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Evaluating mine plans under uncertainty: Can the real options make a difference?

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Received 7 February 2007; received in revised form 20 June 2007; accepted 21 June 2007

Abstract

Over the last few years, many studies have presented the real options valuation (ROV) as a promising technique of valuing natural resource investments under conditions of uncertainty. Apart from the common conclusion that the ROV is better than the conventional net present value (NPV) method in integrating the value of management flexibility and proper handling of cash flows risk, there is a lack of procedures for testing the usefulness and advantages of the ROV over the static NPV method in practice. Arguably, it is not yet clear whether the ROV can deal with the complexity of mining projects and whether it can really be applied to make decisions that improve project value.

This work aims to take steps towards filling the gap in existing literature by dealing with the above-mentioned concerns. First, this paper proposes a simulation-based ROV method that can handle multiple uncertainties as well as the variability of cash flow parameters that characterize mining projects. Second, the paper presents an example for investigating the impact ROV may have on project profitability, by improving the decision making process. A case study of selecting the most profitable design and production sequence for an actual Australian gold mine under multiple sources of uncertainty is provided. Both the conventional NPV method and the proposed real options technique are applied to evaluate the various technically feasible mine plans with fixed schedules so as to select the most economically appealing one. The results show that the design based on value maximization indicated by the static NPV method is different from that of the ROV. Comparing the design values estimated based on the actual market data recommended by both techniques shows that the value of the ROV-based design is 11–18% higher than the value of the NPV-based design.

JEL classification: C63; D81; G13; L72

Keywords: Mine evaluation; Uncertainty; Real options

Introduction

The real options valuation (ROV) has gained much interest over the last two decades. It has been regarded among researchers and economists as a means of better assessing investment proposals under uncertain market conditions which characterize most capital investments. As explained by Mardones (1993), Trigeorgis (1996) and Samis and Poulin (1998), under conditions of uncertainty, the ROV performs better than the conventional discounted cash flow (DCF) methods such as the net present value (NPV) and the internal rate of return (IRR) methods. The main reason is that the ROV can incorporate the value of management flexibility to change or revise decisions with time based on the new market conditions. Therefore, when applying the same discounting procedure, the value of a project estimated by the ROV is always higher than that estimated by the conventional NPV method. Dixit and Pindyck (1994), Moyen et al. (1996) and Miller and Park (2002) illustrate that the difference between the two estimates depends on the levels of uncertainty and profitability of the underlying project. Another important difference between the ROV and the DCF methods is

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0301-4207/$ - see front matter
doi:10.1016/j.resourpol.2007.06.003

related to the way of accounting for risk in cash flow components. As discussed by Samis et al. (2006), the conventional analysis does not account for the difference in risk profile between costs and revenues while that difference is accounted for in the ROV.

The typical practice in valuing mining investments using the ROV is to assume that the mine will be producing a constant, definite amount of metal units throughout its lifetime under uncertain future metal prices, as in Brennan and Schwartz (1985), Dixit and Pindyck (1994), Schwartz (1997), and Kelly (1998). In the mining industry, the situation is much more complex than the simple scenario assumed in most of the current literature. For instance, despite the recent advances in exploration and ore estimation techniques, the total amount of metal units within a deposit can never be known with certainty. Moreover, since the quality of ore varies substantially throughout the deposit, assuming that metal units will flow at a constant rate throughout the lifetime of the mine could be an extreme simplification. In reality, the amount of metal units produced per year is highly variable and uncertain. As explained by Monkhouse and Yeates (2005), ignoring such uncertainties and implementing the valuations using a single set of assumptions about ore tonnages and grades will result in a wrong estimate of project value. In addition to the geological uncertainty, another important source of risk affecting the profitability of mining operations is that related to the uncertainty of foreign exchange rates. This source of risk is of particular importance for major metal producing countries such as Australia, South Africa and Canada. Therefore, if a mining project produces only one commodity, there will be at least three kinds of risk affecting its profitability: geological risk, metal price risk and foreign exchange rate risk. A more complex situation is encountered when a mine produces two or more commodities as with many base-metal mines. In such cases, there will be multiple uncertain metal prices to be dealt with in addition to the geological and foreign exchange rate risks.

The key issue now is to investigate whether the currently available techniques for valuing real options are well suited to face the above-described challenges without introducing unrealistic simplifications. The first, and probably the most famous, model for valuing options is that developed by Black and Scholes (1973) for European financial options. However, as explained by Barraquand (1995) and Berridge and Schumacher (2004), the Black–Scholes model is not suitable for valuing American-style options. Accordingly, the Black–Scholes model is not applicable to valuing real projects that involve compound American-style real options, multiple uncertainties and more complex stochastic models than the simple geometric Brownian motion (GBM) model. Moving forward from the closed-form solution of the Black–Scholes model, a second popular technique for valuing options is "the lattice method" proposed by Cox et al. (1979). The most important characteristic of the lattice technique limiting its practical application is that the level of complexity grows very rapidly with the number of uncertainties. For multi-dimensional problems the technique becomes unmanageable and impractical (Barraquand and Martineau, 1995). The finite difference technique for options valuation developed by Brennan and Schwartz (1977, 1978) suffers from the same dimensionality difficulties as the lattice method (Longstaff and Schwartz, 2001). In addition, it cannot handle the variability of producible metal units with time or the non-uniformity of costs incurred throughout the lifetime of the mine. The last technique for valuing real options is based on simulation. The Monte Carlo method for valuing European options was proposed by Boyle (1977). An improved version that can value American financial options was developed by Longstaff and Schwartz (2001). In general, the advantages of simulation-based techniques are: multiple uncertainties described by complex stochastic models can be handled (Broadie and Glasserman, 1997; Longstaff and Schwartz, 2001) without the need to transform the real complex problem into a simple, but highly unrealistic problem; and, metal unit variability over time and cash flow non-uniformity can be incorporated in the valuation process.

