Modern Strategic Mine Planning

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If you are in a shipwreck and all the boats are gone, a piano top…that comes along makes a fortuitous life preserver. But this is not to say that the best way to design a life preserver is in the form of a piano top. I think that we are clinging to a great many piano tops in accepting yesterday's fortuitous contrivings as constituting the only means for solving a given problem. (Fuller 1969, p. 9)

Richard Buckminster (Bucky) Fuller (1895 – 1983), eccentric futurist and inventor of the Geodesic Dome

Introduction

Strategic mine planning is aimed at one goal: maximizing the value to be realized from extracting a mineral resource. This attempt at value maximization is operationalized via mine planners' suggestions, or "decisions," regarding a number of investment and scheduling alternatives, such as equipment sizes and placements, ore definition (cut-off grade determination), ore access mechanics (shaft location, pit size), and ore and waste removal sequences. The decisions are updated through time, usually annually, as new information becomes available. It is a forward-looking exercise.

Being able to decide upon the value-maximizing suite of forward-looking decisions at any given time for any given deposit depends first and foremost on mine planners being able to *measure* the impact of the various decision alternatives on mine value. This relies upon formal forecasting of uncertain technical and economic outcomes associated with each decision, and the subsequent valuation of those uncertain outcomes taking into account risk tolerances of investors. Uncertainty abounds, and is a central component to both the forecasting and valuation exercises.

We have observed many omissions and incorrect analyses in mine planning models currently in use. One such shortfall is that mine planning is often conducted in a deterministic setting, with little consideration of the many difficulties and opportunities that uncertainty imposes on the exercise. It is also largely devoid of financial and economic fundamentals. For instance, traditional discounted cash flow analysis is used to value the suite of complex options that the mine plan embodies. This valuation tool is unequivocally unsuitable for the job. Finally, current mine planning, via its piecemeal approach, falls short in terms of optimization technique. In essence, current mine planning algorithms are neither likely to produce a value-maximizing suite of mine

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investment and scheduling decisions, nor to value correctly the suite of decisions that it does suggest. Although current mine planning decisions yield suboptimal solutions, it is difficult to estimate the degree of suboptimality. We might estimate that there is 15% to 25% of additional value left on the table. We would also propose that the value being assigned to the decision outputs of mine planning is quite wide of the actual value that the decisions are creating. For instance, suppose that a truly optimized mine plan would generate $1,000 million in value. The actual mine plan may generate $800 million in value, and yet be measured to generate $1,500 million in value because the value measurement is incorrect.

Modern strategic mine planning, a new research initiative at the Colorado School of Mines, seeks to advance the field by introducing four major innovations into the existing framework. The first is the use of appropriate holistic optimization algorithms and solution techniques that consider the entire project. The second is the introduction of stochastics, or uncertainty. Geological and commercial (revenue and cost) uncertainty are likely to be the most important uncertainties to model, followed by political and competitive uncertainties. Accounting for these uncertainties creates the opportunity to develop an optimal portfolio of options within the mine plan. The third innovation is to use modern financial methods to value various option choices and select the optimal portfolio. The fourth innovation is to use modern computational methods to successfully carry out this difficult and large-scale option portfolio optimization problem. The result is a mine plan that dictates what options are to be created, how they are to be created, and when they are to be created. The plan also provides continual guidance as to how and when to exercise these options, and can be continually updated as reconciliation becomes available.

This process of optimal option creation and exercise falls within a field of optimization called real options. The remainder of this paper provides an introduction to the topic of real options and its application to mine planning. While real options has been available as an optimization tool since at least the late 1970s, its application to mine planning to date has been limited. The paper also reviews some recent applications of real options to mine planning, and outlines a path for modern strategic mine planning to more fully exploit this powerful optimization tool.

