Capital Investment Appraisal for Advanced Mining Technology:  
Case Studies in GPS and Information Based Surface Mining Technology

By
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We accept this thesis as conforming to the required standard

The University of British Columbia
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The University of British Columbia
Vancouver, Canada

Date March 3rd 1999
1 Abstract

Canadian, American and Australian mining industries are currently faced with the requirement to streamline their operations in light of new economic realities. Automation has been seen as a key step toward the survival and competitiveness of these industries. Unfortunately, technology providers seldom have the expertise or resources to properly transfer technology from the development stage to the productive stage. Mining companies, the potential customers of technology providers are similarly inexperienced at appraising and implementing these new technologies. The manufacturing industry is well experienced in appraising (referred most commonly in manufacturing as justifying) and implementing new technology and has developed numerous capital investment appraisal (CIA) methods that can more accurately appraise new technology. These techniques offer the potential to be adapted to suit the mining industry.

The primary objective of this thesis is to investigate the usefulness of various decision-making tools in the CIA of advanced technologies for the mining industry. This research discusses the current technological situation in the mining industry to show the requirement for new capital appraisal techniques. The current evaluation methods are analyzed and their weaknesses are identified. The classification schemes and CIA methods derived from the manufacturing industry are adapted to mining. Analytical examples are provided in terms of hypothetical situations and two case studies at an open pit copper mine in British Columbia are described. The first case study reveals the limitations of current CIA methods when applied to advanced technology and applies alternative CIA techniques whose applicability is rated by the decision-maker at the mine as being “very useful”. The second case study uses object based simulation as a CIA tool for a blending project by estimating parameters within the project that were previously only subjective opinion.
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<tr>
<td>METS</td>
<td>Mining and EarthMoving Technology Systems</td>
</tr>
<tr>
<td>MIS</td>
<td>Management Information Systems</td>
</tr>
<tr>
<td>MMD</td>
<td>Moving Map Display</td>
</tr>
<tr>
<td>NC</td>
<td>Numerically Controlled</td>
</tr>
<tr>
<td>NPV</td>
<td>Net Present Value</td>
</tr>
<tr>
<td>PB</td>
<td>Payback</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>---------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>PLC</td>
<td>Programmable Logic Controller</td>
</tr>
<tr>
<td>PM</td>
<td>Preventative Maintenance</td>
</tr>
<tr>
<td>RI</td>
<td>Random Indices</td>
</tr>
<tr>
<td>ROI</td>
<td>Return on Investment</td>
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<tr>
<td>ROR</td>
<td>Rate of Return</td>
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<tr>
<td>RQD</td>
<td>Rock Quality Designation</td>
</tr>
<tr>
<td>SAG</td>
<td>Semi-Autogenous Grinding</td>
</tr>
<tr>
<td>TQM</td>
<td>Total Quality Management</td>
</tr>
<tr>
<td>UBC</td>
<td>University of British Columbia</td>
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<tr>
<td>WAN</td>
<td>Wide Area Network</td>
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</tbody>
</table>
1 Introduction

Canadian, American and Australian mining industries are currently faced with the requirement to streamline their operations in light of the new economic realities. The lowest commodity prices in decades, competition from the Third World and other low cost producers, and environmental and social constraints are forcing mining companies to move to more profitable business environments and rethink their way of mining.

Automation has been seen as a step toward the survival and competitiveness of the industries\(^1\). Several technology related advances in the past 25 years have showed remarkable promise in improvements in productivity and safety\(^2\). Technologies relating to software, automation and communications have been developed and are ready to be transferred into mining operations. Unfortunately, technology providers seldom have the expertise or resources to properly transfer technology from the development stage to the productive stage\(^3\). Mining companies, the potential customers of technology providers, are similarly inexperienced in appraising or implementing these new technologies.

The manufacturing industry is experienced in appraising and implementing new technology\(^4\). This industry has faced many problems similar to those currently facing the mining industry. For example, western manufacturing industries face global competition (low cost producers in Third World countries), environmental constraints, and strong labor unions. The manufacturing industry realized that improving quality and productivity through new technological tools would allow it to remain competitive. Recent technological innovations evolved beyond simple capacity expansion and moved to information and communications based technologies that provide many benefits such as more efficient turn around, better reaction to market demands and better quality\(^5\). Outwardly, however, their benefit has not been as evident as replacing 10 men with one machine and economies of scale. Inherent weaknesses in the traditional CIA techniques brought about initial reluctance to implement the technology. Operations management researchers identified the weaknesses in the CIA

methods and developed new methods that more accurately assess the value of the technology. Implementation practices for new technology were also developed.

The weaknesses of the traditional capital appraisal techniques include; focusing on the short-term profitability and an inability to take qualitative benefits into account. The solution to these problems was to use techniques that take into account more information and to emphasize long term profitability over short term gains.

The appraisal and implementation techniques designed for new technology by the manufacturing industry can be carefully adapted for the mining industry by analyzing assumptions, reasoning, and models that form the alternative CIA techniques. These methods allow mine operators and technology providers to better evaluate the impact of new technologies on mining systems.

New technologies do not necessarily imply greater complexity or more qualitative benefits. The term new technology, for the purpose of this thesis, is defined as technologies that are not purely capacity expansion, labor saving or replacement of machinery. These alternative CIA methods are to be applied to technologies that improve the safety, quality, and productivity of mining activities through information, communications, intelligent design, and automation. Once technology providers, vendors, and mine operators are familiar with these CIA methods, new technologies can be introduced into mining systems in a more accurate and reliable manner.

Implementation is a further significant topic that is important to the success of new technologies in the mining industry; however, since appraisal precedes implementation, this thesis will focus on CIA methods. Implementation, a more complicated and involved topic, constitutes future work.

1.1 Objectives
The primary objective of this thesis is to demonstrate the usefulness of various decision-making tools in the appraisal of advanced technologies for the mining industry. Studies at a particular British Columbian mine are provided to demonstrate the applicability of these tools.

1.2 Contributions
Major contributions considered to be made by this thesis include:

• A discussion of current mining CIA methods and a list of definitions of terms frequently used in the thesis (Chapter 2)

• A classification scheme for new technologies and CIA methods. (Chapter 3)

• A concise review of CIA methods used by the manufacturing industry and a discussion of changes required for use in evaluating new mining technologies for the mining industry. (Chapters 3 and 4)

• Numerical examples of potential new CIA methods, both contrived and practical. (Chapters 4 and 5)

1.3 Methodology

Between September 1997 and December 1998, the author undertook this research study in the University of British Columbia's Mining and Mineral Process Engineering Department. The work was completed under the supervision of Dr. Malcolm Scoble and assisted by Dr. Scott Dunbar and Dr. Mike Lipsett. Several work periods were spent at the Highland Valley Copper mine, in British Columbia, to collect data for the case studies and interact with mine personnel.

1.4 Thesis Structure

Chapter 1 introduces the present work and lists the major contributions and methodology, and describes each chapter.

Chapter 2 provides definitions for important terms used throughout the thesis, and reviews the current managerial practices relating to technology justification by various mining companies.

Chapter 3 discusses the reasoning for using operations management tools developed for the manufacturing industry for advanced manufacturing technology, as justification aids for the acquisition of new technology in the mining industry. Similarities between the mining and manufacturing industries are reviewed. This chapter concludes by classifying technologies and CIA methods into three separate levels based on technological attributes.

Chapter 4 reviews tools available for justification purposes, and provides examples. The chapter is organized according to the classification scheme introduced in the previous chapter.

Chapter 5 provides background information for chapter 6 on the Highland Valley Copper mine and the technologies under study.
Chapter 6 reviews practical examples of the justification of GPS and information-based technologies at the Highland Valley Copper mine, an open-pit copper mine. The results of two case studies are presented along with the reasoning behind the conclusions.

Chapter 7 offers conclusions and recommendations for future work.
2 Definitions & Reasoning

The first section of this chapter defines terms that are frequently used throughout the thesis. This lays the groundwork for the second section, which reveals the inadequacies of current financial justification and implementation methodologies in mining companies and technology developers. It also reviews several technologies developed in Canada that are ready for implementation but have yet to be accepted by the industry. The third section shows that management techniques, widely accepted by mine administration personnel, do not allow proper assessment of the potential of the new technologies.

2.1 Definitions

Consider the terms found in the title: ‘Capital Investment Appraisal for Advanced Mining: Case Studies in GPS and Information Based Surface Mining Technology’.

Appraise – “Fix price of, estimate”.

Justify – “Show the justice or truth of (person, act, statement, claim); be adequate ground for, warrant”.

The CIA methods investigated in this study are assessment techniques that are new to the mining industry. Before a technology, equity stock, or piece of equipment is purchased, there must be reasoning being the acquisition. The appraisal or justification can be financial, technical, environmental or safety related. In this thesis, manufacturing CIA methods are identified and adapted to suit the mining industry for the purpose of providing the mining industry a method of evaluating new technology in a more precise way.

Technology – In this thesis this term represents the technology utilizing information and communications based tools. Some technologies have been developed for other industries while others have been exclusively for mining. New technology can be traditional, capacity expansion or automation (labor replacement) machinery. A classification scheme is provided in the next chapter that defines the various technology levels. These justification studies do not only apply to surface mining automation technologies. Surface mining automation is the focus of this thesis because the practical examples relate to technologies under consideration at the Highland Valley Copper open pit mine, in British Columbia.

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2.2 Inadequacies

Mining engineering university programs\(^9\) and mine management textbooks\(^{10}\) do not appear to teach or even mention non-financial CIA methods. Traditional CIA methods are adequate for most capital asset acquisitions; however, as these new technologies present more important benefits, the value of knowing the proper CIA method becomes similarly important. For example, the international mining automation symposia have been held for over a decade but relatively few mines have implemented the technologies presented at the conferences. Consider tele-remote LHDs, which have been available since the mid-1990s: no mine operations (other than the mines used for the development of the technologies) use the technology. The few mining companies that have developed mining automation technology in-house have yet to have marred success in integrating such technology into their operations. A possible reason for this lack of success is the lack of adequate justification to management. If top management support is uncertain, the support of others in the organization is lacking and therefore the implementation will suffer\(^{11}\). The requirement of an adequate justification is the first step toward implementation, both for reasons of investing in the technology and in gaining support for its eventual implementation.

2.3 Reasons for the Inadequacy of Traditional Justification Schemes

Assuming that justification of new technologies is one of the most important challenges faced by mine management, why are traditional CIA methods inadequate. One basic problem is that many of the technology benefits are more strategic, such as improved flexibility, manpower efficiency, engineering quality, and planning. The business case for implementation is difficult to quantify when using traditional financial CIA methods. Management in both mining and manufacturing has historically justified purchases on the basis of cost reduction or capacity expansion as the ultimate solutions to improve an operation. For example, haul truck size has grown so much in the last decade that the size of a truck is now limited by the tire design. Furthermore, the incremental capital cost of additional payload is becoming less attractive (eventually economies of scale break down). Formal economic justification techniques have defended this trend due to their focus on short-term gain and quantity over quality. There are several historical patterns that exacerbate this predicament.

