Financial impact of resource/reserve uncertainty

by C. Morley, V. Snowden, and D. Day*

Synopsis

In constructing a financial model of a project significant effort is expended on capital and operating cost estimation, commodity price forecasts, and choice of discount rates while uncertainty in the primary input, the reserve, is often completely overlooked. The aim of this paper is to highlight the impact of uncertainty in the resource/reserve estimation process on the assessment of the financial performance of a project.

Four qualitative processes have an impact on resource/reserve uncertainty. These stages are:

1. Ore definition
2. Geological interpretation
3. Resource estimation
4. Ore reserve estimation and mine planning.

Each stage contains a number of tasks that may be considered as key performance activities (KPAs). Optimizing the manner in which these KPAs are completed can remove a great deal of uncertainty and error from the resource/reserve process. Examination of these KPAs within a company can also provide an insight to the quality of the information underlying the project. This will allow the company to identify any shortcomings in the data and to assess the resulting risks (Gilfillan, 1998).

A hypothetical financial model based on a gold operation has been used to estimate the potential effect of resource/reserve uncertainty on revenue. Monte Carlo simulation has been employed to simulate a number of hypothetical scenarios:

1. a base case scenario which assumes no major errors or biases, but contains realistic margins for uncertainty that would exist in any project where work is being completed to the limit of best endeavours
2. a poor sampling scenario which assumes poor sampling practice and lack of understanding of sample preparation
3. a poor resource estimation scenario which assumes poor modelling and inappropriate choice of interpolation technique, and
4. a 'typical' scenario which represents a project where the majority of KPAs are not performed as best as they could be.

The results show that realistic uncertainty ranges can generate changes in the estimate of potential revenue of plus or minus 30%. Therefore, it is important to allow for errors in these processes in any financial analysis or feasibility study.

It is recommended that, when building a financial model, a review of relevant resource/reserve KPAs be carried out and appropriate ranges for uncertainty be applied to provide a range of potential outcomes. These outcomes can then be factored into the detailed cash flow analysis in order to ensure that technical uncertainty is built into financial decisions.

Introduction

Any resource or reserve estimate is guaranteed to be wrong. Some, however, are less wrong than others (Rozman 1998). As a reserve (and sometimes a resource) is the primary input into any financial analysis or feasibility study it can be assumed that this analysis or study will also, therefore, be wrong. Significant effort is often expended on capital and operating cost estimation, commodity price forecasts, and choice of discount rates while uncertainty in the primary input, the reserve, is completely overlooked. The aim of this paper is to highlight the impact of uncertainty in the resource/reserve estimation process on the assessment of potential financial performance of a project.

Figure 1a below presents a schematic illustration of a cash flow model showing the main inputs and outcomes. Each 'layer' in the pyramid is essential to the calculation of the next. One of the shortcomings of this approach is that the foundation of the analysis, the resource and reserve, is often taken as given and assumed to be without uncertainty. Figure 1b includes the additional layer that provides

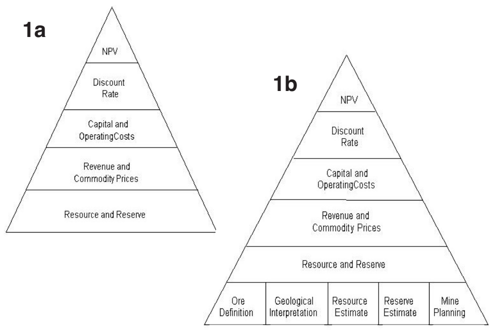

Figure 1—Stages in cash flow analysis of a project

* *Snowden Mining Industry Consultants, 87 Colin Street, West Perth WA. 6005, Australia.*

the basis for the resource/reserve estimate. These technical stages at the base of the pyramid are fundamental to the estimation of the resource and reserve and so, whether it is realised or not, form the foundation of any financial analysis of a project.

In order to highlight the impact that uncertainty in these stages has on the financial performance of a project, each stage is examined below and key activities that influence the potential outcomes are identified. These key activities are then used in a simulation model to show the potential impact that they may have in terms of revenue.

Stages in resource/reserve estimation

Introduction

Unlike financial analysis that deals primarily with quantitative inputs, the resource/reserve estimation process includes many qualitative inputs. The cost of mining, for example, can be measured in dollars per tonne, however the geological interpretation that is used to guide the entire resource/reserve estimation process can not be quantified in units. Such qualitative processes have been grouped into four stages for the purpose of discussion. These stages are:

➤ Ore definition
➤ Geological interpretation
➤ Resource estimation
➤ Ore reserve estimation and mine planning.

Due to the iterative nature of the exploration/ore definition/mining process, there is overlap between many of the activities associated with each stage. For ease of discussion arbitrary boundaries have been drawn between each stage so that the tasks may be examined within a defined framework and context.

