Whittle Consulting ShovelSense™ Economic Assessment

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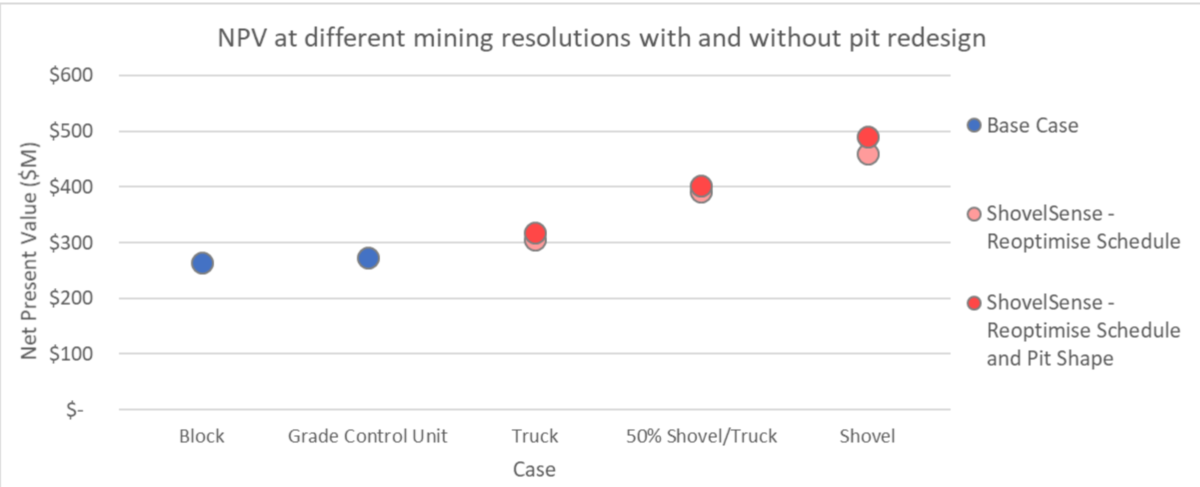
SUMMARY

MineSense Technologies is a pioneer in digital mining solutions, providing real-time, sensor-based ore sorting for large-scale mines. MineSense ShovelSense^{TM} measure-while-loading technology integrates with shovels, loaders and scoops to measure the grade of ore or waste in real time and assign every load to the correct destination, whether mill, stockpile, leach pad or waste pile. By providing accurate, fine-grained data, ShovelSense allows the internal heterogeneity of ore bodies to be exploited.

Whittle Consulting provides Integrate Strategic Planning to mining companies. A model of the mining enterprise, from resource to market, is built. This is then optimised using proprietary software *Prober* to produce a life-of-mine schedule. This methodology also allows the effect of any defined technology on the Net Present Value of a mining enterprise to be calculated by examining before and after cases.

This case study applies ShovelSense technology to a fictional but realistic mining operation. First, an optimal base case mining operation without MineSense is established; this consists of an open pit, mining model, processing model, cost model and throughput limits. In the base case, grade control is carried out at the level of a 20m cubic block (8000bcm), or if better practices are utilised, one sixteenth of this (500bcm). ShovelSense cases are then examined; at best grade control is carried out at the shovel level (23bcm) which requires double-sided truck loading to retain ore segregation. If this is not possible then grade control is at truck-level (114bcm). A 50/50 shovel/truck split case is considered to represent a practical intermediate case. Each ShovelSense case considers schedule optimisation with and without pit shape re-optimisation. The NPV of each case is then compared – see Figure below.



Based on the parameters used, ShovelSense technology offers major potential benefits to the fictional but realistic mining operation modelled in this study. A best-case shovel-level implementation improved NPV by 79%, while the more achievable 50% Shovel/Truck case still provided 47% uplift. The immediate reason for this uplift is higher processing grades early in the life of the mine. ShovelSense creates a high-grade ore fraction that increases the intensity of cash generated through the high-value bottleneck (the Plant). The Plant capacity vacated by the low-grade fraction is filled by increasing the mining rate to reach more high-grade, or with high-grade fractions that would otherwise have been sent to lower-value processes; this swap is termed Metal Exchange.

Provided operational practices can be adapted to use ShovelSense and the ore body contains sufficient variability, real-world mining operations are expected to yield similar benefits to those found here.

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1 INTRODUCTION

MineSense are a Canada-based mining technology company specialising in digital mining solutions, providing real-time, sensor-based ore sorting for large-scale mines. MineSense ShovelSense™ measure-while-loading technology deploys sensors on the bucket of the excavator shovels, which allows grade-control to be carried out at a finer resolution using accurate real-time data.

Whittle Consulting are specialists in Integrated Strategic Planning for the mining industry. Whittle Consulting have executed over 150 Enterprise Optimisation studies for mining companies, in which the whole mining system is modelled and optimal business and scheduling decisions are found. The same optimisation technology makes Whittle Consulting uniquely placed to evaluate the value of mining technologies within in a mining enterprise.

1.1 PURPOSE

Whittle Consulting carried out an investigation to assess the full financial effect of MineSense ShovelSense™ measure-while-loading technology on a hypothetical open pit copper mining operation. This report describes the methodology followed and summarises the findings.

Various other assessments of ShovelSense technology exist in the public domain, however by its nature the value of the technology is difficult to evaluate in isolation. This assessment considers the effect of ShovelSense over a whole mining operation for its entire life-of-mine, with optimised scheduling decisions, so has a larger scope than any assessment based only on unit costs.

1.2 SHOVELSENSE™ MEASURE-WHILE-LOADING TECHNOLOGY

Conventionally, the extraction of orebodies such as Marvin are modelled, planned and executed based on block models with block sizes in the order of 20mx20mx15m resolution (~16000t). Singular mean grade values are assigned to blocks in the model and the assumption is that the grade within blocks is homogeneous. As many studies[1] have shown, material within blocks is often highly heterogenous, with substantial occurrence of ore-in-waste for waste blocks in the model, and waste within ore (dilution) in ore blocks in the model.

ShovelSense™ measure-while-loading technology deploys sensors on the bucket of the shovel to measure the grade of each bucket loaded, compare the loaded grade to the cutoff, and assign a destination for the loaded material based on the measured grade, as opposed to the modelled grade. The system has three advantages over traditional approaches to grade control based on sampling and assay.

The first is the material grade data is highly accurate. The measurement occurs in the shovel after blasting and dilution, rather than using representative assays from a much larger volume prior to blasting and dilution, which affects measurement accuracy. The sensor system itself is also highly accurate; MineSense systems have an assessed accuracy of ±0.05% Cu at 0.2% Cu at 95% confidence.

The second advantage is that decision making on material routing e.g. ore/waste control, ore/leach control, is made near-instantaneously. This compares favourably to traditional sample-based methods which may require a delay of 8 to 24 hours for material routing decisions.

[1] Walters et al (2012), Bamber et al (2016)

The third advantage and that which is assessed in this report, is that the resolution at which grade control is carried out becomes the resolution of the bucket. This is a much finer resolution than allowed by traditional methods. Mid-sized excavator shovels may carry 60-80t (3mx3mx3m) of material, whereas traditional grade control is carried out on masses in the range of one thousand tonnes. The fine-grained measurement resolution provided by ShovelSense allows the heterogeneity of grades and value within a block to be exploited. Both dilution and losses, as well as misclassified leach and mill feed – are substantially reduced, enhancing the feed grade to the mill – and therefore recoveries - and reducing ore losses to waste. A synergistic benefit is the diversion of erroneously classified leach material in the mill feed, and erroneously classified mill feed material in the leach, reducing costs of processing in the first case, and enhancing Cu recoveries in the second.

Figure 1: ShovelSense system installed on a Bucyrus 495 rope shovel

1.3 Whittle Consulting Optimisation Methodology

The full benefit of ShovelSense technology cannot be assessed in isolation. Even a small change in one part of a mining operation affects, to a greater or lesser extent, the optimal operation of all other parts of the enterprise (cut-off grades, stockpiling, plant settings etc.). Therefore, a whole-system approach is required to fully estimate the effect of such an implementation. The approach must also take into account the time-value of money; the most common approach is to discount future cash flows to produce a Net Present Value (NPV) that can be directly compared between different cases.

Whittle Consulting's enterprise optimization methodology is used for this purpose.

1.3.1 Whittle Consulting

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

With technical expertise in a range of disciplines including geology, mining engineering, metallurgy, research, mathematics, computing, finance, operational/ financial modelling and analysis, Whittle Consulting has a thorough appreciation of practical, organisational and contextual reality of mining operations. As experts in embracing and harnessing complexity, Whittle Consulting is not bound by traditional thinking. By challenging existing paradigms and conventional wisdom, the real potential of a mining business is revealed.

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

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

1.3.2 Modelling

The whole mining operation from Resource to Market is modelled. While the pit and phase shapes are created in Geovia Whittle, a software package from Dassault Systemes, the rest of the enterprise is modelled using Prober, a proprietary optimization algorithm that optimizes for NPV. The role of the Prober-user is to *describe* the mining system mathematically and then let the optimizer produce the best mining and processing schedule. This is in opposition to *telling* the software how to schedule a mining system, as in a traditional approach.

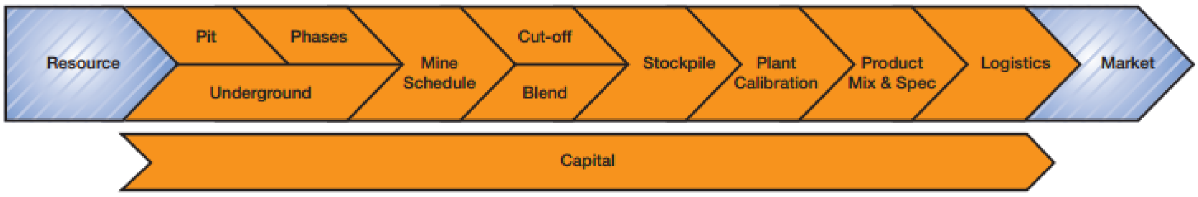

Figure 2: Whittle Consulting Enterprise Optimisation process.

A full Whittle Consulting optimisation may include iteration between pit design in Geovia Whittle and rest-of-system optimisation in Prober.

2 MODEL AND CASES

All mining operations are different and any benefits from using ShovelSense will vary from case to case. Rather than attempting to assess ShovelSense against a large range of mines, this report assesses ShovelSense against a single mining operation to provide an indication of the magnitude of financial benefit.

The model used in this study consists of a fictional ore body 'Marvin', a mining model that varies the unit volume or mining resolution at which the mining technique operates, a simple processing model consisting of both a Heap Leach and a Flotation Plant, and a set of financial parameters that were approximately correct at the time of publishing.

