A simultaneous mining and mineral processing optimisation and sustainability evaluation prepared during the Ivanhoe Platreef Project prefeasibility study

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This paper develops themes presented at two SAIMM Platinum conferences. Optimisation techniques can be used to significantly increase the value of mining businesses by enabling better long-term planning decisions. Open pit and underground mine design, mine scheduling, cut-off grade and blending, stockpiling, and the linking of these to flexible elements of the metallurgical recovery processes are all evaluated together. Transport or sale of intermediate products and the requirements of the product metal markets can also be considered. Experience shows that net present value (NPV) can be increased significantly, usually even before the expenditure of significant amounts of project capital. Whittle Consulting is a leading practitioner of value chain optimisation and recently has entered into a partnership with JKTech to simultaneously evaluate the impact of the optimised solution on the non-financial features of a project or operation.

The case study presented comprised a commercially orientated review of the prefeasibility study designs and cost estimates of Ivanhoe's Platreef project in South Africa, followed by value chain optimisation and sustainability studies of the project carried out simultaneously to identify potential value uplifts to be gained and guide the owners' team going forward into the feasibility study phase of this project. Some of the major aspects of the project that were found to have significant potential to add value included enhancement of the business model by the application of activity-based costing and theory of constraints, focus on the highest net value portions of the orebody in the early years of production, enhanced and optimised scheduling of the underground mining operation, application of dynamic grind and flotation mass pull to concentrate to optimise revenue, application of elevated cut-off grades early in the life of mine, matching the mining and processing capacities, expansion of the operation subject to capital availability, and installation of downstream processing facilities subject to regional third-party capacities.

The investigation of non-financial project features focused on demonstrating that a financially optimised solution could also have a number of other benefits. These are mentioned briefly in the paper, which aims to present the status of the project at an early stage of its development.

This paper was not prepared by or for Ivanhoe Mines, and Ivanhoe Mines takes no responsibility for the preparation or dissemination of the paper.

Introduction

Many software packages exist to optimise various parts of a mining business in isolation. However, it is rare for companies to optimise all parts of their operation or portfolio simultaneously. In the past ten years, Whittle Consulting has focused on expanding the boundaries of integrated optimisation, concentrating on issues faced by large and complex mining and processing operations. Using advanced techniques, an integrated geological, mining, processing, transport, and product model can be constructed. This is manipulated mathematically to optimise the values of those variables that are considered negotiable. Utilising this procedure, it is possible to develop long-term plans that maximise the value of large geological and technical plant asset portfolios. Significant improvements in net present value (NPV) of the business have been demonstrated in many cases.

This methodology is very suitable to be applied to the platinum group metal (PGM) and related sectors of the mining industry. Whittle Consulting recently completed an optimisation study of Ivanhoe Mines' Platreef project in South Africa (Burks. And Jones, 2014) In this paper, the authors discuss some of the optimisation techniques and mechanisms applied and briefly refer to some of the main conclusions and recommendations.

A reminder - what is Enterprise Optimisation?

Enterprise Optimisation can help to solve the production schedule challenges of mining and processing operations with multiple pits, mining faces, and underground mines, multiple metal or mineral products, stockpiling and blending opportunities, and alternative processing options. The combination of these features creates significant long-term planning and analytical problems and opportunities that often exceed the capabilities of commercially available mining optimisation software (Whittle and Burks, 2010; Burks 2012).

Simultaneous optimisation aims to address all steps in the value chain and all assets in the enterprise portfolio together, and does this while also considering all time periods of the planned operation. This is a crucial additional complexity differentiating mining from other businesses. An orebody is a depleting resource; when we decide what to mine and process in one period, we constrain the available options for all future periods.

Figure 1 illustrates the point. There is little or nothing that any enterprise can do to improve the resource in the ground or the international market for the products, but all the other steps illustrated in the figure can potentially be optimised.

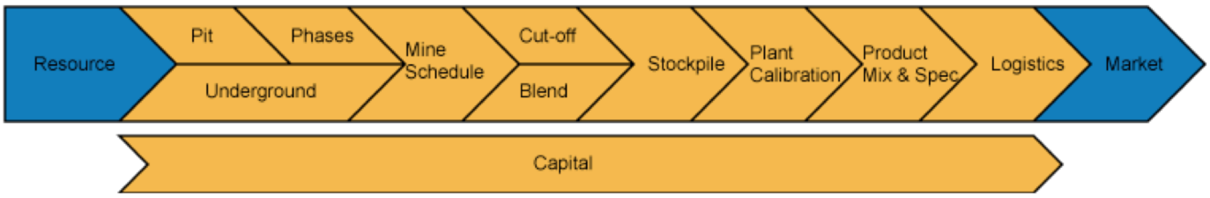

Figure 1. The generic mining enterprise value chain

Enterprise Optimisation concentrates on optimising the NPV of businesses. NPV is the sum of discounted cash flows, normally calculated or forecast annually. It reflects the time value of money and is considered to be a metric for planning and measuring the performance of any business that will be understood and appreciated by executive management, shareholders and other investors, and all stakeholders.