The ROV is not a new technique for natural resource investment applications. Since the first paper applying the ROV to value a simple copper mine was published by Brennan and Schwartz (1985), considerable work has been done employing the same concepts of uncertainty and operating flexibility. For example, Paddock et al. (1988) applied the ROV to value management flexibility to develop petroleum leases. Trigeorgis (1993) discussed the effect of incorporating the interactions among different real options on the value of a natural resource extraction project. Moyen et al. (1996) presented a comparison between the conventional NPV method and the option valuation method using data from Canadian copper mines, showing that the NPV method undervalues mining projects. Kelly (1998) applied the ROV based on the binomial lattice method to value a gold mine. McCarthy and Monkhouse (2003) presented a trinomial lattice method for valuing a copper mine having both a deferral and an abandonment options incorporating the mean-reversion in copper prices. Other important publications include Tufano and Moel (1999), Slade (2001), Kamrad and Ernst (2001), Moel and Tufano (2002), Abdel Sabour and Poulin (2006) and Samis et al. (2006).

The main findings of most previous work in real options applications to valuing mining investments can be summarized as follows:

- The trigger metal price for developing a mine estimated by the ROV is greater than the break-even price determined by the conventional NPV method.
- The value of a project estimated by the ROV is greater than that estimated by the NPV method. In other words, the NPV tends to undervalue mining investments.

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- The ROV is better than the NPV method in dealing with uncertainty and operating flexibility.
- The difference between the ROV and the NPV estimates represents the value of operating or management flexibility, and that difference depends on the uncertainty level and the project profitability.
- The ROV and the NPV method differ fundamentally in the way they discount future cash flows and in the way they deal with management flexibility.

Although there is a clear consensus on most of these findings, still there is doubt on the importance and usefulness of the ROV in practice. It is not yet clear whether the ROV can be applied in the real mining industry and how it may improve the decision making process. One of two important issues that should be clearly addressed is related to the transparency of the ROV and its ability to handle the complexity of real mining projects; specifically, the existence of multiple sources of uncertainty and the non-uniformity of cash flows. Considerable work has been done in modeling and discussing the uncertainty of metal prices, while the other sources of uncertainty such as foreign exchange rate and geological uncertainty are not well addressed. This is mainly due to the difficulty of handling multi-dimensional problems in the common valuation techniques such as the binomial lattice and the finite difference methods. For example, Cortazar et al. (2001) tried to overcome that problem by collapsing price and geological–technical uncertainties into a one-factor GBM model in order to reduce the dimension of the problem to one. This simplification implies that there is a perfect correlation between two completely independent variables such as, for example, the copper price and the grade of a copper deposit. Based on this assumed correlation, a mine planner should expect that the grade of a deposit will be high during high price periods and low during low price periods. Since the market price of a metal and the grade of a deposit in the ground are completely independent, such an assumption is erroneous. The same problem exists in using metal-equivalence to reduce the dimension of the problem to one when evaluating multi-metal mines. This implies perfect correlation between all metal prices in the market, which does not exist in reality.

The second important issue to be addressed concerns the difference the ROV can make to the bottom line. In other words, can the ROV be used in practice to increase project value rather than just estimate it? Apart from assisting the co-decision to start or stop operations, can the ROV improve the mine planning process? Indeed, there is a lack of studies in the existing literature showing how to apply the ROV in practice under multiple uncertainties and non-uniform conditions without oversimplifying reality. Also, there is a need for practical tests investigating the applicability and usefulness of the ROV in solving real-life mining problems.

This study has two objectives. The first objective is to outline a methodology for applying the ROV to a practical mining problem while taking into consideration the non-uniformity of project parameters and the existence of multiple uncertainties such as metal price, foreign exchange rate and geological uncertainty. The second objective is to provide an example demonstrating how the ROV can improve the decision making process. A small Australian open pit gold mine is selected to illustrate the suggested practical investigation. In the next sections, a simulation-based procedure for valuing mine plans will be presented. Then, a case study will be provided illustrating the results of the practical test and investigation.

A simulation-based real options valuation method

In this section, the proposed method of valuing a mining asset under multiple uncertainty and non-uniformity of cash flow components is briefly outlined. The method is based mainly on simulating multiple realizations of the uncertain variables and making the optimal decision at each period using value expectations. The Monte Carlo method was originally proposed by Boyle (1977) for valuing European options and extended to valuing American options by Longstaff and Schwartz (2001). Abdel Sabour and Poulin (2006) extended it further to valuing real capital investments under multiple uncertain market prices and provided a validation for its accuracy in valuing mining investments having compound options. In this study, a step toward practical application is taken by incorporating more sources of uncertainty, such as foreign exchange rate and geological uncertainty, and variability into the real options model.

