Mining Economics and Technology

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ABSTRACT This paper examines the interaction of economics and technology in mining. It is in three parts, the common link being the influence of economics on decisions. The first part highlights how economics underpins choices to explore for mineral commodities. It shows that popular concerns regarding exhaustion of non-renewable mineral commodities are largely unfounded. The second part examines the impact of technology and its effect on mine economics. Using real-world cases it suggests that the industry application of technology is focussing on evident but less-economically-valuable applications and overlooking less-evident but more-economically-important applications. It uses an example of path-dependent processes to highlight the importance of the *process* of mine planning. The third part examines the impact of cyclical commodity prices on mining company decision-making. It concludes that the current phase of the commodity price cycle presents a significant opportunity for implementation of technology in mines for lasting long-term efficiencies.

Keywords: Economics, Technology, Reserves, Computer, Commodity Prices

1 INTRODUCTION

In competitive free market environments economics underpins every choice - in exploring for mineral deposits; in planning for, developing, and operating mines and processing plants; and in the financing and marketing of mineral commodities. Yet, understandably, few technical professionals have a comprehensive understanding of economics. Mining is a multi-disciplinary industry, and, as with elsewhere in the industry where there is overlap between disciplines simplified proxies from the other field are deployed to incorporate the necessary guidelines or requirements.

A grade control engineer in the mine, for example, might only have a rudimentary understanding of processing plant metallurgy, but will use simplified guidelines given to him or her from the plant manager. Likewise, a geologist looking for the latest mineral commodity of interest will incorporate guidelines such as minimum widths, depths, and grades from mining and processing disciplines to inform his exploration targeting. Sometimes these guidelines from other disciplines prove reliable enough for the task at hand, and sometimes not.

What about the overlap with economics – an overlap that impacts all the technical disciplines?

When a planning engineer optimizes something, how well does the "something" translate into the best economic outcomes? What defines the best economic outcome? If we achieve lower costs or better returns in the short term, is this at the expense of higher costs or worse returns in the long term? Are better returns associated with higher risk?

The sections that follow don't answer these questions explicitly, but look at three areas of industry endeavour through an economic lens to arrive at a subjective report card of success or otherwise from an economic perspective.

2 MINERAL COMMODITIES: LONG TERM RESERVES AND PRICES

2.1 Reserves of Mineral Commodities

It is common perception that all the key mineral commodities – non-renewables – are gradually becoming exhausted. Deposits are becoming deeper, harder to find, and more complicated to extract, whilst at the same time the rate of production is increasing. The implication is that we must conserve existing resources and focus on recycling and on the use of alternatives, especially renewables.

Various authors (see: Baumol and Blackman, 1993; Repetto, 1987; Runge, 1998) have looked at world reserves and resources of non-renewable mineral commodities and how they change through time. Table 1 shows the reserves and production for three selected minerals illustrating the situation since 1950.

Even though production in the 30 years following on from 1950 exceeded, or nearly exceeded, the reserves available in 1950, the reserves by 1980 far outweighed the reserves at the start. Even today, with higher production rates and a much stricter definition of what constitutes a "reserve," the current reserve position translates into 26 years of production (for Iron), and more than this for the other commodities. For most commodities the reserve position is typically increasing both in total terms and in years-of-production terms.

This trend is a consequence of simple economics. Exploring for and proving up reserves is costly. It is uneconomic to spend money *now* to prove up reserves too far into the future, because the return from exploiting them only materializes when they are extracted.

The conclusion to be drawn is that there is no evidence yet to suggest that any of the important mineral commodities are becoming exhausted.

2.2 Long-term Prices of Mineral Commodities

When it comes to sustainable production of mineral commodities sufficient reserves are only half the equation however. The other half is "cost." It is of little value if the world reserves of oil were good for (say) 100 years at current production rates but gasoline was going to cost $100/litre.

In a market economy if there is a shortage of any commodity, the price will change (rise) until supply matches demand. The economics will favour additional exploration and deployment of technologies to exploit deposits previously considered uneconomic. At the same time, demand will also reduce. In this purely economic scenario the world will probably never really run out of any mineral commodity.

Is Table 1 just underpinned by ever-increasing commodity prices?