It is important to note that the list of tasks that follow below will not be completely definitive in all situations. However, these tasks will need to be completed during the course of most projects. In the authors' opinion the quality of the results is of fundamental importance to the performance achieved at each stage. It may be useful to consider these tasks as key performance activities (KPAs). By optimizing the manner in which KPAs are completed, a company can remove a great deal of uncertainty and error from the resource/reserve process. This is of special significance to a feasibility study or investment analysis as an examination of these KPAs will provide technical support for the quality of the information underlying the project. This will allow the company to identify any shortcomings in the data and to assess the resulting risks (Gilfillan, 1998).

A summary of the KPAs is presented in Table I for each stage of the resource/reserve process, but it is beyond the scope of this paper to discuss or provide solutions to overcoming uncertainty or errors associated with each of these activities. Some references have been provided with each Table to assist the reader in researching particular issues.

Ore definition

The ore definition stage can be described as the activities associated with defining the geometry and geochemical characteristics of a resource. Different companies treat these activities in different ways because there is usually a grey area between exploration and the commencement of orebody delineation. For the purpose of this discussion it will be assumed that ore definition refers to the activities associated with testing the limits of an orebody to the level of detail required for Indicated and Measured resource categories (JORC 1999). This involves infill drilling of previous exploratory holes, perimeter drilling to establish orebody dimensions, hole logging, sampling, assaying and the compilation of all data into a robust and validated database. KPAs carried out during this stage are presented in Table 1.

Table I

Ore definition key performance activities

Key performance activity	Tasks
Mapping	Lithological, Geochemical, Structural, and Geotechnical mapping
Drilling	Drill hole design, Drilling, Drillers log
Sampling	Sampling method determination, Sample collection
Surveying	Collar, Down hole, Grid conversions
Logging	Geological, Recovery, Geotechnical logging as appropriate
Assaying	Sample preparation, Assaying
Specific gravity	Method of determination of Specific gravity, Sample collection
Database maintenance	Database entry, Transcription of data
Useful references:	Pitard (1993), Francois-Bongarcon (1991), Shaw *et al.* (1998), Lipton (1997), Hartley (1994), Gilfillan (1998), Neuss (1998), Pitard (1998), AusIMM 1992

While geological interpretation and investigation are obviously significant activities carried out during this stage, the activity that has the greatest potential to impact on the final outcome of a project is the sampling procedure. Inappropriate sample collection methods, poor sample handling, inadequate sample preparation and poor analytical practice, or occasionally fraudulent misrepresentation, has significant potential to result in technical errors that will give low levels of accuracy and/or precision, or systematic bias of assays (Gilfillan, 1998). For example, Snowden (1993) describes the effect of inappropriate sampling procedures that led to sample bias during grade control at the Macraes mine. This would have resulted in increased costs as excess waste was milled in error.

Geological interpretation

Having gathered information on the location of lithologies, structures and mineralization, the next stage is to carry out a geological and geotechnical interpretation of the data in order to determine a geological model. Information, in addition to that derived during the ore definition stage, such as regional geological understanding, familiarity with the mineralization style and structural controls will obviously enhance the geological interpretation. This stage involves the conceptualization of the orebody and its geological controls in three dimensions and the definition of controlling features such as lithological, rheological and structural characteristics (Table II).

The most common shortcoming at this stage is the failure to model all features of the orebody in three dimensions and

Table II

Geological interpretation key performance activities

Key performance activity	Task
Database management	Merging survey, Assay and Geological databases
Create digital terrain model	Modelling surfaces in 3D
Geological modelling	Lithological and structural modelling
Geostatistical analysis	Analyse and define spatial relationships in data
Define domains	Identify controls on mineralization
Useful references:	Isaaks and Srivastava (1989), Bischoff and Morley (1994), Snowden (1996), Snowden and Snowden (1988), Snowden (1993)

Table III

Resource estimation key performance activities

Key Performance Activity	Task
Data analysis	Assign domains, Compositing, Code data
Geostatisitcal analysis	Define modelling parameters
Volume modelling	Define limits for estimation of density and grade
Grade estimation	Eg. Ordinary or indicator kriging
Useful References:	Isaaks and Srivastava (1989), Vann and Sans (1995), Snowden (1993 and 1996), Glacken (1996), Glacken and Blackney (1998), Journel and Huijbregts (1978), Deutsch and Journel (1997)

specifically the features that control mineralization. Models are most often developed by the joining of interpretations in section or plan. The combination of these two-dimensional sectional and planar interpretations often results in an interpretation that does not hold together in three dimensions. Joining the dots on polygonal interpretations is a very early step in a complex modelling process. It is essential that geological features (such as lithology, structure, and alteration) are modelled appropriately and used to guide the resource estimation process. For example Snowden (1993) describes a resource model at Girilambone where the use of inappropriate assay boundaries caused artificial bimodality in the distribution of block model grades, effectively underestimating the resource tonnage above cutoff. The life of the mine was extended significantly beyond that predicted in the feasibility study.

