A Process to Improve Expected Value of Mining Operations

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Abstract

This paper presents an improved appraisal process that correctly recognizes the increased expected value of mining operations attributable to intelligent management response to changing operating conditions and market prices. It recognizes the option value of flexibility in the exploitation of deposits, and thus leads to better selection of properties for finance and development. This evaluation method is based upon a computationally efficient procedure for examining the opportunities provided by possible price changes that may occur over the project lifetime. It implicitly looks at all possible future price scenarios using a limited range of typical price profiles, therefore covering the range of possibilities without exploring it exhaustively. It contrasts with conventional analyses that assume that prices do not fluctuate through the lifetime of the project. The procedure was developed in collaboration with experienced mining professionals and actual cases in mining and other extractive industries.

Keywords: Mining finance; Mining economics; Mining valuation; Flexible mine design; Flexible mining operations; Flexibility; Real options; Simulations

List of symbols and acronyms:

NPV: Net Present Value
ENPV: Expected Net Present Value
VARG: Value At Risk and Gain
GBM: Geometric Brownian Motion
$\mu_{monthly}$: monthly average growth factor for commodity price
μ_{60}: average growth factor compounded over sixty months
$\sigma_{monthly}$: monthly volatility in commodity price
σ_{60}: monthly volatility compounded over sixty months
$E[V_{With\ Method}]$ = expected value recognized using proposed method
$ENPV_{With\ Method}$ = expected net present value using proposed method
$NPV_{Basic\ Economic\ Model}$ = net present value using basic economic model

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1 Introduction

Standard appraisals in the mining industry assess the value of mining operations using one or a few constant prices for the product, with possible bounds on high and low values. This approach is recurrent in several industries such as oil and gas extraction, automotive, real estate, and aerospace industries. Typically, no attempt is made at a conceptual evaluation stage to analyze explicitly the consequences for design and operations of the wide range of possible prices over time that affect project value, financial profits, and performance.

Figure 1 presents the general situation. It illustrates the reality that mining operators typically have some flexibility in choosing between different infrastructure and system configurations to operate the mine, depending on the mine type and extraction method. They can adjust operations as conditions and prices change over the life of the project to maximize benefits from current price conditions. Thus in reality there are many possible cash flow scenarios, depending on the operator's responses to price changes.

Initial Design ⇒	Uncertain Variables ⇒	Operating Plan ⇒	Lifetime Performance
Physical infrastructure and system (Many possibilities)	Price vector over project lifetime (Many possibilities)	Best use of existing facilities; development of additional facilities (Many possibilities)	Realized net present value, rate of return, etc. (Many possibilities)

Figure 1: Reality faced by operators in appraisal process of a mining project[1].

The concept of an *operating plan*, or mining plan, is crucial in this connection. It defines how managers should optimally operate the project given the available infrastructure (e.g. crushing mills, trucks, etc), the quality and location of deposit, and the prevailing prices. The determination of the best operating plan for any single set of conditions requires solving a large combinatorial problem that is in general difficult and expensive to analyze. The optimal mine plan can cost thousands of dollars, with a turn-around time of several days, in addition to the time and effort taken to model the deposit so it can be analyzed. In practice, managers of active mines update operating plans periodically, say once every several months to provide improved production forecasts utilizing the latest available data. Crucially, however, analysts evaluating prospective projects usually have substantially less time and limited budgets.

Current appraisals deal with the situation by oversimplifying the problem. The standard analysis, exemplified in Figure 2, considers only one deterministic price vector over the project lifetime. Obviously, professionals know that prices fluctuate and that corresponding operating plans are adjusted accordingly, but they often do not translate this reality into feasible appraisal processes. They account for price and other uncertainties by adjusting these factors in the single cash flow analysis (e.g. through sensitivity analysis). This approach is better than ignoring the uncertainties, but is unrealistic. It neglects that managers routinely tune their operating plans to prevailing situation – exploiting good opportunities and exiting bad situations – in both cases improving on the assumption embedded in the standard appraisal that the project operates on a single fixed operating plan.

Initial Design ⇒	Uncertain Variables ⇒	Operating Plan ⇒	Lifetime Performance
Physical infrastructure and system (Many possibilities)	Price vector over project lifetime (1 scenario)	Best use of existing facilities; development of additional facilities (1 operating plan)	Realized net present value, rate of return, etc. (1 cash flow)

Figure 2: Schema of current practice for the appraisal process[1].

The process presented in this paper breaks this limitation. It introduces a computationally efficient method that reflects the reality that intelligent project management will increase value beyond that indicated by the operating plan associated with a fixed price. This breakthrough is achieved through use of a *catalogue* of operating plans. This catalogue covers the spectrum of possible uncertain scenarios, allowing the analysts to account realistically for price and other variations. Figure 3 indicates where this catalogue fits into the appraisal process.

