Cash Flow Grades - Scheduling Rocks with Different Throughput Characteristics

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Introduction

Scheduling many resources requires the segregation of ore for processing, and barren or low grade rock sent to waste dumps. The rock is ranked so that the highest value material can be separated for processing. Deposits with only one valuable metal, such as gold, normally would use the element grade (oz/t) to rank the resource. In a simple process, the highest grade material is processed to recover the gold and the low grade material sent to a waste dump.

As multi–metal ores are mined, the ranking of the resource may utilise equivalent grades (e.g. Au-Equiv, oz/t) or dollar grades ($/t). These grades are used to find the material that will add greatest value to the operation when processed. More complex ranking systems are required when the minerals are hosted in rocks with different processing rates. A quantitative system is required to decide if it is better to process a few (hard) high gold grade blocks, or more (softer) low gold grade rock. This paper explores a method to rank ores with different processing characteristics.

A New Ranking Method: 'Cash Flow Grades'

In considering how to appropriately rank ores with different throughput rates, the underlying formula used in cut-off grade optimisation was considered (Lane, 1988):

$$V^*(T,R) = \underset{\substack{0 \le r \le R \\ \text{for all ù}}}{Max} \left[c(t,r,\omega) + \frac{V^*(T+t,R-r)}{(1+\delta)^t} \right]$$

In this equation the maximum present value (V*) of the entire resource (R) is calculated at a specific time (T). The maximum present value is calculated by selecting the strategies (ω), for a portion of resource (r), which maximise the sum of the cash flow (c) and the maximum present value of the remaining resource (processed during a time t, with discount rate δ).

Maximum cash flows are a key component used in optimisation of a schedule to determine a cut-off grade strategy and achieve the greatest NPV. When applying a cut-off grade, the best ranking system will result in the maximum cash flow.

A rock classification system has been derived by considering how to maximise the cash flow used in long term schedule optimisation (further details are included in Appendix A). The following formula shows the 'Cash Flow Grade', calculated as a value per time period to rank the rocks for both short and long term scheduling.

$$G_{CashFlow}[\$/hr] = (OreValue[\$/t] - WasteValue[\$/t]) * \text{OreProcessingRate}[t/hr]$$

The *Ore Value* consists of the revenue from the various metal product values and all ore processing costs (e.g. crushing [$/t], concentrate [$/t con], smelting, refining and selling [$/metal mass]). The *Waste Value* in the above equation is negative as this has costs but no revenue components. Materials of different hardness and chemical composition may have a different *Ore Processing Rate*. Some sample *Cash Flow Grade* calculations are given at the end of this paper when open pit and underground *Cash Flow Grades* are compared.

A *Cash Flow Grade* of zero (0) indicates that there is no difference in cash flow whether the material is processed as ore or waste. In process constrained operations, the optimum cut-off grade strategy would always be positive. In a mine constrained operation the *Cash Flow Grade* cut-off strategy may drop to zero (0). Material of the same revenue and cost per ton but different hardness would be ranked separately due to differences in the process throughput rate.

Of significance in this equation is that fixed costs do not impact on the ranking. Regardless of the magnitude of fixed costs that must be paid, the mine wants to process the most profitable ore from the available reserves.

Comparison of Alternate Ranking Systems

In order to test the ability of the cash flow grades to produce the highest cash flow, data were collected from a poly-metallic operation that had throughput rates dependent on ore type. Although the primary value came from the copper, the deposit also contained gold and other metals. The presented data were altered from their original form to show the principles without being distracted by the operation details.

Five different ranking systems were compared as progressively more detail is modelled. The ranking systems that were tested follow:

- **Copper Grade (%/t)**

Simple copper grades were used as the control to compare the case flow and throughput rates of the different cases. This was known to be a poor ranking system since it took no account of the other contained metal values.

- **In-situ Value ($/t)**

The in-situ value was calculated by adding the value of the copper, gold and other metals contained in the ground. No account was taken of the different processing recoveries in this ranking system.

- **Net Value ($/t)**

The net value was calculated by adding the value of the copper, gold and other metals after they have been processed. The different recoveries and processing costs were incorporated in this grade.

- **Net Value with haulage and hardness corrections ($/t)**

The grade uses the net value calculated above, and adds a correction for the haulage distances and the hardness. The haulage correction was calculated from the difference in the haulage cost of ore and waste, depending on the distance from the dumping location.

The hardness adjustment used the ore throughput to calculate the time each block would require for processing. The annual processing fixed cost was proportioned to each block according to how much processing time it would require. A block with a low throughput rate would have a lower adjusted grade than the same grade rock with a higher throughput.