The History of Real Options

Real options emerged as an area of study shortly after the development, in 1973, of a model for managing and valuing financial options. That model, developed by economists Robert Merton, Fischer Black, and Myron Scholes, resulted in what is known as the Black-Scholes or Black-Scholes-Merton option pricing formula. The model revolutionized financial economics, and earned Scholes and Merton the Nobel Prize in economics in 1997 (Black died in 1995 of throat cancer, though were he alive in 1997 he would undoubtedly have shared the prize with Scholes and Merton).

An option is an opportunity to select one action over one or more other actions either now or in the future. The action associated with a financial option, for instance, is the purchase or sale of a financial asset for a fixed price at a time chosen by the option holder. That fixed price may be more or less than the financial asset is worth at any given moment, and so there may or may not be some payoff to acting ("exercising the

option") immediately. A significant component of these options' value, however, is their hold value, whereby the option holder can wait for better economic circumstances before acting. Waiting may or may not end up being the best action after the fact – the game is at each point in time to probabilistically compute whether to immediately act and reap a guaranteed cash flow, or whether to wait an additional period and revisit this question as new economic information is revealed that might lead to opportunities for higher cash flows. In other words, the option must be optimally managed using a forward-looking probabilistic model.

In mine planning, decisions as to how and when to act include the extraction and routing of blocks of ore, the timing of lumpy decisions such as pushbacks or transitions from open pit to underground mining, and the placement of shafts. As with financial options, the goal is to take actions that optimize the present value of the payoffs from acting. In real options the decision over current actions is often conditioned on how those actions create or impact future actions. These are called compound options.

The value of an option is derived from its optimized management in the face of uncertainty. Returning to financial options, Figure 1 is a schematic that depicts the management of a call option to buy a stock for a fixed price or exercise cost. The decision in this case is simply whether to exercise the option or to wait. Given the current stock price and the option's exercise price, this option would generate a positive cash flow to its owner were it exercised immediately (time 0). That value is the option's "intrinsic value." But if there is a substantial chance that the stock price will rise in the future it will be optimal to hold the option beyond time 0. If the stock price is sufficiently unlikely to rise in the future then the option is optimally exercised immediately, and its value will be its intrinsic value. Given possible future movements in the price of the underlying stock, the option in Figure 1 is computed to have substantial hold value, and so it is not exercised at time 0. The optimal current action is to wait. This decision will then be revisited in the next decision period, given any new pricing information that has come to light in the interim. The option's value will also be updated in the next decision period based on whether the stock price moves up or down.

Prior to Black, Scholes, and Merton's work there was no known solution to this optimization problem. Traditional discounted cash flow was available, but it was not possible to use it to manage and value the option since it lacked the dynamic updating that such optimization requires. The Black-Scholes formula makes innovative use of stochastic differential equations to optimally manage and value a very specific type of financial option. The mechanics include correctly calculating the expected payoff, calculating its expected timing, and appropriately valuing in present value terms the deferred income taking into account the riskiness of that deferred income. The Black-Scholes approach is a discounted cash flow technique, and as such is an extension of, rather than a break from, traditional NPV analysis.