The answer is: No. There are short term fluctuations in the price of all commodities, but when these changes are excluded *the long term price of most mineral commodities is either constant in inflation-adjusted terms, or declining*.

Table 1 – World Reserves and Production of Three Selected Minerals

Mineral	Reserves* 1950	Production 1950 – 1980	Reserves 1980	Reserves$^{\beta}$ 2016	Years of Production
Aluminum	1,400	1,346	5,200	7,000 (16,000)	>100 years
Copper	100	156	494	720 (2,100)	36 to 112 years
Iron	19,000	11,040	93,466	85,000 (230,000)	26 to 66 years

* Reserves and Production from 1950 and 1980 from Repetto (1987). Reserves and production for 2016 estimated by the author based on information from the U.S. Geological Survey. Units: *millions of tonnes of metal content*

β Definitions for reserves in 1950 and 1980 are not compatible with the definitions in use in 2016, and include mineralization which would now be classified as "resources." For 2016, the first estimate is quoted reserves, the second estimate in parentheses includes resources (insufficiently well-defined to be classified as reserves under currently accepted definitions).

Figure 1, adapted from Deverell and Yu (2011) shows the price of iron ore since 1885, corrected for inflation and plotted on a relative log scale.

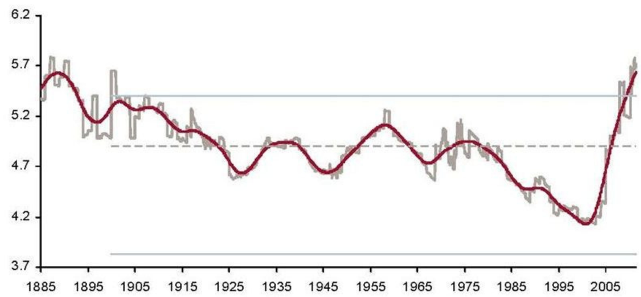

Figure 1 Iron Ore Price since 1885

Apart from the dramatic short-term price spike in the early 2000s, the long-term trend in iron ore price is unambiguously *declining*.

The same trend is evident with the long-term price of copper shown in Figure 2.

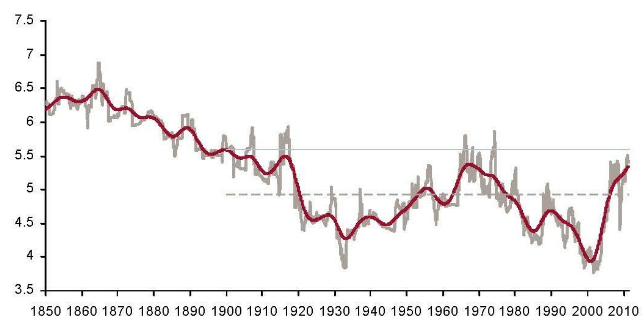

Figure 2 Copper Price since 1850

Despite increased demand, despite deeper more complex and lower-grade orebodies, and despite increased environmental and safety imposts, technology to find and exploit orebodies at competitive commodity prices has more than kept pace with the rate of exhaustion of known deposits over at least 150 years.

The long-term price reflects the fundamental costs of production. This declining trend is almost totally due to advances in technology.

It is technology applied to finding previously unknown deposits or understanding existing deposits better. It is technology applied to the mining of deposits previously considered too difficult, too complex, or perhaps too unsafe to mine. It is technology applied to extracting minerals in ways previously too hard to extract.

Technology finds its way into mining in many ways. It may be widely applicable or narrowly focussed. It might be just different but not necessarily better. For every idea put to practical use there are probably 10 ideas that end up in a dead end. There are probably another 10 ideas that just establish the ground-work – ideas examined years or decades previously in some university or some corporate back-room environment.

This technological advancement is the foundation of how the world advances, however long it sometimes takes to come to fruition in standard-of-living terms, and however unrecognized and unappreciated it often is in the mainstream consumer world.

3 TECHNOLOGY

Technology and <u>economics</u> are integrally linked. Technology and <u>mining</u> are integrally linked.

Runge (1995) examined the growth of technology starting from before the industrial revolution in England, how the mining industry adopted the technology, and how this affected both the industry and the wider community.

