# Aspects of Geological Uncertainty on the Optimal Open Pit

# Peter Rolley & Nic Johnson

Peter Rolley
Qualifications: B.Sc(Hons). Mining. University of Melbourne.
Memberships: AusIMM. Australian Institute of Geoscientists.
Experience: Exploration geologist Freeport of Aust. Chief geologist Mawson Pacific, Elders Resources, Reynolds Yilgarn.
Currently: Geologist with resource assessment group FSSI Aust., Perth, Australia; working in grade control optimisation and sampling issues.

Nic Johnson
Qualifications: B.Sc.(Hons). Geology. LaTrobe University.
Memberships: AusIMM.
Experience: Mine and mine development geologist for open cut and underground gold mines.
Currently: Geologist with resource assessment group FSSI Aust., Perth, Australia.

## Abstract

It is well recognised by mining professionals that the largest uncertainty in determining the optimal open pit is in the knowledge of the mineral resource inventory at any scale. The mining industry has a long history of deposits which have not produced the expected profits as a result of over or underestimation of the tonnage and/or metal grade in a certain locality.

During the open pit optimisation of the resource many companies assess the sensitivity of the optimal pit shell to changes in the resource model by using the dilution and ore loss options within the Whittle software. This may not be the most appropriate way to assess the impact of geological uncertainty because geological risk is related to cut-off grade, scale of mining, sampling density and quality, and grade continuity.

There are a number of resource modelling methods which are able to produce a range of possible resource models for a deposit. The Whittle software can be used to optimise these models to produce a range of possible profits. This paper will not review resource modelling methods but will review the impact of models generated by different methods on pit profitability.

## Introduction

In the gold mining industry it is usual for a mining company to select a single resource model of the metal grade distribution and to use this model for mine planning and optimisation studies. The resource model is usually selected based on the mining company's past experience with various resource estimation methods, the available in-house or consultant expertise, software ownership, and the rapport between the team building the resource estimate and the resource owner. Once a resource model has been built the mining engineering personnel may apply various dilution parameters before generating an optimal pit shell and reporting reserves.

There are a large number of case studies presented in the literature comparing the impact of changes to various mining and milling costs, discount rates, milling recovery, geotechnical parameters, mining ore dilution and loss, and cut-off grade on pit profitability based on a single resource model (various papers in Whittle, 1995). These studies usually indicate that the largest economic risk is related to uncertainty in estimated grade, the gold price and the milling recovery. Small changes in any of these three parameters can result in large changes in the expected profit (Stewart, D. H., 1993).

A review of a number of mining projects around Australia (Warren, M. 1991) clearly indicated that of the three critical parameters for optimisation, the gold grade of the deposit was the least well estimated. The study found that for most gold mines the estimated grade of the deposit was much higher than the grade realised at the mill resulting in reduced profits.

Many gold operations assess the vulnerability of the optimal pit shell to a decrease in actual gold grade by diluting all estimated blocks by some factor within the Whittle software, by reducing the higher gold grades to some lower grade threshold and re-building the resource model, or by reducing all estimated grades within the resource model by a factor (e.g. 10%).

The authors of this paper contend that the uncertainty in the reserve tonnage and grade is related to the geology, the cut-off grade, the spatial continuity of the gold grades, the sample density, the modelling method and the size of the smallest mining unit. We prefer to construct resource models which allow uncertainty in the grade to be directly incorporated in the model rather than introduced as part of the pit optimisation process.

The geostatistical literature presents a number of different grade modelling methods that have been developed for various styles of mineralisation and mining strategies (Schofield, N. A., 1992). Different grade modelling methods applied to the same deposit and using the same sample data will produce different grade-tonnage models of the mineralisation. One of these models may "best" represent the mineralisation as well as it is known.

A number of resource estimation methods also allow the impact of the mining selection strategy on the grade tonnage curve to be reviewed. These methods are loosely grouped together as Recoverable Resource Estimation methods and were developed to minimise the variance of the estimation error (Schofield, N. A., 1995) whilst identifying the distribution of mineable block grades within a mining area (Journel, A. G., 1985).

The smallest mining unit able to be identified and economically mined (the SMU) will be determined by the geology, the cut-off grade and the mining equipment. If the economic portion of the mineralisation (ore) is visually distinct from the non-economic rock (waste) and the grade of the mineralisation is strongly continuous, then the variability of the gold grades within and between SMUs may be small and mining dilution can be minimised. Often though, the ore outline is identified by interpolating a boundary based solely on sample gold grades that are locally spatially discontinuous. The boundaries of the actual ore outlines can be quite uncertain where the data is broadly spaced, as in exploration or development programmes, and ore loss and mining dilution can be significant. The grade tonnage curves will be significantly different for highly visible ore compared to less well structured ore.