While the Black-Scholes formula only held for a specific type of financial option, the financial ideas that were contained in the Black-Scholes approach led to the birth of modern finance. Modern finance contains within it a completely new way of viewing and valuing uncertainty, a view that is applicable to more than the valuation of just financial options.
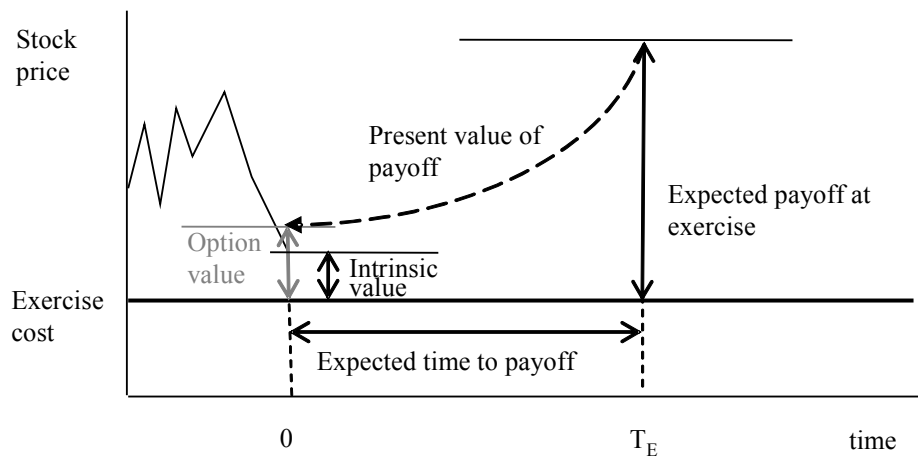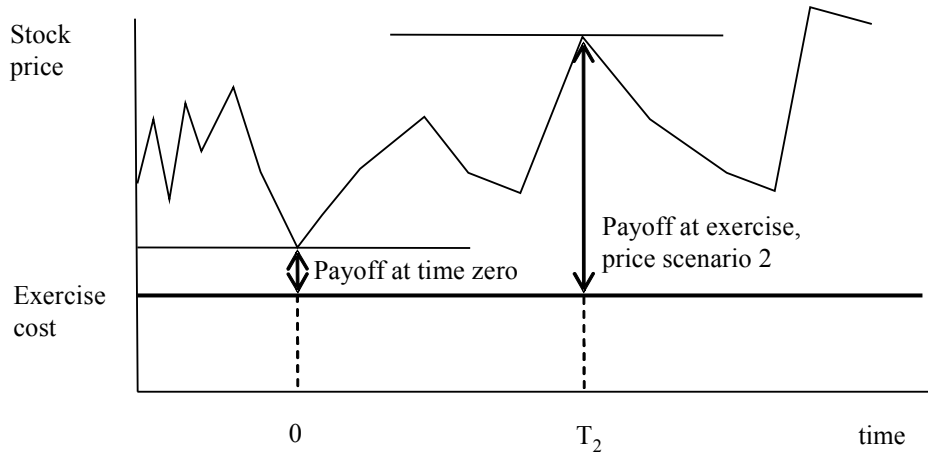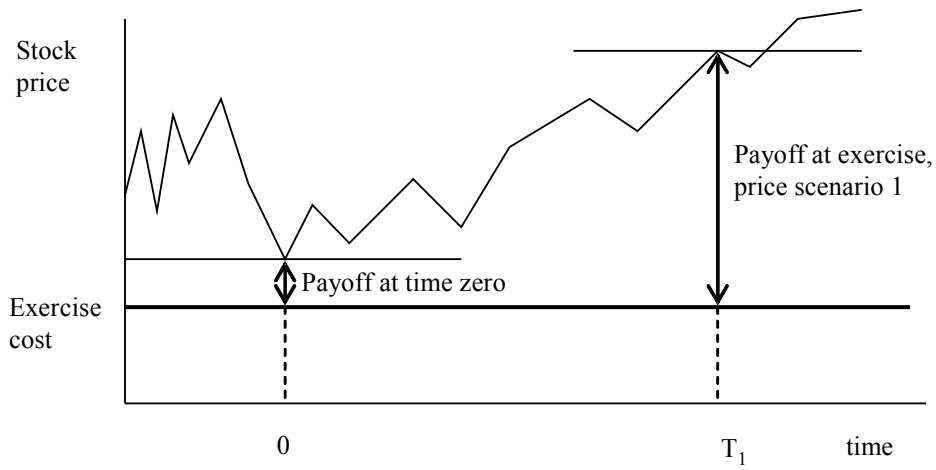
Figure 1: Call option payoffs under two stock price scenarios. In this case waiting is optimal, and the option value is greater than its intrinsic value. Price scenario 1 anticipates the option being exercised at time T_1, and price scenario 2 anticipates the option being exercised at time T_2. The bottom diagram shows that the option value at time 0 is the present value of the expected payoff from holding the option until the anticipated exercise date T_E, taking possible price path scenarios, times to exercise, and investor risk aversion into account.

