Autonomous Haulage Systems Financial Model Assessment

for **Mining Technicians Group - Australia**
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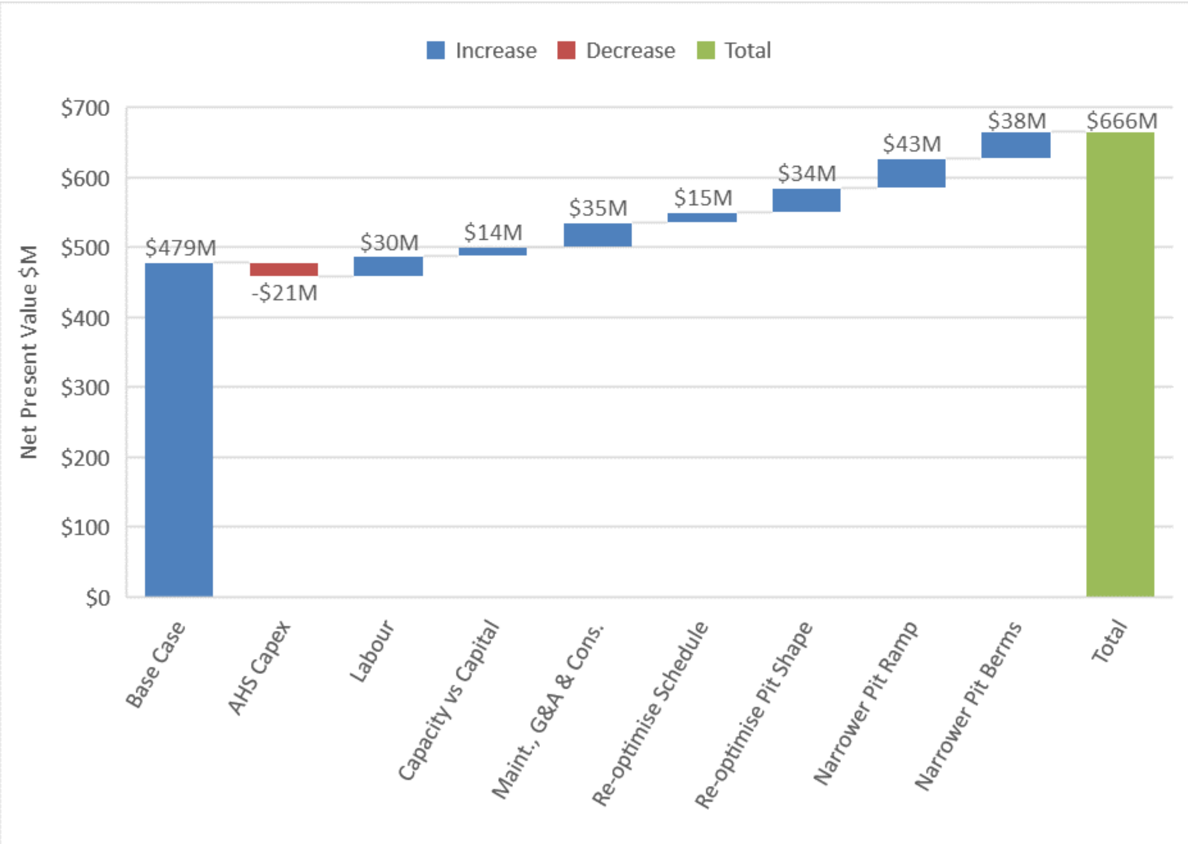
SUMMARY

Mining Technicians Group Australia (MTGA) provide services for Autonomous Haulage System (AHS) deployment for haulage fleets in the mining industry. Whittle Consulting completed an investigation to assess the financial effect of AHS on a hypothetical mining operation.

Whittle Consulting provides Integrated Strategic Planning to mining companies. This planning methodology considers all parts of the value chain, the entire life-of-mine and all stakeholders. It requires cross-functional collaboration across all elements of an organisation so that an accurate model of the whole system, from resource to market, can be built. This is then mathematically optimised using proprietary software *Prober* to produce a schedule. This methodology allows the full effect of any defined technology on the Net Present Value of a mining enterprise to be calculated.

The case study established an optimal base case mining operation, consisting of a realistic copper/gold ore body and optimised pit, defined haulage distances, a trucking fleet and a simple processing plant. Cases 2-6 apply the major AHS cost-related effects one-by-one; these are additional capital, labour cost saving, truck speed and capacity, maintenance savings, consumable savings and G&A savings. Cases 7-9 model a pit redesign based on the re-costed mining system, with cases 8 and 9 also steepening the mean pit slope. AHS is demonstrated to allow the narrowing of the pit ramp and the narrowing of catch-benches to achieve the steeper overall mean slope.



The first improvements to NPV are cost savings to variable, fixed and potentially capital costs. These cost reductions improve the NPV from $479M to $551M, an increase of 15%. Significant further improvements arise from re-optimising the pit design; In this case study this pit redesign process yielded an NPV of $666M, a total increase over the base case of 39%.

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1 INTRODUCTION

Mining Technicians Group Australia (MTGA) are a services provider for Autonomous Haulage System (AHS) technology deployments in the mining industry. MTGA assists clients with the business case analysis, deployment planning and onsite installation of AHS.

Whittle Consulting are specialists in Integrated Strategic Planning for the mining industry.

1.1 PURPOSE

Whittle Consulting carried out an investigation to assess the full financial effect of AHS on a hypothetical mining operation. This report describes the methodology followed and summarises the findings.

Various other AHS assessments exist in the public domain; these typically focus on operating efficiencies (production gain) and budget rationalisation (cost reduction). By contrast, this assessment considers the effect of AHS over a whole mining operation for its entire life-of-mine, with optimised scheduling decisions, so has a larger scope than an assessment based only on unit costs.

1.2 AUTONOMOUS HAULAGE SYSTEMS (AHS)

Mining operations are continually searching for means to improve efficiency and reduce costs via the usage of new technology. Autonomous Haulage Systems (AHS) or colloquially 'Self-Driving Trucks' is one such set of technologies that has demonstrated success in this area and is expected to further improve in the future.

The following components[1] are required for a mining autonomous haulage system:

- haul trucks fitted with electronic devices to allow continuous communication and control;
- software that commands, controls and tracks vehicle movements in real-time;
- a reliable and all-encompassing wireless communications network;
- a team of control room operators and support staff managing the vehicles, equipment, software and network.

In 2017 there were five AHS operations in the Pilbara region of Western Australia, totalling 134 off-highway heavy haul trucks. In addition, there is one established AHS operating in Chile. The longest running of these have operated for a decade and the lessons learned and various market data inform the parameters utilised in this evaluation.

The control rooms for these trucks are situated either in the Pilbara region (not necessarily near the mine) or in Perth, 1000km away. The trucks typically operate with minimal manual interference; they are completely autonomous and self-driving.

The mine site is segmented into autonomous and non-autonomous zones. All vehicles, including non-AHS vehicles in the autonomous zone, are fitted with GPS transponders so they may be tracked and avoided by AHS trucks. While the trucks maintain a minimum safety distance from other tracked

[1] Price, R (2016). "Autonomous Haulage Systems – the Business Case". *Ninth AUSIMM Open Pit Operators' Conference*, 11-17.

vehicles, they also utilise object detection systems (RADAR and LiDAR) to detect potential collisions with any object which will efficiently stop the truck.

The AHS trucks are capable of automatic positioning beneath digger buckets and automatic tipping at material destinations, including both crusher stations and stockpiles.

Autonomous vehicles enable productivity improvements and cost benefits which are quantified using the best available data for the modelling in this report. The figures used for cost and efficiency metrics such as labour, maintenance costs, utilisation rates and G&A costs are in line with those published by the major miners currently utilising AHS.

In addition to the proven effects above, the study provides a conceptual analysis to evaluate the potential benefits of mine design and mine planning optimisations enabled by AHS. The potential improvements include haul road narrowing and catch bench restriction, both of which increase overall pit slope angles. Existing AHS implementations utilise standard mine design parameters; currently there are not any publicly available examples of improvement in these parameters due to AHS, so the analysis here is hypothetical.

Autonomous vehicles also reduce the presence of human personnel in front-line in-pit and haul operations, which reduces the risk of people and asset related incidents.

1.2.1 Labour Costs

AHS trucks do not require a driver each shift to operate, which immediately reduces wage costs. Instead of paying for an operator per truck as in a traditional fleet, the management of an AHS fleet requires control room staff and field staff per shift. This number is near-constant; it does scale slightly depending on the size of the fleet, but is significantly reduced compared to field operational staffing.

Therefore, for any but the smallest of fleets, the AHS fleet requires fewer shift operator salaries and so represents a cost saving.

1.2.2 Capacity per Truck

AHS trucks achieve a higher utilisation rate than non-AHS trucks. They don't require the presence of a human driver; therefore AHS trucks are immediately ready to use whenever activities start or end, do not require operator breaks or changeovers and aren't reliant on schedulers to pair the truck with a driver. This increases the available truck hours per year per truck, which may mean fewer trucks are required in the fleet and capital and fixed costs are saved. Publicly reported data indicates that autonomous trucks provide 700-1,000 additional operational (driving) hours per year than manned equivalents[2].

The AHS trucks also move at a mean speed that is faster than non-AHS trucks. This is because the AHS truck accelerates and decelerates more quickly and evenly, and is able to brake more quickly when potential risks are identified. Typical flat haul speeds are higher with AHS due to the risk reduction of the onboard sensory systems and decrease in process variability.

This has a similar impact to increased utilisation, that it increases the mass distance hauled per truck (tonne-kilometre productivity measure) which allows a reduction in the number of trucks required in the fleet.

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[2] "Rio Tinto to expand autonomous fleet as part of $5 billion productivity drive". *Rio Tinto Media Release*, 12 December 2017.

1.2.3 Maintenance, G&A and Consumables

AHS trucks require an additional scheduled maintenance task; the servicing of the AHS itself, however this is a minor task. AHS trucks also require less unscheduled maintenance time as they have far fewer impacts than manned trucks and therefore there is far less accidental damage to repair. Overall maintenance costs are reduced.

General and Administration (G&A) costs are also reduced, primarily in relation to reduced reliance on labour. As the number of truck drivers is reduced, this also reduces requirement for accommodation, flights and other coordination and management costs.

Sites with AHS trucks report less truck tyre wear and tear; tyre replacement may be scheduled at 6000-7000 hours, or more, instead of 5000 hours. Therefore, tyre costs are reduced. The increase in tyre life is due to less variable driving, more predictable drive pattern and smoother roadways as a result of the trucks having object detection sensory onboard.

Evidence of reduced diesel consumption was not found for AHS trucks in practical usage in Western Australia.

1.2.4 Pit Slope – Narrower Ramps

AHS truck positions and velocities are controlled to within fine tolerances. The localisation system of AHS is high precision GPS, which is accurate to several centimetres. This precision means less allowance is required between the truck and the ramp edges or other trucks travelling in the opposite direction. This allows the ramp width to be reduced, in this theoretical evaluation.

A reduction in haul road width allows the total pit slope used for mine planning to be steeper, without compromising safety. A steeper pit slope typically has several financial benefits; a reduction in waste stripping, an associated benefit that additional ore at the bottom of the pit becomes economic, and potentially the ability to access deeper ore earlier in the life of the mine (if mining tonnage rate is the limiting factor).

An additional benefit not examined in this study is that, as AHS trucks are coordinated precisely, they are better able to utilise one-way haul roads. They can be better coordinated to reach the periodic two-way passing lanes at the right time to minimise wait times. Single lane ramps are often used for bottom pit access during the end-stage of the mine life (referred to as a good-bye cut).

1.2.5 Pit Slope – Narrower Catch-Benches

Autonomous vehicles do not require human operators, which may lower assessed risk levels and allow reduced pit catch-bench widths. Risk assessments typically consider two components to risk, ‘likelihood’ and ‘severity’; as a rock-fall onto an AHS haul truck would have no risk of injuring a human, the severity of an incident is potentially reduced. Or viewed another way, humans spend less time in the areas of the pit where rock falls are a risk (particularly the designated Autonomous Operating Zone), which reduces the likelihood of a negative human outcome following rockfall incident. In some pit designs this may allow the risk categorisation to change and therefore the catch-bench width be reduced.

A similar risk factor reduction may be possible for slope wall angles (inter-ramp angles), however this is not examined in this case study. Inter-ramp angles are dependent on a rock mass classification and a safety factor. While the rock mass characteristics would not change, there is potential in open pit mines with fewer overall personnel and fewer personnel-hours in-pit per annum, to reduce the safety factor.