Initial Design ⇒	Uncertain Variables ⇒	Operating Plan ⇒	Lifetime Performance
Physical infrastructure and system (Many possibilities)	Price vector over project lifetime (Many possibilities)	**A Catalogue of a major possible responses** (Some possibilities)	Realized Net Present Value, Rate of Return, etc. (Many possibilities)

Figure 3: Role of catalogue of operating plans in appraisal process[1].

2 The Catalogue Concept

The catalogue is a limited, representative set of operating plans covering the range of possible plans that would each be associated to a unique evolution of price. In practice, the analysis process matches each possible price scenario with an operating plan drawn from the catalogue. While not optimal, this operating plan will fit reasonably well – certainly much better than the current alternative, which assumes that "one size fits all".

The catalogue enables the appraisal process to examine realistically the range of possible price scenarios that might occur. It is most useful at the desktop/conceptual appraisal phase of the project, prior to pre-feasibility and feasibility studies involving more mining details and data. Associating each price scenario with one of the operating plans in simulations leads to one NPV measure for each price scenario, which further leads to an approximate measure of ENPV. This value measure is more appropriate than calculating an average NPV based on one average price scenario (as stated by Brennan and Schwartz[2]).

This analysis systematically increases the estimated value of projects when compared to standard appraisals. This is because it recognizes that intelligent mine management reduces the impact of low prices and takes advantage of high prices in operations.

3 Proposed Appraisal Process Applied to a Mining Project

This section illustrates application of the proposed appraisal process to a simple hypothetical mining project. It consists of four steps. These build upon a basic economic model of the project, of the sort required for the standard appraisal process. The essence of the steps is to identify the uncertain scenarios, define how the project managers would deal with them, and thus develop a realistic estimate of the overall value of a project.

Basic Economic Model of the Project

The basic economic model includes the following assumptions, embedded in the spreadsheet in Table 1:

- Forecasted ore price: $2,000/ton, based on historical average, with 0% annual growth
- Initial production: 600,000 tons
- Annual production growth: 1%/year
- Initial operating cost: $1,000/ton produced
- Annual operating cost growth: 1%/year
- Fixed annual cost: $75 million
- Capital expenditures: $3.3 billion, half at project start and half at project midlife
- Project duration: 10 years
- Discount rate: 10%

This typical appraisal process calculates value of the discounted cash flow. In this case, the NPV is about $543 million.

Table 1: Spreadsheet for basic economic model of the project.

Year (end of)	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Period	0	1	2	3	4	5	6	7	8	9	10
Price ($/ton)	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000
Production (tons, million)	0.000	0.600	0.606	0.612	0.618	0.624	0.631	0.637	0.643	0.650	0.656
Operating Costs ($/ton)	$0	$1,000	$1,010	$1,020	$1,030	$1,041	$1,051	$1,062	$1,072	$1,083	$1,094
Gross Operating Income ($, million)	$0	$600	$600	$600	$599	$599	$598	$598	$597	$596	$595
Fixed cost ($, million)	$0	$75	$75	$75	$75	$75	$75	$75	$75	$75	$75
Capital Investment ($, million)	$1,650	$0	$0	$0	$0	$1,650	$0	$0	$0	$0	$0
Net Benefits ($, million)	-$1,650	$525	$525	$525	$524	-$1,126	$523	$523	$522	$521	$520
Discount factor	1.00	1.10	1.21	1.33	1.46	1.61	1.77	1.95	2.14	2.36	2.59
PV Net Benefits ($, million)	-$1,650	$477	$434	$394	$358	-$699	$295	$268	$243	$221	$200
NPV ($, million)	**$543**										

Step 1: Define representative uncertain scenarios

Step 1 finds typical price scenarios useful for analysis. Although uncertainty exists in demand for product, mineral content in the deposit, resource and reserves, operating parameters, etc, this paper focuses on price only for demonstration purposes. Other factors can easily be included. Also, there is no one clear approach to identify scenarios spanning all possible outcomes[3]. Brainstorming and expert judgment are particularly useful here.

The analysis starts from deterministic projections of price for the project lifetime, as done in the basic economic model. The price model then incorporates fluctuations based on expert assumptions about relevant probability distributions.

A hypothetical stochastic price process is shown in Figure 4, using a standard GBM model. To be consistent with the assumption of no price growth, the monthly average growth factor $\mu_{monthly}$ is set to 0%. Monthly volatility $\sigma_{monthly}$ can be extracted as well from historical data (here, $\sigma_{monthly} = 2\%$). While hypothetical monthly volatilities and average growth rate are used here, cash flows reported in Table 1 are on an annual basis to simplify presentation, although they can be produced on a monthly schedule. Also, using a smaller time scale for volatility, average growth rate, and cash flows is advisable in the decision-making process as outlined by Nicholas, Coward, Rendall, and Thurston[4].