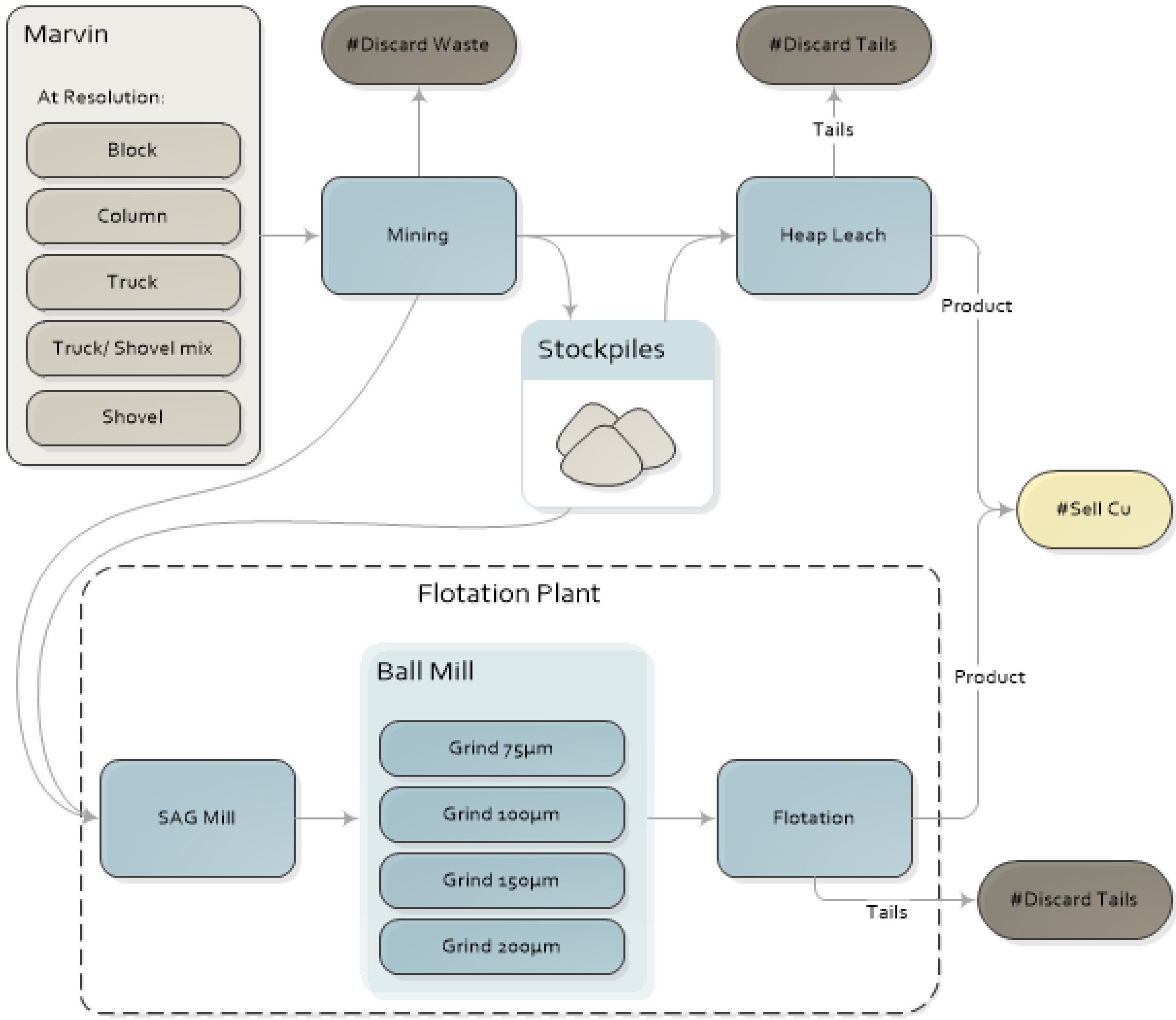

Figure 3: Mining and Processing model. Each case uses a different resolution of the Marvin block model.

2.1 GLOBAL SETTINGS

All currency figures are quoted in Australian dollars (AUD). A discount rate of 10% is used to account for the time value of money. The period length for schedule optimisation is one year. As the operation is fictional it is given a nominal starting year of 2101.

The enterprise is a greenfield operation. Capital of $700M is required. Mining may begin in the first year of operation, however the Plant is not available until the second year.

The copper price is $5500/t less a sell cost (TC/RC) of $1300/t.

2.2 Ore Body

The ore body used 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. For the purposes of this case study, all gold within the model was replaced with additional copper, as MineSense is (at time of publishing) only commercially proven in the detection of copper. Testing on Copper-Gold, Lead-Zinc, Nickel and Iron deposits is in progress. The block model used has a block size of 20m x 20m x 20m.

A single open pit with four phases was sized for each case using the Geovia Whittle software package. In each case the Skin Analysis technique was used to choose the shell with the highest expected NPV.

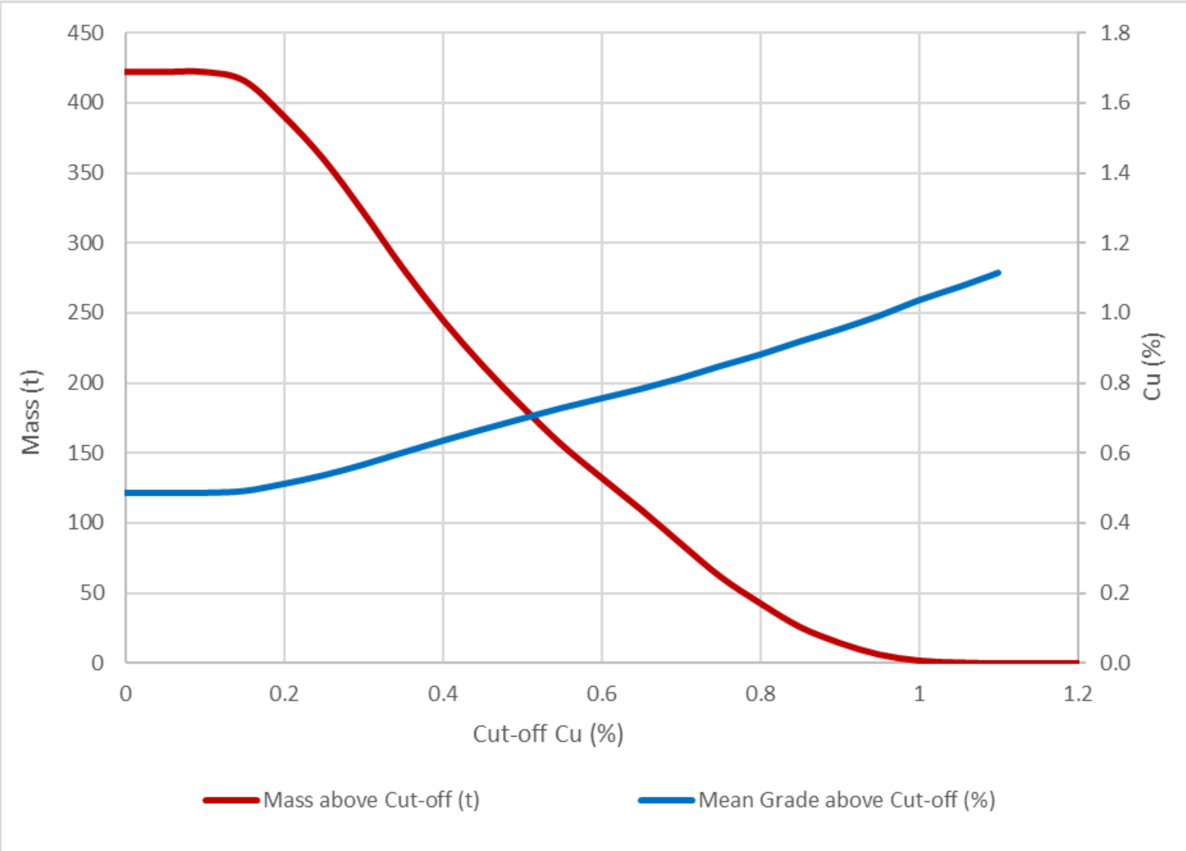

Figure 4: Marvin Copper grade-tonnage curve. Most of the block grades within the model are between 0.2% Cu and 1.0%. At a nominal cut-off of 0.25% Cu the ore-body contains 360Mt of ore with a mean grade of 0.54%.

2.3 Mining Model

ShovelSense alters the accessible resolution of the ore body; instead of handling material within a block or partial block as if it is homogeneous, that material can be broken down into a much smaller shovel-sized unit. Each of these smaller units of material will have a different mean grade; this heterogeneity may then be exploited via a sorting process.

Four resolutions are examined in this study.

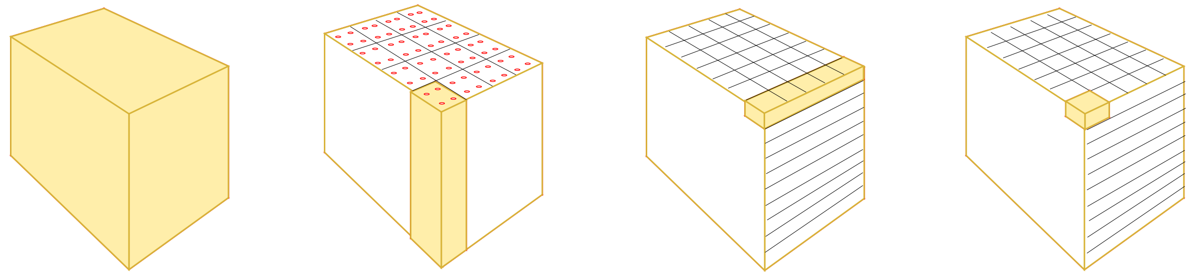

Figure 5: The four resolutions used in this study. From left: Block, Grade Control Unit, Truck, Shovel.

2.3.1 General Settings

The cost rate for mining is \$1.60/t, with an additional \$0.02/t incurred per 20m bench below the surface level, to allow for additional haulage. A nominal mining limit of 70Mt is in place, though this is large enough to rarely be a limiting factor. In addition to variable costs, the mining operation incurs a fixed cost of \$40M per year. This fixed cost may be avoided once in-pit mining is completed and the plant is fed only from the stockpile. Stockpile rehandle incurs a cost of \$0.75/t.

2.3.2 Block

The naïve base case approach is to treat the entire 20m x 20m x 20m block as homogeneous and so make the routing decision for the entire block based on an estimated mean grade.

2.3.3 Grade Control Unit

A more sophisticated standard ore control approach is to handle the material based on a smaller collection of blast-hole samples. Assuming a blast-hole separation of 2.5m, there are 64 blast-holes per block. Best case industry practice observed is to carry out short range ore control at a level no finer than 4 blast-holes. This gives 16 'columns' of material with in-situ dimension 2.5m x 2.5m x 20m. These are referred to as 'Grade Control Units' for the purposes of this study.

2.3.4 Shovel

ShovelSense allows the mining resolution to be increased dramatically. In the ideal case, ShovelSense allows grade control at an individual shovel level.