1.3 Whittle Consulting Optimisation Methodology

The full benefit of reducing mining costs and increasing capacities cannot be assessed in isolation. Similarly, any benefit from increasing pit design slope cannot be assessed only by looking at the size of the pit shells and ore reserves contained within. 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 estimate the effect of a change. This 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

In an Enterprise Optimisation project, the whole mining operation from Resource to Market is modelled; refer Figure 1. 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.

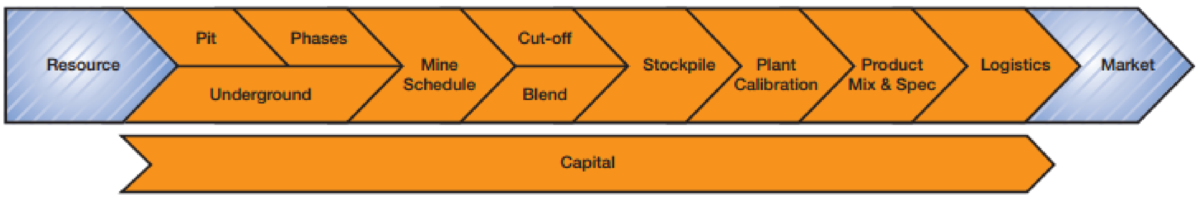

Figure 1: Whittle Consulting Enterprise Optimisation process.

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 AHS will vary from case to case. Rather than attempting to assess AHS against a large range of mines, this report assesses AHS 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 detailed mining and trucking model, a basic processing plant and a set of financial parameters that were approximately correct at the time of publishing.

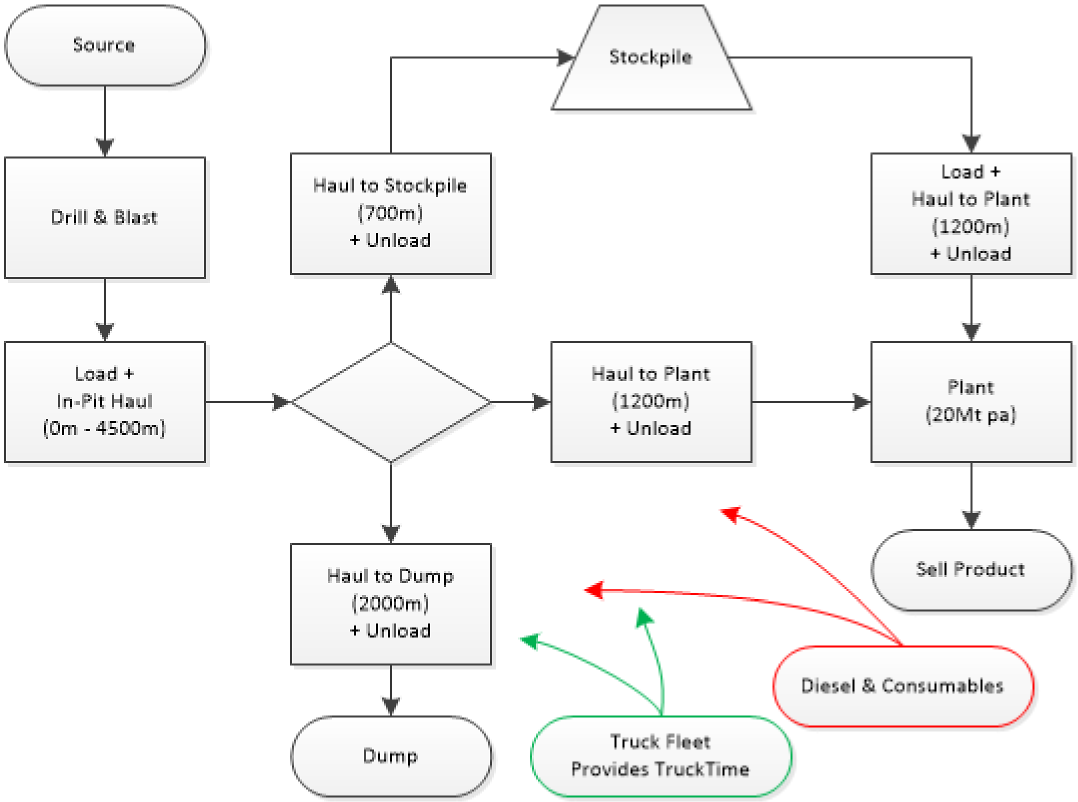

Figure 2: Structure of Model. Each box represents a procedure that may have associated material transformations, variable costs, fixed costs and constraints. A diamond represents a decision. Each arrow represents a possible delivery. TruckTime, Diesel and Consumables are required by all truck movement procedures, though some arrows are omitted in diagram for clarity.

See *Appendix A – Model Diagram: Base Case* for a complete diagram.

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 $1B is required, plus truck capital. Mining may begin in the first year of operation, however the Plant is not available until the second year.

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. Marvin has high gold grade at shallow elevations and a high copper grade at deeper elevations. The 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.

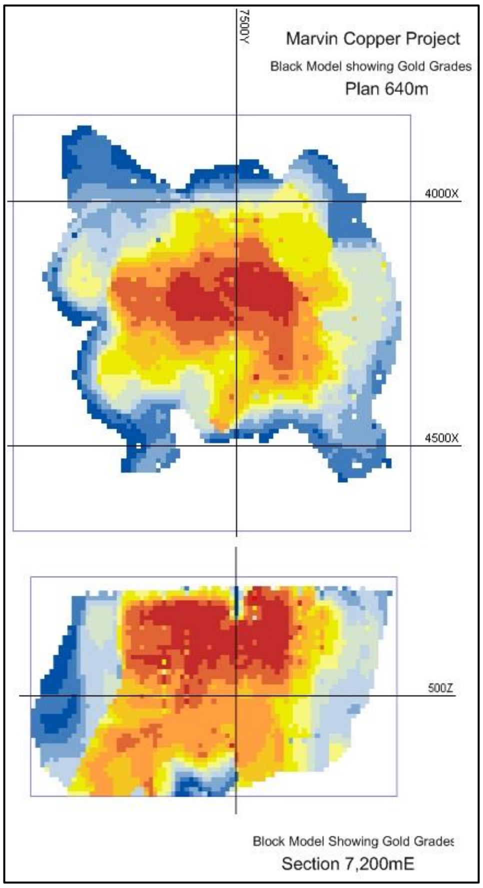

Figure 3: Marvin Ore Body

2.3 Trucking Model

The trucking fleet is modelled as two separate fleets. The Base fleet is present for the entire operation, including the end-of-life stage when mining is complete and the plant is filled by rehandling stockpiled material. The Extension fleet is only present for the mining stage. This split allows the optimiser to cease to incur the fixed costs of the Extension fleet when it is no longer required, without going to the extreme of making the optimiser handle fleet size on an individual truck level.

The truck model used is the CAT 793F with a payload of 226.8t and a width of approximately 8m, which determines the pit ramp width in this case study.

Truck movements are modelled as either stationary during load and unload, or moving at a constant speed. This constant speed depends on whether the truck is laden or un-laden, and whether it is driving within the pit either uphill or downhill, or outside the pit on a flat surface.

The number of trucks present in the model is converted to a Truck Time capacity measure in hours. The optimiser may spend those hours to move material from within the pit to the Plant, stockpile or waste dump, or from the stockpile to the Plant. These movements also consume diesel and other consumables such as tyres based on the tonnage moved and the distance covered.

2.4 Processing Model

The Processing Plant is modelled simply and is unchanged for all cases examined. A single processing tonnage limit of 20Mt per annum is assumed, with associated period costs of $40M per annum. This limit makes the Plant the primary bottleneck in the system.

Table 1: Processing Plant Parameters.

	Oxide	Mixed	Primary
Variable Cost $/t	11	12	13
Gold Recovery	75%	70%	78%
Copper Recovery	70%	45%	75%

2.5 Cases

Nine cases are examined with each effect of AHS applied individually one at a time. Each case uses the previous case as its starting point i.e. it includes all parameter changes present in the previous case.

2.5.1 Case 1: Base Case

The Base Case is an optimised solution to the full model as declared in the previous *Global Settings*, *Ore Body*, *Trucking Model* and *Processing Model* sections. See *Appendix A – Model Diagram: Base Case* for complete documentation of the system.

2.5.2 Case 2: Capital

Each truck plus any associated equipment (including excavation capacity) is assumed to cost $5.5M. An additional $1.5M is required to adapt a truck to use AHS. This capital figure is aligned with public data available on truck conversion costs.

This case does not consider any of the benefits of AHS; those are covered in subsequent cases. This case is modelled by taking the result of the base case and manually applying the changes to parameters; it is not re-optimised.

2.5.3 Case 3: Labour

Trucking labour is modelled as a function of the number of trucks, while it is a fixed cost relative to tonnage mined and transported. AHS requires four operators per shift (two in the control room and two field technicians) for the entire fleet while the base case is one operator per truck per shift. At a shift coverage rate of 3.5 this gives the relationships in Figure 4. Operators are assumed to cost $220k per annum.

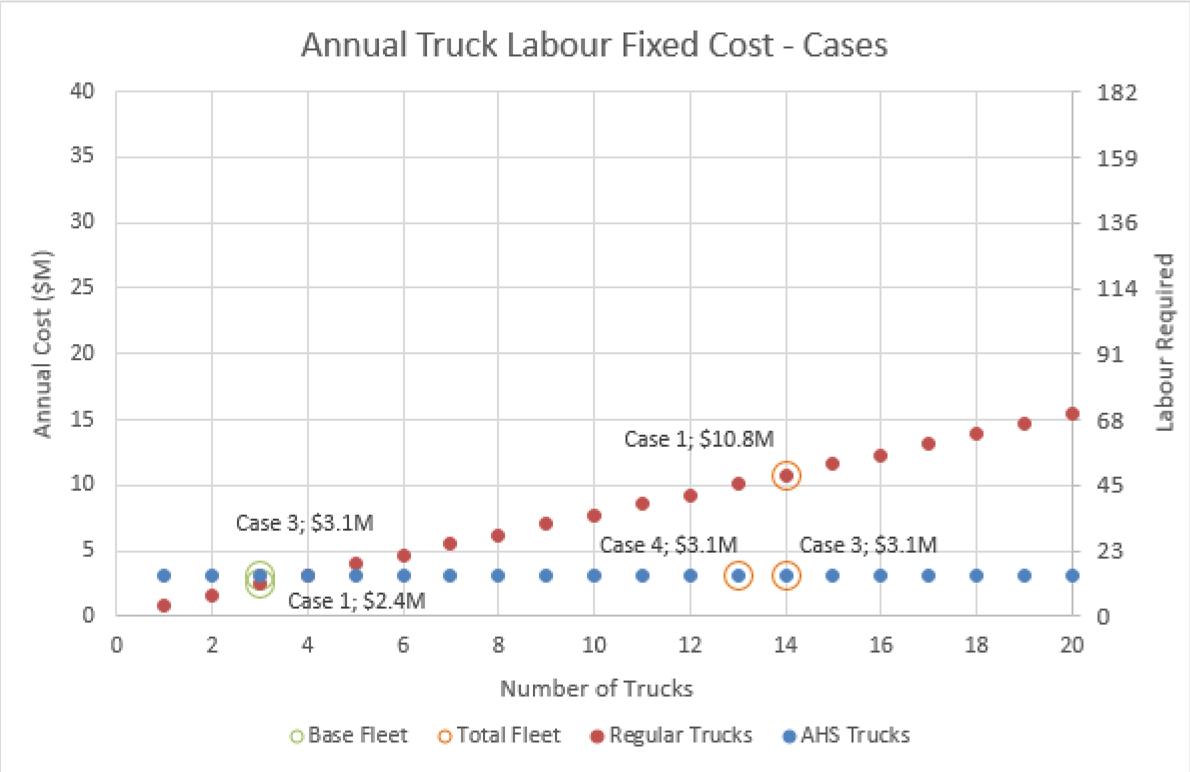

Figure 4: Annual fixed costs for labour, by number of trucks. It is a simplification to assume the AHS labour required is constant; as fleet size increases this figure would eventually need to increase. However, up to a fleet size of 20 trucks it is likely only four personnel would be required, so the scenario modelled here is valid.

This case is modelled by taking the result of the previous case and manually applying the changes to parameters; it is not re-optimised.