Technology is a part of mining now more than ever before. The following sections set out examples from the last 40 years of extensive use of technology in mines around the world to draw some lessons for the mining industry today. The lessons apply to any technology, but the primary focus is on computer technology aimed at planning and operating mines better.

3.1 Computer Applications and Mine Design.

Early computer tools for equipment simulation and mine design were very primitive, but so too would any new technology seem to be when viewed from 40 years in the future. Reliable results from these early applications were only possible if the work was being undertaken by someone well-versed and experienced in the system and aware of its limitations – someone who was wary of the kinds of situations likely to yield unreliable results.

Nevertheless, huge gains were made because the technology allowed things to be done that were previously not possible to do. The analysis of the complex interaction between multiple trucks and loaders was something not hitherto possible. A mine plan that previously took weeks of tedious hard work to schedule just once could be scheduled in less than an hour. For the first time this facilitated analysing alternative mine layouts and alternative schedules that were simply impossible to conceive previously.

Today the tools are immensely more powerful and sophisticated.

Have there been significant *economic* gains? There has been a saving in planning personnel manpower. Complex mines have been commissioned where previously the complexity would have been a barrier to start-up, though this doesn't necessarily mean economic gains over mines from the previous era.

The greatest economic gains come from better decisions, and judging by decision-making in the industry today it is hard to conclude that better decisions are now being made than in previous eras. The problems stem from lesser involvement of experienced personnel with the introduction of technology; from planning personnel distracted by the technology to the detriment of mine economics; and from technology that automates a planning process that is itself flawed or inappropriate to the application.

This is the key conclusion of this paper: *that the advances in computer applications for the analytical aspects of mine planning have not been matched by advancements in the understanding of the process of mine planning, with some of the biggest potential economic benefits not being realized.*

I illustrate this firstly with an example from a study of a large South African dragline mine planned in the late 1980s. A stylized mine layout with the different directions of mining possible is shown in Figure 3.

Dragline mines always progress in strip-by-strip fashion, because the waste from each strip is placed in the mined-out void from the previous strip. The starting point is usually the coal outcrop or some property boundary. In this deposit the topography was undulating and the

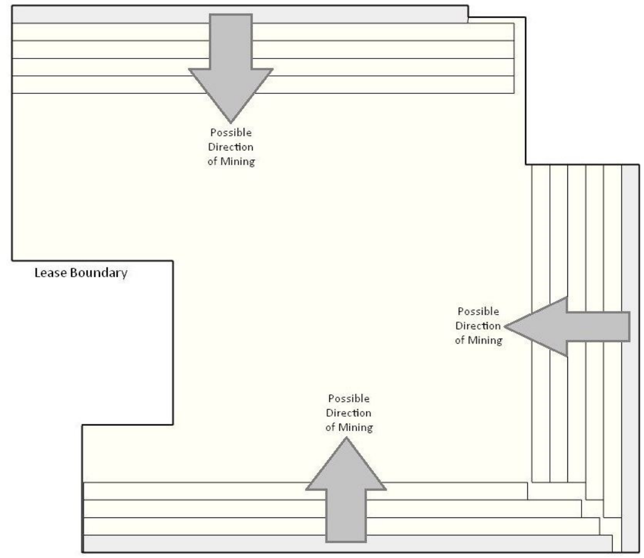

Figure 3 Stylized Plan View of Open Pit Dragline Mine

coal seam was relatively flat-lying and it extended over almost the whole lease area. There was no outcrop, and no obvious place to start mining. Such a case presented a prime target for the new (at the time) technology. For the first time in such an environment it was possible to try multiple different mine layouts with mining advancing in just about any conceivable direction. The company undertook such a study, analysing scores of layouts and schedules. The optimum mine plan was the layout and schedule that yielded the lowest price of coal when assessed on a discounted cash flow, net present value basis.

