# Beyond Naïve Optimisation

**P. H. L. Monkhouse and G. A. Yeates**

**Abstract** Most practitioners would regard the maximising of the net present value (NPV) of a mine by changing mining schedules, push-backs, cut-off grades, ultimate pit shells and stockpile rules and procedures as encompassing current best practice in mine planning. This optimisation is typically carried out for a single set of assumptions about:

- orebody tonnes and grade,
- processing methods and costs,
- maximum sales volumes in the case of bulk commodities,
- commodity prices, and
- discount rates.

About the only thing we can be sure of is that the assumptions on all these factors will be wrong, yet we continue to naïvely optimise our mine plan. This paper argues that this approach is inherently flawed. Recognising that our assumptions will be wrong, and that our actions can alter over time as new information is made available, means that the mine plan that is 'optimal' under a single set of assumptions may well be suboptimal in the real and uncertain world.

---

P. H. L. Monkhouse (✉)
Business Strategy for Carbon Steel Materials, BHP Billiton Limited,
PO Box 86A, Melbourne, VIC 3001, Australia
e-mail: peter.hl.monkhouse@bhpbilliton.com

G. A. Yeates
Mineral Resource Development, Business Excellence,
BHP Billiton Limited, PO Box 86A, Melbourne, VIC 3001, Australia
e-mail: gavin.yeates@bhpbilliton.com

R. Dimitrakopoulos (ed.), *Advances in Applied Strategic Mine Planning*,
https://doi.org/10.1007/978-3-319-69320-0_1

## Introduction

Best practice is a fuzzy term; when applied to mine planning it can mean many things. Current best practice in mine planning, as viewed by most practitioners, encompasses the maximising of the net present value (NPV) of a mine by changing mining schedules, push-backs, cut-off grades, ultimate pit shells and stockpile rules and procedures. This analysis is typically performed for a single set of assumptions, which we can almost guarantee will be wrong. Assumptions typically cover: orebody tonnes and grade; processing methods and costs; maximum sales volumes in the case of bulk commodities; commodity prices; and discount rates.

Planning for a single set of assumptions that turn out to be incorrect will result in a suboptimal, or naïve, mine plan. There are two possible responses to this. The first is to try harder to correctly estimate (forecast) the future. The second response is to recognise that the future is in many respects unknowable, and to subsequently develop mine plans that have the flexibility to respond to changes to assumptions in the future. This flexible—or robust—mine plan will continue to give high mine values over a wide range of input assumptions (both optimistic and pessimistic), rather than a plan that only gives optimal results over a very small range of assumptions.

The key to addressing these issues is understanding uncertainty and risk, and developing methods to incorporate them into the mine planning process. This allows us to value flexibility and the benefit derived from robust mine plans. Whilst acknowledging that this is difficult, we propose that solutions can be found by combining the research from two broad but quite different areas, those of mine planning and real options. Even if robust or flexible plans are developed, the organisational challenge is to act effectively. For example, how many copper mines changed their mine plans when the copper price doubled over a relatively short period of time? How many of these operations are still working to the cut-off, the schedule and ultimate pit that were in place when the copper price was half what it is today? A mine with flexibility, with exposed ore and with surplus stripping capacity would be able to respond by raising the cut-off, raising the head grade and thereby producing more copper during periods of higher prices and hence capturing value during the price spike. How much value is being destroyed by not changing our current operating plans in light of new information?

In this paper, current industry practice in regard to mine planning is briefly reviewed and the generic assumptions that strongly influence the final mine plan are then discussed. Two key sources of uncertainty—orebody uncertainty and price uncertainty—are then reviewed in some detail. A discussion follows regarding current practices within BHP Billiton before concluding with some suggestions for future developments in this area.

## Current Industry Practice

The current practice in industry is to take a single estimate (model) of the orebody, using a single set of mining assumptions, along with a single set of deterministic external economic assumptions, to come up with an 'optimal' ultimate pit design, extraction sequence, and schedule. The term 'optimal' usually means the maximising of a single variable, usually NPV or its proxy, for a given set of assumptions. The optimised model typically defers stripping, brings forward revenue (high grade) and often extends mine life by dynamically changing cut-off grade over time. Sometimes additional effort is applied to look for the potential of additional value in the stockpiling of low-grade material.