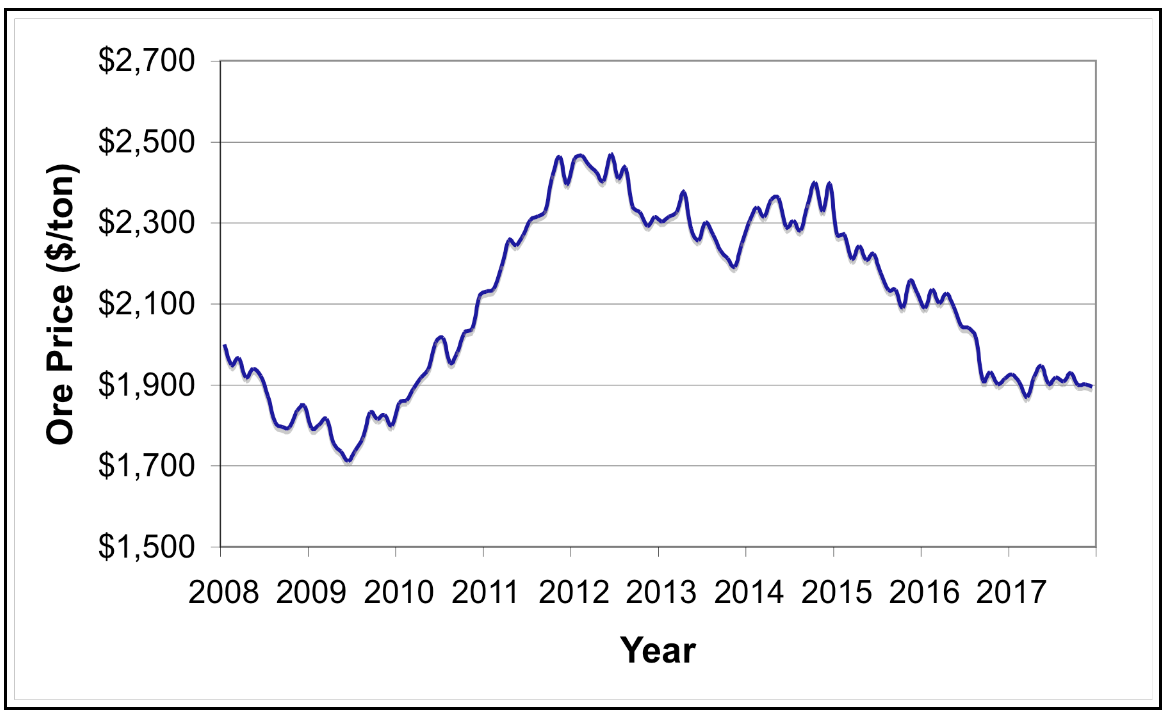

Figure 4: Example of simulated price fluctuations based on a GBM model ($\mu_{monthly}$ = 0%, $\sigma_{monthly}$ = 2%).

The analysis proceeds with simulation of a few price scenarios, and appropriate organization to facilitate visualization (see Figure 5).

Then, scenarios are analyzed to uncover useful characteristics for categorization. Ideally, the characteristics represent adequately the set of possible price scenarios that may emerge in reality. Looking at the price fluctuations in Figure 5, one observes an overall price change over the first few years of the project. This change, expressed in percent, can be used as a characteristic to classify representative scenarios, although analysts may use any characteristic of their choosing.