A wide range of excavator shovel sizes are available, from 5.0m^3 to 50m^3. For this case study a large nominal size was chosen; the CAT-6060 Excavator with a bucket of 34m^3. At a bulk density of approximately 1.5 this gives an in-situ mining unit volume of 22.9m^3, nominally 4.0m x 2.0m x 2.86m in size, of which there are 350 units per block.

Material from each shovel-load excavated must be loaded only into a truck with alike material so as to avoid adverse blending. For this to be possible without significant rehandling, double-sided truck loading is proposed. This allows the excavator to simultaneously load shovel-loads of material destined for two different destinations based on their grade measured by ShovelSense. Ideally, more than two simultaneous trucks for more than two destinations would be available, however, in addition to being impractical, this is also not typically required as ore bodies do not vary to this large a degree.

This case assumes double-sided loading is possible 100% of the time, which is ideal but unlikely to be possible in practice. The Mixed Shovel/Truck case examines a situation when double-sided loading is possible less than 100% of the time.

2.3.5 Truck

In some cases physical constraints may completely prevent double-sided loading, or it may be impossible for other operational reasons. In this case ShovelSense does still offer a benefit, however it is reduced as the mining resolution is essentially reduced to the volume of the haul truck.

The CAT 793F was chosen as the nominal haul truck for this case study, with a volume approximately equivalent to five shovel-loads of material (170m^3 bulk). There are 70 truck-loads per 20m x 20m x 20m block.

2.3.6 Mixed Shovel/Truck

It is anticipated that in real mines, double-sided loading would be possible 50-75% of the time. The remainder of the time only single-sided loading would be possible, due to physical constraints. Therefore, a case is examined where 50% of the grade control is carried out at Shovel resolution and the other 50% at Truck resolution.

2.3.7 Distribution Generation

Mathematically, a Gamma distribution is used to model the internal copper grade distribution within each block. This is chosen because it matches the curve shape of the distributions found in real ore bodies by MineSense. It is similar to a normal distribution at mid to high grades and bunched around zero near the zero point.

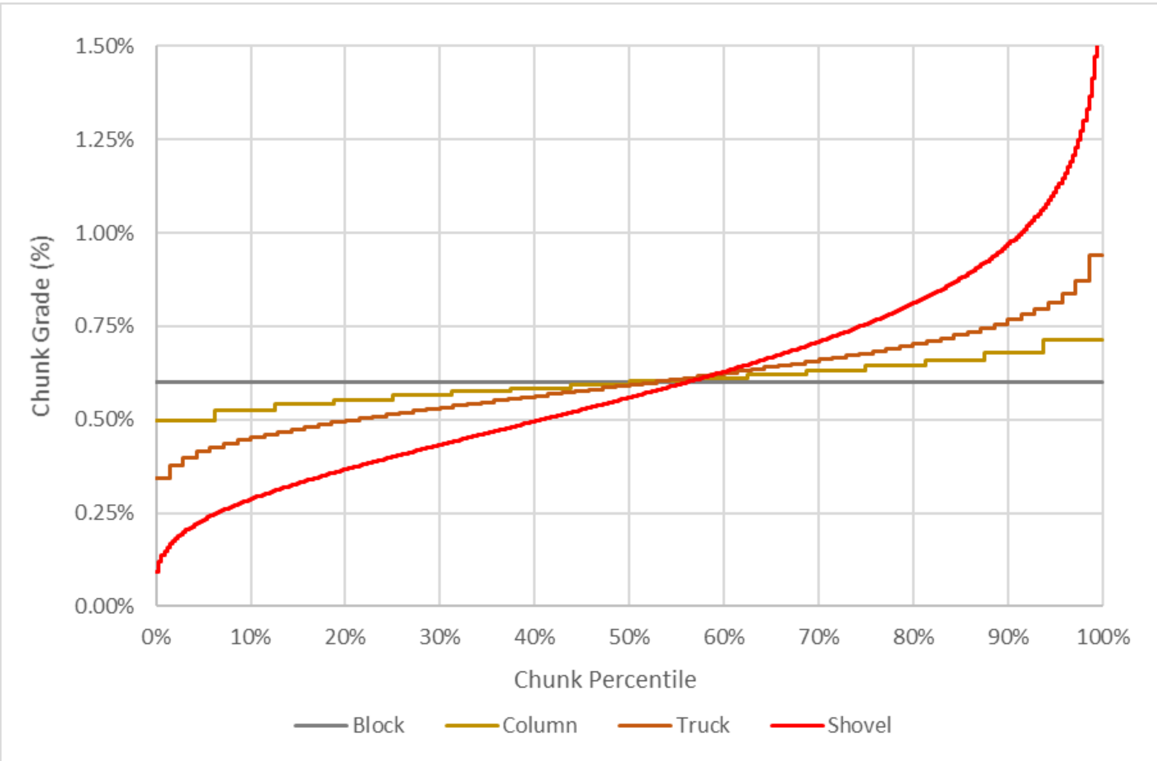

Figure 6: Internal distribution of Copper grade within a 0.60% Cu block at different mining resolutions. The stepped shape of the lines shows each individual Chunk of material within the Block. The exploitable heterogeneity of material is clear from the curves; at the finest resolution a 0.60% Cu block contains some higher grades above 1.0% that should be processed immediately, as well as some lower grades below 0.25% that can be sent straight to the dump, saving plant capacity.

MineSense provided the distribution at Shovel resolution, where there are 350 'chunks' of material per block. The gamma distribution parameter β was a constant 800, while the α parameter must be equal to β multiplied by the grade so that the mean grade of the resultant distribution of chunks is equal to the grade of the original block.

To generate the equivalent distributions for the Truck and Column cases, it was assumed for simplicity that the shovel units making up a truck or column of material were randomly sampled from the distribution. This requires multiplying the β parameter by the number of shovel loads per unit in both cases. It should be noted that the assumption of random sampling is pessimistic, particularly in the per-truck case; shovel-loads of contiguous material are more likely to have a grade similar to each other than to shovel-loads elsewhere in the block.

Table 1: Mining Resolutions and parameters used to generate their gamma distributions. Alpha (α) is the shape parameter and beta (β) is the rate parameter.

	In-Situ Volume (m^3)	**Count per Block**	**α**	**β**
Block	8000	1	∞	∞
Grade Control Unit	500	16	β x grade	17500
Truck	114.3	70	β x grade	4000
Shovel	22.9	350	β x grade	800

2.3.8 Ore-Body Grade Tonnage Curves

Another perspective to conceptualise the effect that the Mining Resolution has, is to view it as fundamentally altering the accessible grade-tonnage curve of the ore body. Figure 7 shows that at finer mining resolutions, the mean grade above any cut-off point (above zero) is *always* higher than it is at coarser resolutions.

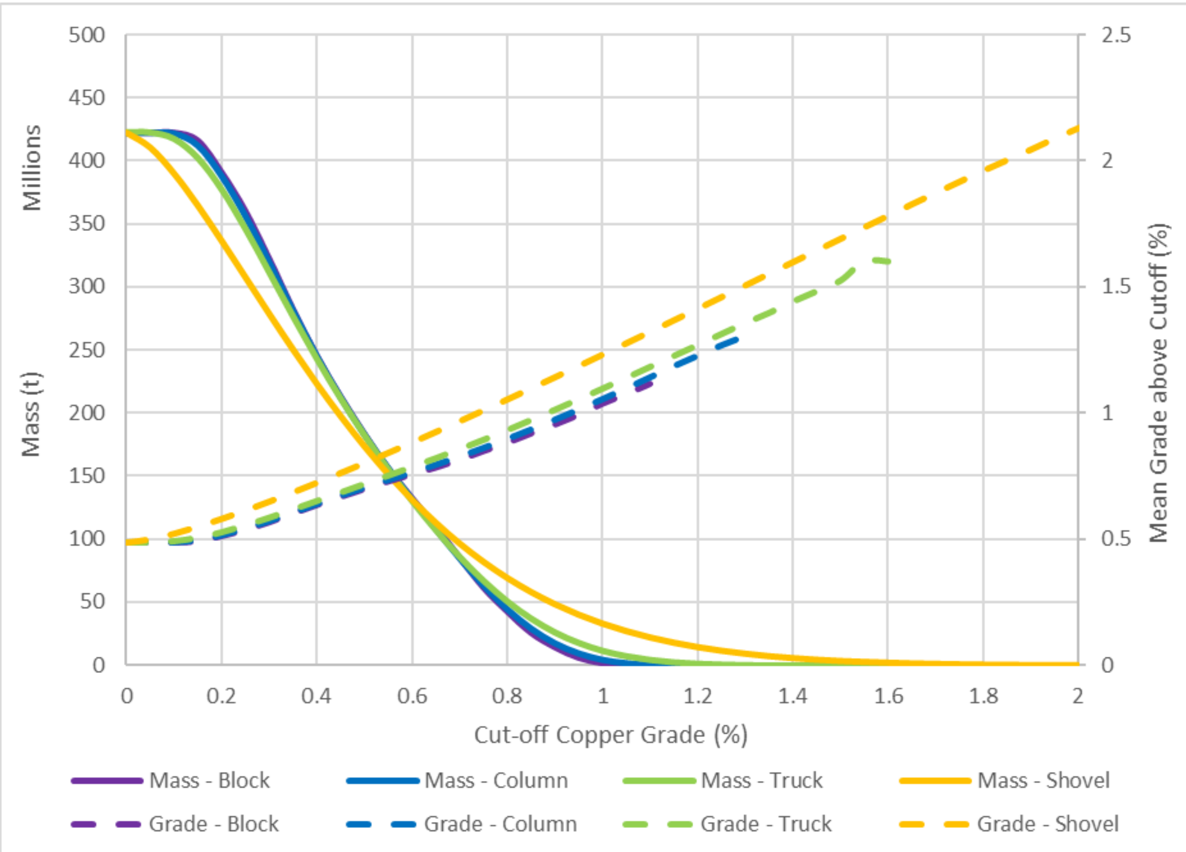

Figure 7: Marvin accessible Grade-Tonnage curve at each Mining Resolution.

2.3.9 Uncertainty

In practice, the Block and Grade Control Unit base cases would also be negatively influenced by inaccuracy in grade estimation. This inaccuracy consists of both the inaccuracy with which sample measurements and models represent the in-situ block grade, and the effect of blasting, ore handling and dilution on the mined material, which is still represented by the previously acquired *in-situ* samples.

This inaccuracy would manifest as sub-optimal routing of material i.e. an overestimation of grade would cause low-grade material to be sent to the plant instead of the dump and vice versa.

ShovelSense provides much-improved accuracy of measurement. The grade measurement is both more fine-grained and taken after blasting and dilution rather than before. Modelling the effect of this on NPV is outside the scope of this study. It should be considered an addendum in favour of ShovelSense.

2.4 Processing Model

The processing model is relatively simple as it is not the focus of this study, however it does contain two key features; throughput limitations (bottlenecks) and the ability to the vary the grind size in the comminution stage to allow the optimisation of the trade-off between grind size, throughput and recovery.