The first historical pattern that assails both the mining and manufacturing industry’s inability to see beyond traditional CIA methods is the current misconception that technology always

\(^9\) Author asked 8 mining students from 4 universities questions which indicated that exclusively, financial justification techniques are taught

\(^{10}\) Sloan & Gentry – referred to further within the thesis


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leads to a reduction in labor\textsuperscript{12}. It should however, lead to higher productivity (or profit) per employee and unit of capital cost employed. Employment opportunities will also tend to be more technical in nature, where computer-programming skills are more valuable than (human) physical exertion. A reduction in labor due to technology may have occurred in the past, however, due to the increased information flow from processes several benefits have been achieved. For example, benefits such as improved safety, lead-time,\textsuperscript{13} flexibility,\textsuperscript{14} and quality\textsuperscript{15} may allow mines to operate more efficiently and profitably. Taylor, the father of modern scientific management, argues that increasing productivity actually creates jobs. For example, if the price of the finished product decreases, the demand for that product increases, thereby the industry must grow to fill the increased demand. However, considering this thesis is focused on the mineral industry, where a single mine cannot control the price of commodities, Taylor's reasoning is not applicable.\textsuperscript{16}

A second impediment that makes new information based technology difficult to justify is the professional evaluation structure of some firms.\textsuperscript{17} In most firms, managers are promoted on their ability to show improvement in their respective departments. Therefore managers may be less interested in projects that are better in the long run or for the overall company since they will not directly to reap the benefits. New technologies have been suggested whose benefits and costs, once implemented, are not easily quantified. These new technologies focus on more efficient information management and improved quality and effectiveness. But these new, more integrated technologies cannot be justified by simple economic methods used to justify cost reduction or capacity expansion technologies. Integrated technology calls for a method of justification that takes into account qualitative benefits. An increase in the productivity in mining due to technology has lead to a lower proportion of direct labor in the unit cost of production but can sometimes lead to an increase in workers involved in support services (i.e. mechanics, computer technicians).

The problems and misconceptions of justifying advanced technology have been addressed by the manufacturing industry through years of research in operations management\textsuperscript{18}. Industry experts have debated the use and applicability of various CIA methods, which vary in complexity. Mining can use these CIA methods to justify advanced mining technologies that have characteristics similar to advanced manufacturing technologies, such as longer payback.

\textsuperscript{13} Example: time to bring a plan, such as a blasting pattern, into the finished product.
\textsuperscript{14} Example: ability to change grade, by mining a different stope, when mill requests such a change.
\textsuperscript{15} Example: better fragmentation or better engineering plans.
\textsuperscript{17} Meredith, and Hill, Ibid., p.50
\textsuperscript{18} Kulatilaka, Nalin, Financial, economic and strategic issues concerning the decision to invest in advanced automation., International Journal of Production Research., vol.22 n.6., 1984., p.950

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periods and qualitative benefits. However, these methods must be modified for application to mining.

Advanced manufacturing technology has allowed that industry to introduce technology as a strategic competitive tool. For example, instead of producing a large volume of a specific product, flexible-manufacturing technology has allowed the manufacturing industry to produce small, quality oriented groups of products by responding quickly to changes in market demand. This type of strategic advantage is not relevant to the mining industry in its current mode of operation; therefore, not all CIA methods devised by the manufacturing industry for justifying advanced technology are appropriate for the mining industry.
Chapter 3 - Classification of Technologies and Justification Techniques

3 Classification of Technologies and CIA methods

The present work considers methods to justify advanced mining technologies by adapting the methods devised by the manufacturing industry, to suit the advanced technologies of the mining industry. This chapter introduces CIA methods used in manufacturing, and then considers their modification for mining.

As the level of complexity and integration increases, the benefits from the technology become more qualitative and increasingly difficult to quantify. As the level of integration of the new technology increases, the justification techniques best suited for that technology also become more complicated and strategically orientated. Classification schemes for the manufacturing industry have been devised to determine the appropriate CIA methods for a certain level of technology integration. This chapter develops a mining version of this classification scheme.

3.1 Classification Scheme

As described in Meredith and Hill (1985) and Meredith and Suresh (1986), new manufacturing technologies vary from stand-alone equipment to full computer-integrated manufacturing (CIM) systems. In the manufacturing industry, stand-alone automated equipment includes robots and numerically controlled (NC) machine tools. Such equipment replaces worn out or obsolete equipment. When design, planning, materials handling, manufacturing, and support systems are all linked together through computer control, the factory is a CIM system. The ultimate result of such an architecture is to fundamentally change the method of manufacturing.

Similarly, in the mining industry, technology can vary between a new piece of standard equipment to a complex integrated system. An example of acquiring a new piece of equipment is the purchase of a modern truck or a new dozer. The benefits and costs achieved are easily calculated and known. Examples of integrated systems in the mining industry are integrated dispatch and management information systems (MIS) and real-time monitoring systems. One of the most integrated systems available is a real-time production monitoring system, the Computer Aided EarthMoving System (CAES) by Caterpillar Inc. The roots of the Caterpillar's integrated mining system may be in the advanced manufacturing technology adopted by Caterpillar's manufacturing facilities. When Caterpillar adopted flexible manufacturing systems (FMS) in its manufacturing facilities, the company enjoyed several benefits that were not accounted for in its economic evaluation. From the experience, the company currently evaluates advanced technology using modified or different evaluation criteria and techniques. As discussed in: Gold, Bela, Charting a Course to Superior Technology Evaluation, Sloan Management Review, Fall, 1988

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20 The roots of the Caterpillar's integrated mining system may be in the advanced manufacturing technology adopted by Caterpillar's manufacturing facilities. When Caterpillar adopted flexible manufacturing systems (FMS) in its manufacturing facilities, the company enjoyed several benefits that were not accounted for in its economic evaluation. From the experience, the company currently evaluates advanced technology using modified or different evaluation criteria and techniques. As discussed in: Gold, Bela., Charting a Course to Superior Technology Evaluation, Sloan Management Review, Fall, 1988
integrated technologies have not yet been widely accepted and the full range of their true costs and benefits (both qualitative and quantitative) has yet to be proven.

According to Meredith and Suresh, there are three main characteristics of these more integrated, information-based technologies that make the justification process more complex than those used for less complex technologies: flexibility, qualitative attributes and risk.

The first characteristic is that these technologies can potentially increase the flexibility of the system. They can increase the ability to perform manufacturing or mining more dynamically. As an added benefit, some argue that this flexibility maintains the value of the equipment for a greater period of time, rather than letting its value depreciate. A further benefit can be achieved when changes in the business structure required to take advantage of the flexibility, allow businesses to re-evaluate their operating practices (to make improvements). Although, this change in business structure may increase the level of risk involved in the proposed project.

The second, more important characteristic that makes the justification process more complex is the many qualitative attributes of these integrated systems. In manufacturing, users of CIM consistently report qualitative benefits from linked systems. The benefits include greater flexibility in product turnaround and better quality. These benefits are difficult to quantify financially because they cannot be separated from other business activities. At present, few truly integrated systems exist in operating mines, although, some moderately integrated systems such as a computer controlled dispatch system do provide qualitative benefits, such as improved supervision and more efficient scheduling (both for equipment allocation and maintenance). If these qualitative benefits can be accounted for in the economic justification, a significant increase in the calculated return on investment can be demonstrated.

The third characteristic that makes the justification process more challenging is the risk involved in implementing the integrated technologies. The risk, particularly for manufacturing, is not only financial but also organizational, since the entire company infrastructure must often be changed to obtain the full benefits that these systems offer. At first glance it appears as though the mining industry does not face the same severity of risk, when implementing these technologies, as the manufacturing industry; the average mine life is shorter than the life of most manufacturing companies. During the construction of a new mine, a new operational system devised with these technologies in mind, can be formulated and implemented. Designing and implementing a new technology into a green field site is

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less challenging than attempting to change an existing operation. Risk can be further mitigated by adopting technology already developed for other industrial sectors and by designing flexibility into the system for possible expansion or modification in open systems. This apparent advantage over the manufacturing industry is a deception since mining has traditionally been slow to accept new technologies, as discussed in chapter 2.

Technologies can be classified into different categories depending on their level of integration into the overall system. For example, a new truck contributes a certain benefit to the production rate of the mine and exacts a certain cost in terms of capital and operating costs over its working life. In contrast, a drilling technology that integrates the engineering office closer to the blast pattern and geology may potentially impact processing costs, engineering costs and drilling costs thereby optimizing the blasting sequence. Therefore a classification scheme would be convenient, so that evaluators can easily determine what CIA methods would be most applicable.

### 3.2 Three justification categories

Meredith and Suresh separate new manufacturing technologies into three separate categories based on the degree of integration of the technology within the production system. The figure below shows the diagram used to represent this distinction.

![Advanced manufacturing technology continuum](image1)

**Figure 3-1: Advanced manufacturing technology continuum**

<table>
<thead>
<tr>
<th>Stand-Alone</th>
<th>Linked</th>
<th>Integrated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robots</td>
<td>FMS</td>
<td>CIM</td>
</tr>
<tr>
<td>NC</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Advanced mining technology continuum](image2)

**Figure 3-2: Advanced mining technology continuum**

For stand-alone systems, where the purpose of the purchase is simply the replacement of old equipment, the standard economic justification approaches can be used. When a moderate amount of synergy (from linked cells, or a few linked pieces of equipment), flexibility, risk and non-economic benefits are present, more analytical methods are required. When considering systems that approach full integration, with clear competitive advantages and a major commitment towards business objectives, more strategic approaches are needed. Tactical and economic benefits must play a role in this last category, but not a dominant one.
Each of the three justification categories covers a great variety of approaches, as seen in the figure below. This diagram represents the suggested justification techniques for certain levels of integration.

Figure 3-3: CIA methods

Meredith and Hill\(^{25}\) classified the technologies into four groups. The diagram below reveals how CIA methods should be chosen for the appropriate level of technology. According to Meredith and Hill, the four levels were also separated according to their level of integration.

Mining technologies suit the original three-level technology classification scheme more accurately, as is explained later in this section. The next few subsections provide the analysis so that a mining version of these technology levels can be formulated, providing a classification scheme for mining technologies for selecting appropriate CIA methods. The analysis is a threefold process. A description of the manufacturing version of the technology level is given, with examples. Finally, the justification schemes that are appropriate for that level of technology are listed, along with any omissions due to incompatibility with mining.

\(^{24}\) Meredith and Suresh, Ibid., p. 1044
\(^{25}\) Meredith and Hill, Ibid p. 52
3.2.1 Level 1

3.2.1.1 Level 1: Manufacturing - Stand Alone Systems

This level of manufacturing technology is mainly machinery that is usually controlled by self-contained computers or programmable logic controllers (PLCs). Examples of this type of equipment are numerically controlled (NC) machine tools and robots. This type of equipment requires only limited information. Stand alone systems are the most common type of manufacturing automation.

When stand-alone systems are purchased, their intended use is usually to simply achieve better efficiency, higher speed (through faster production rates, thereby lower costs) or replace worn-out equipment. There is usually little risk involved in this type of acquisition since the technology is generally known and understood. Since the purpose and implementation of these systems is well understood, common economic methods of justification are adequate. The benefits of employing these purely financial CIA methods are their simplicity, clarity and data requirements. Valuing the direct cost savings and determining the affected variables can be easily performed. Ancillary savings such as decreased set-up labor or maintenance can also be calculated but with less precision.

