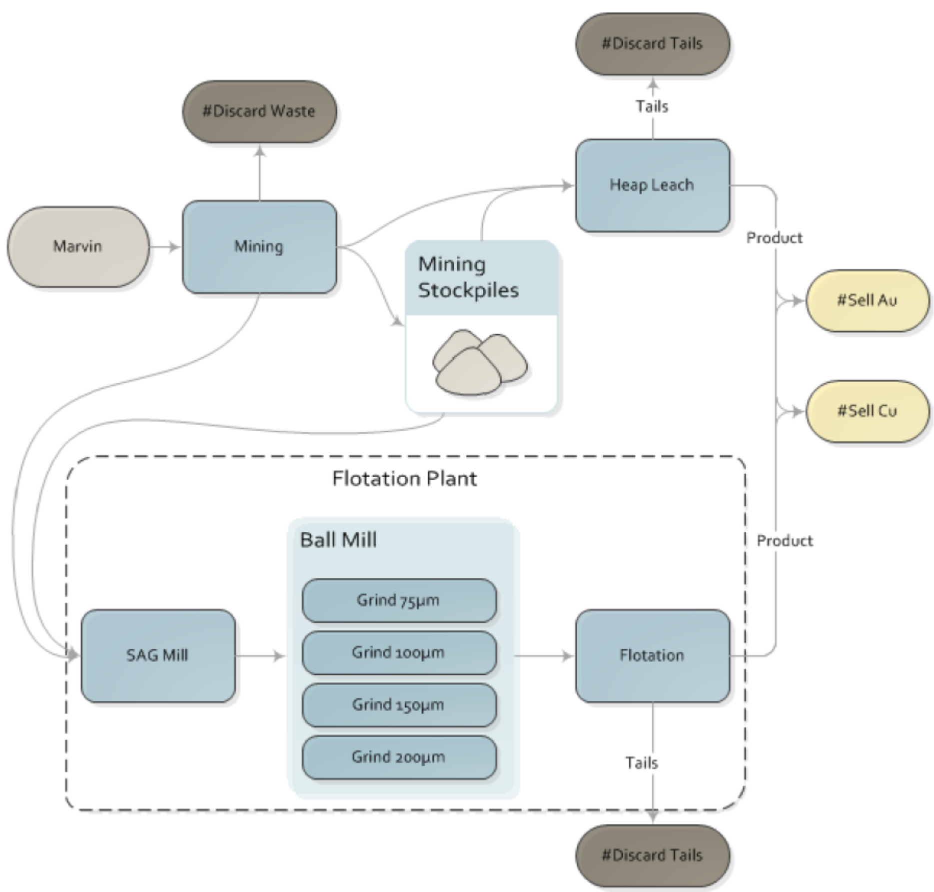


Figure 10: Prober® flowsheet for Base Case

An initial optimized base case (Run 8A) was conducted with blasting powder factor fixed at 1.2 kg/m^3 for all ore except leach-destined Oxide which could be blasted at 0.6 kg/m^3. Waste was blasted at 0.6 kg/m^3 in all runs. All of the Whittle Consulting simultaneous optimisation drivers described in Figure 6, except incremental capital, were employed.

Base case settings are summarised in Appendix 1.1.

Variable mining costs for waste and ore are respectively A$1.30/t and A$1.91/t, plus an additional A$0.02/t per bench at deeper elevations. The mining cost model assumes an owner/miner strategy with leased mobile mining equipment. Total mining period costs are A$111M p.a. Increases in drill and blast activity at higher powder factors and for higher mining rates in Runs 9A-C, are represented as increased period costs for incremental operating labour and equipment lease costs with no capital expense.

The stockpile has a capacity of 10Mt and rehandled material incurs a cost of A$1/t. In Prober® stockpiling implicitly blends input materials with all other materials already on that stockpile.

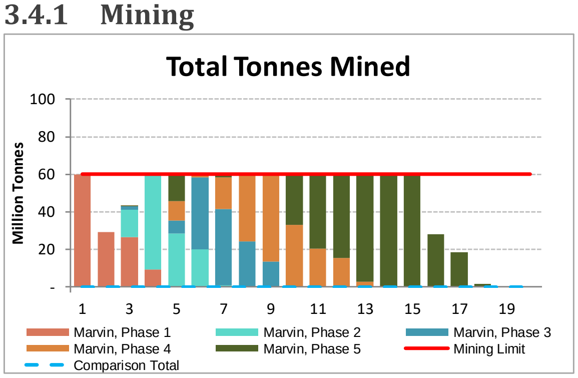
The Heap Leach is limited to 5Mt p.a. and has a variable cost of A$2/t and no period costs. Recoveries are set out in Appendix 1.1 by rock type, in "Heap Leach (Process)".

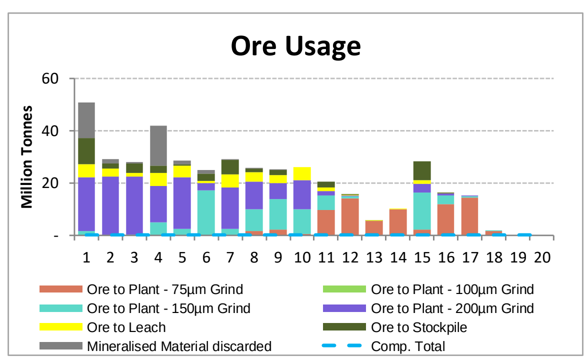
The SAG Mill, Ball Mill and Flotation processes are collectively termed the Processing Plant. The SAG plus Ball Mill and Crusher power draw limit of 277 GW-h p.a. is expected to be the primary bottleneck in the system. The optimiser may choose one of four final grind sizes for each input parcel of material. Coarser grinds incur lower power and steel grind media costs (and reline costs) while having a lower metal recovery. Finer grinds achieve a greater recovery in the Flotation procedure but incur a higher cost of consumption of power and steel media. These recovery/cost/grind size interrelationships are detailed in Appendix 1.1.

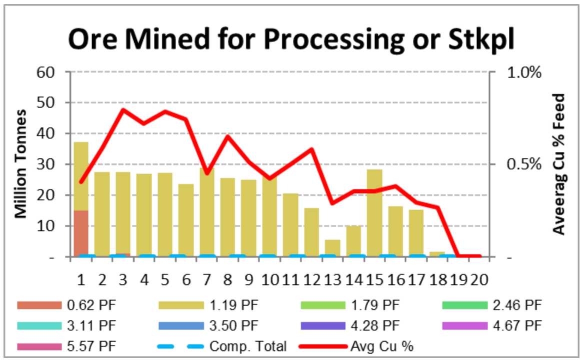
The Flotation procedure recovers gold and copper at a rate that is dependent on the rock type and the input particle size. Whittle Consulting commonly refers to this relationship as the Grind-Throughput-Recovery (GTR) curves. Those rock types and grinds that require greater power input in the SAG/Ball Mill also yield a greater recovery in the flotation circuit, which gives the optimiser a balance to strike. The relationship between grind size and recovery is detailed in Appendix 1.1 in "Flotation (Process)".

Optimised Run 8A outputs are presented in the series of graphs and commentary below through mining, processing and financial metrics.