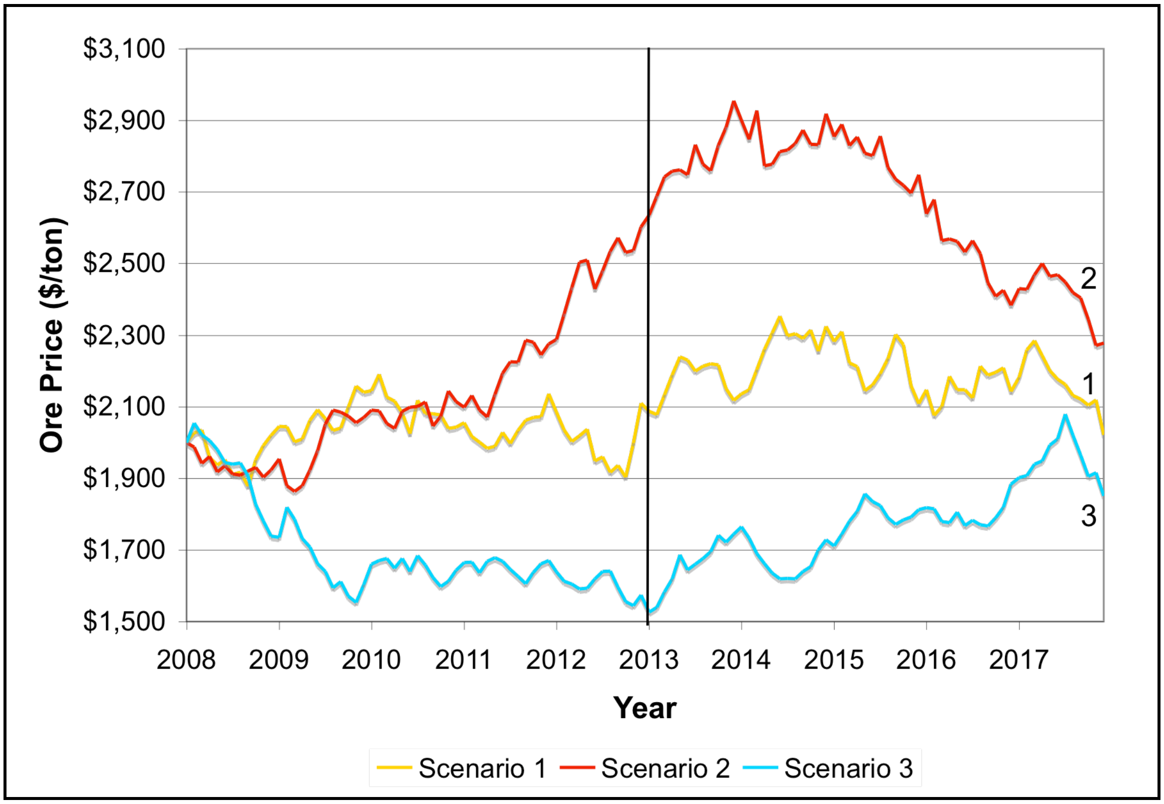

Figure 5: Visualization of price scenarios to uncover characteristics useful for categorization. Three scenarios show examples of close-to-zero (scenario 1), positive (scenario 2), and negative (scenario 3) price change between years 1 and 5.

A useful approach inspired from Cardin[5] uses price percentage change between years 1 and 5 (start of 2008 to the end of 2012) to create three representative categories: 1) positive, 2) zero, and 3) negative price change. These rely on μ_{60}, the average growth factor $\mu_{monthly}$ compounded over sixty months ($\mu_{60} = (1 + \mu_{monthly})^{60} - 1 = 0\%$), and σ_{60}, the compounded monthly volatility $\sigma_{monthly}$ ($\sigma_{60} = \sigma_{monthly}\sqrt{60} = 0.154$). Price scenarios with percentage change greater than $\mu_{60} + \sigma_{60}/2$ are associated to category 1. Scenarios with price change between $\mu_{60} + \sigma_{60}/2$ and $\mu_{60} - \sigma_{60}/2$ are assimilated to category 2, while price changes below $\mu_{60} - \sigma_{60}/2$ are classified as category 3. Category 1 scenarios thus have a price change above 7.7%, category 2 between 7.7% and -7.7%, while category 3 is anything below -7.7%. Table 2 summarizes the categories and price change percentages.

Table 2: Categories used to classify price scenarios with associated percentage changes between years 1 and 5.

Price scenario category	Price change requirement	Boundary values (%)
1	price change > $\mu_{60} + \sigma_{60}/2$	7.7%
2	$\mu_{60} - \sigma_{60}/2 \leq$ price change $\leq \mu_{60} + \sigma_{60}/2$	
3	price change < $\mu_{60} - \sigma_{60}/2$	-7.7%

Step 2: Determine the main sources of flexibility

This step identifies how project managers can alter operations to take advantage of new opportunities, or cut losses, resulting from price fluctuations. Brennan and Schwartz[2] raised such idea of flexibility in operations after the paper by Black and Scholes[6]. In many mining cases, the sources of flexibility are obvious. For example, in open pit mining, managers have the option to change how the pit will be developed. In other situations, such as for underground mines, more effort is needed to define the types of flexibilities to incorporate, and thus the possible operating plans[7]. Frameworks proposed by Bartolomei[8], Cardin[5], Kalligeros[9], de Weck and Suh[10], and Wang[11] help finding potential sources of flexibility.

Following de Neufville[1], the flexibility to change the size of crushing mills, the size of truck fleets, and the type of mining activity (e.g. unearthing easily accessible ore vs. dealing with the overburden vs. completely abandoning the project) are exploited to adjust production capacity to changing price conditions. These sources of flexibility can be easily incorporated in the simulation model in Excel® using conditional statements (e.g. `if, max, min`).

To exploit the flexibility to expand or contract production capacity, the project is separated into two phases. Phase I lasts for the first five years (start of 2008 to the end of 2012) and Phase II the remaining years (2013-2017). Phase I assumes that operations occur according to the assumptions of the basic economic model above. The flexibility gives the right but not the obligation to expand, keep as is, or reduce production capacity at the end of year 2012.