Resource estimation

The activities involved during this stage are primarily associated with the interpolation of data and the estimation of resource tonnes and grade. A range of techniques are available. It is significant to note that company/individual experience and preference often biases the choice of technique. This may be due in part to lack of expertise or familiarity with some techniques but is more often a cultural issue within the company that results from paradigms held by key stakeholders. In an ideal situation, the unique geological features of the orebody, along with statistical and geostatistical analysis of the data, should be used to determine the most appropriate methods for interpolation of grade within the geological model (Table III).

There are two activities most often poorly completed during this stage:

- ➤ the choice of grade estimation technique (mathematical modelling procedure) and its application, and
- ➤ bulk density determination.

The level of uncertainty relating to the grade estimate will depend on decisions made relating to the mathematical modelling procedure. This includes choices between 2D and 3D interpretations, sectional techniques versus block modelling, weighting technique applied and top grade cut applied (Snowden, 1996). Decisions made here directly affect the resource tonnes and grade. Elliott, *et al.* (1997) describe how, in a high nugget effect environment, lack of smoothing can result in loss of revenue through the misclassification of ore as waste.

Bulk density information is required for each and every rock type likely to be mined. This is commonly the worst technical feature of a resource database (Gilfillan 1998). Errors of ± 10% are common and translate directly to the estimated tonnages and contained metal.

Inappropriate resource classification also has significant potential to affect levels of uncertainty. For example a poorly defined resource that is inappropriately classified as Indicated, could be used as the basis for an ore reserve estimate. Subsequently mining may take place on what in reality may have been nothing more than Inferred Resource.

Ore reserve estimation and mine planning

Having developed a resource model, economic parameters can be applied to derive the ore reserve and a mine design can be created. The ore reserve estimation process involves the detailed definition of which parts of the resource can be economically extracted. The design should be optimized in both open pit and underground mines. The optimization process must address all management, financial, geological, mining engineering, metallurgical, geotechnical and operational issues (Table IV). Maximum Net Present Value (NPV) is considered as the bench mark for optimization (Tulp, 1997). The end result of this stage is a reserve statement.

The final stage is the planning and scheduling of the extraction of the resource which must consider the mining technique and equipment to be used. Other factors that must also be considered during the mine planning stage include

Table IV

Ore reserve estimation key performance activities

Key performance activity	Task
Optimization	Determine operating costs, Capital costs, Metal price, Recovery, Dilution, Ore loss, Discount rate, Stope dimensions underground, level interval underground and geotechnical considerations (e.g. pit slope, opening spans)
Mine Design	Design of stopes and development underground or slopes and ramps in open pit.
Scheduling	Short-term and long-term plans
Useful References:	Lane (1988), Whittle (1997), Tulp (1997), Schofield and Rolley (1997), Seymour (1998), Elliott *et al.* (1997)

maintaining consistency of mill feed in both tonnes and grade, blending requirements, geotechnical work such as bolting, pre-splitting and ongoing monitoring, lead time to access ore through underground development, or pre-stripping for open pit mines.

Operating and capital costs can normally be estimated reasonably accurately based on past experience, contract rates, or information from similar projects already in operation. The areas that are most commonly poorly estimated are dilution and ore loss. Both these factors can have a significant impact on underground and open pit operations. Pit slope is also an area that is commonly poorly estimated. Poor scheduling will impact on NPV rather than revenue, however in some situations it can result in the sterilizing of ore and inconsistent mill feed, which has implications for recovery.

Financial Modelling

Introduction

Having identified the KPAs associated with the resource/reserve estimation process, the next step is to integrate uncertainty in these activities into a financial model. A number of studies have been completed using financial simulation techniques to assess risk or uncertainty in mining projects (for example Newendorp 1975, Mallinson 1987, Mackenzie 1994, Rozman 1998). These studies generally focus on variation in quantitative factors such as revenues and costs. Most financial studies either tend to deal with uncertainty in resource or reserve estimates by grouping all risk into a factor which is applied to the final reserve grade and tonnage. While this does address uncertainty in the reserve estimate, the factors applied are typically too conservative. The significance of uncertainty in the resource/reserve estimate is highlighted by a Group de Reflexion correspondent (Centre de Geostatistique, 1994) who reported that, amongst small mining companies in South Africa during the 1980s, 70% failed mainly because of over estimation of the ore reserve tonnages and grade. Beutel Goodman and Co (reported in Centre de Geostatistique, 1994) constructed a summary of North American mine failures listing 40 mines that were then running at only 25% of the capital invested in them. On the basis of a feasibility study or investment analysis, the reserve on which the capital investment decision was made can only be assumed to be far greater than the actual achieved by mining. The uncertainty attributed to the reserve in these cases was obviously inadequate to highlight future potential problems for the investors. The impact of a relatively small margin for error should not be underestimated. Rozman (1998) uses the gold industry as an example, and highlights that in an industry that generally runs at a profit margin of 10% to 20%:

- It is not possible to assay to an accuracy of much better than 10%,
- modelling of orebody outlines to an accuracy of 10% is a challenge, and
- a Proved reserve is only expected to be accurate to about ±15%.

