The Use of Risk Analysis in the Selection of a Mining Method
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ABSTRACT
It is very rare in the underground hard rock environment to find a deposit that is ideally suited to a specific mining method. Usually the irregular shape of the orebody will allow the deposit to be extracted by more than one mining method.

During the prefeasibility stage, a number of conceptual mine designs are generally evaluated to see which offers the best method of extraction for the deposit. The selected method is usually based on key decision criteria such as the overall extraction of the orebody, the amount of metal produced annually and the unit cost of production. Often the prefeasibility study document will state that the project has an NPV of 'x' million dollars. This statement can be made without any quantitative consideration of the likely risks of the mining methods reviewed or the level of confidence in the estimation of the NPV.

By assigning a probability of failure to each component of the mining cycle a measure of the risk for each method can be determined. One mining method may provide the highest NPV when it is performing well, however, there may be a higher risk of a major failure impacting on the performance of that method, eg the failure of a mass blast of a crown or rib pillar.

This paper will present a flowsheet approach to the use of risk analysis for determining the likely production rates of different mining methods. This framework allows the annual metal output to be estimated and from this the NPV for each method. A level of confidence can be applied to the estimated NPV for each option. An example will be presented on how this technique has been used within the Normandy Group.

MINING METHOD COMPARISON
Risk analysis can be used to determine an estimate of the likely production rate that is achievable from a particular mining method based on a number of design criteria for that method and the orebody shape.

As each mining method has different design characteristics or bottlenecks in the mining cycle, risk analysis can be used to model the effect of each element in this cycle. In order to determine the likely output from the underground operation, a flowsheet for each method was developed. The aim of the flowsheet was to layout and illustrate the main design and production factors that could influence the overall output from the underground operation. The flowsheet for the SLC case, shown in Figure 1, depicts the variables that impinge on the tonnage extracted, as well as the grade related variables.

At this stage a brief explanation of how the data in the flowsheets are calculated is prudent:

- data that is depicted in shaded cells are constants that can be changed manually between simulations;
- data in the double outlined cells are variables that have a probability distribution function assigned to them; and
- all the other data depicted in the flowsheets are calculated based on the input constants and variables.

An attempt has been made to determine the production rate and gold output based on first principles using a number of generalised design factors for each method. The production rate using these factors is then compared with an estimated vertical mining rate (VMR).

The use of risk analysis makes it easier to compare two markedly different mining methods. The SLC method is a high production rate method with a relatively high dilution rate whereas the C&S method has a lower production rate but also has a lower amount of dilution. A discussion of the variables for each mining method now follows.

Sublevel caving method
Based on the experience of a selected international consultant with expertise in mining method selection, there should be a lag:lead ratio of 3:1 between levels, ie the horizontal offset distance before production from the level below can commence is three times the face height (level interval). Therefore, with a proposed level interval of 25 m, one level needs to advance 75 m before production from the level immediately below it can commence. In the flowsheet the lag:lead ratio is set as a constant, as is the face height.

From conceptual development layouts for each level, the average number of drawpoints per front can be estimated. A front is defined as a mining panel advancing along strike. If mining commences from the centre of the orebody and is excavated outwards to the north and south then two mining fronts would be available per level. The drawpoints per front is set as a constant in this model.

Drawpoint production is based on a probability distribution. This distribution is based on the combined experience of operators from several similar mines. A triangular distribution was selected for drawpoint extraction with a minimum value of 800 t/d, a most likely value of 1000 t/d and a maximum of 1200 t/d. Table 1 depicts the parameters for this and all other sampled variables in the SLC model. An availability factor for

INTRODUCTION
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By assigning a probability of failure to each component of the mining cycle a measure of the risk for each method can be determined. One mining method may provide the highest NPV when it is performing well, however, there may be a higher risk of a major failure impacting on the performance of that method, eg the failure of a mass blast of a crown or rib pillar.

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the drawpoint is also applied which takes into account down-time due to factors such as hang-ups, poor fragmentation, ring charging problems, ground support rehabilitation and road maintenance.

**Table 1**

Sublevel cave probability distribution parameters.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Units</th>
<th>Distribution type</th>
<th>Minimum value</th>
<th>Most likely value</th>
<th>Maximum value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drawpoint extraction</td>
<td>(t/d)</td>
<td>triangular</td>
<td>800</td>
<td>1000</td>
<td>1200</td>
</tr>
<tr>
<td>Drawpoint availability</td>
<td>(%)</td>
<td>triangular</td>
<td>40</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>Block grade</td>
<td>(g/t)</td>
<td>triangular</td>
<td>2.5</td>
<td>3.4</td>
<td>4.0</td>
</tr>
<tr>
<td>Dilution entry (1)</td>
<td>(%)</td>
<td>discrete</td>
<td>40 @ 20</td>
<td>60 @ 60</td>
<td>80 @ 20</td>
</tr>
</tbody>
</table>

Notes: (1): 40 @ 20 refers to a dilution entry at 40% extraction with a discrete occurrence 20% of the time.