The processing model has a Flotation Plant that consists of a SAG Mill, Ball Mill and Flotation process, and an alternative Heap Leach processing path with lower costs and recoveries (for Sulphide material). Refer to diagram in Figure 3. There is a limitation in the Ball Mill of the Flotation plant, which can only apply a certain maximum rate of energy to grind ore prior to the flotation process. This is expected to be a system bottleneck, which makes the variable grind size options important. Like all other scheduling decisions, the selection of grind size for each portion of ore is decided by the optimiser. The Heap Leach also has a constraint on the maximum annual tonnage that can be processed. Strategic stockpiles are available for managing material flows.

See Appendix A – Optimisation Settings for all equations and constraints.

3 RESULTS

NPV is the primary measure to compare between the cases, while other impacts on pit inventories and cash flow are also documented. Table 2 shows the full list of financial results for each case. Figure 8 shows the change in NPV relative to the Grade Control Unit case for each case. As expected, the NPV is improved when ShovelSense is available and this NPV improvement is greater at higher resolutions than at lower resolutions.

Table 2: Summary of discounted cash for each case. The Base Case is highlighted light blue, the ideal case dark pink and the practical case light pink. See Appendix B – Result Summary for full table including material movements and grades.

	Case Name	Mining (Disc. $M)	Stock Rehandle (Disc. $M)	Heap Leach (Disc. $M)	Flotation Plant (Disc. $M)	Revenue (Disc. $M)	Capital (Disc. $M)	Net Present Value (Disc. $M)	Relative to Base Case
1	Block	-$ 544	-$ 23	-$ 99	-$ 505	$ 2,135	-$ 700	$ 265	**-3%**
2	Grade Control Unit	-$ 546	-$ 23	-$ 99	-$ 505	$ 2,146	-$ 700	$ 274	**0%**
3	Truck	-$ 549	-$ 25	-$ 98	-$ 501	$ 2,179	-$ 700	$ 305	**11%**
3a	Truck (New Pit)	-$ 521	-$ 26	-$ 98	-$ 491	$ 2,154	-$ 700	$ 317	**16%**
4	50% Shovel/Truck	-$ 537	-$ 25	-$ 98	-$ 482	$ 2,232	-$ 700	$ 391	**43%**
4a	50% Shovel/Truck (New Pit)	-$ 597	-$ 25	-$ 102	-$ 504	$ 2,331	-$ 700	$ 402	**47%**
5	Shovel	-$ 538	-$ 24	-$ 94	-$ 474	$ 2,289	-$ 700	$ 459	**68%**
5a	Shovel (New Pit)	-$ 592	-$ 28	-$ 98	-$ 492	$ 2,400	-$ 700	$ 490	**79%**

The ideal ShovelSense case provides a very large increase in NPV of $216M of 79% compared to the base case. The other ShovelSense cases provide lesser benefits and the worst-case Block resolution reduces NPV by 3% compared to the base case.

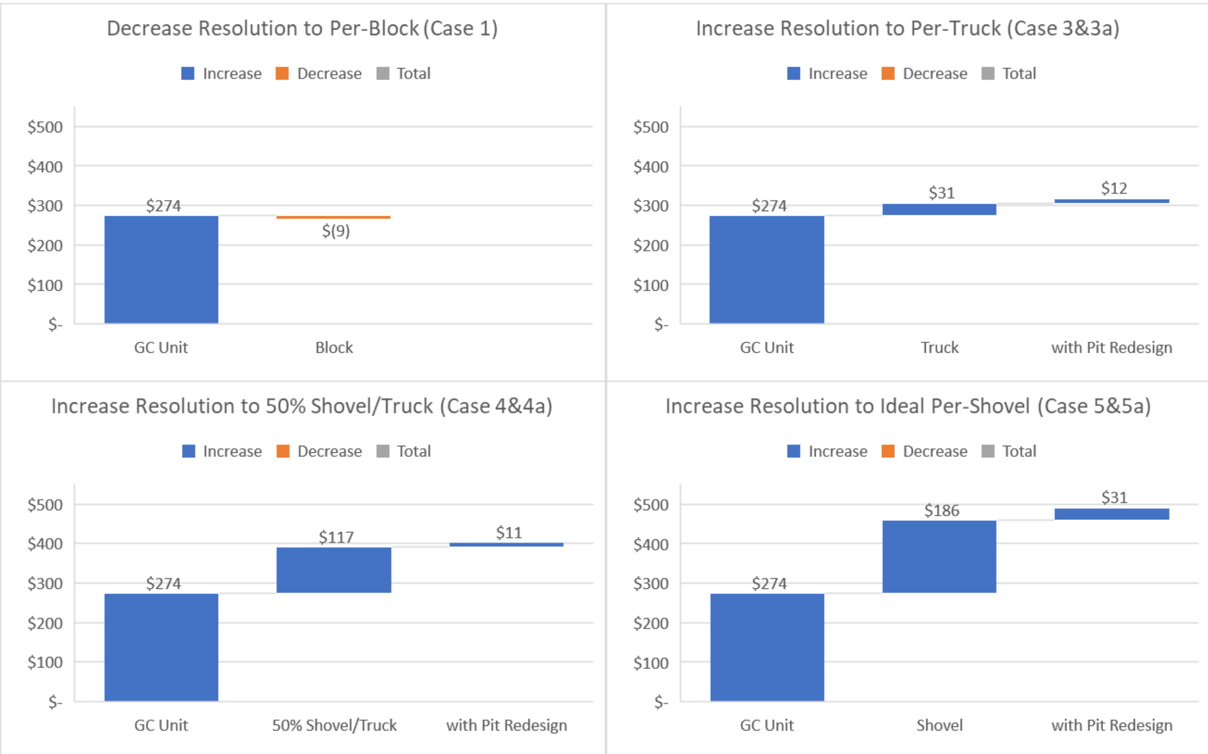

Figure 8: Waterfall chart of NPV effects relative to the Base Case (Case 2) at Grade Control Unit resolution.

In all cases the majority of the NPV uplift is obtained by modifying the schedule without pit redesign; pit redesign adds a smaller amount of additional value to the NPV.

It is also notable that the per-Truck resolution provides much less NPV uplift than the per-Shovel resolution. This is less surprising when considering that the per-Truck distribution curves (see Figure 6 and Figure 7) are much closer to the Grade Control Unit curves than to the per-Shovel curves.

As might be expected, the uplift from the 50% Shovel/Truck case is approximately half way between the per-Truck and per-Shovel cases.

The following analysis of the case progression focusses on the two runs that best demonstrate the effect of ShovelSense; the Base Case at Grade Control Unit resolution and the Ideal Case at Shovel resolution with pit redesign. The intermediate MineSense-enabled runs between these two extremes show similar qualitative benefits to the ideal case but at a smaller magnitude.

3.1 Base Case (Case 2): Grade Control Unit

The chart in Figure 9 shows the cash flows that contribute to the final NPV of $274M. After the initial capital cost, the mine immediately produces a high positive annual net cash rate. This declines over five years until a high value part of the ore body is reached and simultaneously mining rates reduce, causing a jump in cash flow. These latter positive cash flows are of a similar magnitude to the early net cash figures, however are much more heavily discounted.

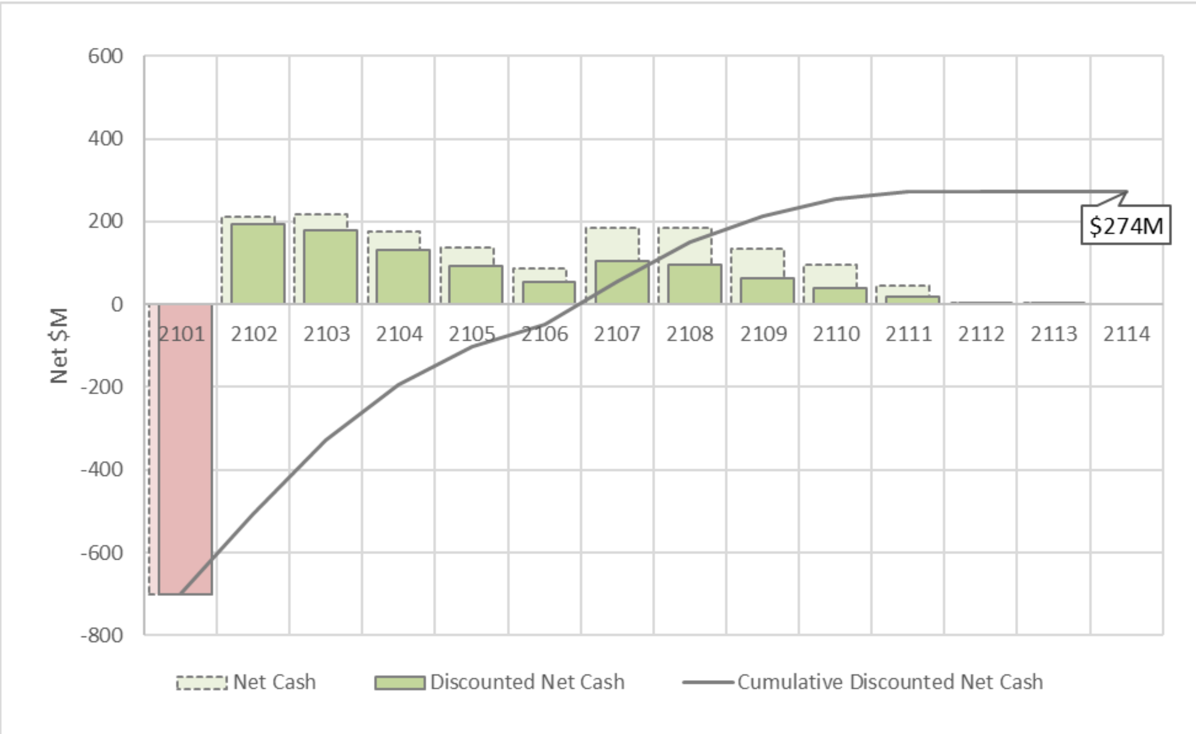

Figure 9: Cash accumulation for Case 2 – Grade Control Unit.

The material movements that drive these cash flows are shown in Figure 10. The mining rate varies significantly, which is not unexpected in an optimal plan. A large waste strip is required in periods four to six to progress deeper into the ore body, before the high-grade pit bottom is reached and then mining ceases from period nine. The Flotation Plant is kept at capacity from period two to part-way through period eight by material transported direct from the pit, after which it operates until period eleven using stockpiled material. The Leach operates through to period thirteen and is at full capacity to period twelve. As would be expected in an optimised schedule, the copper grades processed are high early in the LOM for maximum NPV impact, then fall away before increasing again as the highest-grade ore at the base of the pit is reached. The processed grades then fall significantly as stockpiled low-grade material is processed until exhausted.