3.4.1 Mining





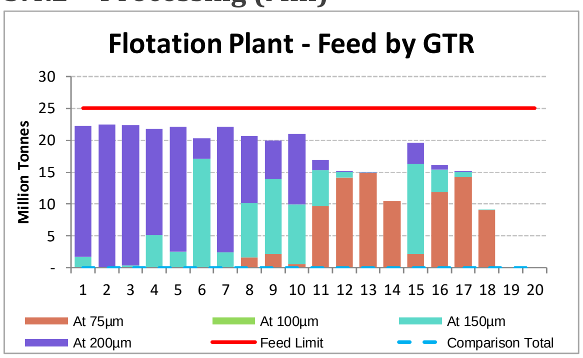


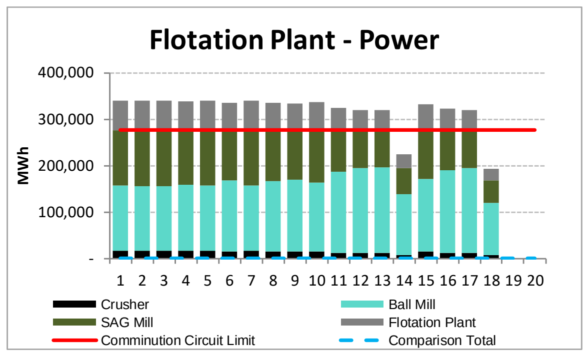
- Mined at maximum 60Mt except in Years 2 and 3 at initial low strip ratio and in oxide zone
- Copper grade maximized early in life
- Mill at capacity until Year 12
- Leach not fully utilized in all periods

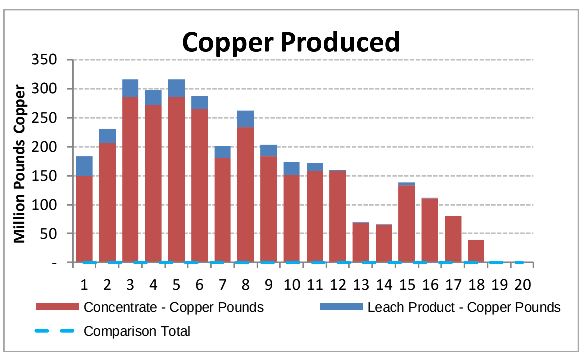
Figure 11: Base Case Run 8A – Mining rate and ore destination

Maximum grind size of 200µm dominates in the first five years in order to maintain production within the comminution power limit while harder ore is mined, sacrificing some metal recovery. As ore specific energy decreases, grind size is reduced to maximize recovery within the power limit.

3.4.2 Processing (Mill)







- Mill runs to power limit in all periods except two years near end of life
- Grind size progressively increased to utilize full power limit to maximize copper output and revenue
- Copper production brought into earliest period within power constraint

Figure 12: Base Case Run 8A – Processing metrics and copper production

3.4.3 Economic

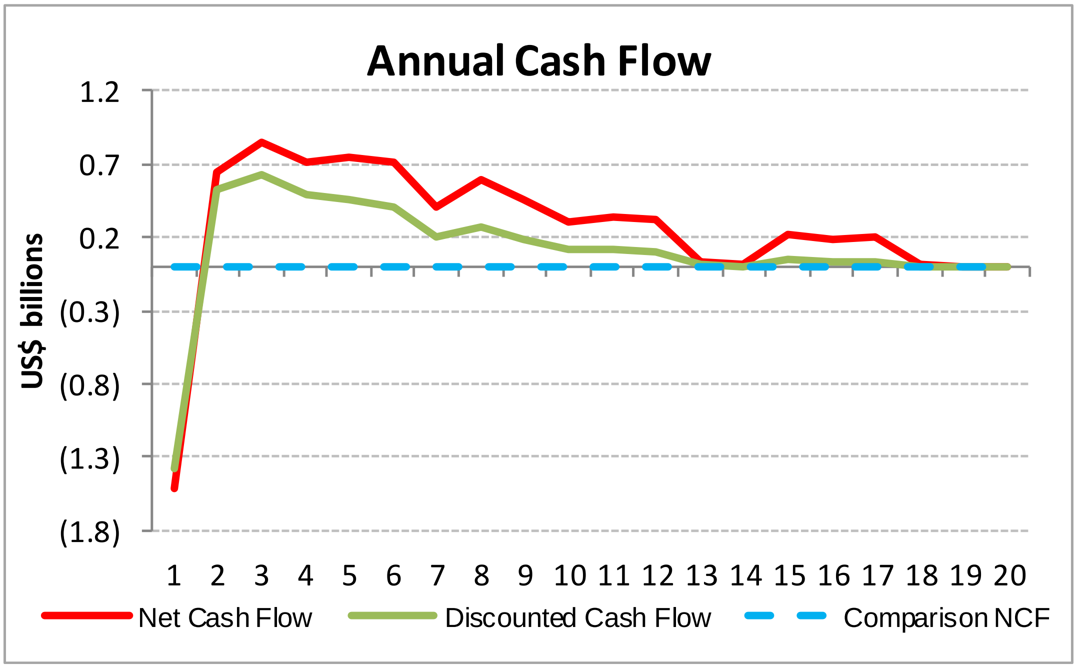


Figure 13: Run 8A – Life of Mine cash flow

Run 8A's NPV is US$2.29 billion from Life-of-Mine copper production of 1.50Mt. Comparisons of the subsequent UHIB scenarios are referenced to the production and cashflow outcomes of Run 8A.

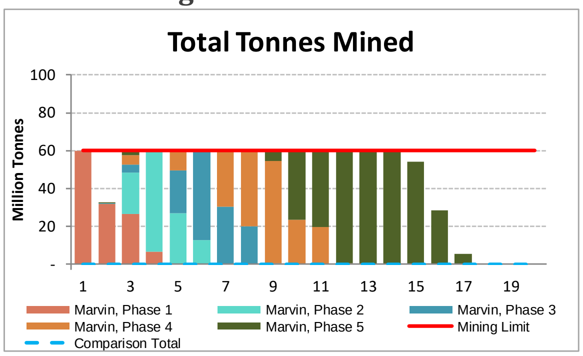
4 RESULTS

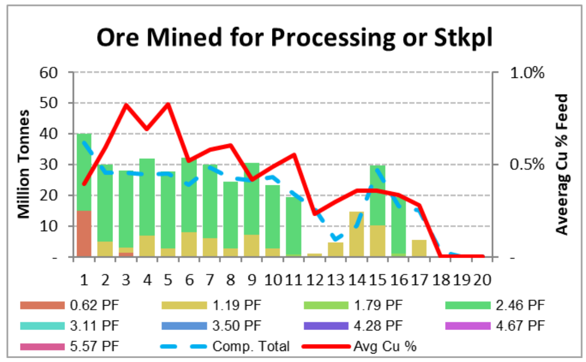
Assessment of the potential optimisation leverage that could be realised from increased blasting intensity was evaluated through stepped increases of powder factor above the optimised Run 8A Base Case that employed 1.2 kg/m^3. Runs 8B, 8C and 8D which are reported below progressively enable higher powder factors to be employed by Prober®, if chosen. A dashboard of standard Prober outputs is presented and discussed in sequence.

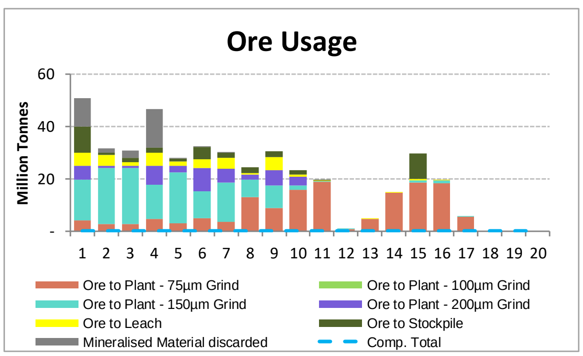
4.1 HIGH INTENSITY BLASTING – RUN 8B

In Run 8B powder factors up to 2.5 kg/m^3 were made available to Prober®.

