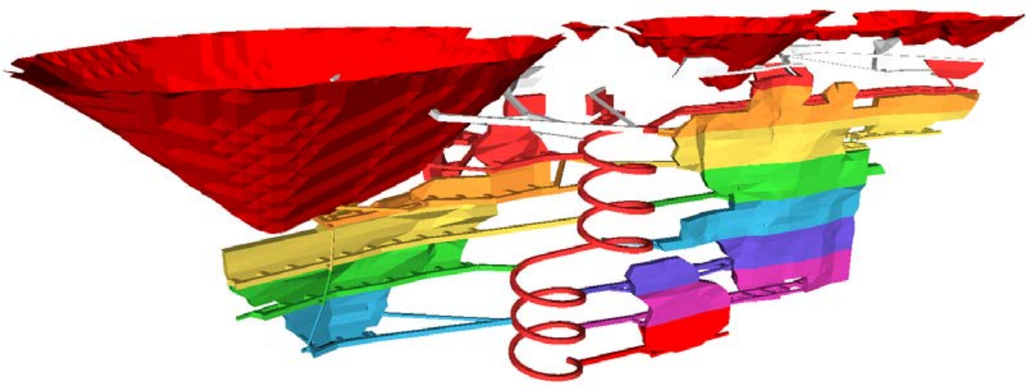
UNDERGROUND MINE OPTIMISATION – THE WHITTLE CONSULTING “MONEY MINING” APPROACH

Gerald Whittle, 25 May 2015

Before we begin, we need to agree on the objective and the measure of success. Any commercial enterprise’s primary ambition is to create economic value through cash flow. Like it or not, money has a time value – that is a law of economics/nature, not just an opinion. Net Present Value (NPV), the sum of Discounted Cash Flows (DCF) is therefore a simple, albeit imperfect, measure of economic value as it accounts for the time value of money. If we are discussing cut-off policy, the optimal policy is therefore the one that maximises NPV (acknowledging that there are other things to consider too).

Secondly, we should not be drawn into talking about “cut-off grade”, it should be “cut-off value”, in the context of “Net Value per Bottleneck Unit”. The “grade” of a block is its metal content divided by tonnes. Grade is a poor surrogate for “Net Value” as different materials have different recoveries and costs to mine and process. The bottleneck in the system, what regulates the rate of Net Value generation, is seldom defined by dry tonnes. It is the “Net Value per Bottleneck Unit” that determines the cash generating rate of the business, and therefore its economic value.

Thirdly, you cannot ask what “the cut-off” is for an underground or open pit mine. The “optimal cut-off” values will be different in every part (zone) of an underground mine due to recovery and cost differences, and will change over the life of the mine due to the opportunity cost associated with when the zone is mined relative to the rest of the deposit. With regard to the opportunity cost, the general case is: “Early in the life of the mine, when the opportunity cost for mining and processing low value material is high (there being so much higher value material out there in the future) so the optimal cut-off value is generally high. Towards the end of the life-of mine, when the resource has been mostly depleted, there is no more opportunity cost and you may as well mine and process everything above the marginal/break-even cut-off value – there is nothing else to do. In between, the optimal cut-off values will be defined by the grade-tonnage curve, the rock types, the ore body structure, the metal prices and costs levels prevailing, where the bottleneck is at the time, and the steadily declining opportunity cost as the ore body is depleted”. Read Ken Lane, the originator of this concept, for a more comprehensive explanation of this rationale.

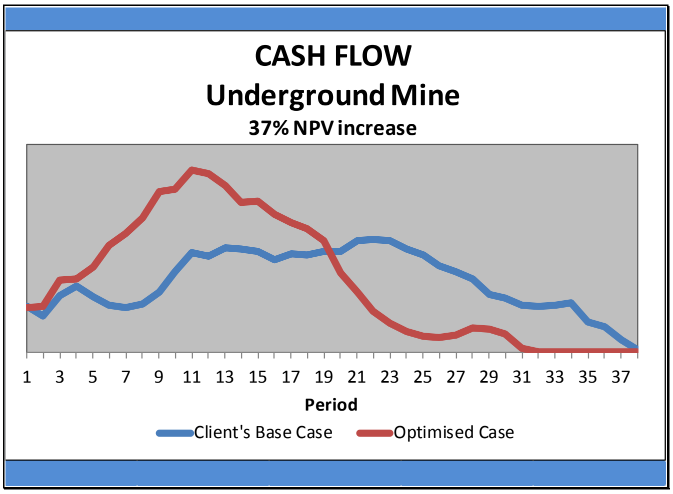


Here is a quick summary of the approach Whittle Consulting takes to underground mining optimisation, including cut-off:

