Application of Enterprise Optimisation Considering Grade Engineering® Strategies

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CRC ORE Optimising Resource Extraction

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SUMMARY

The Cooperative Research Centre for Optimising Resource Extraction (CRC ORE) has worked with Whittle Consulting to combine the principles of Grade Engineering® with Enterprise Optimisation.

Grade Engineering® involves the use of coarse-separation techniques to remove lower-value or uneconomic material prior to energy, water and cost-intensive mineral processing activities. CRC ORE has performed technical proof-of-concept and economic evaluations for Grade Engineering in partnership with more than 20 mining operations and projects around the world. Central to these evaluations are the characterisation of coarse-separation responses within the deposit, identification of value adding strategies for operation and the development of a business case for Grade Engineering within existing and re-optimised strategic mine plans.

Whittle Consulting provides a business optimisation service to the mining industry using a whole-of-business Enterprise Optimisation methodology that models a mining and minerals processing system from resource to market. *Prober*, Whittle Consulting's proprietary Optimisation software, is used to produce a mathematically optimal schedule of material and financial movements through the operation. Of primary consideration is the effect of bottlenecks which control the rate of flow of money through the system. NPV is used as the financial objective as this accounts for the time-value-of-money and allows direct comparison of different cases. The Enterprise Optimisation approach allows determination of the full value from Grade Engineering, as Prober may alter the behaviour of all elements of the mining and mineral processing system to produce an optimal holistic solution.

The synergy between Grade Engineering principles and Whittle Consulting's Enterprise Optimisation was assessed through a case study that examined a potential response for three coarse separation techniques in a hypothetical, but realistic, mining operation. The case study established an optimised base case without Grade Engineering for comparison to all combinations of Grade Engineering coarse separation techniques examined. The coarse separation techniques included screening for natural deportment of grade by size, differential blasting to induce and enhance the deportment of grade by size and sensing and sorting of bulk material streams, using realistic responses from CRC ORE's global database. The implementation of all Grade Engineering techniques yielded a net improvement of 9.9% in NPV over the optimised Base Case.

Whittle Consulting's Enterprise Optimisation considered all components of the mining and mineral processing operation from resource to market. The process optimised the ultimate pit, phases, mining schedule, cut-offs, stockpiles, grind size, product specifications, logistics and capital investment for the Base Case and Grade Engineering Scenarios. The financial result and observations of this case study support previous findings from CRC ORE's technical and economic evaluations of Grade Engineering performed in partnership with mining operations and projects, as well as outcomes previously presented and published.

Grade Engineering's coarse-separation processes yield financial value through two complementary mechanisms that become available as a result of separating a parcel of mined material into higher and lower-value components before processing. The first is a reduction in the pressure on high-value, high-cost processing bottlenecks by separating and rejecting low-value and uneconomic portions of ore previously destined to be processed at these bottlenecks. The second is the replacement of that rejected material with higher-value portions of Grade Engineered material that would otherwise be directed to lower-value destinations such as Heap Leach, Stockpile and Waste. This process has been

termed “Metal Exchange” as metal (and material) is separated and exchanged between processing destinations to yield a higher economic value overall.

When the operation is not limited by the quality and quantity of ore being mined, the rearrangement of mined material into higher and lower-value streams using Grade Engineering will raise the cut-off to the processing facilities, and accelerate the rate at which metal is recovered. This generally occurs early in the life of a mine, when discounted cash flows have a higher weighting on NPV, and may be further supported by increasing the mining rate. The reduced pressure at high-value, high-cost processing bottlenecks allows greater use of higher-value process plant settings, including fine grinding for improved flotation recovery in the case study examined. At the end of the mine’s life, Grade Engineering allows the economic processing of the high-value portion of low-grade material that would otherwise be classified as waste. Therefore, the minimum economic cut-off grade is ultimately lower in a mine with Grade Engineering and ore reserves and resource utilisation are higher.

The value realised by adding multiple Grade Engineering processes to a mining enterprise is not cumulative. The first process added typically yields a larger financial benefit than subsequent processes. This is particularly true when the Grade Engineering processes compete for the same material.

The work documented in this report provides validation for the evaluation of Grade Engineering within Whittle Consulting’s Enterprise Optimisation framework and supports the findings of Grade Engineering assessments performed by CRC ORE. The financial benefits of coarse separation responses used in the case study were found to be in line with business cases previously developed by CRC ORE in partnership with real-world mining operations and projects. Whittle Consulting’s systematic approach was demonstrated to be suitable for the optimisation of entire system value with Grade Engineering within a realistic mining context.

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1 INTRODUCTION

The Cooperative Research Centre for Optimising Resource Extraction (CRC ORE) is a not-for-profit Research Centre funded by the Australian Federal Government in partnership with mining companies, mining equipment and service providers and research institutions. A key outcome from the first term of CRC ORE was Grade Engineering®, a set of technologies, protocols, tests and analysis methodologies that use coarse-separation techniques to remove lower-value or uneconomic material prior to energy, water and cost-intensive mineral processing activities.

CRC ORE has performed technical and economic evaluations for Grade Engineering in partnership with more than 20 mining operations and proposed projects around the world. These evaluations followed a stagged approach through order of magnitude opportunity assessments, production scale demonstrations and detailed feasibility studies for implementation. Central to these evaluations are the characterisation of coarse-separation responses within the deposit, identification of value adding strategies for operation and the development of a business case for Grade Engineering within existing and re-optimised strategic mine plans. These activities are performed through multi-discipline project teams, operational personnel and service providers.

Whittle Consulting provides business optimisation services to the mining industry with a leading focus on strategic mine planning and whole-of-business optimisation termed Enterprise Optimisation. Whittle Consulting have demonstrated the Enterprise Optimisation approach at over 150 mining operations and have reported improvements in net present value (NPV) of at least 5% to 35%. Whittle Consulting also have strong expertise in financial business modelling and actively disseminate the foundations of Enterprise Optimisation to industry professionals and investors through regular “Money Mining and Sustainability” seminars.

1.1 PURPOSE

The purpose of this study was to demonstrate the ability of Whittle Consulting’s Enterprise Optimisation approach to incorporate and evaluate the principles of Grade Engineering coarse-separation techniques. This was achieved through a case study that examined a potential response for three coarse separation techniques across different domains in a hypothetical, but realistic, mineralised deposit. The results from this work provide a basis for potential collaborations in Grade Engineering strategic mine planning and operational optimisation, with the support of mining operations and projects.

This report documents the analysis and results of the case study.

1.2 GRADE ENGINEERING®

Grade Engineering involves the planning, integration and operation of flexible coarse-separation techniques to improve the quality of ore delivered to mineral processing facilities and increases the value of an operation. Grade Engineering coarse-separation techniques include:

1. Screening to exploit the natural deportment of grade by size that may occur during coarse breakage of mineralised material;
2. Differential blasting to induce finer fragmentation in higher-grade regions of a blast block and coarser fragmentation in lower-grade regions to be separated by screening;
3. Sensor-based sorting performed at:

   a) Bulk scale for ROM material on conveyors, trucks, hoppers, shovels or loaders;
   b) Particle scale for sized and screened material streams; and
4. Coarse gravity separation using dense media baths, inline pressure jigs or reflux classifiers.

Responses for screening for natural deportment of grade by size, differential blasting and screening for enhanced deportment of grade by size, and bulk sensing and sorting (items 1, 2 and 3a above) were examined in the current case study.

The benefits provided by coarse-separation techniques evolve during the life of a mine and are dependent on the characteristics of the mineralised deposit (spatial geometry, distribution of economic and marginal material and response to coarse-separation techniques) and operational conditions (quality and quantity of ore mined, processing and operational constraints, prevailing and long-term economic conditions). The benefits from coarse separation techniques may include:

- improved grade, recovery and throughput of material delivered to the processing plant;
- increased unit metal productivity and reduced energy, emission, water and cost intensities of metal production;
- a virtual increase in effective treatment capacity of processing facilities (or reduced pressure at processing bottlenecks) due to the separation of higher and lower value material prior to treatment;
- lowering of minimum economic processing cut-offs, potentially improving the size of the ultimate pit and the conversion of resources to reserves;
- ability to perform Metal Exchanges between processing destinations (refer to Section 1.2.4);
- improved flexibility in treatment options for mined material; and
- improved NPV of the operation or project.

1.2.1 Screening for Natural Deportment of Grade by Size

Some rocks exhibit a natural tendency to concentrate valuable minerals in fine (or coarse) size fractions during blasting or crushing activities. This uneven distribution of value in size fractions creates an opportunity to separate higher and lower-value material streams by screening mined material prior to treatment.

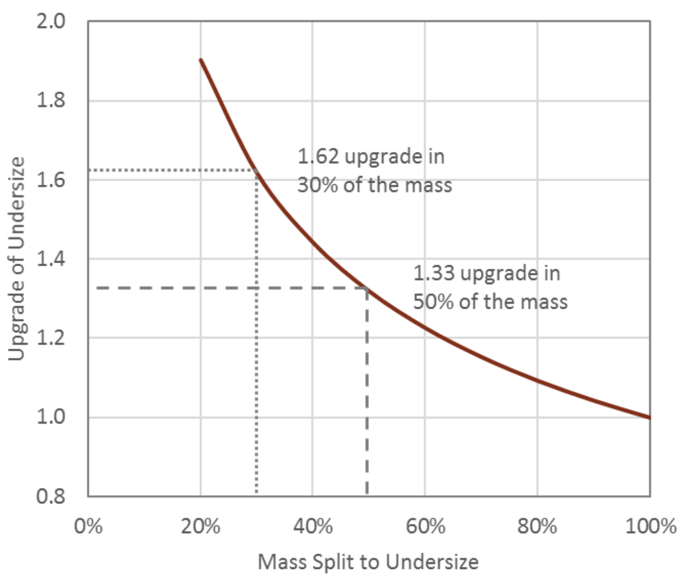


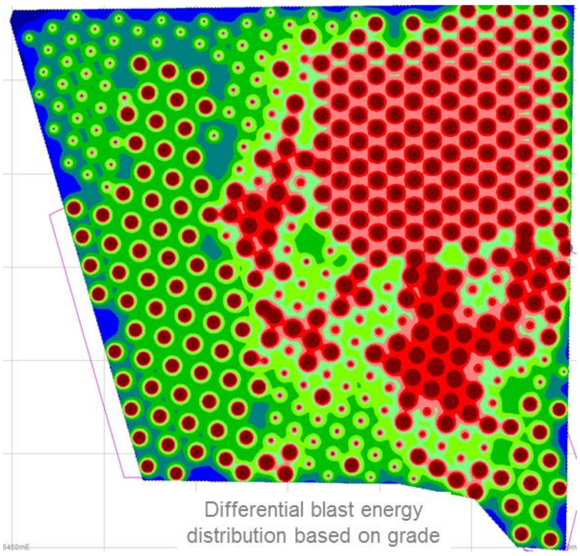
Figure 1-1: Flexibility to exploit a natural deportment of grade by size response

The upgrade response for screening material is dependent on the strength of the natural grade by size response of the rock and the mass split of the screen. The strength of the natural grade by size response within rock types and geo-metallurgical domains can be measured using sampling programs and laboratory testing protocols. The mass split of the screen may be controlled by adjusting screen apertures and the particle size distribution of material sent to the screen. These controls grant the operation flexibility to adjust the grade and mass delivered to different treatment processes based on the responses of material being mined and constraints to production (Figure 1-1).

1.2.2 Differential Blasting and Screening for Enhanced Deportment of Grade by Size

Differential blasting adjusts the energy applied within regions of a blast to induce finer fragmentation in higher grade zones and coarser fragmentation in lower grade zones to allow the separation of higher and lower-value material streams by screening (Figure 1-2). Differential blasting can be used to induce a grade-by-size response in material that exhibits no natural response or to enhance the natural grade-by-size response of material by conditioning in situ zones of high and low grade for screening.

The upgrade response from differential blasting is primarily driven by grade heterogeneity within a blast, but it is also dependent on the strength of the natural grade-by-size response of material, achievable blast fragmentation profiles for the material and screening aperture. Of these dependents, the screen aperture and the blast design provide some flexibility to fine tune the differential blasting response.



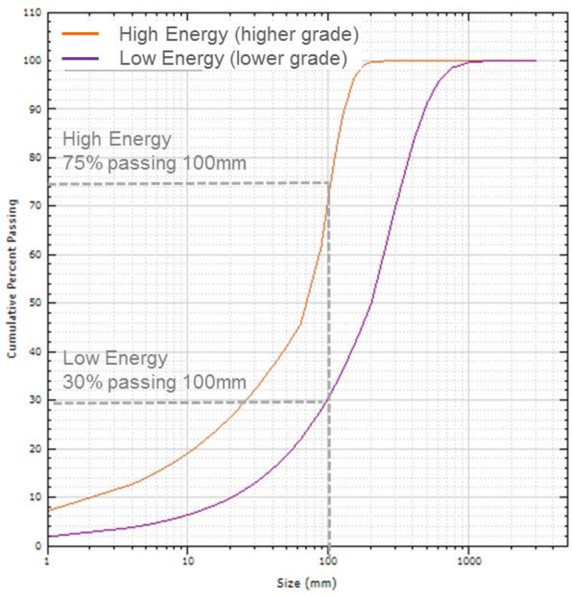


Figure 1-2: Example of differential blast energy distribution (left) and blast energy fragmentation (right)

1.2.3 Sensing and Sorting at Bulk Scales

There are a wide range of sensing technologies available to analyse physical and/or chemical properties of material. These technologies differ in their ability to take penetrative or surface readings which can be used to detect or quantify mineralisations and elements of commercial interest or proxies that can be used to indicate or quantify material value (Figure 1-3). Once the value of the material is quantified or indicated a decision can be made in real time as to accept the material at the planned destination or divert the material to an alternative destination.

Sensing and sorting at bulk scales can be performed using quantitative or indicative readings from material in shovels, loaders, trucks or on conveyors throughout material handling points between mining and processing activities. The upgrade response from bulk sensing and sorting is driven by the heterogeneity present within pods of material, the accuracy in which the sensor can quantify or indicate the value of the material and the efficiency in which a pod of material can be diverted.

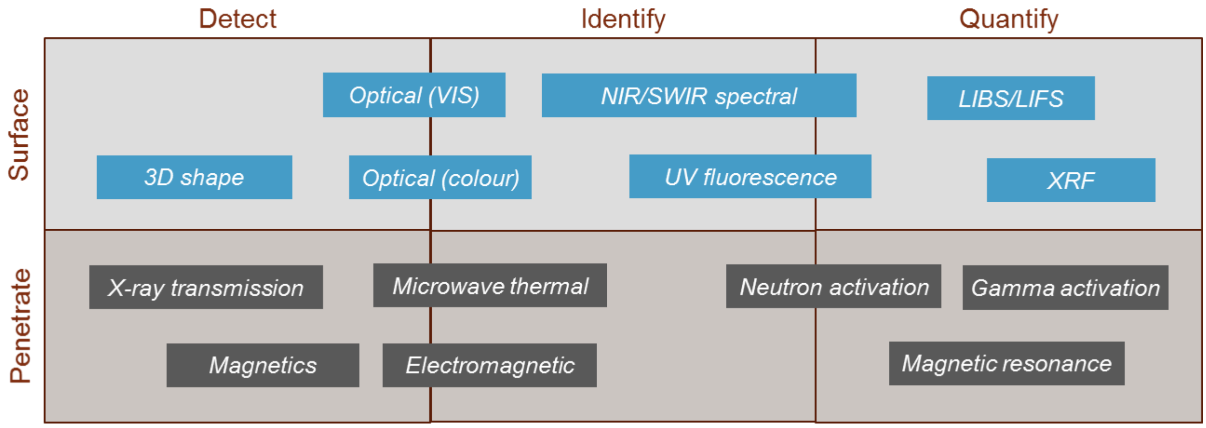


Figure 1-3: The different attributes of sensor technologies

1.2.4 Metal Exchange

The principle of Metal Exchange is built on the ability of Grade Engineering techniques to separate a parcel of mined material into higher and lower value components. This creates opportunities to exchange lower value components of ore previously treated at the processing plant with higher value components of material previously destined for the heap leach, stockpiles or waste storage facilities. These Metal Exchanges allow the operation to use Grade Engineering techniques to redistribute upgraded and downgraded material between treatment destinations to improve the overall economic value of the operation.

1.3 Enterprise Optimisation

Whittle Consulting's Enterprise Optimisation considers all components of the mining and mineral processing operation from resource to market (Figure 1-4).

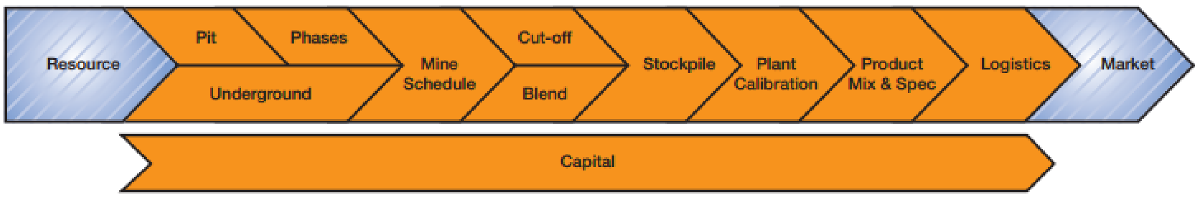


Figure 1-4: Whittle Consulting Enterprise Optimisation process.

A typical Enterprise Optimisation (EO) project consists of three phases:

1. the Base Case in which the existing state of affairs and existing plans through to the end of LOM is modelled to calibrate the EO model;
2. the Optimised Case in which the system is mathematically optimised using the same structure, limitations and parameters as the Base Case, and;
3. then Scenarios in which variations and uncertainties can be evaluated. Dozens or even hundreds of variations may be examined during each project.

Whittle Consulting's Enterprise Optimisation approach has been founded on the following principles.

1.3.1 Time Value of Money

Any methodology for optimising a mining operation, which may have a life of several decades, must take into account the time-value of money. Prober, Whittle Consulting's proprietary algorithm for Enterprise Optimisation, discounts future cash-flows to produce a Net Present Value (NPV) that can be directly compared between different scenarios.

1.3.2 Theory of Constraints

The Theory of Constraints (TOC) was introduced as a management philosophy by Eliyahu M. Goldratt in his 1984 book *The Goal*. It draws upon System Dynamics, Program Evaluation and Review Technique (PERT) and Critical Path Method (CPM) developed in the mid-20th century. The central viewpoint of TOC is that a system managed towards a certain goal (e.g. a company managed to produce money) is limited in maximising its output of that goal by constraints. If constraints can be relaxed, then the throughput in the system can be increased and a greater amount of the objective unit can be produced.

There may be many constraints in a system but of these only a small number, or as few as one, are the primary constraints or bottlenecks. These control the overall throughput through the system.

Common constraints in mining enterprises are plant capacity limits, plant concentration limits, mining tonnage limits, vertical rate of advance limits, stockpile or dump size limits, power and water supply limits, product specifications and pollutant limits.

In an optimized system, the bottleneck should be the constraint that the system operator *has the least ability to change*. This is most commonly the most capital-intensive part of the operation (e.g. an expensive piece of equipment such as a ball mill); though in some cases may also be an externally imposed constraint (e.g. a certain product specification, a regulatory constraint, or a resource supply limitation).

If an Enterprise Optimisation finds that the bottleneck limiting the overall generation of cash by the system is relatively simple or inexpensive to alleviate, then that action should be taken. Cash generated by the operation will then increase until another constraint becomes the bottleneck.

1.3.3 Activity Based Costing

Any model is only as good as its inputs, as per the well-known 'Garbage In, Garbage Out'. In Enterprise Optimisation, it is essential that all resource consumption costs are assigned to the activity that consumes that resource. This is Activity Based Costing.

Furthermore, it is essential that all costs are split into variable (attributable) costs, incurred per unit of resource consumed, and period costs, incurred as a fixed cost to keep a process (e.g. item of equipment) operating over a period of time.

1.3.4 Software

A mining enterprise has so many elements and relationships between those elements that specialised software is required to implement modelling and Optimisation. Whittle Consulting utilises Prober, a proprietary optimisation algorithm that has been continually developed by Jeff Whittle for nearly two decades.

Prober is used to model the mining and processing operation from material inputs to market, which is then optimised for NPV, producing a schedule showing the path of all cash-flows and materials through the system over the life of mine.

Prober receives material inputs with specified sequence rules (e.g. start-afters, minimum leads and lags) however it is not practical to provide block models (which often contain millions of blocks) directly to Prober without prior aggregation of alike material (rock type, grade/value range, processing options).

In open-pit operations the mining shape selection (i.e. pits and phases) are sized using Geovia Whittle pit optimisation software, which utilises the Lerchs-Grossman algorithm to determine optimum pit size and shape. Whittle Consulting use specific techniques to integrate Geovia Whittle with the Prober schedule optimiser, including iteration between the two optimisers if necessary. Underground operations with alternate mining shapes or sequences (prepared by a mining engineer) can be evaluated using a similar approach.

1.3.5 Non-Financial Goals

Prober is only able to optimise for NPV; however non-financial objectives can be incorporated if they can be quantified. This may take the form of constraints on the operation (e.g. on tailings produced, dust disturbance or water consumption). The second approach is to produce scenarios that allow the trade-offs between socio-economic factors and NPV to be examined.

Whittle Consulting has partnered with the University of Queensland's Sustainable Minerals Institute to integrate Enterprise Optimisation with Sustainable Operations (SUSOP), taking into account Manufactured, Social, Human and Natural capital.

1.3.6 Uncertainty

All data inputs to Prober have an associated uncertainty. Uncertainty cannot be incorporated into Prober directly, so risk is typically quantified using a scenario-based approach.

1.4 TERMINOLOGY

Bulk Sort	"Bulk Sort" refers to the coarse-separation technique for Sensing and Sorting ROM material at a bulk scale (100-1000 tonnes).
Cut-off Grade *or* Cut-off Value	The material grade or material dollar value that differentiates material sent to one processing path to material sent to another processing path. The cut-off most commonly discussed is the cut-off between ore and waste, however a cut-off exists for every decision point in the system. A cut-off value expressed as dollars per unit of bottleneck capacity of a system can provide better material allocation decisions but becomes overly complex in multi-mineral, multi-path processing systems that differently favour or penalise each mineral.
Differential Blasting	"Differential Blasting" refers to the coarse-separation technique that adjusts the blast energy applied within high and low grade zones of a blast block to induce or enhance the deportment of grade by size to be separated by screening.
Enterprise Optimisation (EO)	An optimisation of an enterprise where the whole system (within control of the enterprise) is modelled. Contrast to an optimisation that only models a sub-system in isolation and ignores the effect upon the rest of the system.
Processing Plant	In this case study, refers to the SAG Mill -> Ball Mill -> Flotation procedure sequence.
Grade Engineering	A set of technologies, protocols, tests and analysis methodologies that use coarse-separation techniques to separate higher and lower-value material streams prior to mineral processing activities.
Heterogeneity	Within a specified volume, the degree to which sub-volumes have differing properties that influence value e.g. grade, deleterious elements, throughput, recovery, coarse-separation response.
Life of Mine (LOM)	The time period that the mine operates.
Metal Exchange	"Metal Exchange" refers to the use of coarse-separation processes to separate higher and lower-value material streams to support the exchange of metal and material between available processing destinations.
Natural Deportment of Grade by Size	Natural deportment refers to the natural tendency for valuable minerals to deport to finer (or coarser) size fractions in some rock types during blasting and/or crushing activities. Natural deportment is exploited by screening (refer to "Screening" below)
Ore	Material that is sent to the processing plant or is stockpiled so that it can be sent later to the processing plant. There is not a fixed mineral cut-off grade; instead the cut-off characteristics of ore and waste vary by material type and availability over the LOM.
Period Cost	A fixed cost associated with a certain process, over a specified period of time.
Screening	In this case study, "Screening" refers to the coarse-separation technique of screening for the natural deportment of grade by size.
Variable Cost	A cost directly attributable per unit of consumption of a resource used by the system.

3 Methodology

Realisation of the full benefits of Grade Engineering in a mining and mineral processing system requires the ability to alter or re-optimise all parts of the system to maximise value (e.g. pit and phase shapes, mining schedule, stockpile usage, cut-off grades, plant settings). Under CRC ORE's staged approach for technical and economic evaluation of Grade Engineering opportunities, re-optimisation of all areas of the strategic mine plan and scenario based assessments are examined during concept level evaluations and above.

Whittle Consulting's Enterprise Optimisation has the ability to model and mathematically optimise a mining enterprise with all of these facets to support the development of a strategic business planning and scenario based assessment for Grade Engineering.

The Enterprise Optimisation follows a 10 step methodology as shown in Figure 3-1.

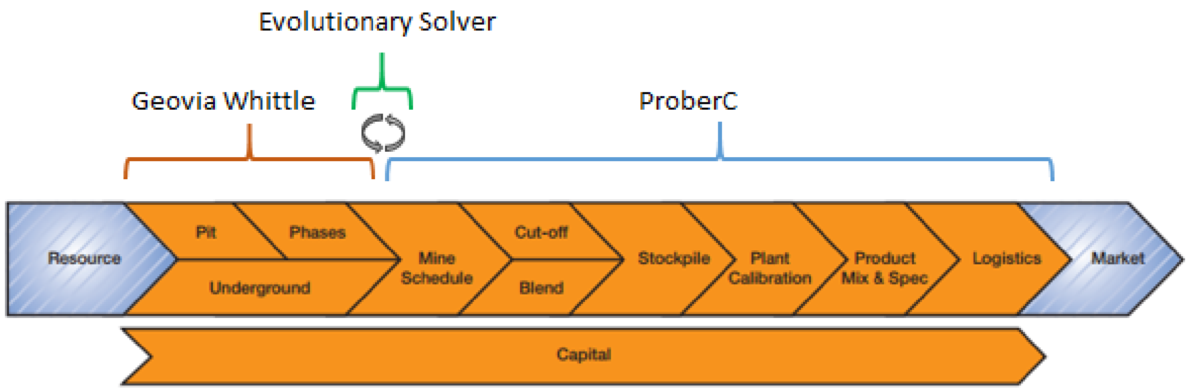


Figure 3-1: The Whittle 10-step methodology with associated optimisation software. Prober 'C' optimises the declared system using pit and phase shapes provided by Geovia Whittle. An Evolutionary Solver may be used to iterate between the two in some circumstances.