4.1.1 Mining





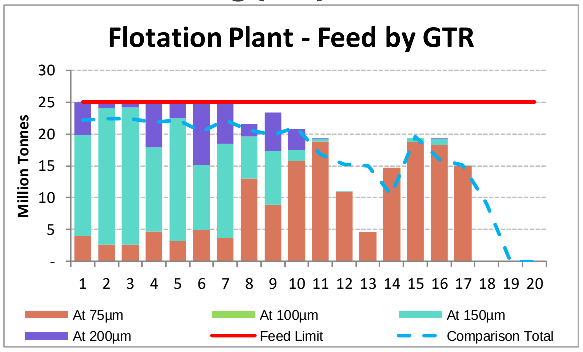


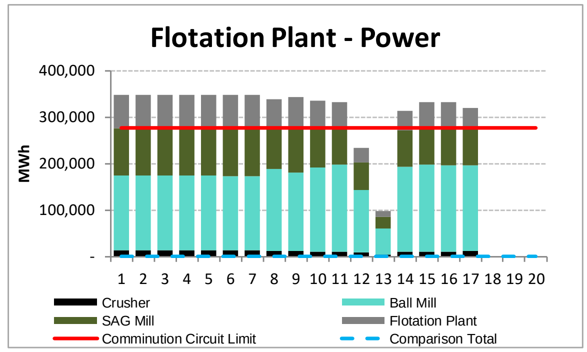
- Mined at maximum 60Mt except in Year 2 at initial low strip ratio and in oxide
- Copper grade increased in Years 2-5 versus Run 8A
- Loss of ore supply in Years 13 and 14 is mining limited, though still optimal
- Majority of ore blasted at maximum 2.5 kg/m^3 (maximum available)

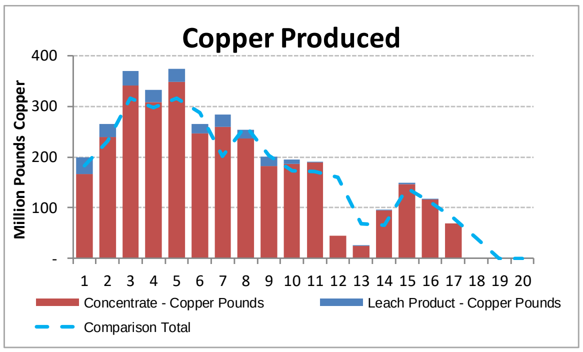
Figure 14: Run 8B – Mining rate and ore destination

Increasing the available blasting intensity de-constrained the mill ore feed rate at maximum power consumption. Prober® took advantage of that lack of constraint by increasing ore throughput to beyond 25Mt p.a. It has been assumed that beyond a 25% increase in feed rate to the flotation section (at 25Mt), reduction in residence time and pumping capacity limits would be likely to induce copper recovery loss. From Run 8B onwards a hydraulic limit of 25Mt p.a. was placed on feed to the flotation section.

4.1.2 Processing (Mill)







- "Comparison" data is from Run 8A
- Mill runs to power limit in all periods except two years when short of ore
- Average grind size stepped down to maximize recovery versus Run 8A
- Copper production brought forward from Years 12-13 to Years 3-7

Figure 15: Run 8B – Processing metrics and copper production

4.1.3 Economic

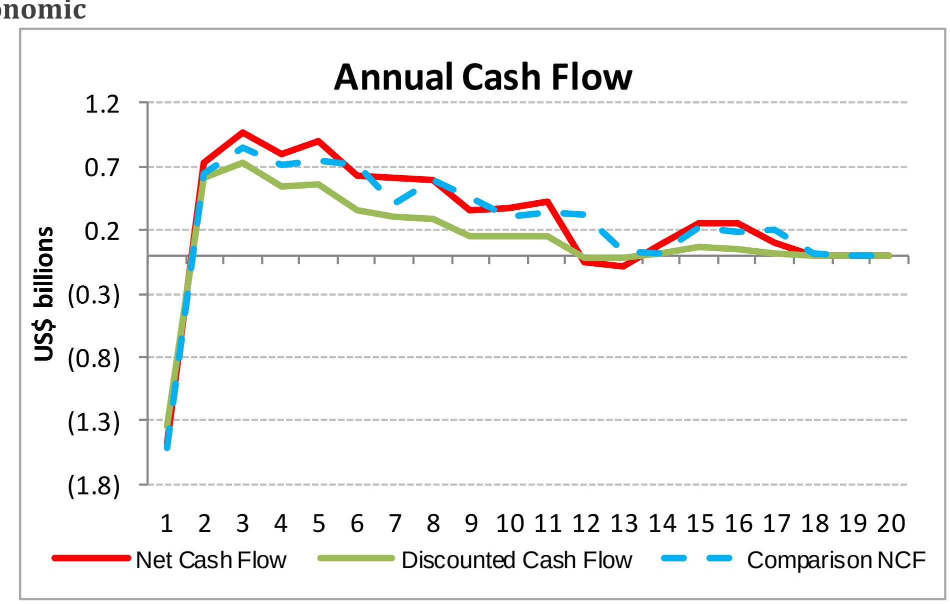


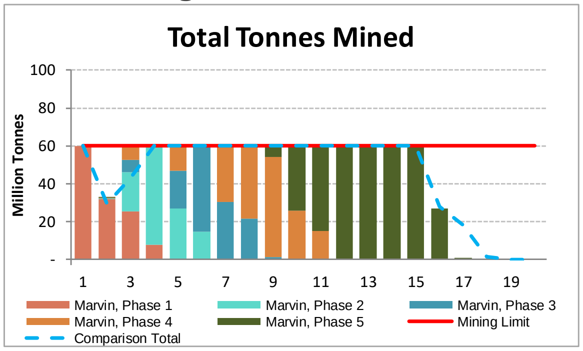
Figure 16: Run 8B – Life of Mine cash flow

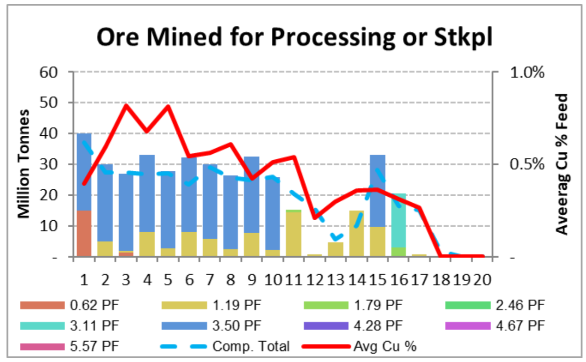
Run 8B's NPV is US$2.61 billion from Life-of-Mine copper production of 1.56Mt.

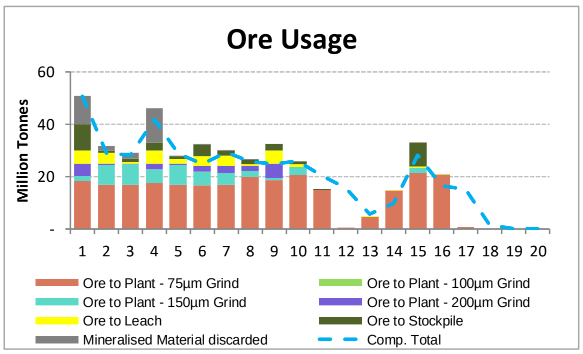
4.2 High Intensity Blasting – Run 8C

In Run 8C powder factors from 1.2 up to 3.5 kg/m^3 were made available to Prober®.

4.2.1 Mining





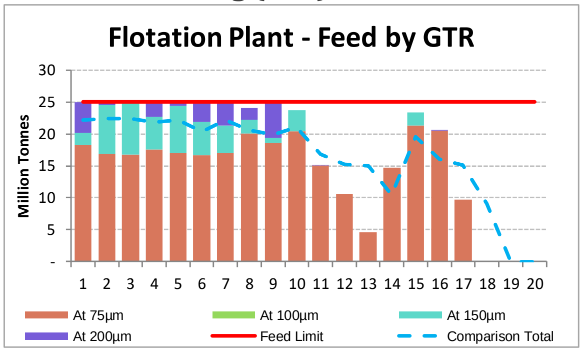


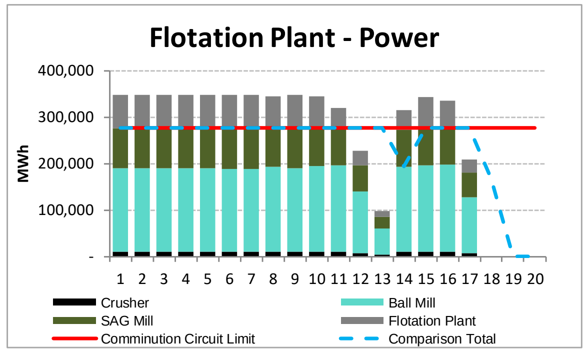
- "Comparison" data is from Run 8A
- Mined at maximum 60Mt except in Year 2 at initial low strip ratio and in oxide
- Copper grade maximized per Run 8A
- Loss of ore supply in Years 13 and 14 is mining limited, though still optimal
- Majority of ore blasted at maximum 3.5 kg/m^3 (maximum available)

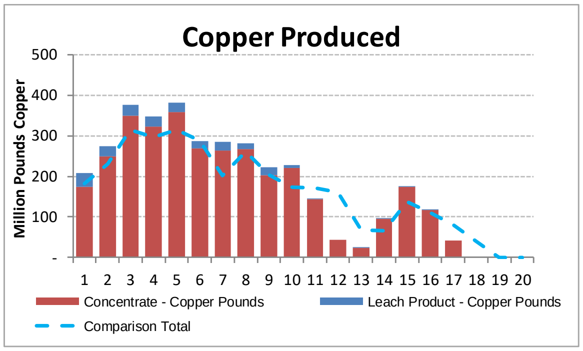
Figure 17: Run 8C – Mining rate and ore destination

Increasing the available range of blasting intensity to 3.5 kg/m^3 has been used by Prober® to considerably increase the average powder factor, although Prober® uses a mix of the maximum and minimum powder factors to optimize energy efficiency, cost and debottlenecking, rather than the full range of available blasting intensities.