Therefore, the range of uncertainty of the ore reserve has potential to have a significant impact on project investment decisions.

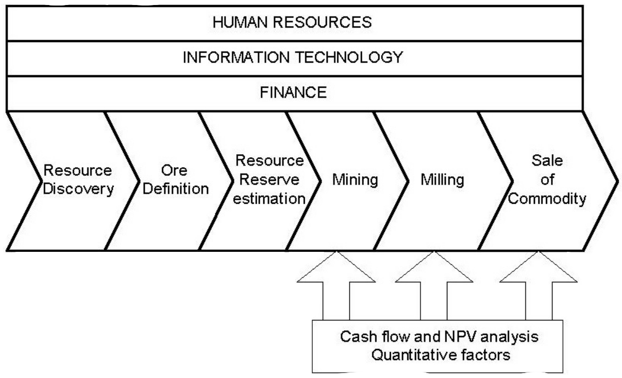

Figure 2—Mining project value chain

A useful way to identify the potential sources of uncertainty in a mining project is to consider the processes that add value to the project. A diagrammatic representation of this process is known as a value chain. Figure 2 presents a schematic value chain for a mining operation. The stages of the chain that are dealt with by 'traditional' financial analysis (quantitative factors) have been highlighted.

Uncertainty in the early part of the value chain (resource discovery, ore definition and resource/reserve estimation) has an impact on the processes that follow. The impact of these early stages has been discussed and financial scenarios are provided below. However, it is essential that the whole chain be considered during the course of a feasibility study or investment analysis. It is beyond the scope of this paper, to review cost estimation and discounted cash flow analysis. Useful papers by Mallinson (1987) and Rozman (1998) conducting this type of analysis are available and so this information will not be repeated here.

A simple hypothetical model has been developed by the authors to allow tonnage and grade values to be varied randomly within given ranges, to highlight the effect that these changes may have in financial terms. It is important to note that the analysis presented is not seen as complete, but rather complementary to traditional financial analysis.

Methodology

Monte Carlo simulation has been used to simulate a number of hypothetical scenarios, as it allows uncertainty to be expressed as a range and distribution of possible values for any number of given variables or inputs (further information on Monte Carlo simulation can be found in texts such as Rubinstein (1981), Law and Kelton (1991).

The authors have dealt with parameters that are not mutually independent by ensuring that the conditional distribution values of the dependent value are determined by using the output from sampling the distribution of the first variable. The statistical inputs to the model have been derived from the industry experience of the authors and through consultation with colleagues within the industry. While every effort has been made to ensure that the inputs are meaningful and realistic, they are not based on empirical data and express the opinion of the authors. The model is simplistic but serves the purpose of highlighting the effect of uncertainty on revenue.

Revenue has been chosen as the most appropriate financial indicator for demonstrating the impact of uncertainty in resource/reserve estimates because:

- revenue is relatively simple to calculate
- revenue does not need to be estimated, it is calculated as commodity quantity by commodity price
- revenue can be quoted in US$ terms which has universal application, and
- it provides a starting point from which costs and discount rates can then be applied to complete the project analysis (a natural input into 'traditional' financial analysis).

A hypothetical gold model has been developed in order to estimate potential revenue. A spreadsheet was constructed (using Microsoft's Excel and Palisade Corporation's @Risk software) containing each of the KPAs discussed previously. Columns for distribution ranges were included for each KPA. These columns allow the user to enter minimum, maximum and most likely uncertainty values for both tonnes and grade, which are then used in a triangular distribution during the simulation. Table V provides an example of this structure from the spreadsheet.

The model was constructed to allow both tonnes and grade to be influenced and both positive and negative effects to result from uncertainty. For example, a sampling bias which under-estimates grade (e.g. -5% in Table V) could have a positive effect in that more metal would be recovered than expected, while if a sampling bias was to result in the over estimation of the grade (e.g. 10% in Table V) there would be less metal recovered from the project—a negative effect.

A triangular distribution has been used to allow the user to guide the simulation by applying more weight towards one end of the distribution by setting the 'most likely' value. For example, dilution from overbreak will, in most cases, have an adverse effect on grade due to additional tonnes of waste being mined. However, in a small number of cases overbreak may result in additional mineralized material being mined, resulting in a positive effect. The triangular distribution is illustrated in Figure 3.