Figure 3-4: Justification Approaches for Advanced Manufacturing Systems, after Meredith and Hill

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26 Meredith and Hill, Ibid., p.53
3.2.1.2 Level 1 – Mining – Production Units

After analyzing the definition of this level of manufacturing technology, a mining equivalent can be approximated. The benefit of acquiring a new piece of equipment such as a new haul truck, with increased capacity and lower fuel consumption, can be easily estimated with common economic tools. Ancillary benefits, such as lower maintenance or increased speed can be estimated with moderate accuracy. The exact benefits and costs can be easily calculated since the technology is known and its effects are understood. This level of integration of these types of technology, into the mining process is similar to those of the level 1 technologies for the manufacturing industry.

The following is a list of mining equipment and service-oriented units that can also be considered as equivalent to stand-alone technologies:

- New equipment such as haul trucks, dozers, shovels, drills or loaders
- More or improved labor such as master blasters, more experienced shovel operators

Shovels may appear to be more integrated into the overall system than haul trucks since fleet management is usually organized around the most important pieces of equipment. The capacity of NC machine tools have to be similarly matched with the down and up-stream processes within the manufacturing process. The effects can be accounted for through operations research (OR). For example, OR has provided tools such as capacity planning, for manufacturing, and queuing theory for fleet management, these effects can be accounted for.

3.2.1.3 Level 1 – Economic CIA methods

Most industries use the same basic economic tools for this level of justification. Both the mining and manufacturing industries use methods such as payback period, ROI and various DCF techniques.

There are some pitfalls that make these justification approaches inappropriate for many technologies. The first deals with hurdle rates. When employing these economic justification techniques, managers use hurdle rates to pass judgement on a proposed project. Hurdle rates can include a maximum payment period, a minimum return on investment, or a high discount rate. For example, if a project has a longer payback period than the minimum allowable period specified by the company (or manager), then the project may be rejected. These hurdle rates are considered to be management’s method of reducing risk or ensuring profitability.

Risk is an important consideration when investing in advanced technology. New technology, even by definition, is not usually widely accepted. Managers protect themselves from perceived risk by increasing the level of profitability required for project acceptance. Hurdle rates and risk are widely debated by the pundits of the manufacturing industry. Three
perspectives on economic justification are provided in this section to take into account the importance of these topics when performing the justification phase of an application for expenditure.

3.2.1.3.1 Simulation over blanket hurdle rates for New Technology
Hundy and Hamblin (1988) argue that current methodologies for financial analysis employed by most manufacturing firms (in late eighties to early nineties) are counter productive and are contributing to the West falling behind countries such as Japan. This situation is being rectified in the manufacturing industry, however, the mining industry still relies on increasing hurdle rates as a protection against risk. Hundy and Hamblin consider financial analysis essential for investments. They argue that financial CIA methods can take account of longer-term strategic aims provided that the acceptance criteria are well understood and applied flexibly. It is also recognized that those who are in a position to assess the benefits must undertake the evaluation.

Hundy and Hamblin argue that the hurdle rates should consist of the cost of capital of the firm. The cost of capital can be assessed by determining the cost of borrowing money on the market, raising venture capital or by using methods that take an objective view of risk such as the Capital Asset Pricing Model (CAPM). Therefore no added risk element should be added to the hurdle rates.

Computers with simulation programming aids, such as spreadsheets, should be used to test the sensitivity of projects to apparent risk rather than blanket application of hurdle rates. Simulators allow more intelligent and customized approach that can take into account the true situation, provided that both the model and data are accurate.

3.2.1.3.2 Acceptable level of Risk & Management's personal attitude towards risk.
Frank Lefley (1997), discusses risk in four main steps.

- Analyses of the nature of risk.
- Determines the acceptable level of risk.
- Discusses management's personal attitude towards risk.
- Identifies the techniques used in the assessment of risk and provides example of how these techniques can be used to take risk into account.

Lefley discusses the use of hurdle rates and how to properly incorporate a calculated risk factor, which is somewhat objective, into financial CIA methods. Due to the risk evaluation aspect, this approach will be discussed in the level 3 CIA methods since that section deals
with risk; however, it is important to note that this section does refer to financial CIA methods, albeit a risk-altered form of these methods.

3.2.1.3.3 Financial Analysis Paramount

Ashford (1988) counters much of the criticism of using financial CIA methods for new technology by stating that the basic axioms of the methods are sound, however, they (the financial techniques) are commonly misapplied. He states that risk must be accepted because 'risk is a part of business'. Ashford emphasizes the use of financial appraisal techniques, because these are the techniques that the business world most understands.

The author begins by enumerating the main criticisms of financial justification techniques:

1. The techniques undervalue long term effects.
2. The viewed industrial activity is much too static, underrating the effects and pace of technological change.
3. There are benefits from these technologies that are difficult to quantify and are often ignored in the appraisal process.
4. The systems of management control in large organizations compound the bias against the long term.

Ashford argues that it is not the methods themselves that cause these problems but the method of application. He gives suggestions on how to correct for these problems. These suggestions are summarized here.

1. Undervaluation of long term effects

According to Ashford, traditional appraisal methods such as the payback method undervalue long term effects. However, he states that manager's reliance on this value should be considerably diminished since it is only a 'rule of thumb', never to be used as a safeguard against risk. It should only be considered as simple measure but managers should acknowledge that it is insensitive to variation among projects and that it takes no account of the long-term advantages. Similarly, Ashford agrees that discounting methods such as the net present value (NPV) and internal rate of return (IRR) also under-emphasize the future benefits of new technology. These problems can be further exacerbated by the application of a risk premium; however, he rebukes that arguments against discounting should rest purely on the magnitude of the discount factor used. Ashford encourages the use of the Capital Asset Pricing Model (CAPM) to calculate the real cost of capital. CAPM is used by financial markets to determine the appropriate return, which is directly proportional to the risk (within the CAPM model). Therefore real estimates of cash flows can be discounted using real capital costs instead of inflated capital costs.
2. Assumptions about the future

Usually, when carrying out traditional investment appraisal, it is assumed that without a particular investment project, the company can operate as before, industry costs remain the same, and the demand stays unchanged. Ashford argues that these assumptions are incorrect: those markets are dynamic. He advocates that the correct approach is to make forecasts or scenarios of the environment that is incorporated into both the base-case and new technology appraisals.

3. Qualitative benefits ignored

Ashford agrees that the current method of appraisal ignores many of the qualitative benefits derived from new technology. He states that the main reason for these omissions is that these benefits are difficult (but not impossible) to quantify. With more vigilance, effort, and knowledge of all processes that the new technology will affect, it is possible to determine quantitative values of the qualitative benefits; however, such an appraisal will take more time, effort, and estimation. Some estimates will not be as precise as required, but quantification is possible.

4. Management Control

Ashford placed a great deal of emphasis on the role of management. Large organizations usually organize their reward system in such a way that managers are rewarded for projects that yield short-term benefits. Those who control the company place less emphasis on long-term benefits. Furthermore, managers are more likely to approve those projects that yield the bulk of their benefits while they are still in their posts, or in their department. Ashford resolves that the only way of remedying this problem is by altering the reward system by commending the managers who promote projects that yield a higher profitability for the entire company to maximize profitability in the long run. This method will also ensure that 'stop-gap' solutions to long term problems do not take precedence.

W. Edwards Demming, considered to be the main inspiration for of quality management, also condemned the use of arbitrary numerical goals. Demming created a list of 14 points that managers should follow to ensure high quality and proper working conditions. Point 10 ("Eliminate arbitrary numerical goals, posters and slogans for the workforce which seek new levels of productivity without providing the methods.") and point 11 ("Eliminate work standards and numerical quotas.") both condemn the use of numerical goals for management.

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Chapter 3 - Classification of Technologies and Justification Techniques

It is understood that the above management control suggestions refer to line management. These arguments, for the purpose of this thesis, are focused toward those who make investment decisions.

3.2.1.3.4 Conclusion to Financial CIA methods
There are several recurring conclusions in the analyses undertaken by the authors mentioned above;

1. Hurdle rates should be applied in an intelligent and per-case basis while understanding the true nature of the base case (understand the true nature of the market)
2. When discounting, the real cost of capital should be used
3. Risk should be evaluated separately, usually using simulation (see section 4.3.3:Risk Analysis)
4. Management philosophy and characteristics should be known, understood and planned for.

An example of how to apply changes in hurdle rates or the base-case, based on an actual situation is presented in the next chapter. The method of calculating the true cost of capital using the CAPM and a formal method is provided below. Risk and simulation is discussed in the ‘analytic justification’ section of this chapter. Finally, management philosophy and characteristics is not within the scope of this thesis however, it is an important aspect of justification and should be explored by the interested reader.

3.2.2 Level 2

3.2.2.1 Level 2: Manufacturing – Cells
According to Meredith and Hill, level 2 systems for manufacturing have:

"...a higher level of interaction and communication. Typically, they consist of multiple pieces of individual, Level 1 equipment, placed or connected in a 'cellular' configuration to perform multiple but ordinary tasks on a family of parts. This cell accomplishes a variety of functions, largely through the ability of the integrated information system."

For manufacturing firms, the main purpose of implementing this type of system is to facilitate a change in the firm’s product mix, capacity, quality and/or lead-time. Flexibility and quality are the main strategies behind this action. Some moderate organizational change is required to reduce the risk of possible incompatibility and increased interfaces and coordination. A manufacturing example of this type of technology is a Flexible Manufacturing System (FMS), where an automated material handling system interconnects several NC machine tools.
Chapter 3 - Classification of Technologies and Justification Techniques

3.2.2.2 Analysis of Mining as a Muck Factory

The mining equivalent of level 2 technology is approached by different views. A brief analysis of a mine will be made in terms of an ore, infrastructure and waste dump building factory. There is a dual purpose behind the analysis. Firstly, the analysis will expose the similarities between the manufacturing and mining processes. Secondly, the value of integrating the processes will be demonstrated.

A process may be defined as the group or series of activities that must be completed to produce a result that has value to a customer\(^30\). Processes have flows of material, energy and information that ideally are combined in the most efficient way to produce the final valuable result.

For the purpose of the analysis, the main objective of a mine is assumed to be to produce ore for the mill. There are several processes such as exploration, production and servicing operations that must be performed before the final product is consumed in the mill. Therefore the mill is the mine's only customer. It is therefore assumed that these processes must be optimized for the customer in mind, for highest possible overall profit and reduced costs (so that the customer in turn can sell the processed product even cheaper). However in most mines, very little effort is placed on determining the overall effect of variations in the mine's processes and product (crushed rock) on the mill. This is mainly due to the lack of competition, since the mine on site has the only ore the mill can 'purchase'. As will be discussed, this level of technology will give the mine the option to optimize the various processes to improve such aspects as engineering, safety, costs (to a lesser degree directly) and the consistency of the quality of the product (ore) by integrating the processes.

3.2.2.2.1 Exploration

An exploration or geology department must accurately delineate the orebody and determine the various grade concentrations. Then a planning department, using the product from the geology department, outlines a general plan that will allow the least expensive extraction possible, taking safety and environmental restrictions into consideration.