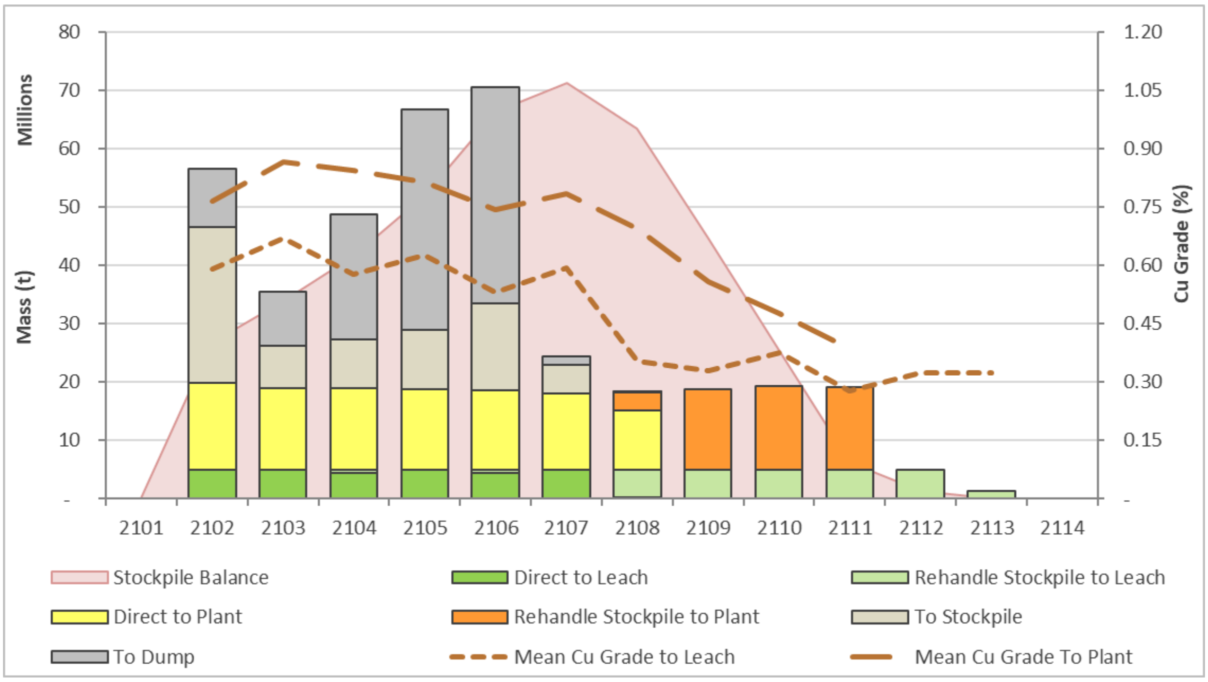

Figure 10: Material Movements Summary for the Base Case (Case 2).

3.2 Ideal Case (Case 7): Shovel Resolution (New Pit)

This ideal ShovelSense case increases NPV by 79% against the Base Case, from $274M to $490M. Figure 11 compares the cash flows in this case against those from the Base Case.

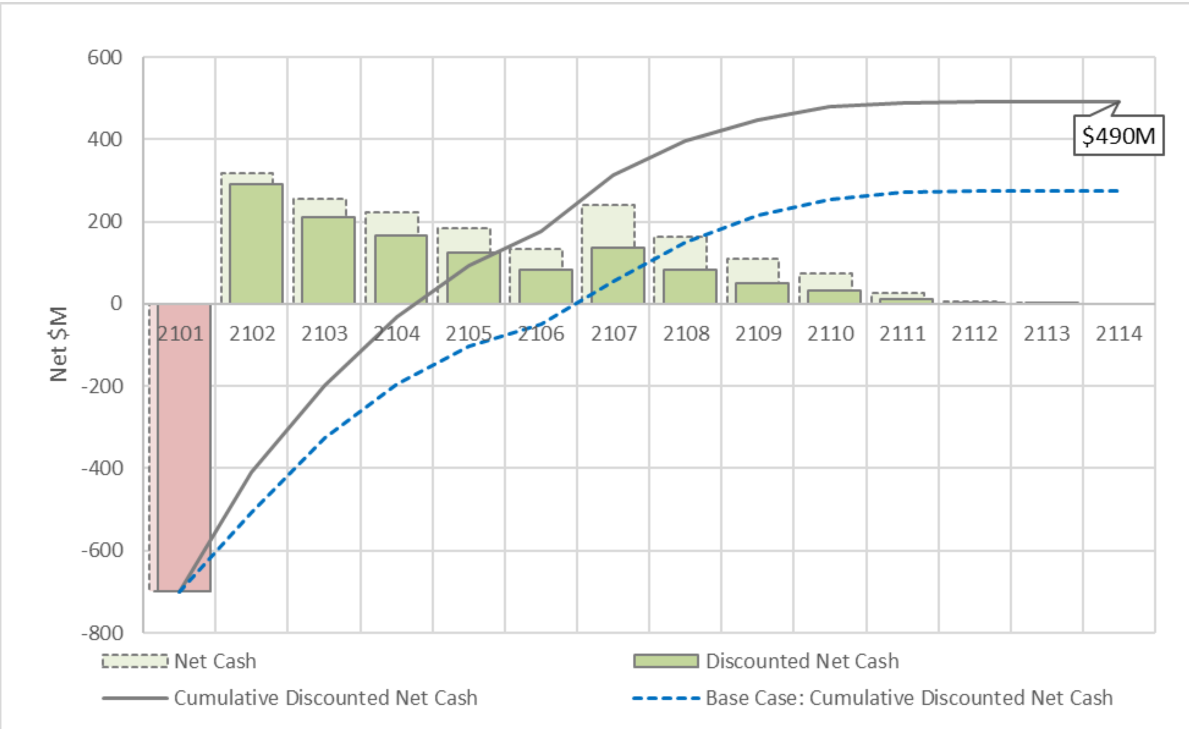

Figure 11: Cash accumulation for Case 5a – Shovel (with New Pit). Base case cash accumulation also shown.

While the latter parts of both cumulative discounted net cash curves are similar, it is in the early years (periods 2-6) that MineSense allows higher cash generation so that the NPV outstrips the base case.

The material movements that generate this extra cash are shown in Figure 12. The clear difference between this Shovel-resolution case and the Base Case is the mean copper grade fed to the plant. In the first six years of plant operation, which also constitute the entire pit life, the mean grade fed to the plant is between 0.10% and 0.25% higher than in the Base Case schedule. This higher feed grade translates directly to recovered copper and therefore revenue, which explains the high early cash flows seen in Figure 11. This high-grade ore was ground at the finest grind size option of 75µm in the Ball Mill for maximum recovery.

The Leach grade in this case is not significantly better or worse than the Base Case schedule; this is a lower-value process and therefore the optimizer finds better value by filling the Plant with high-value sulphides.

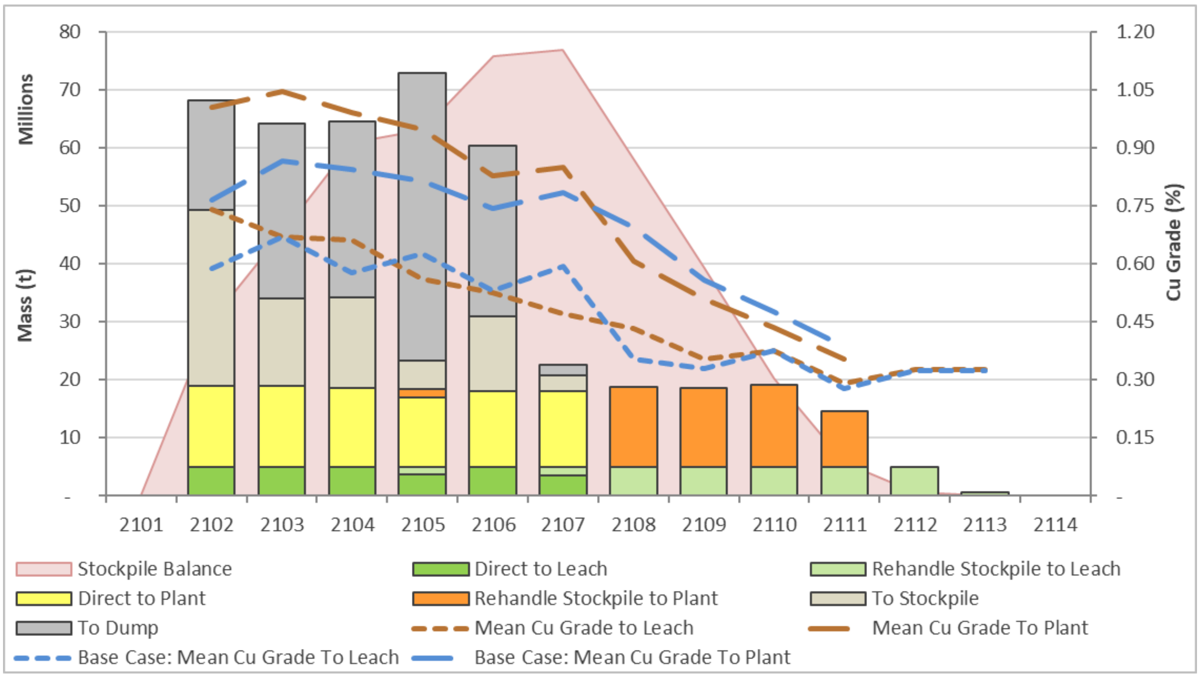

Figure 12: Material movements for Case 5a – Shovel (with New Pit). Base case feed grades are also shown.

The other noticeable characteristic of this schedule is that the mining rates are higher than in the Base Case schedule, particularly in the first three years of operation. Despite bringing large mining costs forward, this is worthwhile to keep up the supply of high grade material to the Plant. The mining schedule is more aggressive than in the Base Case, and might have been even more aggressive had mining not been limited by Vertical Rate of Advance (VRA) limits. As seen in Appendix D – Bottlenecks, this case hits either VRA or mining mass limits in period 3-5, while the Base Case instead hits these in periods 4-6.

These two observations; higher early grades and higher early mining rates, are common in economic evaluations of ore sorting technologies. See Discussion section.

3.3 Practical Case (Case 5) – 50% Shovel/Truck Resolution (New Pit)

The practical case where the mining resolution is per-Shovel 50% of the time and per-Truck the remainder, shows similar characteristics to the ideal case with a lesser magnitude. The final NPV of

$402M is still a 47% improvement over the Base Case and is driven by higher grade to the Plant in the early years, backed by an increased mining rate.