The first step in a mine optimisation typically involves coming up with final pit limits. The tool commonly used is the Whittle pit optimisation, the nested pit version of the Lerchs-Grossmann algorithm (Lerchs and Grossmann 1965; Whittle 1988; Muir 2007). The mine planner's dilemma in using these techniques is that they focus on the final limits. Given that the decision about the final limit is usually far into the future and heavily reliant on external economic assumptions, such as the price at the time the final pushback will be mined, the decision is fraught with difficulty. While this decision is likely to be refined during mine life, key investment decisions are often made on the basis of this information. The next steps in mine optimisation are encapsulated in the seminal book in this area, *The Economic Definition of Ore* (Lane 1988) with the general approach being considered as established practice in the industry.

Unfortunately, the big picture is often lost and the mine planning process blindly followed in the beliefs that the assumptions are right and that the resultant plan is optimal in reality. The key concept regarding all of these factors is that they are only optimal for a given set of assumptions (inputs)—today's optimised mine plans have no flexibility to respond to changed circumstances. This is usually due to the stripping being deferred, all exposed ore being minimised, all stockpiles cut to near zero by the accounting drive to minimise working capital, and material movement matched to the fleet capacity thereby eliminating sprint capacity. Further, if we consider current practice in use at most of our mining operations, the mine plan is often not revised, even when we have significant changes to external assumptions.

## Sources of Uncertainty or Key Assumptions

The key sources of uncertainty that affect the final mine plan are as follows:

*Orebody uncertainty:* The three-dimensional distribution of grade over the orebody is estimated by relatively limited drill hole data coupled with a geological interpretation, which may or may not be correct. This uncertainty, however, is often ignored in the mine planning process. This issue is discussed in more detail in a subsequent section.

*Processing uncertainty:* Just as methods for modelling grade now exist, so do advances in the modelling of what is now called ‘geometallurgical’ performance. It is now possible to deterministically model variables such as ore hardness, flotation or leach recovery, concentrate grade, and ultimately dollars per hour through the mill (e.g. Wooller 1999). Ultimately, these variables can also be simulated to describe the range of possible outcomes that may be encountered in the future operation. This is essentially modelling the current performance through a given process plant (Flores 2005).

*Uncertainty in changing technologies:* Another significant uncertainty far more difficult to model is a major technology change; these step changes could well have major impacts on future mine plans. Examples include atmospheric leaching of nickel ores, leaching of chalcopyrite ores, and the use of high phosphorous iron ore in steel plants. The key uncertainties for these particular changes are threefold: Will the breakthrough occur? If so, when will it occur? If it occurs what will be the size of the step change in cost, recovery and therefore reserve definition?

*Volume uncertainty:* London Metals Exchange (LME) commodities effectively exhibit no volume uncertainty, as product can always be sold and delivered to LME warehouses. However, non-LME commodities, such as coal and iron ore, can only be sold to traders or customers, thereby introducing volume or sales uncertainty. The ability to sell the material is also influenced by its quality.

*Price uncertainty:* The price forecast we enter into our computer models is problematic, especially when the only certainty is that the price forecast we use will be wrong. This will be discussed in more detail later.

*Discount rate uncertainty:* The issue of interest rate uncertainty is more subtle, but no less important, in that it affects what discount rate we use. It affects the trade-off decision between future benefits versus current benefits. Again, the only thing we know about our forecast of interest rates, and hence discount rates, is that they will change over time. Political risk, often allowed for in the discount rate, further complicates this issue. Should we allow for a country risk premium on our annual discount rate that declines with time, as we learn to operate in a country? Or does country risk keep growing exponentially, as is implied in a constant per period discount rate?