3.1 Business Model

The Whittle Enterprise Optimisation process begins with the construction of a Business Model document. The purpose of the Business Model is threefold:

The first 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 and the Business Model is a spreadsheet representation of this. All processes, from Mining through the Plant to product sale, are *Procedures* with inputs and outputs. Material is transported between Procedures by *Deliveries.* Each *Portion* of material has a *MaterialType* and this may be used to vary the treatment of the portion. Costs are incurred as *Variable Costs* and *Period Costs*, while *Revenue* is earned by sending material to the *Sell* procedure. *Stockpiles* are declared similarly to procedures and may have *Rehandle Costs.* Limits are applied to material *Quantities*, either on the total annual figure, on a cumulative figure or as a ratio to another quantity.

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

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

3.2 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 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 are then invoked to size the phases within the pit. As neither of these functions produce outcomes that are purely optimal when taking into account multi-path processing systems, multi-pit mines and discounted cash flows, a Mining 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.

3.3 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.

The Input sheets take a parcels text file which specifies the masses and other quantities associated with each *Parcel* of material. A *Parcel* is a single record of alike material that is spatially connected (i.e. can be mined together); multiples of these make up a *Panel*. In practice when modelling an open pit, a parcel is an aggregation of block model blocks of a certain rock-type, that are expected to be sent down the same processing path (i.e. have similar mineral grade characteristics), within a single bench. An assumption made is that when a panel is partially mined by Prober, an equal fraction of all contained parcels is taken. Panels are contained by *Sequences*, which in an open pit are equivalent to phases.

Prober allows the declaration of sequencing rules between sequences; these may be *Start-After* rules or *Minimum/Maximum Lead* rules. Each panel within a sequence has an implicit start-after relationship with its predecessor.

Prober accepts the input file, checks validity and then proceeds with the simultaneous optimisation of schedule, cut-off, stockpiles, logistics and product mix. Period costs and equipment startup costs are a recent addition to Prober's functionality; prior to this development of these could only be added post-optimisation.

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 the downstream system.

Stockpile blending makes the optimisation problem non-convex; an iterative solution is used to account for this[1].

Prober runs not as a single optimisation but as multiple *Samples* that each return their own schedule and result 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 indication of convergence achieved is shown in Figure 3-2.

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

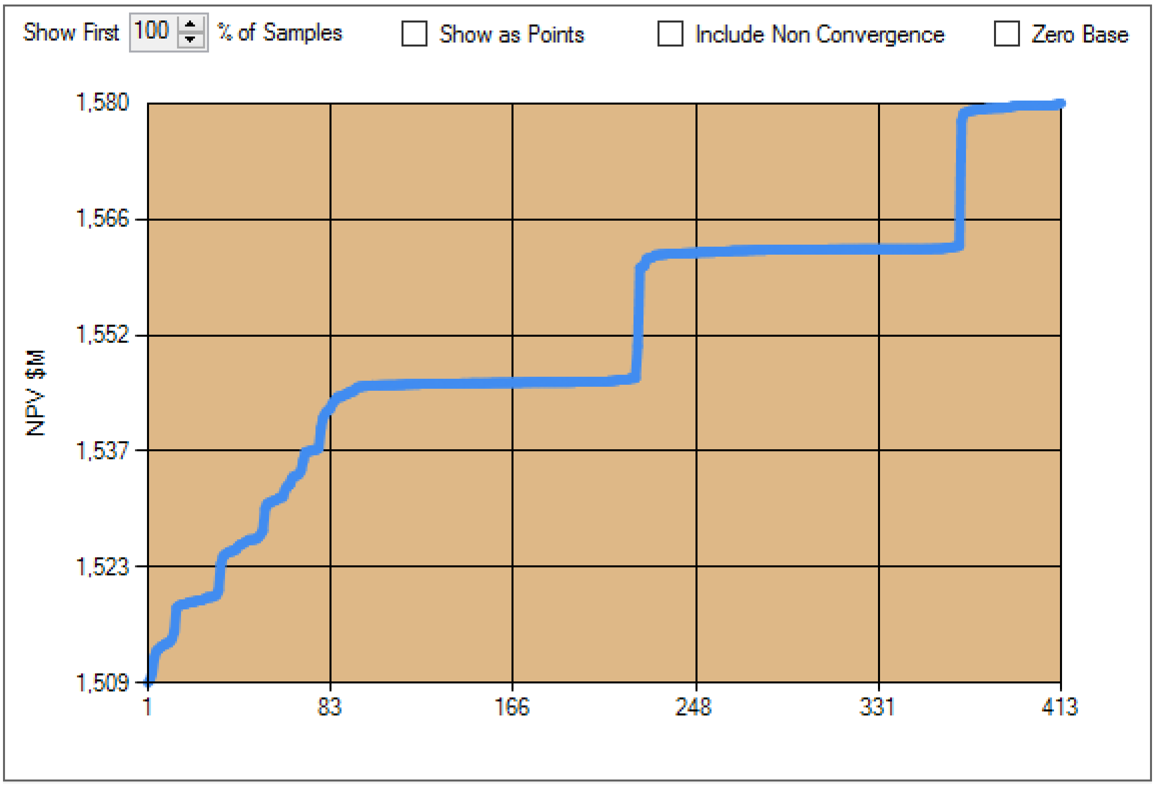


Figure 3-2: Prober samples for run 043 (Case 4), ordered by NPV. Note that NPV is pre-capital.

3.4 Evolutionary Solver

Prober cannot directly solve for integer or Boolean variables. This manifests particularly when choosing between multiple mutually-exclusive versions of the same input pit and phase shapes, or in the case of underground mines, multiple versions of the same stope designed at different cutoff grades.

An Evolutionary Solver as a 'wrapper' around Prober is used to optimise an operation where selection between different versions of the same pits, phases or stopes is required.

[1] Whittle, Jeff & Whittle, Gerald. 2007. 'Global Long-Term Optimisation of Very Large Mining Complexes'. Presented at APCOM 2007 in Santiago, Chile.

4 MODEL AND CASES

All mining operations are different and potential benefits from Grade Engineering will vary from case to case. Assessing Grade Engineering opportunities over a range of real-world mining operations and projects would require a level of sampling and assessment that was outside the scope of the current report. As such, this report examined the principles for coarse separation techniques within a hypothetical mining operation to demonstrate the inclusion of Grade Engineering concepts within Whittle Consulting's Enterprise Optimisation approach.

A hypothetical, but realistic, model of an operation was built in which the principles of coarse-separation techniques for Grade Engineering could be examined. The components of the model were an ore body (as a block model), a mining model, a processing model (with and without Grade Engineering), and a financial model. This model was built using Prober and associated tools and then optimised to get a Base Case result. Alternate versions of the model were made with Grade Engineering processes included.

The operation modelled is a Greenfield project, although coarse separation techniques for Grade Engineering are equally applicable to existing operations.

4.1 GLOBAL SETTINGS

The annual discount rate applied to the system was 10%.

All-inclusive Capital Costs for the operation are $1B. Screening Plant and Bulk Sorting capital were additional to this (and described in Section 4.5.2)

This is a hypothetical case study where the notional first year of operation is 2101. A model time-period of one year is used. Mining may begin in 2101 however ore processing does not begin until 2102 when the plant is completed.

4.2 CASES

The Grade Engineering techniques examined were:

1. Screening for the Natural Deportment of Grade by Size,
2. Differential Blasting and Screening for Induced and Natural Deportment of Grade by Size,
3. Bulk Sensing and Sorting.

Table 4-1: Grade Engineering cases examined

Case	Run	Differential Blasting	Screening for Natural Deportment	Bulk Sensing and Sorting	Pit
1	037	FALSE	FALSE	FALSE	v9
2	041	FALSE	FALSE	TRUE	v9
3	042	FALSE	TRUE	FALSE	v9
4	043	TRUE	FALSE	FALSE	v9
5	044	FALSE	TRUE	TRUE	v9
6	045	TRUE	FALSE	TRUE	v9
7	046	TRUE	TRUE	FALSE	v9
8	035	TRUE	TRUE	TRUE	v9

The Base Case without Grade Engineering is Case 1 and the case with all coarse-separation processes enabled (Differential Blasting, Screening for Natural Deportment and Bulk Sensing and Sorting) is Case 8. Cases 2-7 show the effect of incremental additions of Grade Engineering processes. A matrix of the cases examined is shown in Table 4-1. It should be noted that Differential Blasting and Screening for Natural Deportment of grade by size are complimentary strategies that utilise the same enabling capital for a Screening Plant. As such, opportunities to exploit these complimentary Grade Engineering strategies are normally examined together. However, for the purpose of this case study, Differential Blasting and Screening for the natural deportment of grade by size were assessed separately.

Note that the value of Grade Engineering is assessed in this case study by comparing an optimal mining/processing schedule without Grade Engineering, to an optimal schedule with Grade Engineering. This differs to a typical Whittle Consulting project in which the base case provided by a client is (usually) not an optimised solution.

A full account of structure, material settings and financial settings used for Case 1 and Case 8 can be found in the appendices; *Enterprise Model Case 1: No Grade Engineering* - Settings and *Enterprise Model Case 8: All Grade Engineering Options* - Settings.

4.3 Ore Body

The ore body used in this assessment is the Marvin ore body. This is a realistic copper-gold ore body created over a decade ago by geologist Norm Hanson for use in case studies. Marvin has higher gold grade at shallow elevations and a higher copper grade at deeper elevations, as shown in Figure 4-1.

Different material types were required to demonstrate the effect of differing strengths of response to Grade Engineering processes. The model already contained an Oxide layer, followed by Transitional and Fresh material with some intermingling. To create more material types a geological feature was added to the model. This consisted of an Intrusion descending on an angle through the block model. Inside the Intrusion is domain 1, outside is domain 2. Crossed with the existing OX/TR/FR rock type, this gives six Rock Domains.

The Marvin block model grades were altered several times over the course of this case study, so as to achieve enterprise results judged to be realistic. The grade-tonnage curves for both Copper and Gold are shown in Figure 4-2. Note that 'cut-off' as shown in the charts is for each of gold and copper *in isolation*. Any cut-off grades or values established during the mining Enterprise Optimisation process clearly need to account for both gold and copper together.

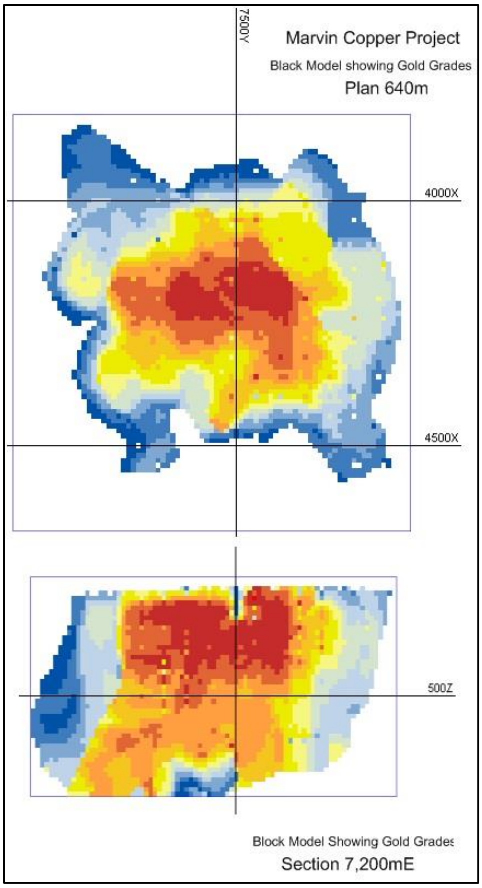


Figure 4-1: Marvin Ore Body

Table 4-2: Sums by Rock Domain. Note that all blocks are mineralised aside from filler FR2 blocks. Grades quoted are over Mineralised Mass.

RockDomain	Total Mass (t)	Mineralized Mass (t)	Au (g)	Cu (t)	Mean Au (g/t)	Mean Cu (%)
OX1	7,857,600	7,857,600	3,291,020	12,433	0.42	0.16%
OX2	14,925,600	14,925,600	4,092,660	22,508	0.27	0.15%
TR1	84,843,370	84,843,370	26,742,051	309,478	0.32	0.36%
TR2	83,493,220	83,493,220	20,726,718	301,006	0.25	0.36%
FR1	43,802,080	43,802,080	4,313,812	71,388	0.10	0.16%
FR2	4,425,916,960	162,377,460	19,156,304	332,162	0.12	0.20%

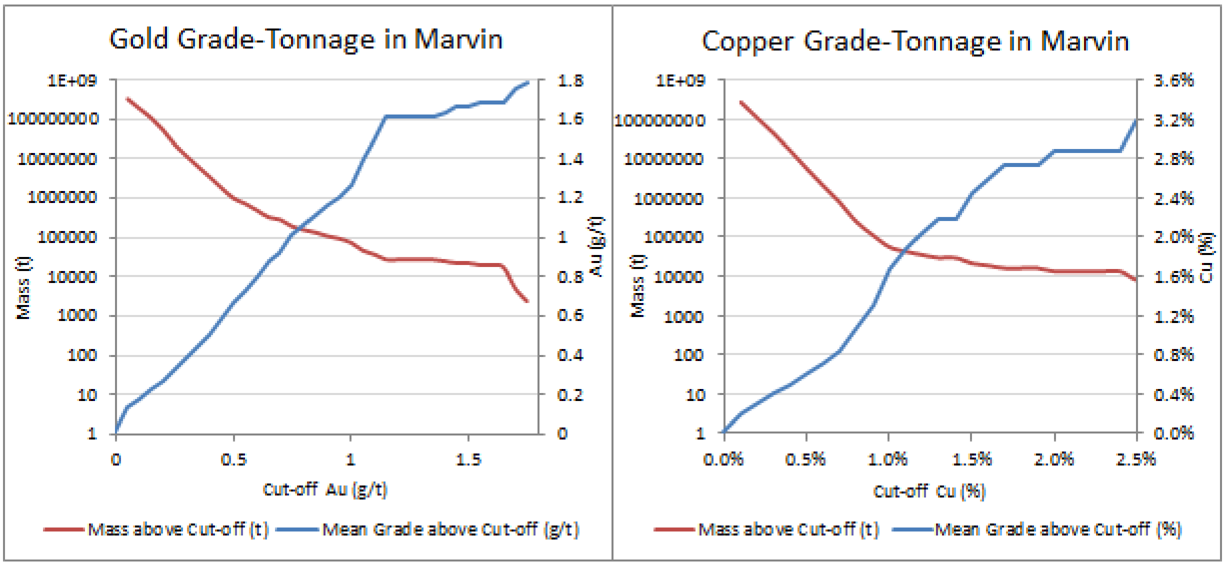


Figure 4-2: Grade-Tonnage curves for Gold and Copper in the Marvin deposit used for this case study.

4.4 Pit and Phases

The Geovia Whittle software package was used for pit and phase sizing. Geovia Whittle does not handle multiple downstream processing options, so the expected cash value for each block is instead fed into the program in the input file. The expected cash value of each block was calculated as the *maximum* that the block could earn from any possible processing path.

In the Base Case (Case 1) there are six possible paths for each block (ignoring stockpiling). With all three coarse-separation techniques active (Case 8) there are 96 possible paths, ignoring stockpiling. See *All Processing Paths* in the Appendices for a list. The maximum net cash path for each block can be calculated for each rock type by gold and copper grade, as shown in Highest Net Cash Paths – Case 1 and Highest Net Cash Paths – Case 8.

It is critical to note that each block will only take the maximum-cash path *when free of all constraints*. In most cases the maximum-cash path becomes a bottleneck, meaning that material blocks must compete to access the bottleneck resource. This competition introduces an opportunity cost to production through the bottleneck which raises the cut-off required for material to be treated at the process bottleneck. Period costs to keep processing equipment available also influence the highest net cash path.

For pit sizing, the assumption was made that, at the base of the pit the processing limits are no longer bottlenecks and therefore opportunity costs of processing pathways do not need to be considered in calculating the maximum cash path for each block. Only the usual mining and processing, variable and period costs need to be considered.

The pits and phases shown in Figure 4-3, Figure 4-4 & Table 4-3 were sized with Geovia Whittle using *only* the six non-Grade Engineering processing paths. Manual intervention was required to create a smaller first phase than Geovia Whittle produced; Prober demonstrates that a smaller first phase typically produces better results when considering the time value of money. This set of phases was used to examine all cases 1-8; this demonstrates the effect of adding Grade Engineering processes to an operation without altering the phase shapes and sizes.

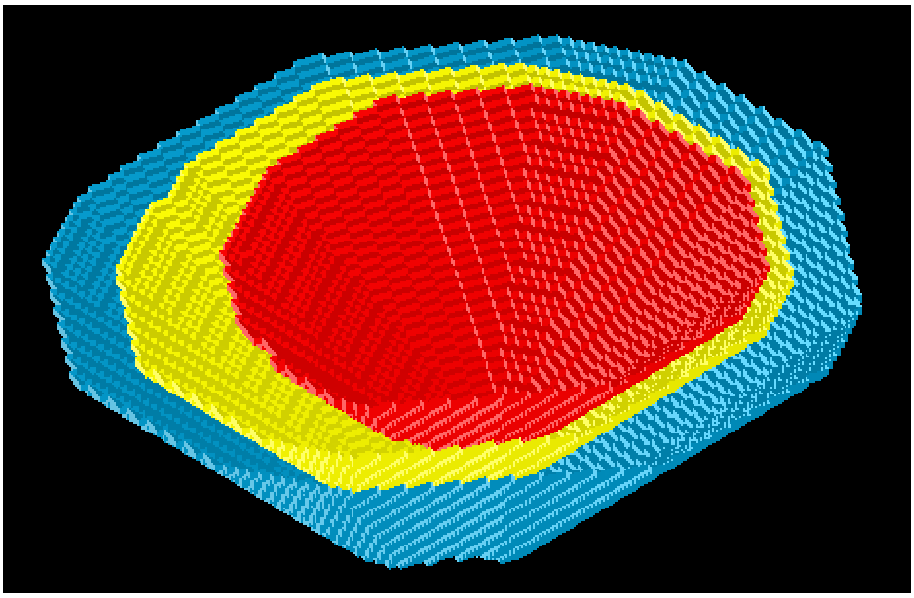


Figure 4-3: The three phases of the pit.

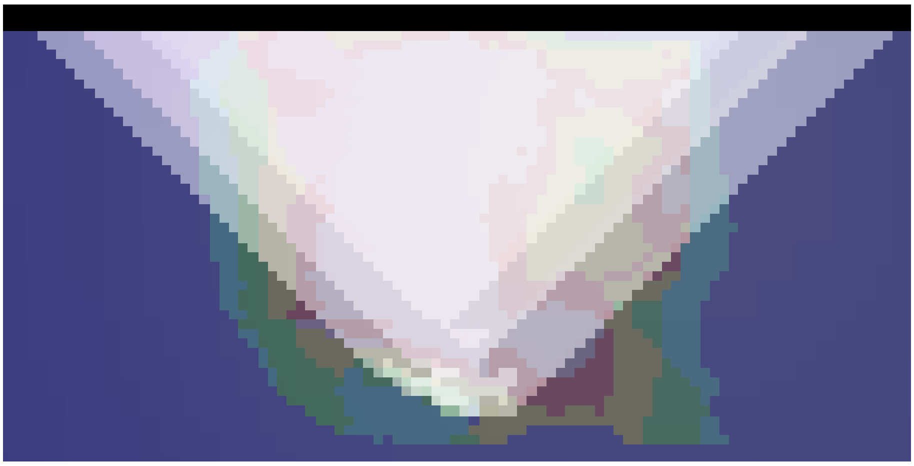


Figure 4-4: The three phases of the pit superimposed over a section of the Marvin ore-body, coloured by gold grade.

Table 4-3: Mass sums and grades by phase.

Phase	Rock Mass (t)	Mineralized (t)	Au (g)	Cu (t)	Mineralized mean Au grade (g/t)	Mineralized mean Cu grade (%)
1	86,156,460	79,449,210	35,297,297	314,754	0.44	0.40%
2	73,088,180	55,614,680	15,454,639	266,964	0.28	0.48%
3	111,322,120	72,203,370	12,980,051	220,837	0.18	0.31%

An additional Grade Engineering case was investigated (Case 9) which involved re-sizing the pits and phases through Geovia Whittle using the maximum cash path for each block considering all 96 potential processing paths with all Grade Engineering coarse-separation techniques active. Due to the spatial geometry of the orebody, with a limited halo of marginal material at depth to expand the ultimate pit, Case 9 resulted in a slightly larger ultimate pit that reduced the NPV of the operation due to a significant increase in the volume of barren material being mined to expose marginal resources at depth.

4.5 MINERAL PROCESSING

The processing model governs all material and cash flows. The model differs for each case depending on which Grade Engineering processes are allowed.

Prior to entry into Prober, the material blocks are aggregated by Phase, Bench, Rock Domain Type, Gold band (0-0.2, 0.2-0.4, 0.4-0.6, 0.6-0.8, 0.8+ g/t) and Cu band (0-0.2, 0.2-0.4, 0.4-0.6, 0.6-0.8, 0.8+ %) to create 'parcels' of like value material through each of the available processing pathways. This allows the Optimisation to proceed more quickly without significantly reducing the accuracy of the result. The mineral processing system is modelled in Prober.

4.5.1 The 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 as shown below in Figure 4-5.

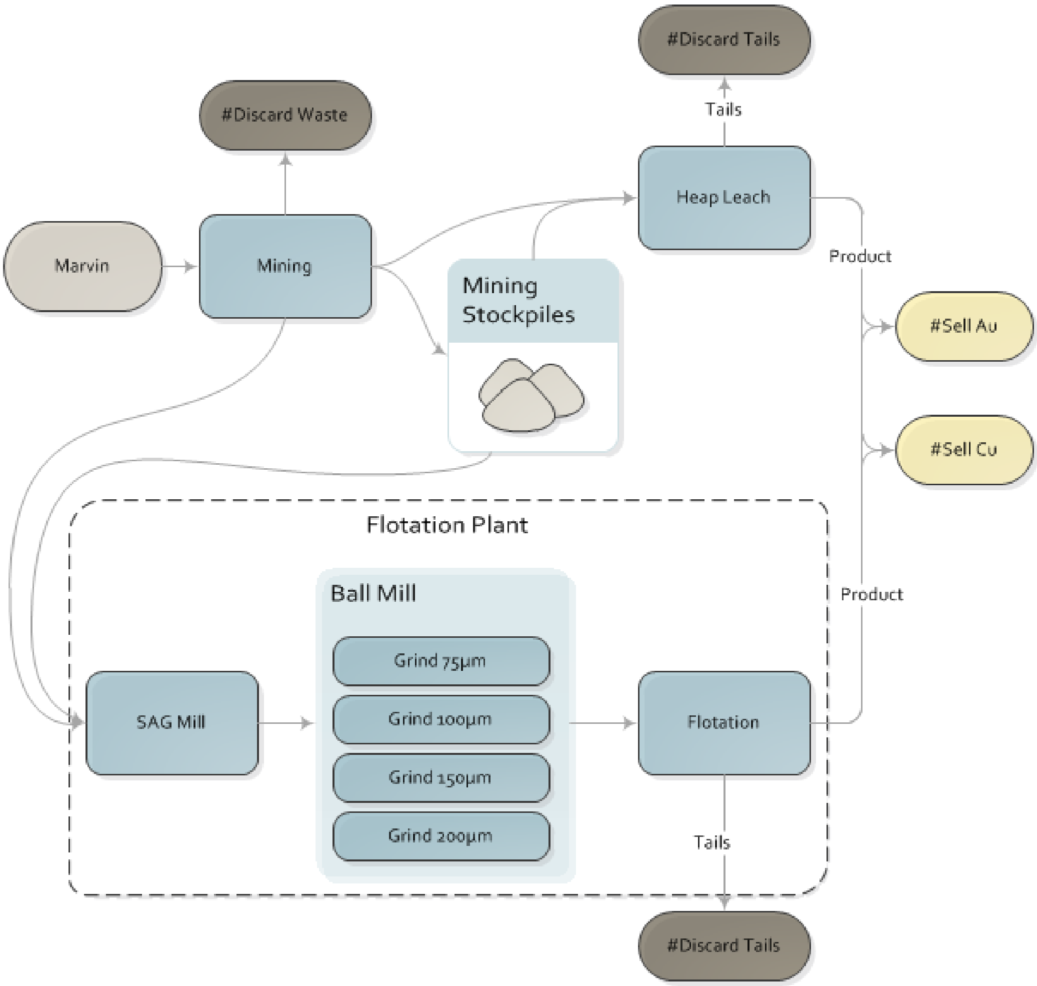


Figure 4-5: Enterprise Model for Case 1 without Grade Engineering.

Mining costs are $1.60/t plus an additional $0.02/t per 10m bench for extra haulage at deeper elevations. Mining period costs are $40M per annum, which is intended to represent that the operation owns the mining fleet rather than using contractors. A nominally high tonnage limit of 70Mtpa is used as mining should not be a bottleneck in the system. The maximum rate of advance is twelve 10m benches per annum. ROM material is assumed to have p80 particle size of 200mm and can be sent to Dump, Heap Leach or SAG Mill, via a stockpile if necessary.

The stockpile is limited to a capacity of 80Mt and rehandled material incurs a cost of $0.75/t. Note that in Prober, stockpiling implicitly blends input materials with all other material already on that stockpile. In this case study, stockpiling is 'best case' where material is stockpiled by its material band (i.e. the aggregations described earlier); as these bands are narrow, very little blending occurs.

The Heap Leach is limited to 5Mtpa and has a variable cost of $2.00/t, with period costs of $5M per annum. Recoveries are shown in Table 4-4.

Table 4-4: Heap Leach recovery by rock type.

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%

The SAG Mill, Ball Mill and Flotation processes are collectively termed the Processing Plant. The SAG Mill grinds input material to a p80 particle size of 10mm. Smaller input particle sizes and softer rock types incur lower power and steel consumption costs, on top of the base rate of $0.30/t. The SAG Mill also incurs $2M of period costs per annum.

The Ball Mill power limit of 200 GWh per annum is expected to be the primary bottleneck in the system. The optimiser may choose one of four grind sizes for each input parcel of material. Coarser grinds incur lesser power and steel costs while having a lower recovery. Conversely, finer grinds achieve a greater recovery in the Flotation procedure but incur at a higher cost from consumption of power and steel. As the Ball mill power limit is expected to be the bottleneck, the grind has a secondary effect where in essence, it imposes an additional penalty on finer grinds and harder materials that consume more of the limited power capacity. Table 4-5 shows this relationship.

Table 4-5: Power and Steel consumption in the Ball Mill.