Philosophically, many mining businesses struggle to identify clear and consistent objectives. For example, maximising metal production, maximising life of mine, minimising costs, maximising resource recovery from the ground, maximising metal recovery from ore mined, and maximising utilisation of equipment are all often cited as being key objectives for operations. However, it is difficult to rank these against each other, and some of them conflict. Enterprise Optimisation therefore focuses on a single objective, to *maximise the economic value of the business.*

From a sustainable development perspective the economic value represents the addition of financial capital to a project. The overall evaluation in this case included potentially enhancing the social, human, and environmental capitals of the project, but this paper describes in detail only the work done to investigate possible increases in financial capital.

Application of optimisation principles to the Platreef Project

This optimisation study provided diverse challenges in several links of the production value chain and is used here to illustrate the flexible nature of the mechanisms and techniques applied. Unfortunately, since the analysis of the results identified operational strategies that could affect the valuation of the operation, specific results could not be provided in this paper, which focuses on describing the approach and mechanisms tested and on the broad trends of the results.

In this study the optimisation work included the whole of the value chain between the resource in the ground and the sale of final metal products.

Description and current status of the Platreef Project

The Platreef project is being developed by Ivanhoe Mines on the northern limb of South Africa's Bushveld Complex. With the support of many partners and stakeholders, including local empowerment beneficiaries in the Mokopane locality, employees, local South African entrepeneurs, and Japanese investors, Ivanhoe's Platreef team is committed to building a safe, large-scale, mechanised underground PGM and base metals mine.

The recently completed prefeasibility study (PFS) covered the first phase of development that would include the underground mine, a 4 Mt/a concentrator, and other associated infrastructure to support initial concentrate production by 2019. As Phase 1 is being developed and commissioned there will be opportunities to define the timing and scope of subsequent expansion phases.

Key features of the Platreef PFS included:

- Development of Phase 1 of a large mechanised underground mine with associated processing plant and surface infrastructure
- Planned initial annual production rate of 433 000 ounces (oz) of 3PGE+Au (platinum, palladium, rhodium, and gold) plus 19 million pounds of nickel and 12 million pounds of copper per year
- Estimated pre-production capital requirement of approximately US$1.2 billion, including US$114 million in contingencies, at a South African rand/US dollar exchange rate of 11 to 1
- Platreef would rank at the bottom of the cash cost curve at an estimated US$322 per ounce of 3PGE+Au net of by-products
- After-tax net present value (NPV) of US$972 million at an 8% discount rate
- After-tax internal rate of return (IRR) of 13%.

A press release from Ivanhoe Mines in January 2015 provided more detail of the PFS production schedules, metal prices, and other parameters with a major influence on NPV (Ivanhoe, 2015).

The optimisation study used the PFS parameters, preliminary designs, and results as a starting point. It commenced with a strategic assessment principally consisting of a two-day workshop attended by delegates drawn from all corporate and project disciplines likely to have any influence on the financial viability of the project. Optimisation principles were discussed and explained, the current business plan of the project was presented, and the personnel who would be responsible later for providing information were identified.

The main items identified for further investigation in the subsequent Enterprise Optimisation study by Whittle Consulting and a related sustainability (SUSOP) study delivered in parallel by JKTech included activity-based costing; theory of constraints; underground mine zone shapes, sizes and sequence rules; mine scheduling; cut-off value policy; selective stockpiling; ore blending; grind-throughput-recovery variability in the metallurgical processing plant; dynamic concentrate mass pull; capital and period cost optimisation; enhancement of the optimisation model by consideration of the non-financial capitals (manufactured, social, human and natural capital); and sensitivity to various external factors such as metal prices.

Description of the optimisation work completed in 2014 (Burks and Jones, 2014)

Methodology

The approach described below is typical of many other similar optimisation studies, except that in this case much more emphasis was placed on the optimisation of mining zone shapes and cut-off grades and subsequent scheduling from the underground mine. The steps below were followed, mainly sequentially but sometimes in parallel.