## Orebody Uncertainty

The traditional approach has been to provide mine planners with a single ‘best’ interpretation of the orebody. This single geological interpretation is then treated as fact. This approach gives no indication of the uncertainty in the interpretation, nor does it communicate the risk that the interpretation could be wrong or the likely range of possible outcomes. Geologists are dealing with imperfect knowledge, they know that the data on which the interpretation is based is incomplete, imprecise and inaccurate. They also know that there are multiple possible interpretations, each of which is valid. Some may have greater probability than others, but each is valid if it can explain the available data. It is now possible to quantify and model some aspects of the geological uncertainty. The use of simulation techniques is well-developed for modelling the grade uncertainty, but also well known is the critical nature of geological interpretation that controls the grade. There are limited examples of quantifying the range of geological interpretations and hence the grade (e.g. Jackson et al 2003; Khosrowshahi, Shaw and Yeates 2017, this volume; Osterholt and Dimitrakopoulos 2017, this volume).

Dimitrakopoulos, Farrelly and Godoy (2002) illustrate a case where, for a range of equally probable geological outcomes, the mine plan developed on a single estimate of the orebody is excessively optimistic. This is partly driven by any misestimation of grades—resulting in a loss of value either by ore being classified as waste and an opportunity loss suffered—or waste being classified as ore and additional processing costs incurred. This resulting 'bias' is what makes many deterministic plans optimistic. It should be noted, however, that the opposite may also occur unpredictably, to stress the limits of the current modelling and optimisation technologies. This finding has been confirmed by internal research at BHP Billiton Technology (Menabde et al 2017, this volume). Further, and more importantly, this work shows consistently that a mine plan can be developed considering the uncertainty in the geological input assumptions, and this mine plan will have a higher NPV on average (i.e. over a wide range of inputs), a finding independently observed in Godoy and Dimitrakopoulos (2004); and Ramazan and Dimitrakopoulos (2017, this volume).

## Price Uncertainty

To illustrate the problems with current best practice, the following hypothetical mine development is used.

### *A Simplified Example*

Consider a mining company that requires an optimal mine plan for a copper orebody shown (simplistically) in Fig. 1.

#### Waste

For the high-grade block, assume:

1. A grade of 1.25% copper and containing 20 million pounds of copper. At a copper price of US$1/lb this block will produce US$20 M revenue.

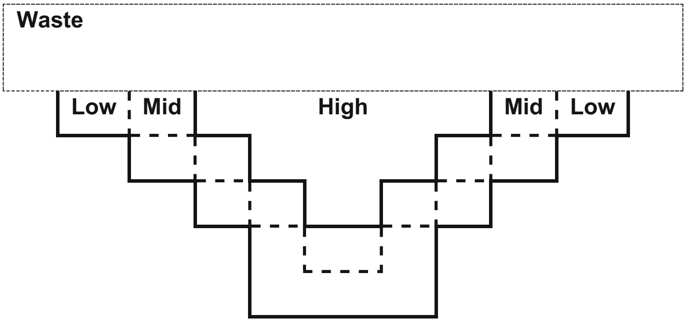

**Fig. 1** A simplistic hypothetical copper orebody

2. The total cost of mining and processing for this high-grade block is US$12 M, split US$6 M for the waste removal and US$6 M for the mining and treatment of the ore. Mining and processing should occur in year 1.

For the mid-grade block, assume:

1. A grade of 1% copper and containing 12 million pounds copper. At a copper price of US$1/lb it will produce US$12 M revenue.
2. The total incremental cost is US$12 M, split between additional waste removal (US$2 M) and mining and processing mid-grade. If mining were to be undertaken, the mining and processing should occur in year 2.

For the low-grade block, assume:

1. The low-grade block is not drilled because the Promoter wants the orebody open at depth, but George the Geologist is convinced it has a grade of 0.65 Cu, containing 12 M pounds copper, for revenue of US$12 M.
2. The incremental cost of removing the low-grade block is estimated at US$14 M, split US$2 M for additional waste removal and US$12 M for mining and processing the ore. If undertaken, the mining and processing of this low-grade block should occur in year 3.