4.2.2 Processing (Mill)







- "Comparison" data is from Run 8A
- Mill runs to power limit in all periods except two years when short of ore
- Average grind size is reduced with 75µm dominant, to maximize recovery
- Copper production brought forward from Years 12-13 to Years 3-7

Figure 18: Run 8C – Processing metrics and copper production

4.2.3 Economic

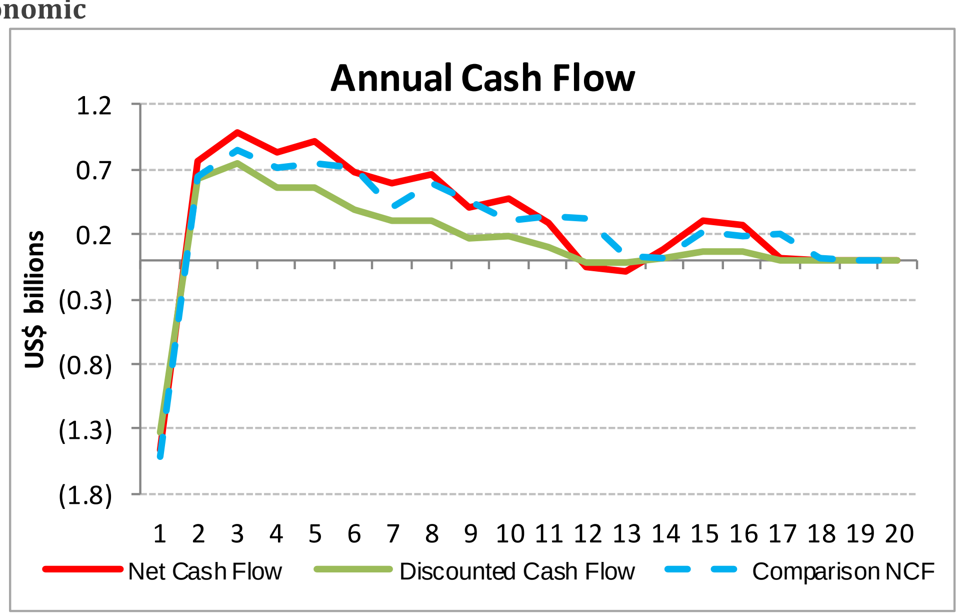


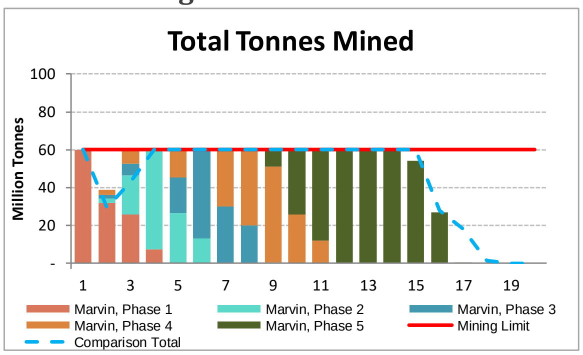
Figure 19: Case 8C – Life of Mine cash flow

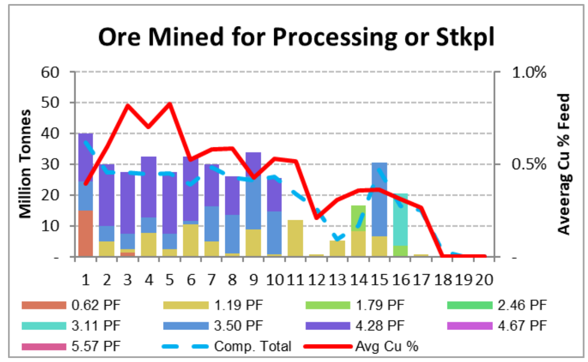
Run 8C's NPV is US$2.77 billion from Life-of-Mine copper production of 1.60Mt.

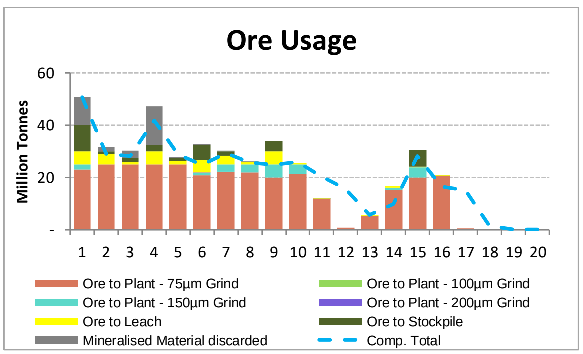
4.3 High Intensity Blasting – Run 8D

In Run 8D powder factors from 1.2 up to 4.7 kg/m^3 were made available to Prober®. A prior case (7C) with all powder factors up to 5.6 kg/m^3 being made available to Prober®, did not produce any incremental benefit. The maximum blasting intensity was not utilized by Prober®.

4.3.1 Mining







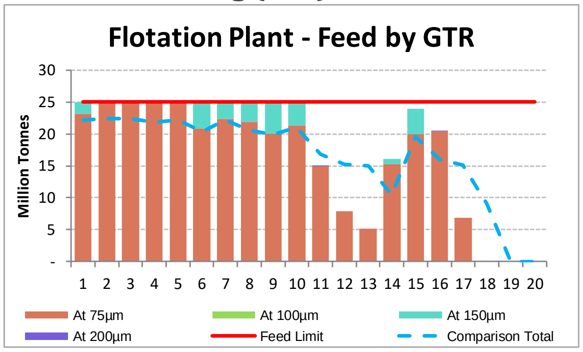
- Mined at maximum 60Mt except in Year 2 at initial low strip ratio and in oxide
- Copper grade maximized per Case 8A
- Loss of ore supply in Years 13 and 14 is mining limited, though still optimal
- Majority of ore blasted at maximum 4.3 kg/m^3 or less (not maximum available)

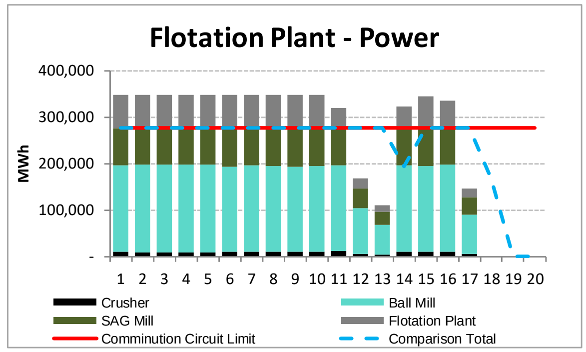
Figure 20: Run 8D – Mining rate and ore destination

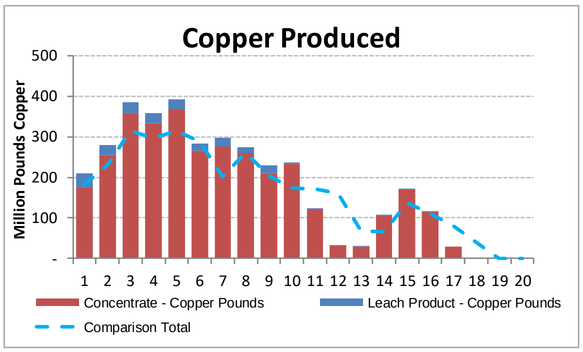
Increasing the available range of blasting intensity to 4.7 kg/m^3 has been utilized by Prober® to increase the average powder factor relative to Run 8C, although Prober® chose to employ a maximum powder factor of 4.3 kg/m^3 in combination with 3.5 kg/m^3 or less.