- Resource model, operational, test work, and study information was collected from each project team department and incorporated into a single data input or business model to be used to prepare the input files for the Prober optimisation software. In addition, the underground mine zone definition and annual mining schedules from the PFS report were also transferred, to be used for the initial stages of the optimisation
- An activity-based cost (ABC) model was set up matching the overall PFS operating costs at the defined 4 Mt/a plant capacity but with some variance in the split between variable and fixed costs (usually fixed only for one annual period and therefore referred to by Whittle Consulting as 'period' costs). Theory of constraints was applied to this ABC model by allocating all period and sustaining capital costs for the entire operation to the overall bottleneck in the system. For the scenario studied in the PFS this happened to be the power available for milling. In the optimisation, the effect of this allocation is to preferentially process higher value (usually higher grade) ore though milling in the early years of the schedule before the annual discount rate significantly reduces the annual discounted cash flow
- A base case optimisation was then prepared using Whittle Consulting's proprietary Prober software. This was compared with the project's current production and financial plan. Several of the input parameters were corrected in an iterative process until the Prober results corresponded well with the PFS expectations of operational and financial performance. The NPV of all other cases generated was compared to this base case. The results were presented using a consistent format including summary tables, dashboards, and waterfall charts to ensure that the owner's team could easily compare new results with earlier cases

- The next stage of work tested the mining and milling/flotation mechanisms of Enterprise Optimisation. The ore mining zone start dates and ramp up schedules were reviewed and a few alternatives were proposed to enable a theoretical schedule with increased early annual cash flows to be generated. This will need to be tested for achievability by the mining consultants in the next phase of the project. Early Prober runs applied fixed processing parameters with a milling P80 of 74 µm and 4% mass pull to final flotation concentrate. After this, variable grind *versus* recovery and concentrate mass pull *versus* recovery relationships based on test work or typical PGM industry experience were applied to determine the impact of allowing flexibility in the processing plant operation
- An exercise to review and re-optimise the cut-off grade policy in each mining zone was now undertaken. For each zone, several alternative cut-off grade policies were applied to develop a series of zone variations for the ore and waste blocks falling within each zone as defined in the PFS. The shape and size of these alternative zones was reduced as the cut-off grade increased, as illustrated for mining zone 14 in Figure 2

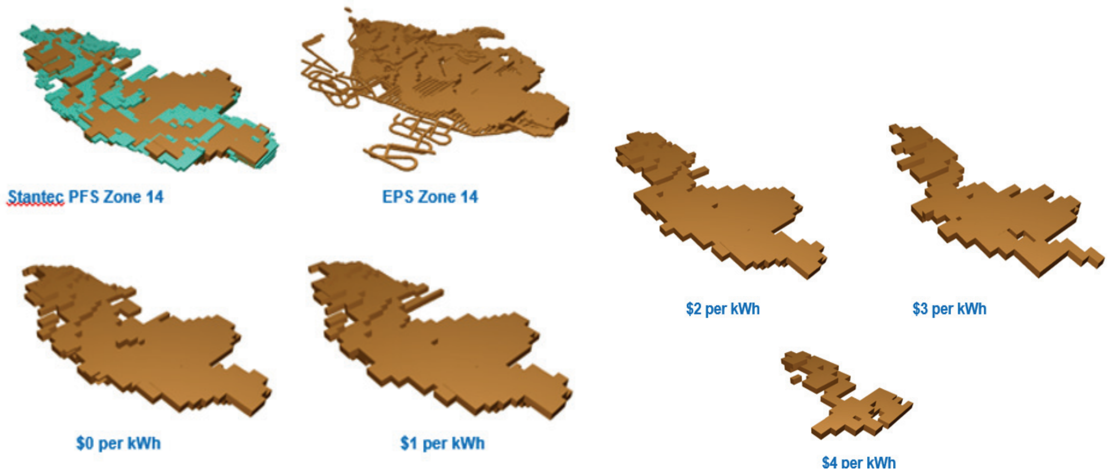

Figure 2. Establishment of alternative shapes for each mining zone

- The new zone shapes were used to develop updated mining and processing schedules in Prober, comparable with, but with cash flows advanced from, the best of the previous set of runs based on the PFS base case at 4 Mt/a processing rate. Initially runs were done at constant cut-offs, with the ore from the re-optimised versions of the first 17 mining zones, being those developed from the Indicated resource category. Manual selections of different combinations of cut-off were then tested, and finally the entire database was imported into Whittle's proprietary Prober C software to apply a novel 'Evolutionary Solver' technique. This complex procedure enables the optimisation software to learn and refine based on past results where options are presented as alternative scenarios (such as underground mine schedules based on different zone shape and cut-off grade combinations). In this case the optimum sequence yielding maximum NPV from the initial 17 mining zones proved to be a combination of the alternatives shown in Figure 2 for zone 14
- Several different combinations of size and start date of shafts and concentrator modules were then tested using the PFS mining zones as well as the optimised set of new zone shapes. The cases testing multiple shafts and processing modules with potential expansions to 12 Mt/a of ore processed were enhanced first by including additional ore zones from the Inferred portion of the resource and then by adding dedicated smelting and base metal refining facilities to be constructed on or close to the Platreef site
- Sensitivities to changes in the metal prices were prepared next. Unlike conventional sensitivity analyses that tend to leave the physical production data unchanged and simply adjust the financials, new Prober runs were prepared for each set of revised commercial parameters in order to test the influence of these on the optimised mining and processing schedules
- Several optimisation runs were prepared making use of modified input parameters such as social costs, water and electricity consumption, project permitting delays. These 'non-financial' capital issues were addressed in the parallel SUSOP study and the optimisation model was then used to quantify their likely impact on financial capital.