Furthermore, assume that all the waste must be extracted in year 0, and that once this decision is made it is very expensive to go back, in either cost and/or time, and re-strip the additional waste.

## *The Problem Facing the Company*

The problem for the mining company is that a decision needs to be made today on what to mine. If the company forecasts the copper price to be US$1/lb:

- Should the company only mine the high-grade block?
- Should it mine the mid-grade block?
- Should it trust George the Geologist and plan to mine the low-grade block?

If our assumption was that the forecast copper price was US$1/lb then we would apply the approach outlined by Lane (1988). Primarily because of the effects of discounting—with cost of waste removal being incurred in year 0 and revenue in years 1, 2 and 3—we would only extract the high-grade block. An alternate approach may be to use a break-even cut-off (and ignore the effects of discounting), where at US$1/lb copper and for the costs outlined previously, a break-even cut-off grade for the high-grade block is 0.75% copper, the mid-grade block is 1% copper, and the low-grade block is some 0.76% copper. Accordingly, using this approach the company would have mined the high- and mid-grade blocks.

Under what circumstances would the company plan on mining all the blocks? How would the company develop a robust (or flexible) mine plan that allows them to respond to changing circumstances? To highlight the impact of price uncertainty, discount rate uncertainty and geological uncertainty, how would the decision change if:

- Analysis of the futures market indicated there was a 50% chance the copper price would exceed US$1.50 in three years' time?
- The deposit was located in a country with a corrupt dictator that may expropriate the operation at any time?
- An independent review of George the Geologist's work indicated there is a 95% chance he is right.

Intuitively, all these assumptions should change the optimal mine plan, yet current best practice would struggle to include these assumptions. It is suggested that the 'best' mine plan should be one that maximises value over a 'reasonable' range of input assumptions.

## *Framing the Questions in the Language of Real Options*

To determine what we mean by 'best' and a 'reasonable' range of assumptions, the previous example will be re-stated.

For the high-grade block, assume:

1. A grade of 1.25% copper containing 20 million pounds of copper. At a copper price of US$1/lb this will produce US$20 M revenue.
2. Total cost of mining and processing the high-grade block is US$12 M, split US $6 M for waste removal and US$6 M for mining and treating the ore. The waste removal will occur in year 0 with mining and processing to occur in year 1.

For the mid-grade block, assume:

1. A grade of 1% copper containing 12 million pounds copper. At a copper price of US$1/lb it will produce US$12 M revenue.
2. For the cost of additional stripping in year 0 of some US$2 M, we have the option to mine and process the mid-grade block in year 2 at a cost of some US $10 M.

For the low-grade block, assume:

1. The low-grade block is not drilled because the Promoter wants the orebody open at depth. George the Geologist is convinced the grade is at least 0.65% copper, and contains 12 million pounds of copper, which would produce revenue of US $12 M if he is correct.
2. For the cost of additional stripping in year 0 of another US$2 M, we have the compound option to mine and process the low-grade block in year 3 at a cost of some US$12 M. It is a compound option because it is conditional on us mining the mid-grade block in year 2. In this example, the low-grade block is only mined if the mid-grade block is already mined. Compound options are highly non-linear and the effects are complex. In general, the second option (on the low-grade block) has the effect of increasing the value of the first option (on the mid-grade block). However, compound options are not that difficult to value.

Considering this scenario, does the company now mine the high grade block? Does the company now buy the (real) option for US$2 M to mine and process the mid-grade block in two years hence? Does the company buy the (real) option over the low-grade block costing a further US$2 M? Unless the options (or flexibility) can be valued, or the benefits of a robust mine plan can be valued, it is unlikely that mine planning will be successful in moving forward. The keys are properly modelling uncertainty and risk, and understanding the value of preserving options and flexibility.

