Dealing With Demands of Technical Variability and Uncertainty Along the Mine Value Chain

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ABSTRACT

There are many critical nodes along the mine value chain, from orebody to mineral product, and inter-disciplinary input is required to analyse the variability and uncertainty at each node in order to identify and mitigate areas of risk.

Mining differs from many other industries in that the variability in the product is dictated largely by the inherent nature of the input material (the orebody). The true characteristics, including the variability of the orebody, are never known exactly and are instead based on estimates derived from sample data. A further difference is that bottom-line gains are largely controlled by world commodity prices, which can vary with time, rather than by local supply and demand issues.

Methods for identifying, reporting and responding to this inherently variable raw material are discussed. These include analytical and reporting methods, equipment and software, risk analysis and reality checks (eg reconciliation). Sampling results, mineral resource and ore reserve estimates and economic assumptions are a function of the variability of the orebody.

Risk quantification should be expressed as a level of confidence, which takes into account the scale or period over which the risk is being assessed (life-of-mine, annual or shorter production periods) and should convey the likelihood, severity and consequence of occurrence of a given event.

The future generation of mining specialists needs to understand the entire mine value chain to better manage risks and maximise mine dollar-value.

INTRODUCTION

Decision-makers need to be better informed of the potential risks and opportunities that exist in mining ventures. At the feasibility stage of a project, the range of most likely scenarios, including upside and downside cases, all need to be tested to determine their effect on economic decision-making. Communication and compilation of all relevant mining risk sources, and their likelihood and consequence of occurrence, is critical to decision making.

MINING IS DIFFERENT – OREBODY DEPENDENT

The risks associated with mining are complex and varied. Depending on their origin, risks may be described as objective, when the risk can be modelled by some mathematical model, or subjective, when personal judgement alters the perceived risk. In addition, the source of risk may be dominated by either potential human intervention or by one's understanding of largely untested geologically controlled factors, such as interpretive models or structural controls. In mining, the dominant source of risk is the orebody itself. Mining is different from many businesses, because knowledge of the product is based largely on estimates, and potential revenue changes and the size of the mineral inventory are largely controlled by world commodity prices and exchange rates.

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Rozman (1998) comments that the variability of an ore reserve can significantly alter critical business decisions. He notes that a reserve is not precise, but rather is dynamic with respect to interpretation and information, and both the upside and downside of a project needs to be recognised. For example, he describes that if the upside at Sunrise Dam in Western Australia had not been recognised, it may never have been mined. In 1998 it had produced 60 per cent more gold than originally estimated.

As Rozman points out, the resource business is about managing risk, not necessarily minimising risk, since this could result in lost opportunities. However, there are numerous examples of mines where planning has proceeded on the basis of the most optimistic outcomes, with a resultant trail of woe and financial disaster. Rozman and West (2001) summarise the various sources of risk in resource and ore reserve estimation and the tools used to estimate mining risk. They comment that there are many assumptions made during mine planning and the risks associated with some of these assumptions can be high. These risks need to be evaluated and understood as part of the appraisal process. Rozman (2001) describes how the information relating to the variability of an ore reserve can be appropriately presented, allowing company boards and management to make the correct, rather than either conservative or ill informed, recommendations and decisions on the future directions of a project.

DEFINING THE MINE VALUE CHAIN

There are many critical nodes of uncertainty along the mine value chain, moving from orebody to mineral product, for example drilling and sampling, assaying, geological interpretation and assessment of grade continuity, determination of geotechnical constraints and slope stability, estimation of mining and processing costs and techniques and mine layouts (eg stope or pit shapes).

Inter-disciplinary input involving complex analysis is required to determine the value-adding opportunity at each node in order to optimise the overall mine process. The value chain must be optimised from the beginning to the end of this process in order to identify those high-risk areas and mitigate their impact, thus maximising mine dollar value. Interdisciplinary components, including geology, geomechanical, mining and metallurgical engineering, are closely linked at each stage from exploration, through feasibility studies, to grade control, mining, processing and marketing. A simplified example of a mine value chain is presented in Figure 1.

The use of risk matrices (sometimes titled probability-impact matrices) help to understand and balance both the magnitude and the impact of risks. An example is presented in Figure 2, showing how the probability of occurrence and the consequence (impact) are linked in order to rank the level of risk associated with a given node of uncertainty. Decisions made at feasibility level based on limited information are often locked in at this time and cannot be changed when additional data becomes available, for example with respect to rock hardness, geotechnical conditions, variability of grade and scale of mining.