2.5.4 Case 4: Capacity per Truck

All trucks are assumed to have an availability rate of 88%, giving 7710 hours per annum. Regular trucks have a utilisation factor of 85% giving 6550 usable truck hours per annum, while AHS have an increased utilisation factor of 95%, allowing 7320 usable truck hours per annum. These additional truck hours per annum are in-line with available data and experience from current mine operators utilising AHS in the Pilbara of Western Australia.

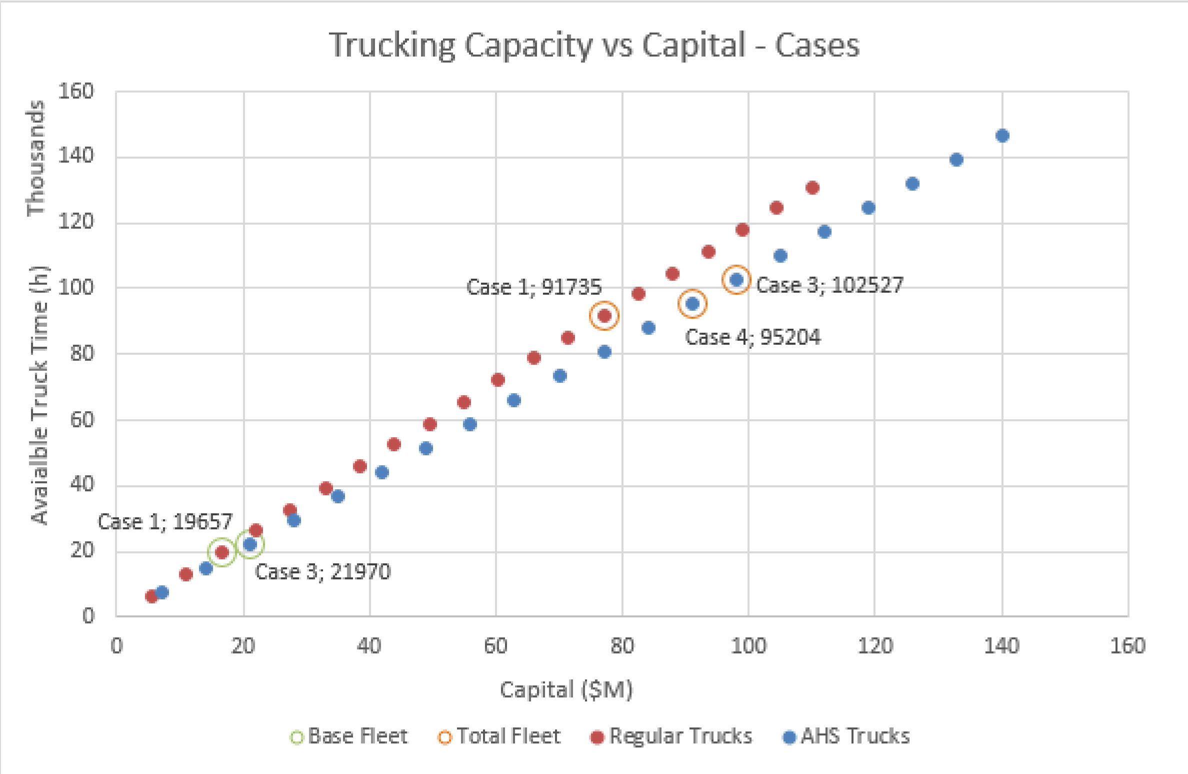

Figure 5: Capacity purchased by capital for regular and AHS trucks. To compare on a pure capacity vs cost basis, the difference in maintenance costs also needs to be considered.

In addition to providing greater utilisable truck time, AHS also allows greater intensity of material movement owing to higher mean truck speed. In this case study AHS trucks are assumed to move at a mean 6% higher speed than regular trucks, whether laden or empty, and travelling on a slope or on the flat.

This case is modelled by taking the result of the previous case and manually applying the changes to parameters; it is not re-optimised.

2.5.5 Case 5: Maintenance, G&A, Diesel and Consumables

Maintenance and General and Administrative (G&A) costs are modelled as functions of the number of trucks in the model; once the number of trucks is chosen they become fixed costs per annum. For both categories a cost curve with an exponent of 0.5 is used to benchmark against a reference study[3] while allowing for economy of scale.

[3] De Lemos Peres, D. (2013). "Surface mining technology: Managing the paradigm shift." *Mining Engineering Magazine*, December, 36-40.

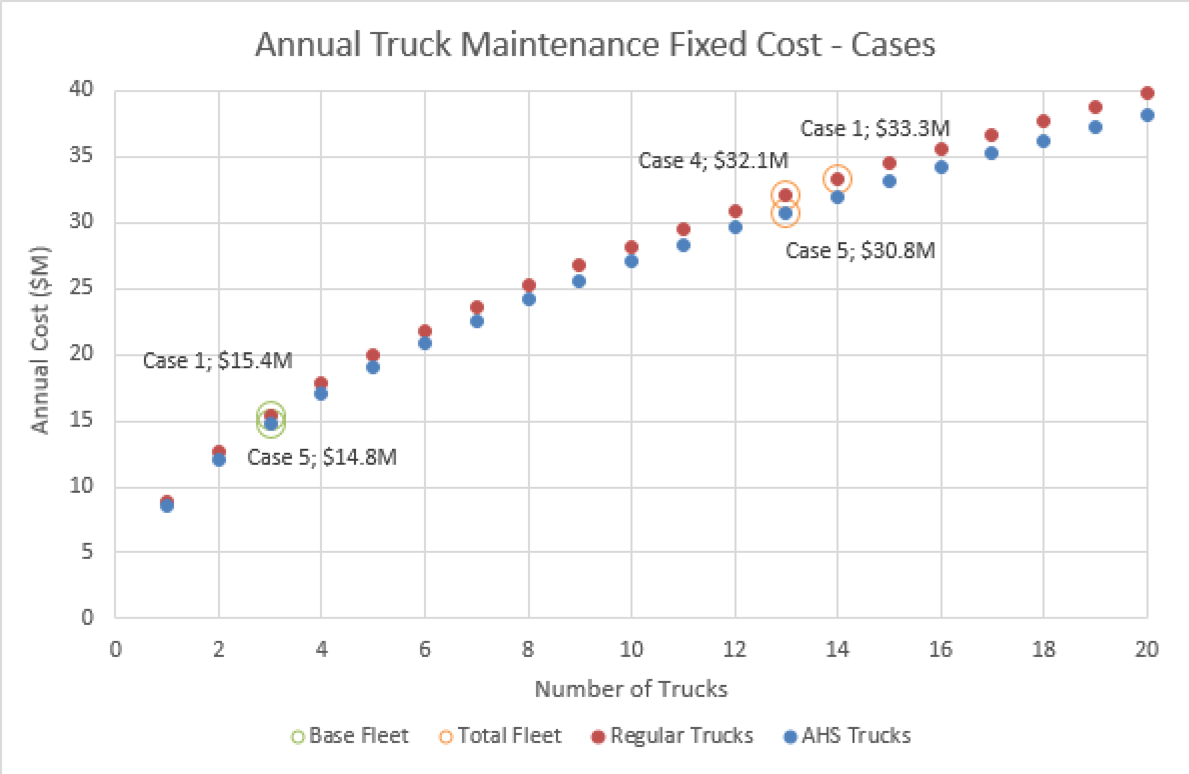

Figure 6: Annual fixed costs for truck maintenance.

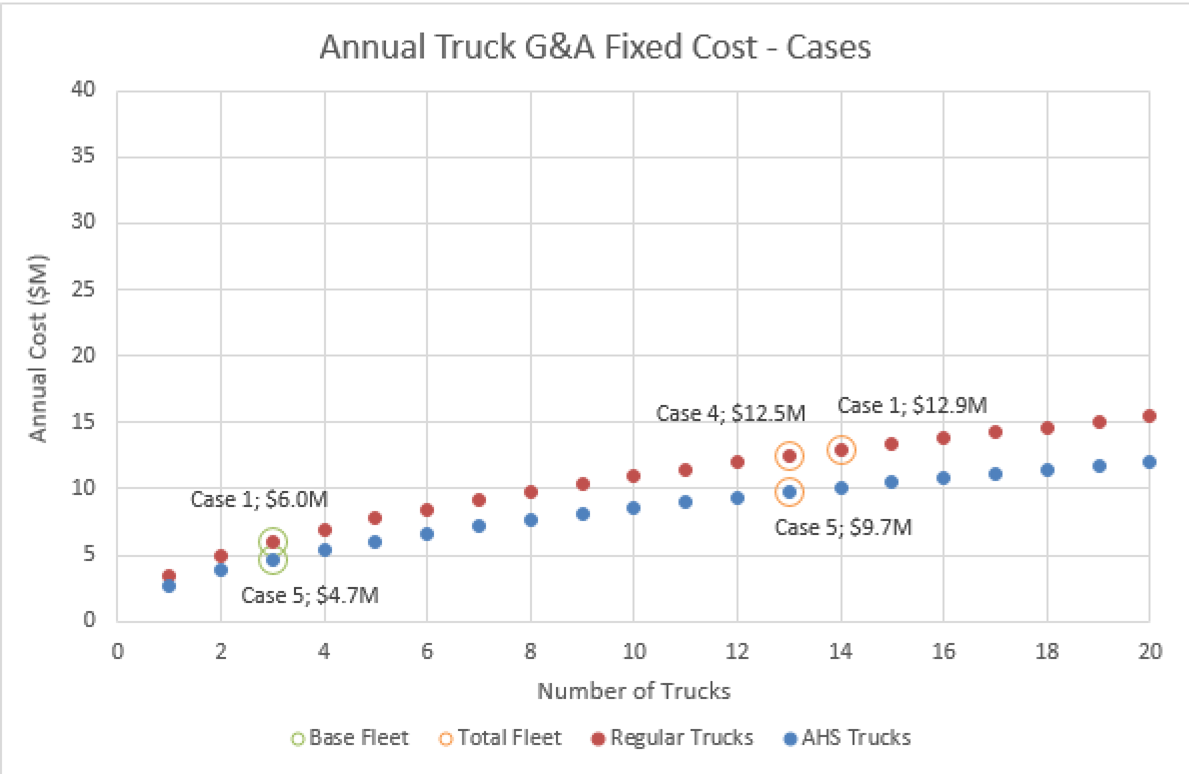

Figure 7: Annual fixed costs for truck-related G&A.

De Lemos Pires (2013) showed an increase in G&A costs for AHS trucks. This is not matched by experience; instead a reduction in cost is expected, especially where the G&A costs are associated with the size of the labour force and particularly so if this labour force is fly-in/fly-out. A reduction in G&A costs is therefore included in the AHS model, as shown in Figure 7.

Diesel and consumables are both consumed primarily on a per-tonne-per-kilometre basis, although there is also a small per-tonne component consumed while loading and unloading material.

De Lemos Pires (2013) estimates a reduction in diesel consumption through the use of AHS, however in usage in Western Australia no such saving has been observed. Therefore, the diesel consumption is assumed to be the same in all examined cases.

A reduction in consumables costs, primarily tyres, is allowed by AHS.

This case is modelled by taking the result of the previous case and manually applying the changes to parameters; it is not re-optimised.

2.5.6 Case 6: Re-optimise schedule

Cases 2-5 were all provided without re-running the optimiser. Prober is able to make better mining sequence decisions, material movement decisions, processing path choices and other financial decisions when all the parameter changes in Cases 2-5 are provided as inputs.

Case 6 provides a valid estimate of the benefits of AHS prior to any pit and phase redesign.

2.5.7 Case 7: Re-optimise pit and phases

Similar to Case 6, major changes to a mining operation's inputs also mean that the pit size and shape should be re-optimised. This case therefore involves using Geovia Whittle to re-size the pit based on the parameters in Cases 2-5, followed again by optimisation using Prober.

Case 7 provides a valid comparison to Cases 8 and 9 so that the benefits of those two cases may be isolated.

2.5.8 Case 8: Pit Sizing – Narrower Haul Ramp

For simplicity, the pit ramp is assumed to a be a uniform two-way road sized for CAT-793F trucks of width 8m. Standard design practice from users of this class of truck is to allow half a truck width at the side of each truck and between trucks, plus a berm of 5m and drain of 1m, giving a total ramp width of 34m. As narrower roads for AHS trucks have not yet been implemented in practice, all AHS sites currently have a total ramp width which follows these design practices.

AHS allows the clearance on each side the truck and between the trucks to be halved to 2m, as well as reducing the berm width to 2m, giving an AHS ramp width of 25m.