First, we will assume that a manager can choose among N mine statuses at each time. For example, when considering the option to abandon alone, there will be two mine statuses available: (1) to continue producing or (2) to abandon the project at that time. In this example, it should be noted that the option to abandon is irreversible. The decision to switch the mine status at time $t<T$, where T is the lifetime of the mine, is made based on the expected values of the different statuses estimated conditional on the prevailing project variables at time t. Therefore, the first step is to simulate many realizations of the uncertain variables affecting the mine value. The most widely used stochastic models for generating realizations of market and economic variables are the GBM and the mean-reverting process (MRP). The GBM model can be represented as (Dixit and Pindyck, 1994)

$$\frac{\mathrm{d}S}{S} = \alpha\,\mathrm{d}t + \sigma\,\mathrm{d}z, \tag{1}$$

where S is the price of a metal, α is the expected trend, σ is the standard deviation, $\mathrm{d}z$ is an increment in a standard Weiner process and $\mathrm{d}t$ is an increment of time. Such a model is usually applied to describe the volatility of non-reverting prices such as stock prices as well as prices of some precious metals like gold. Alternatively, a MRP model can be applied to model variability of reverting variables such as foreign exchange rates and most base-metal prices. A popular model is that proposed by Schwartz (1997)

$$\frac{dS}{S} = \kappa(\mu - \ln S)dt + \sigma\, dz, \tag{2}$$

where κ is the reversion speed at which the log of a price reverts back to a long-term equilibrium log price μ. Based on stochastic models such as those represented in Eqs. (1) and (2), multiple realizations of the uncertain variables can be generated after adjusting for the market price of risk for each variable. Also, it is straightforward to take into account the correlation between those uncertain variables. Geological uncertainty, on the other hand, is modeled using a different spatial stochastic simulation method termed "conditional simulation". As described in Dimitrakopoulos et al. (2002), conditional simulation is a Monte Carlo technique which can quantify the uncertainty and spatial variability of geological variables such as ore grade and tonnage. The main idea behind the technique is the use of conditioning data to produce equally probable realizations of the in situ orebody. The specific technique employed herein is a version of the so-called sequential Gaussian simulation (Dimitrakopoulos and Luo, 2004; Soares, 2001; Painter, 1998). This technique is based upon the decomposition of the posterior probability density function of a stationary and ergodic Gaussian random field into local posterior probability densities that, in practice, are sequentially generated from the available data and sampled in a Monte Carlo sense. More details about conditional simulation and its applications for quantifying geological uncertainty and mine planning can be found in Dimitrakopoulos (2007) and Godoy and Dimitrakopoulos (2004).

After simulating M realizations of metal price and foreign exchange rate, and B orebody models, the dynamic optimization process is carried out recursively for all M simulated paths at each time period t, $t = 1,2,3,\ldots,T-1$. To clarify this point, assume that there are two mine statuses available to mine planner: status i and status j. At period t between 0 and T, the mine planner will choose the optimum status that maximizes mine expected value conditional to sample path $m \in M$ and orebody model $b \in B$. Let V_i denote the expected mine value for status i and V_j the expected value for status j. Both V_i and V_j are functions of the uncertain variables as

$$E(V_{i,j}|m,t,b) = f(S1_{m,t}, S2_{m,t}, \ldots, R_{m,t}, G_{b,t}), \tag{3}$$

where $S1$, $S2$,... denote the prices of metal 1, 2,...; R is the foreign exchange rate and G denotes orebody characteristics (tonnage and grade) simulated by the orebody model b. To determine the optimum mine status, the function forms of both V_i and V_j at time t should be known as well as its parameters. As described in Longstaff and Schwartz (2001), the forms of functions can be approximated by linear combinations of functions such as power series or Laguerre polynomials. The parameters of these functions are estimated at each time period using least-squares regressions. This is carried out by regressing the sum of the discounted values of cash flow beyond time t for each of the operating alternatives i and j, onto their basis functions. After estimating the parameters of each basis function, the optimization process is carried out as follows:

It is optimal to change the mine status from i to j if

$$E(V_i|m,t,b) < E(V_j|m,t,b) - C_{ij}, \tag{4}$$

where C_{ij} is the cost of switching from status i to status j at time t.

The mine status should be changed from j to i if

$$E(V_j|m,t,b) < E(V_i|m,t,b) - C_{ji}, \tag{5}$$

where C_{ji} is the cost of switching the mine status to from j to i at time t.

Otherwise, if

$$E(V_i|m,t,b) > E(V_j|m,t,b) - C_{ij} \tag{6}$$

or

$$E(V_j|m,t,b) > E(V_i|m,t,b) - C_{ji}, \tag{7}$$

the mine status should be left unchanged.

To clarify the mechanism of this valuation process, assume that the only operating flexibility available to the mine manager is to close the mine early. This option is irreversible. At any time t the decision to abandon the mine is made by comparing the expected value of all future cash flows if the mine is kept open and the abandonment cost at time t. The expected value if the mine is kept functional is estimated conditional on the prevailing values at time t of key variables such as metal price, foreign exchange rate, and ore tonnage and grade.