1. What is the primary bottleneck in the system? In underground mines it is usually the shaft or decline – is this volume limited (m3) or mass limited (wet tonnes)? Some underground mines are plant limited, if they share the plant with an open pit they are automatically plant limited – is the plant volume limited (m3), mass limited (wet tonnes), power limited (kWh), reagent (oxygen, acid or whatever) limited or chemistry limited (blending requirements)? At certain times during its life, an underground mine may be development limited (development meters), haulage limited (Wtonne.km or truck/LHD hours), ventilation limited (excavator/truck/LHD hours), work-face congestion limited or traffic congestion limited. You cannot optimise a system if you don't understand what the constraint(s) on the system is (are).

2. What is the Net Value of each block in the resource model? – the revenue less the cost of mining and processing. For the purposes of calculating Net Value, we should not include vertical and horizontal development to gain access to the zone for this block, but we should include sustaining capital that is driven by mining or processing activity or life of mine.
    a) We need to model the cost of vertical and horizontal development and the generic or design relationship of development to the various zones in the ore body, but we do not allocate development cost to ore tonnes – we cannot because we have not determined what ore is yet.
    b) The revenue of a block is simple to calculate – the grade times the recovery (can be complex curves by grade, lithology, etc.) times the metal price (although this can be a highly uncertain assumption).
    c) Determining the cost of mining and processing a block is much more complicated – Activity Based Costing (ABC) is required. ABC involves:
        i. identifying the key activities in the business
        ii. identifying the "driver" of that activity i.e. the cause and effect relationship with physical events/characteristics, and
        iii. determining the period/fixed cost component of each activity, which requires a view on reaction time to changes in volumes and an understanding of the cost structure contractual/social/legal constraints and implications.
3. With 1 and 2 above, we can characterise material in the resource model according to its "Net Value per Bottleneck Unit", and will set up several values for changing bottlenecks and alternative ways of mining or processing.

Now we are ready to optimise! That was all just the preparation.



4. Divide the whole resource into approximately 10 to 50 zones (this is subjective - 3 is not enough and 600 is too many) based on some logical rationale e.g. levels, natural geotechnical breaks, mining areas, or areas with similar geological characteristics.
    a) Apply one of the stope optimisers – Datamine MSO, Maptek, Deswick, VBKOM. This is not in itself an optimisation, but it will generate alternative conceptual designs for each zone within the ore body at different cut-offs starting at $0 Net Value (i.e. the marginal/breakeven cut-off) and moving up in steps. This process is the equivalent of generating nested shells in an open pit optimisation. The tools allow you to set spatial rules on minimum stope width and height (depending on mining method, equipment and geo-tech considerations), and generate a set of nested zone outlines based on various "Net Value per Bottleneck Unit" cut-offs (i.e. not cut-off "grades"!). This generates alternatives for each zone in the ore body, from larger/lower-average-value to smaller/higher-average-value alternatives with the relevant spatial continuity in the material to contemplate mining it. This process is best performed by the mining engineer who understands the ore body and the practical considerations – it is much more time consuming than generating shells for an open pit using Whittle, the process which was generalised 50 years ago by Lerchs-Grossman. This step cannot tell you which variation to use, just what the alternatives are.
    b) As you raise the cut-off bar, some parts of the ore body evaporate into disjointed spots and become useless, but others can hang together nicely to give you potential high value areas to focus on early in the mine life. The general assumption is that if you take the smaller/higher-value variations then you cannot go back later for the lower-value halo left behind – it is assumed to be sterilised due to backfill or instability of the previous working. If, however, the shapes work out so you can take the smaller/higher-value areas now, and then go back in later years for the rest of the material – that is like phasing in a pit and it is even better.
    c) Ideally 4 or 5 variations of each zone can be provided. We would settle for only 2 variations of each zone if that is all that is available, but the more options, the better the granularity of the results.

5. Set up a life-of-mine schedule optimiser. Whittle Consulting uses its proprietary Prober C software for this – a sophisticated and extremely powerful non-linear, multi-variable schedule optimiser. Please note that X-Pac and Mine-2-4-D are schedule "management" tools, not schedule "optimisation" tools. You need them too but they can't solve this problem. One run of Prober C will consider one cut-off version of each zone, the revenues, fixed and variable costs, the development network required to be scheduled, any sequencing constraints, all the capacity constraints on development meters, face mining, hauling, hoisting, ventilation etc. etc. and return a life-of-mine schedule that maximises NPV. This gives you the most economic schedule for one combination of zone cut-offs.