An example of a mining technology that integrates the exploration and primary planning phase is a Geographical Information System (GIS). The numerous benefits that come with the better visualization brought by a GIS are very difficult to quantify, and so customary financial CIA methods are clearly inappropriate.

These first two phases in the mining process are analogous to the planning phases of a manufacturing firm. In manufacturing, a marketing firm explores the possible needs of

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\(^{29}\) Meredith and Hill, Ibid.

\(^{30}\) Shafer, et. al. Ibid, p.110

Masters of Applied Science Thesis. Sean Dessureault
consumers. A planning department then outlines a general factory plan layout that will allow the least expensive assembly possible, taking into account local labor and environmental variables.

3.2.2.2 Production

The production cycle of a mine can be viewed in three steps; the design, rock fragmentation, and materials handling. Before the ore can be blasted, the blast pattern must be designed, taking local geology and the long-term plan into account (there are many other variables, but for the purpose of simplicity, only these will be discussed). The variable nature of geology is a factor that makes daily planning part of the production process for a mine.

The planning (blasthole layout, burden & spacing, and explosives selection) and drilling of a blast pattern can be viewed as a single process in the production of muck (the fragmentation step in the production cycle). Therefore if the process were more integrated, improvements in design, planning and execution would be achievable.

In some mines, further plans are formulated from information gathered during the drilling phase. This is information that can be used when planning for the second phase: blasting. Therefore planning can again be considered to be part of the overall production process and would most likely benefit from increased integration.

The third and final materials handling phase also requires planning. Haul routes are planned and trucks are dispatched by a computer or an individual that undertakes the planning (with the goal of optimizing production). This phase also requires further planning (for grade control or blending purposes) since the desired characteristics of the product depend on the demands of the mill. If a certain grade or fragmentation distribution must be achieved, planning will be needed. Increased information flow due to greater integration may allow the mine planning staff to optimize various processes to improve safety, quality or even costs.

Manufacturing also requires planning. The ideal factory layout, the best connections between the various machines, and the optimum product mix are all goals that must be planned. For example, the flexibility of certain machines allows the factory to easily change the operation to produce the most profitable product in a changing marketplace. The marketing department (through consumer research) determines what that product and price point is, and these technologies allow the processes to be optimized to produce the desired product for the consumer.

These manufacturing technologies are similar to mining technologies in that both allow a process to be optimized for a consumer. The consumer can be the next minor process (such as creating the optimum blast pattern to help ground engaging by the shovel) or the next major process (such as delivering the ideal blend of ore to the mill).
3.2.2.2.3 Discussion of the Analysis

There are two main purposes to the discussion above. The first objective is to show that in some respects, a mine is very similar to a factory in the sense that certain technologies can be used to optimize the processes for the consumer. For example, the quality of the blasting department's product directly influences the consumers, the loading and ground engaging department (if the fragmentation quality is poor, the loading cycle will be bogged down with lower productivity and higher maintenance costs). The quality of a mine's product depends on the demand of its consumer, the mill. Frequently, a mill demands the particular grade and fragmentation distribution that optimizes the profitability of the operation. These quality issues should be the primary objectives of a mine planner.

The second objective of the analysis is to demonstrate the necessity for flexibility in design and in processes. Flexibility is often listed as one of the main benefits of advanced manufacturing technology. Manufacturing firms contend with potentially variable sources of materials and many finicky consumers whose definition of quality varies, whereas a mining engineer contends with a variable geology. To ensure quality, planners in both industries must contend with variables that are dynamic. Flexibility in design and options would allow these variables to be handled easily.

3.2.3 Level 2 Mining – Integrated process

The analysis above drafted an example of a mining equivalent of level 2 manufacturing technologies. As was mentioned above, a mining process such as drilling requires several steps. Similarly, a manufacturing process requires several steps. Level 2 technologies in the manufacturing industry provide an information flow between the steps to allow an improved quality through a more flexible and precise process. An equivalent mining technology would also require an increased information flow between the steps to improve quality through flexibility and precision.

An example of process flexibility (for mining) is the ability to change the blast pattern design, due to new geological data, without greatly increasing the lead-time. Flexibility and autonomy would also provide a safer working environment since most information gathering and distribution in mining is conducted by technicians. For example, instead of sending a technician to delineate with stakes (by climbing on a loose muck pile) the general area of a miss-fire, a GPS location and readout on the shovel would tell the operator the precise location.

An example of an integrated process is the drill-monitoring package offered by Aquila Mining Systems. The positioning component of the technology allows the operator to drill holes with greater accuracy, improving fragmentation. It also improves the process speed since manual surveying is not required. The consistency of design is another improvement.
over the base case. These three aspects, accuracy, speed, and consistency, improve the quality of the product (the muck) by improving the fragmentation, reducing the cost and shortening the lead-time.

The integrated aspect of this system is the more efficient link between surveying (which is no longer a component since no surveying is needed), planning and drilling operations. For example, the system links the engineering blast pattern design directly to the drill by simply downloading the design into the on-board monitoring system. Other useful information that is linked from the machine to the mine office is the geological information or maintenance report that is automatically generated by the instrumentation on the drill. The geological information is collected automatically by the monitoring platform from instruments on the drill-string that measure vibration and mechanical drill parameters (an algorithm is used to determine the geological parameters). This information can then be downloaded into the mine information system to upgrade the geological survey of the areas. This in turn may be used to optimize the blast pattern and sequencing.

It can be seen that this also has a measure of flexibility: the ease with which information can be collected and sent to the drill, the different design options available and availability of technicians who were previously surveying. The design flexibility is the ease with which the blast pattern can change, given new information.

### 3.2.4 Level 2 CIA methods

It is customary to employ level 2 technologies for their broader, less tangible benefits therefore a justification procedure that can harness these benefits is needed. Several CIA methods are suggested, including linear, integer, and goal programming (programming models), scoring models, the Analytical Hierarchy Process (AHP), and option pricing. All of the methods mentioned here will be explained and examples provided in a further subsection. It is important to note that these methods should be complemented with the common economic evaluation techniques; however, their results should not govern the manager’s decision.

### 3.2.5 Level 3

According to the definition provided by Meredith and Hill, level 2 technology is more local: it integrates a single process closer to other processes but does not affect multiple processes. For example, the AQUILA technology discussed above integrates the muck producing process by increasing the information flow between the various activities within the process. Level 2 technology does not integrate processes together such as blasting and hauling. Level 3 does integrate individual processes together. Level 3 technologies are typically more expensive, in terms of initial capital cost, than level 2 technologies, require a significant
amount of organizational restructuring, and affect more than a single process. Project failure or improper implementation may incur significant loss or labor relation breakdowns. Therefore, risk is an important factor when considering level 3 technology.

3.2.5.1 Level 3: Manufacturing - Linked Islands
The third level of technology integration for the manufacturing industry is a set of cells that are connected to form linked islands through an information network. At this level of integration, substantial changes in organizational structure are needed, because many processes and business departments are affected by the technology. Integrated manufacturing allows even more flexibility than level 2 technologies. There are two main advantages to this increased level of flexibility. The first advantage is the ability to easily and quickly generate new types of products to enter new markets or to conform to a change in customer demand. The second advantage is to bring synergy to the production process. These are regarded as barriers to entry for protection against competitors.

3.2.5.2 Level 3: Mining – Total Mine Integration
Competitive advantage and entry barriers are not valid benefits within business units of a single mining property. The mill, the only consumer of the mine product, is usually on-site and owned by the same company, therefore no competition exits. Quality, an entry barrier is important in mine production but it is not the governing concern of mine managers. The balance between quality and costs is vague, where the costs of the mill are directly linked to the mine product. The main question of this dilemma is: where do the costs of good muck and grade distribution rise above the savings at the mill? A similar dilemma can be seen within the mining process itself: where do the costs of better engineering and management rise above the savings of the improved activities in the operations sphere and how are they coupled? Determining this critical balance is not the purpose of this study, but it is important to mention these unresolved issues. Quality may be an important aspect of a mine’s product but the immediate result of improved quality is difficult to measure and is therefore usually ignored by the mine.

The only advantage at this level of technology integration common to both mining and manufacturing is the synergy produced when information flows freely between most processes. The option to study information flows allows engineering departments within the mine and mill the ability to optimize various processes and not simply a local variable. To the author’s knowledge, no mines, at present, use this level of integration. Therefore the advantage of level 3 technologies to the mining industry is the potential to optimize the overall process on a strategic scale. An example of strategic, large-scale optimization is the

31 Meredith and Hill, Ibid. p.55
decreased inventory requirements if technology could keep track of all consumables in the mine. A further example of strategic optimization is the option to feed the mill the grade and fragmentation distribution that maximizes profit.

Economic CIA methods are the mining engineer's most popular justification tools for project assessment. This is due to the simplified financial environment of the mining industry. Mining engineers are rarely faced with quality and service issues when designing a mine. The only method of validating quality in a mining operation would be to view the individual processes within the mine as profit centers.

Few technologies are available that can truly be considered mine-wide integration. The Mining and Earthmoving Technology Systems (METS) being developed by Caterpillar Inc., is a system that is a step toward this level of harmonization. CAES, previously mentioned, is part of the METS product group. Komatsu and Modular Mining are developing similar products. The system proposes to link design directly through to the equipment through a radio-link, where vehicles send geology, position, equipment condition, and maintenance information back to the mine office where plans are updated and maintenance information is processed in real-time. Furthermore, since all equipment is outfitted with positioning systems, a computerized dispatch algorithm optimizes the execution of the mine plan.

Another example of this level of justification is integrating maintenance with planning and operations. Considering most mines spend about 50% of their operating budget on maintenance, a worthwhile project to consider would be integrating production maintenance with the rest of the processes. This would allow maximum equipment utilization; creating a 'lean' mining environment. Enabling technologies such as information systems, on-board diagnostics, wireless LANs, and optimization algorithms would allow such an integration to become reality. The enabling technologies would therefore have to be justified using level 3 CIA methods.

3.2.5.3 Level 3 CIA methods

The previously mentioned CIA methods (level 1 and 2) are still valid at this level, but should not play the governing role in the decision. Level 3 CIA methods are more complicated, require more time to perform, and are data intensive. But these methods can assess costs and benefits that are otherwise difficult to quantify. Many of these methods are probabilistic, such as sensitivity analysis, decision tree analysis, the optimistic-pessimistic analysis, and Monte Carlo simulation (note: some simulations can be deterministic). Value Analysis is an empirical test, where a smaller-scale integration is first tested to verify its applicability. This method reduces the element of risk through experience. Probabilities play an important role

32 Lipsett, Mike, Personal communication, (Tuesday, November 25th, 1998)
in these methods. Examples and explanations of these methods are provided in a later subsection.

The CIA methods at this level of integration require more analysis than the previous two methods since a substantial amount of risk and detail is involved. Detail is required because the justification schemes at this level require the system under study (in this case, mining operations) must be more accurately modeled in order to perform the analysis. The presence of increased risk is due to the fact that more processes are affected by the increased process integration. If the increased information flow is used to devise methods of increasing the overall profitability of the entire system (optimization), even more systems will be affected than if a simple local optimization were performed on a single variable (usually level 2 technology). As mentioned in a previous section, Lefley (1997) undertook an analysis of risk and uncertainty in the appraisal of new technology capital projects. The following subsection describes Lefley's analysis. The analysis examines the differences between risk and uncertainty followed by management's attitudes towards risk. Finally, the methods used to identify the level of risk and to apply this level of risk to project justification is discussed.