The total mining cost's apparent minimum point as depicted in Figure 4, occurs at powder factors between 3.1 and 3.5 kg/m^3 under conditions of constant power draw.

4.3.2 Processing (Mill)







- "Comparison" data is from Case 8A
- Mill runs to power limit in all periods except two years when short of ore
- Grind size of 75µm is heavily dominant, to maximize recovery
- Copper production brought forward from Years 11-13 to Years 3-7

Figure 21: Case 8D – Processing metrics and copper production

4.3.3 Economic

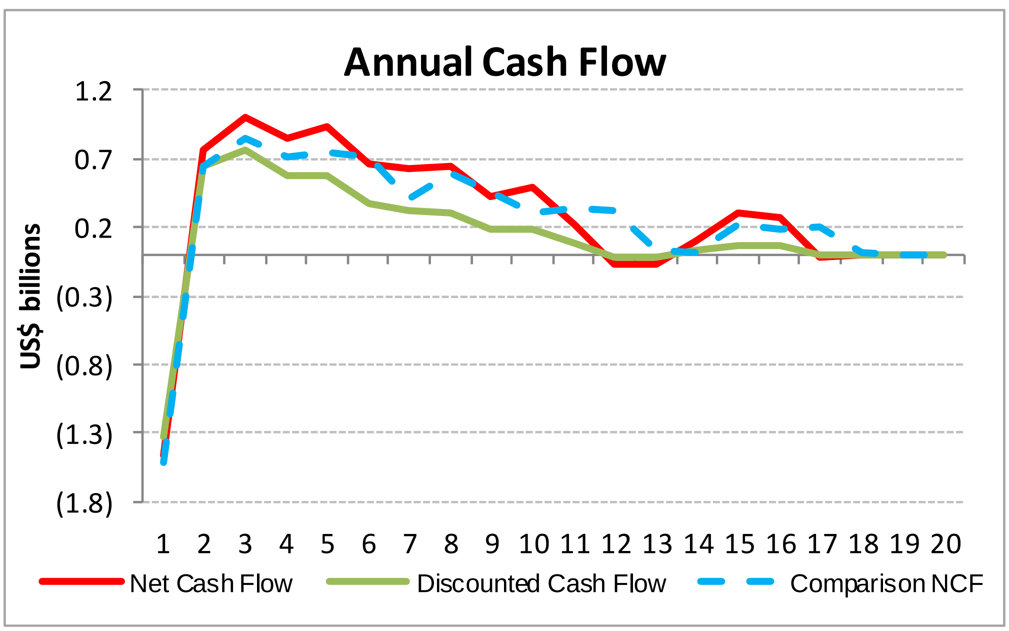


Figure 22: Case 8D – Life of Mine cash flow

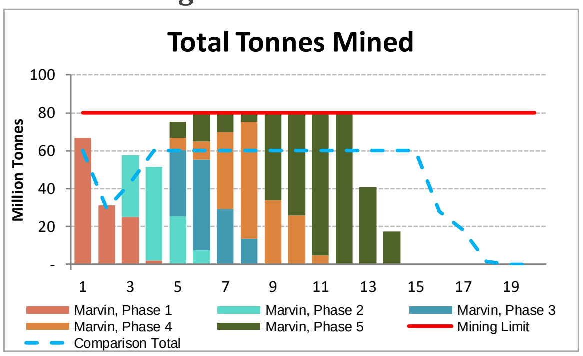
Run 8D's NPV is US$2.80 billion from Life-of-Mine copper production of 1.61Mt.

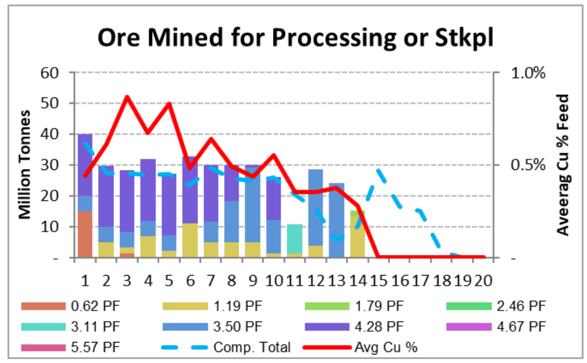
4.4 HIGH INTENSITY BLASTING – RUNS 9A, 9B AND 9C

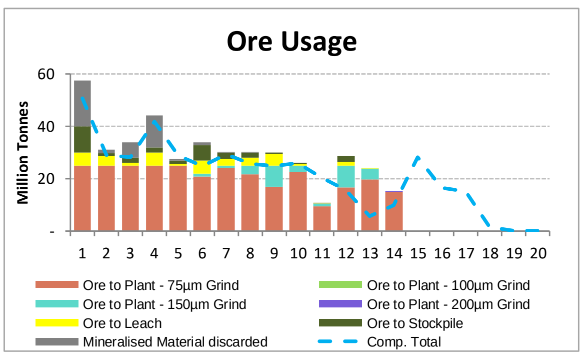
Runs 8A-D were constrained by the available mining rate. In order to quantify the impact of releasing that constraint, a further set of runs was conducted at mining rate limits of 70Mt (Run 9A), 80Mt (Run 9B) and 90Mt (Run 9C).

Relative to Run 8D's NPV of US$2.80 billion the above three runs produced NPVs of US$2.87 billion, US$2.89 billion and US$2.87 billion respectively. The results for Run 9B (the NPV maximum) are provided below. Run 8A results are used as the comparator.

4.4.1 Mining





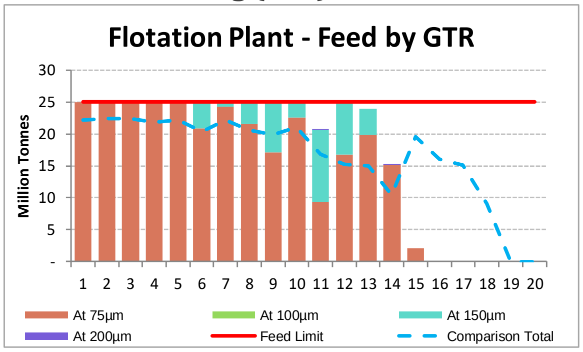


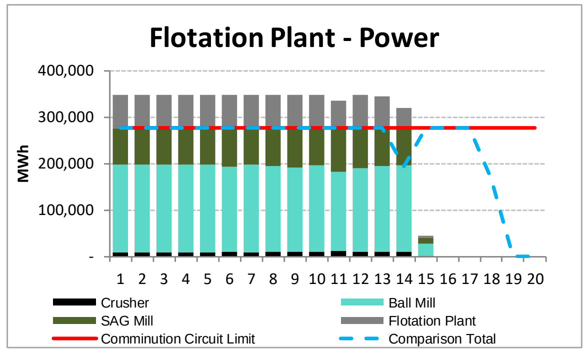
- Mined at maximum 80Mt in Years 5-12
- Copper grade maximized per Runs 8A-D
- Reduced ore availability only in Year 11 and at end of life
- Majority of ore blasted at maximum 4.3 kg/m^3 or less (not maximum available)

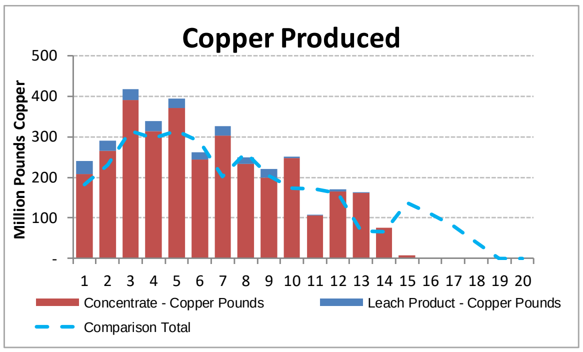
Figure 23: Case 9B – Mining rate and ore destination

Mine life had previously reduced from 18 years in Run 8A to 17 years in Runs 8B-D. In Run 9B the higher maximum mining rate has enabled mine life to be reduced to just over 14 years for the same life of mine copper output. The profile of powder factors is very similar to that employed in Run 8D.