When the above factors are combined a daily and annual ore production rate can be determined. Based on the average ore tonnes per vertical metre (t/mv), the VMR can be calculated. The value of the calculated VMR can then be compared with VMRs from other operations to see if it is within the expected range for mining operations of this type. The VMR can also be set as a constraint.

The main grade related variables are the choke block grade and the dilution entry point, i.e. the point at which dilution material first reports to the drawpoint. In this model, a discrete distribution has been used for dilution entry based on dilution entry at 40 per cent, 60 per cent and 80 per cent. In reality, a continuous distribution should be used, however, dilution diagrams have only been included for the above entry points. See Figure 2 for an example of the 60 per cent dilution entry diagram. The discrete distribution assumes that there is a 60 per cent chance of obtaining a 60 per cent dilution entry point with a 20 per cent chance each of getting 40 per cent or 80 per cent dilution entry. Probability distributions were also assigned to the grades of the dilution material.

![Figure 2 - 60 per cent dilution entry diagram for SLC method.](image-url)
The dilution entry diagrams have been converted into spreadsheet form so that a grade factor can be determined based on a given shut-off grade. The shut-off grade is the grade at the drawpoint at which extraction ceases. This should equate to the economic break even point for delivering ore from that drawpoint to the mill. The dilution diagrams can be used in two ways:

1. Select an expected extraction percentage, e.g., 110 per cent, and then use 'look-up tables' in the spreadsheet to determine what the average grade, shut-off grade and the grade factor for that extraction rate are; or

2. Select a drawpoint shut-off grade and back calculate to determine what the extraction factor should be.

Having the dilution entry diagrams in a spreadsheet format enables the calculations mentioned above to be made a lot easier. In order to determine the average grade for a total extraction of 110 per cent, the incremental draw columns in the dilution entry diagram, depicted in Figure 2, need to be aggregated up to the 110 per cent column. For example: Let block grade (a) = 3.3 g/t;

Dilution (b) = 1.5 g/t, (c) = 1.0 g/t, (d) = 0.5 g/t; then the average grade would be:

\[ \text{60\%} \times a + 10\% \times 0.7a + 0.3 b + 10\% \times 0.5a + 0.5 b + 10\% \times 0.4a + 0.3 b + 0.3 c + 10\% \times 0.2 a + 0.18 b + 0.32 c + 0.3 d = 110\% \times 2.75 \text{ g/t} \]

The shut-off grade at 110 per cent extraction is the grade of the draw column for the last increment calculated above, i.e:

\[ 20\% \times 3.3 \text{ g/t} + 18\% \times 1.5 \text{ g/t} + 32\% \times 1.0 \text{ g/t} + 30\% \times 0.5 \text{ g/t} = 1.4 \text{ g/t} \]

and the grade factor is simply the average grade divided by the block grade:

\[ 2.75 \text{ g/t} / 3.3 \text{ g/t} \times 100 = 83\% \]

A word of warning is required regarding the dilution entry curves: the curves are based on estimates only of what the dilution entry profile might look like for Big Bell. The true shape of the appropriate curve, along with the grade of the dilution will be based on the compilation of data from Big Bell over time.

Mill Recovery is determined based on the mill throughput rate and the bond work index analysis, performed by the Big Bell operations personnel.

The product of the grade and tonnage calculations is an estimate of the gold that would be produced using that mining method. The results displayed in Figure 1 are based on the expected value, not the mean, for each of the probability distributions.

Core and shell method

A similar flowsheet was developed for the core and shell mining method. See Figure 3. The methodology on the tonnage part of the flowsheet is the same as for the SLC method, however, the calculation of the grade factor is more complicated.

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**Figure 3 - Core and shell flowsheet.**
With the C&S method there are three main components in the extraction process and the dilution of those components also vary:
- extraction of the core, with the highest recovery factor and dilution grade of the three components;
- extraction of the rib pillar with a lower expected recovery factor and dilution grade; and
- extraction of the crown pillar with the lowest recovery factor and dilution grade.

With this mining method a design criterion has been used that sets the rib pillar strike length to a 1:1 ratio with the width of the orebody. The thickness of the crown pillar has been set at the distance between levels, is 25 m. As a result, the ratio of core:rib:crown will vary according to the thickness of the orebody. The strike length of the core is fixed, as is the height of the crown pillar.