Step 3: Create the catalogue of operating plans

This step finds the best operating plan for each representative price scenario from step 1. Cardin[5] proposes a structured approach for crafting more detailed operating plans if necessary, such as in pre-feasibility and feasibility evaluation phases. The level of detail is up to the analyst. The proposed process is however most useful at the desktop/conceptual stage, where less detailed mining and treatment data are available.

In light of the three representative categories of price change introduced in step 1, the following three operating plans are suggested in Table 3:

Table 3: Operating plans associated to representative price categories from step 1.

Model Assumptions	Operating Plans (for Phase II only)		
	1) Positive price change	2) Zero price change	3) Negative price change
Initial production for Phase II (tons, million)	1.2	0.6	0.0
Production growth (annual)	2%	1%	0%
Initial operating cost ($/ton)	$1,200	$1,000	$0
Operating cost growth (annual)	2%	1%	0%
Fixed cost ($, million)	$75.0	$75.0	$75.0
Fixed cost growth (annual)	0%	0%	0%
Discount rate	10%	10%	10%
Investment ($, million)	$3,300	$3,300	$0

Operating plan 1 is associated to positive price change category 1 in Table 2. It is conceptualized as one where valuable ore is extracted in areas of the mine where it is easily accessible to take advantage of positive price. It uses for instance large crushing mills and truck fleets to accelerate production. This operating plan expands production capacity right at the beginning of Phase II so that initial production and annual production growth are doubled to 1.2M tons and 2% respectively. This increases operating cost to $1,200/ton, while leaving fixed costs and initial investment untouched.

Operating plan 2 corresponds to initial assumptions of the basic economic model of no price change. If price evolution in Phase I does not justify expansion or contraction of production capacity, the same operating plan is used in Phase II.

Operating plan 3 represents the case where production operations are temporarily abandoned in Phase II due to negative price change. Production and operating costs are therefore zero. Fixed cost remains at $75 million and no further investment is made.

Potential correlations between commodity price scenarios and elements of the operating plan can be explicitly considered at this stage if desired. This is useful to represent the reality that commodity price is typically linked to other economic conditions. For example, one may insert a positive correlation between ore price and initial operating cost. Similarly, one may invest in larger truck fleets and crushing mills for positive price operating plans, or reflect the possible increase in lower cut-off grades mining reserves when prices are favourable. For brevity, these elements are not detailed here, but can be incorporated in the analysis.

Step 4: Assess the project value

Step 4 measures the expected value added to the project by recognizing operators' ability to choose a particular mine plan given observations of prices. This approach uses price vector simulations to approximate what might happen in reality if no forecast is imposed. The usefulness of Monte Carlo simulations in the process development and modelling of mining projects has been demonstrated by several authors[12, 13, 14].

For each scenario, an operating plan is associated to one category presented in Table 2. The value added by the process is the difference between the ENPV obtained using the flexible operating plans, and the value obtained with one operating plan and one deterministic projection of price scenario, as done in the basic economic model.

The approach for valuing the mining project has three parts. First, Monte Carlo simulations are used to represent a variety of possible price vectors over the lifetime of the project. Here, one hundred price vectors are used.

Second, each scenario is associated with an operating plan following the categories defined in step 1, and operating plans built in step 3, leading to one NPV measure. This value is measured from the cash flow stream arising from the application of the operating plan to the particular price scenario.

For example, price scenario 2 in Figure 5 has a percentage change of 32% between years 1 and 5 (Phase I). Table 2 shows that percentage change above 7.7% is associated to operating plan 1 in Table 3 to deal with positive price change. Therefore, operating plan 1 is associated to this simulated scenario, which provides one given NPV measure. Similarly, simulated scenarios with price change between 7.7% and -7.7% are associated to operating plan 2 for no significant price change. All other scenarios with price change below -7.7% are associated to operating plan 3.

NPV results from one hundred price scenario simulations are in Figure 6. The distribution of operating plans assignment is shown in Figure 7. The distribution of NPV outcomes using a VARG curve shows, in Figure 8, a cumulative frequency distribution function of outcomes. For instance, Figure 8 shows there is a 10% chance of obtaining NPV values below -$320 million, and a 10% chance of NPV above $3.5 billion.