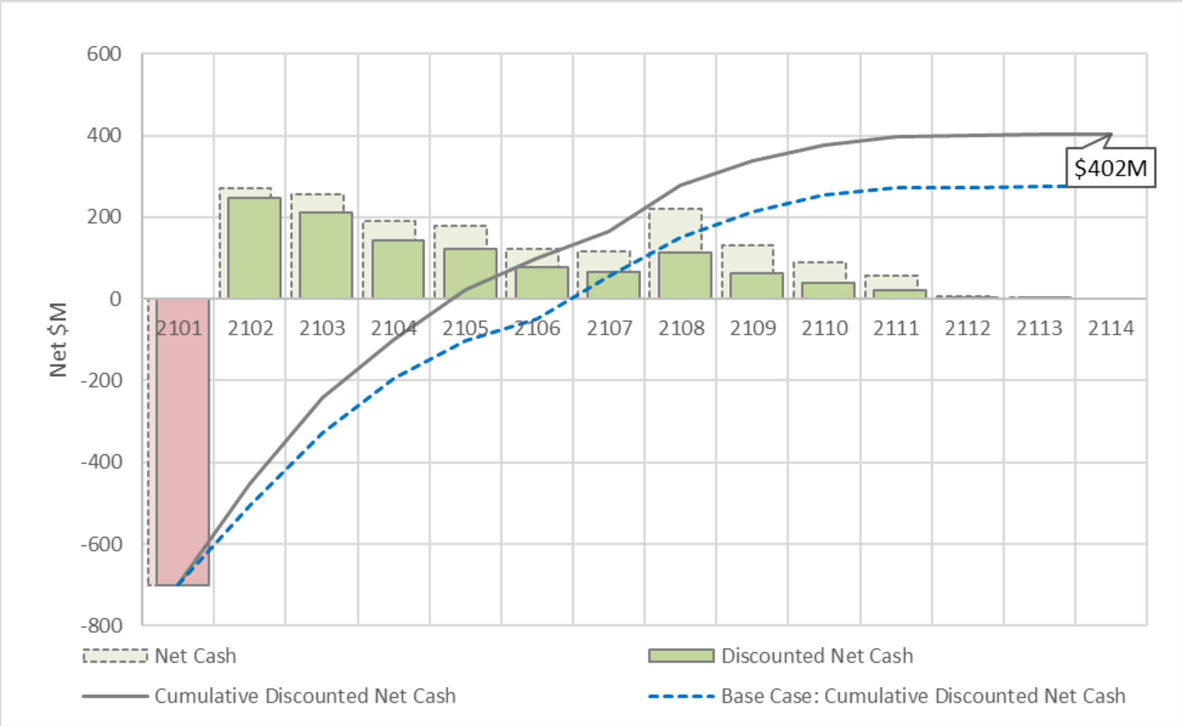

Figure 13: Cash accumulation for Case 4a – 50% Shovel/Truck (with New Pit). Base case cash accumulation also shown.

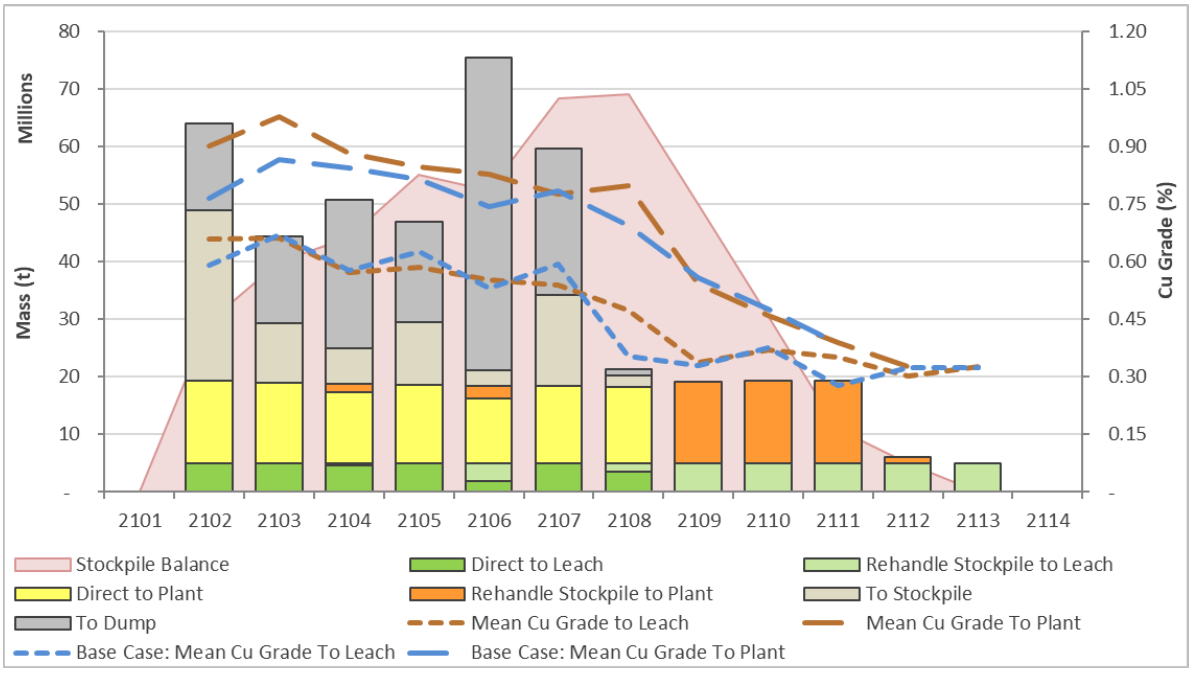

Figure 14: Material movements for Case 4a – 50% Shovel/Truck (with New Pit). Base case feed grades are also shown.

3.4 Discussion

The results for the seven cases demonstrate a strong cause-and-effect relationship between grade-control resolution and NPV. In the fictional but realistic mining operation studied, the presence of ShovelSense technology made possible scheduling and pit decisions that yielded major NPV increases over the Base Case without this technology.

The effect of ShovelSense technology on optimal scheduling decisions is similar to those from other Grade Engineering[2] technologies such as screening, selective blasting and sensor-based sorting. The fundamental mechanism by which it generates value is by creating higher-value and lower-value portions of material from each parcel of ore, which can then be processed differently.

The high-value portion(s) of the ore are more valuable per bottleneck unit (Ball Mill Power, in this study) than the unsorted ore and, as the bottleneck controls the flow of cash through the system, this intensifies cash generation from this material.

The lesser-valued portion(s) that would previously have made up some of the bulk of unsorted ore processed, can instead be routed to the stockpile for later processing. Or, if the grade is particularly low, the waste dump. This is the right scheduling action to take provided that other higher-grade material is available to fill the processing plant bottleneck. There are two means by which this other high-grade material may be found.

3.4.1 Metal Exchange

While MineSense and similar technology generates a low-grade fraction from ore previously destined for the processing Plant, it also extracts a high-grade fraction from material that was to be processed through the next most valuable processing destination. In this case the next best processing destination is the same Plant delayed to the following year (via stockpiling). The highest-grade fraction of the ore that would otherwise have been sent to the stockpile, will be higher value than the lower grade fractions that would otherwise have been sent to the Plant. Therefore, the optimal decision is to swap the processing destinations for these; this is termed Metal Exchange.

The same mechanism works for other cut-off decisions too; the low-grade portion of material that would otherwise be stockpiled would be sent to the waste dump, while the high-grade portion of material that would otherwise be dumped would be sent to the stockpile.

The net effect of this is to raise the cut-off grade between these processing options early in the mine life, which improves NPV.

3.4.2 Increased Mining Rate

The second way to support the MineSense-enabled high-grading of ore to the processing Plant early in the mine life is to raise the mining rate. This is directly observed in this case study. More high-grade material can be found by accelerating the mining rate through the ore body, taking only the highest grades for immediate processing, while stockpiling the mid-grades for later processing. Despite bringing mining costs forward and incurring additional rehandle costs, this approach is financially beneficial because of the very high processing grades and therefore revenue generated.

In this case study the mining rate was increased until mining VRA or tonnage bottlenecks were hit.

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[2] Redwood, N; Scott, M (2016). *Application of Enterprise Optimisation Considering Grade Engineering® Strategies*

3.4.3 Increased Utilisation of High-Value Processing Paths

ShovelSense and similar technologies typically reduce the pressure on the high-value bottleneck in the system, although this is not guaranteed if the mining rate is increased significantly. If the bottleneck pressure is reduced than this makes higher-value processes that consume more bottleneck space, such as fine-grind in the Ball Mill, more attractive. There is less implied penalty for using up bottleneck space, which shifts the optimal balance towards increasing recovery with fine grind rather than increasing throughput with coarse grind.

In this study only a slight increase in usage of fine grind rather than coarse grind was observed in the MineSense cases; this may indicate that additional mining outweighed this mechanism.

4 CONCLUSIONS

Based on the parameters used, ShovelSense technology offers major potential benefits to the fictional but realistic mining operation modelled in this study.

1. An idealised implementation of ShovelSense, where grade control decisions are made at the shovel level, offered a 79% improvement in NPV against the base case in which a typically-sized grade control unit is used.
2. A more practical assumption that shovel resolution is possible 50% of the time (using double-sided loading) and truck-level resolution the remainder, still yielded a large increase in NPV of 47%.
3. Any such improvements rely on the mining enterprise having sufficient sophistication to effectively implement real-time shovel-level and truck-level grade control.
4. The proximate reason for the improvement in NPV is higher processing grades early in the life of the mine.
5. The underlying reasons for the improvement in NPV are that;
    a. High-value ore fractions increase the intensity of cash generated through the high-value bottleneck (the processing Plant);
    b. Low-value fractions vacate the bottleneck and are replaced by higher-value fractions from material that would otherwise have been processed via lesser-valued paths, or by more high-grade material found be accelerating the mining rate.