It was in 1979 that a Brazilian Ph.D. student at the University of California, Berkeley noted that the development of a natural gas field had similar characteristics to the exercise of a financial option on a stock (Tourinho 1979). One could assume that the development cost of the gas field was known and constant through time (as is assumed in a financial option), that this development cost was spent in acquiring an operating gas field (equivalent to the stock in a financial option), that the natural gas in the field may be more valuable in the future than it is in the present, and that there was some period over which the gas field development decision could be deferred. The task was then to optimally time the development of the gas field and value that development payoff in present-value terms using the Black-Scholes technique. With this, real option applications—the application of financial option pricing techniques to real assets— were born.

Fortuitously for our industry, the first application of real options was in extraction, and this has led to considerable work to extend Tourinho's model. Tourinho's planning model was a very simple one, with the only decision being when to develop and begin to extract the gas in the field. All other decisions regarding the field were assumed to be given at the outset, and not necessarily optimal. With the financial support of the Canadian federal taxation authorities, financial economists Michael Brennan and Eduardo Schwartz made the next major breakthrough in real options, publishing a paper in the Journal of Business in 1985 that looked at the optimal development timing of a copper mine. Brennan and Schwartz extended Tourinho's gas field development model in two important ways. The first advance was a rigorous modeling of the commercial risk characteristics of mining. The second was to allow for operating options once the mine was developed; the mine owner had the option to close an open mine at any time for a fixed cost or to open a closed mine at any time for a fixed cost. The closed mine incurred maintenance costs, and the mine could be abandoned at any time for a fixed abandonment cost. The result was a model that gave fairly powerful insights into optimal mine planning and the factors that influenced that planning. Quoting from the paper's introduction:

> "The general type of model presented here lends itself to use in… corporations considering *when, whether, and how, to develop a given resource*; to financial analysts concerned with the valuation of such corporations; and to policymakers concerned with the social costs of layoffs in cyclical industries and with policies to avert them. The model is well suited to analysis of the effects of alternative taxation, royalty, and subsidy policies on investment, employment, and unemployment in the natural resource sector." (italics added)

When, whether, and how to develop a given resource is exactly the strategic mine planning problem. Again, however, the decision space was very sparse, with only the decision to mine or not to mine at any point in time, and through this the decision as to when to start mining. The reserve was taken to be homogeneous and of known grade, and there was no consideration of uncertainty other than that of copper price.

Still, the paper provided a foundation for modern strategic mine planning, and sowed the seeds for what mine planning might look like in a stochastic, dynamic context.

Economists Avinash Dixit and Robert Pindyck published the first text-length introduction to real options in 1994, a book titled <u>Investment under Uncertainty</u>. There has since been the publication of approximately twenty texts and hundreds of academic journal papers on the subject. There are real options consulting groups, real options web forums, and a real options analysis Wikipedia entry. There is an annual international real options conference attended by hundreds of academics and practitioners. Universities worldwide offer graduate-level training in real options, and most MBA programs devote one or two weeks of their corporate finance or investment courses to the topic of real options. Real options models of relevance to mining planning include optimizing exploration drilling programs (Cortazar, Schwartz, and Casassus 2003, Davis and Samis 2006), optimal mine development timing (Moel and Tufano 2000), optimal reserve and stockpile management (Samis, Davis, Laughton, and Poulin 2006), optimal production levels in single-stage (Cherian, Patel, and Khripko 2000) and two-stage (Cortazar and Casassus 2000) mining operations, the latter including stockpiling decisions, and optimal mine re-opening decisions (McCarthy and Monkhouse 2003). All of these papers, however, and others not mentioned here, treat the decision space as very sparse, with only one or two decisions needing to be made at each point in time in the face of only one or two sources of uncertainty. This is mainly a result of the recognition that including more sources of uncertainty and an enlarged decision space would render the problem intractable. With advances in computing power and advances in the field of operations research, research in modern strategic mine planning is now poised to make a step-change towards more realistic models of the mine optimization problem.