4.4.2 Processing (Mill)







- "Comparison" data is from Run 8A
- Mill runs to power limit in all periods
- Grind size of 75µm is heavily dominant, maximizing recovery
- Copper production brought forward from Years 11-18 to Years 1-10

Figure 24: Run 9B – Processing metrics and copper production

4.4.3 Economic

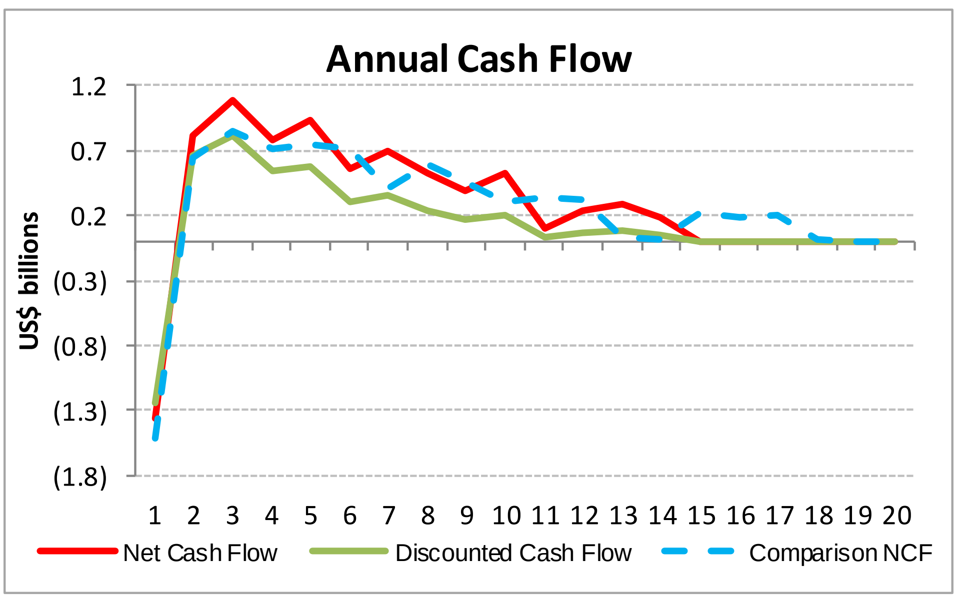


Figure 25: Run 9B – Life of Mine cash flow

Run 9B's NPV is US$2.89 billion from Life-of-Mine copper production of 1.59Mt.

Utilization of high intensity blasting to debottleneck *Marvin*'s processing power limit increased the mine's NPV by US$0.60 billion or 26%. Copper production increased by 6% while Life-of-Mine CO_{2e} emissions in the final 3 years of the original mine life have been eliminated, a 17% reduction. Figure 26 illustrates the emission patterns.

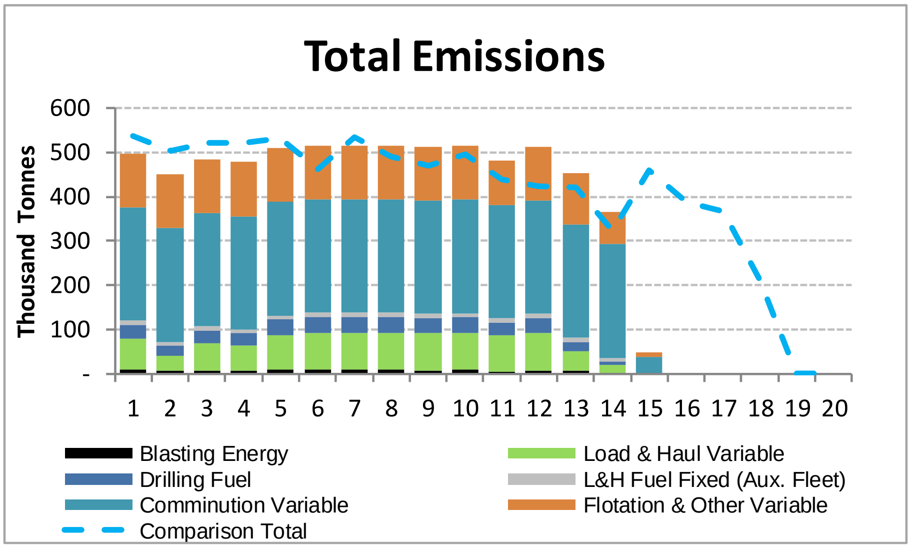


Figure 26: Life of Mine GHG emissions with high intensity blasting

The driving force of both economic and emission efficiency is the differential energy efficiency between blasting (highest efficiency unit operation) and comminution (lowest efficiency unit operation). Application of Enterprise Optimisation's theory of constraints, activity based costs and Prober®'s computational power has facilitated a 52% increase in NPV per unit of CO_{2e} emissions.

5 DISCUSSION

The Mine-to Mill methodology for optimisation of integrated mining operations has been employed by the mining industry for over 25 years. Its original objective focused primarily on minimising integrated production costs over the entire mining value chain. Production cost minimisation included the role of capacity debottlenecking that enabled expansion of operating scale and revenue.

Mine-to-Mill optimisation has exploited the large difference in energy efficiency between blasting and comminution, which represent the greatest and least energy efficient unit operations in mining, respectively. Increased energy input to create new surface area via fragmentation from blasting has the effect of unloading the required energy input in the comminution processes.

Prior desktop research and industrial trials were static assessments of Mine-to-Mill effects. No prior work, other than one Whittle Consulting client study, has sought to assess the impact of variable fragmentation on enterprise economic value over the mine's life. This study has examined the use of variable blasting intensity as a driver of economic value maximisation over the mine's life, using a sophisticated simultaneous optimisation method.

The following conclusions are supported by the case study analysis.

1. *Does high intensity blasting facilitate integrated production costs reduction?* Very little reduction in total unit production costs per tonne of ore or tonne of product metal, is evident over a wide range of blasting powder factors. Over a powder factor range of 1.2 kg/m^3 to 4.7 kg/m^3 unit production costs varied over US$12.0 ± 0.2 kg/m^3, a variation of ± 1.4%.
2. *Can increases in enterprise value be demonstrated by using Prober® dynamic optimisation software with blasting intensity as an independent variable?* The NPV of an optimised life-of-mine plan employing a conventional 1.2 kg/m^3 powder factor, can be increased by 26% by selectively employing powder factors up to 4.3 kg/m^3.

   Figure 27 illustrates the progression of incremental NPV that is enabled by greater blasting intensity. The NPV progression from Run 8A through to 8D indicates a trend of diminishing impact on value growth as blasting intensity is increased.