Power Consumption (kWh/t)						Rock Type
Output P80	OX1	OX2	TR1	TR2	FR1	FR2
75µm	10.0	10.0	14.3	14.3	17.3	17.3
106µm	9.0	9.0	13.5	13.5	16.1	16.1
150µm	8.0	8.0	12.4	12.4	15.0	15.0
200µm	7.0	7.0	11.3	11.3	13.5	13.5

Steel Consumption (kg/t)						Rock Type
Output P80	OX1	OX2	TR1	TR2	FR1	FR2
75µm	0.7	0.7	1.2	1.2	1.5	1.5
106µm	0.6	0.6	1.0	1.0	1.2	1.2
150µm	0.5	0.5	0.8	0.8	0.9	0.9
200µm	0.3	0.3	0.5	0.5	0.6	0.6

The Flotation procedure itself 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 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 shown in Table 4-6

Table 4-6: Gold and Copper recovery in the Flotation procedure.

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%

Flotation incurs a flat $1.00/t variable cost and a period cost of $10M per annum. The product from the Flotation circuit is a concentrate product and is sold with gold yielding $1300/tr.oz and copper $5500/t.

4.5.2 Grade Engineering Cases

Cases 2-4 with Grade Engineering examine the effect of adding a single coarse-separation technique, while cases 5-7 combine two coarse-separation techniques and case 8 has all three coarse-separation techniques enabled. The Grade Engineering processes were added between the Mining procedure and the Processing procedures (Heap Leach and the Processing Plant). See *Enterprise Model Case 8: All Grade Engineering Options – Diagram* in the Appendices for a flow diagram of the full model with all Grade Engineering procedures.

Material flows from the Mining procedure to any of the three coarse-separation processes, or bypasses Grade Engineering and flows directly to the Processing Plant or Heap Leach. The flow of material to Grade Engineering processes may occur via a Mining Stockpile except in the case of sending stockpiled material to Differential Blasting, as the choice to execute Differential Blasting only occurs when material is extracted.

This case study only examined the separation of material through either the Screening Plant (Natural Deportment of Grade by Size or Differential Blasting) or Bulk Sorting, whereas in reality material coming from the Screening Plant to the Processing Plant could also be treated through Bulk Sorting. However, this would add unnecessary complexity to the case study and was not examined.

4.5.2.1 Screening Plant (Natural Deportment of Grade by Size and Differential Blasting)

Coarse separations using the Natural Deportment of Grade by Size and Differential Blasting require the installation of a Screening Plant at the operation. The Screening Plant was located in close proximity to the Processing Plant. Fines (higher-grade) from the Screening Plant can be conveyed a short distance to the Processing Plant ($0.10/t) or loaded into trucks and transported to Heap Leach ($0.75/t). Coarse (lower-grade) material from the Screening Plant was loaded into trucks and transported to the Heap Leach or the Dump ($0.75/t). All material treated at the Screening plant incurred a variable cost of $0.15/t and $0.5M per annum in period costs. Material treated through Differential Blasting incurred an additional variable cost of $0.05/t to cover alterations made to the blast design.

All material types were given an average Natural Grade by Size response across the domain. The average response for Domain 1 types (within the intrusion) had a significantly greater average response than the equivalent rock type in Domain 2 (outside the intrusion). Coarse material was assumed to retain a p80 particle size of 200mm, when in reality the p80 would increase, while fines were assumed to have a p80 particle size equal to the mesh size of the selected screen.

The response rankings (RR) for each element, domain and coarse separation process are displayed in Table 4-7. Response rankings were developed to describe the strength of a natural grade by size response, across different mass pulls to undersize, using a single metric. The larger this number the stronger the natural grade by size response. Differential Blasting and Bulk sorting responses may also be expressed as a response ranking for a given screening mass pull to undersize, in the case of Differential Blasting, or percentage of mass accepted, in the case of Bulk Sorting.

Table 4-7: Grade Engineering response rankings (RR) by coarse-separation process, domain and element

Rock Type / Domain	OX1		OX2		TR1		TR2		FR1		FR2	
Element	Au	Cu	Au	Cu	Au	Cu	Au	Cu	Au	Cu	Au	Cu
Differential Blasting (RR) at 61% Mass Pull to Undersize					150	130	40	30				
Screening for Natural Deportment(RR)	120	80	70	50	120	80	20	10	120	80	70	50
Bulk Sorting (RR) 20% Accept									50	86	50	86
Bulk Sorting (RR) 40% Accept									89	122	88	122
Bulk Sorting (RR) 60% Accept									87	136	87	136
Bulk Sorting (RR) 80% Accept									54	154	54	154

Only Transitional material was assumed to be treated through Differential Blasting and was modelled using a single average response that enhanced the natural grade by size response across the domain. Once again, Transitional material in Domain 1 (inside the intrusion) had a greater average Differential Blasting response than Transitional material in Domain 2 (outside the intrusion).

After the Differential Blast procedure, the material is screened. It is assumed that material is sent to the Screening Plant although this is only implicitly modelled; a screen size is not specified. Fines from the screening of material that has been treated via Differential Blasting were given a p80 particle size of 150mm while the coarse oversize from the screening of Differential Blasting material retains the p80 input size of 200mm. Differential Blasting tonnages contributes to the overall Screening Plant throughput and is therefore subject to the same capacity constraint and period costs associated with the Screening Plant.

Instead of setting a fixed throughput limit on the Screening Plant, the optimiser is able to purchase capacity as required over the LOM at a cost of $2.00/t.

All material leaving any of the Grade Engineering processes can be rehandled to a stockpile ($0.75/t).

4.5.2.2 Bulk Scale Sensing and Sorting

Coarse separation using Bulk Sensing and Sorting, using a cross belt analyser, was performed on the conveyor feeding the coarse ore stockpile (COS) of the Processing Plant. Material diverted from this conveyor is staked and loaded into trucks and rehandled to Heap Leach or Dump ($0.75/t). Accepted material incurs no cost and continues along the conveyor to the COS. No variable cost was applied to sense material but the sensing and sorting equipment incur $1.5M per annum in period costs.

Only Fresh material was assumed to respond to Bulk Sorting. Both high-grade and low-grade outputs retain a p80 particle size of 200mm.

4.5.2.3 Grade Engineering Responses

The response of material for each rock domain type in each Grade Engineering processes is shown in **Error! Reference source not found.** and Figure 4-7. These figures depict the relative portion of fines from the screening plant for Differential Blasting and Screening for Natural Deportment (or the accept stream for Bulk Sorting) as positive mass separations on the primary y axis; with the corresponding relative portion of coarse or reject material presented as negative mass separations on the same axis. The relative change in the grade of fines (upgraded or accepted material) and coarse material (downgraded or rejected material) from each Grade Engineering process is presented on the secondary y axis. Each of the grade Engineering processes are presented on the x axis.

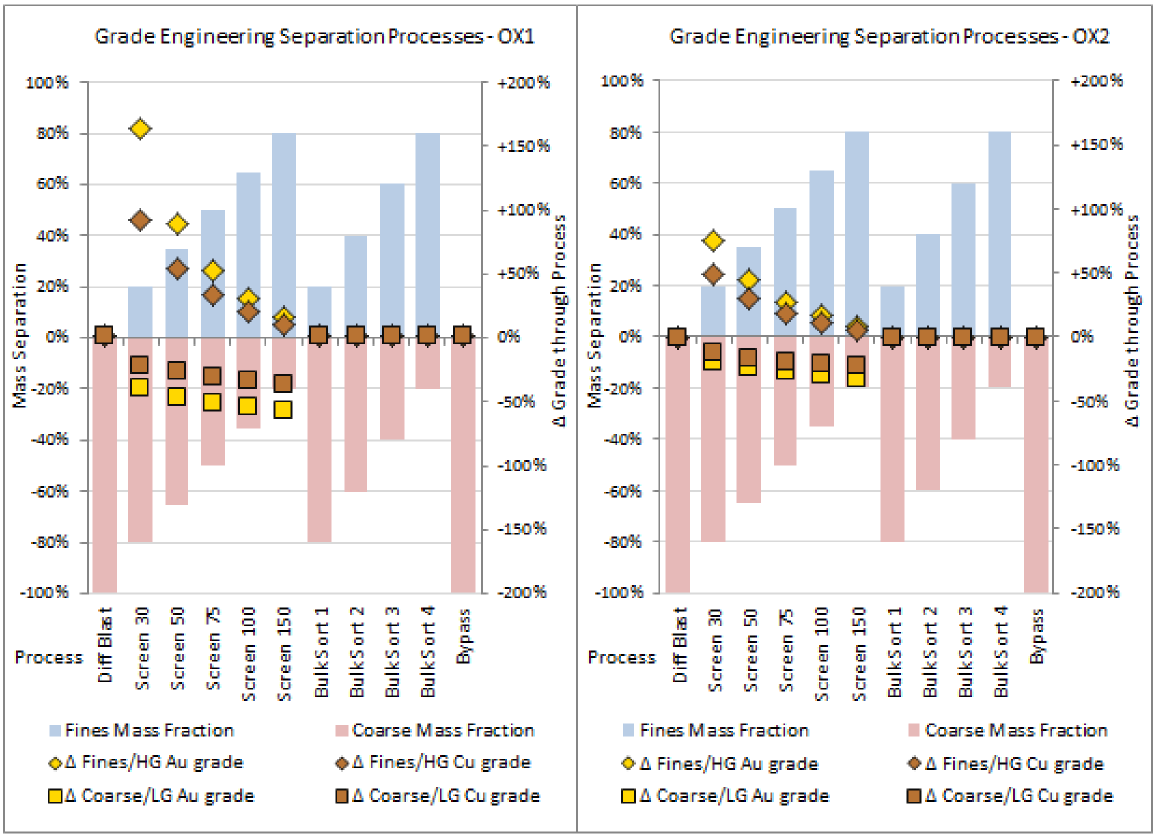


Figure 4-6: Oxide responses to Grade Engineering Processes.

Oxide material only responded to Screening for natural deportment of grade by size, Bulk Sensing and Sorting and Differential Blasting had no effect on Gold and Copper deportment. OX1, like other Domain 1 materials, has a greater response to Screening for natural deportment than OX2.

TR1 responds to both Screening for natural deportment and Differential Blasting, while Bulk Sensing and Sorting has no effect on Gold and Copper deportment. TR2 has a very weak response to all Grade Engineering processes. It is expected to bypass Grade Engineering.

Both FR1 and FR2 respond to Bulk Sensing and Sorting and Screening for natural deportment of grade by size. FR1, like other Domain 1 materials, has a greater response to screening for natural deportment than FR2.

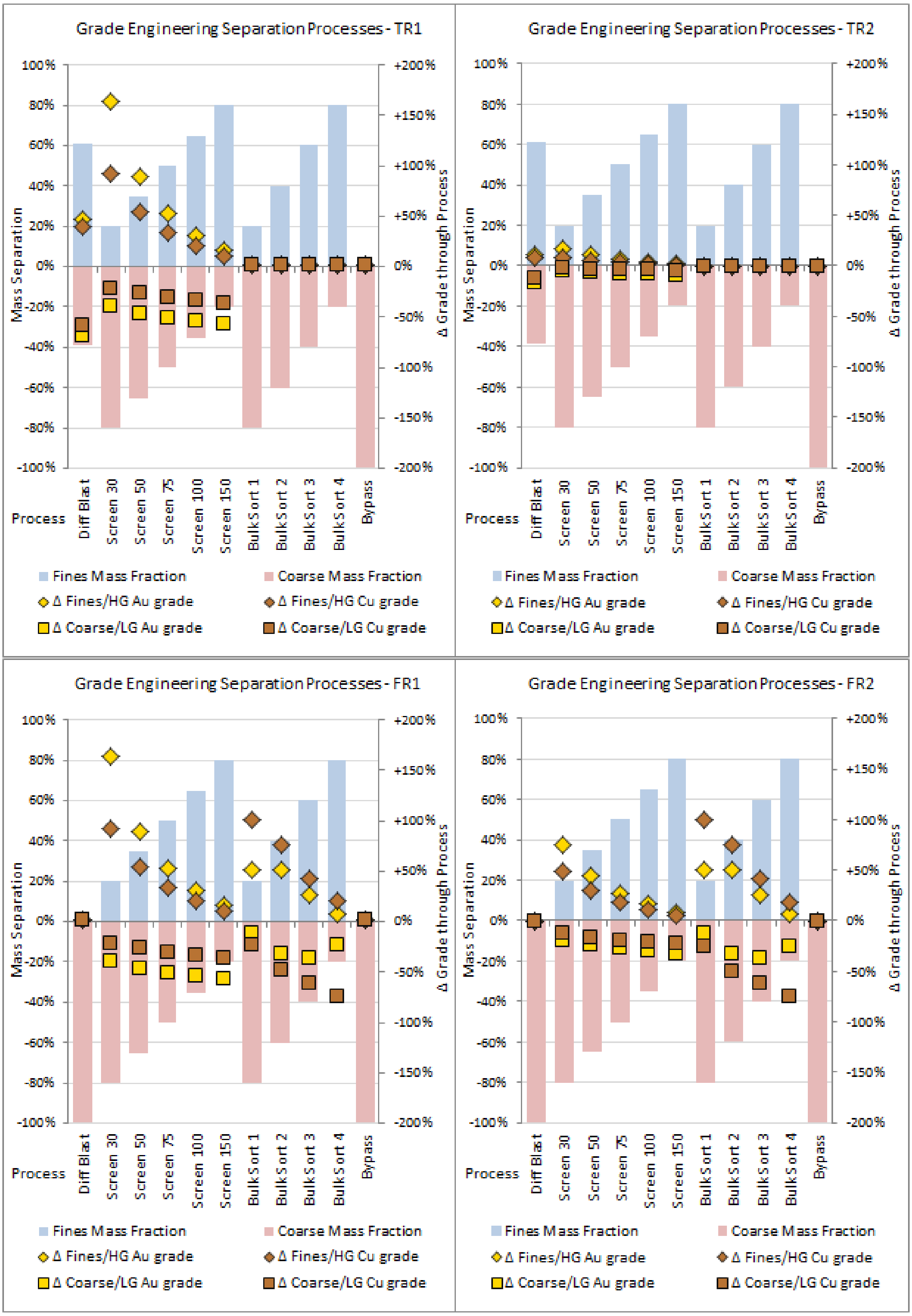


Figure 4-7: Transitional and Fresh material responses to Grade Engineering Processes.

5 Results

5.1 Base Case

The result of the optimised Base Case (Case 1) without Grade Engineering is documented here.

Table 5-1: Base Case (Case 1) Result

Case	Run	Differential Blasting	Screening for Natural Deportment	Bulk Sensing and Sorting	Pit	All-inclusive NPV
1	037	FALSE	FALSE	FALSE	v9	$ 628,247,865

5.1.1 Base Case - Financial

The summary of cash-flow over the LOM is shown in Figure 5-1. After initial capital expenditure the operation produces large positive cash flow for four years, primarily through processing high-grade ore in the Processing Plant. From 2106 to 2111 lesser cash-flows are recorded as material processed in the Processing Plant is sourced from stockpiles and is of lower grade. In 2111 the Processing Plant ceases operation and the Heap Leach continues operating until 2113, when the whole operation is shut down.

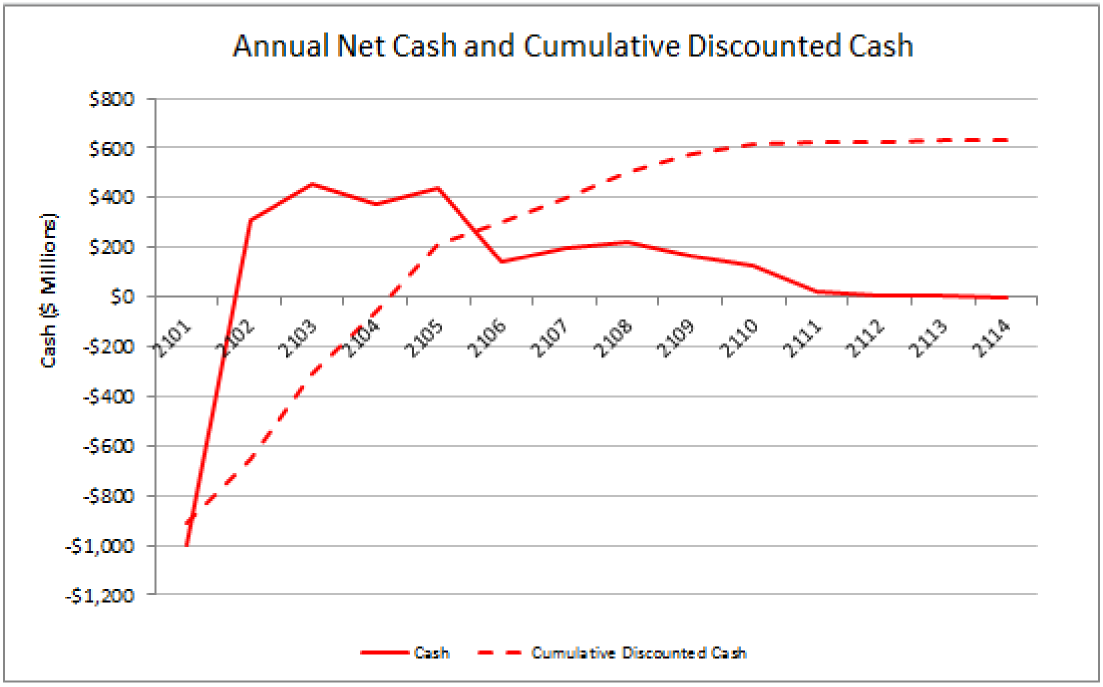


Figure 5-1: Base Case cash-flow

A more detailed breakdown of the source of revenue and costs is shown in Figure 5-2. The Processing Plant contributes the vast majority of revenue, of which the larger portion is copper. The initial capital expenditure is large compared to the other cost, while the majority of ongoing costs are variable processing costs.

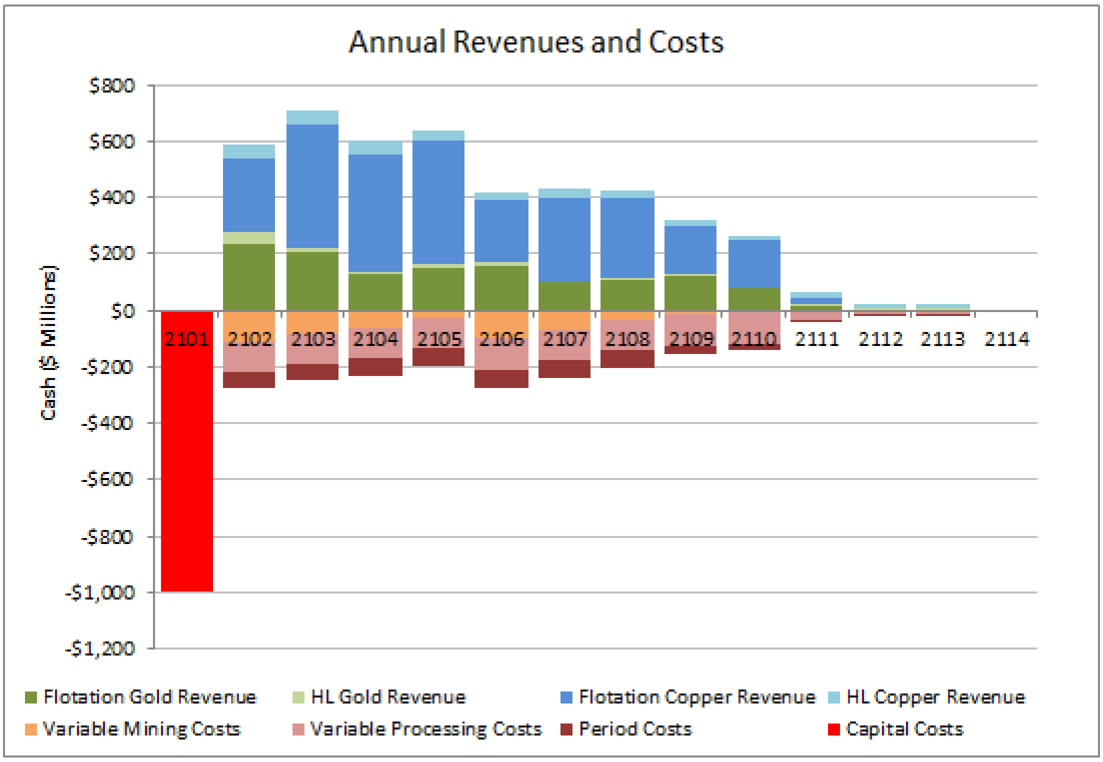


Figure 5-2: Breakdown of revenue and expenditure for Base Case. Note that these cash-flows are not *discounted.*

5.1.2 Base Case - Behaviour

Mining rates vary significantly from year to year. This is not considered a problem by Whittle Consulting provided that physical mining and processing limitations are not encountered (e.g. congestion of mobile mining equipment and maintaining sufficient availability of ore for mineral processing) and there is sufficient financial benefit to justify varying the use of mining equipment, operators and supporting facilities.

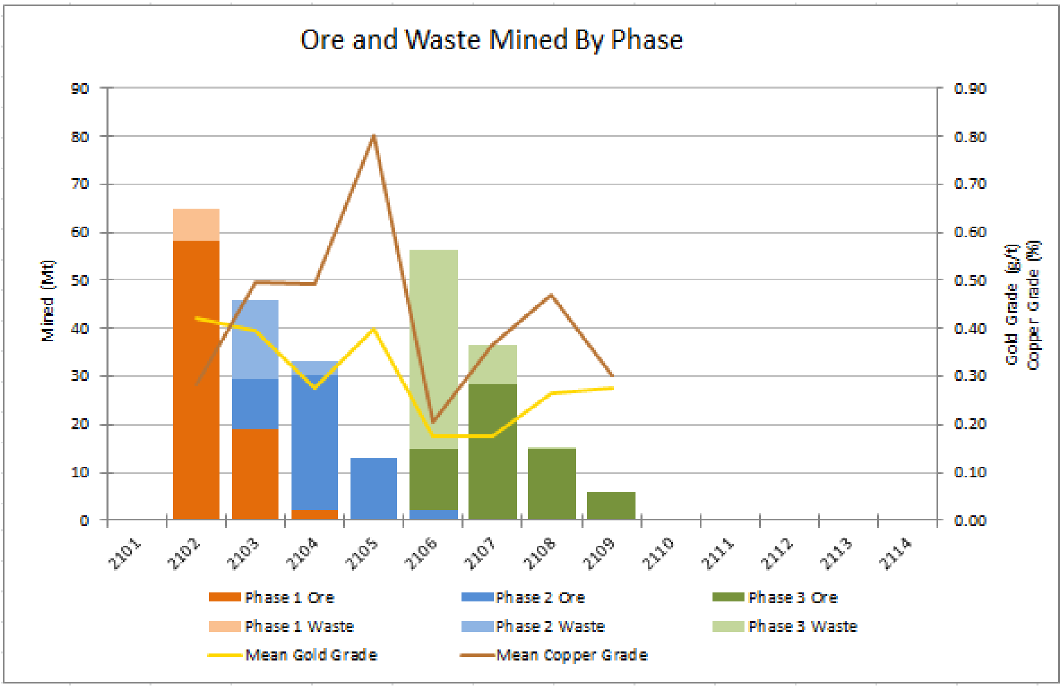


Figure 5-3: Base Case mining of each phase, showing gold and copper grades present in ore.

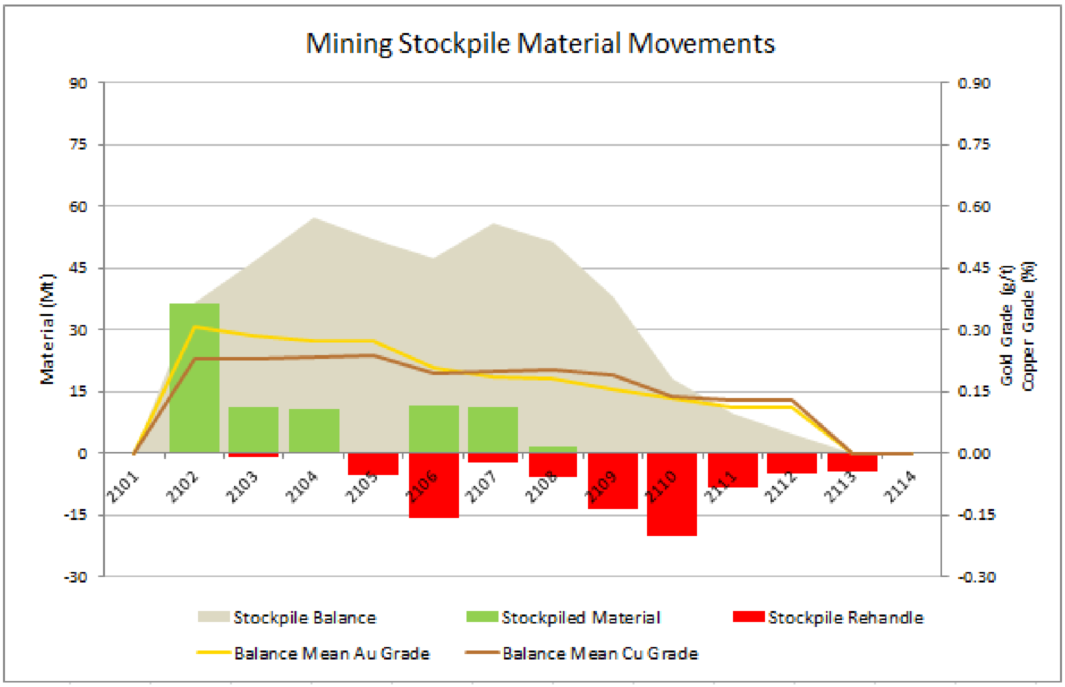


Figure 5-4: Material added to and rehandled from stockpiles for the Base Case. Note that what appears here as a single stockpile is modelled in Prober as many stockpiles for different material types and grades.

The optimised operation initially builds a large stockpile, owing to the large quantity of low-value ore in phase 1 and a high initial mining rate. The mean stockpile grade drops over time as the cut-off grades to the Processing Plant and Heap Leach reduce and correspondingly the mean stockpile input grade reduces.

The operation of the two revenue-earning processing lines, the Processing Plant and the Heap Leach, over the LOM is shown in Figure 5-5 and Figure 5-6.