How Does Modern Strategic Mine Planning Differ from Traditional Mine Planning?

As we noted in the introduction, modern strategic mine planning seeks to advance mine planning by introducing four major innovations into the existing framework. We briefly describe each of these in turn.

a) The application of appropriate holistic optimization algorithms and solution techniques that optimize the entire project at once, rather than in disjointed pieces.

Modern strategic mine planning seeks to remove as many simplifying assumptions as possible. For example, in open pit mine planning, simplifying assumptions include: (i) the blocks to be extracted lie within predetermined ultimate pit limits; (ii) the cutoff grade is fixed exogenously; and (iii) blocks are sequenced within each predetermined pushback independently. Those blocks that lie within the ultimate pit limits have been arbitrarily chosen based one or more non-market prices in a static analysis. In fact, in any ore body of interest, each block could be considered for extraction. Myopically considering only blocks for extraction within a pushback, independently of blocks in other pushbacks that might be better scheduled for extraction simultaneously, can lead to suboptimal results. These suboptimal results are the same conceptually as those obtained from solving several subproblems and using those subproblem solutions for a monolith problem. In fact, not only can this result in a lower

value than would otherwise be obtained, but it could also result in an infeasible monolith solution. Other mine planning domains in which suboptimal models appear exist in underground mine block sequencing and mine design, for example. Cut-off grade is itself an ore selection outcome. The selection of ore and waste should be done endogenously within the model, and not imposed upon the optimization.

Adding these refinements to traditional mine planning will result in large models, i.e., models containing many decision variables and constraints (restrictions). These can be computationally difficult to solve. Care must be taken to identify the best hardware and software available, and to use it correctly. If a model is not solvable in its monolithic (complete) form, various formal decomposition and relaxation procedures exist that can provide near-optimal solutions in a reasonable amount of computing time. Additionally, heuristics can also be applied. Although heuristics are commonly used, often users do not specify the quality of their solutions (i.e., how far from optimal the solutions are). And, in fact, particularly poor heuristics can lead to infeasible (unimplementable) solutions. Therefore, correctly identifying appropriate techniques for solving models is very important and nontrivial. The extant academic real options research has yet to address these issues.

b) The introduction of stochastics, or uncertainty.

This has been the main focus of real options research to date. The focus on uncertainty leads to mine planning decisions that can be quite different from decisions that seem optimal in a deterministic setting. Waste dump placement, for example, may be more remote under modern strategic mine planning than under traditional mine planning given the former's realization that nearby satellite reserves that are currently uneconomic could become economic in the future. Analysis under uncertainty may compute that the additional cost associated with more remote placement is less than the value of the satellite reserve option created.

The focus on uncertainty has perforce made the mine planning problem more difficult. The response has been to reduce the decision space to only one or two coarse decisions in each planning period. What is needed now is to recover the granularity of traditional mine planning while introducing uncertainty into the optimization algorithm.

c) The use of modern financial methods to value various option choices and select the optimal portfolio.

Uncertainty introduces considerable complexity into the mine planning exercise not only because it makes the problem larger and less tractable, but also because it makes measuring the value outcomes of the various decision alternatives more difficult. Traditional mine planning uses a valuation approach called net present value (NPV) analysis. NPV analysis has been used since the late 1800s to value and manage natural resource projects. The NPV technique involves forecasting the cash flows associated with a given mine plan, discounting those cash flows to the present using a risk-adjusted discount rate, and then summing the resultant discounted values. Where there is a series of mutually exclusive mine planning alternatives, the NPVs are compared across the alternatives and that alternative which produces the highest NPV is selected. One

alternative is to delay an action that could otherwise be taken immediately. This is called the "now or later" alternative. An example is when to start development drilling. Traditionally, NPV analysis does not include delay in its set of alternatives, and for this reason it had been deemed "now or never" analysis.