This concluded the main part of the optimisation study, in which over 150 Prober runs were completed over a seven-month period. The output of each run consisted of over 50 data tables and 70 charts illustrating trends in the key operating parameters as well as providing an overall financial analysis of the effect of changes in the input settings.

In December 2014 and January 2015 some supplementary optimisation work was done to test the following:

- The effect of expected delays in the initial mining and processing of ore
- The impact of new flotation recovery data
- The influence of improved capital and operating cost estimates for downstream processing facilities
- The influence both on NPV and peak funding requirements of deferring development and commissioning of some of the shafts and concentrator modules by several years.

Qualitative description of trends observed in a typical Prober run

Due to the sensitivity of the revised financial forecasts generated in this type of analysis, it is not possible at this stage to present the full results of the final optimisation runs that have been selected as a guide for the feasibility study team working on the next phase of the Platreef project. The charts and explanatory notes that follow are therefore intentionally not identified explicitly in terms of the input parameters that were applied to generate them and they do not all refer to the same Prober run. Also, they have been amended by removing most of the production, grade, and monetary figures. These charts illustrate key trends in major production metrics that were observed in all completed optimisation runs.

Figure 3 illustrates how the model was set up to enable the optimiser to schedule waste development, ore development, and ore extraction from production stopes in each zone, with built-in lags from initial waste development to the other phases of mining. This summary table was produced for each Prober run. It facilitated a very rapid visual check in each case to ensure that zone sequence rules were being followed in respect of their physical location in relation to the shafts and the ability of the mining teams to access specific zones. The number of zones being mined in any year and the progression from waste development into ore mining could also be followed, enabling the amount of mining equipment and labour as well as the ventilation requirements to be inferred. Mechanisms of this type are important in any strategic optimisation exercise to ensure that the solution being offered is likely to be practicable as the design and development of a project progresses.

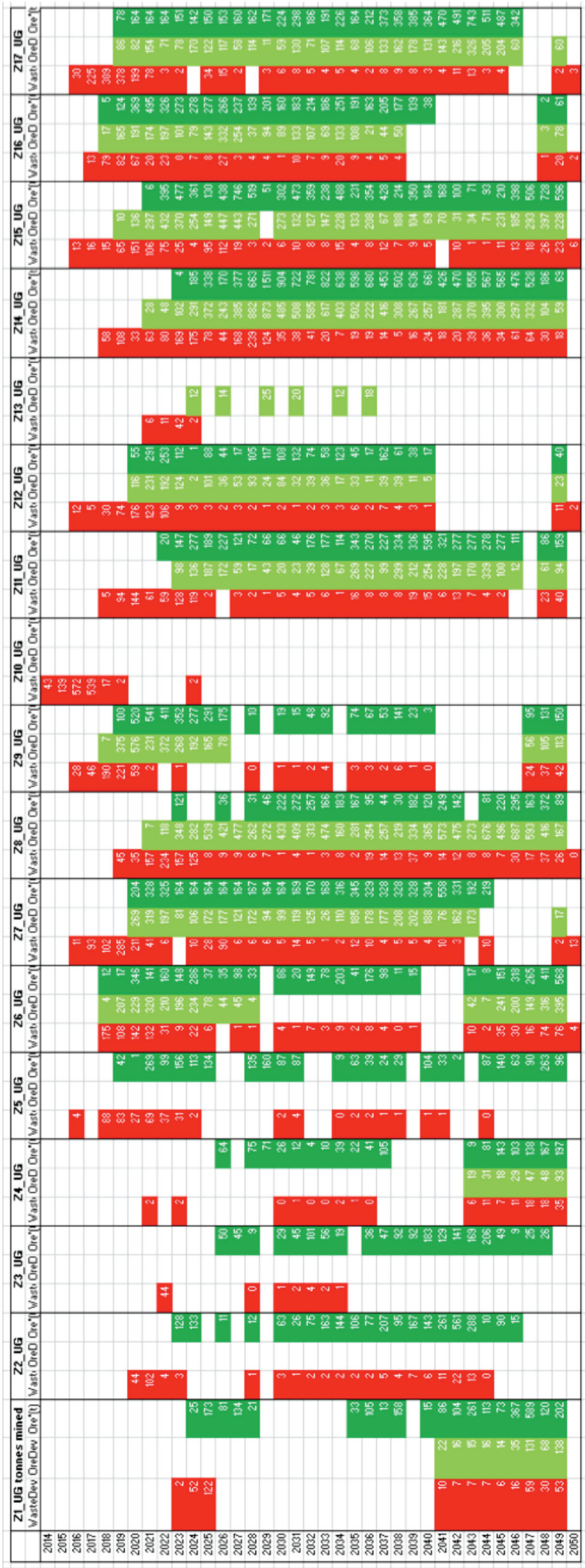

Figure 3. Typical overall mining sequence by year for each zone

Figure 4, extracted from the PFS document, is a plan view of the mining zones in relation to the planned shaft locations. This provides some context for the need to provide zone sequencing rules in the scheduling process. Clearly some zones have to be mined before others in order to open up new areas and provide access to outer zones Various Anon, 2014).