3.2.5.3.1 Analysis of risk and uncertainty
Risk is assumed by most decision-makers as being negative even though risk is defined as the action of undertaking an uncertain future. Therefore risk should be seen as being possibly positive or negative. Decision-makers perceive risk as the probability of not achieving a given target return, or the degree of expected returns. Most project risk can be separated into two components: uncertainty about the capital outlay and uncertainty about future cash flow.

3.2.5.3.2 Management's attitude towards risk
According to empirical data collected by Lefley33 (the results of his findings are discussed in the following 2 sub-sections), several characteristics of management in industry create risk averse decision-makers. Firstly, the reward system in most large organizations encourages risk aversion, because most managers are rewarded based on returns, not potential returns. This in turn induces a short-term solution mentality among most executives. Empirical evidence shows that managers in Western society tend to be risk averse compared to Japanese manager who tend to make more business risks (especially when it comes to new technology). This has been attributed to the fact that Japanese business culture tends to aim to long-term growth rather than short-term business performance and the more consensus-driven decision process which ensures management decision are in tune with executive vision (and distributes responsibility for the risk in a decision)34. Finally, according to empirical

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34 Lipsett, Mike, Personal communication, (Tuesday, November 25th, 1998)
data, age has a direct correlation with an individual's risk acceptance, when dealing with business. Younger business people tend to accept more risk in business than older individuals. This is has been attributed to the younger individual's requirement to 'prove' him/herself (and a difference in perception of risk).

3.2.5.3.3 Risk identification

Lefley listed and described four techniques used in the identification and assessment of risk. For example, he determined through empirical research, that 81% of US manufacturing companies use the payback period in their evaluation of new technology projects\textsuperscript{35}. He warns that the use of this technique is ineffective since it is only a measure of 'time risk', and that there are many other aspects of project risk that may be missed using this evaluation technique.

Sensitivity analysis uses a range of outcomes to determine how sensitive projected cash flows are to changes in the forecasted cash flows. Those projects that show a high variation in projected cash flows from small variations in forecasted cash flows are considered to be high risk. Empirical evidence suggests that sensitivity analysis is the second most popular technique to gauge risk and is used by 43% of large US manufacturers\textsuperscript{36}. This has sharply increased in the last decade due to the availability of analysis tools such as spreadsheets.

Probability analysis, also known as decision analysis uses probabilities to determine the worth of a project through the use of decision trees (the exact method is presented in a further section). This technique also has the option to include the assessment of personal risk preference with the use of the utility function (also explained in a further section). This method is used by only 19% of US manufacturers in the appraisal of new technology projects despite its obvious applicability\textsuperscript{37}.

Monte-Carlo simulation or risk analysis techniques, are a standard technique of random selection where the occurrence of the outcome of a number of variables cannot be determined mathematically but where analytical relationships exist. Due to the availability of software and microcomputers, 18% of US manufacturers use this technique in the evaluation of risk\textsuperscript{38}.

3.2.5.3.4 Risk application

There are several techniques are used to incorporate risk when evaluating capital investments. Adjustment of the hurdle is the most popular method of dealing with risk; for example, shortening the maximum payback period or increasing the discount rate are the\textsuperscript{35} Lefley, Frank and J. Sarkis. Short-termism and the appraisal of AMT capital projects in the US and UK., International Journal of Production Research., vol. 35 no. 2., p.341-368
\textsuperscript{36} Lefley Ibid, p.360
\textsuperscript{37} Lefley, Ibid, p. 26
\textsuperscript{38} Masters of Applied Science Thesis. Sean Dessureault
most common methods. Research shows that 49% of US manufacturing companies adjust the hurdle to take risk into account.

Many critics argue against adjusting hurdle rates. Baldwin argues that the ROR should be inviolate and should be presented as two figures: a pure, unaltered state and a risk adjusted state, so that the effect of risk can be judged. Other pundits state that the true cost of capital should be used instead of a risk adjusted discount rate. Some critics even argue that time and risk are logically separate variables. Furthermore, the UK National Economic Development Council supports this view, stating in 1971 that varying the discount rate with riskiness is a somewhat arbitrary way of dealing with risk and uncertainty.

One method of taking risk into account that is acceptable to Lefley is the certainty equivalent value (CEV). This value is used to alter uncertain values, which reduce in the case of revenues and increase in the case of cost. The main disadvantage of this method is the subjectivity that is applied when determining the risk factor used to calculate the CEV. A current survey shows that 3.4% of US firms use the CEV approach when taking risk into account when evaluating new technologies. CEV is also known simply as certainty equivalent (CE). It is presented in the Decision Analysis section of this paper.

The capital asset pricing model (CAPM) suggests that there is a certain level of profit expected for an acceptable level of risk. The method determines the level of systematic (inherent) risk and labels this value beta. The method can then suggest the appropriate level of profitability that would be expected by the stockholders. Some argue that extending the CAPM beyond its original framework for the purpose of new technology appraisal, reduces the applicability of the method, however it is still considered to be a good predictor of returns and is better than anything else available. Current research shows that no US manufacturing companies use the CAPM method; however, 2.8% of UK companies do.

These methods are obviously complicated and time consuming to perform, and so only projects with long-planning horizons warrant the use of these sophisticated risk measurement techniques. A further obstacle of using such techniques is that they require interpretation of the results. Managers prefer easy to understand results such as those that come from

38 Lefley, Ibid, p.28
43 Lefley, Ibid., p.29
decreasing the minimum payback period. Decision-makers seldom choose to spend time trying to understand the results from a simulation or decision analysis. Management attitudes towards risk are also a major influence on the outcome of the proposed project. If a manager is very risk averse, he is unlikely to support any project that includes the integration of new technology. As the use of computers and simulation in industry increases, the use of similar tools in the appraisal of capital projects will facilitate management's acceptance of the more realistic estimates of the effects of risk.

3.2.6 Level 4

3.2.6.1 Level 4: Manufacturing – Full integration

Full integration links the entire manufacturing process and all its overhead processes through an extensive information network. The general term for this level of integration is computer integrated manufacturing (CIM). (Note: CIM is classified in a third category by Meredith and Suresh (1985); however, the classification scheme used here is the scheme devised by Meredith and Hill (1986)) The main advantages of this level of integration are competitive advantage and strategic importance. The risks involved are considerable. Usually, the entire corporation must undergo changes. Furthermore, a reliance on highly complex, relatively new technology is also necessary. Examples of actual systems are: Pratt & Whitney’s compressor blade plant in Georgia, GM’s “factory of the future” in Michigan and several others.

3.2.6.2 Level 4: Mining – Blue-Sky R&D

This level of integration in mining is difficult to conceive. The inherent unknowns in mining due to ground and geological conditions make this type of endeavor impossible considering today’s technology. An intensive look at a fully automated mine by INCO’s Mines Research department through the mining automation program (MAP) is the only project that the author is aware of that resembles this level of integration; however, the key factors, which are strategic in nature, that motivate manufacturing industry into developing CIM (such as competitive advantage, entry barriers and business objectives) are much less relevant in the mining context. There are no unique technologies that allow a copper ore producer to make its ore more attractive to a potential concentrator or smelter that could eliminate his competitor. Cost could seen to be the only motivator that would induce a competitive advantage in mining. XXX TMS \( \rightarrow \) Jon Peck & Jim Gray

\[\text{Lefley, Ibid, p.31}\]
3.2.7 Classification Conclusion

The mining classification scheme divided the present levels of mining technology into three separate levels. Each level of technology corresponds to a certain justification scheme. The figure below is a mining altered figure originally presented by Meredith and Hill (pasted at the beginning of the section) for the manufacturing industry. Level 4 was not considered since no technology exists that fully integrates a mine/milling operation.

The figure below is used to suggest which possible CIA method is most appropriate at a certain level of technology. For example, the vertical dotted line represents the situation where a level 2 technology is under investigation. It should be seen that the most intensely shaded areas (region closest to the shaded-white border) are opposite the 'portfolio methods'. Therefore at level 2, the most appropriate CIA methods are the portfolio methods. The financial methods remain in the shaded area, therefore they are still useful in the evaluation. Therefore all justification schemes still in the region above the horizontal dotted line are appropriate.

Figure 3-5: Choosing the appropriate CIA method

The table below can be used to further clarify some of the definitions of each level and to compare the mining and manufacturing specifications.
### Table 3-1: Manufacturing/Mining Comparisons

<table>
<thead>
<tr>
<th>Manufacturing Step</th>
<th>Mining Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning, determining the most efficient manner of manufacture. Structuring the various machines and steps in assembling a component</td>
<td>Determining mine method, optimal pit depth, provable reserves, deciding the most profitable shape and sequence of the mine.</td>
</tr>
<tr>
<td><strong>Level 1:</strong> NC machine tool— • basic tool, does not provide any specific benefits other than its designed activity. Little flexibility in unplanned design change</td>
<td><strong>Level 1:</strong> Truck (operator) • basic tool, does not provide any benefits other than its allocated task. Drill (&amp; operator) • basic tool, relatively little flexibility in unplanned design change. Shovel - important tool, used to size truck fleet, does not provide any benefits other than its allocated task.</td>
</tr>
<tr>
<td><strong>Level 2:</strong> enabling technology (ET) – PLCs Cells • Integrates a series of activities into a single process. • Provides less human interaction thereby can be more repetitive and hence produce manufactures with higher quality FMS • Uses robots that have the capabilities to perform many different operations. • Flexible to unplanned design changes</td>
<td><strong>Level 2:</strong> ET – GPS, drill monitoring, organizational theory GPS assisted planning &amp; drilling • Integrates a series of activities, such as planning, map updating, drilling and surveying into a more integrated process • Provides less human interaction thereby can be more repetitive and hence produce designs with higher quality • Flexible to unplanned design changes • Can take more factors into account during planning thereby increasing quality of design</td>
</tr>
<tr>
<td><strong>Level 3:</strong> enabling technology: IS Linked Islands • Integrates many major activities into a single process • Can take advantage of market changes • Greatly reduces human interaction thereby is less prone to human error • Greatly reduces transcribing information • Reduces repetitive human tasks • Produces components with better quality</td>
<td><strong>Level 3:</strong> enabling technology: IS, CAES, GPS, OR Mine-Mill integration: • Integrates many major activities into a single process • Can take advantage of market changes • Greatly reduces human interaction thereby is less prone to human error • Greatly reduces transcribing information • Reduces repetitive human tasks • Produces ore of better quality</td>
</tr>
<tr>
<td><strong>Level 4:</strong> CIM • Same benefits as above although amplified</td>
<td></td>
</tr>
</tbody>
</table>


Sean Dessureault
4 Analytical Examples

This chapter reviews the justification methods introduced in the previous chapter. Equations, methodologies and numerical examples are provided for most schemes. The examples are organized into the three levels described in the previous chapter.