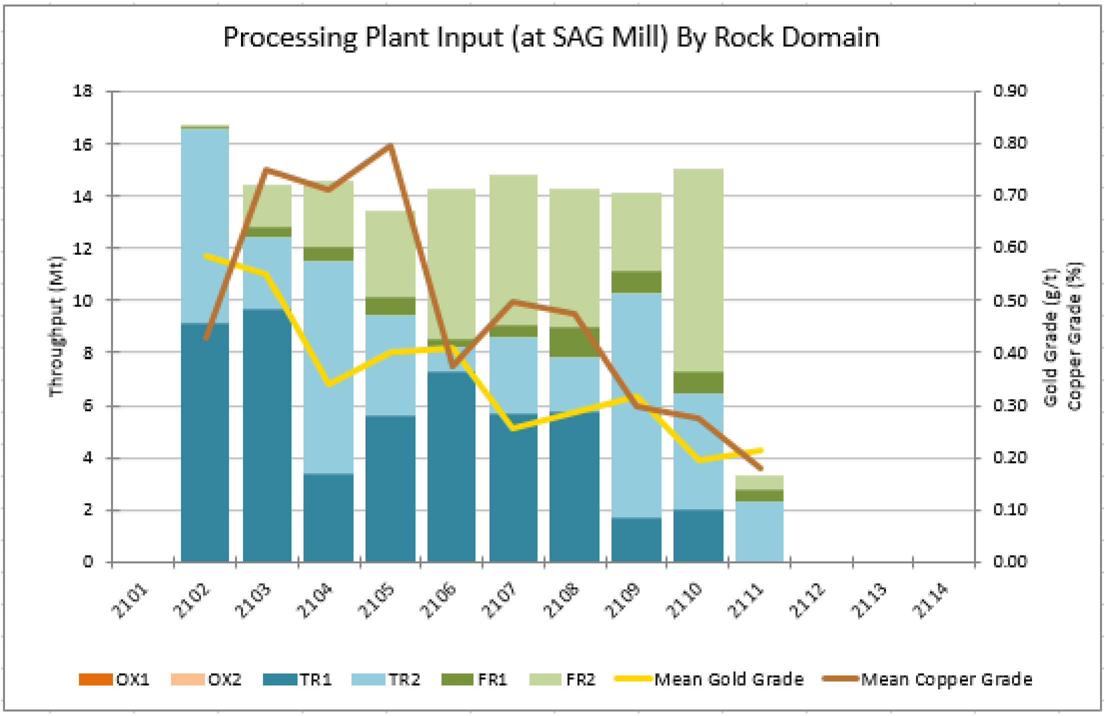


Figure 5-5: Processing Plant input for Base Case.

The Processing Plant processes significantly higher-grade ore compared to the Heap Leach, in line with the maximum cash path calculations in the *Highest Net Cash Paths – Case 1* in the Appendix. However, this is only an important comparison for Transitional material (TR1 and TR2); the Processing Plant processes all Fresh material and the Heap Leach all Oxide material owing to the comparatively better recovery rates achieved.

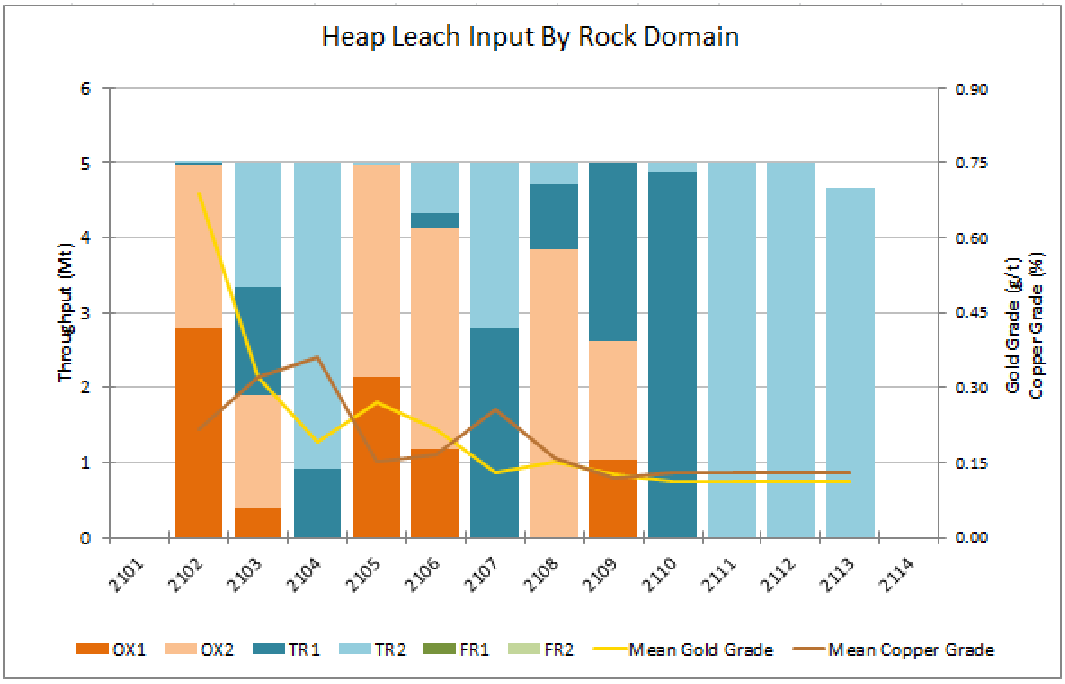


Figure 5-6: Heap Leach input for Base Case.

5.1.3 Base Case - Bottlenecks

Consistent with the Whittle Methodology, the primary bottleneck in the system is the most capital-intensive component. This is the Ball Mill in the Processing Plant, which is constrained by the amount of Power (kWh) that it can apply to the milled material.

The Ball Mill throughput is shown in Figure 5-7. The optimiser has the ability to choose the grind size to which each portion of material is processed. Only the coarsest grind (200µm) and finest grind (75µm) are used; the coarse grind to process lower-grade at a greater throughput and the fine grind to process higher-grade material at a higher recovery rate.

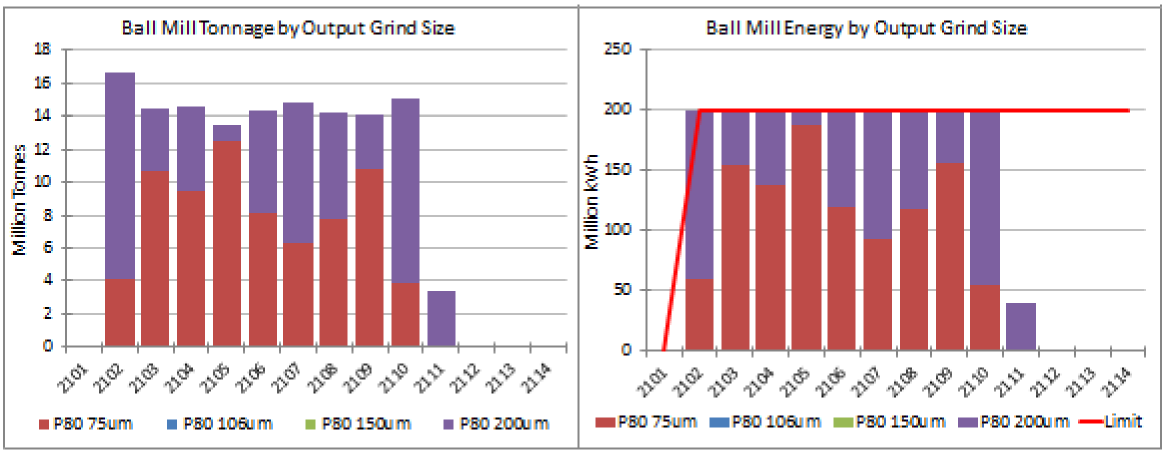


Figure 5-7: Base Case Ball Mill throughput over the Life of Mine.

The Heap Leach, which is parallel to the Mill-Flotation processes, is also governed by a bottleneck. This branch of the processing system is significantly less lucrative than the Processing Plant, owing to lesser recoveries, so has a lesser effect on the total cash generated by the operation than the Ball Mill bottleneck does.

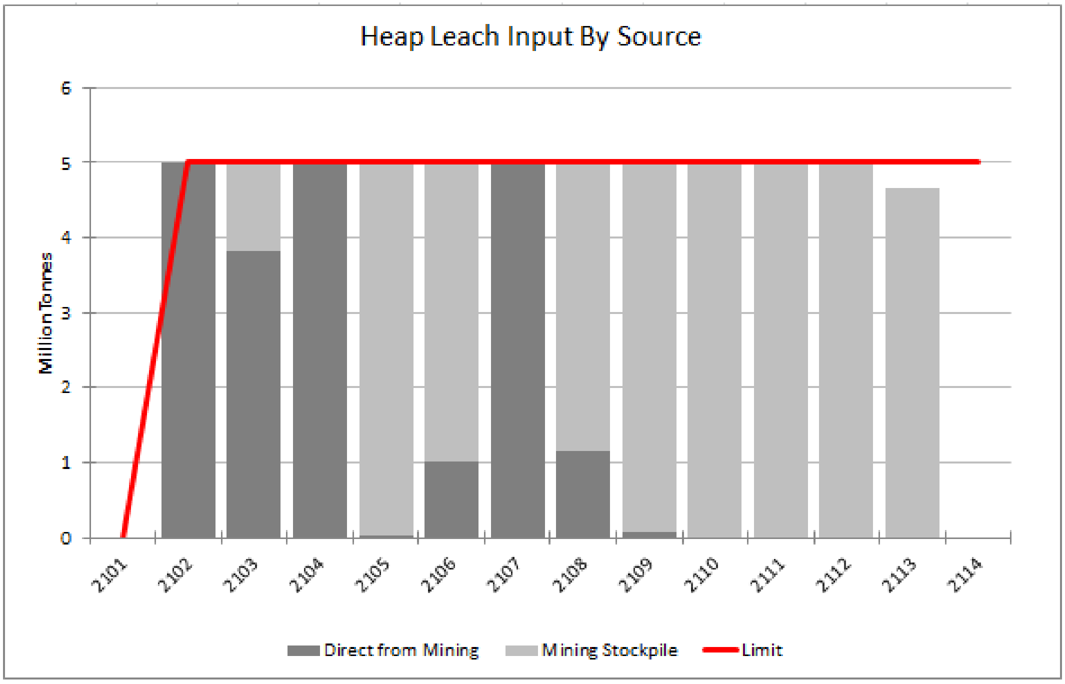


Figure 5-8: Base Case Heap Leach throughput with constraint.

Mining tonnage is not a bottleneck upon the system here; however, a Vertical Rate of Advance (VRA) limit does constrain the system in some years.

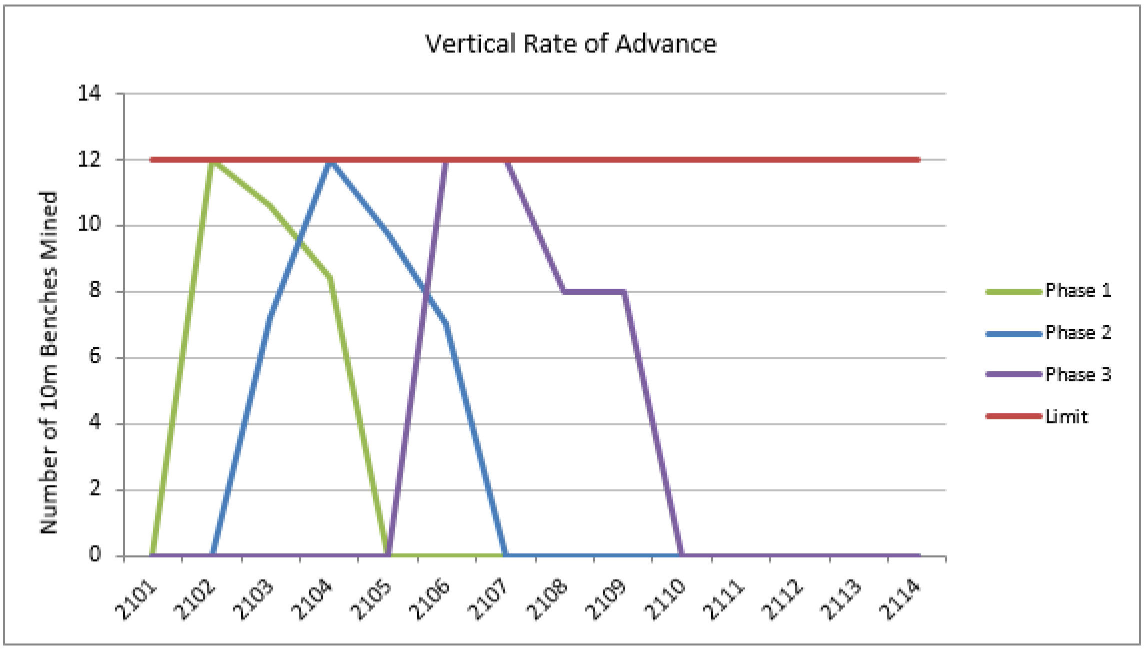


Figure 5-9: VRA for each phase, with constraint.

5.2 Grade Engineering

An improvement in financial value was observed in all Cases when adding Grade Engineering coarse separation processes to the operation and re-optimising using Prober.

Table 5-2: Run Matrix with each combination of Grade Engineering coarse separation processes.

Case	Run	Differential Blasting	Screening for Natural Deportment	Bulk Sensing and Sorting	Pit	All-inclusive NPV	Increase over base
1	037	FALSE	FALSE	FALSE	v9	$ 628,247,865	
2	041	FALSE	FALSE	TRUE	v9	$ 645,226,809	2.7%
3	042	FALSE	TRUE	FALSE	v9	$ 659,246,393	4.9%
4	043	TRUE	FALSE	FALSE	v9	$ 675,749,432	7.6%
5	044	FALSE	TRUE	TRUE	v9	$ 669,918,561	6.6%
6	045	TRUE	FALSE	TRUE	v9	$ 689,107,617	9.7%
7	046	TRUE	TRUE	FALSE	v9	$ 679,313,692	8.1%
8	035	TRUE	TRUE	TRUE	v9	$ 690,535,263	9.9%

5.2.1 Grade Engineering - Financial

Whittle Consulting typically presents optimised net cash results as a red line, against a blue line for the non-optimised case. For this case study, the base case is already optimised and so is represented by a red line, while the improved cases are re-optimised with the Grade Engineering processes added; these are represented by yellow-orange lines.

Figure 5-10 shows where the Grade Engineering Case 8 (where all coarse separation processes are active) outperforms the Base Case (Case 1). Grade Engineering brings cash-flow forward by accelerating the rate that gold and copper pass through the system's bottlenecks.

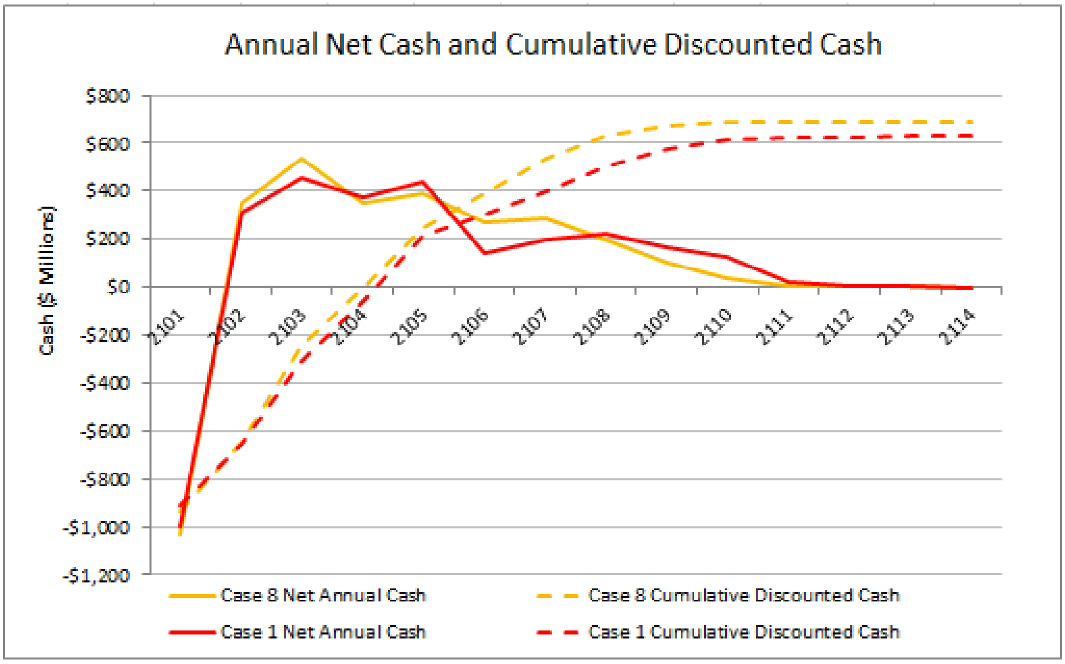


Figure 5-10: Comparison of Grade Engineering Case 8 and the Base Case (Case 1) cash generation.

Total copper and gold recovered and total revenue generated over the LOM was also higher in Grade Engineering Case 8; despite less ore, gold and copper being processed overall (Table 5-3). These results show the principle of value-based Metal Exchanges between the Heap Leach and the Processing Plant, using coarse-separation processes that increased global metal recovery of the system.

Table 5-3: Comparison of total material processed in the Base Case and Grade Engineering Case 8

Process	Base Case (Case 1)			Grade Engineering (Case 8)			Difference from Base Case		
	Ore (Mt)	Au (oz)	Cu (t)	Ore (Mt)	Au (oz)	Cu (t)	Ore (Mt)	Au (oz)	Cu (t)
Heap Leach (HL)									
Material Treated	59.7	407,632	113,494	58.1	382,194	105,467	-1.6	-25,438	-8,027
Grade (Au g/t, Cu %)		0.213	0.190		0.205 g/t	0.182		-0.008	-0.009
Metal Recovered		105,203	67,179		100,115	63,166		-5,088	-4,014
Avg Recovery		25.8%	59.2%		26.2%	59.9%		0.4%	0.7%
Flotation Plant (FP)									
Material Treated	134.9	1,602,855	674,025	125.8	1,603,793	675,450	-9.1	938	1,425
Grade (Au g/t, Cu %)		0.370	0.500		0.396	0.537		0.027	0.037
Metal Recovered		990,292	492,140		1,007,225	498,137		16,933	5,997
Avg Recovery		61.8%	73.0%		62.8%	73.7%		1.0%	0.7%
Total Processed (HL+FP)									
Material Treated	194.6	2,010,487	787,518	183.9	1,985,987	780,917	-10.7	-24,500	-6,602
Grade (Au g/t, Cu %)		0.321	0.405		0.336	0.425		0.014	0.020
Metal Recovered		1,095,495	559,319		1,107,340	561,302		11,845	1,983
Avg Recovery		54.5%	71.0%		55.8%	71.9%		1.3%	0.9%

Compared to the Base Case, Grade Engineering Case 8 incurs greater Capital and Period costs per year for coarse-separation equipment, however Period costs were saved at the end of the LOM as Grade Engineering completes processing at the Processing Plant earlier than in the Base Case. Variable costs are also lower due to reduced lifetime of the SAG Mill, Ball Mill, Flotation and Heap Leach, plus steel and power savings owing to smaller particle size at entry to the SAG Mill.

Revenue in Grade Engineering Case 8 is greater than Base Case revenue in the first six periods of plant operation and more than 10% greater in the first two periods, in which cash has greater present value than later revenue.

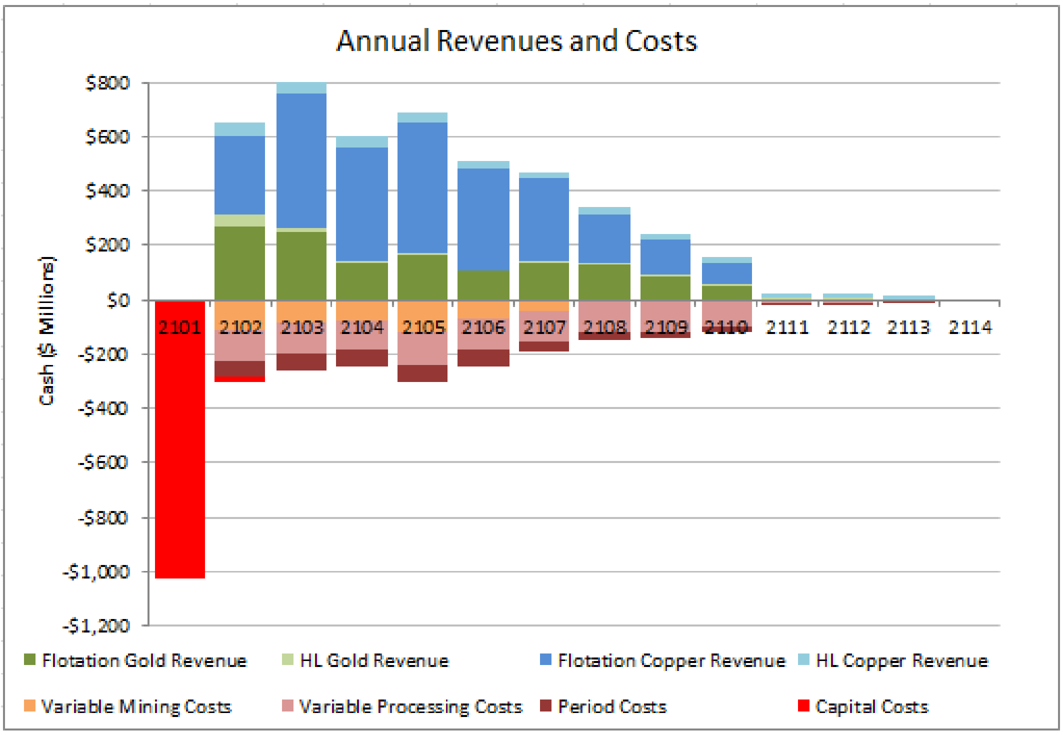


Figure 5-11: Breakdown of revenue and expenditure for Grade Engineering Case 8.

5.2.2 Grade Engineering - Behaviour

The rate of mining is significantly higher in Grade Engineering Case 8 than in the Base Case, with Mining completing in 2107 rather than 2109.

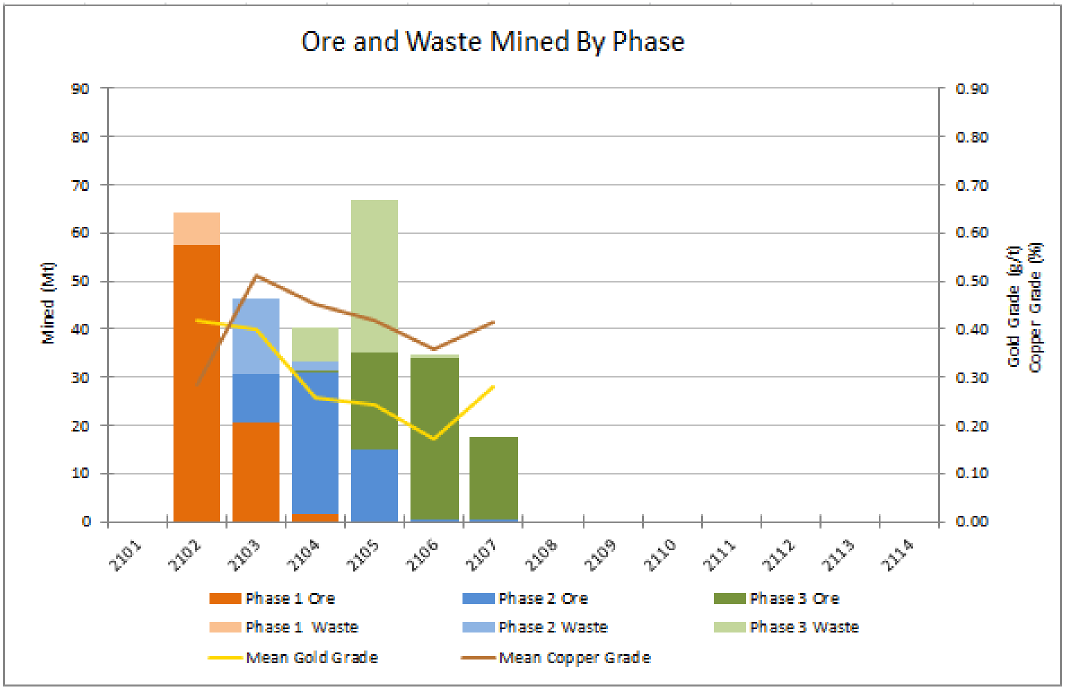


Figure 5-12: Mining in Grade Engineering Case 8

Grade Engineering Case 8 also makes considerably more use of the stockpile than Case 1, to the point where the stockpiles hit the capacity limit of 80Mt in 2106.

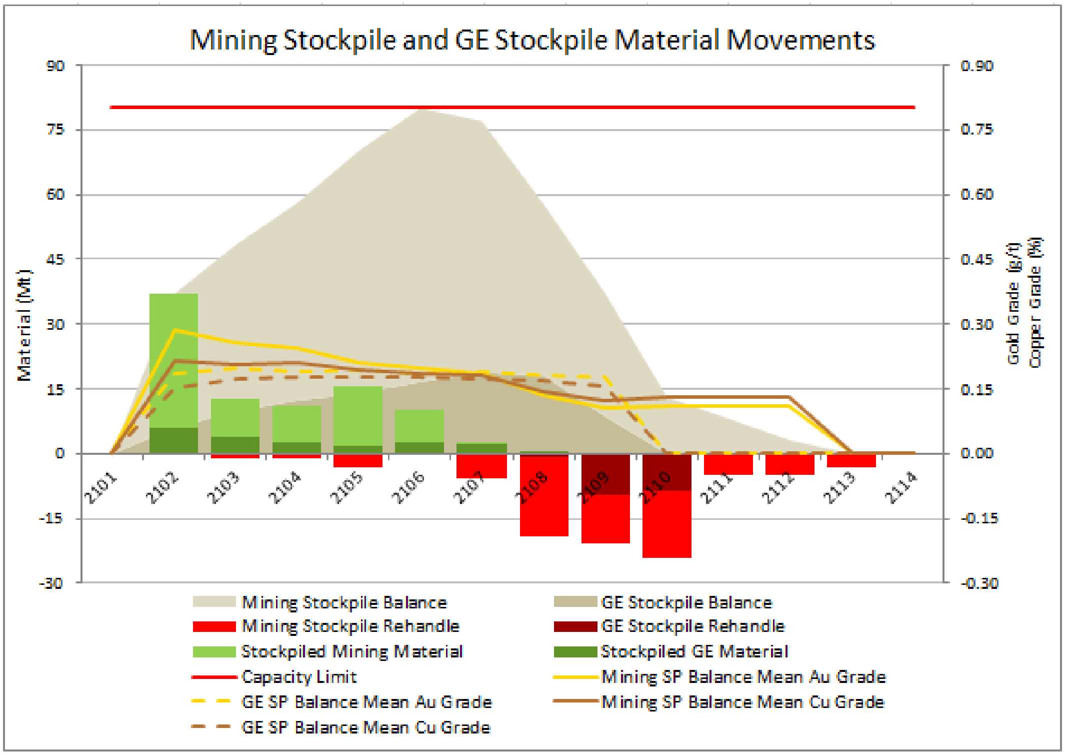


Figure 5-13: Combined Mining and GE stockpile material movements in Case 8. Note that all *GE material stockpiled is coarse low-grade; all higher-grade fine fractions from Grade Engineering go straight to processing.*

A higher mining rate combined with greater stockpile usage demonstrates an important means by which Grade Engineering improves enterprise value; it allows a greater vertical rate of advance through the ore-body searching for high-value ore, as most of the ore can be stripped of a low-grade fraction so that the high-grade takes up less space in the bottlenecks.