This optimization process is carried out for all orebody models and all simulated realizations of metal price and foreign exchange rate throughout all time periods. The cash flows for all paths are then discounted at the risk-free rate and the various statistics of mine value are generated. This simulation-based method has two important advantages. First, it can handle the complexity and non-uniformity of cash flows as well as complex taxation systems such as the loss-carry-forward system. Second, it enhances transparency of the ROV since the cash flow components throughout the lifetime of the mine are generated and reported in the ordinary format. Therefore, it is possible to check and track the estimated project value as well as the reasons for which the optimal decision is reached.

Practical application: selecting the design for an Australian gold mine

The ultimate objective of mine planners and decision makers is to implement decisions that seem to be the best based on the information available at the planning time. In this respect, a plan, or an alternative, A is considered to be better than Plan B if the value generated by Plan A is greater than the value generated by Plan B. Since the actual value cannot be known in advance, decision makers use evaluation techniques such as the NPV method to compare the expected values obtained from the various plans and then select the plan with the maximum expected value. However, due to the existence of uncertainty, the actual values can be completely different from expected values, making one or more of the rejected plans better than the expected preferred plan. Although it is impossible to know future outcomes of value, it is still important to make every effort to reach the best decision based on the available information.

In this section, the applicability and usefulness of the simulation-based ROV method presented in the previous section will be investigated. Both the proposed method and the conventional NPV method will be applied to choose the best mine plan among different feasible options with fixed production schedules. A small, 3-year life, Australian open pit gold mine is selected to carry out the reality investigation. The orebody being mined is a disseminated low-grade epithermal quartz breccia gold deposit occurring in volcanic rocks.

It is assumed that the decision had to be taken in Year 2003 and the pit started production at the beginning of 2004. Now, at the beginning of 2007, the actual gold prices and exchange rates throughout the 3-year life of the mine are known. Therefore, it is possible to compare the discounted value of cash flows that would be generated if the mining plan decision made in 2003 were based on the ROV to the discounted value of cash flows generated if the decision were based on the NPV method. This will help to determine whether the ROV can in reality indicate a better decision. Also, the stability and consistency of investigation results will be tested by comparing the discounted values given different scenarios.

Mine design selection using the NPV method and ROV

As shown in Table 1, there are 12 different fixed mine designs with different sequences of extraction, expected tonnages, operating costs and gold grades. These designs can be obtained by inputting each of the simulated orebodies into a conventional open pit optimizer. In this work, the nested Lerchs–Grossman algorithm is used (Whittle, 1999). The mine planner must choose the best of the 12 designs based on available information under three sources of uncertainty related to geology, the gold price and the exchange rate ($US/$AU). The overall metallurgical recovery is assumed to be 84%. The geological uncertainty is incorporated into the problem using the conditional simulation technique by generating multiple equally probable orebody realizations. The stochastic behavior of gold price is modeled using the GBM model represented by Eq. (1) while that of the $US/$AU rate is modeled using the MRP of Eq. (2). A correlation coefficient of, approximately, 0.36 between the rates of change in the value of the Australian dollar and the gold price in US$/oz is used to generate correlated realizations of future gold prices and exchange rates. Table 2 lists the economic information and the parameters for both the gold price and the $US/$AU rate models. The Australia corporate tax rate is 30% and the tax system allows for loss carry-forward. No capital investments will be incurred, since mining and processing operations will be carried out by contractors. For the sake of simplicity while emphasizing the main concept of the paper, it is assumed that the mine can be abandoned any time at no cost (i.e., the abandonment cost is assumed to be 0). However, the approach presented in the paper can accommodate any complex abandonment cost formulation.

The 12 designs were evaluated using both the NPV method and the proposed simulation-based method. Only one type of operating flexibility is considered, the flexibility to abandon. Other kinds of flexibility such as temporary closure and reopening, and expanding and contracting mine size are not considered. Fig. 1 shows the expected values of the 12 designs estimated by both the NPV and the ROV. Two important conclusions can be drawn from Fig. 1. First, the NPV valuations show large variations in design values compared to the ROV. Specifically, the

Table 1
Data for 12 possible mine designs

Mine design	Ore tonnage (tonne)			Operating cost ($AU/tonne)			Grade (g/tonne)		
	Year-1	Year-2	Year-3	Year-1	Year-2	Year-3	Year-1	Year-2	Year-3
1	925 360	860 451	903 591	24.41	25.16	27.36	2.42	1.80	1.50
2	1 021 141	876 780	60 599.1	24.74	25.28	23.80	2.47	1.74	1.49
3	955 141	852 045	182 569	24.65	24.90	24.57	2.46	1.75	1.62
4	1 042 777	780 285	517 351	25.29	25.49	26.64	2.46	1.75	1.62
5	1 015 688	779 731	292 940	24.17	25.52	24.69	2.43	1.76	1.52
6	917 128	856 977	442 722	24.31	26.16	26.93	2.48	1.83	1.68
7	1 019 285	782 184	190 467	24.17	24.49	30.45	2.42	1.72	1.79
8	971 795	920 220	770 199	24.51	26.34	25.19	2.45	1.80	1.50
9	997 262	846 177	628 824	24.39	26.02	33.01	2.47	1.78	1.54
10	974 649	899 295	485 592	24.84	25.30	25.79	2.50	1.73	1.56
11	1 206 364	698 324	936 122	25.14	26.41	25.92	2.36	1.77	1.48
12	937 852	782 868	954 335	24.92	24.48	26.37	2.47	1.78	1.50