4.1 Level 1 CIA methods – Common Economic

There are numerous formulae and approaches that firms use to evaluate the potential economic performance of a proposed project. The techniques most common in the mining industry include the payback method, incremental rate of return (IRR, also known as internal rate of return) or return on investment (ROI, referred to also as discounted cash flow rate of return (DCF-ROR) or simply DCF). Manufacturing statistics indicate that the overwhelming majority (91%) of firms in manufacturing use the payback method and ROI methods. These figures may also reflect some habits of mining management.

This section will begin by presenting some of the techniques currently used in industry for economically justifying new projects. Criticisms of the various methods are also provided. Those techniques that will be used for the applied section of this thesis will be explored in detail in this section. The basic economic methods include payback, discounted cash flows (DCF) and internal rate of return (IRR).

4.1.1 Payback

One of the most common evaluation criteria used by mining companies is the payback method. The payback period is relatively simple: it is the amount of time for the initial investment of the project to be paid-back from the cost reductions or amount of income it creates.

4.1.1.1 Analytical Example of the Payback Method

Given the following example: A mining company is considering improving its grade distribution to the mill. There are several options available:

Project 1: A GPS based shovel-monitoring system that has many other options; however, the estimates only reflect the improved grade distribution and avoidance of load misdirection.

Project 2: Automated trip selector that the shovel operator can activate via radio link to indicate to the truck driver where the load should go.


Gentry, Ibid., p.256
Project 3: re-training the truck drivers and buying an electronic trip counter to keep track of operator performance

The table below summarizes all the economic variables involved in the calculation of the payback period.

**Table 4-1: Economic variables for Payback Example**

<table>
<thead>
<tr>
<th></th>
<th>Project 1</th>
<th>Project 2</th>
<th>Project 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial capital input</strong></td>
<td>$220,000</td>
<td>$100,000</td>
<td>$18,000</td>
</tr>
<tr>
<td><strong>Operating costs</strong></td>
<td>$2,000</td>
<td>$3,000</td>
<td>$15,000</td>
</tr>
<tr>
<td><strong>Revenue</strong></td>
<td>$50,000</td>
<td>$30,000</td>
<td>$20,000</td>
</tr>
<tr>
<td><strong>Risk Adjusted Int. r</strong></td>
<td>15%</td>
<td>10%</td>
<td>5%</td>
</tr>
<tr>
<td><strong>Project life</strong></td>
<td>7</td>
<td>6</td>
<td>4</td>
</tr>
</tbody>
</table>

The table below calculates the payback periods of each of the projects. Analysis of the results is discussed following the table.

**Table 4-2: Payback Example Results**

<table>
<thead>
<tr>
<th>Project year</th>
<th>Annual Net Cash Flows</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>HT</strong></td>
</tr>
<tr>
<td>investment</td>
<td>$220,000</td>
</tr>
<tr>
<td>1</td>
<td>$48,000</td>
</tr>
<tr>
<td>2</td>
<td>$48,000</td>
</tr>
<tr>
<td>3</td>
<td>$48,000</td>
</tr>
<tr>
<td>4</td>
<td>$48,000</td>
</tr>
<tr>
<td>5</td>
<td>$48,000</td>
</tr>
<tr>
<td>6</td>
<td>$48,000</td>
</tr>
<tr>
<td>7</td>
<td>$48,000</td>
</tr>
<tr>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td><strong>Payback (yrs.)</strong></td>
<td>4</td>
</tr>
<tr>
<td><strong>Total profit</strong></td>
<td>$116,000</td>
</tr>
</tbody>
</table>

According to this method, if a manager were selecting a project based on payback period, projects 2 or 3 would be selected instead of the most profitable project 1. This method can increase in complexity when considering added variables. Added complexity may add accuracy, or more realistic estimates. However, if the proposed project has not yet been implemented (there is no historical data on which to base estimates), accuracy decreases.

4.1.1.2 Analysis of the Validity of the Payback Method

When analyzing this method, several disadvantages can be seen. Primarily, the payback period is much too simple to model a complex system. In a complex system, some variables may not be easily accounted for, such as flexibility or improved engineering plans. For example, if a new engineering planning software package is being evaluated, the increased
compatibility of the new system with other software may not be easily accounted for. This disadvantage is shared with most economic evaluation methods.

A second disadvantage of the payback period is that it fails to consider the timing of cash flows, therefore it cannot be used to assess profitability. For example, consider the example used above. Proposal 2 has the lowest payback period yet it has the lowest overall profit.

A third disadvantage of the payback period is that the timing of payments is disregarded. A further disadvantage is some projects are more risky than others. In the example used above, the cost of capital and risk is ignored. These drawbacks are easily accounted for by utilizing a risk adjusted discounted payback period, as seen in the table below.

Table 4-3: Payback Example Results using Discount factor

<table>
<thead>
<tr>
<th>Project year</th>
<th>Annual Net Cash Flows</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HT</td>
</tr>
<tr>
<td>investment</td>
<td>$220,000</td>
</tr>
<tr>
<td>1</td>
<td>$48,000</td>
</tr>
<tr>
<td>2</td>
<td>$41,739</td>
</tr>
<tr>
<td>3</td>
<td>$36,295</td>
</tr>
<tr>
<td>4</td>
<td>$31,561</td>
</tr>
<tr>
<td>5</td>
<td>$27,444</td>
</tr>
<tr>
<td>6</td>
<td>$23,864</td>
</tr>
<tr>
<td>7</td>
<td>$20,752</td>
</tr>
<tr>
<td>8</td>
<td>$-</td>
</tr>
<tr>
<td>Payback (yrs.)</td>
<td>6</td>
</tr>
<tr>
<td>Total profit</td>
<td>$9,655</td>
</tr>
</tbody>
</table>

From the results of the example, it can be seen that the first project is no longer the most profitable, furthermore, project 2 has a longer payback period than project 3.

4.1.1.3 Reasoning for Selecting the Payback method

Despite the numerous shortcomings of the payback method, it is still highly utilized in the mining industry. The following is a list that provides some of the reasons, given by management, why this method is so popular. The main reason the payback method was selected to be used in this case study is due to its popularity. However, this method is considered to be inadequate due to its numerous deficiencies.

1. Simplicity

The payback period is very simple. Managers can easily calculate the figure and understand the reasoning. Furthermore, it is much simpler to have an index, or common figure, that can

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49 Gentry, Ibid., p.259

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be used as a comparison between competing projects. A further simplifying factor is that the break-even point is very obvious.

2. Lack of interest in new techniques

Managers are well familiar with this technique, which has been used in the industry for decades. A sense of traditionalism has evolved around certain techniques, to the exclusion of new techniques. This is an important problem but a social-managerial issue and will therefore not be covered in this study. Established techniques may still be applicable but not in all cases.

3. Risk reduction

A shorter payback period is considered to prevent management from being exposed to risk. For example, if a risky project were being considered, a shorter payback period would leave the company exposed to risk for a shorter period of time. The validity of this argument was discussed in a previous section.

The manager must decide what the appropriate payback period should be. This value is often very subjective. Also, selection of appropriate discount rates is an issue that will be raised for every economic evaluation method.

### 4.1.2 Discounted Cash Flow Techniques (DCF)

Discounted cash flow (DCF) techniques use a discount rate, usually in terms of a percentage, to represent risk. The discount rate is usually either a hurdle rate or the true cost of capital. Several versions of discounted cash flows are used in the following economic evaluation methods: NPV, ROI and IRR. Other DCF methods will not be explained.

#### 4.1.2.1 Net Present Value

This method is highly valued as one of industry’s favorites. The net present value represents the amount of money the project is worth at the present time \((t=0)\). The number is calculated by summing the inflows and outflows of cash, discounted at the selected discount rate. The choice of the discount rate is an important issue. The discount rate can be the true cost of capital or a value set by the corporation that can be adjusted to take risk into account. The general equation that best represents the NVP is presented below. Typically, if the net present value is a negative value, the project should be rejected.

The NPV is given by below:
Net present value = \sum \text{present value of cash benefits} - \sum \text{present value of cash costs}

Equation 4-1: Net Present Value

4.1.2.1.1 Numerical Example of the NPV method

Consider the following example:

Table 4-4: Data to be used in NPV example

| Initial investment | $4,000  |
| Operating cost     | $3,000  year 1 |
| Operating cost     | $450 per year |
| Revenue            | $4,000 per year |

Table 4-5: NPV example

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net investment</td>
<td>$4,000</td>
<td>$3,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating Cost</td>
<td>$450</td>
<td>$453</td>
<td>$457</td>
<td>$460</td>
<td>$464</td>
</tr>
<tr>
<td>Revenue</td>
<td>$4,000</td>
<td>$4,000</td>
<td>$4,000</td>
<td>$4,000</td>
<td>$4,000</td>
</tr>
<tr>
<td>Income</td>
<td>$450</td>
<td>$547</td>
<td>$3,543</td>
<td>$3,540</td>
<td>$3,536</td>
</tr>
<tr>
<td>Income (DCF@12%)</td>
<td>$481</td>
<td>$2,744</td>
<td>$2,412</td>
<td>$2,121</td>
<td></td>
</tr>
<tr>
<td>NPV@12%</td>
<td>$7,308</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.1.2.1.2 Validity of the NPV method

Two characteristics make this technique popular and more accurate than the payback period. This subsection will list these qualities and determine whether these qualities apply when evaluating advanced technologies.

1. Takes into account the time value of money

Using a discount rate takes into account the time value of money. Determining the appropriate discount rate is one of the difficulties of this method. The number is very subjective and sometimes set by corporate objectives. Some discount rates are set excessively high as a hedge against risk. This is very common when managers are considering new technology that has not yet been widely accepted.

2. Simple to compare projects

Similar to the payback method, NPV provides a single number upon which comparisons can be made between two projects with similar goals; however, one of the main problems with this method is that it does not measure profitability. For example, consider two projects with...
different capital input but identical NPVs. The project that is more capital intensive yet still profitable may be selected over a project that requires less capital but is more profitable. These deficiencies can be overcome by using a version of this method called the profitability index (PI) or the benefit/cost ratio (B/C).

\[
\text{B/C ratio (PI)} = \frac{\sum \text{PV of net cash inflows}}{\sum \text{PV of net cash outflows}}
\]

**Equation 4-2: Benefit/Cost ratio**

4.1.2.1.3 Reasoning for selecting the NPV method

Despite its shortcomings and its misuse, NPV can be modified to better estimate the economic impact of advanced technology on the operation. More variables can be taken into account to consider the qualitative benefits. A lower discount rate can be used to represent the unquantifiable qualitative benefits. Therefore the reasons for choosing this method for this case study are its accuracy, popularity and possible applicability to new technology.

4.1.2.2 Internal Rate of Return (IRR)

Variations of the IRR method include rate of return (ROR) and return on investment (ROI). This economic justification method is used by the mineral industry more than any other technique. The internal rate of return can be defined as the interest rate (discount rate) that allows the sum of the present value of all the inflows and outflows of cash to equal zero. This definition satisfies the equation below.

\[
\sum \text{PV cash inflows} - \sum \text{PV cash outflows} = \text{NPV} = 0
\]

**Equation 4-3: Internal Rate of Return**

4.1.2.2.1 Numerical Example Illustrating the IRR method

Using spreadsheet solvers, the IRR can be easily found. Prior to the introduction of spreadsheets, this calculation was done by trial and error. The example below was solved using the solver in Excel. Microsoft's Excel solver is used in the example in the section describing level 2 technologies.