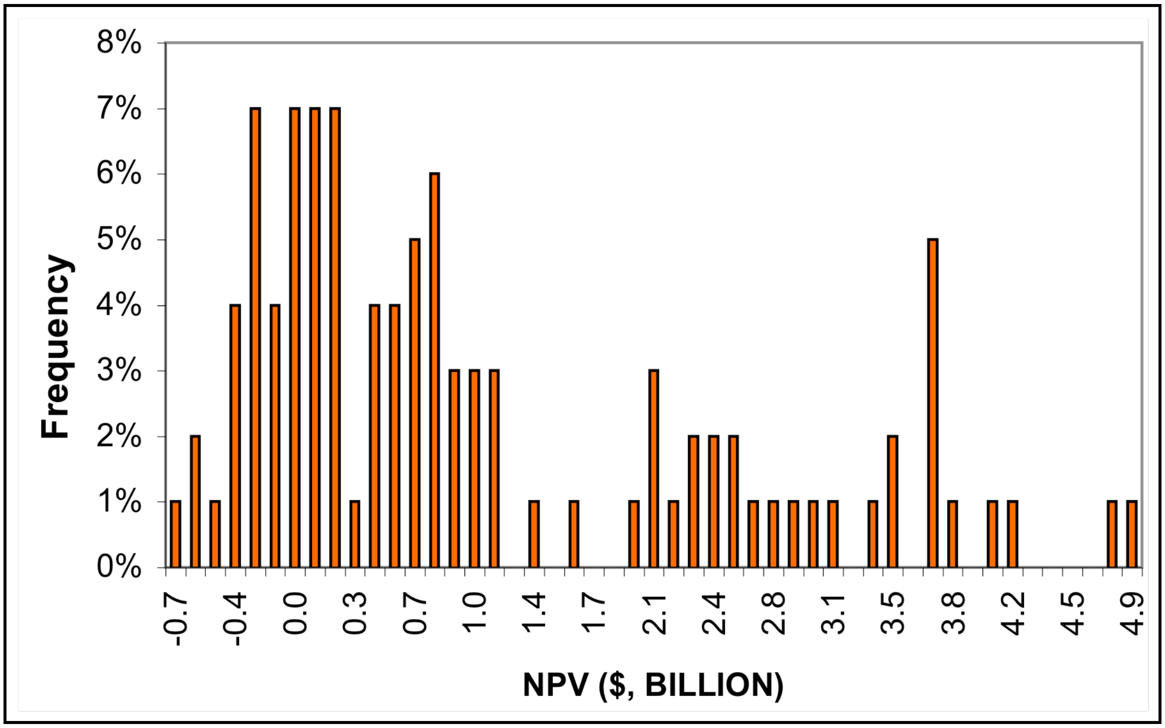

Figure 6: Example of histogram distribution resulting from Monte Carlo simulations using the catalogue of three operating plans.

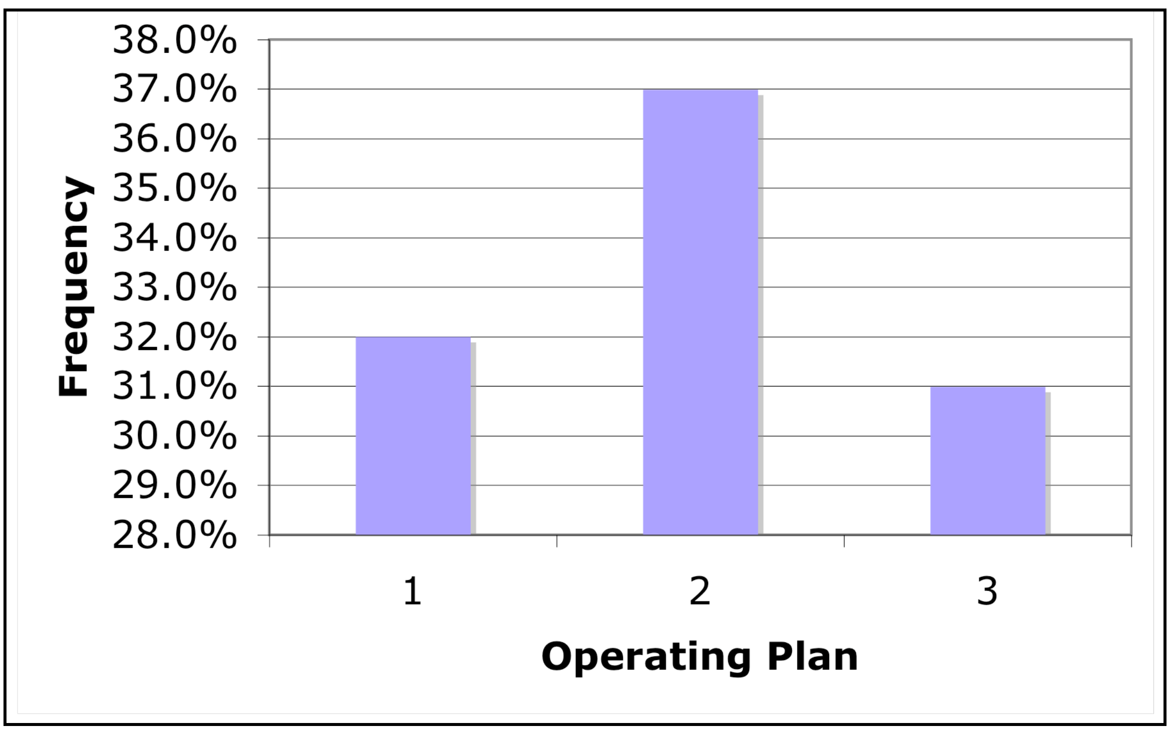

Figure 7: Assignment frequency for the three operating plans across one hundred simulations of price scenario.