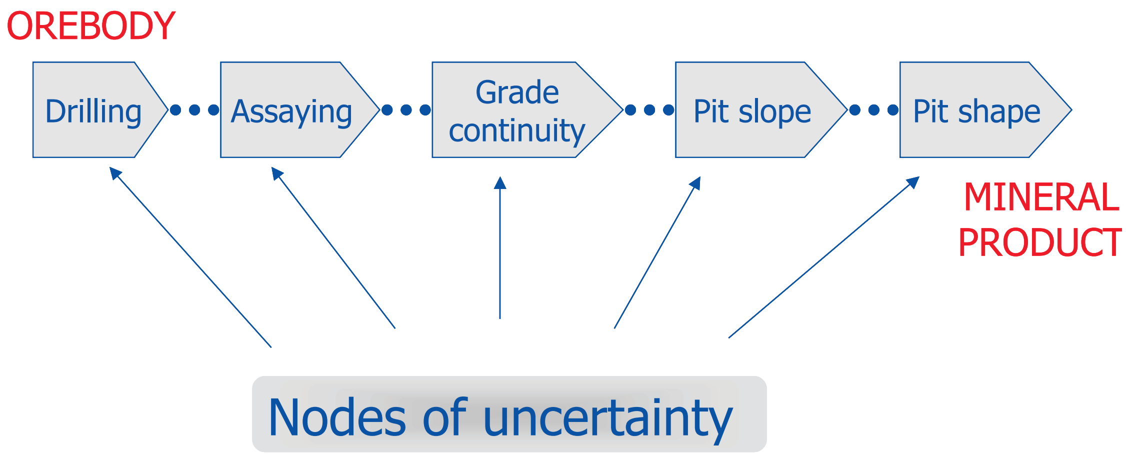

FIG 1 - Simplified mine value chain illustrating nodes of uncertainty.

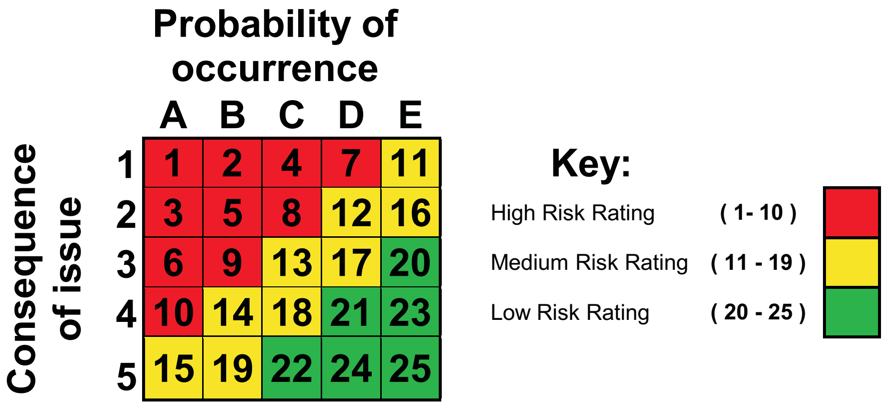

FIG 2 - Example of a probability-impact matrix relating the probability of occurrence and the consequence of the item under examination.

OREBODY VARIABILITY AND UNCERTAINTY

Variability

At the heart of risk analysis is the understanding of variability. It is particularly important to assess variability at an early stage of the project. The misunderstanding of grade variability, in particular, is a common reason for new mine project failure (Warren, 1991). Techniques for recognising, quantifying and analysing grade variability include:

- twinned holes;
- field duplicate analysis;
- analytical repeats;
- sample size analysis;
- plots of data grade trends with RL, northing or easting;
- analysis of the nugget effect;
- variography to quantify spatial continuity (variability);
- quantifying the changes in key parameters with increases or decreases in data;
- kriging efficiency, slope of regression and effective model block size; and
- conditional simulation.

Once variability is understood, the risk profile of the resource/ore reserve can be established. This allows for more effective decision-making with respect to some or all of the following actions:

- infill drilling;
- adjustments for assay bias;
- change in resource block size to reduce uncertainty;
- re-design of mine plan to mitigate risk;
- increase/decrease mine size and/or plant size; and
- account for low precision in the schedule by understanding the inverse relationship between precision and reporting period.

Quantifying uncertainty

Resource risk is a function of uncertainty in geological and analytical input data and its interpretation. Resource estimates quoted in terms of tonnes and grade, contain inherent errors. The intended operation could be sensitive to either or both of these. Risk assessment should thus take into account both the likelihood and impact of this uncertainty in order to assess the risk profile.

Global uncertainty versus local uncertainty

Global estimates of tonnes and grade will have different levels of risk depending on the total size of the resource. A large resource, which will be mined over many years, inherently has a lower risk than a small resource mined very quickly. This should be reflected in the confidence classification for the resource. Figure 3 displays the relative confidence in a metallic resource when the scale of production, from individual selective mining units through to quarterly production units, is explicitly considered. This shows that there is low confidence in the estimated grade of individual selective mining units but that once these are grouped into larger production units, there is an increased confidence that production will achieve what has been estimated.

Local estimates of tonnes and grade thus have different levels of risk depending on the reporting period. Shorter reporting periods have higher levels of inherent uncertainty. The impact of uncertainty on the tonnes and grade within a given period will depend on the commodity and its inherent spatial variability (as quantified via the variogram), product specification limits, the processing tolerance (particularly for impurities) and the scheduling/blending protocol. Whilst the greater uncertainty in predictions of shorter production periods is understood, it is often ignored when assessing the risk.

Precision versus accuracy

A high degree of variability or poor precision may not necessarily give rise to poor accuracy, depending on the reporting period. Poor accuracy (ie a bias between the estimated result and the true value) may occur despite good precision, in cases where a grade bias exists. There is a direct impact of poor precision on the misclassification of ore and waste, as illustrated in the matrix in Figure 4. In this example, the envelope defining the block grade estimate versus the actual value needs to be as narrow as possible (precise) with minimal bias (accurate) to minimise misclassification (sectors 3 and 4).