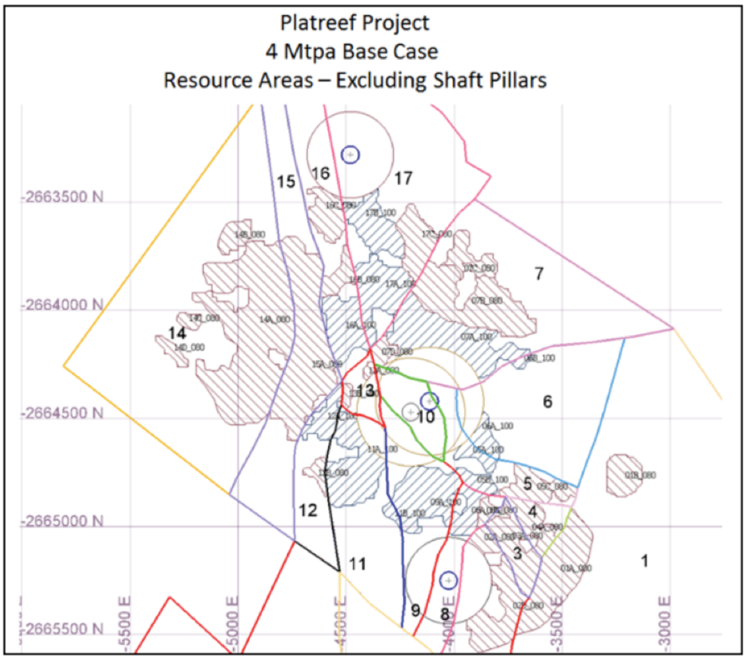

Figure 4. Plan view of mining zones and shaft locations

Figure 5 is also from the PFS report. The third column shows the stratigraphy of the reef in this specific orebody, with the T1, T2 Upper, and T2 Lower rock types being of interest.

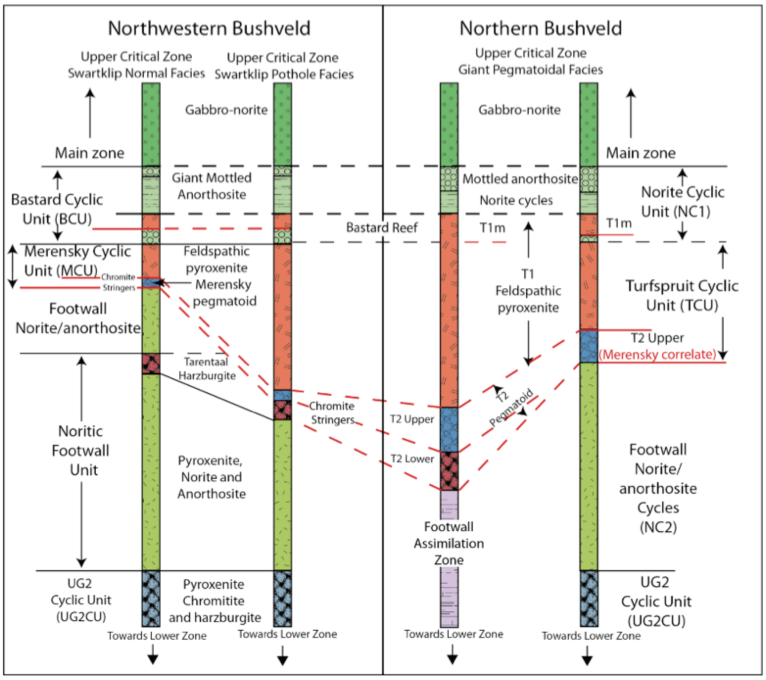

Figure 5. Stratigraphy of the Platreef Northern Bushveld deposit

Figure 6 illustrates some features of the mining schedules of a typical optimisation run. The first three charts are to the same scale and show respectively the tons of ore mined annually by stratigraphic rock type, the total tons of rock mined by method (vertical and lateral waste development, ore development, ore mining by one of three different methods planned), and the tons of ore mined by zone. The final chart in the bottom right-hand corner of Figure 6 shows the average platinum grade mined each year for each rock type. This particular run was used to establish the base case prior to optimisation, and it can be seen that the logical sequencing of zones in the PFS based on their location meant that peak ore grade, usually closely correlated to net value, could be achieved only by about year 15 of the mining schedule.