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Table 2
Economic data and model parameters[a]

Item	Description
Risk-free rate (%)	6.5
Inflation (%)	2.63
Income taxes (%)	30
Gold price ($US/oz)	417.25
Volatility (%), gold price	13
Real trend, gold price	0
$US/$AU rate	1.333
Volatility (%, $US/$AU)	9.18
Reversion speed/year ($US/$AU)	0.24
Long-term ($US/$AU)	1.489

[a]The parameters of the gold price and the $US/$AU rate models are estimated using the historical data obtained from Reserve Bank of Australia (http://www.rba.gov.au/Statistics/Bulletin/index.html) and the US Geological Survey (http://minerals.usgs.gov/minerals/pubs/commodity/gold). The income tax rate is obtained from Australian Taxation Office (http://www.ato.gov.au). Dixit and Pindyck (1994), pp. 74–78, provide explanation on estimating the stochastic model parameters for oil and copper prices from historical data.

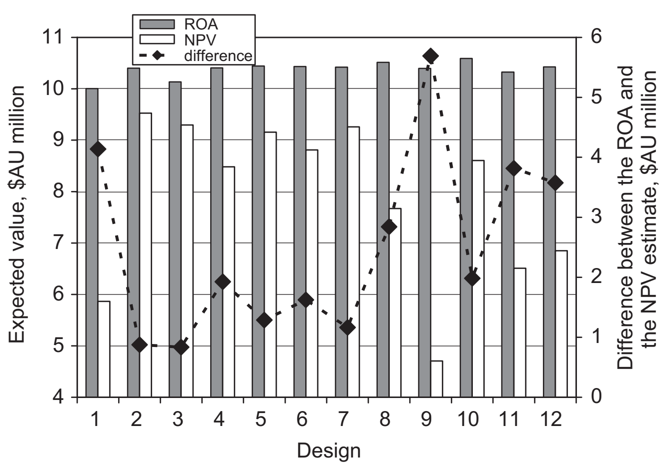

Fig. 1. NPV and ROV valuations for the 12 mine designs of Table 1.

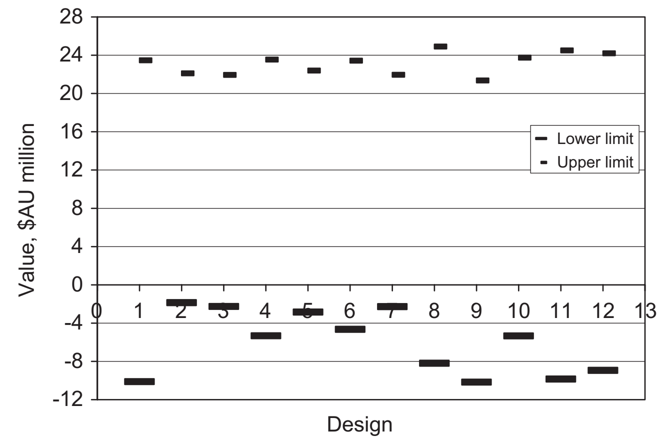

Fig. 2. Lower and upper value limits for the 12 mine designs of Table 1 estimated by the NPV.

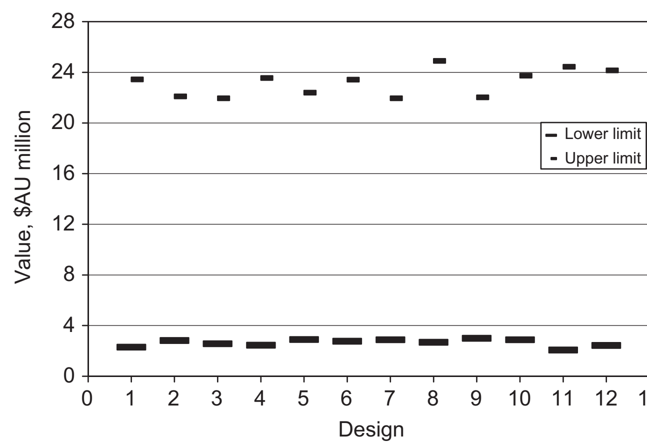

Fig. 3. Lower and upper value limits for the 12 mine designs of Table 1 estimated by the ROV.

