ABSTRACT
Planning an iron ore mine uses a rectangular block model, from exploration drilling. The objective is to produce ore close to target grade vector through the life of the mine, without rehandling and blending. The target grade includes iron and also contaminants, phosphorus, silica and alumina. While maintaining the grade objective, the mining sequence must be technically feasible, removing overlying material in sequence, with walls within a safe height. The problem is NP hard, with astronomically many feasible sequences for mining several thousand ore blocks. The unattainable global optimum necessitates a “satisficing” mining sequence.

The multiple-grade objective is recast as minimising a single dimensionless “stress” measure. Viewing feasible mining as a sequence of “Available Block Lists” (ABLs), a greedy algorithm trims each ABL for a short-term optimum. The greedy algorithm does not immediately yield a long-term optimum, but it can be modified to provide a long-term satisficing solution.

INTRODUCTION
An open pit mine is planned from exploration data. Samples collected during exploration drilling are assayed to evaluate the mineral grade and its distribution. The mineral grade is generally a vector of multiple components, comprising the mineral or minerals of value, plus relevant contaminants. For example, with an iron ore mine the grade vector includes not only iron but also the major contaminants silica, alumina and phosphorus, which affect the behaviour of the ore when fed into a blast furnace.

The source data comprise assay values of samples taken from the exploratory drill holes, which are usually widely spaced across the proposed mine site. Standard geo-statistical techniques are used to create a block model, a rectangular grid of uniform spacing in each of the three dimensions. Vulcan (2008) is a commercial computer package for creating block models.
Hustrulid and Kuchta (2006) discuss the planning of an open pit mine. Essentially, the problem is to design a mining sequence that maximises the expected value of the mine, where the expected value is the net present value of the revenue for the extracted ore, minus the costs of extraction and restoration of the site. Atael and Osanloo (2003) and Cacetta and Hill (2003) discuss aspects of this problem.

Given a rectangular block model, each block can be characterised as either ore or waste. Typically ore is defined as material satisfying a cut-off vector grade (for example, above a minimum value in iron, and below minimum values in the contaminants silica, alumina and phosphorus). The mine planning problem is then to devise a mining sequence so that marketable ore is delivered through the life of the mine, to maximise the mine’s lifetime value.

At any stage during the mining process, there will be an Available Block List (ABL), which is the set of ore blocks each of which can be accessed without first removing any other ore blocks. For a feasible mine plan, each ore block mined is within the current ABL, with the ABL being revised after the removal of the block. Selection of the optimal sequence is NP hard (like the travelling salesman problem). For example, a moderate sized project might have 9,000 ore blocks, with a typical ABL of 300 blocks. So each of the 9,000 blocks mined is taken from about 300 choices. The number of feasible mine sequences is therefore of the order of $300^{9000}$, or 10 to the twenty thousand. Clearly these cannot all be enumerated, and the problem is not continuous, because each choice made can discontinuously alter the following choices that become available. Accordingly, whatever the objective function, no solution can be assuredly optimal.

The problem is further complicated by the following considerations:

1) The block model grade values are, at best, estimates, with statistical uncertainty

2) The distinction between ore blocks and waste blocks is not clear-cut. An apparently waste block may be useable as ore if it can be combined with rich ore blocks.

3) The composition that can be produced may vary over the life of the mine. This is highly likely, because the ore composition usually varies with depth, and the mine will tend to reach greater depths through its life.

4) The mine output may be blended with output of different composition, from other mines.

5) The composition required by market demand is not uniquely defined: a range of products might be marketable, at a range of prices that may vary over the life of the mine.

6) The composition supplied by competitors’ is also not defined uniquely and may also vary over the life of the mine.
The optimally marketable composition is potentially a compromise between the above six factors.

Given the market uncertainties and statistical variation, it is unreasonable to seek a hard and fast mine plan. Instead, an adaptive planning method is required, which can be revised continually as the mine and market unfold.

From experience, mine planning as practiced suffers two major deficiencies:

**Feasible Path**

There tends to be an assessment of the whole mine value, without adequate consideration of the feasible path by which it is to be achieved.

**Grade Quality**

Choice of material to be mined is commonly based on constraints. For example, a mineral grade will typically have a target value and a tolerance. Ore just within tolerance and ore spot on target are treated as equally acceptable, but ore just outside tolerance is rejected. Because of statistical error, ore just outside tolerance could actually be just within, and vice versa. Treating tolerance as a constraint is in effect applying vertical walls, with the requirement that each mineral lies within its tolerance range (see Figure 1).

The method to be described treats tolerance as a continuum, so that instead of vertical walls we have a U-shaped continuum, with the requirement that the grade lies preferably close to the bottom of the U. Thus, the tolerance constraint is replaced by a tolerance-based objective function.

This paper outlines a method to identify a feasible quasi-optimal mine plan by establishing an objective function for the grade vector, and applying a greedy algorithm to link together a series of selection steps. The method enables adaptive plans, since the model can be re-run with different target grade vectors, which may be time variant across the life of the mine.

**THE MODEL**

Let the ore have grade vector $X = \{X_k\}$, where $k = 1 \ldots K$ represent the minerals of concern. Consider a target grade vector $T$, with a tolerance of $+/t$. The objective could be defined as producing a stream of ore with composition lying in the range $T+/-t$. This constraint-based approach is often applied in practice, but suffers from three deficiencies: grade estimates are subject to error, the grade components have to be given a priority order, and the method is essentially discontinuous and therefore unstable.
Stress as an Objective Function

A preferable approach is to define an objective function “Total Stress”, to be minimised. For a grade vector $X$, we define its total stress “$S$” as a vector with dimensionless components:

$$S^2 = \frac{(X-T)}{t} \quad |S|^2 = |(X-T)/t|^2 = \sum [(X_k-T_k)/t_k]^2$$

(1)

Figure 1 shows the difference between using the target and tolerance to define a smooth objective function instead of using the tolerances discontinuously as constraints. Each mineral component’s contribution to the total stress function is squared, so departure from target adds a U-shaped contribution to Total Stress, as shown.