Unfortunately, the planning personnel inadvertently fell into the "knowledge problem" trap that was the subject of the paper referred to in Runge (1995). The "knowledge problem" isn't a problem explicitly associated with technology, but technology – in this case by using the power of the computer to examine many hundreds of cases – can deceive us into believing that our assessment has been comprehensive. In this case, although the personnel involved were experienced mining engineers, they had limited knowledge of dragline operations, and simply failed to examine a set of cases that were (as it turned out) 30% more cost efficient than the best case previously studied. The selected case started with a boxcut in the centre of the deposit (excavated by shovels and trucks) and

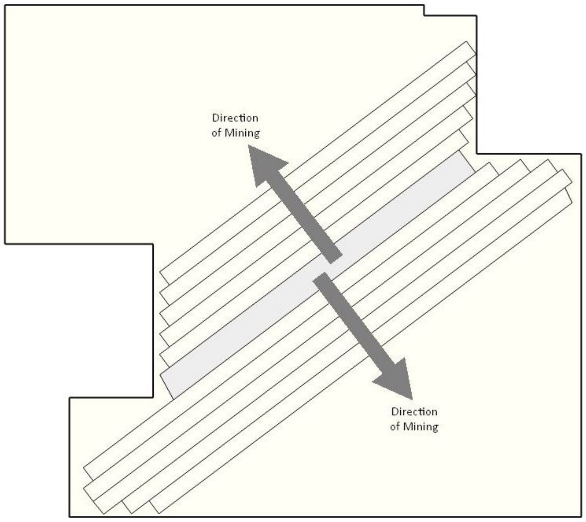

Figure 4 Final Configuration and Mine Layout

progressed in two directions outward as shown in Figure 4.

Technology is a tool, but deciding how to use it and how to rely on it is a task quite different to the task of using it. This is not a case of "garbage in, garbage out." Nor is it a shortcoming in the computer program. It is an example of a shortcoming in the *process* of planning a mine.

"Experience" definitely provides some protection against this shortcoming, but it isn't the only tool that can provide such guidance. Nevertheless, with the advent of advanced technology the value of experience has often been overlooked. Sometimes other computer tools can help make these choices (i.e. to determine if something is worth studying, or not). The lesson, however, is that the task is not something that can be assigned to a lesser experienced person simply because he or she has the requisite computer skills to drive the program. Understanding the *process* is something quite different to undertaking the *tasks* that make up the process.

This example showed a 30% lower cost of production than the case that might otherwise have been chosen. Such huge changes in economics are not uncommon *at the start of mining projects*.

This characteristic of mining, e.g. the inability at the start to define a comprehensive set of alternatives for evaluation and consideration, is something that sets our industry apart from most other industries.

3.2 Early Stage Assessments and Choices Subject to Uncertainty

This section extends the example from above, and again illustrates the importance of correct *process* in early-stage assessments.

Figure 5 shows a classical sub-vertical-trending metalliferous orebody that is subject to possible mine development either as an open pit mine or as an underground mine. Two high-grade zones (Zone 1, and Zone 2) have been identified, with a third ill-defined region of lower-grade mineralization (Zone 3) also