The magnitude of usage of Grade Engineering processes is shown in Figure 5-14. Screen capacity purchased at a cost of $2/t is 13.2Mt.

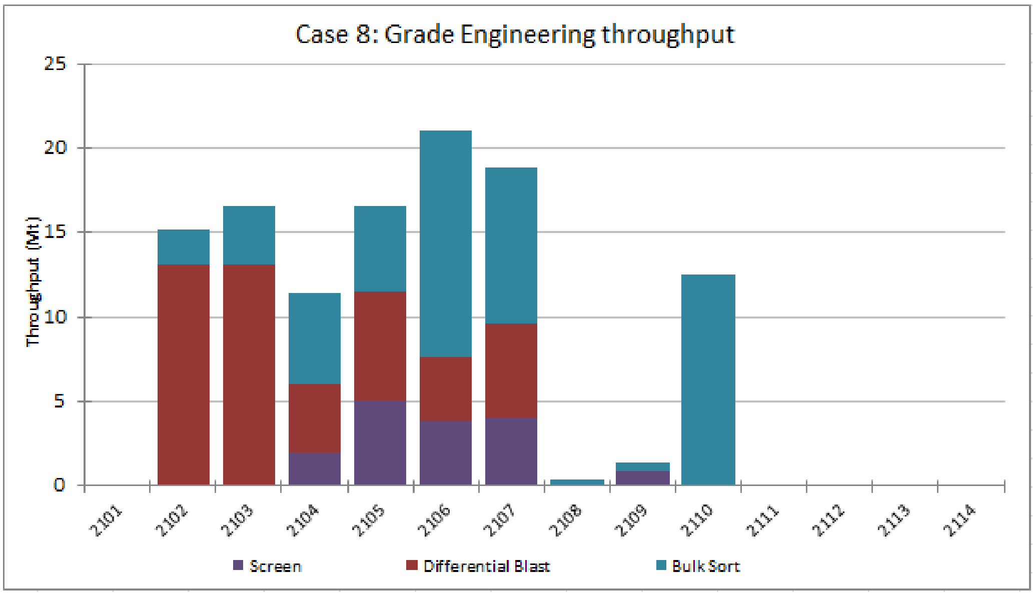


Figure 5-14: Usage of Grade Engineering processes in Case 8. All Differentially Blasted material is TR1. The majority of Screened material is also TR1. The majority of Bulk Sorted material is FR2.

The Processing Plant processes a slightly lower mass of ore compared to the Base Case (Case 1), however that ore is of a notably higher grade, particularly in the first six years of operation. This has a major impact on discounted revenue generation.

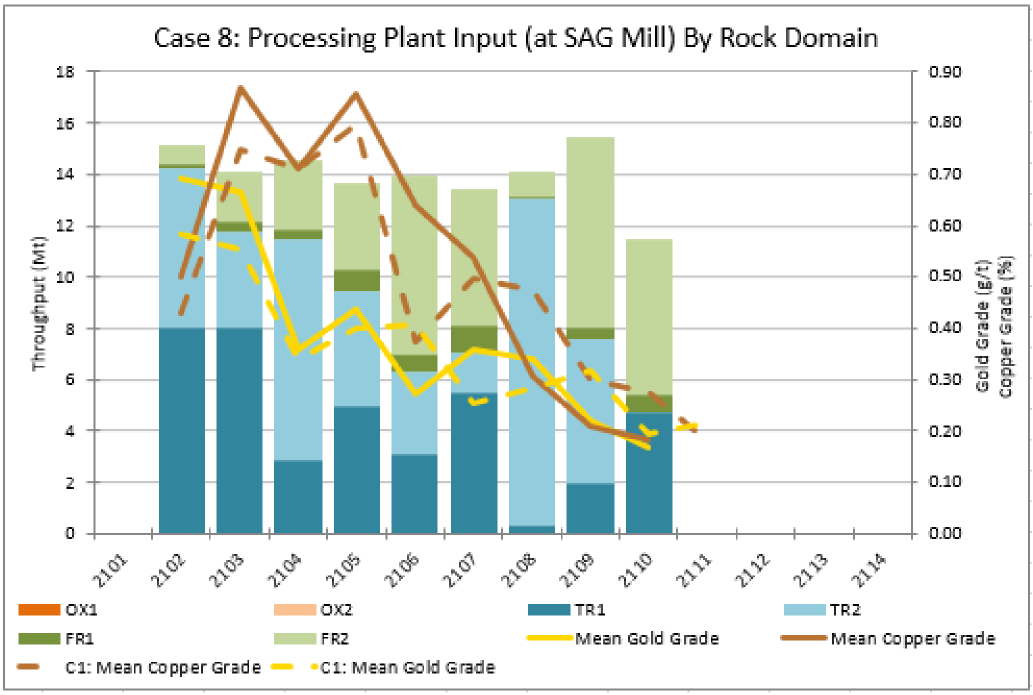


Figure 5-15: Processing Plant throughput in Case 8, with comparison grades from Figure 5-5 for Case 1.

By contrast, the grade of material sent to the Heap Leach is not significantly different from the Base Case.

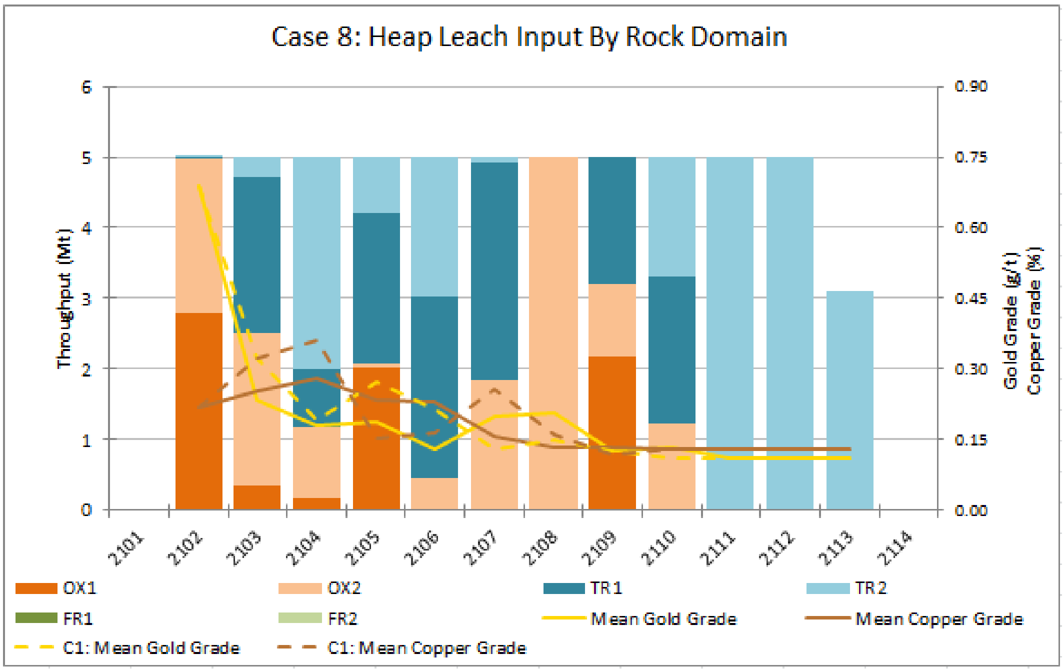


Figure 5-16: Heap Leach throughput in Case 8, with comparison grades from Figure 5-6 for Case 1.

5.2.3 Grade Engineering - Bottlenecks

It is difficult to directly quantify the reduction in pressure on the primary bottleneck from Grade Engineering; however it is observable in the Ball Mill grind size. In Figure 5-17 it can be observed that the proportion of material ground to a fine grind (75µm) is greater in Grade Engineering Case 8 than in the Base Case (Case 1). This will yield higher recovery in Flotation and magnifies the already-higher grade of ore at the Processing Plant with Grade Engineering compared to the Base Case. This indicates that the penalty imposed on power usage by the Ball Mill power bottleneck is lower in Grade Engineering Case 8 than it is in the Base Case.

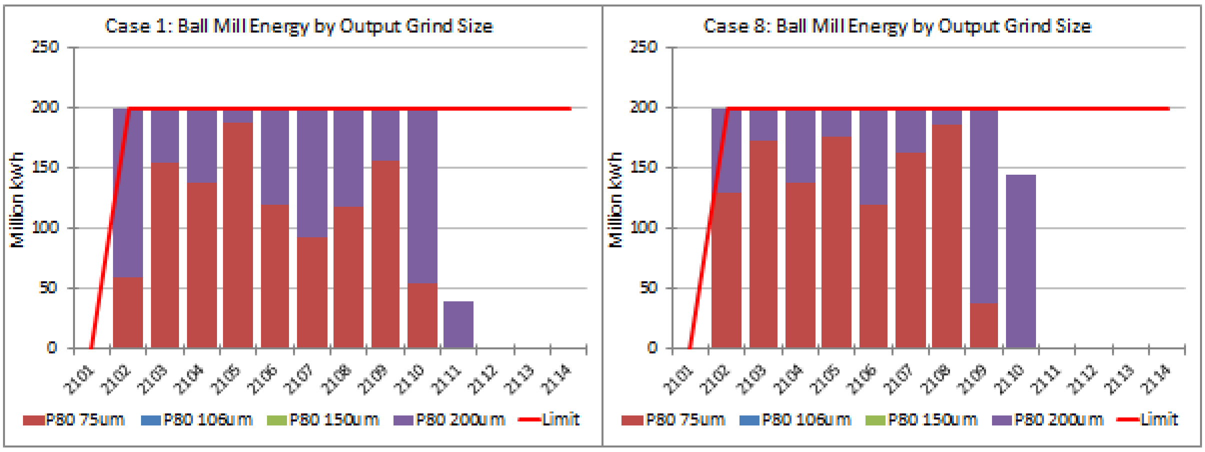


Figure 5-17: Comparison of Ball Mill throughput by power usage between the Base Case (Case 1) and Grade Engineering Case 8.

The increase in the usage of a fine grind is made possible by the reduction in pressure on the Ball Mill power bottleneck due to Grade Engineering processes. The majority of the material processed through the Processing Plant over the LOM in Grade Engineering Case 8 is the higher-grade product (Screening Plant fines and Bulk Sort accept streams) from coarse-separation processes.

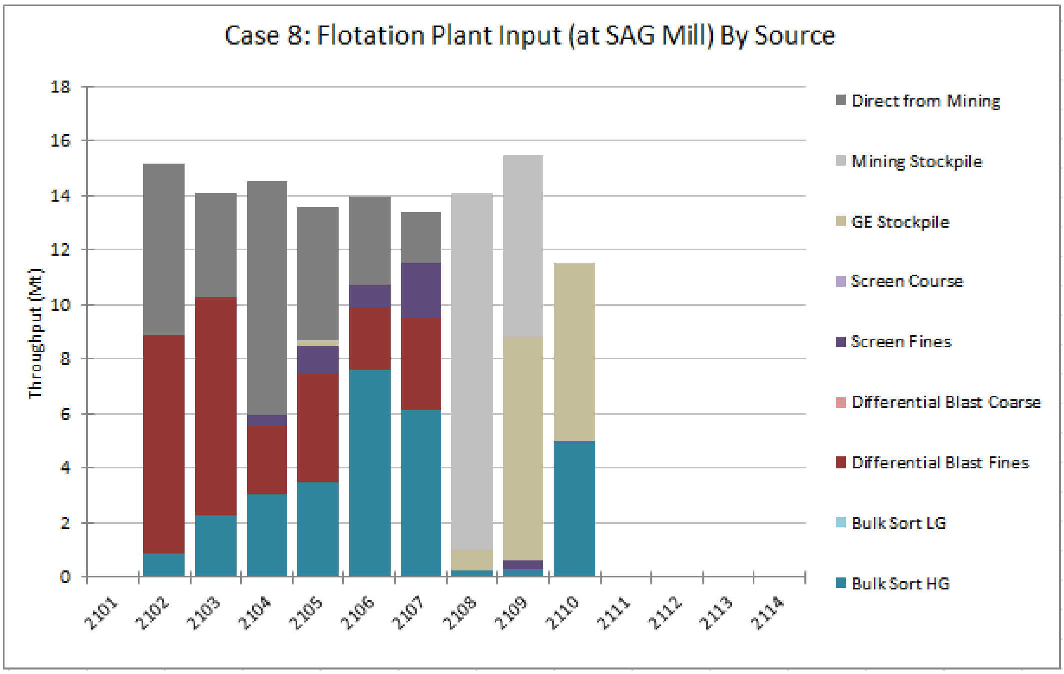


Figure 5-18: Processing Plant input by material source.

Some of the lower-grade material (coarse product from the Screening Plant and diverted material form Bulk Sensing and Sorting) separated through Grade Engineering processes is instead processed through the Heap Leach (directly or via the stockpile), however much of it is sent to the Dump. Without Grade Engineering this sub-economic material would occupy valuable space in the Processing Plant or Heap Leach.

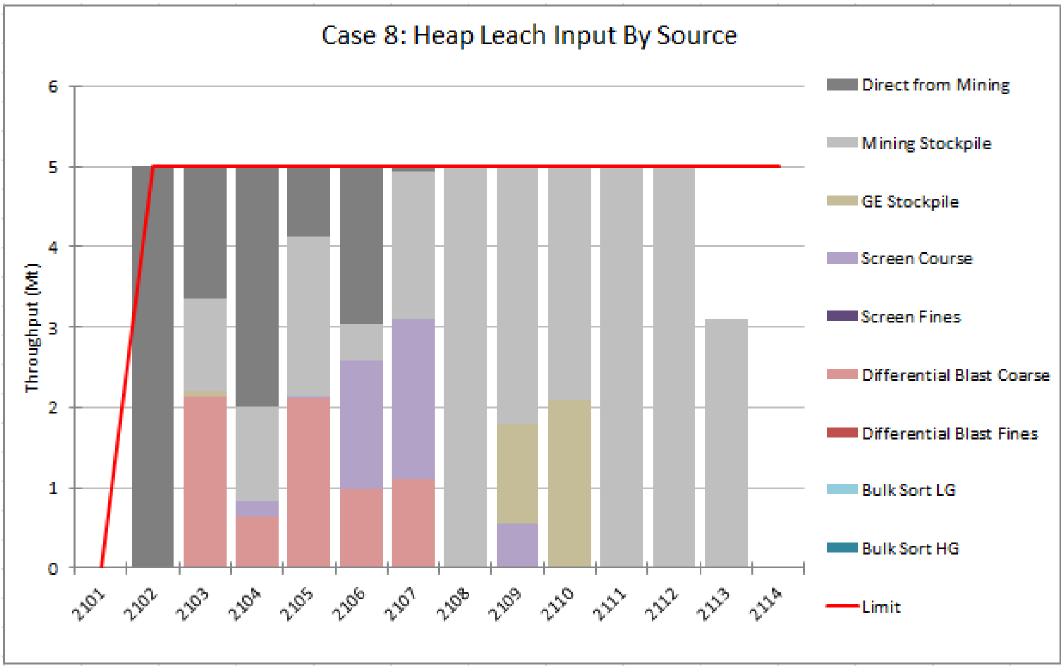


Figure 5-19: The Heap Leach processes some of the coarse material produced by Grade Engineering processes.

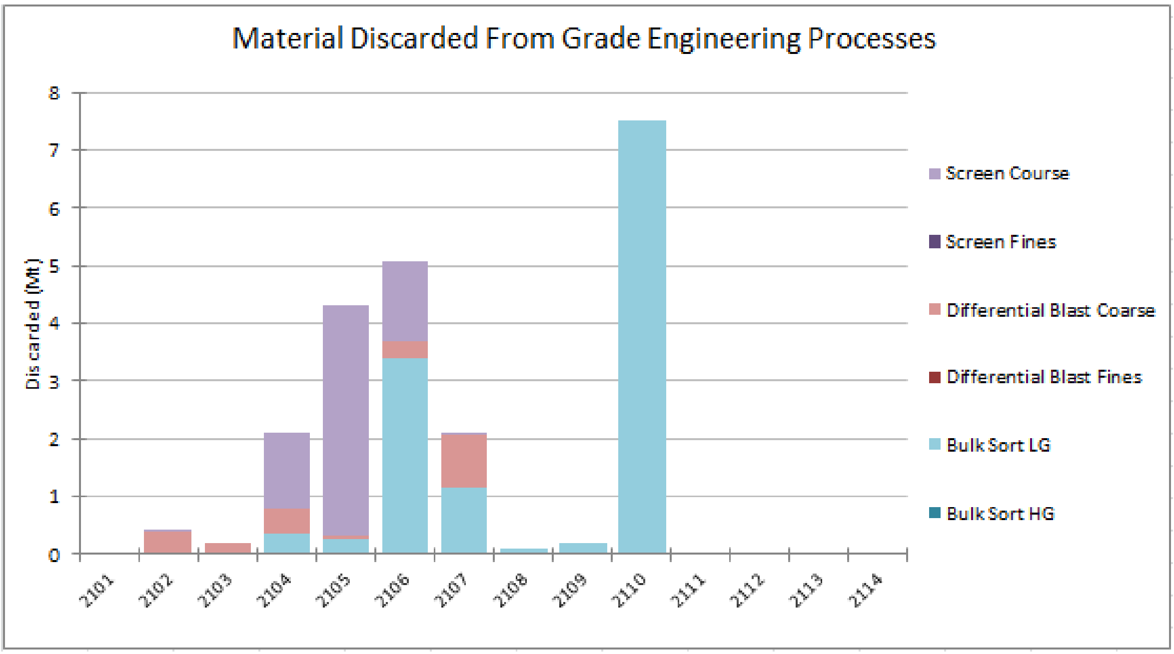


Figure 5-20: Some of the coarse and low-grade material from the Grade Engineering processes is sent to the dump rather than being processed. This is true of all the Bulk Sort LG generated, as this has a low recovery in the Heap Leach.

Vertical Rate of Advance limits were only of minor importance in the Base Case, however in Grade Engineering Case 8 they become a significant limiting factor. Grade Engineering and stockpiling allows processing of the ore body to be accelerated in the search for high-grade material. In Case 8 the VRA is a constraint that prevents Grade Engineering from having an even greater impact.

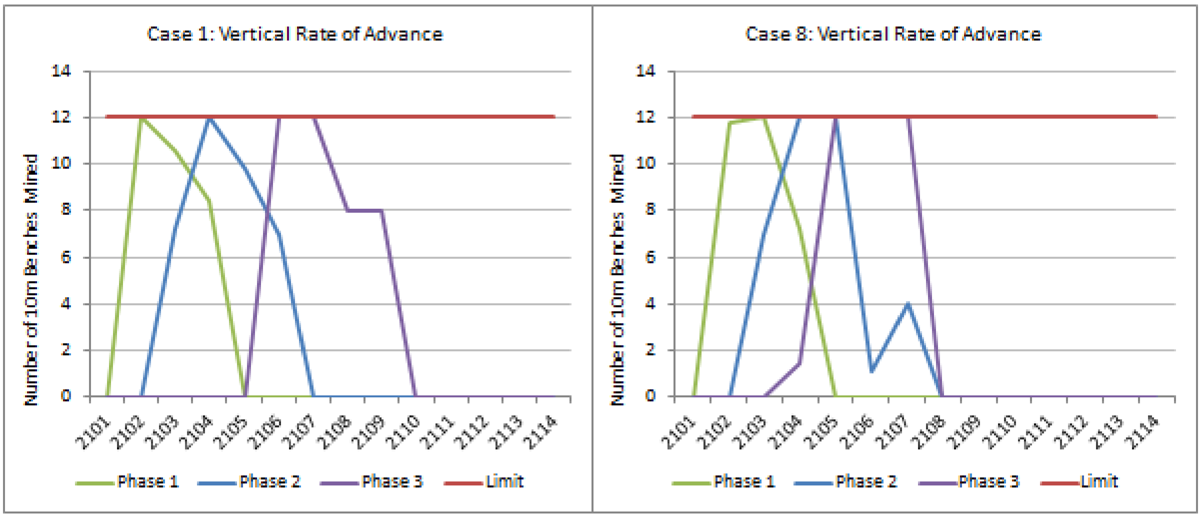


Figure 5-21: Comparison of VRA rates in the Base Case (Case 1) and Grade Engineering Case 8

5.2.4 Energy Efficiency

If the purpose of a business is to make money and power is consumed in order to achieve that, then the relevant metric to measure energy efficiency is energy consumed over net cash generated. However, analysis demonstrates this ratio should and does vary enormously over a mine's life.

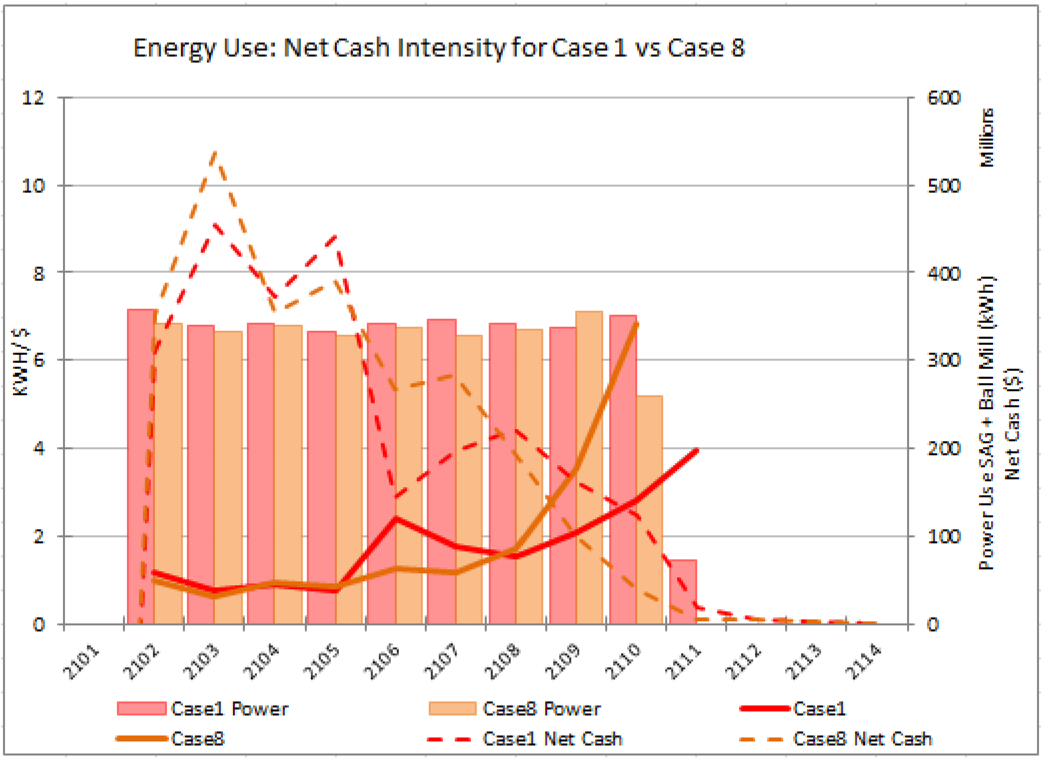


Figure 5-22: Cash generation vs Energy consumed by operation (in SAG and Ball Mill) over LOM.

As energy usage in the Ball Mill is the primary bottleneck, there is little difference between the two cases in energy consumption until the end of the LOM. The net cash generated in Grade Engineering Case 8 is higher however.

This is a broad all-inclusive measure and it is not guaranteed that processes such as Grade Engineering will lead to an improvement in this metric. However, in this case study Grade Engineering has improved the Net Cash Intensity of energy used, from a mean of 2.18kWh/$ in the Base Case to 1.97kWh/$ in Grade Engineering Case 8. The same is true of the average energy intensity of production, with the average energy intensity of the Base Case being 3,004kWh/CuEq.t. decreasing to 2,804kWh/CuEq.t. in Grade Engineering Case 8. However, these results can substantially change when a large amount of marginal ore is made available due to Grade Engineering reducing the economic cut-off for production and expanding the Ultimate pit.

5.2.5 Pit Re-Optimisation

As outlined in *Pit and Phases*, Case 9 is where the pit and phase shapes were re-optimised using all 96 possible processing paths in a system with all Grade Engineering coarse-separation processes enabled. However as shown in Table 5-4, after sizing the new pit in Geovia Whittle and then running this through Prober, the NPV decreased rather than increased.

Table 5-4: Case 8 against two revisions of Case 9. Neither produced a higher NPV than Case 8.

Case	Run	Diff Blast	Screen	Bulk Sort	Pit	All-inclusive NPV	Increase over base
8	035	TRUE	TRUE	TRUE	v9	$ 690,535,263	9.9%
9a	036	TRUE	TRUE	TRUE	vGE5	$ 664,806,778	5.8%
9b	039	TRUE	TRUE	TRUE	vGE5rev2	$ 673,389,957	7.2%

Two likely reasons were identified to explain this. The first is the inexact match between Geovia Whittle and Prober; Geovia Whittle does not account for the time-value-of money and has limited capability to model multiple downstream paths and constraints. It also has a tendency to significantly over-size the first phases of a pit. Workarounds are often used to find a more advantageous first phase (as determined by Prober) and to ameliorate the other shortcomings, however these are not optimal.

The second likely reason is that the Marvin ore body is a vertical ore-body which is accessed through nested conical phases. There are only small differences between different sets of these and therefore the magnitude of change from re-optimising Pits and Phases is small and likely to be dwarfed by the Optimisation error described above.

The authors speculate that, given enough revisions of the Grade Engineering pit resizing process, there would be an improvement in NPV, however benefits are likely to be minimal and were not found to date.

6 DISCUSSION

The results of this case study demonstrate the integration of fundamental coarse-separation principles for Grade Engineering within Whittle Consulting's Enterprise Optimisation approach.