difference between the expected values of the NPV best and worst designs is $AU 4.82 million, while the value difference of the ROV best and worst designs is $AU 0.585 million. This indicates that a great part of downside risk, which is the main driver for value discrepancy, can be avoided when integrating management flexibility to abandon the mine into the valuation process. This point can be clarified by analyzing the risk profiles of the expected values of the designs. Figs. 2 and 3 show the 5% (lower limit) and the 95% (upper limit) percentiles of the expected values estimated by the NPV and the ROV, respectively. Comparing the figures, it is obvious that while the upper limits of both techniques are identical, there are large differences between the estimated lower limits. As shown in Fig. 2, the lower limit estimated by the static NPV varies considerably with design. All lower limits are negative and range from −$AU1.87 to −$AU10.12 million. In contrast, the lower limits estimated by the ROV (Fig. 3) are less variable and range from $AU2.06 to $AU3.00 million. Also, all lower limits based on the ROV estimate are positive, which strengthens the previous finding that the downside risk is limited by incorporating the abandonment flexibility. The second and probably the most important conclusion is that the design having the maximum NPV does not have the maximum value based on the real options analysis. As shown in Fig. 1, Design 2 has the maximum NPV, while Design 10 has the maximum value estimated by the ROV. From Fig. 2, it is clear, based on the results of the static NPV method, that Design 2 is the least risky since it has the highest lower limit. From the ROV results shown in Fig. 3, Design 10 is also a good design given the high lower and the upper limits. Therefore, a mine planner would select Design 2 based on the NPV method or Design 10 based on the ROV.

As shown in Fig. 1, the difference between the ROV expected values and the NPV expected values varies with designs. It ranges from $AU0.84 to $AU5.69 million. This difference represents the value of abandonment flexibility specific to each design. It is worthwhile to investigate where the flexibility value comes from by focusing on the expected annual cash flows throughout the 3-year life of the mine rather than the overall expected value of each design. Basically, when carrying out the evaluation process on an annual basis, there are three decision points: at times 0–2. The decision to abandon at time 0 is made based on the overall expected mine value estimated conditional on the current economic and technical conditions. Since the expected values of all designs are positive, no abandonment will take place at time 0 and the mine will be producing during the first year for all simulated paths. Therefore, the expected cash flows at the end of the first year estimated by both the NPV and the ROV are identical. At the beginning of the second and the third production years (times 1 and 2, respectively), the abandonment decision is made based on prevailing economic conditions at those times, which are not known with certainty. In this case, the abandonment decision is taken based on the expected value of remaining cash flows conditional on the simulated realizations of the economic and technical parameters. Therefore, based on the ROV, the mine will be abandoned at the simulated paths corresponding to negative expected remaining values while it will be producing at the paths with positive expected remaining values. On the contrary, based on the static NPV, the mine will be kept producing at all possible simulated scenarios. This results in expected DCFs estimated by the NPV method lower than the ROV expected discounted cash flows at the end of the second and the third production years (Figs. 4 and 5). To clarify this point, assume that there are only three simulated realizations of the economic variables at a future period with corresponding net cash flows, in $AU million, of 6, 3 and −3. According to the static NPV, the expected cash flow is $AU2 million, which is the average of the three simulated cash flows. When incorporating the option to abandon, the cash flow of the third path, in $AU million, will be 0 instead of −3. Then, the expected cash flow for that production year estimated by the ROV will be $AU3 million, which is 50% higher than the static NPV estimate.

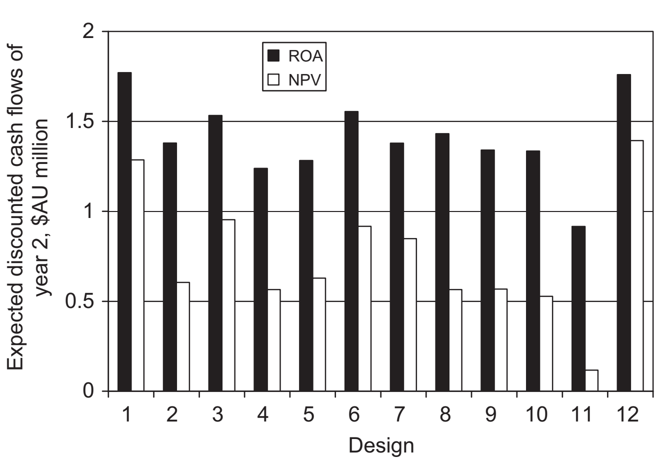

Fig. 4. Gold mine cash flows for the second production year.

As shown in Figs. 4 and 5, the expected cash flows estimated by both techniques are positive during the second year, while for the third year the static NPV expected cash flows are negative for almost all designs. According to the NPV results, it is not economical to mine out the ore scheduled for the third year and the mine life should be limited to 2 years. In this case, it is appropriate to take the negative third-year cash flows out of the NPV estimates and base mine design selection on the expected NPV of the first 2 production years. Fig. 6 shows the valuation results after eliminating third-year cash flows from the NPV estimates. Compared to Fig. 1, the NPV estimate of the expected values from the 12 designs is less variable and the difference between the ROV and the NPV estimates has also decreased for almost all designs. More importantly, as shown in Fig. 6, the design with the maximum NPV is Design 7, instead of Design 2 (Fig. 1), while the ROV-based selection remains unchanged.

In summary, based on the expected values of the 12 feasible mine designs estimated by the NPV method and

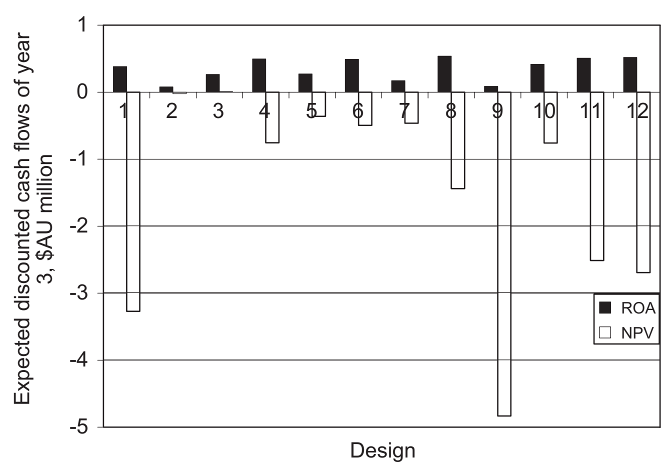

Fig. 5. Gold mine cash flows for the third production year.