Although real options is also a discounted cash flow technique that compares alternative courses of action and selects that which is anticipated to produce the highest NPV, it differs from traditional NPV analysis in three important ways. First, real options analysis puts particular emphasis on dynamic decision making, the "now or later" alternative. This derives from real options' financial roots relating to optimal exercise timing in the face of circumstances that could change for the better (see Figure 1). Second, and in our view more importantly, real options uses financial theory to price correctly the risk associated with future uncertain cash flows that are realized when a mine planning decision is expected to be taken. This pricing of risk is needed whether or not the action is exercised now or later. NPV analysis attempts to do this with a single risk-adjusted discount rate. In real options, the risk discounting is done within the cash flow elements, rather than at the level of the net cash flows. The result is an "effective" time-varying net cash flow discount rate that is an output of, rather than an input to, the valuation process. Third, real options correctly estimates future cash flows when there is uncertainty surrounding those cash flow estimates. It does this by taking into account the optimal dynamic management of the asset and the inherent non-linearities in the cash flows created by such dynamic management. Even in the absence of dynamic management the cash flows will have non-linearities that require correct stochastic cash flow estimation (Samis et al. 2006). NPV analysis augmented by simulation attempts to do this, but without the rigorous definition of the uncertainties surrounding the cash flow estimates and without the ability to iteratively compute optimal dynamic managerial reactions to those uncertainties as new information is revealed to the manager. In essence, real options values the asset while at the same time anticipating how the asset will be optimally managed, conditional on the information available and options available to the manager in each decision period.

These differences between traditional NPV analysis, NPV analysis augmented by simulation or decision trees, and values calculated using real options have often been blurred. Laughton (2007) prepared what he calls the Banff taxonomy to differentiate the analyses (Figure 2). That taxonomy has the treatment of uncertainty on the vertical axis and the pricing of uncertainty on the horizontal axis. For our purposes the valuation methods located in three of the four corners of the taxonomy are of interest. Traditional NPV analysis is located in the south-west corner of the taxonomy, DCF [discounted cash flow] 1-point Forecasts. This is where mine planning currently sits. Mining companies typically place mining engineers in mine design and valuation positions, and for this reason these analyses tend to be long on technical analysis and short on financial and stochastic analysis. Surveys in the 1990s indicate that between 20% and 40% of North American mining companies still do not use NPV in their project evaluations. Only 10% of those surveyed use real options or Monte Carlo analysis. Of those firms that do use NPV analysis, 40% use a "subjective" risk-adjusted discount rate. This is akin to using a "subjective" grade, rather than calculating it from drilling data via a geostatistical package. Many companies use the same corporate-wide discount rate for all project
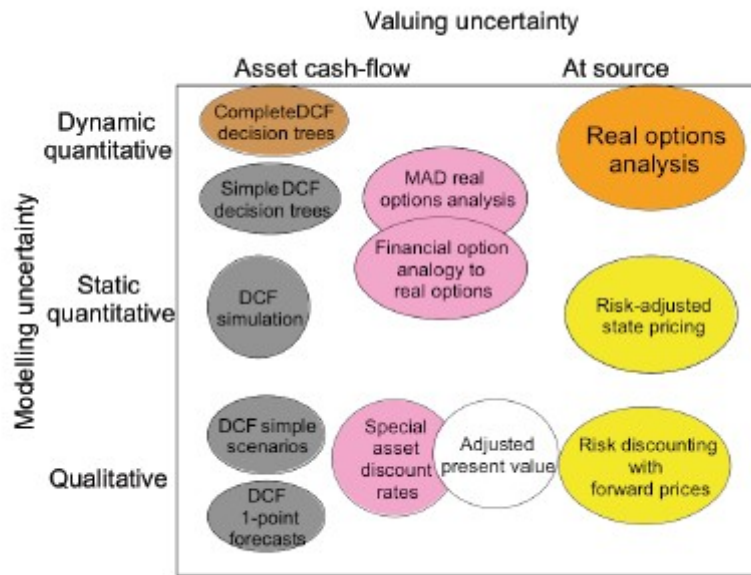
Figure 2: The Banff Taxonomy (Laughton 2007)