This reduction allows the pit mean slope to be increased from 40.0° to 42.1°. See *Appendix C – Slope Calculation* for details. This allows a re-optimisation of the overall pit and intermediate phase shapes, which may go deeper for more ore, narrower at the surface for less waste strip, or both.

2.5.9 Case 9: Pit Sizing – Narrower Catch-Benches

In this case study, it is assumed that safety considerations are such that AHS allows a reduction in catch-bench width from 8.5m to 6.4m and an increase in bench face angle from 65° to 67°. This allows the mean pit slope to be increased from 42.1° to 45.1°.

See *Appendix C – Slope Calculation* for details.

This case represents complete implementation of AHS. See *Appendix B – Model Diagram: AHS Case 9* for the entire model diagram.

2.6 Calibrate Truck Fleet Size

Prior to setting out the results of the cases, it is essential that the number of trucks in the base case is first optimised. This is done by running Prober to produce an NPV with the total number of trucks fixed at each value over a range (11 to 16). As seen in Figure 8, the optimal number of trucks in the base case is 14. This fleet is broken down into a base fleet of three trucks, sufficient to fill the plant each year from the stockpile at the end of the mine life, and an extension fleet of eleven trucks during the mining years.

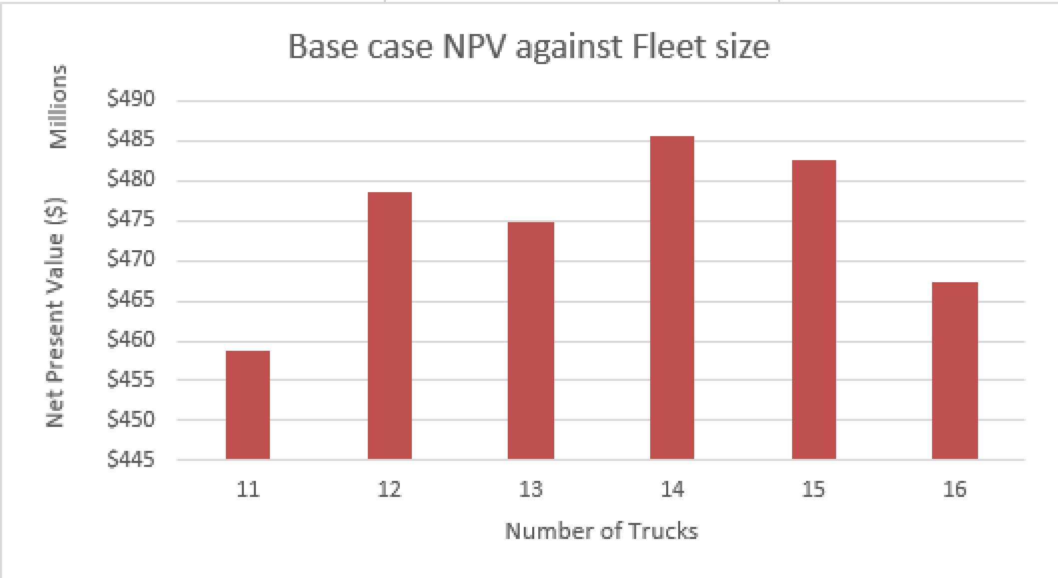

Figure 8: The optimal number of trucks in the operation, based on the model structure and parameters provided, is fourteen.

From *Case 4: Capacity per Truck*, the optimal number of trucks reduces to thirteen.

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3 Results

NPV is the primary measure to compare between the cases, while other impacts on pit inventories and cash flow are also documented.

AHS allowed an improvement in total Net Present Value from $478.6M to $665.6M once all benefits were counted. Figure 9 shows each incremental step from the base case to case nine.

The AHS effects in cases 2-6 are all cost savings, which improve NPV by $72.2M. Redesigning the pit considering these cost savings yields a larger pit, more ore and a higher NPV in case 7. If the pit is instead redesigned with narrower ramps and berms then this both decreases waste and slightly increases ore and product, for an additional boost to NPV. The difference between pit sizes, mass flows and financial flows may be seen in Table 2.

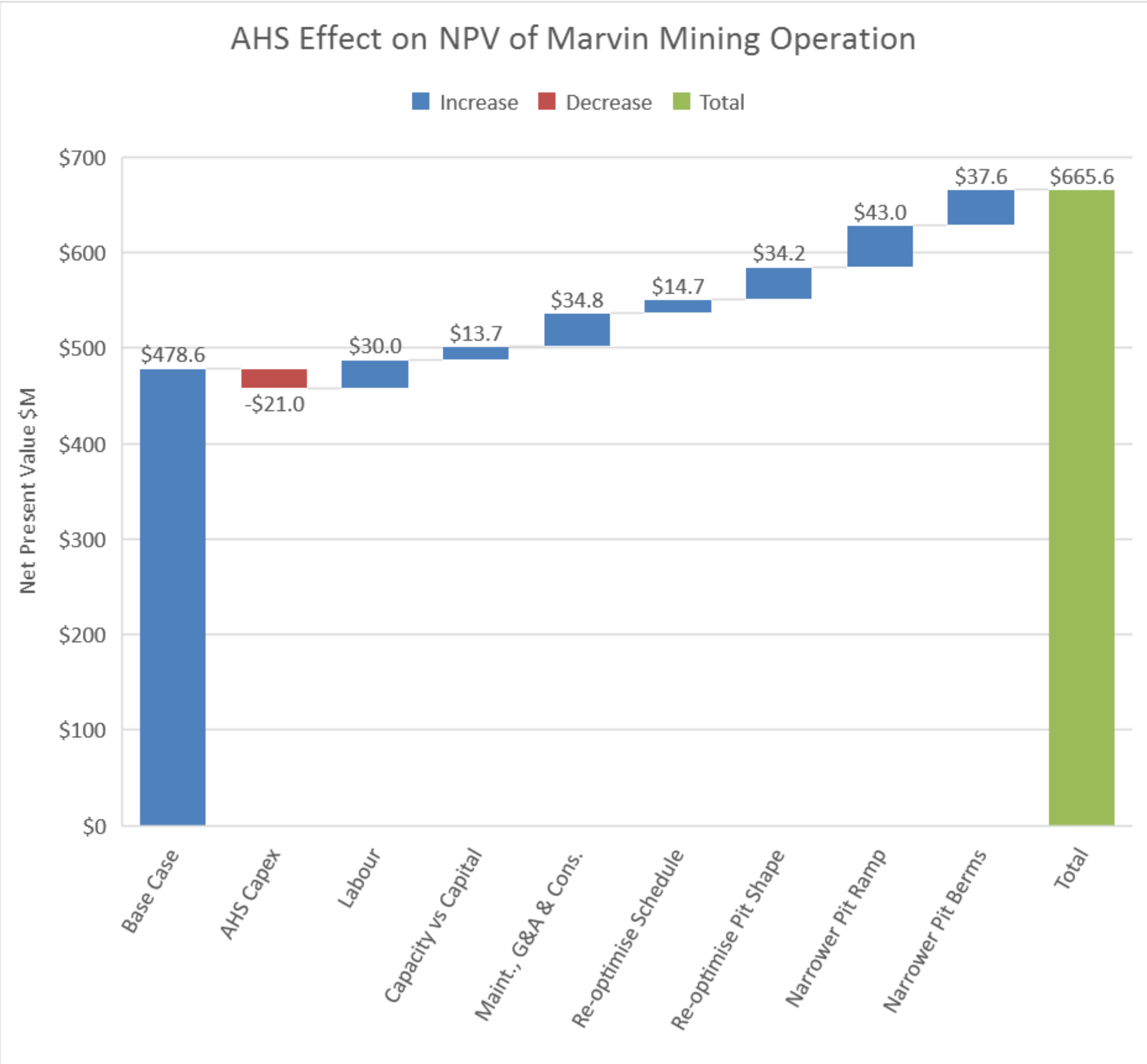

Figure 9: Waterfall chart of NPV effects as AHS benefits are applied step by step.

Table 2: Summary of outcomes for each case. Numbers light grey unless different to that for the previous case. See Appendix E – Result Summary for additional detail.

	1	2	3	4	5	6	7	8	9
	Base Case	AHS Capex	Labour	Capacity vs Capital	Maint., G&A & Cons.	Re-optimise Schedule	Re-optimise Pit Shape	Narrower Pit Ramp	Narrower Pit Berms
Mining									
Mass (Mt)	298.0	298.0	298.0	298.0	298.0	298.0	331.9	324.2	308.5
Cu (kt)	1,130	1,130	1,130	1,130	1,130	1,130	1,193	1,211	1,220
Au (kTr.Oz)	5,015	5,015	5,015	5,015	5,015	5,015	5,386	5,474	5,505
Drill & Blast Costs (Disc. $M)	-$ 221.4	-$ 221.4	-$ 221.4	-$ 221.4	-$ 221.4	-$ 216.6	-$ 243.4	-$ 241.9	-$ 238.6
Trucking Costs (Disc. $M)	-$ 498.8	-$ 498.8	-$ 468.9	-$ 462.2	-$ 427.3	-$ 426.0	-$ 458.9	-$ 454.2	-$ 442.5
Ore									
Mass (Mt)	196.7	196.7	196.7	196.7	196.7	196.7	210.6	213.7	214.8
Processing Costs (Disc. $M)	-$ 1,571.7	-$ 1,571.7	-$ 1,571.7	-$ 1,571.7	-$ 1,571.7	-$ 1,572.4	-$ 1,639.3	-$ 1,654.2	-$ 1,659.7
Product									
Cu (kt)	600	600	600	600	600	600	637	648	656
Au (kTr.Oz)	3,520	3,520	3,520	3,520	3,520	3,520	3,779	3,849	3,881
Revenue (Disc. $M)	$ 3,847.6	$ 3,847.6	$ 3,847.6	$ 3,847.6	$ 3,847.6	$ 3,856.9	$ 4,017.4	$ 4,069.3	$ 4,097.5
Capital									
Capital (Disc. $M)	-$ 1,000.0	-$ 1,000.0	-$ 1,000.0	-$ 1,000.0	-$ 1,000.0	-$ 1,000.0	-$ 1,000.0	-$ 1,000.0	-$ 1,000.0
Truck Capital (Disc. $M)	-$ 77.0	-$ 98.0	-$ 98.0	-$ 91.0	-$ 91.0	-$ 91.0	-$ 91.0	-$ 91.0	-$ 91.0
NPV	$ 478.6	$ 457.6	$ 487.6	$ 501.3	$ 536.1	$ 550.8	$ 584.8	$ 628.0	$ 665.6

3.1 Cost Reduction

Improvements in NPV for cases 2-5 are entirely due to changes in trucking costs. These trucking costs are shown as each case is applied step by step in Figure 10. Labour, Maintenance, G&A and Consumable costs are reduced and this provides a direct benefit.

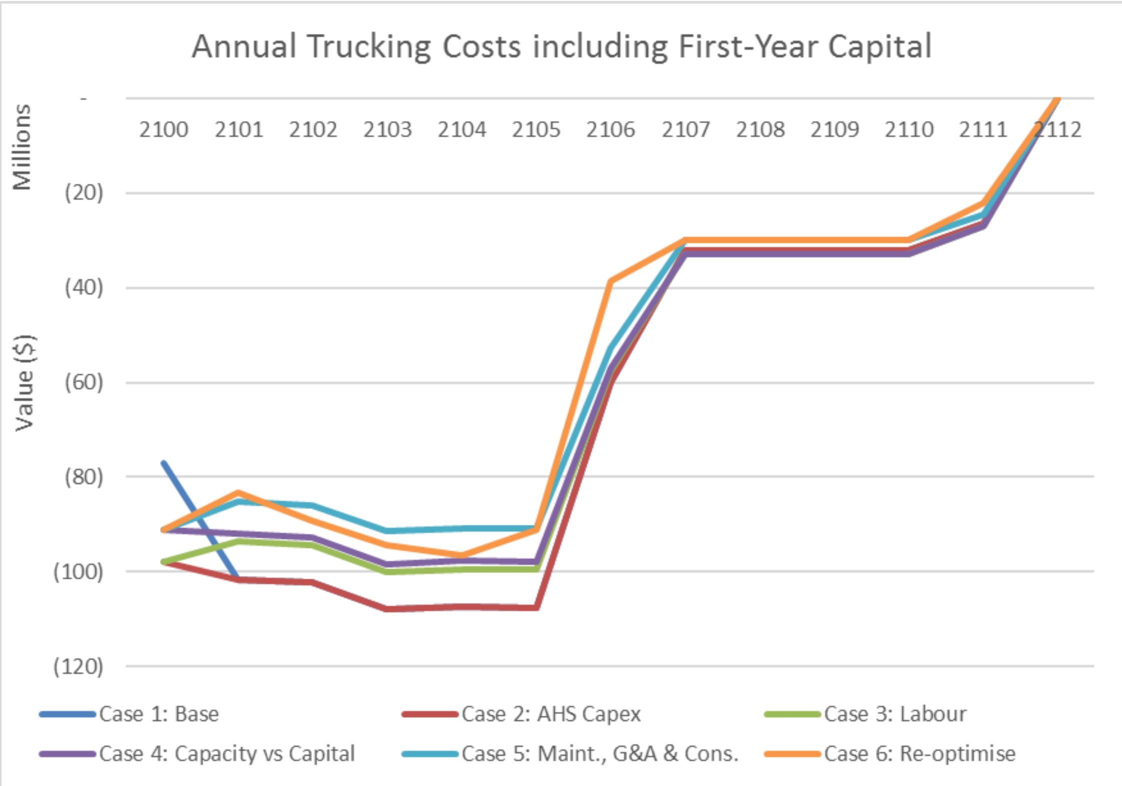

Figure 10: Change in annual trucking costs over life of mine for first six cases.