Methods for assessing uncertainty

Statistical tools

Quality assurance and quality control rely on statistical tools to assess variability and to determine the precision at the various stages of data collection; for example, drillhole or blasthole sampling, laboratory subsampling and assaying. Q-Q plots allow the comparison between two distributions. Relative precision plots, Thompson-Howarth plots and scatter plots demonstrate the degree of correlation between the results of duplicate samples or assays.

Sensitivity analysis

Sorentino and Barnett (1994) describe sensitivity analysis as the process of examining the impact of errors. It is assumed that one variable is changed at a time independently of other variables. Sensitivity analysis can be used to vary risk tolerance to determine at what point the decision changes. It is widely used in the mining industry to assess the impact of errors in grade, metal price, metallurgical recovery, pit slope angles and other technical parameters ('*Mother Nature'* risks) on project value (NPV). The time value of money is the fundamental concept upon which such evaluations are based. As noted by Barnett and Sorentino (1994), the net present value, NPV, of a future sum, S, is $S/(1+r)^t$, where t = years and r is the interest rate. The principal method used to analyse the worth of a project is discounted cash flow (DCF) analysis. The selection of interest rate depends on how finance is arranged and is a function of the cost of debt finance and the cost of equity. The greater the risk, the higher the interest rate used.

Barnett and Sorentino (1994) discuss the problem of sunk costs that influence managers' decisions to remain committed to a project that has obviously gone bad. However, money already spent should no longer influence current and future decisions which should be forward looking, that is consider only future cash flows.

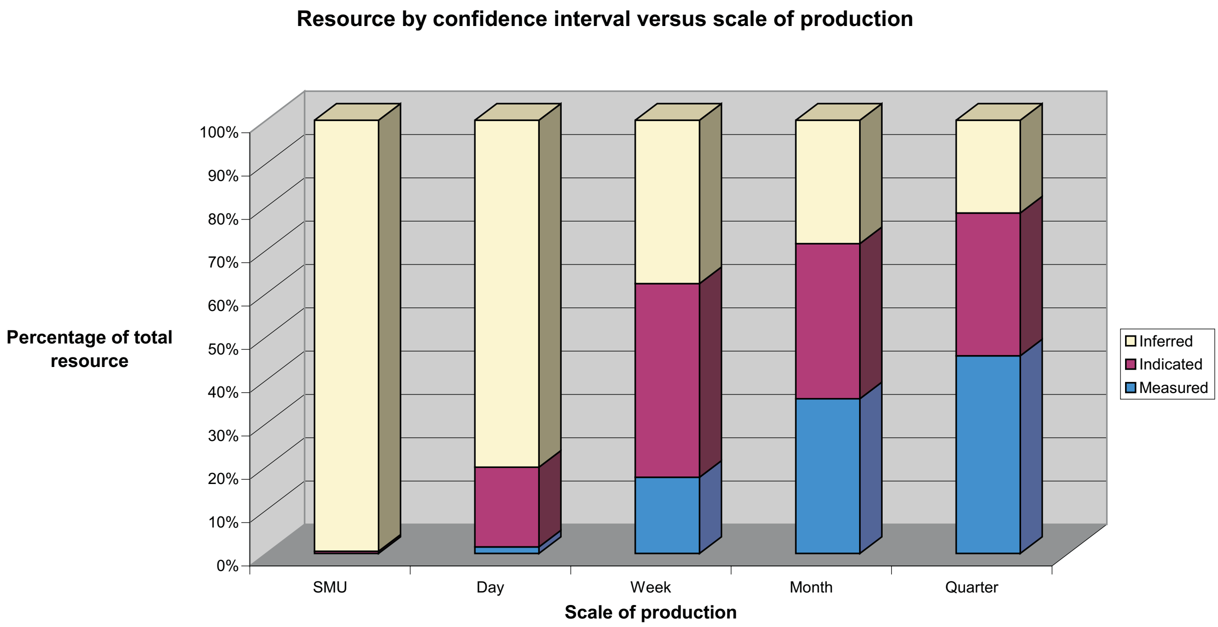

FIG 3 - Chart showing the relationship between the scale of production units considered and the relative confidence in the resource (expressed in terms of the percentages of inferred, indicated and measured).

Monte Carlo simulation

Monte Carlo simulation is a tool for developing a model of uncertainty which can incorporate risk profiles for decision alternatives. Risk analysis using Monte Carlo simulation techniques began in the petroleum industry in about 1967 and has been used by nearly every major petroleum company involved in exploration for oil and gas since the early-1970s (Newendorp, 1975). It allows the explorationist to describe risk and uncertainty as a range and distribution of possible values for each unknown factor, rather than a single, discrete average. The purpose of a simulation analysis is to be able to account for potential variability in profitability. This technique is equally useful for the mining industry and tools such as @RISK have been applied to assessing financial models as well as technical options in mining engineering (Vose, 2001).