evaluations, which is like using the same average corporate-wide metal grade for all project valuations.

The introduction of stochastics and the ability to plan for and react to those stochastics is denoted as Complete DCF Decision Trees, in the top left corner. Here simulation or decision trees are added to the analysis. The valuation framework, though, is still the constant discount rate method, and so while this is a more sophisticated planning method, the measurement of value is still incorrect. The Black-Scholes-Merton work has laid bare the techniques for the measurement of value under uncertainty, and these now must be applied to the mine planning exercise such that value is measured correctly. Only when Complete DCF Decision Trees is combined with modern financial valuation methods, listed as valuing uncertainty "At Source," is real options achieved. More detail about the various approaches can be found in Laughton (2007).

d) The use of modern computational methods to carry out successfully this difficult and large scale option portfolio optimization problem.

Modern mine planning, with its consideration of a monolithic optimization problem in the face of uncertainty and conditional decision making, is computationally complex. Modern computational methods, many of them developed by operations researchers to solve other large, complex problems, must be brought to the mine planning problem such that solutions can be found in reasonable amounts of computing time.

What Biases Arise With Traditional Mine Planning Analysis?

Since a mine is a series of options to locate and extract ore, it can only be properly valued using real options theory. Through the application of real options analysis to mining problems over the past two decades we have come to learn that traditional NPV analysis is likely to introduce five biases into the mine planning exercise that will be corrected through modern strategic mine planning:

i) traditional mine planning induces too much investment to bring production forward in mines where the commodity is subject to long-term equilibrium forces (i.e., all but the precious metals). This can also be seen as overvaluing investment in productive capacity and undervaluing long-term positive cash flows (long-life, low production rate mines);

ii) traditional mine planning overvalues (under-represents the liability of) long-term negative cash flows such as remediation costs, and as a result tends to downplay remediation as a factor in mine planning;

iii) traditional mine planning underestimates the liabilities associated with contingent tax and royalty payments, and as a result will not give full value to mine plans that reduce these payments;

iv) where costs are less risky than revenues, traditional mine planning undervalues investments or actions that improve the operating margin. There will not be enough investment to upgrade product quality or lower production costs, and any endogenously-selected cut-off grade will be too low;

v) traditional mine planning undervalues the ability to manage down-side risk and overvalues the ability to capitalize on upside potential when there is flexibility to respond operationally to the stochastic environment. This means that abandonment options will be exercised later and at lower prices under traditional mine planning than under the real options approach, since under traditional mine planning abandonment (the avoidance of negative cash flows) is undervalued. Similarly, price-induced expansion options into low grade material will be undertaken sooner and at lower prices under traditional mine planning than under the real options approach. The net effect will be too few occurrences of abandonment and too much capacity expansion within the stochastic plan.

One bias that is often alleged is that real options analysis produces a higher asset value than traditional mine planning. This is not true! Any NPV analysis with a low enough discount rate (inappropriately low) can produce a project value that is higher than the real options analysis. NPV analysis introduces valuation error, but that error is not necessarily biased. It tends to undervalue world class, high-grade deposits. It correspondingly overvalues small, low-grade deposits, many of which would have a positive NPV but a negative real options value.