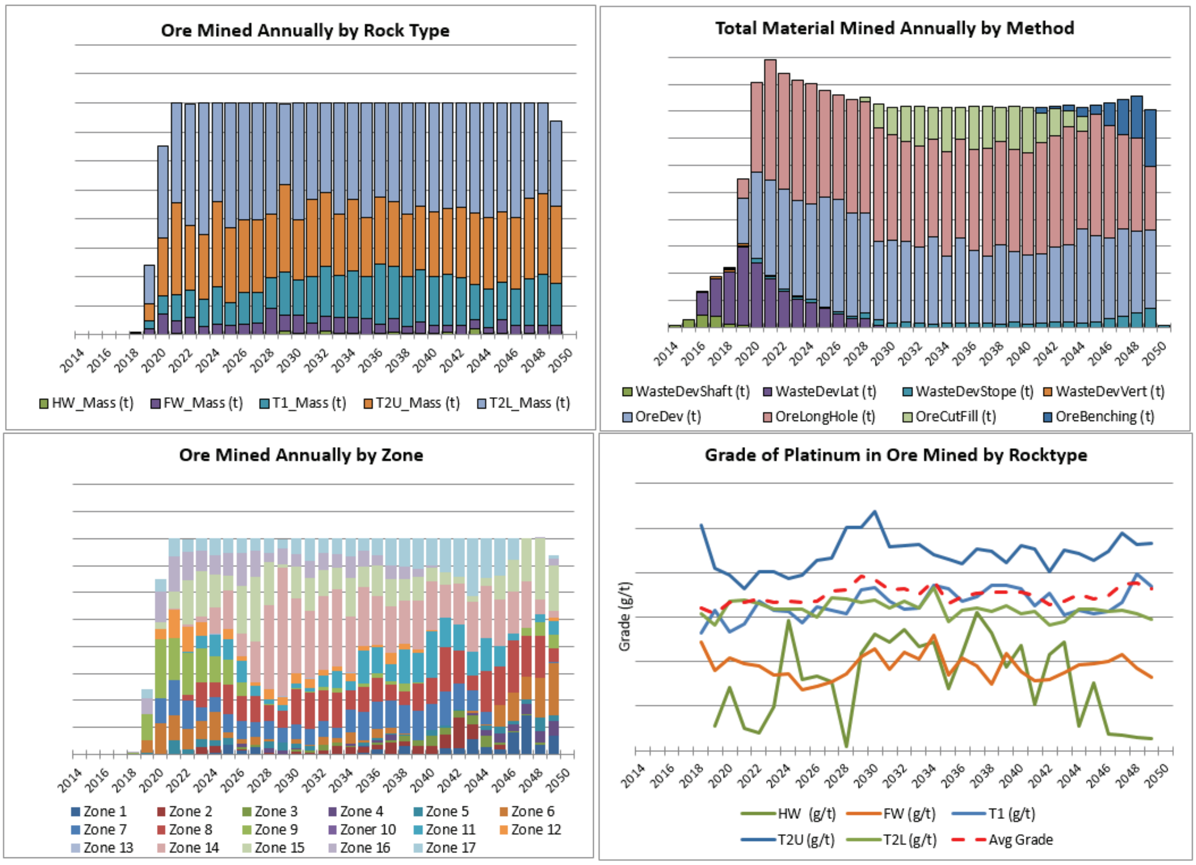

Figure 6. Annual mining schedules from an early base case run

One implication of the optimisation process was that the metal grades mined in the early years of the schedule were increased. This was a consequence of a combination of the zone selection, mining schedule, cut-off grade, and stockpiling optimisation mechanisms being applied. The net result was a benefit in early cash flow and NPV.

The PFS and therefore also the base case for the optimisation study specified a main production shaft with 6.5 Mt/a of rock hoisting capacity but a metallurgical plant with only 4 Mt/a of milling and flotation capacity. In this scenario, milling is the production bottleneck.

A comprehensive set of metallurgical test data was made available at the beginning of the optimisation study, and this included milling and flotation test work providing information on the specific power consumption and metal recoveries possible at different grind sizes. As would be expected, metallurgical recoveries peaked at a mill product classification of about 80% passing 74 µm. However, the drop in recovery at 106 and 150 µm was relatively little, whereas the specific power consumption for these coarser grinds dropped off sharply. This introduced the opportunity to specify the system bottleneck as mill power available (111 GWh/a for the base case 4 Mt/a plant) and allow the optimiser to select the optimum grind size each year to achieve maximum life of mine net present value.

Figure 7 shows the result from one Prober run. On the left, the annual power consumption is plotted and always reaches the red line which depicts the maximum power limit. In other words, the bottleneck was limiting production, as should be the case. On the right-hand side it can be seen that the optimisation process selected a coarse grind for some of the ore in the first fifteen years of the schedule, allowing the recovery to drop while processing significantly more than 4 Mt/a of ore. In later years, as the head grade to the plant decreased it was necessary to increase recovery as much as possible to maintain a minimum concentrate grade to smelting, and this caused the optimiser to revert to a finer grind. Sufficient additional capital was added in runs with this mechanism to ensure that the downstream flotation circuit could process the additional material.