Conditional simulation

Conditional simulation is a technique used to assess risk by means of a spatial Monte Carlo analysis. It uses geostatistical parameters to provide several grade models, each of which are equally likely, honour the geological boundary constraints, honour the input data at sample locations and obey both the sample histogram and sample semivariogram. Conditional simulation models provide a distribution of grades for every block in the grade model and for groups of blocks of any size. There is thus the opportunity to investigate the risk associated with potential mining scenarios. A detailed risk analysis can be undertaken by considering the probability of a given outcome for a given block, for example, the probability that the grade of a block exceeds a grade cut-off. Thomas, Coombes and Richards (1998) describe conditional simulation software tools that allow such risk analysis to be undertaken quickly and accurately.

The mine planner can assess both long-term and short-term risk in the reserve and can use a suite of conditional simulations to assist, for example, with stockpile planning and prediction of mill feed variability. Grade control applications allow cost minimisation and optimisation of profit according to mill or mine constraints (Thomas, Coombes and Richards, 1998).

Option theory

There is an inherent value in features such as safety and/or flexibility in a mine plan, which may not be readily quantifiable by normal cash flow methods of evaluation. Option theory can determine the value of safety and flexibility in the mine plan. As described by Seymour (1998), there is a need for compromise between maximising the value, minimising the risk and maximising the life of mine. A flexible mine plan comes at a cost resulting in a lower NPV.

The value of flexibility and/or safety can be added to the cash NPV to give a total NPV, which should be maximised in the planning process. Seymour suggests that it can be strategic for mines to make non-recoverable investments for a given period if this means balancing the return on investment and the risk of operation. This is contrary to the usual practice of operation, which uses a cut-off grade approach and maintains incremental positive returns throughout the mine plan.

Decision analysis

Clemen (1990) discusses how to tackle difficult decisions using decision analysis. These tools allow one to quantify whether the potential gains in the proposed project are considered to be worth the additional risk. If so, the decision maker will go ahead with the project. He also notes that risk can be offset by deferring decisions until further information is obtained. For example, in mining, it may be relevant to plan an infill drilling programme prior to finalising stope design. In this manner, a conceptual mine plan on which a pre-feasibility study is based, with the attendant high degree of uncertainty, can be transformed to an actual mine design for a feasibility study once the data has been collected to improve knowledge of grade boundaries and ground conditions.

As described by Clemen (1990), multiple objectives and trade-offs require ranking different outcomes relative to each other. Decision trees help the decision maker define the structure of the problem and display all the technical elements of risk for each decision. This involves clearly specifying chance outcomes, choices and pay-offs. Making a choice involves assigning probabilities to uncertain events and picking the alternative with the highest expected (usually) monetary value.

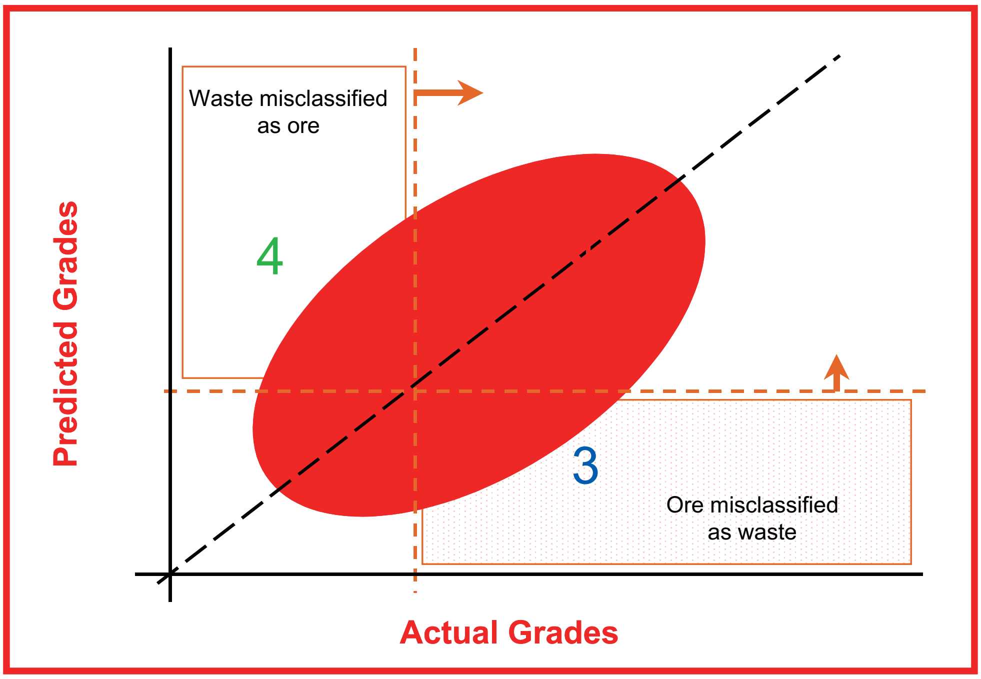

FIG 4 - Ore reserve misclassification matrix showing four sectors, of which 3 and 4 relate to misclassification.

Business risk period

Seymour (1998) proposes an alternative method for incremental pit shell selection that considers what risk a mine would be prepared to accept. A business risk period (BRP) is described as the period of time over which the owner is prepared to invest capital. During the BRP the mine would be prepared to make non-recoverable investments and the associated costs and risks should be fixed and quantifiable over the entire BRP cycle, but no longer. The mine can thus react to change within the BRP timeframe without having to alter incremental pit shell limits. This allows the company to maintain a strategic risk profile.