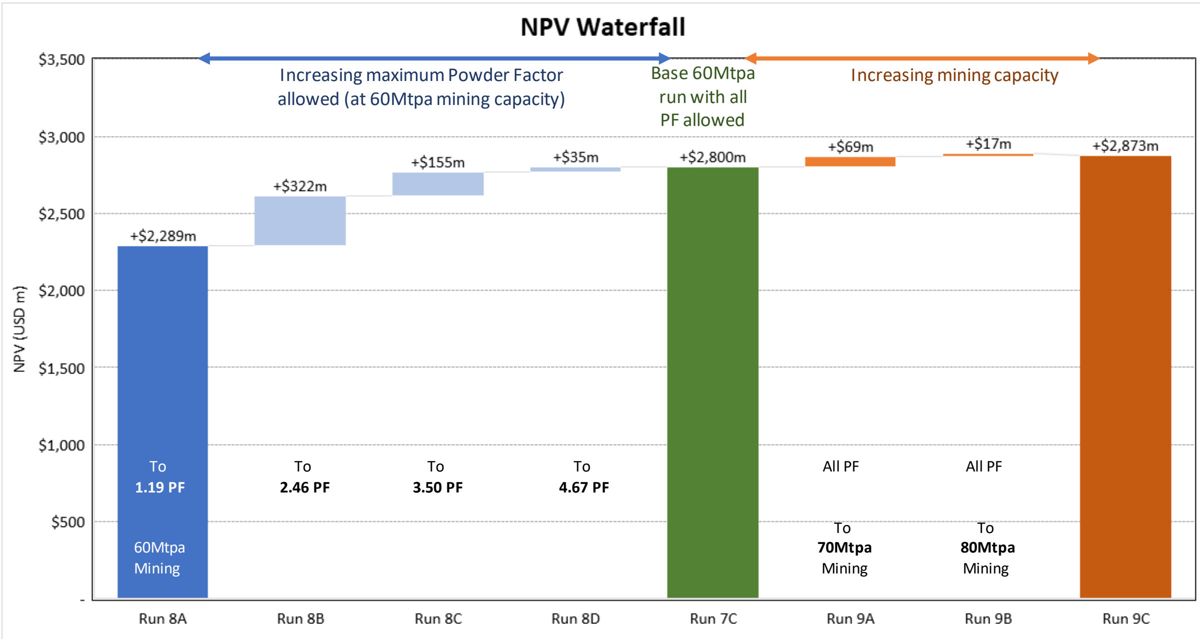


Figure 27: Optimized NPV progression with high intensity blasting

3. *For mill power constrained base metal operations, what scale of debottlenecking and economic value improvement is feasible from applying Ultra-High Intensity Blasting in conjunction with Enterprise Optimisation techniques?* In the *Marvin* case study, NPV growth of 26% was enabled by increased blasting intensity. An estimated 30-40% of that NPV uplift occurs by increasing powder factor from 1.2kg/m^3 to 2.0kg/m^3, the upper end of conventional blasting practice. The residual 60-70% of the prospective NPV uplift requires use of UHIB practices in order to increase powder factor to 4.3 kg/m^3. Little, if any value increase occurs beyond 3.5 kg/m^3.

   Ore production increases of approximately 20% are estimated to be achievable at constant mill power consumption, by increasing powder factor to its upper limit of typically 2.0 kg/m^3 using conventional blasting practice.

   Application of UHIB practices with powder factors up to 3.5 kg/m^3 has an indicated potential to increase production by 40-50%. However, downstream processing limits or loss of metal recovery are likely to constrain the extent of production growth that is economically and physically practical. In the case study production growth without capital investment was limited to 25%, as an input constraint.

All base and precious metal mining operations that are processing power constrained have the opportunity to maximize cash flow and asset NPV by increasing blasting intensity up to the maximum that is feasible with modern conventional blasting practice. Capture of that value uplift and maximisation of the economic potential of the mine is facilitated by employing Life-of-Mine enterprise optimisation as enabled by Whittle Consulting's Prober® strategic mine planning software.

The extent to which additional mine value growth can be accessed by applying even greater blasting intensity up to 4.3 kg/m^3 powder factor, will depend on the feasibility of using UHIB practices at that specific mine. UHIB is in its developmental phase with a limited number of known industrial scale production trials. Management of in-pit water, deposit geotechnical conditions, blast hole stability and neighbour/regulatory constraints will determine the boundaries on implementation of UHIB at individual operations.

This study highlights that an objective of total production cost minimisation would not have driven the maximisation of enterprise NPV. Under the influence of variable blasting intensity, NPV growth of 26% was indicated with no change in unit production cost, although the cost mix had shifted.

Many characteristics of an ore body change during the course of its extraction, notably metal grade, geometallurgy, ore domain/type and strip ratio. Mine planning decisions and mining activity in one time period effect all subsequent mining activities. Ore body heterogeneity and time interdependence of a depleting mineral asset require dynamic, integrated, simultaneous optimisation tools to assess performance strategies.

Static analyses and optimisation techniques which are dominant in mining operations and research, may indicate optima in a particular period of a mine’s life but are likely to be unsuited to guiding life-of-mine value maximisation decisions.

6 Appendices

APPENDIX 1: Enterprise Optimisation Settings

APPENDIX 1.1: ENTERPRISE MODEL CASE 8A: NO HIGH INTENSITY BLASTING

Name	Globals	**Type**	Global
Limits	None	**Costs**	No initial capital
Notes	Discount rate of 10%. Twenty Periods modelled. One model time period equals 1 year.		
Name	Marvin	**Type**	Material Parcels

Inventory

Phase	Rock Mass (t)	Mineralized (t)	Au (g)	Cu (t)	Mineralized mean Au grade (g/t)	Mineralized mean Cu grade (%)
1	125,085,105	115,854,565	62,366,310	658,676	0.54	0.57%
2	114,880,315	83,814,610	31,735,984	526,377	0.38	0.63%
3	125,165,040	70,919,750	22,980,678	385,666	0.32	0.54%
4	182,630,663	77,748,000	21,527,303	359,541	0.28	0.46%
5	352,492,415	74,478,250	19,253,823	254,327	0.26	0.34%

Notes Five phases, sized in Geovia Whittle based on this processing model. Ten metre benches. Material aggregated for Prober by Phase, Bench, Rocktype and Net Value per cominution circuit kWh usage

Name	Mining	**Type**	Procedure
Limits	60Mtpa. 12 benches VRA		

Costs

Variable Costs:

Variable Mining Cost $/t	Powder Factor kg/m3		
	WASTE	ORE	
	0.59	0.62	1.19
TOTAL VARIABLE MINING COST	1.30	1.44	1.91

Period Costs: Net Period Cost is determined by proportioning each period cost element by the % split by powder factor of tonnes moved

Period Costs ($p.a.) before pro-rata allocation	Powder Factor kg/m3		
	WASTE	ORE	
	0.59	0.62	1.19
ANNUAL MINING PERIOD COST	$38 .2m	$73 .8m	$73 .4m

Notes Mining is constrained in most years on the 60Mtpa limit. Processed OX1/OX2 can be mined at 0.62PF and 1.19PF. Processed TR1/TR2/FR1/FR2 can be mined using 1.19PF

Name	#Discard	**Type**	Waste Dump
Limits	NA	**Costs**	As per 0.59PF mining costs above
Notes	Discard of mining waste and Flotation tails.		
Name	Mining Stockpiles	**Type**	Stockpile
Limits	10Mt total	**Costs**	$1/t rehandled
Notes	Material stockpiled by material type (i.e. the aggregations described in the Marvin section). This means very little blending occurs.		
Name	Heap Leach	**Type**	Procedure
Limits	5Mtpa	**Costs**	$2.00/t No Period Costs.

Process

Recovery						Rock Type
Rock Type	OX1	OX2	TR1	TR2	FR1	FR2
Au Rec.	30%	30%	20%	20%	10%	10%
Cu Rec.	80%	80%	50%	50%	30%	30%

Notes 5Mtpa is a constaint - fully utilised in years 1-10

Name	Crusher/SAG/Ball Mill	Type	Part of Plant Procedure
Limits	276.6 GWh per annum across total Crusher, SAG and Ball kWh usage	Costs	See Variable Mill Cost table below. Period costs of $20.38M p.a.

Variable Mill Cost		All PFs
Tailings Dam Wall Lifts	$/t	1.43
Other process & maintenance consumables	$/t	0.70
Flotation Reagents	$/t	0.55
Grinding Media	$/kWh	0.05
Re-lining	$/kWh	0.04
Direct Power	$/kWh	0.07

Period costs of $20.38M p.a.

Process

Power Consumption (kWh/t)	Powder Factor kg/m3
	1.19
Crusher	0.7
SAG	5.5
Ball 75µm	12.4
Ball 106µm	10.3
Ball 150µm	7.7
Ball 200µm	6.2

SAG Throughput %	Powder Factor kg/m3
	1.19
% of Crusher Feed fed to SAG	96.74%

Notes Power limit is fully utlised in most years.

Name	Flotation	Type	Part of Plant Procedure
Limits	25Mtpa	Costs	$2.851/kWh

Process Input particle size P80 is variable.