## A case study

There are few case studies in the Australian mining literature which compare the result of optimising a number of resource models for the same deposit for the same mining and economic parameters. The gold deposit in this case study is located in the Archaean Yilgarn Block of WA and shows a number of features which are observed in a large number of gold deposits including:

- near surface enrichment
- shallow depletion zone
- supergene enrichment zone
- a primary bedrock zone of mineralisation
- a variable weathering profile
- a variable bulk density profile
- variable geological controls on mineralisation
- gold grades located in a number of different rock types
- a highly skewed histogram of gold grades
- the higher gold grades have different spatial continuity compared to lower gold grades
- strong directional control of mineralisation.

## Resource models

The exploration drilling information is predominantly RC sampling from a drill hole pattern of 20m by 20m with samples collected at 1m down hole intervals. A small area of the central part of the deposit has been drilled out on a 10m by 10m grid. All samples were composited to 2m down hole before estimation work proceeded.

In this case study four resource models of the deposit were constructed. Table 1 shows the resource estimates (with tonnes and grades factored for confidentiality) and Figure 1 shows the grade tonnage curves for the models. All models cover the same area and are based on the same exploration data. Each resource model has been checked for global unbiasedness and plotted on the informing exploration data. The models are briefly described as follows.

1. An ordinary block kriging model. The block size is 3m across strike, by 5m along strike by 2.5m vertical (bench height). The composited grades were cut to a maximum value of 30g/t Au before block kriging commenced. Only the blocks above a cut-off grade of 0.50g/t Au are presented to Whittle.
2. A multiple indicator kriging (IK) model. The panel size is 10m by 20m by 5m to reflect the sample density. As demonstrated by Schofield (1995) a panel size which is consistent with the

sample density is more likely to minimise the variance of the estimation errors. This model only reports the average grade of each of the panels and so reflects a minimum mining unit of 10m by 20m by 5m. Only the panels above a cut-off grade of 0.50g/t Au are presented to Whittle.

3. A multiple indicator kriging model with mining selection based on gold grades only. The SMU size is 3m by 5m by 2.5m and does not consider the impact of geological control on ore selection. The block variance correction (based on the Indirect log-normal method as described in Isaaks and Srivastava (1989, pp472-486) is large because the gold grade semi-variograms have short ranges and a high nugget. Only the proportion above a cut-off grade of 0.50g/t Au is presented to Whittle.

4. A multiple indicator kriging model with mining selection based on gold grades and geological control. The SMU size is 3m by 5m by 2.5m. The block variance correction is not as large as in model 3 because the geology is reasonably continuous. This model is presented to the Whittle 4D software in two forms.

   a) Only the proportion above a cut-off grade of 0.50g/t Au is presented to Whittle. The cut-off grade selected is the marginal cut-off grade. Each panel with ore has one ore parcel of x tonnes and y metal.

   b) The mineralisation within each panel is discretised into 15 cut-off grades and these are presented as ore types within a panel (Schofield, N. A., 1995).

| **Cut-off grade** | | **Model 1** | **Model 2** | **Model 3** | **Model 4** |
|---|---|---|---|---|---|
| 0.25 g/t | Tonnes x 1000 | 1745 | 1880 | 1610 | 1405 |
| | g/t Au | 0.9 | 0.9 | 1.0 | 1.1 |
| 0.50 g/t | Tonnes x 1000 | 1025 | 1080 | 870 | 740 |
| | g/t Au | 1.2 | 1.2 | 1.5 | 1.7 |
| 0.75 g/t | Tonnes x 1000 | 675 | 770 | 575 | 475 |
| | g/t Au | 1.6 | 1.5 | 1.9 | 2.3 |
| 1.00 g/t | Tonnes x 1000 | 470 | 545 | 410 | 340 |
| | g/t Au | 1.9 | 1.7 | 2.2 | 2.7 |