It should be noted that towards the end of the optimisation study most of the runs considered an alternative scenario with shaft and plant capacity matched much more closely. In these cases the shaft became the bottleneck and the optimisations therefore always selected a grind size that would maximise metallurgical recovery.

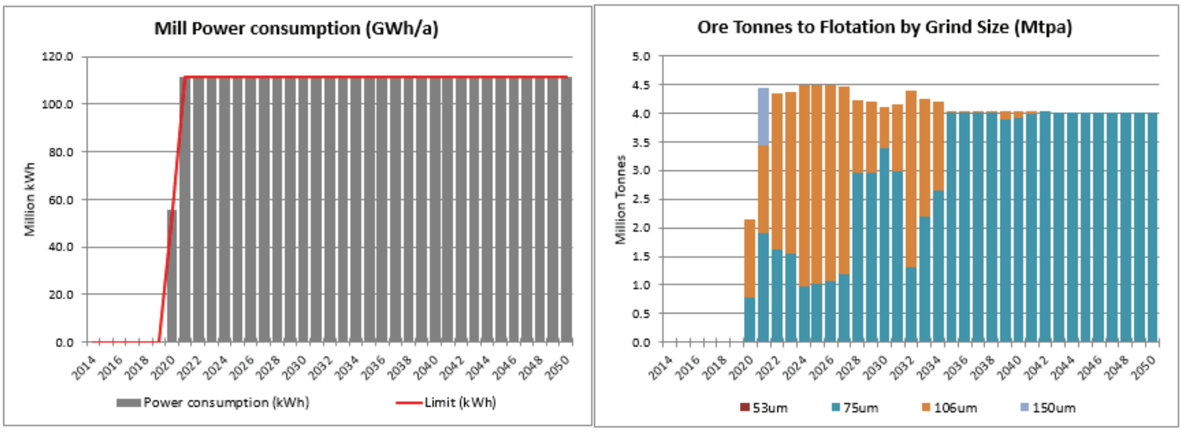

Figure 7. Optimisation of mill grind to achieve maximum NPV

In any flotation process, metal recovery can be improved by increasing the mass pull from ore to concentrate. The PFS specified a fixed mass pull throughout the life of mine but also referred to a minimum 3PGE+Au grade that would be acceptable to toll smelters without incurring penalty charges. The optimisation model was set up to increase cash flow by operating flotation at higher mass pulls while specifying that the minimum 3PGE+Au grade would always be achieved. Figure 8 illustrates the variability that occurred in many runs when this mechanism was applied. It can be seen that in one year the optimisation even incurred a penalty charge for low concentrate grade.