Au Recovery	Rock Type					
Input P80	OX1	OX2	TR1	TR2	FR1	FR2
75µm	43%	43%	63%	63%	73%	73%
106µm	40%	40%	60%	60%	70%	70%
150µm	38%	38%	58%	58%	68%	68%
200µm	35%	35%	55%	55%	65%	65%

Cu Recovery	Rock Type					
Input P80	OX1	OX2	TR1	TR2	FR1	FR2
75µm	53%	53%	73%	73%	83%	83%
106µm	50%	50%	70%	70%	80%	80%
150µm	48%	48%	68%	68%	78%	78%
200µm	45%	45%	65%	65%	75%	75%

Notes Feed is around 22Mtpa - 25Mtpa is not a constraint. Majority grindsize changes over time - at 200µm in first 5 years, then increased used of 150µm then in final 8 years heavily 75µm

Name	Downstream / #Sell	Type	Procedure
Limits	None	Revenue	$1000/tr.oz Au ($32.15/g) $3/lb Cu

Costs

Downstream Costs		All PFs
Pipe	A$/Con Tonne	0.50
Truck	A$/Con Tonne	30.00
Freight - Shipping	A$/Con Tonne	200.00
Smelter Cost	A$/Con Tonne	200.00
Smelter/Ref Charge	A$/Cu Recov Tonne	95.00
Ref Charge	A$/Au Recov oz	7.50
Royalty Cu	A$/Cu Recov Tonne	110.00
Royalty Au	A$/Au Recov oz	26.00

Table 3: Model Inputs – Case 8A, Conventional Blasting Intensity

APPENDIX 1.2: ENTERPRISE MODEL CASE 9C: OPTIMISED HIGH INTENSITY BLASTING

Name	Globals	**Type**	Global
Limits	None	**Costs**	No initial capital
Notes	Discount rate of 10%. Twenty Periods modelled. One model time period equals 1 year.		

Name	Marvin	**Type**	Material Parcels

Inventory

Phase	Rock Mass (t)	Mineralized (t)	Au (g)	Cu (t)	Mineralized mean Au grade (g/t)	Mineralized mean Cu grade (%)
1	125,085,105	115,854,565	62,366,310	658,676	0.54	0.57%
2	114,880,315	83,814,610	31,735,984	526,377	0.38	0.63%
3	125,165,040	70,919,750	22,980,678	385,666	0.32	0.54%
4	182,630,663	77,748,000	21,527,303	359,541	0.28	0.46%
5	352,492,415	74,478,250	19,253,823	254,327	0.26	0.34%

Notes Five phases, sized in Geovia Whittle based on this processing model. Ten metre benches. Material aggregated for Prober by Phase, Bench, Rocktype and Net Value per cominution circuit kWh usage

Name	Mining	**Type**	Procedure
Limits	90Mtpa. 12 benches VRA		

Costs

Variable Costs:

Variable Mining Cost $/t	Powder Factor kg/m3				
	WASTE	ORE			
	0.59	0.62	1.19	1.79	2.46
TOTAL VARIABLE MINING COST	1.30	1.44	1.91	2.41	2.96
	ORE				
	3.11	3.5	4.28	4.67	5.57
TOTAL VARIABLE MINING COST	3.34	3.59	4.20	4.56	5.24

Period Costs: Net Period Cost is determined by proportioning each period cost element by the % split by powder factor of tonnes moved

Period Costs ($p.a.) before pro-rata alloca	Powder Factor kg/m3				
	WASTE	ORE			
	0.59	0.62	1.19	1.79	2.46
ANNUAL MINING PERIOD COST	$38 .2m	$73 .8m	$73 .4m	$73 .2m	$73 .1m
	ORE				
	3.11	3.5	4.28	4.67	5.57
ANNUAL MINING PERIOD COST	$73 .1m	$73 .0m	$73 .0m	$73 .0m	$72 .9m

Notes Mining is constrained by tonnage limit only in later phase development. Processed OX1/OX2 can be mined at 0.62PF and higher. Processed TR1/TR2/FR1/FR2 can be mined using 1.19PF and higher. In run results majority of FR/TR material destined for Mill is blasted at 3.50 or 4.28PF

Name	#Discard	**Type**	Waste Dump
Limits	NA	**Costs**	As per 0.59PF mining costs above
Notes	Discard of mining waste and Flotation tails.		

Name	Mining Stockpiles	**Type**	Stockpile
Limits	10Mt total	**Costs**	$1/t rehandled
Notes	Material stockpiled by material type (i.e. the aggregations described in the Marvin section). Stockpile balance is regularly churned over throughout LOM		

Name	Heap Leach	**Type**	Procedure
Limits	5Mtpa	**Costs**	$2.00/t No Period Costs.

Process

Recovery						Rock Type
Rock Type	OX1	OX2	TR1	TR2	FR1	FR2
Au Rec.	30%	30%	20%	20%	10%	10%
Cu Rec.	80%	80%	50%	50%	30%	30%

Notes 5Mtpa is a constaint - fully utilised in years 1-10

Name	Crusher/SAG/Ball Mill	Type	Part of Plant Procedure
Limits	276.6 GWh per annum across total Crusher, SAG and Ball kWh usage	Costs	See Variable Mill Cost table below. Period costs of $20.38M p.a.

Variable Mill Cost		All PFs
Tailings Dam Wall Lifts	$/t	1.43
Other process & maintenance consumables	$/t	0.70
Flotation Reagents	$/t	0.55
Grinding Media	$/kWh	0.05
Re-lining	$/kWh	0.04
Direct Power	$/kWh	0.07

Period costs of $20.38M p.a.

Process

Power Consumption (kWh/t)	Powder Factor kg/m3							
	1.19	1.79	2.46	3.11	3.5	4.28	4.67	5.57
Crusher	0.7	0.6	0.5	0.5	0.4	0.4	0.3	0.3
SAG	5.5	5.0	4.4	3.9	3.7	3.3	3.2	3.0
Ball 75µm	12.4	11.1	9.8	8.7	8.2	7.4	7.1	6.6
Ball 106µm	10.3	9.2	8.1	7.2	6.8	6.1	5.9	5.5
Ball 150µm	7.7	6.9	6.1	5.4	5.1	4.6	4.4	4.1
Ball 200µm	6.2	5.5	4.9	4.4	4.1	3.7	3.5	3.3

SAG Throughput %	Powder Factor kg/m3							
	1.19	1.79	2.46	3.11	3.5	4.28	4.67	5.57
% of Crusher Feed fed to SAG	96.74%	95.12%	93.49%	94.80%	93.76%	92.72%	91.68%	90.64%

Notes: Power limit is fully utlised in most years.

Name	Flotation	Type	Part of Plant Procedure
Limits	25Mtpa	Costs	$2.851/kWh

Process

Input particle size P80 is variable.

Au Recovery	Rock Type					
Input P80	OX1	OX2	TR1	TR2	FR1	FR2
75µm	43%	43%	63%	63%	73%	73%
106µm	40%	40%	60%	60%	70%	70%
150µm	38%	38%	58%	58%	68%	68%
200µm	35%	35%	55%	55%	65%	65%

Cu Recovery	Rock Type					
Input P80	OX1	OX2	TR1	TR2	FR1	FR2
75µm	53%	53%	73%	73%	83%	83%
106µm	50%	50%	70%	70%	80%	80%
150µm	48%	48%	68%	68%	78%	78%
200µm	45%	45%	65%	65%	75%	75%

Notes: Feed is at 25Mtpa limit, though power is the key constraint. Primarily 75µm used for grind with <10% at 150µm

Name	Downstream / #Sell	Type	Procedure
Limits	None	Revenue	$1000/tr.oz Au ($32.15/g) $3/lb Cu

Costs

Downstream Costs		All PFs
Pipe	A$/Con Tonne	0.50
Truck	A$/Con Tonne	30.00
Freight - Shipping	A$/Con Tonne	200.00
Smelter Cost	A$/Con Tonne	200.00
Smelter/Ref Charge	A$/Cu Recov Tonne	95.00
Ref Charge	A$/Au Recov oz	7.50
Royalty Cu	A$/Cu Recov Tonne	110.00
Royalty Au	A$/Au Recov oz	26.00

Table 4: Model Inputs – Case 9C, Optimized High Intensity Blasting

APPENDIX 2: GLOBAL MODEL SETTINGS

Global Setting	**Units**	**Value**	**Commentary**
Exchange rate	US$/A$	0.75	
Copper price	US$/lb	3.00	Long term incentive price & 4Q17 spot price
Gold price	US$/oz	1,100	Consensus long term price
Discount rate	Real, after tax	5%	Equivalent to 10% nominal, pre-tax
Initial Capex	US$ m	2,000	Construction and commissioning