---

50 Gentry, Ibid., p.267
Table 4-6: IRR example data

<table>
<thead>
<tr>
<th></th>
<th>Project 1</th>
<th>Project 2</th>
<th>Project 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial capital</td>
<td>$110,000</td>
<td>$80,000</td>
<td>$6,000</td>
</tr>
<tr>
<td>yr 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>yr 2</td>
<td>$110,000</td>
<td>$30,000</td>
<td>$8,000</td>
</tr>
<tr>
<td>total</td>
<td>$220,000</td>
<td>$110,000</td>
<td>$14,000</td>
</tr>
<tr>
<td>Operating costs</td>
<td>$1,000</td>
<td>$3,000</td>
<td>$15,000</td>
</tr>
<tr>
<td>Revenue</td>
<td>$40,000</td>
<td>$30,000</td>
<td>$20,000</td>
</tr>
<tr>
<td>Project life</td>
<td>7</td>
<td>6</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 4-7: IRR example results

<table>
<thead>
<tr>
<th>Year</th>
<th>Annual Net Cash Flows</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Project 1</td>
</tr>
<tr>
<td>investment --&gt;</td>
<td>($110,000)</td>
</tr>
<tr>
<td>1</td>
<td>$39,000</td>
</tr>
<tr>
<td>2</td>
<td>($64,710)</td>
</tr>
<tr>
<td>3</td>
<td>$32,396</td>
</tr>
<tr>
<td>4</td>
<td>$29,526</td>
</tr>
<tr>
<td>5</td>
<td>$26,910</td>
</tr>
<tr>
<td>6</td>
<td>$24,526</td>
</tr>
<tr>
<td>7</td>
<td>$22,353</td>
</tr>
<tr>
<td>8</td>
<td>$-</td>
</tr>
<tr>
<td>IRR</td>
<td>10%</td>
</tr>
</tbody>
</table>

As can be seen in the results above, project 2 has the highest IRR. The acceptance or rejection of a single project using the IRR method depends on the hurdle rate set, usually by the corporation or manager.

4.1.2.2.2 Validity of the IRR method

There are several reasons for IRR’s widespread popularity as a financial evaluation tool. The primary advantage is that it provides a single value that can be used to judge the project. A further advantage is that the result is presented as a percentage. According to Gentry (1984) engineers prefer percentages to absolute values such as NPV. A third advantage is that this method takes into account the timing of the payments. Another advantage is that it does not require a subjective input in the form of a pre-established discount rate.

4.1.3 Risk Considerations

Risk is an important component to the justification of projects. There is a great deal of literature on the assessment of risk when investing in new technology. The uncertainty of new technologies is an important consideration and therefore risk plays a dominant role in the evaluation of technology-based projects. Risk and how to identify it and take it into account in economic evaluation is discussed in the sections describing level 3 technologies and justification schemes.
4.2 Level 2 Justification Schemes - Portfolio & Scoring models

Level 2 justification schemes include programming models, scoring models, non-numeric arguments and growth options. Programming models include linear, integer and goal programming. Programming models and growth options are considered to be portfolio models since the securities industry uses them to optimize investment portfolios. Scoring models include weighted scoring and the analytical hierarchy process (AHP). Non-numeric models are the sacred cow and operating necessity arguments. Descriptions and examples of most of these methods will be provided.

4.2.1 Programming models

Linear programming (LP) was developed by George Dantzig, then a young mathematician. He named the algorithm used to solve an LP problem the simplex method. It was designed to solve complex logistics during WWII in the effort to supply Britain with vital war material. The algorithm can quickly solve complex linear problems. The problems can be solved even faster using computers. LP is frequently used in the manufacturing industry. However, LP is uncommon in the mining industry, despite its obvious application due to the frequent logistics involved in mining.

Integer programming is similar to linear programming except there is a finite set of possible results or inputs. For example, it can be used to select the optimum set of projects from a list of various inter-related projects. In this situation, the model's objective can be to maximize the NPV under various restrictions.

Goal programming allows the evaluator of the proposed project to consider separate objectives independently and on different weighted bases. Many restrictions are possible on the various resources.

The following subsections include examples of integer programming and goal programming. It should be noted that all examples given in this text are illustrative, not exhaustive.

4.2.1.1 Integer Programming

Optimization models where some or all of the variables must be integers are called integer programming (IP) models. An example of how to build and execute a model on a modern spreadsheet tool is provided. Microsoft's Excel program is used to formulate and solve the IP model.

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51 Dantzig, G. The Diet Problem. Interfaces 20 no.4, 1990 p. 43-47
53 Meredith and Hill, Ibid., p.54

Sean Dessureault
Example: Minecomp, a fictitious underground base metal mine, is considering investing in one of several different technologies. Minecomp is considering upgrading its communications system to provide possible automation. The monetary values of both the investment and estimated return are provided in the table below. Some restrictions are imposed on the model due to technology incompatibilities. These restrictions are also presented below.

Table 4-8: Data for Minecomp Example

<table>
<thead>
<tr>
<th>Investment</th>
<th>Description</th>
<th>Abreviation</th>
<th>Cash Required</th>
<th>NPV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Leaky feeder (low capacity)</td>
<td>LFL</td>
<td>$150</td>
<td>$200</td>
</tr>
<tr>
<td>2</td>
<td>Leaky feeder (high capacity)</td>
<td>LFH</td>
<td>$250</td>
<td>$400</td>
</tr>
<tr>
<td>3</td>
<td>Distributed antenna system</td>
<td>DAS</td>
<td>$400</td>
<td>$800</td>
</tr>
<tr>
<td>4</td>
<td>Radio tech 1</td>
<td>R1</td>
<td>$150</td>
<td>$500</td>
</tr>
<tr>
<td>5</td>
<td>Radio tech 2</td>
<td>R2</td>
<td>$100</td>
<td>$1,750</td>
</tr>
<tr>
<td>6</td>
<td>Both Radio techs</td>
<td>RR</td>
<td>$250</td>
<td>$3,500</td>
</tr>
</tbody>
</table>

Table 4-9: Restrictions for Minecomp Example

Restrictions:
- Radio tech 1 cannot function with LFL
- DAS cannot function with LFL
- Total Budget of $730,000

The main components of this assessment are:

- The investments chosen
- The cash required for the investments
- Total NPV of the chosen investments

This model was developed on Microsoft Excel® for Office 97®. (It can be developed on versions of Excel since Excel 5.) The data was entered into the spreadsheet as seen in the figure below. The changing cells were in the investment decision row. The goal of the algorithm was to maximize the NPV subject to the constraints. The solver was invoked and constraints applied. The solver changed the cell in array B2:G2 to reflect the maximized NPV given the constraints.

---

55 Winston, Ibid. p.214


Sean Dessureault
Figure 4-1: Optimal Solution for Minecomp Example

As can be seen from the figure above, the solution to the problem would be to invest in a DAS, while using radio technologies 1 and 2. This example may appear trivial, but real situations may require many more variables and constraints.

4.2.1.2 Goal Programming

Goal programming is ideal for situations where a company wants to achieve several objectives, given limited resources. Sometimes it is impossible to realize all the objectives simultaneously, but in the solution process, an optimum is usually achieved. If the company cares to prioritize its objectives, goal programming can still be used. This method of prioritizing objectives is called a preemptive goal programming approach.

Example:

A fictional open pit mining company, OPMC, would like to improve its drilling operations. Management has identified three key variables that measure drill performance. The mill would like a specific size distribution, making fragmentation a key variable. Due to the geological conditions, accurate drill position is another important variable. Finally, the drilling operation is taking too much time to set-up the drill and begin drilling, therefore set-up time is another variable.

Management has identified two possible solutions. The first is to undertake an intensive operator-training program. There is an incremental improvement in the three key variables governing drill performance, as seen in the table below. The second solution is the purchase of a drill navigation package offered by Aqmod, a fictitious mining technology provider. Each navigation package purchased provides an incremental improvement in the three drill improvement variables. A total budget of $170 000 has been budgeted to this project. These data are summarized in the tables below.

---

**Table 4.1: Investment Decision and Costs**

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>LFL</td>
<td>LFH</td>
<td>DAS</td>
<td>R1</td>
<td>R2</td>
<td>RR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Investment decision</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Restrictions</td>
<td>A + B = 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Investment Cost</td>
<td>$150</td>
<td>$250</td>
<td>$400</td>
<td>$150</td>
<td>$100</td>
<td>$250</td>
<td>RR ≥ R1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>$200</td>
<td>$400</td>
<td>$600</td>
<td>$500</td>
<td>$1750</td>
<td>$3500</td>
<td>RR ≥ R2</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>NPV</td>
<td>$650</td>
<td>$300</td>
<td>$400</td>
<td>$500</td>
<td>$1750</td>
<td>$3500</td>
<td>DAS ≥ LFH</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>c = $730</td>
<td>$730</td>
<td>Budget</td>
<td></td>
<td></td>
<td></td>
<td>R1 = LFH</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>total cost</td>
<td>$650</td>
<td>c = $730</td>
<td>$170,000</td>
<td>Budget</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>$650</td>
<td>c = $730</td>
<td>$170,000</td>
<td>Budget</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>total NPV</td>
<td>$2,350</td>
<td>$2,350</td>
<td>$2,350</td>
<td>$2,350</td>
<td>$2,350</td>
<td>$2,350</td>
<td>$2,350</td>
<td>$2,350</td>
<td>$2,350</td>
</tr>
</tbody>
</table>

---

56 Winston, Ibid. p. 338
58 will not be explained here but readers are encouraged to review the Winston (1997)
Table 4-10: Goals for OPMC Example

<table>
<thead>
<tr>
<th>Description</th>
<th>Abbreviation</th>
<th>% Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>goal 1: improve fragmentation</td>
<td>Frag</td>
<td>31%</td>
</tr>
<tr>
<td>goal 2: improve blast hole position</td>
<td>Pos</td>
<td>20%</td>
</tr>
<tr>
<td>goal 3: decrease set-up time</td>
<td>S-t</td>
<td>30%</td>
</tr>
</tbody>
</table>

Table 4-11: Improvement Methods for OPMC Example

<table>
<thead>
<tr>
<th>Description</th>
<th>Abbreviation</th>
<th>Frag</th>
<th>Pos</th>
<th>S-t</th>
<th>Cost/unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>method 1 Higher level train</td>
<td>Training</td>
<td>1%</td>
<td>2%</td>
<td>3%</td>
<td>$3,300</td>
</tr>
<tr>
<td>method 2 Aqmod drill</td>
<td>Aqmod</td>
<td>17%</td>
<td>8%</td>
<td>11%</td>
<td>$80,000</td>
</tr>
</tbody>
</table>

A spreadsheet model, similar to the integer programming model above, will be formulated. The main components of this model are listed below:

- Number of improvement method units purchased
- Cost of the methods
- Overall improvement

The spreadsheet model was formulated as shown in the figure below. The solver determined the values in cells B8 and C8; they represent the optimized solution. The optimal solution is to train three operators, while purchasing two Aqmod drill packages. Changing the estimated improvement values incurred from the two methods can alter the solution. Increasing or decreasing the percentage values of the goals can alter their importance. For example, if the management considers that decreasing the set-up time is of prime importance, the goal value may be changed from 30 to perhaps 40. Therefore this solution is only as valid as the estimated improvements or management goals.