Triangular probability distributions have been assigned to the recovery factors, dilution percentages and dilution grade for each of the three zones, except for the recovery of the core which was set at a constant (95 per cent recovery). A triangular distribution was also used for the width of the orebody. The parameters for these distributions are presented in Table 2.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Units</th>
<th>Distribution type</th>
<th>Minimum value</th>
<th>Most likely value</th>
<th>Maximum value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drawpoint extraction</td>
<td>(ld)</td>
<td>Triangular</td>
<td>1500</td>
<td>2000</td>
<td>2500</td>
</tr>
<tr>
<td>Block grade</td>
<td>(g/t)</td>
<td>Triangular</td>
<td>2.5</td>
<td>3.4</td>
<td>4.0</td>
</tr>
<tr>
<td>Core dilution thickness</td>
<td>(m)</td>
<td>Triangular</td>
<td>1.5</td>
<td>2.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Core dilution grade</td>
<td>(g/t)</td>
<td>Triangular</td>
<td>1.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Rib recovery</td>
<td>(%)</td>
<td>Triangular</td>
<td>70</td>
<td>95</td>
<td>100</td>
</tr>
<tr>
<td>Rib dilution amount</td>
<td>(%)</td>
<td>Triangular</td>
<td>20</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td>Rib dilution grade</td>
<td>(g/t)</td>
<td>Triangular</td>
<td>0.7</td>
<td>1.2</td>
<td>1.7</td>
</tr>
<tr>
<td>Crown recovery</td>
<td>(%)</td>
<td>Triangular</td>
<td>60</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Crown dilution amount</td>
<td>(%)</td>
<td>Triangular</td>
<td>20</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td>Crown orebody grade</td>
<td>(g/t)</td>
<td>Triangular</td>
<td>0</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Orebody width</td>
<td>(m)</td>
<td>Triangular</td>
<td>12</td>
<td>30</td>
<td>38</td>
</tr>
</tbody>
</table>

**DISCUSSION OF THE SIMULATION RESULTS**

A sampling technique similar to Monte Carlo, the Latin Hypercube technique, was used to simulate the outcome based on the input distributions. @RISK software was used to perform the simulations and analysis.* One thousand iterations per simulation were used for each mining method.

* @RISK is a risk analysis and simulation add-in for Excel or Lotus 1-2-3 spreadsheets produced by Palisade Corporation.

After running the simulations, probability distributions and cumulative probability distributions for the estimated gold production can be plotted. An example of a cumulative probability curve for gold production using the SLC method is depicted in Figure 4. This curve can be used for deriving statements such as: ‘There is an 80 per cent chance of achieving greater than 110 000 ounces per annum’ or ‘There is approximately a ten per cent chance of achieving a target of 150 000 ounces per annum’.

As well as compiling data for the annual gold production, statistics on the gold head grade, extraction factor, VMR and ore tonnes mined were gathered.

Key findings from the results were:
- the SLC method was limited by the vertical mining rate and not the other design layout factors;
- the C&S method was limited by the design layout factors and not the vertical mining rate;
- the head grade for the C&S method was higher than for the SLC method; and
- the extraction factor for the SLC method was higher than for the C&S method.

These points will now be discussed in greater detail.

**Vertical mining rate/design layout**

With the SLC method two levels can be in production at any one time with two mining fronts per level. This layout yields, on average, seven drawpoints available for production. The effective level interval for this method is 25 m.

The C&S method is more complicated as the extraction sequence consists of extracting a number of primary stopes (cores), followed by the extraction of the rib pillars and the crown pillar. This relates to an effective level interval of 75 m. With the limited strike of the orebody this method can only produce from one level at a time with only two fronts available, yielding a total of two drawpoints available for production at any one time.

The reason for the C&S method being limited by the design factors is that there are less drawpoints available at any one time for this method compared to the SLC method.

**Difference in head grade for each method**

The C&S method extracts approximately 38 per cent of the ore in the core, i.e. at block grade with minimal dilution. The rib and
crown pillars have lower recoveries and higher dilution than the core, however, the product of these factors is an overall grade recovery factor of 86 per cent.

With SLC the total production is from a choke draw extraction scenario where the overall dilution is higher than for the C&S method. The overall grade recovery factor for the SLC method is 83 per cent.

Extraction factor
The extraction factor for the SLC method is dependant on the block grade and the shut-off grade supplied to the model. By specifying a specific shut-off grade the dilution entry diagram can be used to determine what the extraction factor needs to be to satisfy the predetermined shut-off grade.

With the C&S method the extraction factor is a weighted average of the three separate extraction factors for the core, rib and crown. These factors are displayed in the flowsheets for each case. The main reason for the overall extraction factor being slightly lower for the C&S method compared to SLC is due to the low recovery of the crown pillar, approximately 73 per cent.