This last point is very important, as there have long been complaints that there is too much long-term supply in the industry, forcing prices down. Real options is questioned by practitioners in part because it is often seen as promoting the development of low-grade projects due to the flexibility to manage downside risk, whereas these projects would not be developed under traditional NPV analysis that ignores such conditional asset management. In fact, real options analysis would probably result in fewer marginal mines moving through the planning process to production. Moreover, in (v) above we see that traditional mine planning increases current supply from existing mines compared with supply that would be warranted under a real options analysis. Traditional mine planning is in many ways an aggressive approach to mining, and real options analysis would curb that aggression.

Who in the Mining Industry is Using Real Options Analysis?

The industry has been intuitively using real options analysis for some time in both its decision making and valuation exercises. There are many situations in which traditional NPV analysis is completely unhelpful in making operational decisions or in valuing projects or assets. Early-stage exploration is an example, where any sampling or drilling project will have a negative NPV under traditional valuation analysis given the long lag between expenses and expected income. Exploration has been managed as a portfolio of real options, even though this has not been accompanied by formal analytics.

Oil companies, which were already using decision trees in the 1960s and 1970s, found it relatively easy to adopt real options in the 1980s and 1990s. Certain major mining companies looked heavily into real options in the mid 1990s, but were not successful in having it impact design decisions and valuations, in part because of a lack of buy-in from top management. Rio Tinto publicly stated in 1999 that it had been using simple real options models for 10 years. In 2003 staff at BHP Billiton published a journal article on the use of real options to manage a closed copper mine. Many financial services companies, banks, and mining analysts (e.g., HSBC, CIBC, UBS) purport to use real options, though their applications are of questionable quality. The U.S. Department of Interior's Minerals Management Service has used real options to evaluate its oil and gas lease terms. AMEC Mining and Metals (Toronto) has a financial economics team that performs real options analysis on client projects, though confidentiality precludes listing specific company names.

A significant hurdle with the introduction of any new technology is the lock-in of the existing technology, even if that technology is suboptimal. The QWERTY keyboard and the internal combustion engine are frequently-cited examples. NPV analysis is another example, being so pervasive and so transparent that even though biased and unreliable as a planning and valuation tool, there is strong resistance to the more complex real options analysis. This resistance is being reduced via technology transfer efforts such as the one-day and three-day short courses on real options techniques being offered by the Colorado School of Mines, Ernst & Young, and CRC Mining. Some 500 mining professionals have attended these courses to date, engendering at least a common language across all participants through which dialogue and evaluation can take place. The Banff taxonomy is also a useful took in this regard (see Figure 2). Nevertheless, real options is not yet a mainstream planning or valuation tool in mining or other industries.

What Are the Next Steps?

Because of the small numbers of experts in this area the research program to date has been limited and isolated. Economists have focused on commercial risk, and there is the need to start to incorporate technical risks. Operations researchers have focused on enriching the decision space, but have ignored modern finance principles and still use traditional NPV maximization as their objective. Mine planners have the industry knowledge and experience, but lack both financial modeling capabilities and advanced operations research skills. Real options mine planning applications are slowly gaining complexity, but there is much work to be done before they can be reliably used for anything other than general inferences about project value and optimal project planning and management.

It took over 50 years for NPV to replace payback period and accounting rate of return as project planning and valuation tools. Real options is now in its third decade and is still relatively unused in the mining industry. The successful advance of real options such that it can replace traditional mine planning will require an extended and well-funded coordinated research effort between academics and industry, with continuity of the researchers and research program, using a team of world class financial and operations research academics and industry mine planners, over a sustained research period of perhaps 7 to 10 years. CRC Mining's research program is the ideal environment in which to advance modern strategic mine planning in both application and research, as it embodies all of these desirable characteristics. If successful, the research outcome will revolutionize mine planning and valuation, adding value across the industry and guiding the path through what is forecast to become a more and more difficult mining environment as grades drop and mines become larger in size.

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