**Table 1** Resource models.

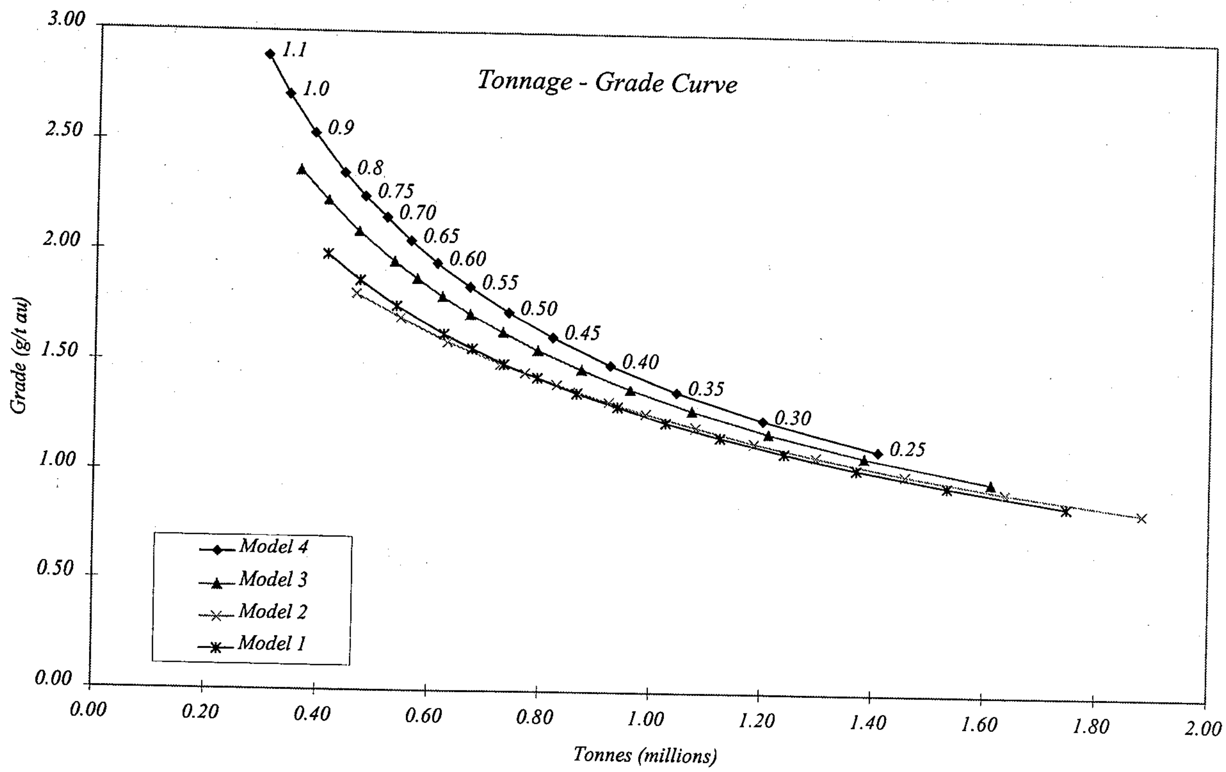

**Figure 1** Grade tonnage curves for the four resource models.

### Pit optimisation

Each of the resource models was prepared for Whittle 4D format and the same parameter files used to optimise each the resource models. The optimisation parameters are actual mining and milling estimates provided by the mine management. Only the maximum profit pit shell for a nominated gold price for each of the resource models is retained for comparison.

Model 1, the ordinary krige model, was re-blocked in Whittle 4D to 9m by 20m by 5m to be consistent with the IK models. Table 2 presents the results of the optimisation. The DCF and the IRR are the discounted cash flow and internal rate of return respectively, as presented in the Whittle 4D results file from FDAN.

| | **Model 1** | **Model 2** | **Model 3** | **Model 4a** | **Model 4b** |
|---|---|---|---|---|---|
| Tonnes (x 1000) | 705 | 815 | 770 | 665 | 655 |
| Grade g/t Au | 1.4 | 1.4 | 1.5 | 1.8 | 1.8 |
| DCF | $1.7M | $3.2M | $5.2M | $6.8M | $7.2M |
| IRR | 15% | 23% | 34% | 40% | 44% |
| Strip Ratio | 7.1 | 6.8 | 7.4 | 9.1 | 9.5 |

**Table 2** Resources within an optimised pit shell.

## Results

The various resource models have resulted in a range of optimal pits. Although all the pits proceed to the same base depth, which in this case study is near to the limit of regular drilling, there are large differences between the profitability and volume of the maximum profit pit shells. The differences in the pit shells can be related to the different mining selectivity (geologic uncertainty) and to the different modelling methods (estimation uncertainty).

The ordinary krige resource model (Model 1) is based on small sized blocks relative to the drill hole density. This has produced a resource model with a large number of blocks of similar grade, a direct result of grade smoothing and a large estimation error. Although the small block resource model looks visually appealing it does not reflect the variability of the grade of the mineralisation and results in a poor estimate of the in-situ resources. The resultant optimum pit shell is the smallest pit with the lowest profit and could result in the resource owner losing several million dollars through the pit being too small (Hanson, N., 1995).