Although this was a hypothetical case study, it has confirmed the potential of Grade Engineering to unlock financial value in new and existing operations and supported the results of detailed Grade Engineering assessments performed by CRC ORE in partnership with operations and proposed projects. Several general principles were also confirmed during the case study, which have been previously presented at CRC ORE annual assemblies and published by CRC ORE's students during its first term of appointment.

6.1 PRIMARY VALUE-GENERATING MECHANISMS

Grade Engineering yields financial value by making two complementary behaviours available to the optimiser. The first is that the lowest value ore that would have filled the plant bottleneck is now separated to create a smaller, higher-value distribution of ore. This material is more valuable per unit of bottleneck and, as the bottleneck controls the overall flow of cash through the system, intensifies cash generation.

The complement to this is that by removing the low-value fraction from the ore, bottleneck capacity is vacated. This could be used to reduce processing costs however, provided that the system bottleneck is still in the same place, this would be sub-optimal. Instead the low-value ore is replaced by higher value ore generated in one of two ways.

The first is via Metal Exchange. The low-value fractions of ore rejected from the Processing Plant is exchanged with the Grade Engineered high-value fraction of material that was previously destined to be treated at the Heap Leach or deferred to a Stockpile. This Metal Exchange between the Heap Leach and the Processing Plant improves the global recovery of metal from the operation, while Metal Exchange between the Stockpile and the Processing Plant moves the recovery of this metal forward in time.

The second mechanism used to keep the Processing Plant at full capacity with higher value ore is to increase the mining rate. The ore body may be mined faster and a large portion of this material separated using Grade Engineering, with the higher value fraction processed immediately for maximum NPV benefit and the lower value stockpiled for later processing or treated at the Heap Leach.

The above mechanisms are both observed in this case study. Figure 5-18 shows that in the early years of the Grade Engineered case, the highest value ore mined still proceeds directly to the high-recovery, high-cost, limited-capacity Processing Plant bottleneck, while the remainder of the Processing Plant is filled with high-value fractions of Grade Engineered ore. Correspondingly, a large fraction of the Heap Leach input in the first six years, as shown in Figure 5-19, is the low-value fraction of Grade Engineered material, as is all of the material deferred to the GE Stockpile shown in Figure 5-13. The result of this is that both the cut-off and the mean grade of ore to the Processing Plant are increased in the early to mid LOM. This effect on grade can be observed in Figure 5-15 where the Grade Engineering Case 8 Processing Plant input grade is higher in early time periods than the Base Case (Case 1) Processing Plant input grade.

The value of increasing the grade through the Processing Plant in early periods is the large boost this provides to NPV.

The mining rate is observed to increase significantly to support the above mechanisms, such that mining is completed two years earlier in the Grade Engineered Case than in the Base Case (Figure 5-3 and Figure 5-12). Had the Grade Engineered Case not been limited by the mining Vertical Rate of Advance (Figure 5-9) and the stockpile capacity in the mid-LOM (Figure 5-13), this accelerated mining would likely have been even more pronounced. While a stockpile capacity bottleneck does not prevent this accelerated approach to mining, it does impair the economics as the low-value fraction from Grade Engineering can no longer be accumulated on the stockpile for later processing.

These observations support previously published findings that identified a virtual or pseudo increase in the effective treatment capacity of the processing plant as a key value driver from the pre-concentration of mill feed[2].

6.2 Increased Utilisation of High-Value Processing Paths

Grade Engineering reduces the pressure on the high-value bottleneck, the Ball Mill, in this case study. Pressure on a bottleneck means that there is an implied penalty, measured in dollars per bottleneck unit, applied to material sent to this bottleneck. Lower-value material ‘competing’ to access the bottleneck is not able to overcome this implied penalty as the optimiser instead chooses to process other higher-value material.

In this case study the bottleneck is power usage at the Ball Mill. However, there are also different grind options at the Ball Mill that affect consumption of power. Fine grinding consumes a greater quantity of bottleneck resource than coarse grinding, however the penalty effectively incurred from doing this is lower per unit in the Grade Engineering case than in the Base Case. This pushes the balance towards finer grinding for greater gold and copper recovery with Grade Engineering.

This can be observed in Figure 5-17, showing the greater usage of fine-grind through the Ball Mill in Grade Engineering Case 8 than in the Base Case (Case 1).

6.3 Lower Late Cut-Off

At the end of the LOM, the ore/waste cut-off in an operation utilising Grade Engineering falls to a lower value than in an operation without Grade Engineering. This is not observed at the entrance to the Processing Plant or Heap Leach, where the final cut-off grade is the same between cases, but at the exit of the mine itself or the mining stockpile. This observation further supports the work published in the reduction of the minimum economic cut-off grades with pre-concentration techniques[2].

In this case study the magnitude of this effect is only very slight. The mean grade of material leaving the mining stockpile at end of LOM in Grade Engineering Case 8 is the same to 2 decimal places as that for the Base Case.

The difference can be observed elsewhere though. See the comparison between TR in the *Highest Net Cash Paths – Case 1* appendix and TR1 in the *Highest Net Cash Paths – Case 8* appendix. The discard

[2] Scott, MC 2014, 'Evaluation of Energy-Efficiency, Emission Pricing and Pre-Concentration for the Optimised Development of a Au-Cu Deposit ', PhD thesis, The University of Queensland.

zone is slightly smaller in Grade Engineering Case 8, as the option to use Screen050 to extract a high-grade portion yields a marginally positive net cash return.

It should be noted that often the lowering of cut-off is ultimately a small driver of net cash, typically realised at the end of the LOM when cash is heavily discounted. However, CRC ORE has worked on a proposed project where Grade Engineering and the lowering of cut-offs supported a complete re-design of the proposed site layout and made it possible to join a series of pits that unlocked significant value for the project.

6.4 Benefits Not Cumulative

The improvement in enterprise value from adding a Grade Engineering process depends on the existing state of the enterprise. The results demonstrate that once a Grade Engineering process is added, each subsequent process typically has a lesser benefit than it would in isolation.

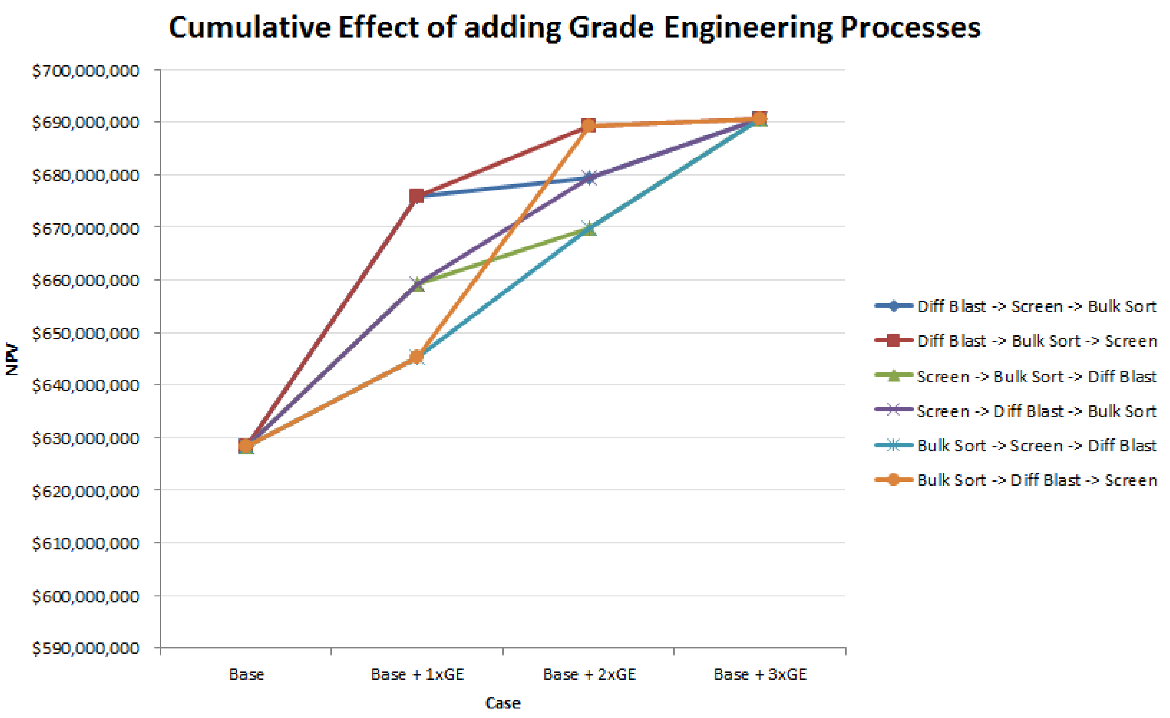


Figure 6-1: The value of a Grade Engineering process depends on which other Grade Engineering processes the operation already has. Adding processes one at a time, in different orders, demonstrates how the first process added typically provides the largest boost to NPV, while the processes added later provide a lesser boost.

This can be seen in Figure 6-1, which shows the effect of adding Grade Engineering processes one at a time to the Marvin enterprise. The single largest NPV increase from adding a Grade Engineering process is $47.5M, realised when Differential Blast is added to a base-case enterprise. By comparison, if the operation already includes Bulk Sort and Screening, the improvement from then adding Differential Blast is only $20.5M. This is because the Grade Engineering processes compete with one another for material (remembering that in this case study, each parcel of material can be sent to only one Grade Engineering process).

This competitive behaviour is best demonstrated by observing the minimal improvement in NPV in Figure 6-1 whenever Screening for the natural deportment of grade by size is added to an enterprise that already has Differential Blasting. Screening for the natural deportment of grade by size is worth $31M in NPV when added to a base case operation and is still worth $24.7M if the operation already has Bulk Sort. However, Screening for natural deportment of grade by size is only worth $3.5M if added to an operation with Differential Blasting. In this case study this behaviour is due to the generally superior response Differential Blast has for TR1-type material when compared to Screening for the natural deportment of grade by size. In Optimisation run 046 with both enabled, Differential Blast processes 45.5Mt of TR1 material while Screening only processes 16.0Mt of TR1 (plus 12Mt of FR material), so Screening for the natural deportment of Grade by size provides a relatively small benefit in the case study examined. However, it is important to acknowledge that this is largely a product of how this case study was constructed and the coarse separation responses that were applied across each domain. In reality, Screening for the natural deportment of grade by size and Differential Blasting to induce and enhance the natural deportment of grade by size are complementary Grade Engineering strategies that utilise the same enabling infrastructure (a Screening Plant). As such, the benefits of each are normally examined together.

In this case study nearly all financial value of Grade Engineering can be attained by implementing Differential Blast and Bulk Sort. This will vary for different mining operations depending upon the ore-body, mining method, processing plant and all other components of the system.

6.5 Effect on Life of Mine and Processing Costs

The benefits initially claimed for Grade Engineering are a reduction in processing costs and in increase in the LOM, however in a mining enterprise optimised to maximise NPV these may or may not be true.

This case study does yield a small reduction in total processing costs, however the optimiser also raises the proportion of material that is ground to a fine grind of 75µm which increases the variable cost rate. It is conceivable that Grade Engineering could lead to an increase in processing costs in an optimal mining operation, provided that this was justified by an increase in NPV.

The LOM of the case study operation does not change significantly between Case 1 and Case 8. This is because the Heap Leach continues to produce a small amount of product in years after the Processing Plant closes. The Processing Plant closes a year *earlier* in Grade Engineering Case 8 compared to the Base Case (Case 1). Despite closing a year earlier, the Case 8 Processing Plant produces a greater quantity of copper and gold over its life *and* ceases operation processing a lower mean ore grade than the Case 8 Processing Plant. While Grade Engineering processes do lower the ultimate cut-off grade of mined material in an operation, they also accelerate the throughput of product through the high-value bottleneck; the effect of this upon LOM may or may not be an increase.

It may be argued that extending the LOM has other non-financial benefits or that NPV overly discounts long-term financial considerations. However, the position of Whittle Consulting is that NPV is of primary financial value metric and non-financial considerations should also be modelled (if possible) using SUSOP.

7 Conclusions

1. The fundamental principles of coarse separation processes for Grade Engineering were successfully demonstrated in Whittle Consulting's Enterprise Optimisation approach for the hypothetical, but realistic, case study examined.
2. Whittle Consulting's Enterprise Optimisation provides a valid means to evaluate the financial value of Grade Engineering as it allows all aspects of the system to be re-optimised taking into account the availability of Grade Engineering processes.
3. Grade Engineering, consisting of Differential Blasting, Screening and Bulk Sort processes, produced a financial benefit to NPV of 9.9% in the representative mining enterprise modelled.
4. The observations provided by Whittle Consulting support the results of technical and economic evaluations for Grade Engineering performed in partnership with CRC ORE and its mining participants, as well as outcomes previously presented at CRC ORE annual assemblies and publications made by CRC ORE's PhD students during its first term.
5. Grade Engineering creates a higher-value distribution of ore that increases the value per bottleneck unit through the Processing Plant. As the bottleneck determines the overall flow of money through the system, this increases the rate of cash generation intensity.
6. The bottleneck capacity vacated by the direction of low-value ore fractions away from the high-value, high-cost processing bottleneck, is filled by;
   a. Metal Exchange; the Grade Engineered high-value fraction of ore that would otherwise be processed on a lower value path, and;
   b. Increasing the mining rate.
7. The financial impact of the mechanisms employed is observed as an increase in cut-off value through the bottleneck early in the Life of Mine. This improves NPV.
8. The reduction in bottleneck pressure allows greater usage of high-value processing paths such as fine grind in the Ball Mill, which consume more bottleneck resources than lower-value paths such as coarse grind.
9. Grade Engineering may allow the processing of the high-value fraction of low-grade material that would otherwise be classified waste. The net result of this may be to increase the Life of Mine, however this is not guaranteed considering the other levers utilised in a system optimised for NPV.
10. The value achieved by adding multiple Grade Engineering processes to a mining enterprise is not cumulative. Subsequent processes yielded a lesser benefit compared to previously-added processes.
11. Real-world mining enterprises bear many similarities to the mining enterprise modelled in this case study; in particular, they are generally constrained by comminution bottlenecks and Grade Engineering alleviates this. It is therefore concluded that many real-world mining enterprises would derive similar financial benefits from Grade Engineering processes to those found here.

7.1 Further Considerations

7.1.1 The Ultimate Pit

Establishing the extents of the ultimate pit requires the value of each block to be known, which requires the treatment pathway, time of extraction and active operational constraints for all material to be known. Grade Engineering techniques can add a substantial number of potential treatment pathways to the operation; in the case study examined, there were 96 potential treatment pathways assessed. While it is possible to determine the maximum value for each block with a substantial number of potential treatment pathways and identify the likely time of extraction and active operational constraints through an iterative assessment, future examinations should explore alternative approaches and re-examine the assumptions used in the current assessment for the development of the ultimate pit with Grade Engineering.

7.1.2 Grouping of Like Value Parcels of Material

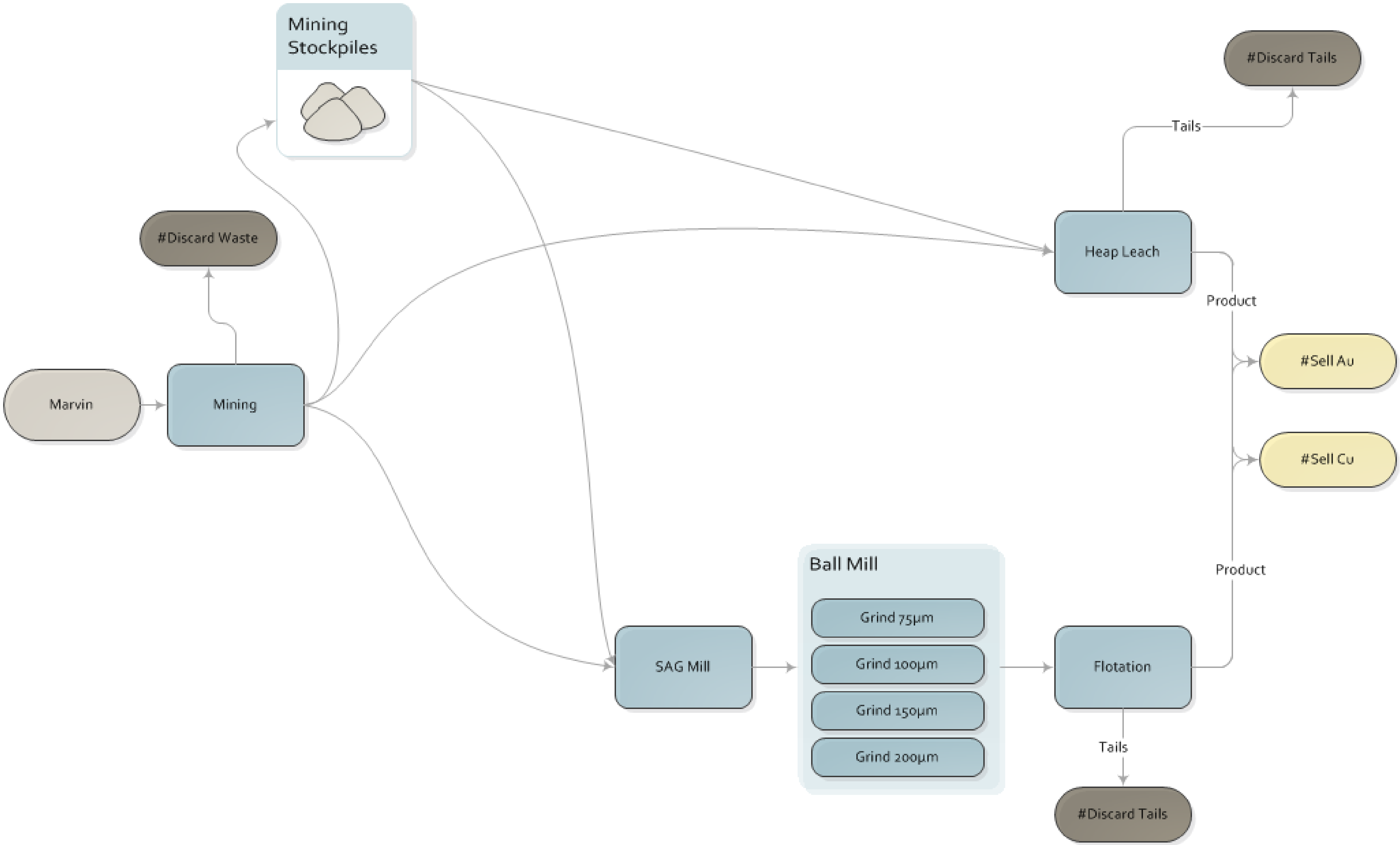
In the case study presented, each domain of the orebody was assessed using a unique Grade Engineering response for each of the coarse separation techniques examined and parcels of material were grouped by rock type (domain) and grade bins. However, Grade Engineering responses may vary across a rock type group and may be confined to localised regions of in-situ grade heterogeneity. Future assessments will need to extend the grouping of like value parcels of material to incorporate a range of potential Grade Engineering responses within rock types and spatial regions.

7.2 Acknowledgements

The work presented in this report represents the collaborative efforts of Whittle Consulting and CRC ORE. Acknowledgements should be made to Gerald Whittle, Nick Redwood and Norm Hanson from Whittle Consulting and extended to Michael Scott, Carlos Espejel and Luke Keeney from CRC ORE for their time and effort put into this collaboration.

8 APPENDICES

8.1 Enterprise Model Case 1: No Grade Engineering - Diagram



8.2 Enterprise Model Case 1: No Grade Engineering - Settings

Name	Globals	**Type**	Global
Limits	None	**Costs**	$1B Capital
Notes	Discount rate of 10%. First year of operation 2101. 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	86,156,460	79,449,210	35,297,297	314,754	0.44	0.40%
2	73,088,180	55,614,680	15,454,639	266,964	0.28	0.48%
3	111,322,120	72,203,370	12,980,051	220,837	0.18	0.31%

Notes Three phases, sized in Geovia Whittle based on this processing model. Ten metre benches. Material aggregated for Prober by Phase, Bench, Rock Type, Gold band (0-0.2, 0.2-0.4,0.4-0.6, 0.6-0.8, 0.8+ **g/t**) and Cu band (0-0.2, 0.2-0.4,0.4-0.6, 0.6-0.8, 0.8+ **%**)

Name	Mining	**Type**	Procedure
Limits	70Mtpa. 12 benches VRA	**Costs**	$1.60/t plus additional $0.02/t per bench below surface. Period costs of $40M per annum.
Notes	Tonnage limit is very high; mining is almost unconstrained. High period costs assume Operation has its own mining fleet rather than using contractors.		

Name	#Discard	**Type**	Waste Dump
Limits	NA	**Costs**	NA
Notes	Discard of mining waste, Heap Leach and Flotation tails.		

Name	Mining Stockpiles	**Type**	Stockpile
Limits	80Mt total	**Costs**	$0.75/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	0 tonnes in P1 5Mtpa P2+	**Costs**	$2.00/t Period costs of $5M per annum.

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 Assumed no impact of input particle size on recovery.

Name	SAG Mill	**Type**	Procedure
Limits	None	**Costs**	$0.30/t Period costs of $2M per annum.

Process

Input particle size is variable. Output particle size is 10mm. Power cost is $0.10/kWh. Steel cost is $1.50/kg.

Power Consumption (kWh/t)						Rock Type
Input P80	OX1	OX2	TR1	TR2	FR1	FR2
30mm	6.0	6.0	7.0	7.0	8.0	8.0
50mm	6.5	6.5	7.5	7.5	8.5	8.5
75mm	7.0	7.0	8.0	8.0	9.0	9.0
100mm	7.5	7.5	8.5	8.5	9.5	9.5
150mm	8.0	8.0	9.0	9.0	10.0	10.0
200mm	8.5	8.5	9.5	9.5	10.5	10.5
250mm	9.0	9.0	10.0	10.0	11.0	11.0

Steel Consumption (kg/t)						Rock Type
Input P80	OX1	OX2	TR1	TR2	FR1	FR2
30mm	0.20	0.20	0.35	0.35	0.40	0.40
50mm	0.25	0.25	0.40	0.40	0.45	0.45
75mm	0.30	0.30	0.45	0.45	0.50	0.50
100mm	0.35	0.35	0.50	0.50	0.55	0.55
150mm	0.40	0.40	0.55	0.55	0.60	0.60
200mm	0.45	0.45	0.60	0.60	0.65	0.65
250mm	0.50	0.50	0.65	0.65	0.70	0.70

Notes	Process 1 in Processing Plant. Input particle size is only variable in Grade Engineering cases.		
Name	Ball Mill	**Type**	Procedure
Limits	0 kWh in P1 200 GWh P2+	**Costs**	$0.50/t base cost. Variable steel and power costs. Period costs of $5M per annum.
Process	Input particle size P80 of 10mm. Output grind size is variable. Power cost is $0.10/kWh. Steel cost is $1.50/kg.		

Power Consumption (kWh/t)						Rock Type
Output P80	OX1	OX2	TR1	TR2	FR1	FR2
75µm	10.0	10.0	14.3	14.3	17.3	17.3
106µm	9.0	9.0	13.5	13.5	16.1	16.1
150µm	8.0	8.0	12.4	12.4	15.0	15.0
200µm	7.0	7.0	11.3	11.3	13.5	13.5

Steel Consumption (kg/t)						Rock Type
Output P80	OX1	OX2	TR1	TR2	FR1	FR2
75µm	0.7	0.7	1.2	1.2	1.5	1.5
106µm	0.6	0.6	1.0	1.0	1.2	1.2
150µm	0.5	0.5	0.8	0.8	0.9	0.9
200µm	0.3	0.3	0.5	0.5	0.6	0.6

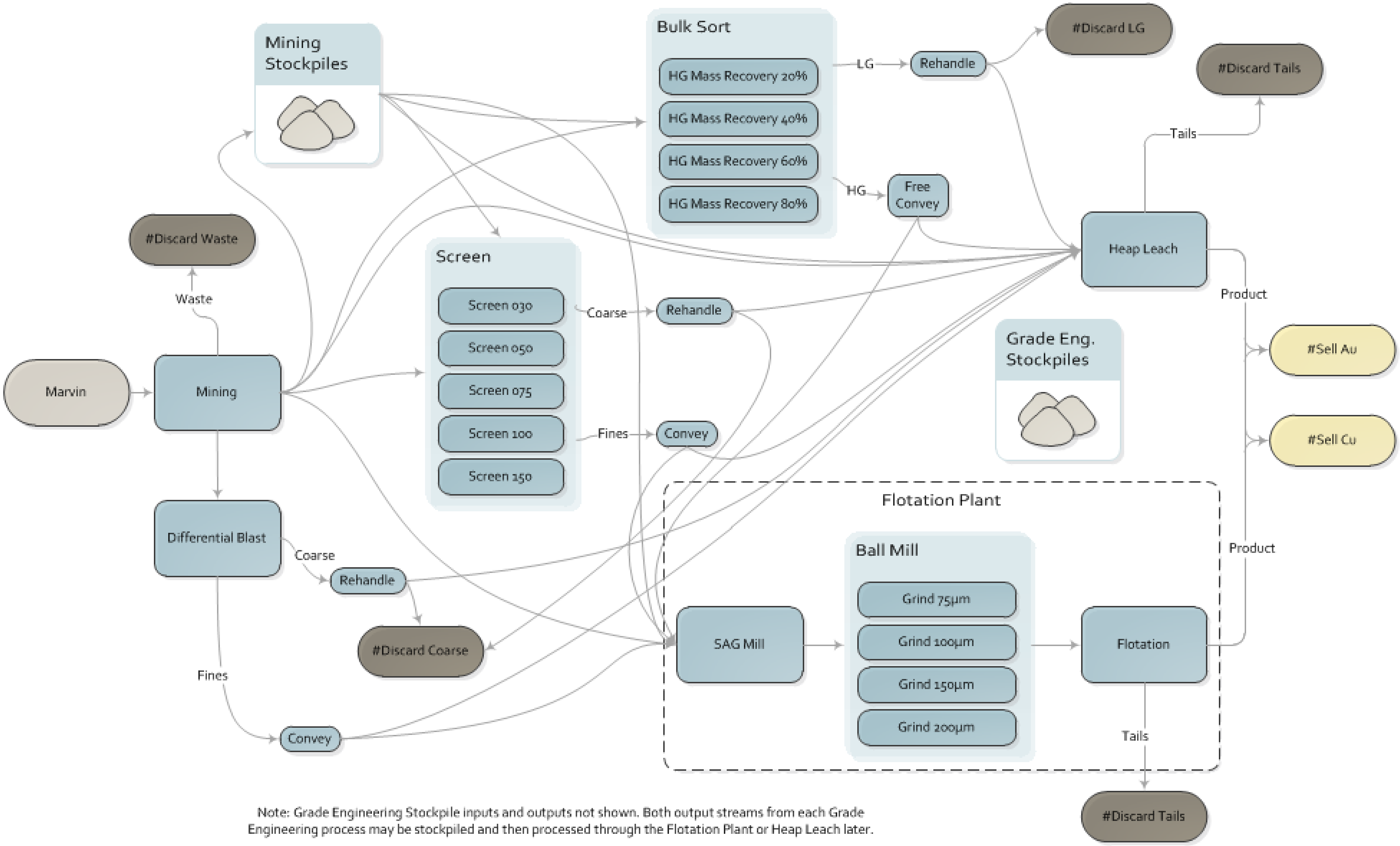
Notes	Process 2 in Processing Plant		
Name	Flotation	**Type**	Procedure
Limits	None	**Costs**	$1.00/t Period costs of $10M per annum.
Process	Input particle size P80 is variable.		