If the system is mining-limited then introducing AHS would also have a large benefit by increasing the overall throughput of material and cash through the system. In most cases (except perhaps where congestion limited), a similar effect might be achieved simply by purchasing additional trucking capacity; these options would then be compared on a cost-per-capacity basis. Generally however, the increased haulage capacity per truck equates only to a cost saving which is realised by being able to meet haulage requirements using fewer trucks.

Case 6 is a re-optimisation and there is therefore no guarantee that maximal NPV be achieved purely by minimising trucking costs, however in this case trucking costs do stay close to the low costs found in Case 5, as can be seen in Figure 10.

3.2 Schedule and Pit Re-Optimisation

Additional value is unlocked by re-optimising the system considering both the cost savings and pit design changes allowed by AHS.

Figure 11 and Figure 12 focus on the three major cases (Base Case, AHS using same pit shapes, AHS with redesigned pit shapes) to show where NPV improvements are achieved. The NPV of AHS case 6 gradually outstrips the base case, primarily due to superior cash flow in years 2102-2104. The Redesigned Pit case tracks closely to the plain AHS case before outperforming in the final five years.

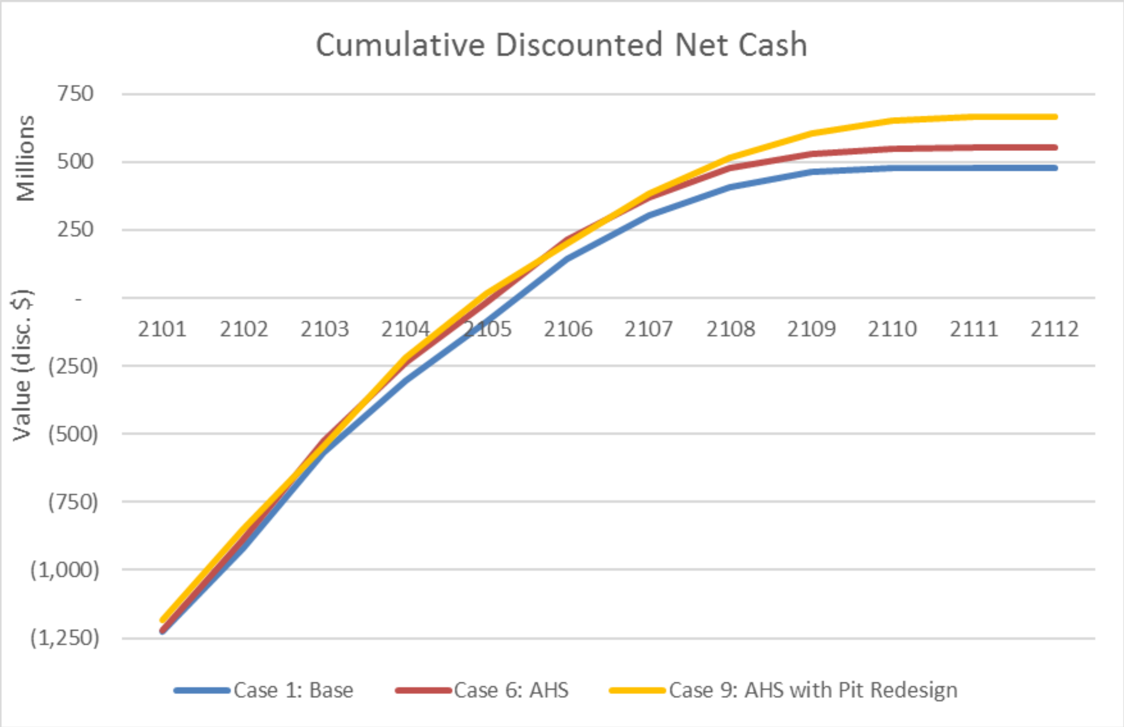

Figure 11: Accumulation of discounted cash in three major cases.

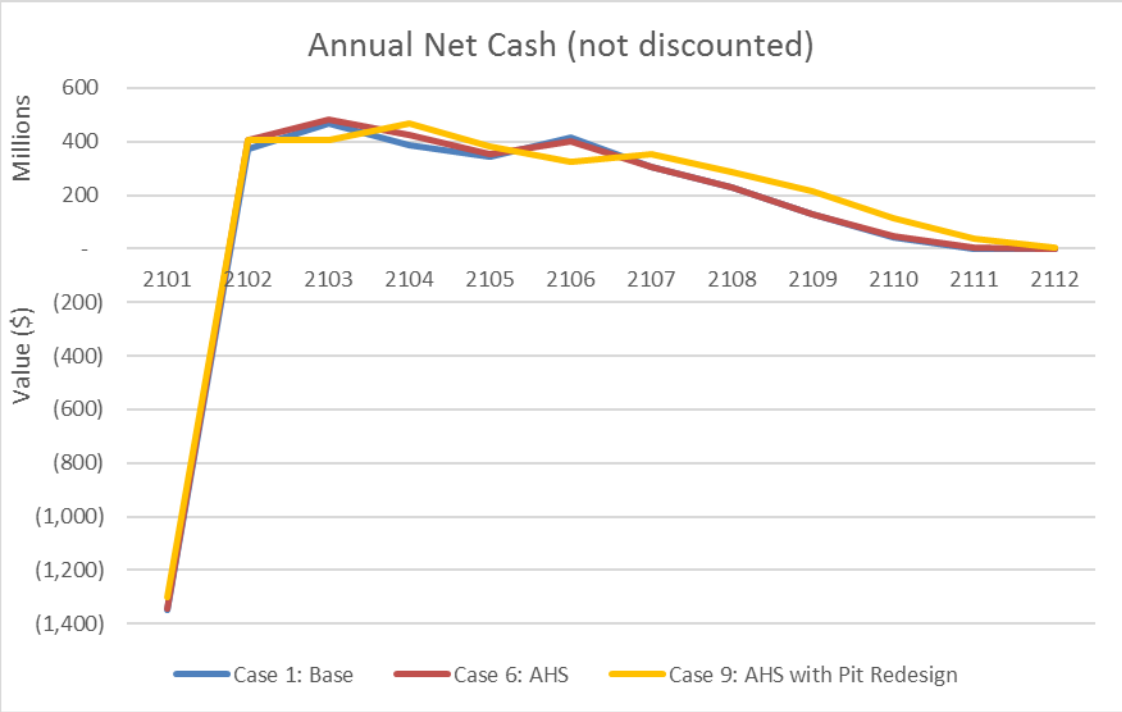

Figure 12: Annual un-discounted net cash for three major cases.

Figure 13, Figure 14 and Figure 15 show material movements for the three cases. Case 1 and Case 6 differ little; while all changes in variable and fixed cost rates do influence optimal schedule behaviour, in practise here the differences are small.

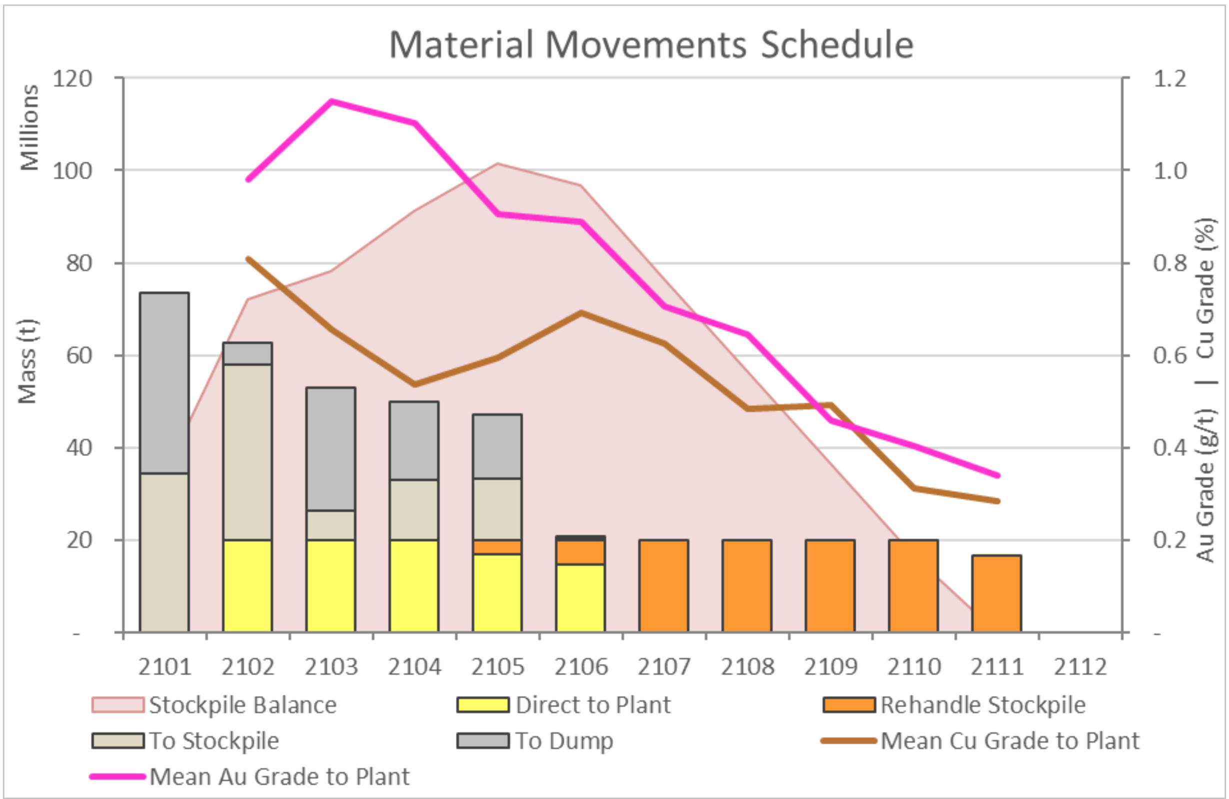

Figure 13: Case 1: Base Case

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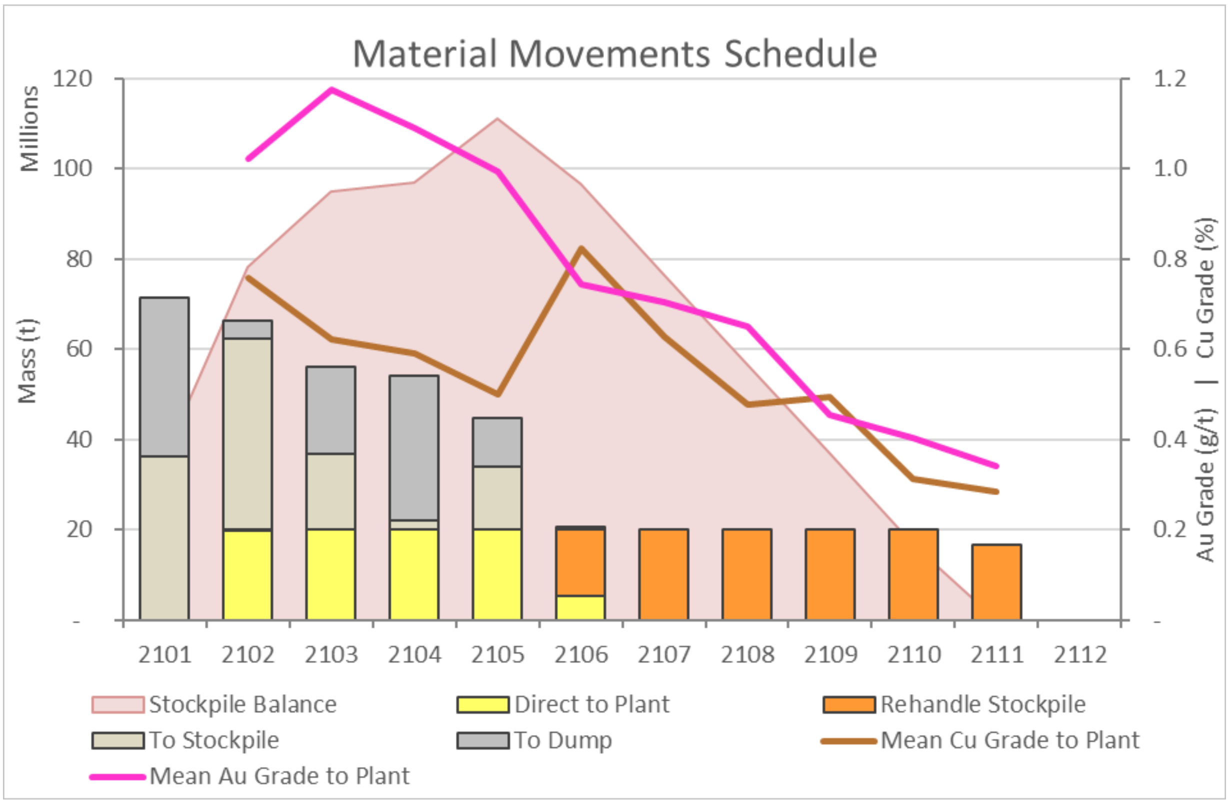


Figure 14: Case 6, AHS Case with base case pit.