- **Cash Flow Grade ($/hr)**

The final grade used to rank the material was calculated with the '*Cash Flow Grade*' formula derived in this paper.

Exactly the same blocks were scheduled in each case to isolate the impact of the ranking system. The processing capacity was tested from 50 to 150% of the nominal capacity. Figure 1 compares the results of these different ranking systems to the base copper grade ranking without changing the total material mined in the period.

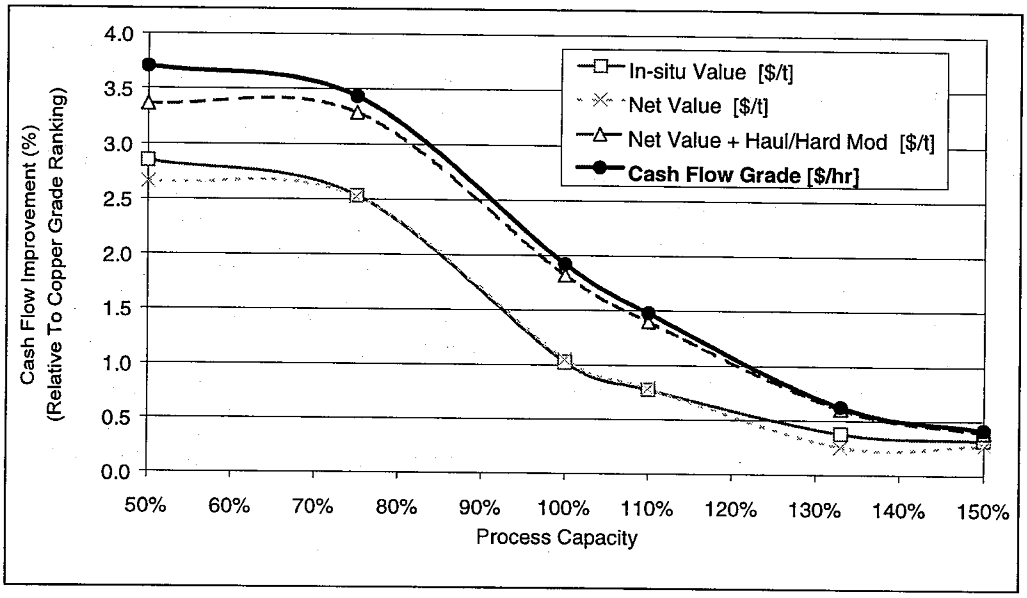

Figure 1: Comparison of Ranking Systems

The mine used a ranking system like the Net Value with corrections for haulage and hardness. Some observations from this chart are:

- The *Cash Flow Grade* gave the highest value at all processing capacities. This implies that it is an appropriate way of ranking material to maximise the cash flow.
- The greatest benefit of using *Cash Flow Grade* ranking occurs with relatively small processing capacities. As the processing capacity increases to treat more material as ore, the difference between the ranking systems reduces. In the limiting case, processing all the material would have no differences between ranking systems. The graph would also return to no difference in the value if there were no processing capacity. These areas of the graph were not explored further due to negligible importance.
- Generally, as more detail was modelled, the cash flow increased. The overlapping of the In-situ and Net Value shows that these ranking systems do not incorporate all the relevant information to maximise the cash flow.
- Because the hardness corrections applied to the Net Value were dependent on the fixed costs, low fixed costs would drive this curve down closer to the unadjusted Net Value curve.

The differences in the total cash flows are relatively small because it is only low grade material that is moved between ore and waste in each system. What is more significant is that 2-3% more material could be processed without expanding or upgrading the mill. Further improvements in the value of the changing the ranking systems would be realised if the blocks mined in the period were re-sequenced. This was not done in order to isolate and clearly compare the value of the alternate ranking systems.

Application

Cut-off Grade Strategy

For *Cash Flow Grades* to be used in developing a cut-off grade strategy, the cash flow must be calculated with the relevant constraints applied. To calculate the cash flow contribution from the rocks processed as ore, the average ore cash flow grade must have the waste value corrections removed. It may be easier to separately calculate the cash flow based on the raw block information (e.g. copper grade, gold grade, concentrate mass). It is apparent that the grade used for ranking and splitting ore from waste does not have to be used in the calculating the cash flow.