Table V

Example of spreadsheet format

KPA	Minimum	Most likely	Maximum
Sampling	-5%	1%	10%

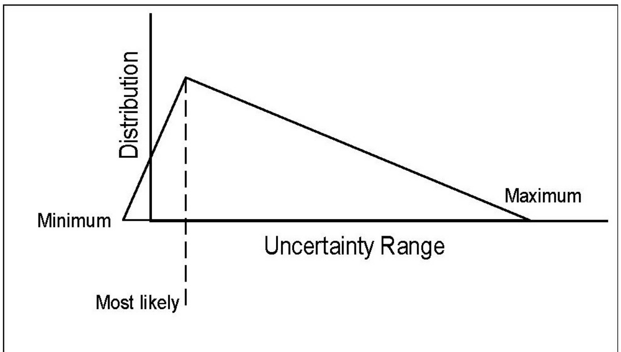

Figure 3—Triangular distribution as applied to uncertainty

The ranges applied to each KPA are described for each model later in the paper.

Monte Carlo simulation was used to vary the KPA distribution ranges. This means that the tonnage and grade for each KPA was varied randomly between the ranges of uncertainty assigned. An arbitrary number of simulations was selected (2,000 scenarios) with the only criteria being that sample convergence was within appropriate ranges for the majority of the simulations. On the completion of each simulation, probability distribution graphs were produced and compared.

The author's choice of uncertainty and the bias is completely arbitrary. Industry experience has shown that problems with technical procedures or methodologies can bias results high or low and in most cases some cancelling effect is present. In each case cited the authors have chosen only one scenario to illustrate the impact on revenue.

Four simulations are presented. The first is a base case scenario which, in the authors' opinion, uses realistic ranges for uncertainty in a project. This scenario assumes no major errors or biases, but contains realistic margins for uncertainty that would exist in any project where work is being completed to the limit of best endeavours. This base case is used as a bench-mark to show the impact that increasing uncertainty in specific KPAs has on revenue.

The second scenario assumes poor sampling practice and lack of understanding of sample preparation. This is a widespread and a common problem facing many projects.

The third scenario assumes inappropriate resource estimation which is expressed by poor modelling and inappropriate choice of interpolation technique.

The fourth scenario represents a project where the majority of KPAs are not performed as best as they could be. The aim of this scenario is to highlight the cumulative nature of uncertainty in the early stages of a project. All uncertainty ranges are still relatively small, but the cumulative effect of a slightly increased amount of uncertainty across a large number of variables has significant impact.

Assumptions

The hypothetical model is based on a 10,000,000 tonne, approximately 800,000 ounce gold deposit with an *in situ* grade of approximately 2.5 g/t. A US$ gold price of $287/oz was used in all models (based on London closing spot gold price at the time of writing).

A resource to reserve conversion rate has been assumed for both the tonnes and grade of the hypothetical model. This is kept constant in all scenarios. Tonnes have arbitrarily been assigned a 60% conversion from resource to reserve (i.e. 60% of all resource tonnes convert to reserve) while grade has been assumed to increase by 5% (i.e. reserve grade is 105% of resource grade).

Financial simulations

Base case

The base case assumes no major errors or biases, but contains realistic margins for uncertainty that would exist in any project where work is being completed to the limit of best

Table VI
Base case input variables

Stage	Key performance activity (KPA)	Variable	Tonnes (%)			Grade (%)		
			Min	Most likely	Max	Min	Most likely	Max
Ore definition	Mapping	tonnes	-0.5	0.0	0.5	0.0	0.0	0.0
	Drilling	grade	0.0	0.0	0.0	-1.0	1.0	3.0
	Sampling	grade	0.0	0.0	0.0	-2.0	1.0	10.0
	Surveying	tonnes & grade	-1.0	0.0	2.0	-1.0	0.0	1.0
	Logging	tonnes & grade	-1.0	0.0	1.0	-0.5	1.0	2.0
	Assaying	grade	0.0	0.0	0.0	-2.0	1.0	10.0
	Specific gravity	tonnes	-1.0	2.0	4.0	0.0	0.0	0.0
	Database maintenance	tonnes & grade	-0.5	0.0	0.5	-0.5	0.0	0.5
Geological Interpretation	Database management	tonnes & grade	-0.5	0.0	0.5	-0.5	0.0	1.0
	Digital terrain model	tonnes	-1.0	0.0	2.0	0.0	0.0	0.0
	Geological interpretation	tonnes & grade	-2.0	1.0	2.0	-2.0	1.0	2.0
	Geological model	tonnes & grade	-2.0	0.0	2.0	-2.0	0.0	2.0
	Geostatistical analysis	grade	0.0	0.0	0.0	-1.0	1.0	2.0
	Definition of domains	tonnes & grade	-1.0	0.0	1.0	-0.5	0.5	1.0
Resource estimate	Data analysis	grade	0.0	0.0	0.0	-1.0	2.0	3.0
	Geostatistical analysis	grade	0.0	0.0	0.0	-1.0	1.0	2.0
	Construct volume model	tonnes	-1.0	1.0	2.0	0.0	0.0	0.0
	Grade estimation	grade	0.0	0.0	0.0	-0.5	2.5	3.0
Ore reserve estimation and mine planning	Optimization	tonnes & grade	-1.0	0.5	1.0	-1.0	0.5	1.0
	Mine design	tonnes & grade	-5.0	2.0	5.0	-5.0	2.0	5.0
	Scheduling	tonnes	-0.5	0.0	0.5	0.0	0.0	0.0