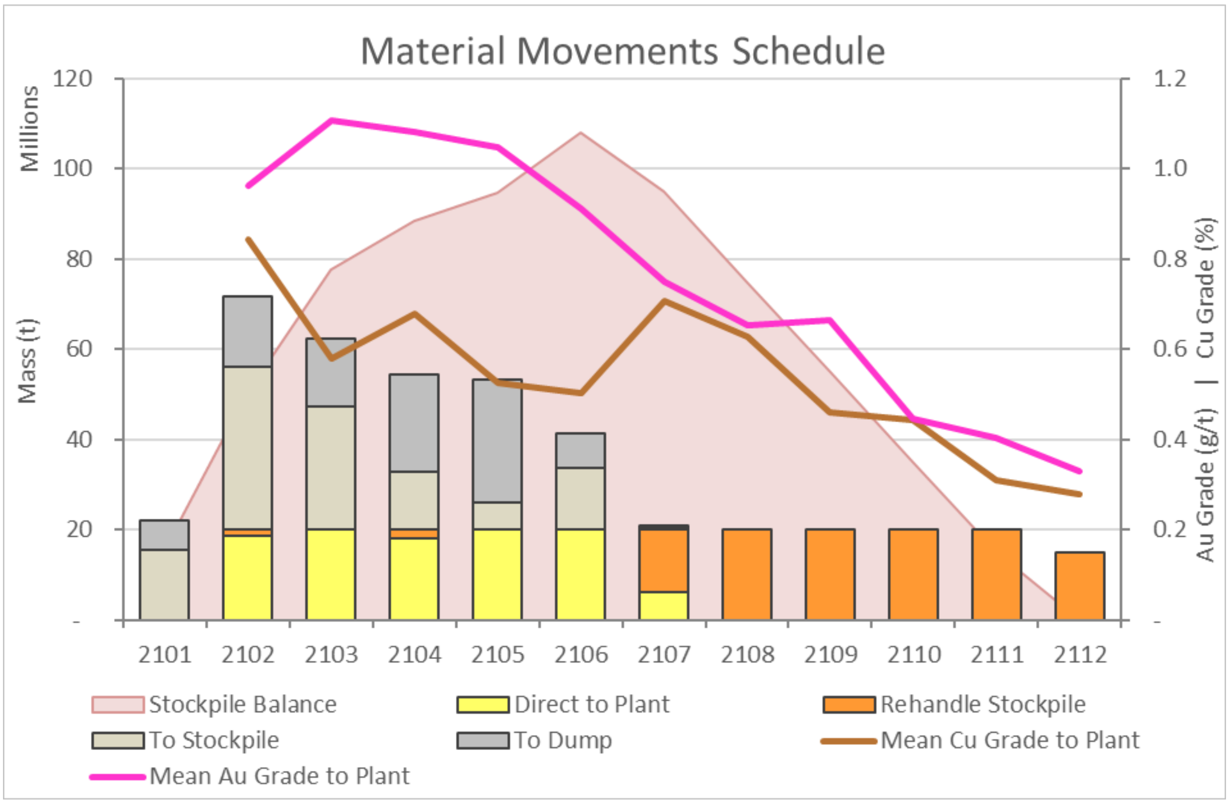


Figure 15: Case 9, AHS Case with steeper redesigned pit.

The material movements in Case 9 are more noticeably different to the previous cases. Firstly, there is much less pre-stripping in the first period required to access high-grade ore for the plant. This saves up-front cost which are important as they're not heavily discounted.

The second difference is that the plant runs for an additional year while also maintaining a higher grade than Case 6 during the stockpile rehandle years 2108-2110. This is because there is extra ore in the pit; ore that was previously uneconomic due to the waste stripping required, but that becomes economic at steeper pit slopes.

This relationship is seen in Figure 16, which shows the mass mined at each bench in the Base Case, the final case and also case 7 in which the pit is resized based only on the AHS cost reductions but without changing the pit slope. The mass profile for Case 7 is similar to that of Case 1, but larger as costs are lower and the mass of economically accessible ore increases. The Case 9 pit by contrast, has both less material at the top of the pit (primarily waste) and more material at the bottom of the pit (primarily ore).

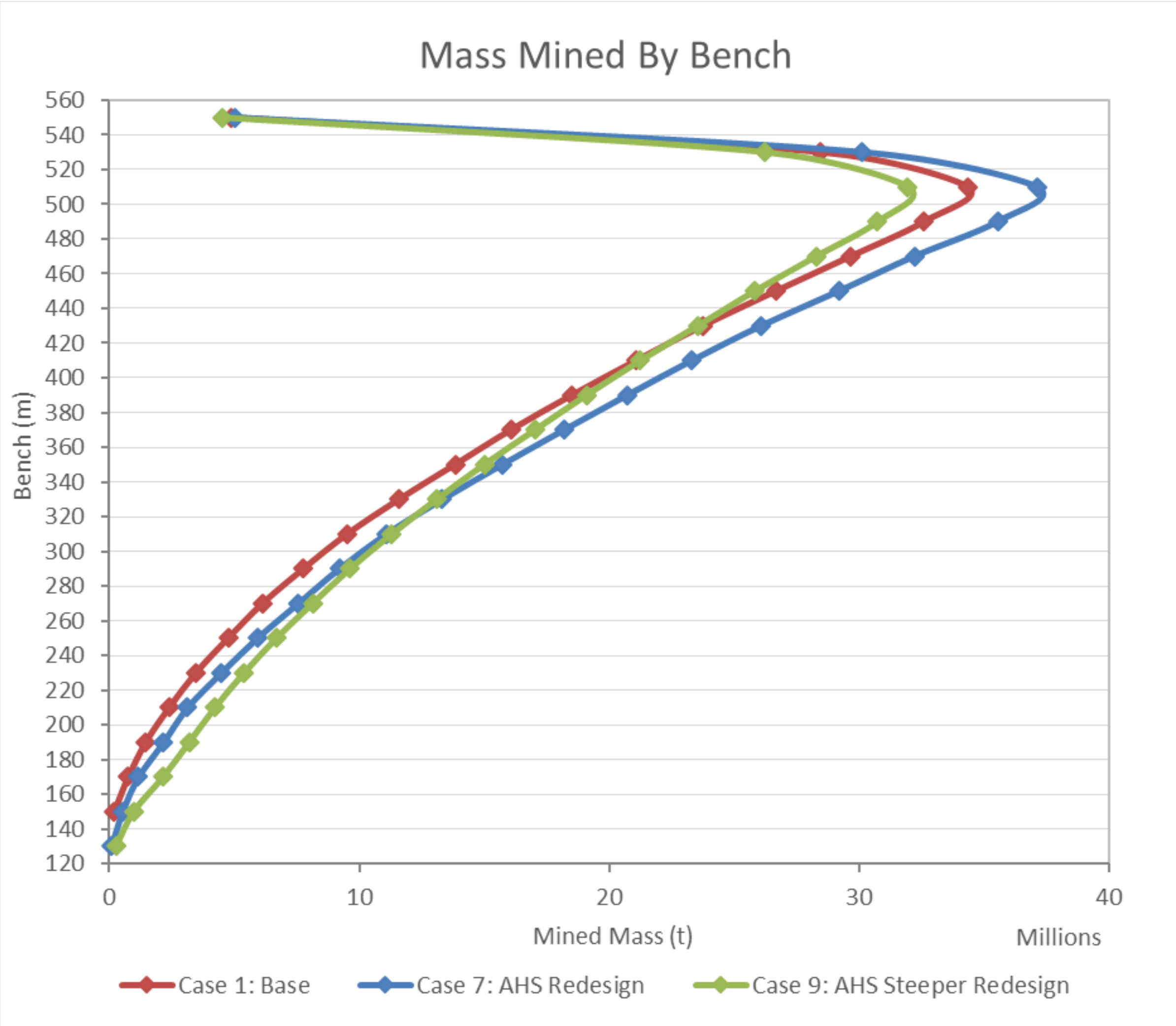


Figure 16: Profile of mass per bench for Cases 1, 7 and 9.

3.4 Conclusion

Based on the parameters used, the fictional Marvin operation would gain significant financial benefit by utilising an AHS fleet from the beginning of mine life.

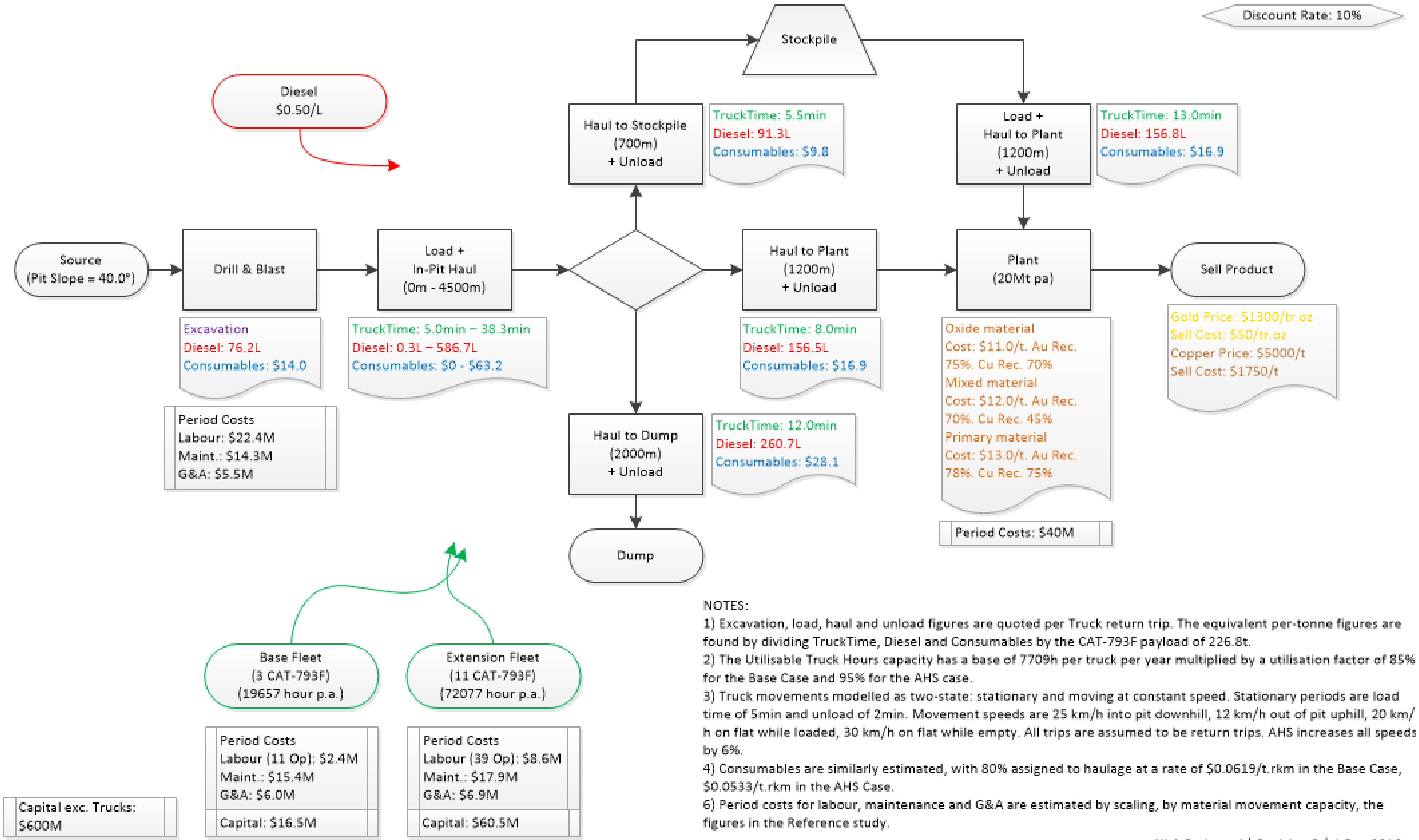
The first NPV benefits arise directly from converting trucks to autonomous vehicles; each of the improved performance characteristics ultimately represent cost savings to variable, fixed and potentially capital costs. These cost reductions improve the NPV here from $478.6M to $550.8M, an increase of 15%.