Constraints that must be applied to any schedule include mining capacities (e.g. truck hours, shovel mass, phase sinking limits, undercutting), processing capacities (e.g. conveyer mass, SAG time, Sulfur mass, concentrate mass) and marketing capacities (e.g. metal production and sales constraints). Regardless of how material is separated for processing, all the constraints must be applied so that only feasible schedule solutions are allowed.

Figure 2 shows an example of a cut-off grade strategy that uses cash flow grades to separate the material going to the mill and waste dumps. Mining and processing capacities constrain the schedule.

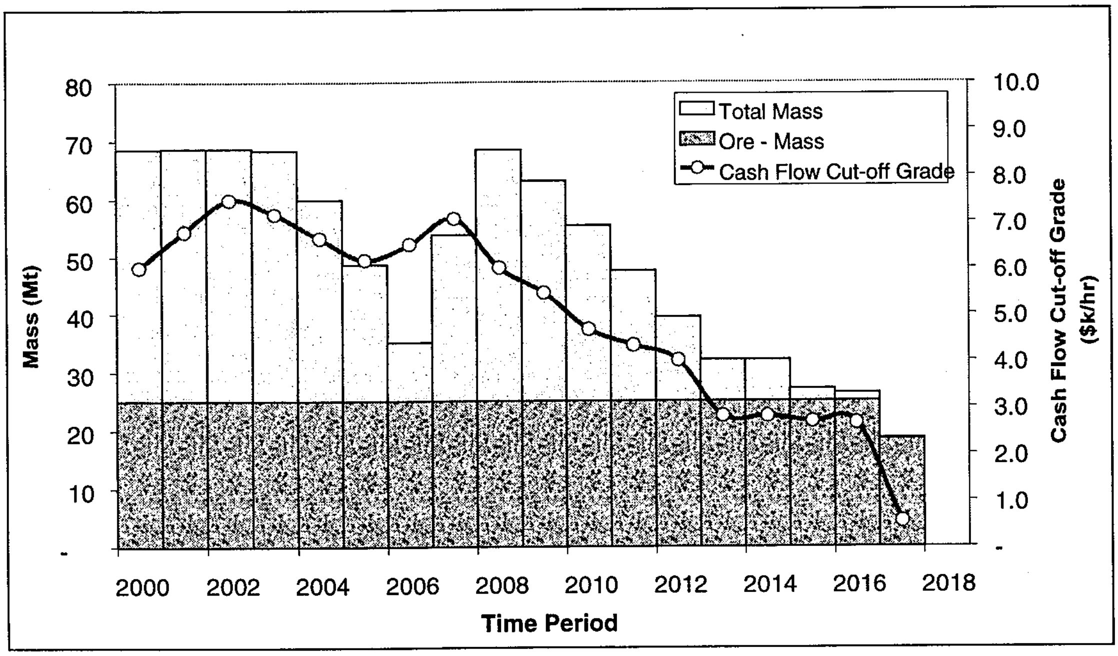

Figure 2: Cash Flow Cut-off Grade Strategy

Stockpiles

Stockpiles capture material that can be processed economically at a later time. Stockpiling to help maintain blended targets is not included in this discussion since this normally falls outside the scope of cut-off grade optimisation problems. If sufficient space exists, a number of stockpiles may be created to separate ores of different values. The same principles may be used to separate material going to each stockpile as were used to separate material to be processed as ore and waste. The *Ore Value* would include the revenue generated when the material is processed, costs to dump to the stockpile, costs to reclaim from the stockpile, processing costs and marketing costs. Again the fixed costs are not included in ranking the material, though they must be recovered from the total value of the material after processing. An additional complexity with stockpiles is the time between depositing and reclaiming. Ideally, the ore value should be discounted to reflect the time, relative to when waste dump costs are incurred, that the value is earned. Due to the complexity of this calculation, the stockpile value time corrections may be applied outside of the schedule optimisation.

Processing Configurations

Processing plants may be configured to run to different objectives. These objectives may include maximising recovery, minimising reagents, maximising throughput and maximising cash flow. At the heart of cut-off grade optimisation theory is the maximisation of the cash flow within the long term NPV context (Lane, 1988). Extension of Lane's work shows how cut-off grade and mill throughput/recovery can be optimised simultaneously (King, 1997). The range of cut-off grade and mill throughput/recovery configurations is examined to determine the maximum sum of cash flow and remaining value for each increment of material.

Figure 3 shows how the cash flow cut-off grade and mill throughput can be optimised simultaneously throughout the mine life. In this case the annual mill capacity was allowed to increase from 25Mt to 40Mt with a percent drop in recovery for an extra 1Mt throughput.