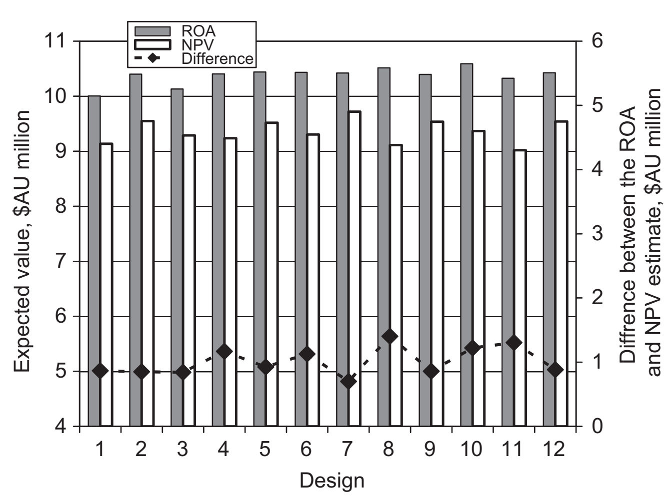

Fig. 6. NPV and ROV valuations after eliminating third year negative cash flows.

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the upper and lower expected value limits, Design 2 should be selected when considering all cash flows of the 3-year production schedules. After eliminating third year negative cash flows from the NPV valuations, Design 7 becomes the most economically appealing design. However, the ROV valuations integrating operating flexibility to abandon the mine into the valuation process indicate that Design 10 should be selected.

Practical investigation using actual gold prices and exchange rates

The important question now is which design should be selected, Design 2 (based on the crude NPV), Design 7 (based on the NPV after eliminating third year negative cash flows) or Design 10 (based on the ROV selection)? Basically, there are no standard procedures or theoretical models to judge which technique leads to better selection. Even an empirical judgement is not straightforward because it requires carrying out the plan indicated by each technique and then comparing the actual cash flows generated, which is impossible. To overcome this problem and provide some kind of reliable practical judgement, it is assumed that the planning time was at the end of 2003 and production started at the beginning of 2004. Now (at the start of 2007), the actual gold prices and exchange rates over the lifetime of the mine (3 years) are known. The actual tonnages and grades produced from the mine are of no importance to the practical test because they depend on the design applied. As mentioned, to know the actual tonnages and grades corresponding to each design the mining should be carried out according to each design. Since this is not possible, the practical comparison will be based on the minimum, maximum and average values of designs calculated from the actual gold prices and exchange rates and all simulated orebody models. Then, the above question is slightly modified as such: based on the actual gold prices and exchange rates throughout the life of the mine, would the project profitability have been better if the design selection at the planning time were based on the results of the NPV or on the ROV? The average gold prices during Years 2004–2006 in $US/oz were 411, 444.90 and 601.30, respectively, while the $US/$AU rates were 1.358, 1.315 and 1.335. Standing at the decision time, these actual gold prices and exchange rates represent only one possibility of an infinite number of future possibilities. The net values at Year 2003 are estimated by discounting after-tax cash flows at 8% discount rate. Table 3 lists the minimum, average and maximum values of the 12 designs. These values are obtained for each design using the actual gold prices and exchange rates throughout the 3-year mine life and the tonnages, grades and production costs corresponding to each of the simulated orebody models. The total value generated from Design 10 is $AU1.8 million greater than that of Design 2 and $AU1.12 million greater than that of Design 7. These differences represent approximately 18% and 11% of the expected values from

Table 3
Minimum, average and maximum gold mine values based on actual gold prices and exchange rates

Design	Value ($AU million)		
	Minimum	Average	Maximum
1	8.077	11.576	15.803
2	7.443	9.695	11.570
3	7.652	10.161	11.811
4	8.812	11.532	14.163
5	8.779	10.651	13.415
6	8.736	11.494	13.700
7	7.927	10.343	12.444
8	9.582	12.229	14.659
9	5.939	9.657	11.472
10	8.936	11.464	13.987
11	9.893	12.071	15.893
12	9.702	12.539	15.215

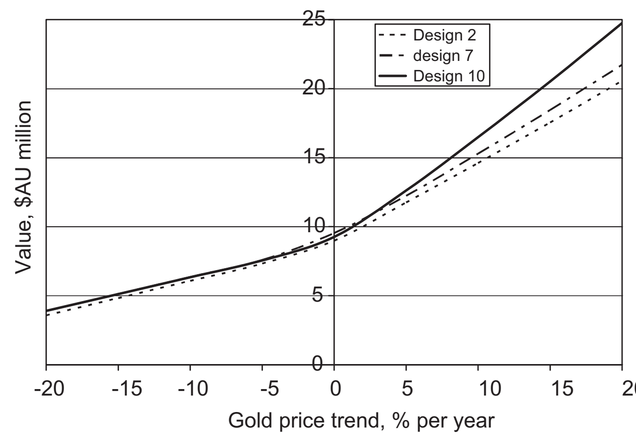

Fig. 7. Values of Designs 2, 7 and 10 at different gold price trends.