The second category of improvements arise from re-optimising the pit design considering both the cost reductions above and the potential that AHS provides to steepen mean pit slopes. In this case study this pit redesign process yielded an NPV of $665.6M, a total increase over the base case of 39%.

As evidence continues to accumulate to demonstrate the cost savings from AHS haulage, the technology continues to improve, and particularly if the potential for pit redesign to improve pit economics is recognised, it seems likely that the economic case in favour of AHS will become even stronger. It would therefore be reasonable to forecast that the rate of adoption of AHS will continue to increase.

4 APPENDICES

4.1 Appendix A – Model Diagram: Base Case



NOTES:

1) Excavation, load, haul and unload figures are quoted per Truck return trip. The equivalent per-tonne figures are found by dividing TruckTime, Diesel and Consumables by the CAT-793F payload of 226.8t.

2) The Utilisable Truck Hours capacity has a base of 7709h per truck per year multiplied by a utilisation factor of 85% for the Base Case and 95% for the AHS case.

3) Truck movements modelled as two-state: stationary and moving at constant speed. Stationary periods are load time of 5min and unload of 2min. Movement speeds are 25 km/h into pit downhill, 12 km/h out of pit uphill, 20 km/h on flat while loaded, 30 km/h on flat while empty. All trips are assumed to be return trips. AHS increases all speeds by 6%.

4) Consumables are similarly estimated, with 80% assigned to haulage at a rate of $0.0619/t.rkm in the Base Case, $0.0533/t.rkm in the AHS Case.

6) Period costs for labour, maintenance and G&A are estimated by scaling, by material movement capacity, the figures in the Reference study.

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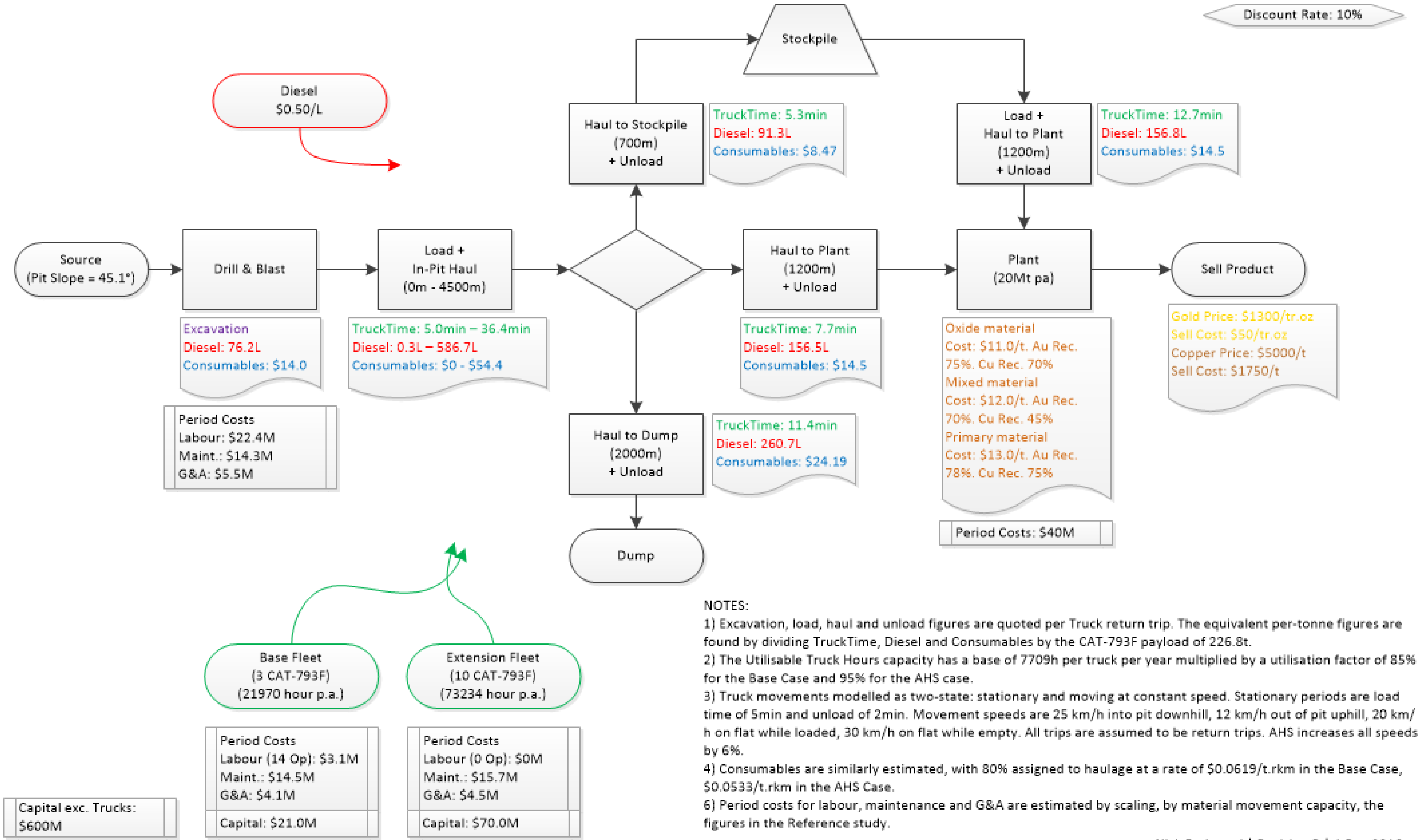
4.2 Appendix B – Model Diagram: AHS Case 9



NOTES:
1) Excavation, load, haul and unload figures are quoted per Truck return trip. The equivalent per-tonne figures are found by dividing TruckTime, Diesel and Consumables by the CAT-793F payload of 226.8t.
2) The Utilisable Truck Hours capacity has a base of 7709h per truck per year multiplied by a utilisation factor of 85% for the Base Case and 95% for the AHS case.
3) Truck movements modelled as two-state: stationary and moving at constant speed. Stationary periods are load time of 5min and unload of 2min. Movement speeds are 25 km/h into pit downhill, 12 km/h out of pit uphill, 20 km/h on flat while loaded, 30 km/h on flat while empty. All trips are assumed to be return trips. AHS increases all speeds by 6%.
4) Consumables are similarly estimated, with 80% assigned to haulage at a rate of $0.0619/t.rkm in the Base Case, $0.0533/t.rkm in the AHS Case.
6) Period costs for labour, maintenance and G&A are estimated by scaling, by material movement capacity, the figures in the Reference study.

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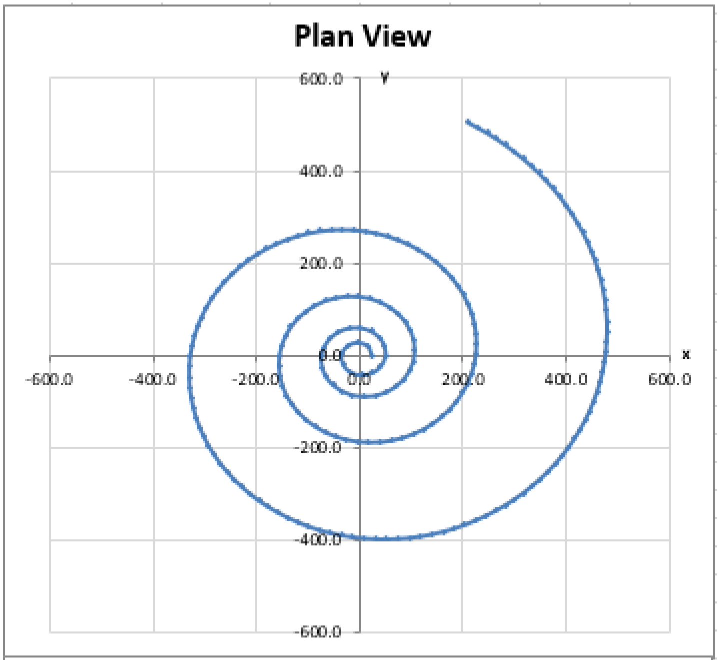
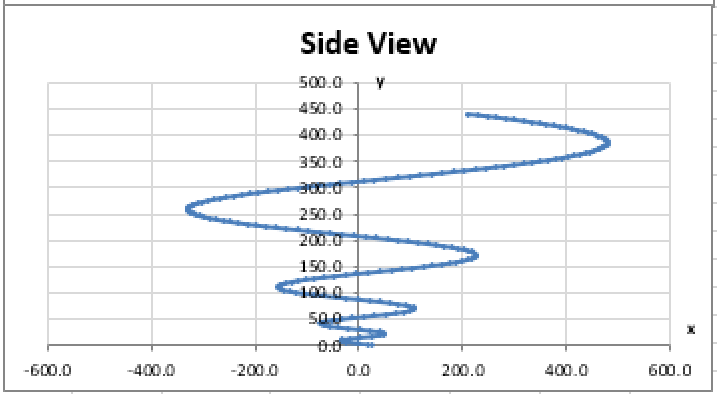
4.3 Appendix C – Slope Calculation

AHS allows the haul ramp width to be reduced from 34m to 25m in Case 8. In Case 9 it allows the catch-bench width to be reduced from 8.5m to 6.4m and the bench face angle increased from 65° to 67°.

As the Marvin pit is near-conical, a spiral descending down a cone at a constant slope of 1:10 was used to estimate the number of haul road loops required to reach the bottom. Just over four loops are required to reach the base of the pit (where a box cut would be performed) in the base case and Case 8. Note that in Case 9, the increased mean slope was such that an additional half-loop was allowed.

Pit Slope	°	40.0	42.1	45.1
Vertical Total	m	420	420	420
Assume pit depth	m	420	420	420
Horizontal Total	m	501	465	419
Bench Faces	m	195	195	178
Design Bench Face Angle	°	65	65	67
Ramp	m	136	100	112.5
Total Ramp Width	m	34	25	25
Truck width	m	8	8	8
Separation	m	4	2	2
Drain	m	1	1	1
Ramp berm	m	5	2	2
Number road loops in descent		4.0	4.0	4.5
Catch-Benches	m	170	170	128
Bench Height	m	20	20	20
Number Catch-Benches		20	20	20
Design Bench Face Angle	°	65	65	65
Catch-Bench Width	m	8.5	8.5	6.4





Note: In both the base case and the AHS cases, the actual pit slope will be steeper at the top of the pit due to fewer haul roads per vertical metre, and less steep closer to the bottom of the pit due to a greater number of haul roads per vertical metre. This complication is ignored here.