Tools and technology

Current trends towards web-based management information systems allow for rapid access to on-line data and relevant documentation for management decision-making. Access to software has also become more global and immediate. Automation is another area of development which affects the quality of input data – for example, the use of robotics in laboratories has become fairly widespread and allows for automation of procedures and standardisation of quality. Pit recording and dispatch using GPS and data logging removes the potential for transcription errors as well as automating survey control, mining reconciliation and resource model depletion. Automated belt sampling, sample splitting and/or on-line analysis improve the turn-around time for responding to unexpected run-of-mine grade problems. The trend is for all of these data sources to be integrated into a single enterprise resource planning (ERP) system, thus providing a firm foundation for high-level business decisions. This is illustrated in Figure 5, which shows conceptually that the fundamentals of ore definition, geological interpretation, resource and reserve estimates, and mine plans all underpin the project cash flow.

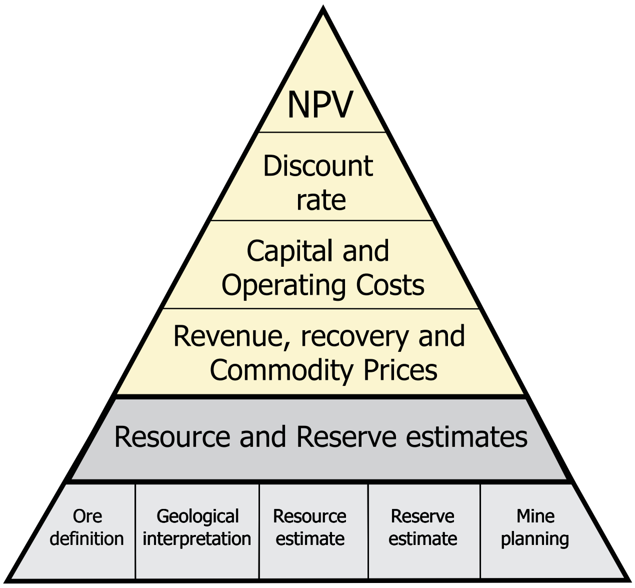

FIG 5 - Conceptual diagram illustrating the reliance of project cashflows on the fundamentals such as the geological interpretation and the resource and reserve estimates.

SOURCES OF UNCERTAINTY

There are many sources of uncertainty along the mine value chain. These range from uncertainty associated with the representativity of the orebody samples, through the way in which the samples are prepared and assayed, human related uncertainty introduced during compilation and storage of the database, inherent geological and geostatistical uncertainty in resource models and uncertainty associated with ore reserve modifying factors. It is important that decisions based on this uncertain data be subjected to a reality check through the process of reconciliation.

Sample and assay uncertainty

Sample representativity

The assessment of the orebody characteristics and products are based on estimates and the estimates are in turn based on sampling results. The assumption is that the sampling results are representative of the orebody at the scale of mining so that these results can be used to estimate the mining characteristics of the orebody. There are a number of sources of potential error that need to be minimised during sampling to ensure that this is indeed the case.

The sampling density, orientation and method (including sample volume) of drilling and sample collection should provide representative and unbiased samples of the orebody. The final choice of method depends on the characteristics, particularly the variability, of the orebody. Sample spacing and orientation are determined by the interpreted mineralisation style and geometry of the orebody. Sample volumes and drillhole types should depend on the heterogeneity of the orebody. However, these choices are generally modified by practical considerations and such compromises may introduce additional uncertainty into the sample data.

Sample reduction

Sample preparation effectively begins in the field when the samples are collected. The samples for ore reserve estimates are generally taken from drill core or drill chips. In most cases the sample consists of only a portion of the drilled sample volume. In the case of drill core, the core is either halved or quartered during initial sampling. Drill chip material from non-coring drillholes that tend to have larger hole volumes than cored holes, is generally reduced to only a fraction of the original volume using, for example, a riffle splitter. This subsampled material is then sent to the laboratory for further preparation before analysis. The sample preparation generally consists of a series of crushing and grinding and sample reduction steps resulting in a only a few 100 grams of sample pulp from which the final few 10s of grams are selected for final analysis.

An appreciation and quantification of the inherent variability of the material being sampled and the subsequent errors, including the 'fundamental sampling error', introduced through the sample preparation stages can be assessed through a number of specific tests. This information can then be used to design a sample preparation protocol that reduces the errors introduced during sample reduction to acceptable limits. At the same time the actual methods and equipment used must be selected to ensure representative sampling, particularly to manage the effects of segregation of particle size and density that can lead to sampling bias.

Sample analysis

The final sample results are determined and reported from the assay of the prepared sample material using an appropriate analytical technique. However, different analytical techniques have different levels of precision and in some cases even accuracy, depending on the element being determined and its mode of occurrence. For example, a choice of analytical techniques exists for each of gold, platinum-group elements, nickel and copper. The choice of technique depends on the concentration, type of mineralisation, and even the ultimate recovery method to be used in metallurgical production (Elder, 2000).