6. However, we should consider all variations of zone cut-offs, each zone could be at a different cut-off. Some zones will "promote" to a smaller/higher-average-value version and come earlier in the life of the mine. Note the positive language – we consider this an opportunity to increase the value of the ore processed, by reducing the quantity of low value material diluting it. Other zones will hang around the middle of the schedule at medium-size/medium-average-value versions, and some will slide to the back end of the schedule at larger/lower-average-value versions. If we want to try many combinations of zone cut-offs then we have a mathematical dilemma. If you have 2 cut-off variations of 15 zones to consider that is 33,000 potential combinations. If you have 5 variations of 25 zones that is 300 million-billion potential combinations – don't you love maths! Evaluating a few of these in a spreadsheet is not really going anywhere. Our procedure is to apply an Evolutionary (genetic) algorithm to control a whole series of Prober C runs – firing off Prober C runs with various combinations of zone cut-offs, killing off combinations that do not give good results and propagating

variations of combinations that give good results. We find that running this on 100 computer processors over a day or two (depending on the number of permutations), involving several thousand Prober C runs (each a complete life-of-mine schedule optimisation) converges on some very good results.

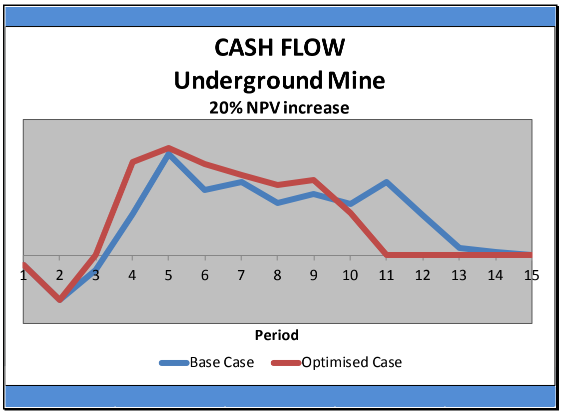
Don't overlook the following:

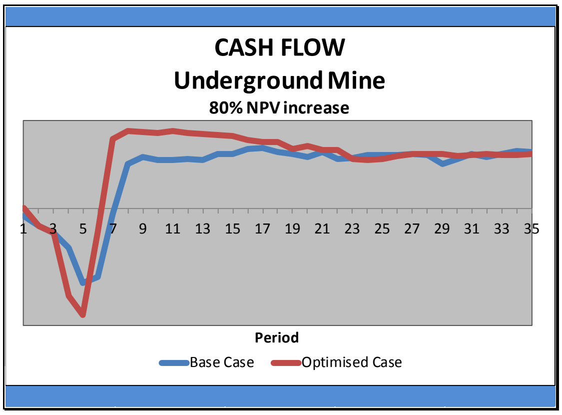
7. Involve a cross functional team throughout – firstly so the modelling and analysis is correct, and secondly so that those who will have to implement it all understand and buy into the results. It is wise to engage mixed groups as the positive energy from the management and finance people from the spectacular economics will counter the grief of the resource geologist who struggle to accept that some low value material will be left in the ground, and tempering the nerves of the mining engineers who have to step up to a higher standard of mine planning.

8. Repeat the whole process for a range of market scenarios, operational performance levels and system sizes.

9. Hand over the selected case to the mine planners for implementation and make sure they don't try and "improve" it (i.e. ruin it) by trying to sneak more tonnes back into the design. Consider changing their job description, management reporting, KPI's and incentive's to align with the real objectives of the business.

No one said it was easy, but in our experience the result can be 10% - 50% increase in economic value of the underground project/operation – the benefit can be measured in 100's of millions of dollars and make or break the economic case for the plan.





Brace yourself for some criticism and abuse. E.g. "But you are sterilising 20% of the ore body!!" which is not always the case, but if it is then your response should be "Your approach is potentially sterilising 100% of the ore body, because without the benefit of cut-off optimisation this underground project/operation is uneconomic and there isn't going to be a mine at all."

Gerald Whittle

CEO, Whittle Consulting Pty Ltd

June 2015

Whittle Consulting helps mining companies achieve their full economic potential. For more information see www.whittleconsulting.com.au