Designs 2 and 7, respectively. Also, the minimum value of Design 10 is $AU 1.50 million more than that of Design 2 and $AU1.01 million more than that of Design 7. The maximum value of Design 10 is $AU2.40 million more than the maximum of Design 2 and $AU1.54 million more than that of Design 7. Based on this practical investigation, it may be concluded that design selection based on the ROV will generate a higher value than the design selection based on the conventional NPV method.

It is worthwhile to investigate whether the above result indicating the advantage of the ROV over the static NPV method holds if market gold prices had evolved in some way other than the actual realization. To do this, it is assumed that market gold prices had kept increasing or decreasing beyond year 2003 at 5%, 10%, 15% and 20%. In each case, the mine value is estimated based on the production schedules of Designs 2, 7 and 10. As shown in Fig. 7, Design 10 is generally better than both Designs 2 and 7. The difference in value between the three designs decreases when gold prices depreciate and increases when gold prices appreciate. When gold prices decrease the

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option to abandon becomes deep-in-the-money for the three designs. In this case, the negative cash flows in later years are avoided regardless of their magnitudes and consequently the difference between the values of the three designs decreases. In contrast, for positive trends, the option to abandon becomes out-of-the-money. Accordingly, the mine will continue producing and the difference in value between the three designs increases since the potential benefit of high prices in later years is greater for Design 10 than for Designs 2 and 7.

This process of investigating the economic performance of designs at different gold price trends does not work backwards. In other words, it is not possible to estimate the NPV of the possible designs based on assumed price evolutions and choose the best design manually without applying the simulation-based real options analysis. This is neither possible nor feasible for three reasons. First, since the actual price evolution is more complex than the simple constant trend assumption, implementing this process requires assuming multiple price scenarios with each scenario possibly producing a different best design. Second, such a process would be very complex practically when considering multiple sources of uncertainty, such as the uncertainty over exchange rates and metal prices for the case of multi-metal mines. Therefore, to ensure that the mine design was selected based on multiple equally probable scenarios for all sources of uncertainty, the simulation and valuation analysis should be performed as described in the previous section. Third, the decision to abandon should be made based on the expected value estimated conditional on the prevailing key parameter values at the decision times not on the basis of the deterministic individual value of each price realization.

An interesting conclusion that can be drawn from Table 3 is that although Design 10 is better than both Designs 2 and 7, it is not the absolute best design out of the 12 designs based on the actual gold prices and exchange rates data. From Table 3, Designs 1, 4, 6, 8, 11 and 12 have average values greater than that of Design 10. This result highlights that no technique can predict future outcomes. Therefore, the performance of a technique is usually measured by its ability to generate the best forecast based on the information available at the planning time. This also raises a concern about the adequacy of the expected value and conventional risk analysis applied in mining industry as the bases for selecting among alternative plans under uncertainty. Although the risk analysis can provide additional helpful information and insights to mine planners, its usefulness is limited for two reasons. First, since the risk measures are not additive, the preference for an alternative over other alternatives is determined by subjective judgement, particularly when no significant differences in risk measures exist between the various alternatives and in absence of an outstanding option. Second, in some cases the risk analysis generates confusing results showing that each alternative is good in some risk measures and bad in others, making the selection of an option tricky. Since the actual outcome can be completely different from the expected outcome, there is a need for a system that uses different aspects of cash flow components and risk analysis measures to rank alternatives under uncertainty rather than depending only on the expected values and the subjective interpretation of the conventional risk analysis results.

Conclusions

This paper presented a practical method for applying the ROV to evaluating mining investments. The proposed simulation-based method is able to handle multiple uncertainties and non-uniformity of project parameters. To investigate the advantage of the method, and generally the ROV, over the conventional NPV method and its usefulness in practice, both methods were applied to select the best design for an Australian gold mine out of a number of feasible options with fixed production schedules. The results showed that a design that has the maximum NPV is not necessarily the design that has the maximum value based on the ROV valuations. Comparing the actual values that would be generated if the mine design were selected based on the recommendation of each technique showed that the ROV-based optimum design would result in an 11–18% increase in the net mine value. Further investigation was conducted to compare the outcomes of the best design indicated by each method given different scenarios. It was found that in general the design indicated by the ROV performs better than the design indicated by the NPV method for the various scenarios tested. However, in the practical investigation the optimum design based on the maximum ROV expected value was not the best design out of the 12 designs. Further studies should address the adequacy of the expected value and the conventional risk analysis in assisting selection of the best alternative under uncertainty. Also, more operating flexibilities such as the possibility to expand mine size when metal prices increase should be taken into account in the process of mine design selection.

The result of the practical investigation obtained in this study, that indicates the advantage of the ROV over the conventional NPV in improving project value, is specific to the provided case study. Generalization of this result is not possible unless it is confirmed by a large number of practical tests. The study in this paper presents an example that could be followed to compare the ROV to the NPV in various applications following the same suggested procedure or using modified ones.

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