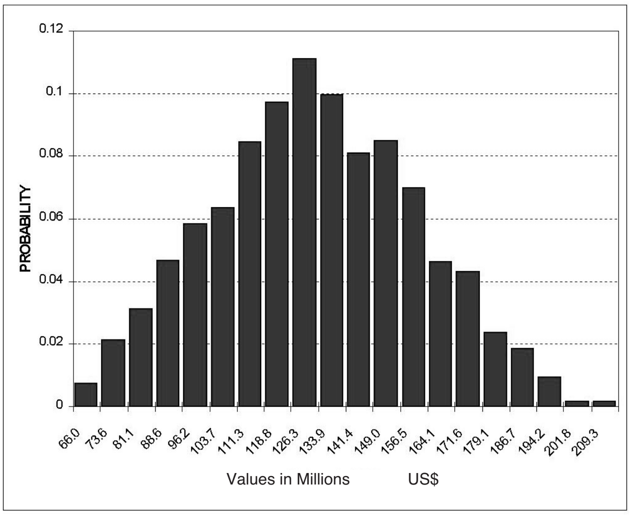

Figure 4—Frequency distribution diagram showing base case scenario results

endeavours. The results from this case are then used as a bench-mark for all other cases. Table VI presents the ranges applied in the base case. A positive value refers to the degree of overestimation assumed. Results of the simulation are presented in Figure 4.

From Figure 4 it can be seen that the hypothetical orebody has the potential to generate revenue between US$66 and US$209 million with the most likely scenario being US$126 million.

Projects with poor sampling practice and sample preparation

In this case the authors, have chosen to show the effect of poor sampling and assaying procedures where results have a positive bias, that is, are consistently higher than what is actually the case. This has been achieved by taking the base case and increasing the uncertainty in the sampling and assaying KPAs. The only inputs altered from the base case are as shown in Table VII.

Table VII
Inputs altered from base case for poor sampling case

Stage	Key performance activity (KPA)	Variable	Tonnes (%)			Grade (%)		
			Min	Most likely	Max	Min	Most likely	Max
Ore definition	Sampling	grade	0.0	0.0	0.0	-30.0	-20.0	15.0
	Assaying	grade	0.0	0.0	0.0	-25.0	-15.0	10.0

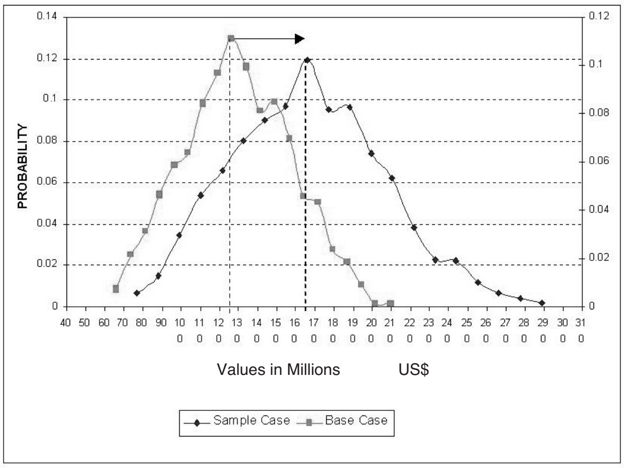

Figure 5—Comparison between base case and poor sampling case

Table VIII

Inputs altered from base case for poor resource estimation case

Stage	Key performance activity (KPA)	Variable	Tonnes (%)			Grade (%)		
			Min	Most likely	Max	Min	Most likely	Max
Geological interpretation	Geological interpretation	tonnes & grade	-5.0	5.0	10.0	-5.0	5.0	10.0
	Geological model	tonnes & grade	-5.0	5.0	10.0	-5.0	5.0	10.0
	Definition of domains	tonnes & grade	-5.0	5.0	10.0	-5.0	5.0	10.0
Resource estimate	Construct volume model	tonnes	-5.0	10.0	20.0	0.0	0.0	0.0
	Grade estimation	grade	0.0	0.0	0.0	-10.0	10.0	20.0