SENSITIVITY ANALYSIS
For each case a sensitivity analysis is conducted for each selected output. Using the @RISK software it is possible to conduct a sensitivity analysis which will determine the sensitivity of each selected output variable to its input variables. Figure 5 depicts the sensitivity of the input variables on the gold production in the C&S case. In Figure 5, a regression value of zero indicates that there is no significant relationship between the input and the output, while a regression value (beta coefficient) of ±1 indicates a ±1 standard deviation change in the output for a 1 standard deviation change in the input. In this case the gold output is mostly sensitive to the block grade and the drawpoint production rate, followed by the amount and grade of dilution during the extraction of the crown.

The sensitivity plot in Figure 5 is influenced by the different standard deviations that the probability distributions for the inputs have; each input is sampled each iteration. A conventional sensitivity analysis plots the change in the selected output based on changing only one input variable at a time. Like conventional sensitivity analysis this technique identifies the input variables that need to be monitored more closely or have more work done on them.

COMPARISON OF MINING METHODS
In order to compare the comparative risk of the two mining methods it is necessary to compare the standard deviation of the output distributions as these give an indication of the amount of risk, or deviation from the most likely output. Figure 6 presents the probability distributions of the likely gold production for both methods using the same number of classes with the same range for each class.

The distribution for the likely gold production for each method approximates that of a normal distribution. Using the mean (μ) and the standard deviation (σ) from the simulation data the normal distributions can be plotted. (See Figure 7) By plotting the normal distributions it is easier to see the effect σ has on the overall spread of likely results.

As well as collecting data on the gold production, data was also collected for the annual production rate, equivalent vertical
mining rate based on a fixed t/m, and the extraction factor. Table 3 summarises the mean and standard deviation data for these outputs. The standard deviation as a percentage of the mean is greater for all the selected outputs for the SLC method compared to the C&S method. This implies that there is greater risk, i.e. more chance of not achieving the expected outcome. However, when referring back to Figure 7 one can see that although the standard deviation is larger there is still a greater probability of achieving a higher production output with the SLC method.

**Table 3**

*Summary statistics for the selected output variables.*

<table>
<thead>
<tr>
<th></th>
<th>Production (Mt/a)</th>
<th>VMR (m/a)</th>
<th>Extraction (%)</th>
<th>Au Produced (oz/a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sublevel cave method</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>µ</td>
<td>1.81</td>
<td>65.8</td>
<td>110</td>
<td>130 080</td>
</tr>
<tr>
<td>σ</td>
<td>0.21</td>
<td>8.5</td>
<td>5.7</td>
<td>18 345</td>
</tr>
<tr>
<td>σ as % of µ</td>
<td>11.5</td>
<td>12.9</td>
<td>5.2</td>
<td>14.1</td>
</tr>
<tr>
<td>Core and shell method</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>µ</td>
<td>1.46</td>
<td>54.6</td>
<td>107</td>
<td>116 675</td>
</tr>
<tr>
<td>σ</td>
<td>0.15</td>
<td>5.8</td>
<td>3.1</td>
<td>15 790</td>
</tr>
<tr>
<td>σ as % of µ</td>
<td>10.2</td>
<td>10.5</td>
<td>2.9</td>
<td>13.5</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

The aim of this paper was to discuss the use of risk analysis to determine the likely production outputs for two different mining methods after applying appropriate risk profiles (probability distributions) to the relevant variables.

The risk analysis discussed in this paper was for a scoping or pre-feasibility study level of accuracy. Risk analysis has also been used to model the likelihood of production blasting problems with both methods and their impact on the net present value of the two cases. In this paper the impact of blasting problems is incorporated simplistically in the draw point availability factor depicted in the flowsheets.

Based on the preliminary analysis, discussed above, and a more detailed analysis of the possible blasting problems not presented in this paper, sublevel caving was the preferred method out of the two methods compared in this exercise.

No discussion on the NPV evaluation has been presented in this paper. After conducting the preliminary analysis and identifying the variables that are the most sensitive to the output variables being modelled additional flowsheets can be designed to model them in greater detail. The flowsheet approach has made it easier to visualise how the various components interact in the evaluation.

The risk analysis has allowed the likely production output to be determined along with the likely probability of achieving that figure.

One caveat to this process is that like any computer model, the output is only as good as the quality of the input data. As a result, the models should be reviewed whenever better estimates of input variables or actual figures are available. Bear in mind that the sensitivity analysis will highlight which of the variables should be studied in more detail.

At the scoping or prefeasibility level of accuracy, one should not make the model too detailed with a plethora of input distributions. An experienced engineer should be able to determine the main variables to be modelled. As the required level of accuracy increases as a project moves into the feasibility and detailed engineering stages, the number of variables to be sampled can be increased.

**ACKNOWLEDGEMENTS**

The author would like to thank Normandy Mining Limited for allowing the paper to be published.