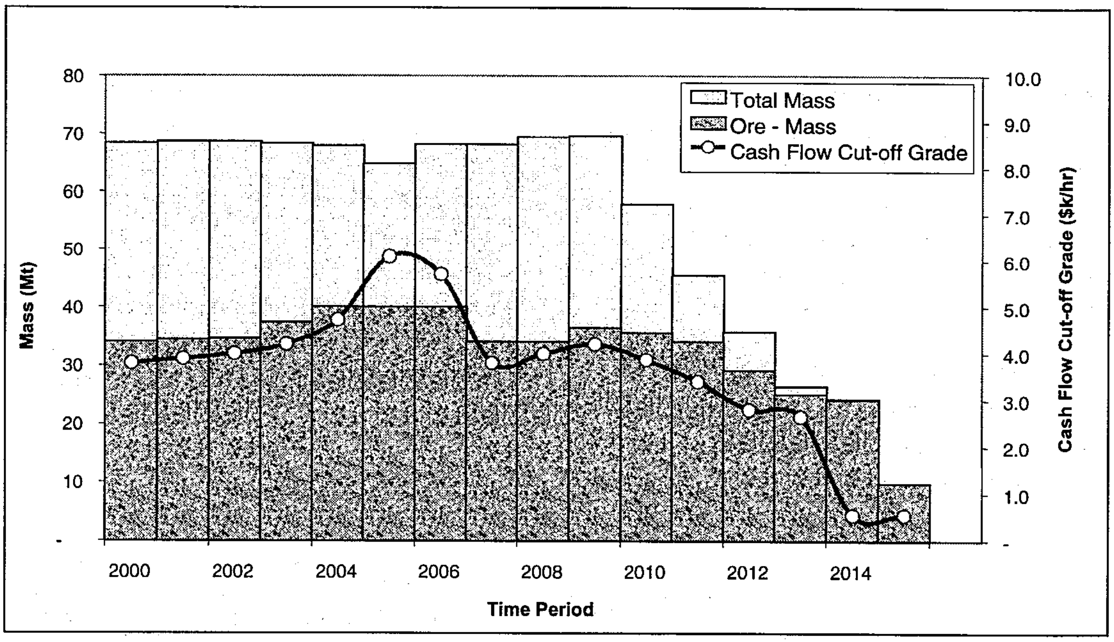

Figure 3: Cash Flow Cut-off Grade & Throughput Strategies

The simultaneous solution of both cut-off grade and mill throughput shows both these strategies trending in the same direction. Wooller (1999) shows how the mill throughput can be modelled as another grade to which a second cut-off can be applied.

Multiple Processes

Although this paper addresses ore and waste separation, the same principles apply to two different ore processing streams (e.g. two different concentrators). For example, consider the case of floatation and heap leach circuits.

As well as determining which material is sent to waste dumps, question arises of which material to send to flotation and heap leach processes? It is clear that a second dimension exists to this problem. The same approach as was described to separate ore and waste can be used to separate material sent to each ore process.

A formula to separate ore streams could have the following form:

$$G_{CashFlow}[\$/hr] = (FloatationValue[\$/t] - HeapLeachValue[\$/t]) * FloatationThroughput[t/hr]$$

Two ranking systems would be implemented by first determining what should be mined as ore, then determining what ore should be sent to each process. Material would be separated as shown in Table 1.

Ranking System		Concentration Ranking	
		Low	*High*
Waste/Ore Ranking	High	Heap Leach Ore	Floatation Ore
	Low	Waste	

Table 1: Multiple Process Ranking

An observation from following this approach is that the Heap Leach throughput rate does not feature in the above equation. This suggests that potential exists to find a better ranking system for separating the process feeds. Answering this question is a topic for further research and investigation.

Underground and Open Pit Scheduling

In working with deposits that schedule both underground and open pit resources, a cut-off grade strategy needs to be developed that is consistent across all resources. The *Cash Flow Grade* is calculated for underground resources by using the same formula as the open pit. In underground mines, the waste value may be zero if material in a stope can be left in-situ, or the full mining cost if the material must be removed during development. For example, *Cash Flow Grades* for several blocks found in open pit and underground reserves are evaluated in Table 2.