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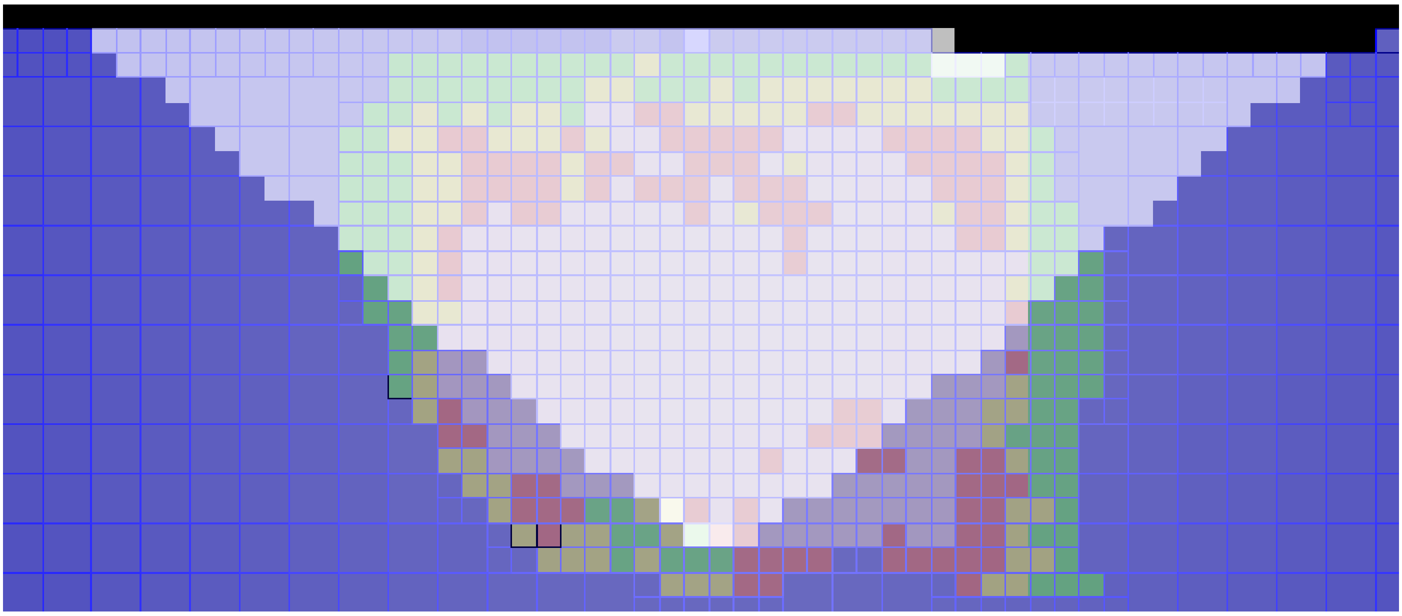
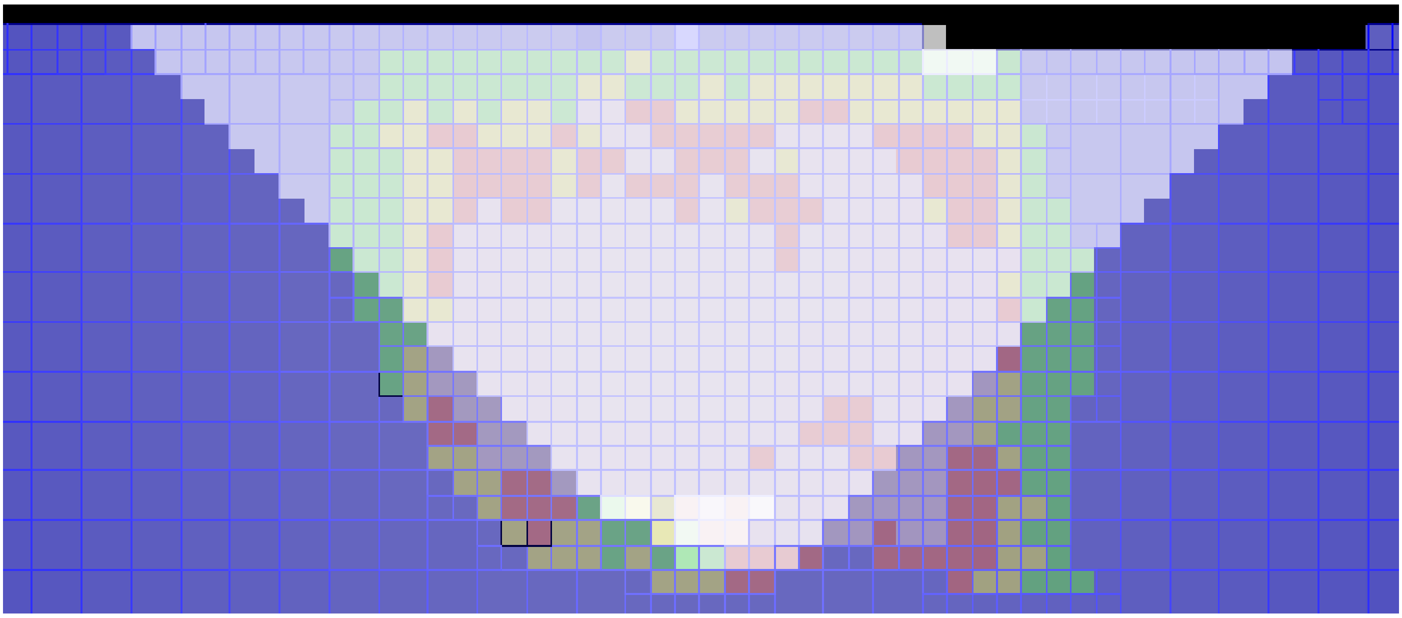
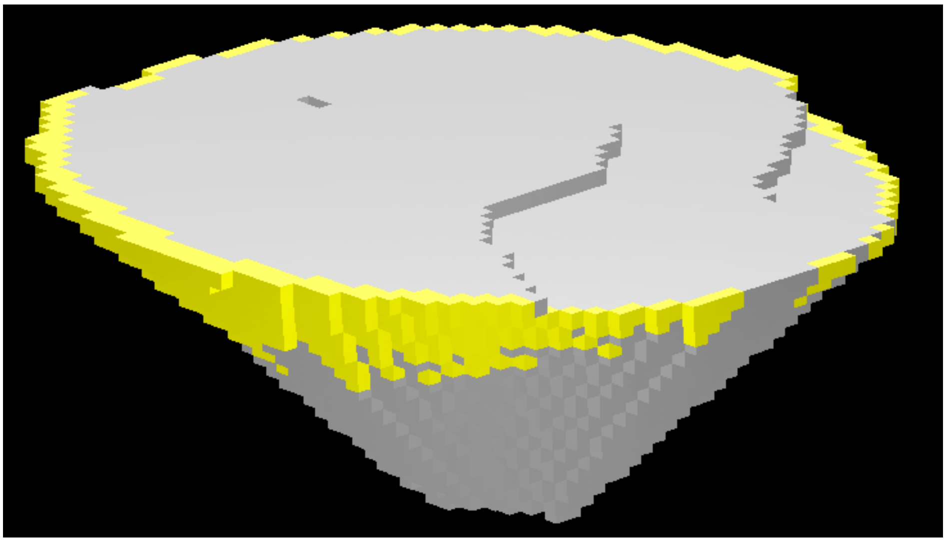
4.4 Appendix D – Pit







Top: Base Case ultimate pit cross-section with blocks coloured by Copper grade.

Middle: Case 9 pit cross-section.

Left: Overlap between Case 1 ultimate pit (yellow) and Case 9 ultimate pit (grey).

4.5 APPENDIX E – RESULT SUMMARY

	1	2	3	4	5	6	7	8	9
	Base Case	AHS Capex	Labour	Capacity vs Capital	Maint., G&A & Cons.	Re-optimise Schedule	Re-optimise Pit Shape	Narrower Pit Ramp	Narrower Pit Berms
Mining									
Mass (Mt)	298.0	298.0	298.0	298.0	298.0	298.0	331.9	324.2	308.5
Cu (kt)	1,130	1,130	1,130	1,130	1,130	1,130	1,193	1,211	1,220
Mean Cu grade (%)	0.379%	0.379%	0.379%	0.379%	0.379%	0.379%	0.359%	0.373%	0.395%
Au (kTr.Oz)	5,015	5,015	5,015	5,015	5,015	5,015	5,386	5,474	5,505
Mean Au grade (g/t)	0.524	0.524	0.524	0.524	0.524	0.524	0.505	0.525	0.555
Drill & Blast Costs ($M)	*-$ 293.0*	*-$ 293.0*	*-$ 293.0*	*-$ 293.0*	*-$ 293.0*	*-$ 284.7*	*-$ 334.9*	*-$ 333.8*	*-$ 329.9*
Drill & Blast Costs (Disc. $M)	*-$ 221.4*	*-$ 221.4*	*-$ 221.4*	*-$ 221.4*	*-$ 221.4*	*-$ 216.6*	*-$ 243.4*	*-$ 241.9*	*-$ 238.6*
Truck Time Used (kh)	592	592	592	592	592	575	647	638	610
Trucking Costs ($M)	*-$ 741.9*	*-$ 741.9*	*-$ 703.2*	*-$ 694.2*	*-$ 640.9*	*-$ 635.1*	*-$ 711.9*	*-$ 710.3*	*-$ 696.5*
Diesel	*-$ 251.5*	*-$ 251.5*	*-$ 251.5*	*-$ 251.5*	*-$ 251.5*	*-$ 252.8*	*-$ 286.5*	*-$ 282.2*	*-$ 269.9*
Consumables	*-$ 54.1*	*-$ 54.1*	*-$ 54.1*	*-$ 54.1*	*-$ 46.6*	*-$ 46.9*	*-$ 53.1*	*-$ 52.3*	*-$ 50.0*
Fixed Costs	*-$ 436.2*	*-$ 436.2*	*-$ 397.5*	*-$ 388.5*	*-$ 342.8*	*-$ 335.5*	*-$ 372.3*	*-$ 375.8*	*-$ 376.5*
Trucking Costs (Disc. $M)	*-$ 498.8*	*-$ 498.8*	*-$ 468.9*	*-$ 462.2*	*-$ 427.3*	*-$ 426.0*	*-$ 458.9*	*-$ 454.2*	*-$ 442.5*
Ore									
Mass (Mt)	196.7	196.7	196.7	196.7	196.7	196.7	210.6	213.7	214.8
Cu (kt)	1,088	1,088	1,088	1,088	1,088	1,088	1,146	1,165	1,177
Mean Cu grade (%)	0.553%	0.553%	0.553%	0.553%	0.553%	0.553%	0.544%	0.545%	0.548%
Au (kTr.Oz)	4,838	4,838	4,838	4,838	4,838	4,838	5,184	5,278	5,320
Mean Au grade (g/t)	0.765	0.765	0.765	0.765	0.765	0.765	0.765	0.768	0.770
Stripping Ratio	0.515	0.515	0.515	0.515	0.515	0.515	0.576	0.517	0.436
Processing Costs ($M)	*-$ 2,788.5*	*-$ 2,788.5*	*-$ 2,788.5*	*-$ 2,788.5*	*-$ 2,788.5*	*-$ 2,788.5*	*-$ 2,993.0*	*-$ 3,037.7*	*-$ 3,055.1*
Processing Costs (Disc. $M)	*-$ 1,571.7*	*-$ 1,571.7*	*-$ 1,571.7*	*-$ 1,571.7*	*-$ 1,571.7*	*-$ 1,572.4*	*-$ 1,639.3*	*-$ 1,654.2*	*-$ 1,659.7*
Product									
Cu (kt)	600	600	600	600	600	600	637	648	656
Au (kTr.Oz)	3,520	3,520	3,520	3,520	3,520	3,520	3,779	3,849	3,881
Revenue									
Revenue ($M)	*$ 6,349.2*	*$ 6,349.2*	*$ 6,349.2*	*$ 6,349.2*	*$ 6,349.2*	*$ 6,349.2*	*$ 6,793.0*	*$ 6,917.4*	*$ 6,983.5*
Revenue (Disc. $M)	*$ 3,847.6*	*$ 3,847.6*	*$ 3,847.6*	*$ 3,847.6*	*$ 3,847.6*	*$ 3,856.9*	*$ 4,017.4*	*$ 4,069.3*	*$ 4,097.5*
Capital									
Capital (Disc. $M)	*-$ 1,000.0*	*-$ 1,000.0*	*-$ 1,000.0*	*-$ 1,000.0*	*-$ 1,000.0*	*-$ 1,000.0*	*-$ 1,000.0*	*-$ 1,000.0*	*-$ 1,000.0*
Truck Capital (Disc. $M)	*-$ 77.0*	*-$ 98.0*	*-$ 98.0*	*-$ 91.0*	*-$ 91.0*	*-$ 91.0*	*-$ 91.0*	*-$ 91.0*	*-$ 91.0*
NPV	$ 478.6	$ 457.6	$ 487.6	$ 501.3	$ 536.1	$ 550.8	$ 584.8	$ 628.0	$ 665.6