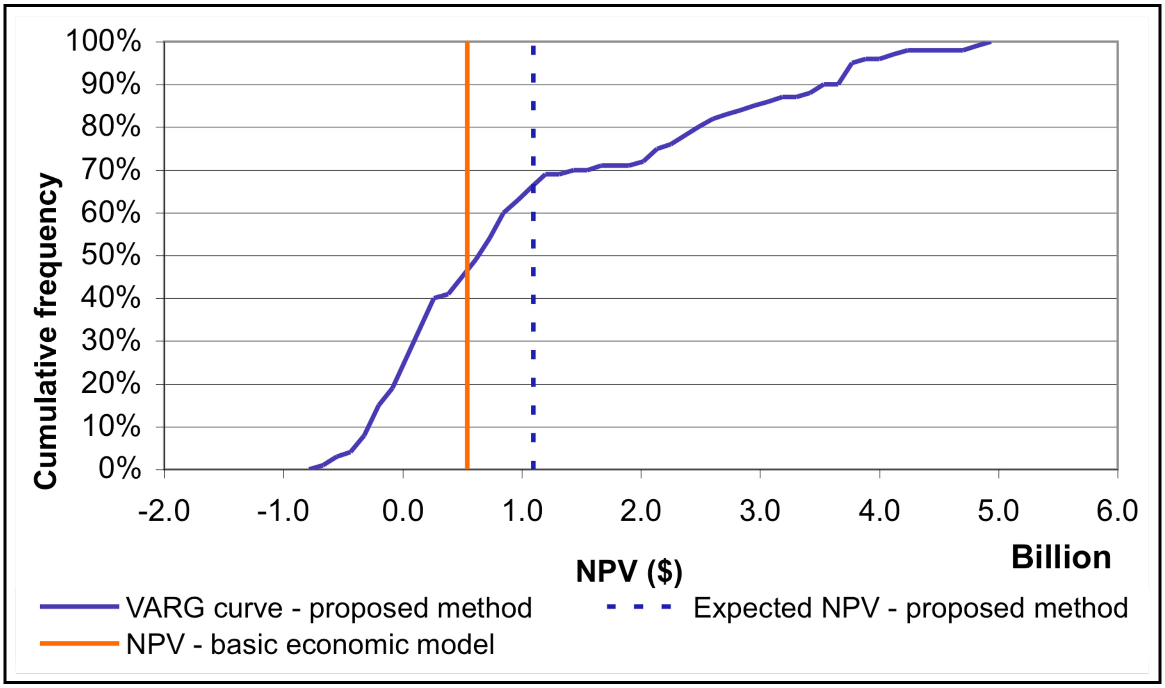

Figure 8: Example of VARG curve depicting the range of NPV outcomes for a particular mining project. The deterministic NPV (solid) and ENPV (or mean NPV) (dashed) are shown as vertical lines.

Simulations also provide central and dispersion measures, as Table 4 shows. Such information is not available for the basic economic model using a deterministic price projection. The ENPV ($1.1 billion) is now higher than the one obtained using deterministic price projections in Table 1 ($0.5 billion).

Table 4: Result comparison between the proposed method and the basic economic model with a deterministic forecast.

	Proposed method (in billion $)	Basic economic model (in billion $)
Expected NPV	$1.1	$0.5
Standard Deviation	$1.4	N/A
Maximum NPV	$4.9	N/A
Minimum NPV	-$0.8	N/A

Third, the expected value recognized by the appraisal process is calculated as follows:

$$E[V_{With\ method}] = ENPV_{With\ method} - NPV_{Basic\ economic\ model} = \$1.1 - \$0.5 = \$0.6 \text{ billion}$$

This quantity is an approximate measure of the value added by recognizing 1) the flexibility incorporated in design to ease transitions in operations between different price manifestations, and 2) the flexibility to adjust operations to changing uncertain conditions. The analysis indicates that the value of the asset, using the standard method, is underestimated by ignoring the incorporated flexibility component in design and operations.

4 Discussion and Conclusion

The proposed evaluation method recognizes value already existing in mining operations by making use of a catalogue of operating plans at a conceptual/desktop evaluation stage. It introduces a computationally efficient appraisal process that correctly recognizes the value of projects inherent to the intelligent management of the mine, by explicitly considering flexibility in design and management of the system prior to operations.