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	Process 3 in Processing Plant		
Name	#Sell	**Type**	Market
Limits	None	**Revenue**	$1300/tr.oz Au ($41.80/g) $5500/t Cu
Notes			

8.3 ENTERPRISE MODEL CASE 8: ALL GRADE ENGINEERING OPTIONS – DIAGRAM



Note: Grade Engineering Stockpile inputs and outputs not shown. Both output streams from each Grade Engineering process may be stockpiled and then processed through the Flotation Plant or Heap Leach later.

8.4 Enterprise Model Case 8: All Grade Engineering Options - Settings

All settings from Case 1 are retained. The following are settings for the Grade Engineering additions.

Name	#Discard	**Type**	Waste Dump
Limits	NA	**Costs**	NA
Notes	Discard of Bulk Sort LG, Differential Blast Coarse or Screen Coarse material.		

Name	Grade Engineering Stockpiles	**Type**	Stockpile
Limits	80Mt total	**Costs**	$0.75/t rehandled
Notes	Capacity limit is shared with Mining Stockpiles. Material stockpiled by material type (i.e. the aggregations described in the Marvin section, plus particle size and in the case of Bulk Sort output, LG/HG classification). This means very little blending occurs.		

Name	Screen	**Type**	Procedure
Limits	Capacity purchased at $2.00/t. Shares limit with Diff. Blast.	**Costs**	$0.15/t $500k per annum period costs.

Process

Domain 1 materials have strong responses to Screening.

Screen 30						Rock Type
Fines	OX1	OX2	TR1	TR2	FR1	FR2
Mass Rec.	20%	20%	20%	20%	20%	20%
Au Rec.	53%	35%	53%	24%	53%	35%
Cu Rec.	38%	30%	38%	22%	38%	30%

Screen 50						Rock Type
Fines	OX1	OX2	TR1	TR2	FR1	FR2
Mass Rec.	35%	35%	35%	35%	35%	35%
Au Rec.	66%	51%	66%	39%	66%	51%
Cu Rec.	53%	46%	53%	37%	53%	46%

Screen 75						Rock Type
Fines	OX1	OX2	TR1	TR2	FR1	FR2
Mass Rec.	50%	50%	50%	50%	50%	50%
Au Rec.	76%	64%	76%	54%	76%	64%
Cu Rec.	66%	60%	66%	52%	66%	60%

Screen 100						Rock Type
Fines	OX1	OX2	TR1	TR2	FR1	FR2
Mass Rec.	65%	65%	65%	65%	65%	65%
Au Rec.	84%	76%	84%	68%	84%	76%
Cu Rec.	77%	72%	77%	66%	77%	72%

Screen 150						Rock Type
Fines	OX1	OX2	TR1	TR2	FR1	FR2
Mass Rec.	80%	80%	80%	80%	80%	80%
Au Rec.	92%	87%	92%	82%	92%	87%
Cu Rec.	88%	85%	88%	81%	88%	85%

Notes Fines are Conveyed to next destination, while Coarse has to be rehandled, incurring greater cost.

Name	Differential Blast	**Type**	Procedure
Limits	Shares Screen Limit	**Costs**	$0.20/t Keeps Screen plant operating so may incur $500k per annum period cost.

Process

Only Transitional material responds to Differential Blasting in this case study.

Recovery						Rock Type
Fines	OX1	OX2	TR1	TR2	FR1	FR2
Mass Rec.	#N/A	#N/A	61%	61%	#N/A	#N/A
Au Rec.	#N/A	#N/A	88%	67%	#N/A	#N/A
Cu Rec.	#N/A	#N/A	84%	66%	#N/A	#N/A

Notes	Material that is differentially blasted must then be screened into fines and coarse. It is assumed this uses the same Screen plant as the Screening procedure, however it is not specified which screen setting is used, and the cost is built into the Differential Blast cost. Fines are Conveyed to next destination, while Coarse has to be rehandled, incurring greater cost.		

Name	Bulk Sort	**Type**	Procedure
Limits	None	**Costs**	$0.00/t $1.5M per annum period costs.

Process

Only Fresh material responds to Bulk Sort in this case study.

Bulk Sort at 20% Mass Recovery						Rock Type
High Grade	OX1	OX2	TR1	TR2	FR1	FR2
Mass Rec.	20%	20%	20%	20%	20%	20%
Au Rec.	20%	20%	20%	20%	30%	30%
Cu Rec.	20%	20%	20%	20%	40%	40%

Bulk Sort at 40% Mass Recovery						Rock Type
High Grade	OX1	OX2	TR1	TR2	FR1	FR2
Mass Rec.	40%	40%	40%	40%	40%	40%
Au Rec.	40%	40%	40%	40%	60%	60%
Cu Rec.	40%	40%	40%	40%	70%	70%

Bulk Sort at 60% Mass Recovery						Rock Type
High Grade	OX1	OX2	TR1	TR2	FR1	FR2
Mass Rec.	60%	60%	60%	60%	60%	60%
Au Rec.	60%	60%	60%	60%	75%	75%
Cu Rec.	60%	60%	60%	60%	85%	85%

Bulk Sort at 80% Mass Recovery						Rock Type
High Grade	OX1	OX2	TR1	TR2	FR1	FR2
Mass Rec.	80%	80%	80%	80%	80%	80%
Au Rec.	80%	80%	80%	80%	85%	85%
Cu Rec.	80%	80%	80%	80%	95%	95%

Notes: High Grade output is Free-Conveyed to next destination, while Low-Grade is rehandled, incurring greater cost.

Name	Free Convey	**Type**	Procedure
Limits	None	**Costs**	$0.00/t
Process	Output = Input		
Notes	For Bulk Sort HG material only, as assumes Bulk Sort separator is positioned over the input conveyer to the SAG Mill. Any HG material therefore continues on the conveyor to the SAG Mill.		

Name	Convey	**Type**	Procedure
Limits	None	**Costs**	$0.10/t
Process	Output = Input		
Notes			

Name	Rehandle	**Type**	Procedure
Limits	None	**Costs**	$0.75/t
Process	Output = Input		
Notes	Rehandle cost consistent with Stockpile rehandle cost.		

8.5 All Processing Paths

	ID	Separator	Coarse/LG Fraction				Fines/HG Fraction				
Base Case	1	(Null)	#Discard								
	2	(Null)	SagMill	BallMill075	Flotation	#Sell					
	3	(Null)	SagMill	BallMill106	Flotation	#Sell					
	4	(Null)	SagMill	BallMill150	Flotation	#Sell					
	5	(Null)	SagMill	BallMill200	Flotation	#Sell					
	6	(Null)	HeapLeach	#Sell							
Grade Engineering Cases	7	DiffBlast	Rehandle	#Discard			ShortConvey	SagMill	BallMill075	Flotation	#Sell
	8	DiffBlast	Rehandle	#Discard			ShortConvey	SagMill	BallMill106	Flotation	#Sell
	9	DiffBlast	Rehandle	#Discard			ShortConvey	SagMill	BallMill150	Flotation	#Sell
	10	DiffBlast	Rehandle	#Discard			ShortConvey	SagMill	BallMill200	Flotation	#Sell
	11	DiffBlast	Rehandle	#Discard			Rehandle	HeapLeach	#Sell		
	12	DiffBlast	Rehandle	HeapLeach	#Sell		ShortConvey	SagMill	BallMill075	Flotation	#Sell
	13	DiffBlast	Rehandle	HeapLeach	#Sell		ShortConvey	SagMill	BallMill106	Flotation	#Sell
	14	DiffBlast	Rehandle	HeapLeach	#Sell		ShortConvey	SagMill	BallMill150	Flotation	#Sell
	15	DiffBlast	Rehandle	HeapLeach	#Sell		ShortConvey	SagMill	BallMill200	Flotation	#Sell
	16	Screen1	Rehandle	#Discard			ShortConvey	SagMill	BallMill075	Flotation	#Sell
	17	Screen1	Rehandle	#Discard			ShortConvey	SagMill	BallMill106	Flotation	#Sell
	18	Screen1	Rehandle	#Discard			ShortConvey	SagMill	BallMill150	Flotation	#Sell
	19	Screen1	Rehandle	#Discard			ShortConvey	SagMill	BallMill200	Flotation	#Sell
	20	Screen1	Rehandle	#Discard			Rehandle	HeapLeach	#Sell		
	21	Screen1	Rehandle	HeapLeach	#Sell		ShortConvey	SagMill	BallMill075	Flotation	#Sell
	22	Screen1	Rehandle	HeapLeach	#Sell		ShortConvey	SagMill	BallMill106	Flotation	#Sell
	23	Screen1	Rehandle	HeapLeach	#Sell		ShortConvey	SagMill	BallMill150	Flotation	#Sell
	24	Screen1	Rehandle	HeapLeach	#Sell		ShortConvey	SagMill	BallMill200	Flotation	#Sell
	25	Screen2	Rehandle	#Discard			ShortConvey	SagMill	BallMill075	Flotation	#Sell
	26	Screen2	Rehandle	#Discard			ShortConvey	SagMill	BallMill106	Flotation	#Sell
	27	Screen2	Rehandle	#Discard			ShortConvey	SagMill	BallMill150	Flotation	#Sell
	28	Screen2	Rehandle	#Discard			ShortConvey	SagMill	BallMill200	Flotation	#Sell
	29	Screen2	Rehandle	#Discard			Rehandle	HeapLeach	#Sell		
	30	Screen2	Rehandle	HeapLeach	#Sell		ShortConvey	SagMill	BallMill075	Flotation	#Sell
	31	Screen2	Rehandle	HeapLeach	#Sell		ShortConvey	SagMill	BallMill106	Flotation	#Sell
	32	Screen2	Rehandle	HeapLeach	#Sell		ShortConvey	SagMill	BallMill150	Flotation	#Sell
	33	Screen2	Rehandle	HeapLeach	#Sell		ShortConvey	SagMill	BallMill200	Flotation	#Sell
	34	Screen3	Rehandle	#Discard			ShortConvey	SagMill	BallMill075	Flotation	#Sell
	35	Screen3	Rehandle	#Discard			ShortConvey	SagMill	BallMill106	Flotation	#Sell
	36	Screen3	Rehandle	#Discard			ShortConvey	SagMill	BallMill150	Flotation	#Sell
	37	Screen3	Rehandle	#Discard			ShortConvey	SagMill	BallMill200	Flotation	#Sell
	38	Screen3	Rehandle	#Discard			Rehandle	HeapLeach	#Sell		
	39	Screen3	Rehandle	HeapLeach	#Sell		ShortConvey	SagMill	BallMill075	Flotation	#Sell
	40	Screen3	Rehandle	HeapLeach	#Sell		ShortConvey	SagMill	BallMill106	Flotation	#Sell
	41	Screen3	Rehandle	HeapLeach	#Sell		ShortConvey	SagMill	BallMill150	Flotation	#Sell
	42	Screen3	Rehandle	HeapLeach	#Sell		ShortConvey	SagMill	BallMill200	Flotation	#Sell
	43	Screen4	Rehandle	#Discard			ShortConvey	SagMill	BallMill075	Flotation	#Sell
	44	Screen4	Rehandle	#Discard			ShortConvey	SagMill	BallMill106	Flotation	#Sell
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	46	Screen4	Rehandle	#Discard			ShortConvey	SagMill	BallMill200	Flotation	#Sell
	47	Screen4	Rehandle	#Discard			Rehandle	DiffBlast	HeapLeach	#Sell	
	48	Screen4	Rehandle	HeapLeach	#Sell		ShortConvey	SagMill	BallMill075	Flotation	#Sell
	49	Screen4	Rehandle	HeapLeach	#Sell		ShortConvey	SagMill	BallMill106	Flotation	#Sell
	50	Screen4	Rehandle	HeapLeach	#Sell		ShortConvey	SagMill	BallMill150	Flotation	#Sell
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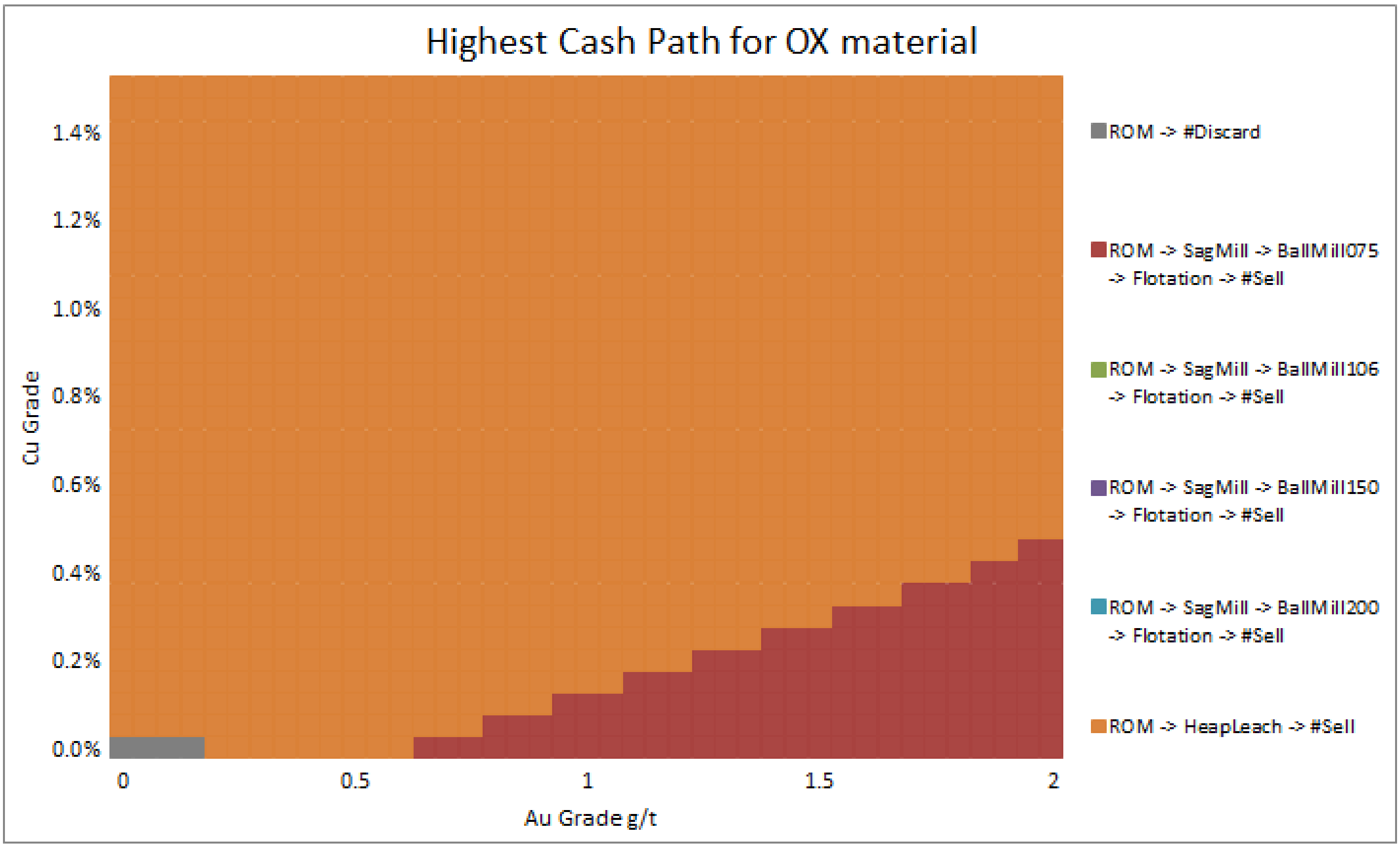
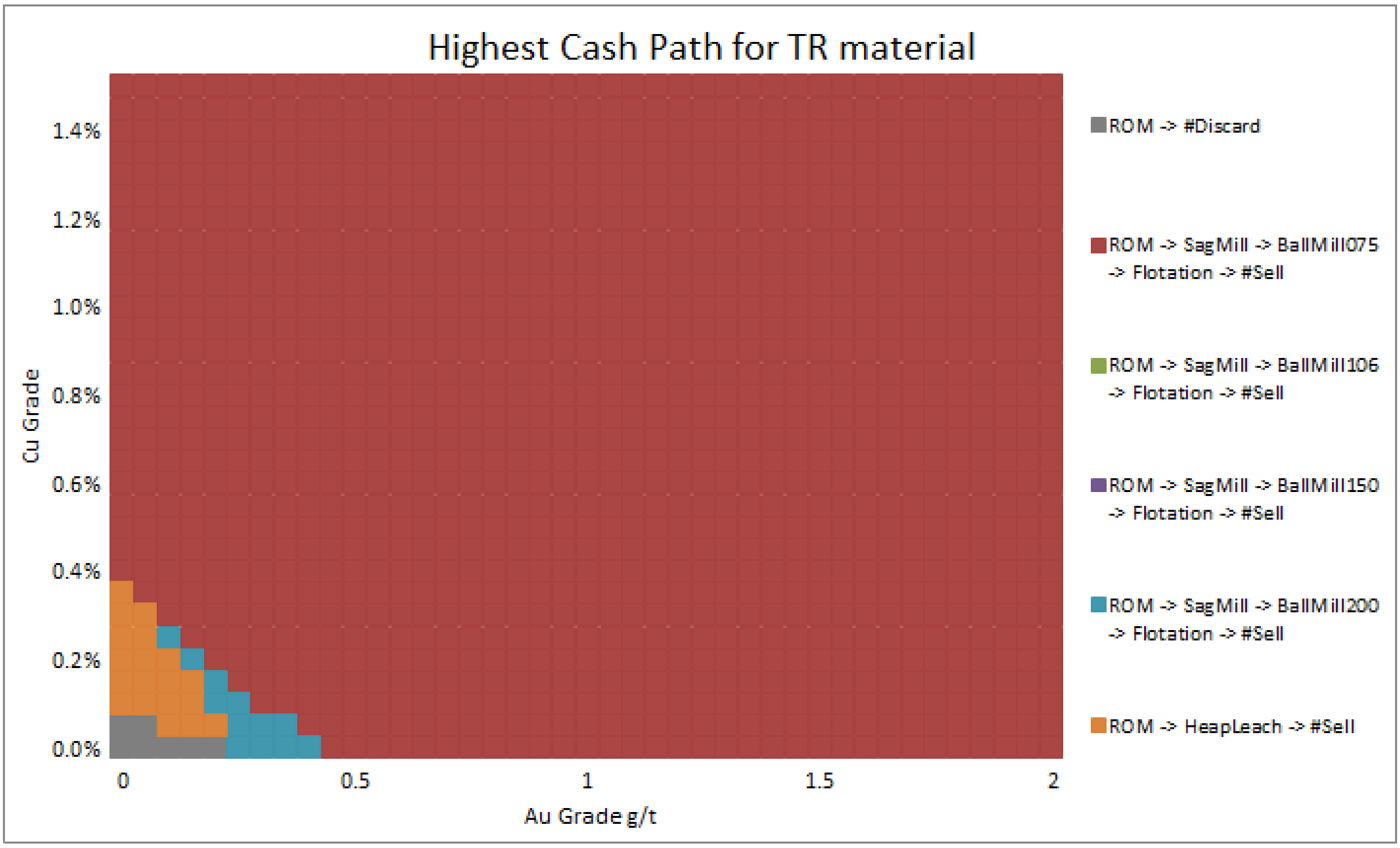
	52	Screen5	Rehandle	#Discard			ShortConvey	SagMill	BallMill075	Flotation	#Sell
	53	Screen5	Rehandle	#Discard			ShortConvey	SagMill	BallMill106	Flotation	#Sell
	54	Screen5	Rehandle	#Discard			ShortConvey	SagMill	BallMill150	Flotation	#Sell
	55	Screen5	Rehandle	#Discard			ShortConvey	SagMill	BallMill200	Flotation	#Sell
	56	Screen5	Rehandle	#Discard			Rehandle	HeapLeach	#Sell		
	57	Screen5	Rehandle	HeapLeach	#Sell		ShortConvey	SagMill	BallMill075	Flotation	#Sell
	58	Screen5	Rehandle	HeapLeach	#Sell		ShortConvey	SagMill	BallMill106	Flotation	#Sell
	59	Screen5	Rehandle	HeapLeach	#Sell		ShortConvey	SagMill	BallMill150	Flotation	#Sell
	60	Screen5	Rehandle	HeapLeach	#Sell		ShortConvey	SagMill	BallMill200	Flotation	#Sell

ID	Separator	Coarse/LG Fraction				Fines/HG Fraction				
61	BulkSort1	Rehandle	#Discard			FreeConvey	SagMill	BallMill075	Flotation	#Sell
62	BulkSort1	Rehandle	#Discard			FreeConvey	SagMill	BallMill106	Flotation	#Sell
63	BulkSort1	Rehandle	#Discard			FreeConvey	SagMill	BallMill150	Flotation	#Sell
64	BulkSort1	Rehandle	#Discard			FreeConvey	SagMill	BallMill200	Flotation	#Sell
65	BulkSort1	Rehandle	#Discard			FreeConvey	HeapLeach	#Sell		
66	BulkSort1	Rehandle	HeapLeach	#Sell		FreeConvey	SagMill	BallMill075	Flotation	#Sell
67	BulkSort1	Rehandle	HeapLeach	#Sell		FreeConvey	SagMill	BallMill106	Flotation	#Sell
68	BulkSort1	Rehandle	HeapLeach	#Sell		FreeConvey	SagMill	BallMill150	Flotation	#Sell
69	BulkSort1	Rehandle	HeapLeach	#Sell		FreeConvey	SagMill	BallMill200	Flotation	#Sell
70	BulkSort2	Rehandle	#Discard			FreeConvey	SagMill	BallMill075	Flotation	#Sell
71	BulkSort2	Rehandle	#Discard			FreeConvey	SagMill	BallMill106	Flotation	#Sell
72	BulkSort2	Rehandle	#Discard			FreeConvey	SagMill	BallMill150	Flotation	#Sell
73	BulkSort2	Rehandle	#Discard			FreeConvey	SagMill	BallMill200	Flotation	#Sell
74	BulkSort2	Rehandle	#Discard			FreeConvey	HeapLeach	#Sell		
75	BulkSort2	Rehandle	HeapLeach	#Sell		FreeConvey	SagMill	BallMill075	Flotation	#Sell
76	BulkSort2	Rehandle	HeapLeach	#Sell		FreeConvey	SagMill	BallMill106	Flotation	#Sell
77	BulkSort2	Rehandle	HeapLeach	#Sell		FreeConvey	SagMill	BallMill150	Flotation	#Sell
78	BulkSort2	Rehandle	HeapLeach	#Sell		FreeConvey	SagMill	BallMill200	Flotation	#Sell
79	BulkSort3	Rehandle	#Discard			FreeConvey	SagMill	BallMill075	Flotation	#Sell
80	BulkSort3	Rehandle	#Discard			FreeConvey	SagMill	BallMill106	Flotation	#Sell
81	BulkSort3	Rehandle	#Discard			FreeConvey	SagMill	BallMill150	Flotation	#Sell
82	BulkSort3	Rehandle	#Discard			FreeConvey	SagMill	BallMill200	Flotation	#Sell
83	BulkSort3	Rehandle	#Discard			FreeConvey	HeapLeach	#Sell		
84	BulkSort3	Rehandle	HeapLeach	#Sell		FreeConvey	SagMill	BallMill075	Flotation	#Sell
85	BulkSort3	Rehandle	HeapLeach	#Sell		FreeConvey	SagMill	BallMill106	Flotation	#Sell
86	BulkSort3	Rehandle	HeapLeach	#Sell		FreeConvey	SagMill	BallMill150	Flotation	#Sell
87	BulkSort3	Rehandle	HeapLeach	#Sell		FreeConvey	SagMill	BallMill200	Flotation	#Sell
88	BulkSort4	Rehandle	#Discard			FreeConvey	SagMill	BallMill075	Flotation	#Sell
89	BulkSort4	Rehandle	#Discard			FreeConvey	SagMill	BallMill106	Flotation	#Sell
90	BulkSort4	Rehandle	#Discard			FreeConvey	SagMill	BallMill150	Flotation	#Sell
91	BulkSort4	Rehandle	#Discard			FreeConvey	SagMill	BallMill200	Flotation	#Sell
92	BulkSort4	Rehandle	#Discard			FreeConvey	HeapLeach	#Sell		
93	BulkSort4	Rehandle	HeapLeach	#Sell		FreeConvey	SagMill	BallMill075	Flotation	#Sell
94	BulkSort4	Rehandle	HeapLeach	#Sell		FreeConvey	SagMill	BallMill106	Flotation	#Sell
95	BulkSort4	Rehandle	HeapLeach	#Sell		FreeConvey	SagMill	BallMill150	Flotation	#Sell
96	BulkSort4	Rehandle	HeapLeach	#Sell		FreeConvey	SagMill	BallMill200	Flotation	#Sell

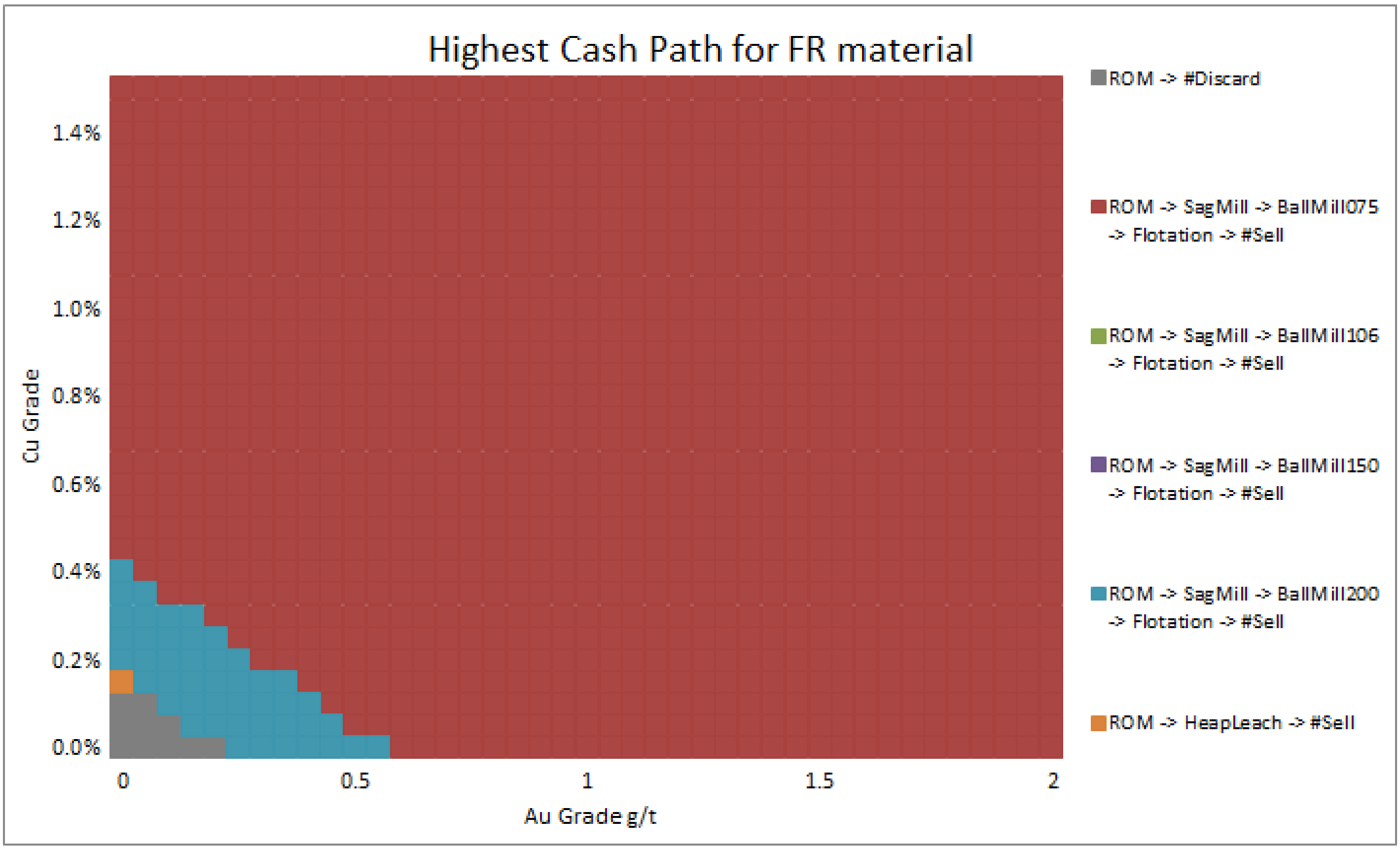
8.6 Highest Net Cash Paths – Case 1

The following charts do not take into account either period costs or the effect of bottlenecks. These cause the separation lines to shift.