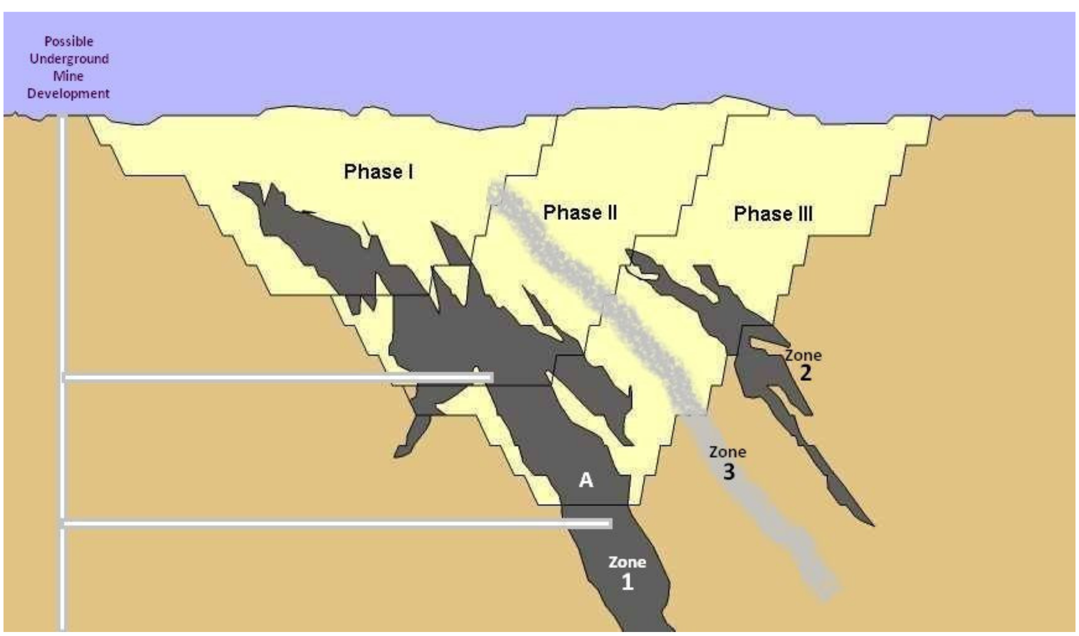

Figure 5 – Example Metalliferous Deposit and Possible Mining Methods

present. The highest grade of ore so far identified in the deposit is located at "A."

Consider now the characteristics of this deposit and the decision-making environment that might lead to an optimum way of exploiting it. Five characteristics are shown in Table 2.

Table 2 only covers a few of the differences between the mining methods. Also, the mining methods are themselves not necessarily exclusive - open pit mining can coexist with underground mining, and frequently does in mines around the world. Choices are not "digital" – hundreds of variations and combinations are possible, and not all of the subtle differences between the variations can be identified in advance, or even reduced to economic criteria. The complexities in this example are similar to the example shown in the previous section.

In the previous section the shortcoming in the process of evaluation was ascribed to the "knowledge" problem. This section introduces another aspect of the process that can lead to sub-optimal results, namely, the risk of *path-dependent evaluation processes*.

For example, at the early stages of evaluation, if a geologist believes that the deposit is likely to be mined by underground methods, then he or she can logically and rationally choose to ignore the uneconomic mineralization in Zone 3. It costs money to drill out and evaluate deep deposits and there is little point in doing so if it will never be mined. This omission will have no bearing on the net present value of any future underground mine.

Consider now any subsequent assessment of the deposit *as an open pit mining proposition.* The mineralization in Zone 3 won't be evident - it likely won't even be shown on geological plans. The net present value of any open pit mine will not benefit from this inclusion. Due to the early-in-the-process assumption by the geologist the comparison between open pit and underground mining options has been biased towards the underground mining option. Indeed, this result "confirms" the judgement of the geologist in the first place to exclude the mineralization in Zone 3. The process just followed is a path-dependent one. The wrong result will potentially be arrived at even though

Table 2 Deposit Characteristics with Open Pit Mining and Underground Mining Alternatives.

Characteristic	Typical Open Pit Mining Method	Typical Underground Mining Method
Sequence of Mining	The highest grade ore will not be accessible until the last stages of the mine life	There is scope to mine the highest grade ore relatively early in the mine life
Ore Grade for Economic Viability	Ore in zone 3 is viable to mine because the material has to be extracted anyway. Once there is already a processing plant in place and once the material has already been hauled to the surface, the return from this lower grade ore is attractive	Zone 3 is uneconomic when mined using underground methods. Narrow ore zones within Zones 1 and 2 may also not be mineable.
Reserves	Maximum extraction of in-situ mineralization	Proportion of in-situ mineralization that can be extracted is much less.
Development Effort and Timing	Requires extraction of the shallower reserves first. Even the shallow reserves may require a lot of waste to be prestripped before reaching the first ore. Initial development work (prestripping) can be expedited using contract earthmoving	More flexibility in choosing which ore can be mined first. Initial development work (shafts, drives, stope development) constrained (cannot easily be expedited) because of limited access and tasks undertaken in series
Exploration Effort and Data Reliability	Reserves that are mined first are best known (shallowest, easiest to drill out) reducing risk and increasing reliability of plant design and marketing.	Deep reserves are expensive to drill out in advance. Higher cost, up-front geological assessment.

all choices leading to that point were logically and systematically made.