5 APPENDICES

5.1 APPENDIX A – OPTIMISATION SETTINGS

Mining

Variable Cost = \$1.60/t + *BenchDepth* * \$0.02/t

where *BenchDepth* = *(Depth - SurfaceLevel)/BenchHeight*

with *SurfaceLevel* = 825m, *BenchHeight* = 20m

Fixed Cost = \$40M/y

Limit = 70Mt/y

Stockpile Rehandle Cost = \$0.75/t

Stockpile Accumulation Limit = 80Mt

Heap Leach

Variable Cost Rate = \$2.00/t

Fixed Cost = \$5M/y

Limit = 5.0Mt/y (from period 2)

Recovery = OX: $0.96 – 0.1/ CuFraction_{Input}$ [or $CuMass_{Output} = CuMass_{Input} * 0.96 – TotalMass_{Input} * 0.1$]

MX: $0.65 – 0.1/ CuFraction_{Input}$ [or $CuMass_{Output} = CuMass_{Input} * 0.65 – TotalMass_{Input} * 0.1$]

SU: $0.42 – 0.1/ CuFraction_{Input}$ [or $CuMass_{Output} = CuMass_{Input} * 0.42 – TotalMass_{Input} * 0.1$]

(this is a linear fixed-tail recovery curve)

Plant

Variable Cost Rate = *SagMillCost* + *BallMillCost* + *HardnessCost* + *FlotationCost*

where *SagMillCost* = \$1.30/t,

BallMillCost = \$0.50/t,

FlotationCost = \$1.00/t,

HardnessCost =

	75 µm	106 µm	150 µm	200 µm
OX:	\$1.05/t	\$0.90/t	\$0.68/t	\$0.45/t
MX:	\$1.80/t	\$1.50/t	\$1.20/t	\$0.75/t
SU:	\$2.25/t	\$1.80/t	\$1.35/t	\$0.90/t

(hardness cost is to pay for power and steel, which depend on oxide type and selected grind size)

Fixed Cost = \$20M/y

Plant Limit = Ball Mill Power Limit = 200,000,000 kWh/y

where *BallMillPowerConsumption* =

	75 µm	106 µm	150 µm	200 µm
OX:	10.0 kWh/t	9.0 kWh/t	8.0 kWh/t	7.0 kWh/t
MX:	14.3 kWh/t	13.5 kWh/t	12.4 kWh/t	11.3 kWh/t
SU:	17.3 kWh/t	16.1 kWh/t	15.0 kWh/t	13.5 kWh/t

Product

Copper price = \$5500/t

Selling cost = \$1300/t

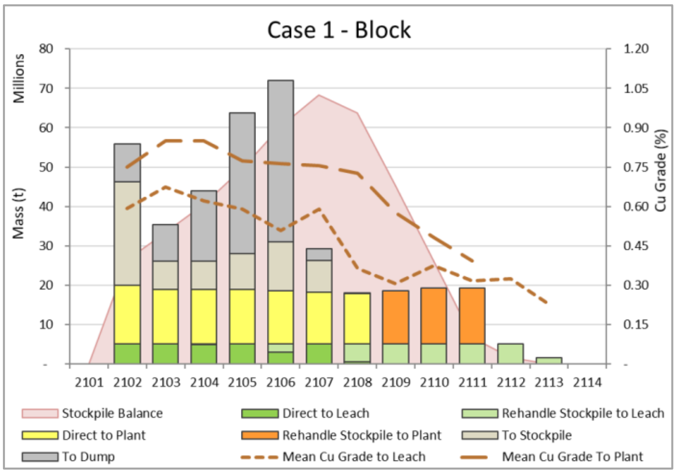
Pit Optimisation

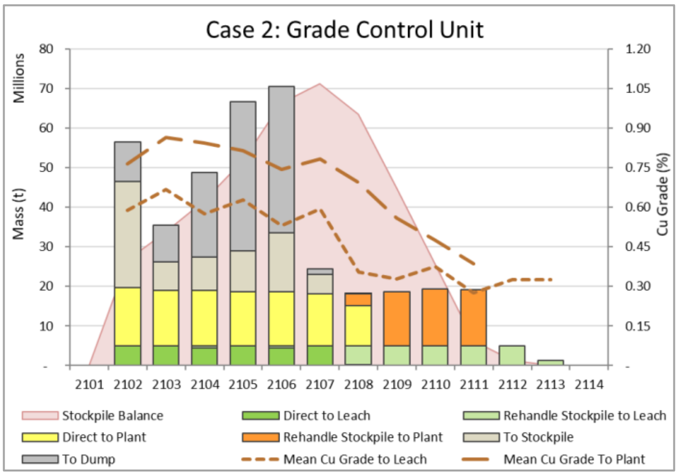
Mean pit slope angle = 42°

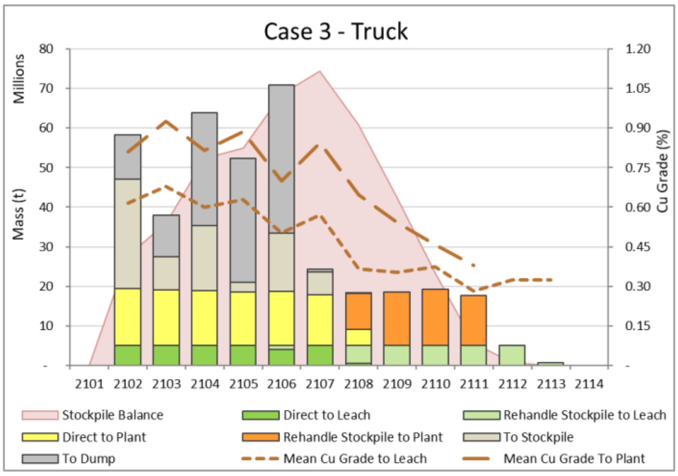
5.2 Appendix B – Result Summary

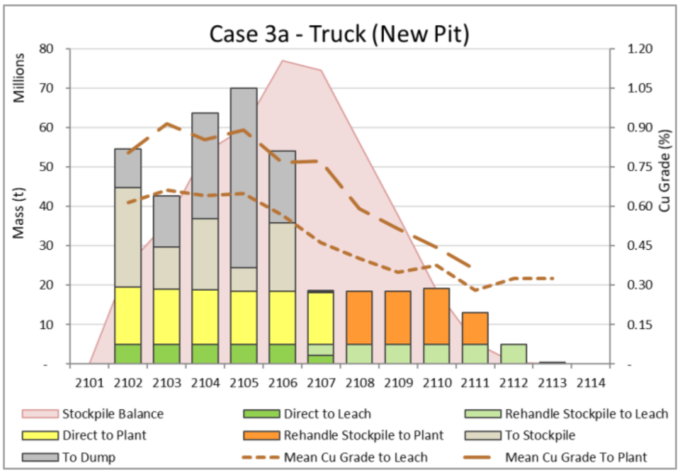
	1	2	3	3a	4	4a	5	5a
Case Name	Block	Grade Control Unit	Truck	Truck (New Pit)	50% Shovel/Truck	50% Shovel/Truck (New Pi	Shovel	Shovel (New Pit)
Case Branching: Vary *Mining Resolution* and *Pit Design*	Decrease Resolution: Block	Mining Resolution & Pit Designed for: GC Unit	Increase Resolution: Truck	Redesign Pit: Truck	Increase Resolution: 50% Shovel/Truck	Redesign Pit: 50% Shovel/Truck	Increase Resolution: Shovel	Redesign Pit: Shovel
Mining								
Mass (Mt)	311.6	311.6	311.6	300.8	311.6	353.9	311.6	348.1
Cu (kt)	1,299	1,299	1,299	1,272	1,299	1,406	1,299	1,394
Mean Cu grade (%)	0.417%	0.417%	0.417%	0.423%	0.417%	0.397%	0.417%	0.400%
Mining Costs ($M)	*-$ 770.9*	*-$ 769.2*	*-$ 765.9*	*-$ 712.1*	*-$ 733.9*	*-$ 852.9*	*-$ 733.1*	*-$ 802.8*
Mining Costs (Disc. $M)	*-$ 543.6*	*-$ 545.5*	*-$ 549.1*	*-$ 521.5*	*-$ 536.6*	*-$ 596.5*	*-$ 538.4*	*-$ 592.1*
Ore								
Mass (Mt)	195.1	194.7	191.5	187.1	183.0	199.4	174.5	188.0
Cu (kt)	1,222	1,224	1,222	1,198	1,215	1,309	1,207	1,290
Mean Cu grade (%)	0.627%	0.628%	0.638%	0.640%	0.664%	0.657%	0.692%	0.686%
Stripping Ratio	0.597	0.600	0.627	0.608	0.703	0.775	0.786	0.852
Stockpile Rehandle Costs ($M)	*-$ 52.8*	*-$ 54.3*	*-$ 56.6*	*-$ 58.0*	*-$ 55.5*	*-$ 58.2*	*-$ 51.4*	*-$ 61.0*
Stockpile Rehandle Costs (Disc. $M)	*-$ 22.7*	*-$ 23.4*	*-$ 24.8*	*-$ 26.0*	*-$ 25.2*	*-$ 25.3*	*-$ 24.2*	*-$ 27.7*
Heap Leach								
Mass (Mt)	56.6	56.3	55.6	55.4	55.5	60.0	51.3	55.7
Cu (kt)	267	266	267	268	265	286	246	272
Mean Cu grade (%)	0.471%	0.473%	0.480%	0.483%	0.479%	0.477%	0.479%	0.489%
Processing Costs ($M)	*-$ 169.9*	*-$ 168.8*	*-$ 166.7*	*-$ 166.2*	*-$ 166.4*	*-$ 180.0*	*-$ 154.0*	*-$ 167.1*
Processing Costs (Disc. $M)	*-$ 99.0*	*-$ 98.6*	*-$ 98.0*	*-$ 97.8*	*-$ 97.9*	*-$ 102.2*	*-$ 93.6*	*-$ 98.1*
Product Cu (kt)	137	137	138	138	136	146	127	140
Plant								
Mass (Mt)	138.4	138.4	135.9	131.7	127.5	139.4	123.2	132.3
Cu (kt)	956	957	956	930	949	1,023	961	1,017
Mean Cu grade (%)	0.690%	0.692%	0.703%	0.706%	0.744%	0.734%	0.780%	0.769%
Processing Costs ($M)	*-$ 818.8*	*-$ 818.3*	*-$ 809.4*	*-$ 782.8*	*-$ 758.5*	*-$ 818.7*	*-$ 737.5*	*-$ 786.6*
Processing Costs (Disc. $M)	*-$ 504.9*	*-$ 504.8*	*-$ 501.3*	*-$ 491.0*	*-$ 481.7*	*-$ 504.3*	*-$ 473.6*	*-$ 491.7*
Product Cu (kt)	645	646	650	631	652	700	667	705
Revenue (Less Sell Costs)								
Revenue ($M)	*$ 3,284.9*	*$ 3,290.4*	*$ 3,305.7*	*$ 3,232.4*	*$ 3,309.7*	*$ 3,552.5*	*$ 3,335.8*	*$ 3,550.3*
Revenue (Disc. $M)	*$ 2,135.2*	*$ 2,146.3*	*$ 2,178.5*	*$ 2,153.6*	*$ 2,232.3*	*$ 2,330.7*	*$ 2,289.2*	*$ 2,400.1*
Capital								
Capital ($M)	*-$ 700.0*	*-$ 700.0*	*-$ 700.0*	*-$ 700.0*	*-$ 700.0*	*-$ 700.0*	*-$ 700.0*	*-$ 700.0*
Capital (Disc. $M)	*-$ 700.0*	*-$ 700.0*	*-$ 700.0*	*-$ 700.0*	*-$ 700.0*	*-$ 700.0*	*-$ 700.0*	*-$ 700.0*
NPV	$ 265.0	$ 273.9	$ 305.3	$ 317.2	$ 391.1	$ 402.3	$ 459.4	$ 490.5
Relative to Base Case	**-3%**	**0%**	**11%**	**16%**	**43%**	**47%**	**68%**	**79%**