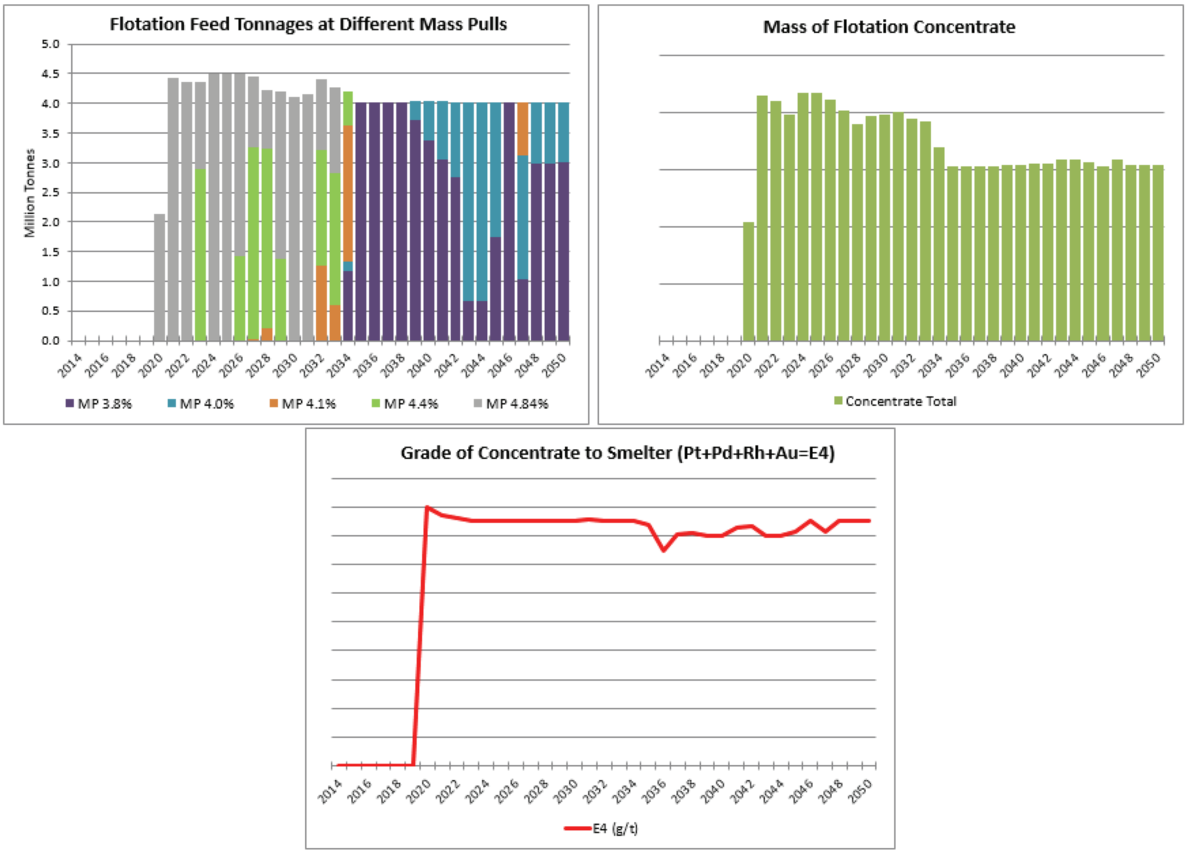

Figure 8. Optimisation of mass pull to flotation concentrate

Figure 9 presents a comparison of cumulative undiscounted cash flow between the base case (blue) and one of the expansion cases studied (red). It is evident that it should be possible to fund at least a portion of any expansion from operating cash flow. However, the extent to which this would be possible would depend on the timing and size of the expansion as well as metal prices and operational performance of the initial project after commissioning.

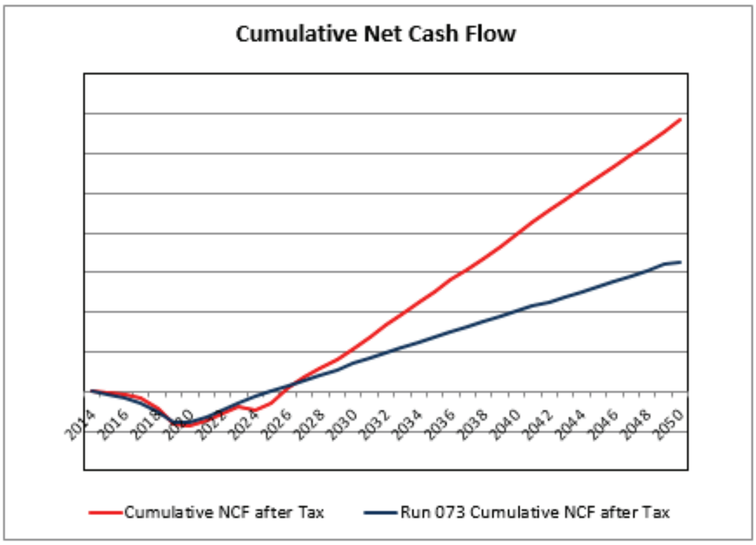

Figure 9. Influence of possible expansions on cumulative cash flow

Conclusions of the Platreef optimisation study

The study base case used the mining and processing plans already developed during the prefeasibility study. The potential NPV of the project could be influenced positively by:

- Applying the theory of constraints to evaluate the orebody zones in terms of net value per bottleneck unit, resulting in the location of the most profitable ore being identified
- Applying a novel massive iteration process to test all possible combinations of net value applied to each mining zone, resulting in an optimised model for scheduling purposes, with distinct cut-off values defined for each zone
- Bringing forward revenue and cash flow using enhanced scheduling, cut-off grade, and stockpiling optimisation techniques to the defined mining zones, subject to the technical limitations on mining defined in the PFS
- Applying dynamic grind to increase processing rates and dynamic mass pull to flotation concentrate to increase recovery where possible, both resulting in increased early cash flow.

Natural capital initiatives were identified with potential to reduce electricity and water usage per unit of metal produced in concentrate, and also to introduce mining and backfilling practices to increase utilisation of the resource in each zone over the life of mine.

The optimisation study also considered different sizes and configurations of mining and processing operations. Some of the preliminary conclusions reached were:

- The NPV of the project could potentially be increased by making use of the mining infrastructure already planned for the project during the PFS more effectively. The development shaft could be converted to production to supplement the main shaft. By matching the ore processing capacity of the metallurgical plant to the total shaft hoisting capacity an optimised overall solution could be generated
- The peak funding requirements for the project could be reduced by commissioning an initial small-scale operation as early as possible, then constructing and operating expansions a few years later
- The possibility of building a dedicated smelter and base metal refinery at Platreef was considered and investigations commenced. This should ultimately increase the amount of net cash generated by the operation but would require significant additional capital expenditure.

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