The reliability of the assay results should be checked against the results for blanks, standards and duplicate assays from the same batch or period of analysis. Whilst this comparison is normally performed by the laboratory, the resource estimator should at least review this information to be aware of the degree of reliability of the reported assay results.

Sample database

Once all relevant geological and assay data have been collected and approved, then this data should be stored in a final database. The further processing of results, including the geological and grade model of the resource and ore reserve, rely on the integrity of this data. Gilfillan (2001) addresses the technical requirements for due diligence review of geological data leading to the estimation of Mineral Resources and Ore Reserves. He comments on the potential for error that derives from poor manual compilation practices and the lack of verification of physical and analytical data entered into drill logs. He also notes that analytical results often show poor accuracy and/or precision. It is thus essential to test the quality of the data that underlies the estimates and assumptions on which the mine plan is developed.

Mineral resource estimates

The mineral resource modelling and estimation method needs to be fit-for-purpose, for example global estimation for scoping studies or selective estimation for more advanced feasibility and production studies. In both cases, grade continuity should be assessed using variography. The effect of modelling method on over- or under-smoothing of the grade estimates and the effect of this on the reported grade and tonnage should be understood and communicated. As described by Rozman (2001), another factor of importance is the appropriateness of the lower cut-off grade, which is dependent on both geological continuity and product revenue and should be assessed within the context of the mining method (open pit or underground).

Geotechnical assessments

The traditional approach to assessing geotechnical uncertainty is based on a constant factor of safety. In contrast, a risk based minimum total cost approach, which is site specific, recognises the uncertainty of key variables and is based on probabilistic analysis. This method considers the cost of failure versus the initial excavation cost. The optimum open pit slope angle, for example, is that for which total cost is minimised.

Ore reserve estimates

Ore reserve estimates are generated by applying modifying factors to Mineral Resources. The impact of dilution and/or ore loss on ore reserve estimates needs to be fully examined and quantified. This can be particularly important with respect to underground operations. With respect to the ultimate mining limits, a number of techniques currently in use or being developed rely on the optimisation of either open pit operations, underground mining shapes, or the interfaces between open pit and underground operations.

Glacken, Noppe and Titley (2000) demonstrate the use of conditional simulation in representing the risk associated with mining at different bench heights at the Wallaby project in Western Australia. The results were used by mine planners to quantify the variability in reserves for each bench height.

Coombes *et al* (2001) present a study assessing the risk of incorrect prediction of head grade and tonnage for the Murrin Murrin nickel/cobalt orebody in Western Australia. They demonstrate the use of conditional simulation techniques to investigate the variability and to quantify the uncertainty in volume (or grade) at different cut-offs for each geological domain.

Morley, Snowden and Day (1999) examine the potential financial impact of uncertainty with respect to the technical variables fundamental to the estimation of the resource and reserve. Financial simulations using Monte Carlo analysis show that up to 20 per cent of the revenue can be lost due to the introduction of increased levels of uncertainty due to poor sampling practice, inappropriate modelling and resource estimation techniques or a combination of a number of small problems, all representing realistic scenarios. The paper concludes that the most significant single assumption in any financial model relates to the quality of the reserve. This sentiment is endorsed by Amos (2001), who states that, from the project financier's perspective, the most important element is the reserve base, since this provides the sole security for project bank funding.

Economic assumptions

The key economic assumptions in mine planning and orebody evaluation are commodity price, exchange rate and discount rate. While some intelligence may be gained as to the likely value of these key parameters, the risk associated with their (unknown future) values can best be addressed via a simulation study using @RISK or other software. This allows the full range of key economic parameters to be input into cashflow models and ensures that the potential upside and downside is addressed. Rozman (2001) comments that it is never too early in a project's life to attempt to financially model the project. He presents a tabulation of variables such as ore grade and tonnes milled, mill maintenance cost and mill labour cost, together with suggestions as to the distribution type with best and worst case input, to use for risk assessment. Rozman concludes that the risks to a project can often be foreseen from judicious financial modelling at an early stage of a project. This reduces the probability of encountering 'bottle-necks' or 'show stoppers' as the project progresses.

Reality check (reconciliation)

Once projects are in production it is important to check and validate the key assumptions made during the project evaluation. The only way to satisfactorily achieve this is through the process of reconciliation, that is the comparison of actual production (tonnes, grade and metal) with predictions (resources, reserves, mine plans). This is an often-ignored but vital aspect of the mine value chain and allows a reality check on the feasibility process. The difficulty of obtaining an efficient reconciliation should not be an excuse for omitting this process.

QUANTIFYING CONFIDENCE LIMITS

The issue of quantifying confidence limits is thus complex and needs to take into account precision and accuracy, global versus local uncertainty, reporting periods and the scale of production and commodity-specific influences, such as the product specifications required by various customers.

It is thus recommended that a system of relative risk is used. This should reflect the likelihood of risk within nominated limits (depending on impact, eg high impact ±10 per cent, medium impact ±20 per cent, low impact ±30 per cent or more) on tonnes and/or grade as appropriate within a specified reporting period as appropriate.

Taking resource classification, an example of the reporting of the associated risk may be as follows:

Measured — There is a low risk of the quarterly grade being outside nominated limits of the predicted grade (eg 90 per cent confidence that the grade is within ±10 per cent of the actual grade).