In our example the two key questions are: What options should be purchased? When, if at all, should options be exercised? To answer the first question the company must know the cost of purchasing the option—in the above example this is US$2 M to undertake the additional stripping. The harder question is: What is the value of acquiring this option, or flexibility? If the option is worth more than it costs, then the company will want to purchase it, and develop a flexible, or robust mine plan. Yet there are limits to the amount of flexibility that should be acquired. To answer the second question about when to exercise the options, the company needs to know the value of keeping the option alive, and the value of exercising the option. Again, we will exercise the option, or mine the mid- and possibly the low-grade blocks if the value of exercising the option is greater than the value of keeping the option alive. The harder issue is valuing the option, not the value of exercising it (developing the mine).

## *Valuing the Real Options for Price Uncertainty*

Price uncertainty can be modelled in a real options framework by building a price tree. To simplify the mathematics in this example, it is assumed that the prices will be constant for one year, and then may vary. It is further assumed that the price distribution is log-normal[1] and that the volatility of the copper price is 20% per annum. It is also assumed that this price tree is a risk-neutral price tree, as obtained from futures data. It is **not** the price tree of expected copper price movements. This distinction is very important to ensure price risk is handled properly. With these assumptions, the up price factor is 1.2214 and the down price factor is the reciprocal, or 0.8187. Assuming a 5% per annum risk-free rate (continuously compounded) and these up and down factors it follows that the risk-neutral probability of an up price movement is 0.5775 and the risk-neutral probability of a down price movement is 0.4225.

### Copper Price Tree

Given the above assumptions, and assuming the current copper price is US$1/lb, the copper price tree is shown in Table 1.

### Value of High-Grade Block

Given there are 20 M pounds of copper and the mining and processing costs are US $6 M, the cash flows from mining the high-grade block (assuming the waste removal has already occurred in year 0) is shown in Table 2.

**Table 1** Copper price tree with and copper price at US $1/lb

| Now | Year 1 | Year 2 | Year 3 |
|---|---|---|---|
| | | | 1.82 |
| | | 1.49 | |
| | 1.22 | | 1.22 |
| 1.00 | | 1.00 | |
| | 0.82 | | 0.82 |
| | | 0.67 | |
| | | | 0.55 |

---

[1] This assumption is discussed in detail in corporate finance textbooks (eg., Brealey and Myers 2003, Chap. 21; Hull 2000, Chap. 9).

**Table 2** Cash flows from mining the high-grade block (assuming the waste removal has already occurred in year 0)

| Now | Year 1 | Year 2 | Year 3 |
|---|---|---|---|
| | 18.43[a] | | |
| | 10.37 | | |

[a] Calculated as (1.2214 * 20)−6.0

Assuming the risk-free interest rate is 5% per annum (continuously compounded) and that the waste removal has already occurred, the value tree is shown in Table 3.

After spending US$6 M on waste removal we should have a value of US $14.29 M. Thus, before we even start the project it has a value of some US$8.29 M and indicates that the high-grade block should be mined.

## Value of Mid-Grade Block

Using the same price tree as above and given there are 12 M pounds of copper and the mining and processing costs are US$10 M, the cash flows from mining the mid-grade block (assuming the waste removal has already occurred in year 0) are shown in Table 4.

Assuming the risk-free interest rate is 5% per annum (continuously compounded) and that the waste removal has already occurred, the value tree is shown in Table 5.

**Table 3** Value tree, assuming the risk-free interest rate is 5% per annum (continuously compounded) and that the waste removal has already occurred

| Now | Year 1 | Year 2 | Year 3 |
|---|---|---|---|
| | 18.43 | | |
| 14.29[a] | | | |
| | 10.37 | | |

[a] Calculated as (18.43 * 0.5775 + 10.37 * 0.4225)/exp(0.05). The exponential term is because the interest rate is expressed on a continuously compounded basis

**Table 4** Cash flows from mining the mid-grade block (assuming the waste removal has already occurred in year 0)

| Now | Year 1 | Year 2 | Year 3 |
|---|---|---|---|
| | | 7.90 | |
| | | 2.00 | |
| | | −1.96 | |

**Table 5** Value tree, assuming the risk-free interest rate is 5% per annum (continuously compounded), and that the waste removal has already occurred

| Now | Year 1 | Year 2 | Year 3 |
|---|---|---|---|
| | | 7.90 | |
| | 5.14 | | |
| 3.27 | | 2.00 | |
| | 1.10 | | |
| | | 0.00 | |