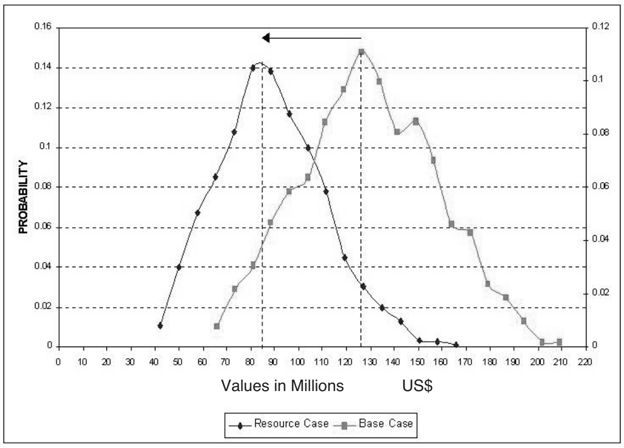

Figure 6—Comparison between base case and poor resource estimation case

It is significant to note that the -30% minimum and +15% maximum uncertainty used in this case may still be conservative. Poor sampling practice has the potential to generate bias or errors of much higher magnitude. The aim of this model is not to present an extreme example, but a realistic situation that could occur on many sites that have not adequately addressed sampling and assaying issues. The results of this model are presented in Figure 5. For ease of comparison the results have been plotted as a curve (rather than a histogram) and the results from the base case are also shown.

Figure 5 shows that the increased uncertainty due to poor sampling practice has had the effect of increasing the most likely revenue by approximately US$40 million, or 30% (the arrow in Figure 5 shows the shift in the curves).

These results have serious implications for an investment decision. The financial modelling using poor sampling and assay data suggests the project has the capacity to generate revenue between US$75 million and US$290 million with a most likely revenue of US$165 million. In reality the project only has the potential to generate revenue between US$65 million and US$210 million with a most likely revenue of US$125 million. This project could commence operation and may never meet the production and revenue targets expected. Depending on the hurdle rates adopted by a potential investor it is possible that this project could commence when, in fact, it does not meet the investment criteria and may even be uneconomic.

Project with poor modelling and inappropriate resource estimation technique

In this case the authors have chosen to show the effect of poor modelling and inappropriate resource estimation techniques that result in an under-estimation of the potential revenue. This has been achieved by taking the base case and increasing the uncertainty in interpretation, modelling and resource estimation KPAs. Again, the authors have not used extreme ranges for uncertainty but have used ranges which in their experience reflect what does occur in many projects. The only inputs altered from the base case are as shown in Table VIII.

The results of this scenario are presented in Figure 6. Again, for ease of comparison, the results have been plotted as a curve and the results from the base case are also shown.

Figure 6 shows that uncertainty, due to poor modelling and resource estimation techniques, has had the effect of reducing revenue from that achieved in the base case by approximately US$40 million or again 30%.

This scenario also has significant implications to any investment decision. The biased results are suggesting that the potential revenue is significantly lower than that which would actually be achieved if mining was to take place. At small differences (10 to 15%) this could be regarded as 'healthy conservativeness'. However, 30% under-estimation could result in the project being overlooked because the returns may not meet corporate hurdle rates. In reality mining could produce results above production and revenue targets and provide better than expected results for the investor.