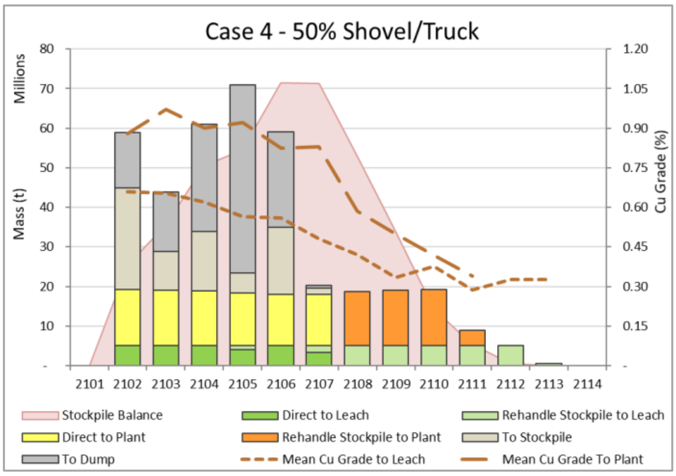
5.3 Appendix C – Material Movements Summary

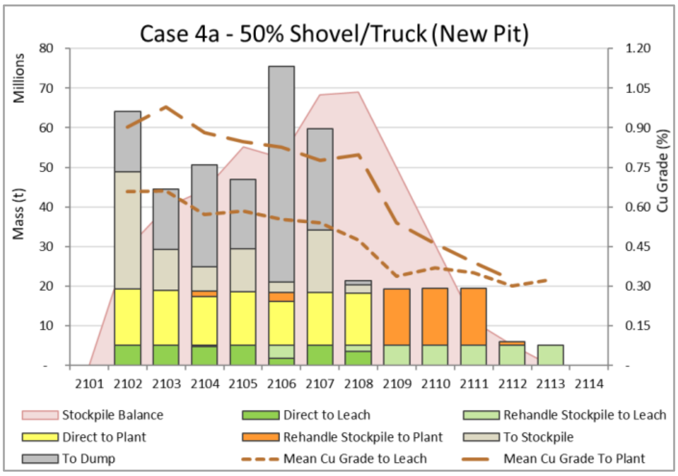


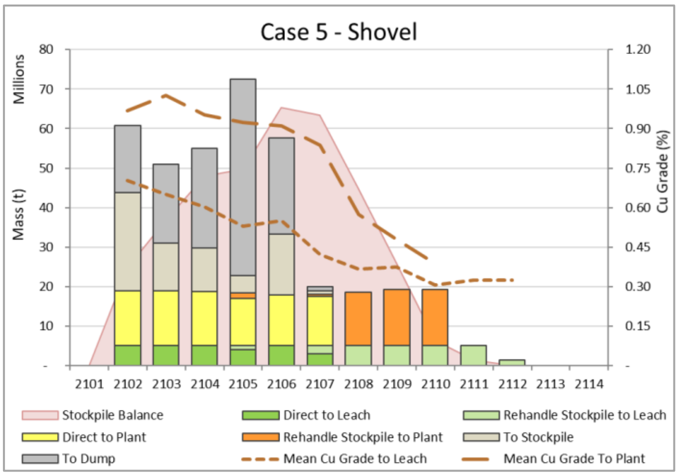


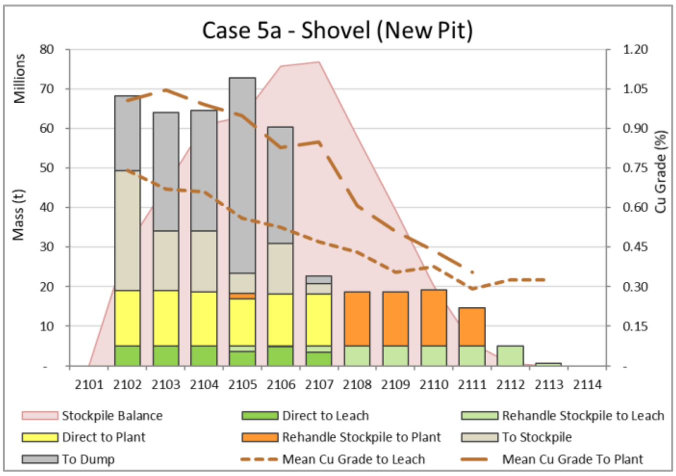










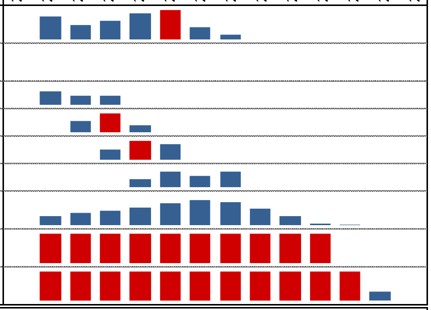


5.4 Appendix D – Bottlenecks

Case 1 - Block

Limit Name	Bottleneck
Mining Tonnage	Yes
Bench Limits (VRA)	
Phase 1	No
Phase 2	Yes
Phase 3	Yes
Phase 4	No
Stockpile Cumulative Tonnage	No
Flotation Plant Energy	Yes
Heap Leach Tonnage	Yes

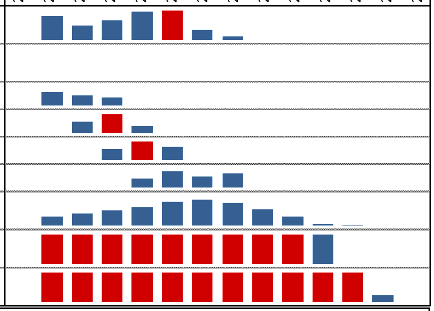
Year: 2101 2102 2103 2104 2105 2106 2107 2108 2109 2110 2111 2112 2113 2114



Case 2 - Grade Control Unit

Limit Name	Bottleneck
Mining Tonnage	Yes
Bench Limits (VRA)	
Phase 1	No
Phase 2	Yes
Phase 3	Yes
Phase 4	No
Stockpile Cumulative Tonnage	No
Flotation Plant Energy	Yes
Heap Leach Tonnage	Yes

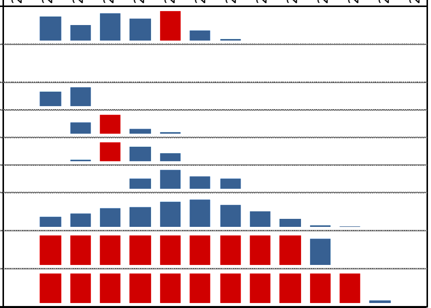
Year: 2101 2102 2103 2104 2105 2106 2107 2108 2109 2110 2111 2112 2113 2114



Case 3 - Truck

Limit Name	Bottleneck
Mining Tonnage	Yes
Bench Limits (VRA)	
Phase 1	No
Phase 2	Yes
Phase 3	Yes
Phase 4	No
Stockpile Cumulative Tonnage	No
Flotation Plant Energy	Yes
Heap Leach Tonnage	Yes

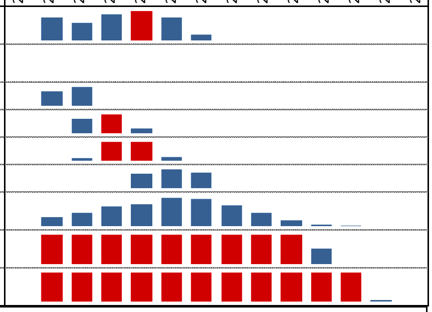
Year: 2101 2102 2103 2104 2105 2106 2107 2108 2109 2110 2111 2112 2113 2114



Case 3a - Truck (New Pit)

Limit Name	Bottleneck
Mining Tonnage	Yes
Bench Limits (VRA)	
Phase 1	No
Phase 2	Yes
Phase 3	Yes
Phase 4	No
Stockpile Cumulative Tonnage	No
Flotation Plant Energy	Yes
Heap Leach Tonnage	Yes

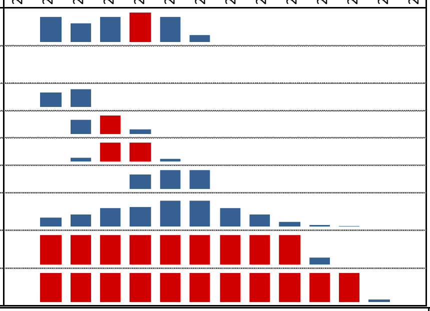
Year: 2101 2102 2103 2104 2105 2106 2107 2108 2109 2110 2111 2112 2113 2114



Case 4 - 50% Shovel/Truck

Limit Name	Bottleneck
Mining Tonnage	Yes
Bench Limits (VRA)	
Phase 1	No
Phase 2	Yes
Phase 3	Yes
Phase 4	No
Stockpile Cumulative Tonnage	No
Flotation Plant Energy	Yes
Heap Leach Tonnage	Yes

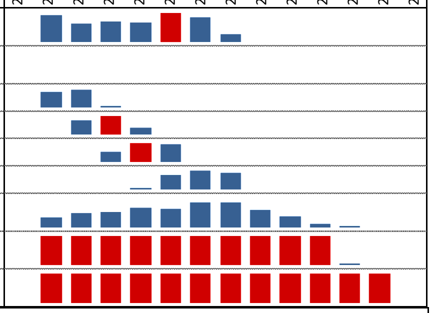
Year: 2101 2102 2103 2104 2105 2106 2107 2108 2109 2110 2111 2112 2113 2114



Case 4a - 50% Shovel/Truck (New Pit)

Limit Name	Bottleneck
Mining Tonnage	Yes
Bench Limits (VRA)	
Phase 1	No
Phase 2	Yes
Phase 3	Yes
Phase 4	No
Stockpile Cumulative Tonnage	No
Flotation Plant Energy	Yes
Heap Leach Tonnage	Yes

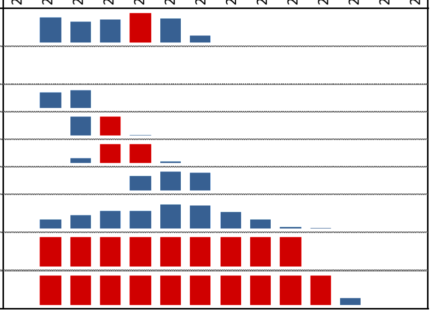
Year: 2101 2102 2103 2104 2105 2106 2107 2108 2109 2110 2111 2112 2113 2114



Case 5 - Shovel

Limit Name	Bottleneck
Mining Tonnage	Yes
Bench Limits (VRA)	
Phase 1	No
Phase 2	Yes
Phase 3	Yes
Phase 4	No
Stockpile Cumulative Tonnage	No
Flotation Plant Energy	Yes
Heap Leach Tonnage	Yes

Year: 2101 2102 2103 2104 2105 2106 2107 2108 2109 2110 2111 2112 2113 2114



Case 5a - Shovel (New Pit)

Limit Name	Bottleneck
Mining Tonnage	Yes
Bench Limits (VRA)	
Phase 1	No
Phase 2	Yes
Phase 3	Yes
Phase 4	No
Stockpile Cumulative Tonnage	No
Flotation Plant Energy	Yes
Heap Leach Tonnage	Yes

Year: 2101 2102 2103 2104 2105 2106 2107 2108 2109 2110 2111 2112 2113 2114