Spending US$2 M on additional waste removal should give us a value of US $3.27 M. Thus the project, before we start, has a value of some US$1.27 M and means the company should at least undertake the prestrip for the mid grade block. However, we will only mine the mid-grade zone if the copper price is US$1/lb or above. We will not mine the mid-grade zone if the copper price is the low price in year 2 of US$0.67/lb. Ultimately, it is the ability to defer this mining decision that is creating the value, and thus facilitating the mining of the mid-grade zone in some circumstances.

A possible counterintuitive result is also evident from this example. Consider the case where the copper price remains at US$1/lb through the mine life. In this case the company will end up mining the mid-grade block because:

- the option analysis commits the company to undertake the prestrip, as the copper price might rise; however
- when the company gets to make the mining decision it decides to mine even if the copper price is only US$1/lb because the **prestripping is now a sunk cost** and is excluded from the analysis.

More of the deposit is mined if the copper price turns out to be a constant US$1/lb under the robust mine planning framework compared to a current 'best practice' framework. This is despite the fact that if we had perfect foresight we would not have committed to this prestripping and the mining of the mid-grade block. This is of obvious benefit to the host country.

## Value of Low-Grade Block

Now let us repeat this procedure for the low-grade block. The price tree is the same as in the previous example. Given that there are 12 M pounds of copper and the mining and processing costs are US$12 M, the cash flows from mining the low-grade block (assuming the waste removal has already occurred in year 0) are shown in Table 6.

Assuming the risk-free interest rate is 5% per annum (continuously compounded), and that the waste removal has already occurred, the value tree is shown in Table 7.

Spending US$2 M on additional waste removal should give us a value of US $2.60 M. The project, before we start, therefore has a value of some US$0.60 M. This means the company should do the prestrip for the low-grade block as well, but

**Table 6** Cash flows from mining the low-grade block (assuming the waste removal has already occurred in year 0)

| Now | Year 1 | Year 2 | Year 3 |
|---|---|---|---|
| | | | 9.87 |
| | | | 2.66 |
| | | | −2.18 |
| | | | −5.41 |

**Table 7** Value tree, assuming the risk-free interest rate is 5% per annum (continuously compounded) and that the waste removal has already occurred

| Now | Year 1 | Year 2 | Year 3 |
|---|---|---|---|
| | | | 9.87 |
| | | 6.49 | |
| | 4.15 | | 2.66 |
| 2.60 | | 1.46 | |
| | 0.80 | | 0.00 |
| | | 0.00 | |
| | | | 0.00 |

will only mine the low-grade zone if the copper price is above US$1.22/lb. The low-grade zone will not be mined if the copper price is only US$0.82/lb or less. At the risk of labouring the point, it is the ability to defer this mining decision that is creating the value, and thus facilitating the mining of the low-grade zone in some circumstances.

Note that more of the deposit is mined under the robust planning framework than under the current 'best practice' framework. The expected amount of material mined at the start of the mining operation is greater under the robust mine planning framework than any other framework, with significant benefits to the company, shareholders and the host country.

## Introducing Additional Sources of Uncertainty in the Analysis

The simplified example shown previously introduced an additional source of uncertainty. Should the company trust George the Geologist's intuition and plan to mine the low-grade block? What about the risk that George is wrong? Should this risk be allowed for in the analysis? Before discussing this in more detail we need to introduce another concept from corporate finance, namely diversifiable risk and non-diversifiable risk. The key issue is that some (non-diversifiable) risks are priced (investors will pay to avoid them, e.g. commodity price risk, interest rate risk), and other (diversifiable) risks are unpriced (investors are indifferent about bearing them, e.g. geological uncertainty). This concept forms the bedrock of the Capital Asset Pricing Model or CAPM (Brealey and Myers 2003, Chaps. 7 and 8).