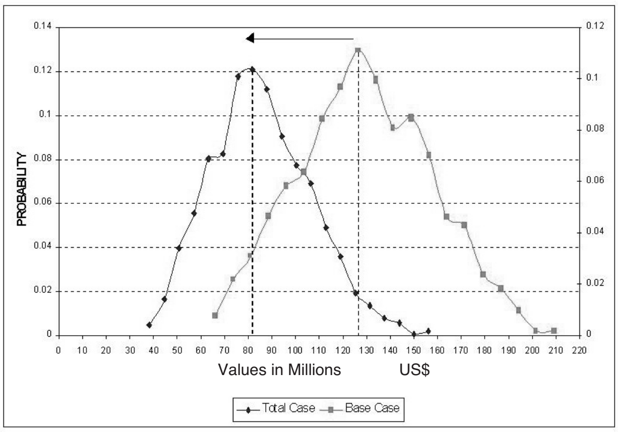

Figure 7—Comparison between base case and 'typical' case

Table IX

Inputs for the 'typical' case

Stage	Key performance activity (KPA)	Variable	Tonnes (%)			Grade (%)		
			Min	Most likely	Max	Min	Most likely	Max
Ore definition	Mapping	tonnes	-0.5	0.0	0.5	0.0	0.0	0.0
	Drilling	grade	0.0	0.0	0.0	-2.0	2.0	5.0
	Sampling	grade	0.0	0.0	0.0	-2.0	10.0	15.0
	Surveying	tonnes & grade	-1.0	0.0	2.0	-1.0	1.0	2.0
	Logging	tonnes & grade	-1.0	0.0	1.0	-0.5	2.0	3.0
	Assaying	grade	0.0	0.0	0.0	-5.0	10.0	20.0
	Specific Gravity	tonnes	-5.0	5.0	12.0	0.0	0.0	0.0
	Database maintenance	tonnes & grade	-0.5	0.0	0.0	-0.5	0.5	1.0
Geological interpretation	Database management	tonnes & grade	-0.5	0.0	0.5	-0.5	0.5	1.5
	Digital terrain model	tonnes	-1.0	0.0	2.0	0.0	0.0	0.0
	Geological interpretation	tonnes & grade	-2.0	2.0	5.0	-2.0	2.0	5.0
	Geological model	tonnes & grade	-2.0	1.0	5.0	-2.0	0.0	5.0
	Geostatistical analysis	grade	0.0	0.0	0.0	-1.0	1.5	2.5
	Definition of domains	tonnes & grade	-1.0	1.0	2.0	-0.5	1.0	2.0
Resource estimate	Data analysis	grade	0.0	0.0	0.0	-1.0	3.0	4.0
	Geostatistical analysis	grade	0.0	0.0	0.0	-1.0	1.5	3.0
	Construct volume model	tonnes	-2.0	5.0	10.0	0.0	0.0	0.0
	Grade estimation	grade	0.0	0.0	0.0	-0.5	5.0	10.0
Ore Reserve estimation and mine planning	Optimization	tonnes & grade	-1.0	2.0	7.0	-1.0	2.0	5.0
	Mine Design	tonnes & grade	-5.0	5.0	10.0	-5.0	5.0	10.0
	Scheduling	tonnes	-1.0	0.0	1.0	0.0	0.0	0.0

'Typical' case with a number of small problems in most KPAs

With this case the authors have attempted to model a 'typical' mining operation where there are a number of small biases, with both positive and negative effects, occurring. The aim of the scenario is to highlight the impact that small increases in uncertainty, at all the stages of the resource/reserve estimation process have on potential revenue. This is a 'typical' project in that, for any single KPA uncertainty remains at low levels, but is typically higher in all activities than a project with quality procedures. The inputs altered from the base case are as shown in Table IX.

The results of this scenario are presented in Figure 7 below. Again, for ease of comparison, the results have been plotted as a curve and the results from the base case are also shown.

Figure 7 shows that an increase in uncertainty due to poor practice at all stages in the resource/reserve estimation process has the effect of reducing revenue from that achieved in the base case by approximately US$40 million (approximately 20% of the total revenue). A lack of quality procedures and techniques overall can thus be seen to have as significant an impact on the estimated performance of a project as significant problems in only one or two areas.

Conclusions and recommendations

Investment decisions are commonly made on the basis of financial analysis using tools such as net present value (NPV), discounted cash flow analysis, and investment hurdle rates (for example, internal rate of return (IRR) or weighted average cost of capital). Construction of these financial models requires accurate estimation of revenues and costs associated with the project. It is not uncommon for cost estimates (both capital and operating) to have uncertainty ranges quoted and more recently simulation techniques (such as Monte Carlo simulation) have been used to assess the impact of sensitive variables such as commodity price, capital costs and operating costs (Stewart, 1994). However, the most significant assumption in any financial model relates to the quality of the reserve. O'Leary (1994) concludes that in the majority of projects the cash flows are more sensitive to the grade than to any other factor, excluding the commodity price, and in many cases this sensitivity can be two to three times as large as, for example, capital cost. The models which have been presented here highlight the impact that increased uncertainty can have on the accuracy of predictions about revenue-generating potential of an orebody. Realistic uncertainty ranges have been shown to generate reductions and increases in the estimate of potential revenue of up to 30%.

Some companies take significant pride in achieving production and revenue results that are greatly in excess of the targets they predicted. While this on face value does appear to be quite good, the results discussed suggest it could also mean that the companies procedures and methodologies are very poor. Obviously there are many factors to consider. However, the authors suggest that where the reconciliation between predicted results and achieved results has a greater difference than plus or minus 10 to 15%, caution should be exercised and procedures should be reviewed. A company announcement stating, for example, that grades achieved were 150% greater than what was expected suggests that serious problems exist with the company's procedures in estimating those grades, and who can guarantee that these results will not suddenly change to 150% below what should be expected.

Due to the effect that uncertainty in the resource and reserve estimate process can have on a project, it is important to allow for errors in these processes in any financial analysis or feasibility study. It is recommended that, when building a financial model, a review of relevant resource/reserve KPAs be carried out and appropriate ranges for uncertainty be applied to provide a range of potential outcomes. These outcomes can then be factored into the detailed cash flow analysis in order to ensure that technical uncertainty is built into investment decisions.

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