	Location					
	Open Pit		**U/G Stoping**		**U/G Development**	
Rock	**A**	**B**	**C**	**D**	**E**	**F**
Ore Revenue	$12.0 /t	$15.0 /t	$25.0 /t	$30.0 /t	$12.0 /t	$15.0 /t
Ore Mining Cost	$1.0 /t	$1.0 /t	$15.0 /t	$15.0 /t	$50.0 /t	$50.0 /t
Ore Processing Cost	$2.0 /t	$2.2 /t	$2.0 /t	$2.2 /t	$2.0 /t	$2.2 /t
Ore Throughput	140 t/hr	80 t/hr	140 t/hr	80 t/hr	140 t/hr	80 t/hr
Waste Cost	$1.5 /t	$1.5 /t	$0 /t	$0 /t	$50 /t	$50 /t
Ore Value ($/t)	$9.0 /t	$11.8 /t	$8.0 /t	$12.8 /t	-$40.0 /t	-$37.2 /t
Ore Value ($/t) - Waste Value ($/t)	$10.5 /t	$13.3 /t	$8.0 /t	$12.8 /t	$10.0 /t	$12.8 /t
Cash Flow Grade ($/hr)	***$1,470 /hr***	***$1,064 /hr***	***$1,120 /hr***	***$1,024 /hr***	***$1,400 /hr***	***$1,024 /hr***

Table 2: Underground & Open Pit Ranking using Cash Flow Grades

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As can be seen in the Table 2, the same cash flow grade formula can be used to rank both open pit and underground resources. The different revenues, mining costs and throughput are all considered in the *Cash Flow Grade* to maximise the period value. Table 2 also shows how misleading the simple ore revenue and ore values are for ranking material.

Conclusions

Cash Flow Grades (e.g. \$/hr) were derived from considering how a project's NPV is built up from period cash flows. In mines where mill throughput rates do not vary with ore feed, functions to rank material are relatively simple and will be proportional to the *Cash Flow Grade*. Mines which process ores with different throughput characteristics, and can selectively mine these ores, are likely to realise higher throughput, annual cash flows and increased NPV by adopting cash flow based cut-off grades.

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Appendix A

Cash Flow Maximisation and Material Ranking

Ranking of rock types should enable the cash flow to be maximised when applying a cut-off grade to separate what is processed, stockpiled and sent to a waste dump.

The cash flow may normally be calculated on an annual basis but can be calculated at any time period (e.g. annual, quarterly, monthly, weekly, daily or hourly). Since it is the cash flow for a set period that is maximised in the schedule, the cash flow for a fixed time period is used as the foundation to calculate the value of any material type.

The value of material mined to mill (Ore) for a fixed time period (for example a year or an hour) is calculated using the following equation:

$$OreValue[\$/hr] = (OreMetalValue[\$/t] + OreConValue[\$/t] + OreMassValue[\$/t]) \times OreProcessingRate[t/hr] + FixedValue[\$/hr]$$

Where:

$$OreMetalValue[\$/t] = MetalGrade[t\ metal/t] * MetalPrice[\$/t\ Recovered\ Metal] * Recovery\left[\frac{t\ Recovered\ Metal}{t\ metal}\right]$$

$$OreConValue[\$/t] = \frac{MetalGrade[t\ metal/t] * Recovery\left[\frac{t\ Recovered\ Metal}{t\ metal}\right] * ConValue[\$/t\ con]}{ConGrade\left[\frac{t\ Recovered\ Metal}{t\ con}\right]}$$

$$OreMassValue[\$/t] = MassValue[\$/t]$$

Likewise the value of processing the same material as waste would be given by a similar, less complicated, equation. In calculating the value of this material if it was mined as waste, the same ore processing rate is used to ensure an equal quantity of material is mined as waste. This last assumption does not always hold true since waste may be processed at different rates depending on the location and rock characteristics.

$$WasteValue[\$/hr] = (WasteMassValue[\$/t]) \times OreProcessingRate[t/hr] + FixedValue[\$/hr]$$

The benefit of processing material as ore instead of waste can be quantified by simply looking at the difference between the ore and waste cash flows. Material with the greatest benefit to process as ore will contain the highest difference in value, therefore ranking the rock with all other material.

$$G_{CashFlow}[\$/hr] = OreValue[\$/hr] - WasteValue[\$/hr]$$

or

$$G_{CashFlow}[\$/hr] = (OreValue[\$/t] - WasteValue[\$/t]) * \mathrm{OreProcessingRate}[t/hr]$$

One significant feature of this equation is that the fixed costs do not have an impact on the ranking of material. A corollary is that the highest cash flow that can be realised from a resource is independent of what fixed costs must be paid. As with any algorithm derivation, if the assumption base does not represent the problem, an optimal ranking is not guaranteed. Tests with other ranking systems can be used to assess the applicability of the derived formula.