By recognizing explicitly uncertainty through Monte Carlo simulations, the process changes the paradigm from using one price scenario, one operating plan, and one NPV measurement (as done in the basic economic model) to a *distribution* of possible NPV outcomes (Figure 6). More information about the project's expected value, volatility, and dispersion becomes available to operators and decision-makers (e.g. ENPV, standard deviation, maximum and minimum NPV). Recognizing flexibility acts on the distribution of outcomes. Capitalizing on upside opportunities extends further to the right the VARG curve on Figure 8, while reducing exposure to downside risk pushes further to the right the left end tail of the curve.

The proposed appraisal process may affect the selection and properties of the best project for finance, development, and optimization of operating parameters. It is transparent and intuitive to mining professionals, and measures more realistically the value of mining project than currently done in industry.

Acknowledgments

The authors thank Miguel Romero Casanova and Juan Carlos Peña from Codelco Norte, as well as Felipe Azócar H., Cristián Barrientos Parant, Miguel Cabrera Reyes, and Juan Camus from Codelco Casa Matriz for their advice and experience in the mining industry, in support of the ideas developed in this paper. We are also grateful for the financial support provided by BP, the MITRE Corporation, the Fonds Québécois de la Recherche sur la Nature et les Technologies, and the Natural Sciences and Engineering Research Council of Canada.

Figure Captions

References

[1] R. de Neufville: 'Analysis Methodology for the Design of Complex Systems in Uncertain Environment: Application to Mining Industry', Internal Report, Engineering Systems Division, MIT, Cambridge, MA, 2006.

[2] M.J. Brennan and E.S. Schwartz: 'Evaluating Natural Resource Investments', *The Journal of Business*, 1985, **58 No. 2**,135-157.

[3] R. Bratvold, S.H Begg, and J.C. Campbell: 'Would you know a good decision if you saw one?', *Proceedings of SPE ATCE*, 2002, **Paper #77509**.

[4] G. Nicholas, M. Rendall, S. Coward, and M.Thurston: 'Decision-Making using an Integrated Evaluation Model versus Sensitivity Analysis and Monte Carlo simulation', CIM Conference and Exhibition: Energy and Mines, 2007.

[5] M-A. Cardin: 'Facing Reality: Design and Management of Flexible Engineering Systems', MS Thesis, Engineering Systems Division, MIT, Cambridge, MA, 2007. http://web.mit.edu/macardin/www/papers/Cardin2007-MIT_Thesis.pdf

[6] F. Black and M. Scholes: 'The Pricing of Options and Corporate Liabilities', *Journal of Political Economy*, 1973, **81 No. 3**, 637-654.

[7] Z. Mayer and V.N. Kazakidis: 'Decision Making in Flexible Mine Production System Design Using Real Options', *Journal of Construction Engineering and Management*, ASCE, 2007, **133 No. 2**, 169-180.

[8] J. Bartolomei: 'Qualitative Knowledge Construction for Engineering Systems: Extending the Design Structure Matrix Methodology in Scope and Perspective', PhD Dissertation, Engineering Systems Division, MIT, Cambridge, MA, 2007. http://ardent.mit.edu/real_options/Real_opts_papers/Bartolomei%20Thesis.pdf

[9] K. Kalligeros, K.: 'Platforms and Real Options in Large-Scale Engineering Systems', Doctoral Dissertation, Engineering Systems Division, Massachusetts Institute of Technology, Cambridge, MA, 2006. http://ardent.mit.edu/real_options/Real_opts_papers/Kalligeros%20Dissertation.pdf

[10] O. de Weck, O. and E.S. Suh: 'Flexible Product Platforms: Framework and Case Study', DETC2006-99163, Proceedings of IDETC/CIE 2006 ASME 2006 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, Philadelphia, PA, 2006.

[11] T. Wang: 'Real Options 'In' Projects and Systems Design – Identification of Options and Solutions for Path Dependency', PhD Dissertation, Engineering Systems Division, MIT, Cambridge, MA, 2005. http://ardent.mit.edu/real_options/Real_opts_papers/tao%20dissertation.pdf

[12] W.D. Kelton, R.P. Sadowski, and D.A. Sadowski: 'Simulation with Arena', 2nd edition, 2002, Boston, MA, McGraw-Hill.

[13] S.A. Kenzap, L. J. Peloquin, and V. N. Kazakidis: 'Use of Discrete-Event Simulation for Evaluation of Quality in Hard Rock Mine Lateral Development', *International Journal of Mineral Resources Engineering*, 2007, **12 No. 1**, 49-72.

[14] J.R. Sturgul and Z. Li: 'New Developments in Simulation Technology and Applications in the Minerals Industry', *International Journal of Surface Mining, Reclamation and Environment*, 1997, **11**, 159-162.