The Total Stress provides an objective function, to be minimised over the life of the mine. If the Total Stress is kept below 1.0, then no mineral grade will fall outside its tolerance range. If four component grades were at their tolerance limits, then the Total Stress would be 2.0.

This leaves the timing unresolved, because short-term grade optimisation may be achieved at the cost of greater future stress.

There is also the question as to what tonnage of ore the stress is to be measured over. Clearly, small tonnages will show more grade variability than large tonnages. If there were no serial correlation in variability, then the squared stress would decline in proportion to the tonnage over which it is averaged, though in practice positive serial correlation generally causes the stress to decline more slowly with tonnage. Ore is generally stockpiled, or handled in large shipments, so we need to control the stress smoothed over such parcels. A moving average could be used, but an exponentially smoothed average is better behaved. Everett (2007) discusses this issue.
Selecting Ore from the Available Block List

At each point in the mine’s life, we have an Available Block List (ABL) of all the ore blocks that could each be mined without any other ore block being removed. Figure 2 illustrates the definition of an ABL. The ABL comprises all the Live Ore blocks that can be mined without removing any other ore blocks. Dead Ore blocks are unavailable because either they are overlayed by other ore blocks, or extraction would create walls more than one block high.

Figure 3 shows how the removal of Live Ore revises the ABL.

A Real Example

The discussion will be illustrated by a real iron ore prospect, for which the mine plan had to be based upon about 9,000 ore blocks. For the present discussion, the target grade will be taken as the mine life average composition of the ore blocks, so the problem is essentially to examine whether the mine could operate at constant grade output through its lifetime. This is only the first step in mine planning, but we will see how the method to be described can be applied iteratively to develop a time variant mine plan.

Extracting Complete ABLs

The simplest mine plan would be to mine the first ABL, creating a second ABL which can be mined exposing a third ABL, and so on until the mine is exhausted.

Figure 4 shows the total stress history over the life of the mine, if this policy were followed. It is clear that such a simple policy is unacceptable. Mineral grades would be well outside their tolerance limits early and late in the mine life.
Using a Greedy Algorithm

In the example being considered, the first ABL comprises 116 ore blocks. Aggregating all 116 blocks gives a Total Stress of about 4.0. Of the 116 blocks, remove the block whose removal minimises the Total Stress of the remaining 115 blocks. This process can be repeated, successively trimming the remaining portion of the ABL so as to minimise its Total Stress at
each step. Figure 5 shows the resulting decline in Total Stress as the ABL is trimmed. Moving down the curve towards the left, we see that the Total Stress can be reduced to about 0.3 before it passes its first minimum and begins to behave erratically.

This process defines a greedy algorithm, comprising the following steps:

1) Trim the ABL successively until its Total Stress reaches a minimum.
2) Mine the trimmed ABL
3) Identify the new ABL.

Repeating the three steps until the mine is exhausted gives a Total Stress history as shown in Figure 6. The results using this greedy algorithm are worse than for the naive method of Figure 4. It illustrates the common situation that brutally optimising the short-term outcome can jeopardise the long-term performance.

![Total Stress, Using Greedy Algorithm](image)

**Figure 6: Trimming ABLs with the Greedy Algorithm**

**Modifying the Greedy Algorithm**

Referring back to Figure 5, it is clear that there was no need to trim the first ABL back to its minimum Total Stress. A perfectly acceptable Total Stress of 1.0 is achieved if the trimming stops at 75 blocks. If this modified algorithm is applied, trimming each ABL back until its Total Stress is reduced to 1.0, the greatly improved performance of Figure 7 is achieved.

Figure 5 shows that, by relaxing the trimming a little more, 77 blocks can be retained to give the first ABL a Total Stress of 1.1. Applying this criterion to all the ABLs gives the quite satisfactory performance shown in Figure 8. The Total Stress can be kept within the limit of 1.1 until the mine is very nearly exhausted, by which time the stripping ratio (waste needing to be removed divided by ore recoverable) would probably be unacceptably high anyway.
Figure 7: Modified Greedy Algorithm, Trimming Total Stress < 1.0

Figure 8: Modified Greedy Algorithm, Trimming Total Stress < 1.1

Individual Minerals

Figure 8 showed the Total Stress performance achieved.

The component stresses for each of the important minerals {Fe, P, SiO2, Al2O3} are in Figure 9. These graphs show that none of the minerals fall outside the tolerance range during the life of the mine (until close to its end). However, while the iron grade can be maintained constant, there could be some advantage in planning a gradual increase in the phosphorus grade through the life of the mine. The silica target might also be usefully decreased during the life of the mine. These considerations may be especially relevant if the mine output is to be blended with the output from other mines.
Figure 9: Component Stresses, Trimming Total Stress < 1.1
CONCLUSION

The method described here allows for quick re-runs changing any parameters, targets and tolerances as desired. It thus provides a useful discussion tool for the development team. In any mine planning and development process there are many constraints and objective function components that cannot be readily programmed. Accordingly, a tool like this provides a convenient means of combining human judgement skills with the computer’s speed and accuracy.

One feasible extension of the method is to compute the discounted Net Present Value of the exponentially smoothed Total Stress. The model can then be run iteratively, changing the values of the ore/waste cut-offs and the grade targets so as to minimise the Net Present Value of the exponentially smoothed Total Stress. This would provide a point of interaction with marketing personnel, potentially enabling the Net Present Value to be computed in dollars rather than stress.

REFERENCES