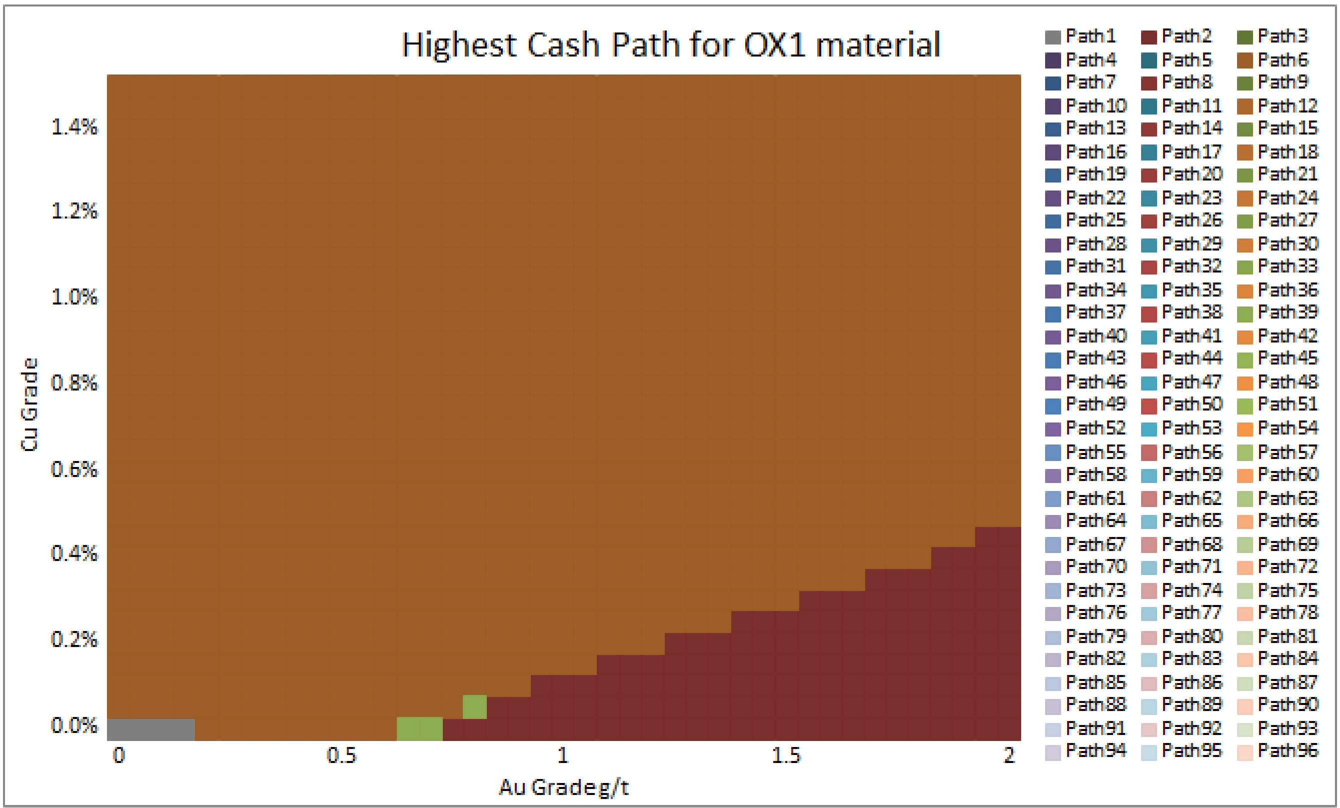


jh



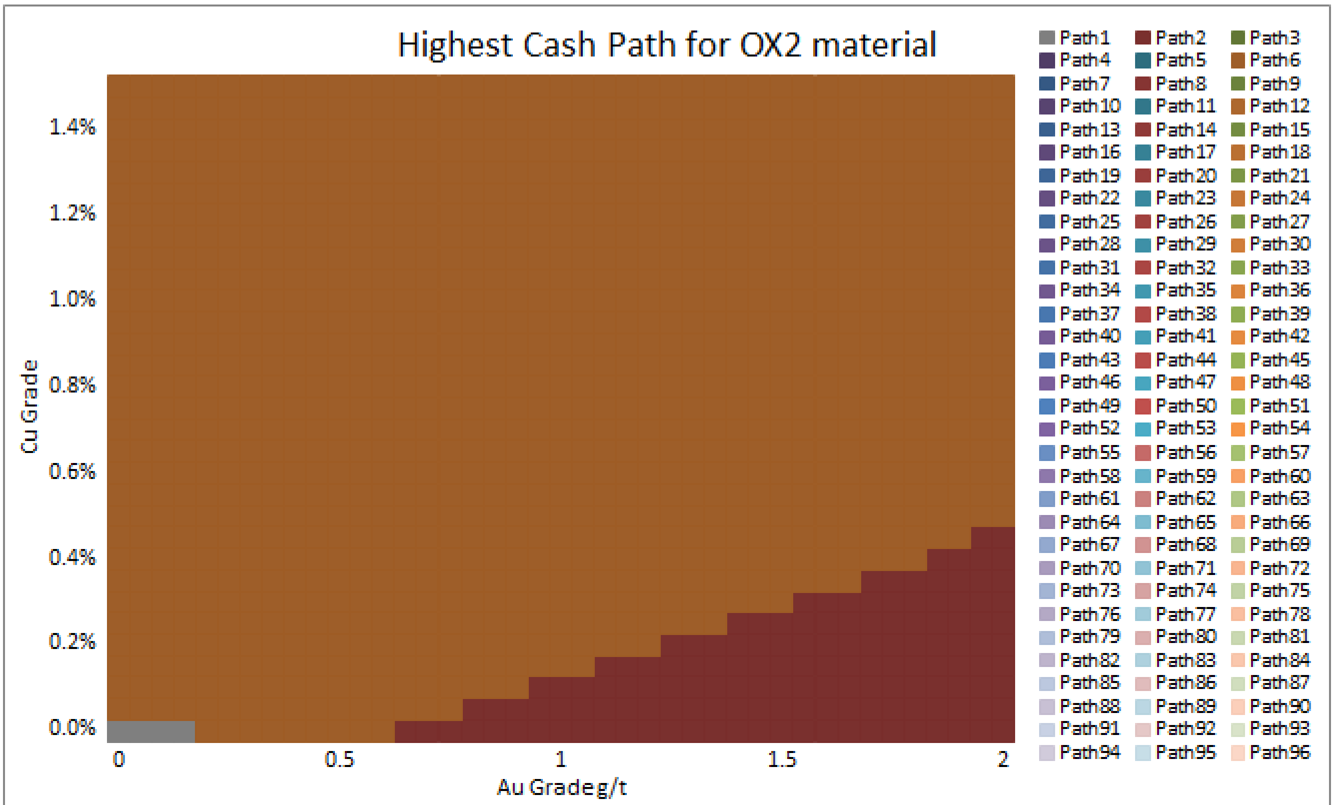
These charts were generated from a large number of individual data points rather than deriving the line equations mathematically; this explains the blocky nature of the charts.

8.7 Highest Net Cash Paths – Case 8

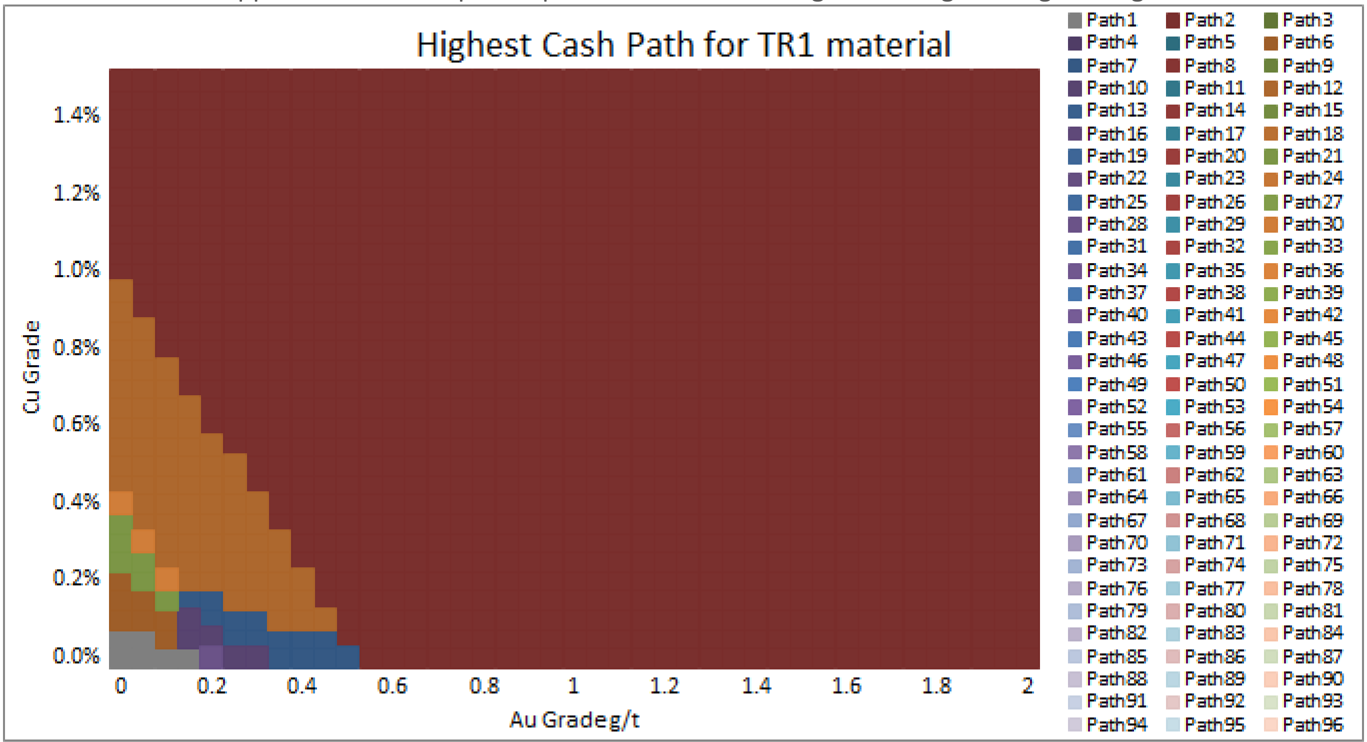


Same as Pre-GE but with addition of Path 39

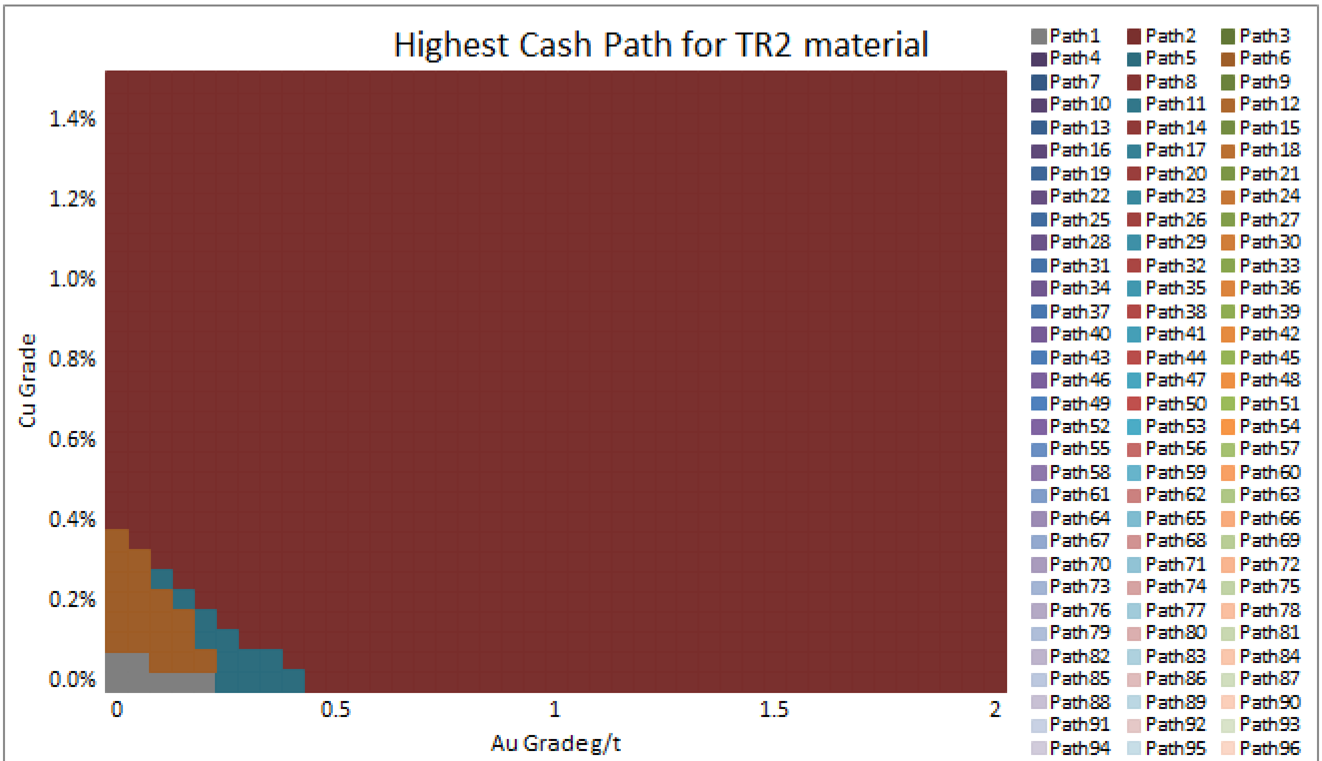
ROM -> Screen3 -> 1: {Handle -> HeapLeach -> #Sell}; 2: { ShortConvey -> SagMill -> BallMill075 -> Flotation -> #Sell}



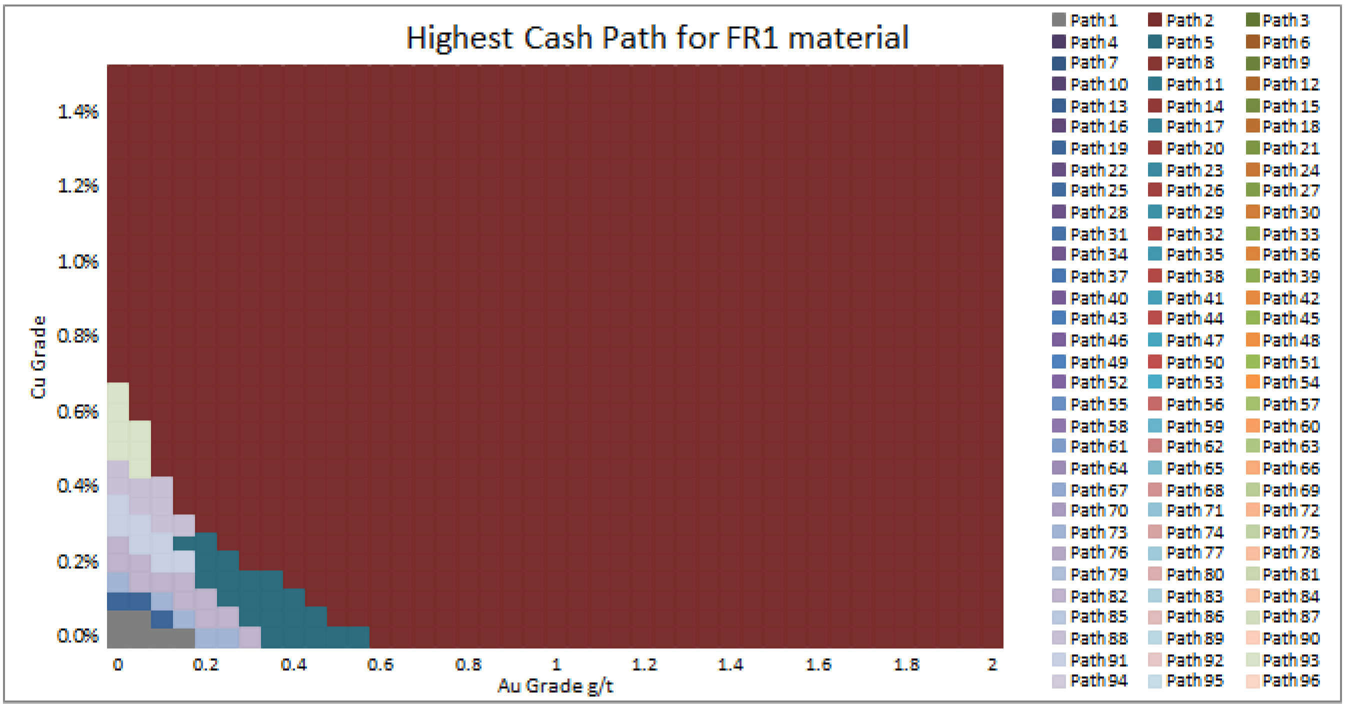
Same as Pre-GE



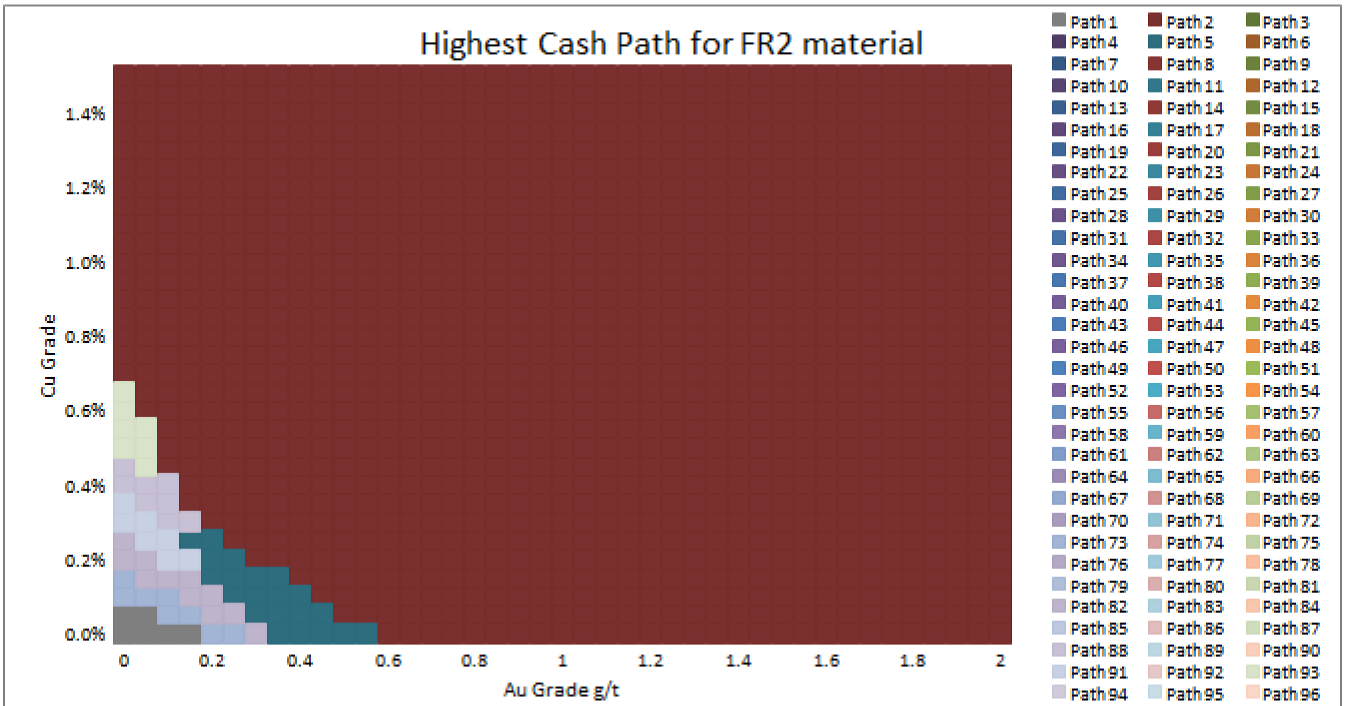
Red (2)	ROM -> SagMill -> BallMill075 -> Flotation -> #Sell
Light brown (12)	ROM -> DifferentialBlast -> 1: {Handle -> HeapLeach -> #Sell}; 2: {ShortConvey -> SagMill -> BallMill075 -> Flotation -> #Sell}
Peach (30)	ROM -> Screen2 -> 1: {Handle -> HeapLeach -> #Sell}; 2: {ShortConvey -> SagMill -> BallMill075 -> Flotation -> #Sell}
Green (21)	ROM -> Screen1 -> 1: {Handle -> HeapLeach -> #Sell}; 2: {ShortConvey -> SagMill -> BallMill075 -> Flotation -> #Sell}
Mid brown (6)	ROM -> HeapLeach -> #Sell
Blue (7)	ROM -> DifferentialBlast -> 1: {Handle -> #Discard}; 2: {ShortConvey -> SagMill -> BallMill075 -> Flotation -> #Sell}
Dark purple (10)	ROM -> DifferentialBlast -> 1: {Handle -> #Discard}; 2: {ShortConvey -> SagMill -> BallMill200 -> Flotation -> #Sell}
Light purple (28)	ROM -> Screen2 -> 1: {Handle -> #Discard}; 2: {ShortConvey -> SagMill -> BallMill200 -> Flotation -> #Sell}
Grey (1)	ROM -> #Discard



Same as Pre-GE



Red (2)	ROM -> SagMill -> BallMill075 -> Flotation -> #Sell
Light green (93)	ROM -> BulkSort4 -> 1: {Handle -> HeapLeach -> #Sell}; 2: {FreeConvey -> SagMill -> BallMill075 -> Flotation -> #Sell}
Light lilac (88)	ROM -> BulkSort4 -> 1: {Handle -> #Discard}; 2: {FreeConvey -> SagMill -> BallMill075 -> Flotation -> #Sell}
Light blue (91)	ROM -> BulkSort4 -> 1: {Handle -> #Discard}; 2: {FreeConvey -> SagMill -> BallMill200 -> Flotation -> #Sell}
Turquoise (5)	ROM -> SagMill -> BallMill200 -> Flotation -> #Sell
Mid lilac (82)	ROM -> BulkSort3 -> 1: {Handle -> #Discard}; 2: {FreeConvey -> SagMill -> BallMill200 -> Flotation -> #Sell}
Mid blue (73)	ROM -> BulkSort2 -> 1: {Handle -> #Discard}; 2: {FreeConvey -> SagMill -> BallMill200 -> Flotation -> #Sell}
Dark blue (19)	ROM -> Screen1 -> 1: {Handle -> #Discard}; 2: {ShortConvey -> SagMill -> BallMill200 -> Flotation -> #Sell}
Grey (1)	ROM -> #Discard



Red (2)	ROM -> SagMill -> BallMill075 -> Flotation -> #Sell
Light green (93)	ROM -> BulkSort4 -> 1: {Handle -> HeapLeach -> #Sell}; 2: {FreeConvey -> SagMill -> BallMill075 -> Flotation -> #Sell}
Light lilac (88)	ROM -> BulkSort4 -> 1: {Handle -> #Discard}; 2: {FreeConvey -> SagMill -> BallMill075 -> Flotation -> #Sell}
Light blue (91)	ROM -> BulkSort4 -> 1: {Handle -> #Discard}; 2: {FreeConvey -> SagMill -> BallMill200 -> Flotation -> #Sell}
Turquoise (5)	ROM -> SagMill -> BallMill200 -> Flotation -> #Sell
Mid lilac (82)	ROM -> BulkSort3 -> 1: {Handle -> #Discard}; 2: {FreeConvey -> SagMill -> BallMill200 -> Flotation -> #Sell}
Mid blue (73)	ROM -> BulkSort2 -> 1: {Handle -> #Discard}; 2: {FreeConvey -> SagMill -> BallMill200 -> Flotation -> #Sell}
Grey (1)	ROM -> #Discard