Indicated — There is a medium risk of the annual grade being outside nominated limits of the predicted grade (eg 70 per cent confidence that the grade is within ±20 per cent of the actual grade).

Inferred — There is a high risk of the global grade being outside nominated limits of the predicted grade (eg 50 per cent confidence that the grade is within ±30 per cent of the actual grade).

INTEGRATING AND INTERPRETING THE RESULTS

The main learnings over the last five years are encompassed in the words *integrity, integration and impact*.

Integrity

Data integrity has been the subject of numerous papers (Gilfillan, 2001; Lewis, 2001) and the importance of getting the raw data right has been recognised throughout the industry. Current and future trends cover the areas of geological logging (automatic logging devices), survey accuracy (GPS), bulk density measurements (different techniques), subsampling (fundamental sampling error tests), analytical accuracy (standards, checks, duplicates and blanks) and data integrity management including online information and backup systems.

Integration

Resource and ore reserve models demand the integration of analytical results from all the nodes of study, including geological modelling (three-dimensional visualisation), geostatistical analysis (statistics and variography), mining constraints (block size analysis), variability studies (conditional simulation), geotechnical modelling (pit slope stability), recovery issues (metallurgical testing and beneficiation) and financial sensitivities.

Impact

Reality checks using reconciliation information, bulk sampling and mine call factors are brought into consideration when quoting ore reserves, taking into account factors beyond the raw data. Risk analysis using conditional simulation allows the impact of different scenarios to be assessed, for example dilution/ore loss at various bench heights, probability of ore/waste misclassification at different cut-off grades. Financial analysis and scenario testing allows project value ranges to be assessed with respect to corporate exposure during feasibility studies.

THE FUTURE

The future will see higher levels of acceptance of computer modelling and geostatistical tools. Advanced geophysical and geochemical techniques, along with structural interpretation, will lead to better geological control of geostatistical estimates. The emergence of the resource geologist as a recognised profession within the ambit of the earth sciences will lead to formal educational programmes and industry courses. This in turn will lead to better education of resource geologists, and more corporate and commercial support for them to use appropriate tools.

Ravenscroft (1994) describes the use of simulations in the context of reserve estimation and mine planning. He calls for more efficient techniques to allow faster analysis in reasonable time and for mine planning packages to use the distribution of the range of outcomes rather than just the estimated value for each block. Developments in both software and hardware should allow this to happen. But, as Ravenscroft comments, the difficulty is in communicating the information in a meaningful way to financial analysts.

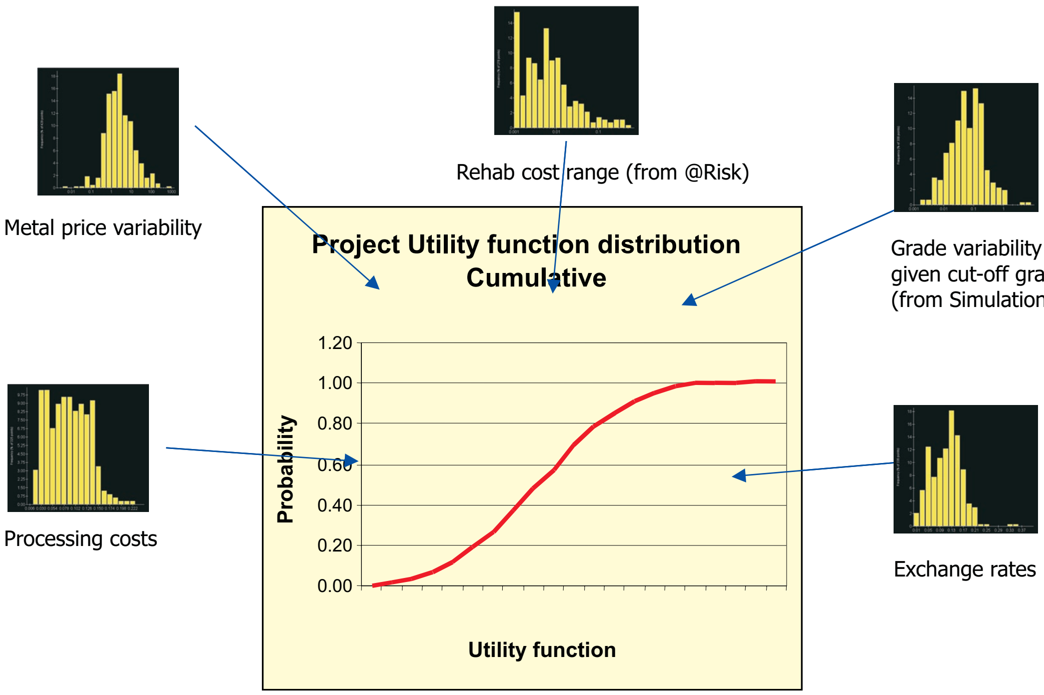

FIG 6 - Illustration of the concept of a project utility function combining the key sources of project risk.