This path dependency is an endemic characteristic of any decision process where there is uncertainty that can be resolved only at a cost that itself impacts the viability of the project. Path-dependent processes don't necessarily yield incorrect answers, and even where they do few operators would even be aware of it because the alternative path that was not followed (the opportunity cost) is seldom evident. Runge (2000, p. 128) sets out a number of examples of such processes.

As with the previous example, the evaluation of the various alternatives in this case is definitely one for modern computer tools. But the lesson with use of these tools is the same: the greatest economic value added (or greatest loss of economic value suffered, even if unknowingly) occurs at the start of projects, and is a function of the process followed and the choices as to which cases are to be examined.

4 DECISIONS THROUGH THE COMMODITY PRICE CYCLE

Decision-making in the mining industry extends across a spectrum from the urgent (survival) to choices spanning decades. All the of the previous examples been on the less urgent part of this spectrum. This section considers decisions on the more shorter-term part of the spectrum.

The impact of shorter term commodity price changes can be dramatic, and any assessment and valuation of the economics of mines in the longer term must also consider how well-equipped the mine is to handle circumstances in the shorter-term. Mines that can readily adapt – either because of deposit characteristics, or because of mining methods selected, or because of some other characteristic - are to be preferred over mines that are less adaptable.

4.1 Technical and Economic Impact of Commodity Price Changes

Figure 6 shows the price of iron ore over the last 8 years.

The price changes from an initial high of US$180/tonne in early 2008, to a low of just one-third of that later in the same year; to a high of more than US$180/tonne in early 2011, and to a low of less than US$40/tonne at the end of 2015. The current price (March, 2017) is around US$90/tonne.

Commodity price changes over the last eight years may have been more dramatic than in most 8-year periods, but nevertheless, these

Figure 6 Iron ore price 2008-2016

Import price of Iron Ore fines (62% Fe) into China. Price in US$ per dry metric tonne. Data from www.fullertreacymoney.com fluctuations are a characteristic of mining much more than most other industries. Imagine the impact on industries such as motor vehicle manufacturing, or house construction if the selling price of their product fell by two-thirds in less than one year (2008 in the above figure) or more than doubled in price in one year (as in 2016 in the above figure)?

How can price changes of this magnitude (and changes in the way that the mine is operated) be reconciled with the long-term trends and application of technology discussed in the first part of this paper?

Assuming you were involved in assessing an iron ore deposit, or in planning a mine, or in managing a mine during this period, how would price changes like the ones shown in Figure 6 impact your decision-making?

Reserves: The tonnage of reserves that are viable at $40/tonne will almost certainly be less than the tonnage when the selling price is $180/tonne. What should be the basis for reporting reserves? How should exploration effort be prioritized over this period with change in selling price? If some mineralization is clearly not viable at current prices, but is likely to become viable under some future envisaged price scenario, should it be examined now, and at what cost?

Mine Design: An "Optimum" pit when the selling price is $40/tonne is surely much smaller and a different shape than an "Optimum" pit when the selling price is $180/tonne. If a mine has been designed, and is in operation, using the "optimum" pit shape based on the "$180/tonne" price, then at some other price how much "less-than-optimum" is it, and what should be the strategy for changing the design to accommodate the changed price?

Management: Anyone can look good managing a mine during periods of high commodity prices. But when selling prices are low many operating mines are unprofitable and require a lot of cash to keep running. Closure might not be a viable option, because high closure costs might require even more cash. Yet low points in the commodity price cycle are when the raising of cash is the most expensive - when the marginal cost of capital is highest. What should be the strategy to avoid this vicious circle? Is there anything that can be done prior to mine start-up, or is it something that can really only be addressed operationally?

These are not just rhetorical questions. It is not sufficient to simply focus on keeping the costs of production in the lowest quartile of the industry. Mining companies have failed because the commodity price remained below the long-term trend price for too long, and they ran out of money waiting for the upturn.

The answer to the questions is one for each specific mining operation, however there are guidelines to be drawn and lessons to be learnt that apply to all mines.

4.2 Change.

Every mine changes throughout its life. It changes because the orebody changes. It changes because the price of the product changes. It changes because demands of the customers change. And it changes because technology changes.