If George's estimate of the grade is truly a central estimate then because geological risk is, at least to a first order approximation, unpriced, we should not introduce any additional value reduction because of the 'risk', even if the distribution of possible outcomes is incredibly wide. The key issue is whether George's estimate is a central estimate because, unlike copper price, the risk of the possible outcomes does not enter the valuation.

## More General Comments on Uncertainty and Risk

The latter example has introduced two key corporate finance concepts: namely real options,[2] and diversifiable and non-diversifiable risk, but this paper cannot do justice to these concepts.[3] Together these two concepts allow for the classification of risks into priced and non-priced risks, and where they are priced an analytical tool to evaluate them is provided. It allows the valuation of mine plans (and risk) from the perspective of shareholders and allows the company to then compare the cost of acquiring flexibility, versus the value of having flexible mine plans.

Failure to adequately address risk (such as using expected spot prices instead of risk-neutral prices) means that we get the garbage-in-garbage-out problem, a very large problem. Properly valuing the risk introduced by real options is complex. We can quickly end up in the world of stochastic differential equations, or large-scale numerical methods. Yet failing to properly value risk means we are wasting our time. The authors believe that we are better off relying on our intuition than doing some pseudo-maths that does not properly allow for risk.

## Possible Criticisms of the Proposed Approach

In these examples, a flexible or robust mine plan means removing all the waste in year 0, which goes beyond standard practice in the industry. One possible criticism of this approach is that the decision to prestrip is made up-front and is artificial. In practice you could go back and prestrip for the mid- and the low-grade blocks if the price spiked. While this is to some extent correct, it can be argued that:

1. going back and undertaking additional prestripping will contribute to cost and time penalties, although these can be modelled if considered appropriate;
2. in a real-world approach you need to model mean reversion in the commodity prices, which means that any time delays suffered could well cause a significant value loss; and
3. in any mining operation, the time taken to do any additional stripping is measured in years.

In any event, the mere fact that we are thinking how we will respond to changed economic circumstances is the whole point of this paper. The aim, in real options

---

[2] The Nobel Prize in Economics in 1997 was awarded to Scholes and Merton for adequately handling risk in (financial) option valuations. The earlier tool of the Capital Asset Pricing Model—while important and underpinning all NPV analysis – does not allow risk to be accurately valued when we have option-type pay-offs. The seminal option paper by Black and Scholes (1973) effectively provided a numerically quantifiable way of handling non-diversifiable (or priced) risk in option-type pay-offs. This concept has since been extended to real options.

[3] The application of real options is discussed in Copeland and Tufano (2004). The application of real options to a mining example is discussed in McCarthy and Monkhouse (2003).

talk, is to acquire flexibility for less than its inherent value—if that can be done by alternative and lower cost means then so much the better. It could be argued that all this is too hard and that sensitivity analysis will get us most of the way there, but at a fraction of the complexity. To the extent that sensitivity analysis builds intuition, then that is a great outcome. But of itself, sensitivity analysis will have limited benefit in generating a robust or flexible mine plan as it will be unable to justify the cost of investing in flexibility. This can only be achieved by implementing real options analysis as described previously.

## State of Play in Bhp Billiton

Within BHP Billiton it is well-recognised that there are limitations to optimising a mine plan for a given set of assumptions that will inevitably turn out to be incorrect. Further, it is accepted that this approach will lead to suboptimal outcomes, for both our shareholders and the host country. Overcoming this deficiency is crucial; it requires the development of new mine planning techniques, and—just as importantly—it requires the development of management systems to facilitate changes to the mining operations in response to changing economic conditions. At BHP Billiton we are developing robust and flexible mine plans, and we have adjusted budgets and incentives to reflect changed economic circumstances. We believe we already have a competitive edge in this area, but we are the first to admit that there is a lot more work to be done.