There is as yet no single tool that allows us to combine all the uncertainties of mining when assessing risk. One of the challenges for the mining industry is to develop a tool for overall risk control allowing financial and resource/reserve evaluation personnel to address the bigger picture which encompasses technical, financial, corporate, political, health and safety risk. This will lead to an improved understanding of the key input parameters and their effect on the bottom line.

One promising approach has been proposed by Rendu (1999), who describes the concept of the *risk utility function*. Rendu describes this conceptual approach as a way of linking a number of critical project indicators (eg NPV, cash cost, production rate, environmental liability, geological risk) to the value of a project. Values are developed for each of these critical project indicators (which are defined by conventional sensitivity analysis, simulation, or expert opinion) and their contribution to the overall project utility function is also assessed using a mixture of quantitative and qualitative tools. Simulation is used to develop a distribution of values for the project utility function and this distribution is compared against hurdle rates for project selection. The great advantage of this approach is that it attempts to integrate all of the key project risk indicators into a single numerical value. This approach is conceptually illustrated in Figure 6.

REFERENCES

Amos, Q G, 2001. Resources and risk – a lenders's view, in *Mineral Resource and Ore Reserve Estimation – The AusIMM Guide To Good Practice*, pp511-517 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Barnett, D W and Sorentino, C, 1994. Discounted cash flow methods and the capital asset pricing model, in *Proceedings Mineral Valuation Methodologies 1994 (VALMIN '94)* pp 17-35 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Clemen, R T, 1990. *Making Hard Decisions – An Introduction to Decision Analysis*, 557 pp (Duxbury Press: California).

Coombes, J, Thomas, G S, Jepsen, L and Gifford, M, 2001. Assessing the risk of incorrect prediction – a nickel/cobalt case study, in *Mineral Resource and Ore Reserve Estimation – The AusIMM Guide to Good Practice*, pp527-533 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Elder, D J, 2000. Leachwell versus fire assay: comments from assay quality assurance at Tarmoola Gold Mine, in *Proceedings Fourth International Mining Geology Conference*, pp 43-52 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Gilfillan, J F, 2001. The resource database audit, in *Mineral Resource and Ore Reserve Estimation – The AusIMM Guide to Good Practice* pp 91-96 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Glacken, I M, Noppe, M A and Titley, M, 2000. Mining bench height evaluation for the Wallaby resource – a conditional simulation case study, in *Proceedings Fourth International Mining Geology Conference*, pp 195-205 (The Australasian Institute of Mining and Metallurgy: Melbourne).

JORC, 1999. Australasian Code for Reporting of Mineral Resources and Ore Reserves (The JORC Code), The Joint Ore Reserves Committee of The Australasian Institute of Mining and Metallurgy, Australian Institute of Geoscientists and Minerals Council of Australia.

Lewis, R W, 2001. The resource database: now and in the future, in *Mineral Resource and Ore Reserve Estimation – The AusIMM Guide to Good Practice,* pp 43-48 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Morley, C, Snowden, D V and Day, D, 1999. Financial impact of resource/reserve uncertainty, *Colloquium on Bankable Feasibility Studies and Project Financing for Mining Projects* (South African Institute of Mining and Metallurgy: Johannesburg).

Newendorp, D, 1975. *Decision analysis for petroleum exploration* (The Petroleum Publishing Company: Tulsa, Oklahoma).

Ravenscroft, P, 1994. Conditional simulations for mining: practical implementation in an industrial environment, in *Geostatistical Simulations: Proceedings of the Geostatistical Simulation Workshop, Fontainebleau,* (Eds: M Armstrong and P Dowd) 99, pp 79-88 (Kluwer Academic Press).

Rendu, J M, 1999. Geostatistical simulations for risk assessment and decision making: the mining industry perspective, *International Symposium on Geostatistical Simulations in Mining,* (The W H Bryan Centre and the Geostatistical Association of Australasia).

Rozman, L I, 1998. Measuring and managing the risk in resources and reserves, in *Towards 2000 — Ore Reserves and Finance*, pp 43-55 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Rozman, L I, 2001. Measuring and managing the risk in mineral resources and ore reserves, in *Mineral Resource and Ore Reserve Estimation – The AusIMM Guide to Good Practice,* pp 519-526 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Rozman, L I and West, R F, 2001. Risk in resource and reserve estimation, in *Mineral Resource and Ore Reserve Estimation – The AusIMM Guide to Good Practice,* pp 499-503 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Seymour, C, 1998. Risk analysis in open pit mine planning, in *Proceedings AusIMM '98 Annual Conference — The Mining Cycle*, pp 129-134 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Sorentino, D and Barnett, D W, 1994. Financial risk and probability analysis in mineral valuation, in *Proceedings Mineral Valuation Methodology 1994 (VALMIN '94)* pp 81-101 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Thomas, G, Coombes, J and Richards, W L, 1998. Practical conditional simulation for geologists and mining engineers, in *Proceedings Third Regional APCOM Symposium*, pp 19-26 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Vose, D, 2001. *Risk Analysis – A Quantitative Guide*, 418 pp (Wiley: England).

Warren, M J, 1991. Pre-feasibility and feasibility studies: A case for improvements, in *Proceedings Mining Industry Optimisation Conference (MINOPT '91)* pp 1-11 (The Australasian Institute of Mining and Metallurgy: Melbourne).