One lesson from the last 8 years is that our ability to adapt to change has been found wanting. This isn't surprising since when mines are being planned few operators plan for adaptability.

Classically mine assessments are based on relatively fixed scenarios, albeit examining multiple alternative mine plans consistent with that scenario. The scenario is initially taken as a given by the mine planners because it involves inputs outside of his or her area of expertise – expected selling price, cost of capital (required return on investment), market characteristics etc. Sensitivity studies are conducted to assess the impact on the net present value of various changes to these starting assumptions.

However in the face of significant change in some fundamental parameter operators don't just accept the change as implied by the sensitivity analysis. The mine plan changes to respond to the external changes. Only then does the ability and resilience of the mine to respond to change become evident.

Could this "ability and resilience of the mine to respond to change" have been understood *before the mine was commenced?* If so, a more robust alternative plan better able to cope with the change might have materialized.

How do mining enterprises value plans that are more resilient over plans that have less ability to change and adapt? How can increased expenditure leading to increased adaptability ever be justified when under any base case (fixed) scenario the less adaptable alternative (with lower capital requirements) will yield a higher return on investment?

4.3 Commodity Price Cycles and Management Decision-Making

Most technological advances and long term cost-of-production efficiencies originate with technical professionals, often in conjunction with operations personnel who have the most knowledge of aspects of the mine that might be done better.

Improving efficiency means change – doing something a "better way." At least initially this takes additional time, effort and investment compared to simply maintaining the status quo. At what stage does implementing change make sense?

Implementing change takes time that may not be available. Short-term commodity price changes exacerbate the problem. As a technical person focussed on improving efficiency how can these constraints be reconciled?

Consider again Figure 6 as a proxy for any short term commodity price cycle, characterized in three phases, labelled "A", "B", and "C."

Commodity Prices Increasing (Phase "A"). During the "up" phase of the cycle, few mining enterprises are interested in efficiency; they are interested in expansion, and production (often "at all costs"). Skilled operational personnel are hard to find, and operational efficiencies suffer. Economics favour expansion and maximization of production because the profit from an additional tonne is more important than increased profit from [more efficient] current production tonnes. This phase is *not* characterised by mine efficiency.

Commodity Prices Decreasing (Phase "B"). During this "down" phase of the cycle company management is focussed on cutting costs. The focus is on reducing any costs where the return is not immediate – exploration and long term planning, for example. The economic driver is survival and protection of cash, meaning reduction of working capital and minimization of development effort. This too is not the phase characterised by mine efficiency.

Stability, and "Reasonable" Returns (Phase "C"). This phase – the current phase of the commodity price cycle – represents the best opportunity for technology professionals to really make a difference to mine efficiency. Commodity prices have risen from the cyclical low point, cash flows have improved, and debt has been reduced. Mining companies are aware than many of the cost savings during the previous phase were of a temporary nature. Also some savings achieved were at the expense of higher costs later in the mine life. Whilst in this phase few mining companies have any appetite for large capital expenditures, modest capital expenditure on technological improvements justified on the savings from these improvements can be supported.

5 CONCLUSION

There is a well-known saying commonly considered to be a Chinese curse about "living in interesting times," and that certainly describes the mining industry over the last decade. Yet for those of us on the technology and economic assessment side of the industry the situation today offers many opportunities for challenging and interesting jobs and improvements across the whole spectrum of mining.

- The industry is now entering an efficiency regime from previous expansion and cost cutting regimes. Opportunities abound.
- Whilst the opportunities to add the greatest economic value present themselves at the *start* of projects, the same conditions occur with any major change in the mine – particularly changes that facilitate recapitalization following change of ownership or change of mining method. Judicious use of technology, coupled with more robust evaluation processes, can yield great returns in this environment.
- For mines already in operation there is scope for changes that can also yield great returns. Even without quantum changes, myriads of

smaller changes can lead to efficiencies that aggregate into large economic improvements. New mines commence with limited knowledge of many characteristics – the orebody, processing limitations and subtleties, and market requirements. Now, after some time in operation, all of these things are better known. Re-examining all aspects of the mine to refine operations (often termed de-bottlenecking) can yield high marginal returns for relatively small additional investment.

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