The average grade IK resource model (Model 2) is built with panels which are 10m by 20m by 5m. Theory suggests that this panel size is appropriate for the drill hole pattern, however there are likely to be a large number of panels which are not wholly mineralised and within which ore can be selected from waste, thus improving the expected profitability of the operation. This model is not useful for optimisation.

The IK model (Model 3) which does not incorporate geologic constraints is also built with panels which are 10m by 20m by 5m. The IK modelling method not only produces the average grade of a panel but also provides a histogram of the possible SMU block grades within each of the panels. The model can therefore provide an estimate of the proportion of the panel which is above a certain cut-off grade for a specified SMU size. In this model the SMU blocks are 3m by 5m by 2.5m and ore selection is based on the assumption that there are no visual geological features to assist in selecting ore from waste, that is high geologic uncertainty. Large uncertainty in the location of the ore will cause in dilution of the ore and loss of ore, and therefore lower profits. This is certainly the case when comparing the optimal pit for Model 3 against the optimal pit for Model 4a.

The geologic IK model (Model 4) is based on the same sized panels and SMUs as Model 3.

In Model 4 it is assumed that the ore can be visually identified and therefore there is less dilution and ore loss, and mining can be more selective (the block variance correction is less than for Model 3). The profit increase for this model clearly shows the benefit of having geological features to aid ore selection. However if the exploration model of the geology is not supported by information gained during mining or by further drilling then this resource model may not be useful.

The only difference between Models 4a and 4b is the manner in which they are imported into Whittle 4D software as described above. Model 4b allows Whittle to be more selective of SMUs within the panels than model 4a.

The resource models 3 and 4 provide a measure of the uncertainty in the resource model due to incomplete geological knowledge. Both resource models produce similar sized maximum profit pits but have significantly different grade estimates and expected profits. In this case study it could be a serious error to rely on the OK resource model for pit optimisation.

## Conclusions

The use of Whittle 4D has clearly shown the impact of various resource models on pit profitability. Appropriate resource models need to consider the sample density, the geology and the mining strategy. There is no benefit to be gained by building resource models with small mining units where the exploration data is broadly spaced. This causes a high degree of smoothing and large estimation errors in individual block grades. Recoverable resource models can be built which honour the characteristics of the geology and the mineralisation as well as they are known, and incorporate mining selectivity.

The greatest cause of mining dilution is uncertainty in the location of the ore, which is different to the dilution due to the mechanics of blasting and mining. Generally higher grades are less continuous than lower grades and this results in greater uncertainty in the location and extent of the higher grade material compared to the lower grade material. High uncertainty in precisely knowing the location of the higher grade areas results in high grade material being incorporated with low grade material, particularly in the absence of visual ore controls.

This grade dilution, which will vary for different grade ranges, needs to be incorporated into the resource model and should not be accounted for by imposing a constant dilution factor to the estimated grade of all resource blocks. Recoverable resource estimation methods can be used to incorporate the uncertainty in the knowledge of the location of the higher grade material. The dilution facility in Whittle 4D should then be used to impose dilution due to the actual mining process.

In the case study the maximum profit pit shells have been identified for different mining strategies, geological control, and estimation methods. The study clearly shows the benefit of reducing the estimation variance through using recoverable resource estimation methods, and maximising profit through a geological understanding of the mineralisation. At a mine development stage, knowledge of the geology and the location of the higher grades improves with higher density drilling.

## References

Hanson, N.1995. *The big picture: A safer future using Lerchs-Grossmann pit optimization linked to cash flow analysis.* In "Optimizing with Whittle - Perth 1995." Proceedings of the 1995 Whittle conference.

Isaaks E.H. and Srivastava R.M. 1989. *An Introduction to Applied Geostatistics.* Oxford University Press, New York.

Journel, A.G. 1985. *Recoverable reserves estimation - the geostatistical approach.* Mining Engineering June 1985 pp563-568.

Schofield, N.A. 1995. *Recoverable resource models and optimisation.* In "Optimizing with Whittle - Perth 1995." Proceedings of the 1995 Whittle conference.

Schofield, N.A. 1992. *Mineral resource mapping methods and algorithms: a discussion of their strengths and weaknesses.* The AusIMM Annual Conference, Broken Hill, pp33-37.

Stewart, D.H. 1993. *Optimising new mining projects- where the risk lies and how to reduce it.* In "Applications of Computers in the Mineral Industry, University of Wollongong, NSW, October 1993. Editor E. Baafi.

Warren, M. 1991. *Prefeasibility and feasibility studies: A case for improvements.* MINOPT Conference, 1991.

Whittle, 1995. *Various papers in "Optimizing with Whittle - Perth 1995."* Proceedings of the 1995 Whittle conference.