## Concluding Remarks

This paper has discussed current best practice in mine planning and has identified a key shortcoming. The fact that the key assumptions underpinning our mine plans will inevitably prove to be incorrect means that our mine plans are no longer optimal over a reasonable range of real world outcomes. Possible sources of uncertainty were highlighted and discussed. The paper then focused on two key sources of uncertainty: price uncertainty and geological uncertainty. By using a simplified example it was shown that mine plans will change if price uncertainty is explicitly recognised. The issue of geological uncertainty was also introduced in the simplified example and it was indicated that plans will likely change to extract more ore. Perhaps counterintuitively, it was argued that the risk of geological uncertainty did not affect the mine plan and was of a fundamentally different character to that of commodity price risk. Possible criticisms of the proposed approach were also discussed.

What needs to be remembered is that every day mine planners are making decisions about:

- What is waste and what is ore?
- How much exposed ore should we carry?
- When should we run down our levels of exposed ore?
- What sequence of push-backs should we use?
- What stockpiles should we carry?
- How much 'excess' mining capacity we should carry?

We cannot stop the mining operations to perform the analysis. We have uncertainty regarding geology, processing, new technologies, market, prices and discount rates; the opportunity cost of suboptimal mine plans is large. At BHP Billiton we are mindful of the limitations of conventional optimisation techniques, and are developing methods and tools to assist us in valuing flexibility and ultimately developing robust mine plans.

## References

Black F, Scholes M (1973) The pricing of options and corporate liabilities. J Political Econom 81:637–659

Brealey RA, Myers SC (2003) Principles of corporate finance, 7th edn. New York, McGraw Hill Irwin

Copeland, T, Tufano, P (2004) A real-world way to manage real options. Harvard Business Rev, March, 90:9

Dimitrakopoulos R, Farrelly CT, Godoy M (2002) Moving forward from traditional optimization: grade uncertainty and risk effects in open-pit design. Trans Inst Min Metall, Section A, Mining Technology 111:A82–A88

Flores L (2005) Hardness model and reconciliation of throughput models to plant results at Minera, Escondida Ltda, Chile In: Proceedings 37th canadian mineral processors conference, Ottawa, 18–20 January

Godoy MC, Dimitrakopoulos R (2004) Managing risk and waste mining in long-term production scheduling. SME Trans 316:43–50

Hull J C (2000) Options, futures and other derivatives, 4th edn (Prentice Hall)

Jackson S, Frederickson D, Stewart M, Vann J, Burke A, Dugdale J, Bertoli O (2003) Geological and grade risk and the golden gift and magdala gold deposits Stawell, Victoria, Australia. In: Proceedings fifth international mining geology conference, pp 207–213 (The Australasian Institute of Mining and Metallurgy: Melbourne)

Khosrowshahi S, Shaw WJ, Yeates GA (2017) Quantification of risk using simulation of the chain of mining—a case study at Escondida Copper, Chile, in this volume

Lane K (1988) The economic definition of ore. Mining Journal Books, London

Lerchs H, Grossmann L (1965) Optimum design of open-pit mines. Trans CIM, LXVII, pp 17–24

McCarthy J, Monkhouse PHL (2003) To open or not to open—or what to do with a closed copper mine. J Appl Corporate Finan, Winter, 63–73

Menabde M, Froyland G, Stone P, Yeates GA (2017) Mining schedule optimisation for conditionally simulated orebodies, in this volume

Muir DCW (2007) Pseudoflow, new life for Lerchs-Grossmann pit optimisation. In: Orebody modelling and strategic mine planning, second edn (ed: R Dimitrakopoulos), pp 113–120 (The Australasian Institute of Mining and Metallurgy: Melbourne)

Osterholt V, Dimitrakopoulos R (2017) Simulation of orebody geology with multiple-point geostatistics—application at Yandi channel iron ore deposit, WA and implications for resource uncertainty, in this volume

Ramazan S, Dimitrakopoulos R (2017) Stochastic optimisation of long-term production scheduling for open pit mines with a new integer programming formulation, in this volume

Whittle J (1988) Beyond optimisation in open pit design. In: Proceedings Canadian conference on computer applications in the mineral industries, Rotterdam, pp 331–337

Wooller R (1999) Cut-off grades beyond the mine—optimising mill throughput. In: Strategic mine planning conference, pp 217–229 (Whittle Programming Pty Ltd: Melbourne)