![Figure 4-2: Optimal Solution for the OPMC Example](attachment:image.png)
### 4.2.2 Scoring Models

The two scoring models explained in this section are the weighted average and analytical hierarchy process. The weighted average method is relatively simple and is used in many industries. The analytical hierarchy process (AHP) is a multi-objective decision making tool. Both these methods are used by the manufacturing industry to justify a technology acquisition. Mining examples are provided with an explanation.

#### 4.2.2.1 Weighted Average Method

The weighted average method is simple and easy to use, but it is very subjective. The method can be used to decide between different projects, or to ensure that the project conforms to certain pre-established criteria. This method consists of quantifying the importance of different objectives, then estimating the importance of each factor. To obtain a solution, the hierarchy of the objectives is multiplied by the rating of the factors to yield a comparative score.

Consider the following example:

An underground mining company, UMC, which uses a vertical retreat mining method, is contemplating three different technologies for mucking out the open stopes. There are eight variables (objectives) that management considers to be of top importance for the mucking cycle: capital cost, operating cost, productivity, operator acceptance, maintenance cost, infrastructure requirements, unfamiliarity of the technology, and safety. Each technology being evaluated has a different rating on these factors on a scale of 1 to 10, here a higher number signifies a more attractive outcome. For example, if technology A has a lower capital cost, it receives either an 8 or a 10. A weight is also given to each objective, depending on the importance of the objective to the mine management. The three technologies under consideration are described below:

**Option 1:** line of sight tele-operated system. This system is well accepted by miners due to its long widespread use in mines. However, many operators are accidentally killed or injured due to operator error (controlling the machine from an unprotected area).

**Option 2:** Controlling the LHD from a control room on the same level. This technology is relatively straightforward, but communications infrastructure is required. Productivity is slightly higher since higher speeds can be used.

**Option 3:** Controlling LHD from surface. This technology is state-of-the-art. The miner is not exposed to danger, and less ventilation is required in the area. Increased productivity can be achieved since the LHD can operate at higher speeds and since work can begin as soon as the miner arrives at the surface workstation. However, no mines currently use such systems in a production capacity. A further drawback would be the operator resistance to the
technology since more intense work hours are possible and the technology is unfamiliar. A final drawback is the considerable extension of communications infrastructure that would be required beyond option 2.

A manager can then rate the projects according to the table below. The scoring is subjective. For example, the opinion of the importance of safety may be increased or decreased depending on the manager, or the corporate policies.

Table 4-12: Weighted Scores for UMC Example

<table>
<thead>
<tr>
<th>Factor</th>
<th>LSTR</th>
<th>TRL</th>
<th>TRS</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost</td>
<td>8</td>
<td>6</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Operating Cost</td>
<td>9</td>
<td>6</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Productivity</td>
<td>6</td>
<td>8</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Operator acceptance</td>
<td>8</td>
<td>7</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Maintenance Costs</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Infrastructure requireme</td>
<td>10</td>
<td>7</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Unfamiliarity</td>
<td>10</td>
<td>7</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Safety</td>
<td>4</td>
<td>7</td>
<td>10</td>
<td>2</td>
</tr>
</tbody>
</table>

The final results are presented in the table below. This result was achieved by multiplying the weight of each project objective by the rating each project receives. The weights are summed, then normalized for ease of comparison. According to the manager at this mine, the line-of-sight remote control LHD is the best decision in this case. The power of this CIA method lies in the ability to quantify qualitative factors such as safety or operator acceptance.

Table 4-13: Results of Weighted Average Method for UMC Example

<table>
<thead>
<tr>
<th>Factor</th>
<th>LSTR</th>
<th>TRL</th>
<th>TRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost</td>
<td>56</td>
<td>42</td>
<td>21</td>
</tr>
<tr>
<td>Operating Cost</td>
<td>72</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>Productivity</td>
<td>60</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Operator acceptance</td>
<td>48</td>
<td>42</td>
<td>30</td>
</tr>
<tr>
<td>Maintenance Costs</td>
<td>49</td>
<td>42</td>
<td>35</td>
</tr>
<tr>
<td>Infrastructure requireme</td>
<td>30</td>
<td>21</td>
<td>15</td>
</tr>
<tr>
<td>Unfamiliarity</td>
<td>40</td>
<td>28</td>
<td>24</td>
</tr>
<tr>
<td>Safety</td>
<td>8</td>
<td>14</td>
<td>20</td>
</tr>
<tr>
<td><strong>Sum:</strong></td>
<td>363</td>
<td>317</td>
<td>293</td>
</tr>
<tr>
<td><strong>Normalized</strong></td>
<td>1.00</td>
<td>0.87</td>
<td>0.81</td>
</tr>
</tbody>
</table>

4.2.2.2 The Analytical Hierarchy Process (AHP)

The analytical hierarchy process (AHP) is another multi-objective decision making tool. Tomas Saaty developed the technique to overcome inconsistency in human judgment. This powerful decision tool is used by many disciplines including accounting, finance, marketing,
energy resource planning, microcomputer selection, sociology, history, architecture and political science\textsuperscript{60}. The power of this decision process is that it quantifies qualitative values so that they can be evaluated with the naturally quantitative values. For example, qualitative benefits can be considered with financial values. This method is similar to the weighted average evaluation technique where objectives or factors are assessed. The power of this method is the ability to compare the importance of two different factors through a method called the Pairwise Comparison Matrix. An example is given along with a pragmatic explanation of the mathematics involved.

To obtain the weights the Pairwise Comparison Matrix is formed. The entry rows are labeled $i$ and entry columns $j$. Priority or importance is measured on an integer 1-9 scale, according to the definitions provided in the table below. The phrases in the table are comparative phrases, to help the evaluator compare two variables. The values may seem discrete, however, more experienced evaluators may use a continuous scale.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
Value of $a_{ij}$ & Interpretation \\
\hline
1 & Objectives $i$ and $j$ are equally important \\
3 & Objective $i$ is slightly more important than $j$ \\
5 & Objective $i$ is strongly more important than $j$ \\
7 & Objective $i$ is very strongly more important than $j$ \\
9 & Objective $i$ is absolutely more important than $j$ \\
\hline
\end{tabular}
\caption{Interpretation of Values in Pairwise Comparison Matrix\textsuperscript{61}}
\end{table}

The following is an example of how pairwise comparisons are made. If an evaluator were judging a situation where there are three objectives, the matrix would contain a 3x3 pattern.

\[ A = \begin{pmatrix}
    a_{11} & a_{12} & a_{13} \\
    a_{21} & a_{22} & a_{23} \\
    a_{31} & a_{32} & a_{33}
\end{pmatrix} = \begin{pmatrix}
    1 & a_{21} & a_{31} \\
    1/a_{21} & 1 & a_{32} \\
    1/a_{31} & 1/a_{32} & 1
\end{pmatrix} \]

Equation 4-4: Pairwise Comparison Matrix for 3 objectives

Equations above represent a situation where there are three objectives. To illustrate, if objective 1 is strongly more important than objective 2, then $a_{12} = 5$ and $a_{21} = 1/5$. Correspondingly, if objective 3 is very strongly more important than objective 1, then $a_{31} = 7$ and $a_{12} = 1/7$. Finally, if objective 2 is slightly more important than objective 3, then $a_{23} = 3$ and $a_{32} = 1/3$. The matrix below is obtained using these values.

\textsuperscript{60} Winston, Ibid, p.371
\textsuperscript{61} Winston, Ibid, p.364

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An open pit iron ore mine, IOM, is trying to determine what technology, if any, should be implemented. IOM has a large mill throughput therefore fragmentation is very important for the mill recovery. A further difficulty is that the complicated geology makes the large blast patterns difficult to design. Grade control is also important in iron ore mines. At IOM, it is difficult for shovel operators to distinguish between low and high grade. Management has several objectives that resulted in the decision to invest in technology:

- Objective 1: Fragmentation
- Objective 2: Lead-time for blast pattern design changes from geological updates
- Objective 3: Cost of equipment
- Objective 4: Grade control

Several technologies might help the manager achieve the objectives mentioned above. One suggestion is to continue using the same tools so that costs do not increase, another is to implement drill monitoring technology, a third is to implement shovel monitoring technology while a fourth, is to implement both the drill and shovel monitoring technology. The figure below summarizes the objectives and solutions:

### Table 4-15: Objectives and solution options for IOM example

<table>
<thead>
<tr>
<th>Description</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective 1 Ideal fragmentation for Mill</td>
<td>Fragment</td>
</tr>
<tr>
<td>Objective 2 Flexibility of design changes</td>
<td>Flexibility</td>
</tr>
<tr>
<td>Objective 3 Cost of equipment</td>
<td>Cost</td>
</tr>
<tr>
<td>Objective 4 Better grade control</td>
<td>Grade</td>
</tr>
<tr>
<td>Option 1: Without drill technology</td>
<td>No tech</td>
</tr>
<tr>
<td>Option 2: Drill tech</td>
<td>Drill</td>
</tr>
<tr>
<td>Option 3: Shovel tech</td>
<td>Shovel</td>
</tr>
<tr>
<td>Option 4: Both shovel &amp; drill tech</td>
<td>All techs</td>
</tr>
</tbody>
</table>

Solution to IOM problem:

Step 1: Determine the Pairwise Comparison matrix. The manager, after careful contemplation, forms the following pairwise comparison matrix, on a spreadsheet:

\[
A = \begin{pmatrix}
1 & \frac{1}{5} & 7 \\
5 & 1 & \frac{1}{3} \\
\frac{1}{7} & 3 & 1
\end{pmatrix}
\]
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Figure 4-4: Pairwise Comparison Matrix for Objectives for IOM example

From the matrix above, it can be seen that the manager considers fragmentation strongly more important than flexibility.

Step 2: determine the weights. Take the sum of each of the columns, and divide each value in the column the sum of the column. (This normalizes the column.) The values obtained for the normalized matrix are:

\[
\begin{array}{cccc}
\text{Fragment} & \text{Flexibility} & \text{Cost} & \text{Grade} \\
\text{Fragment} & 0.4918 & 0.4167 & 0.5714 & 0.4444 \\
\text{Flexibility} & 0.0984 & 0.0833 & 0.0476 & 0.1111 \\
\text{Cost} & 0.1639 & 0.3333 & 0.1905 & 0.2222 \\
\text{Grade} & 0.2459 & 0.1667 & 0.1905 & 0.2222 \\
\end{array}
\]

Figure 4-5: Normalized Pairwise Comparative Matrix

An example of the calculation used for the above matrix is:

\[
a_{11}(\text{normalized}) = \frac{a_{11}}{a_{11} + a_{12} + a_{13} + a_{14}} = \frac{1}{1 + \frac{1}{5} + \frac{1}{3} + \frac{1}{2}} = 0.4918
\]

Step 3: Determine the weights of the objectives. The weight of each objective is calculated by taking the average value of each row. From the matrix above, the resulting 1x4 vector is found to be:

\[
w = \begin{pmatrix} 0.4811 \\ 0.0851 \\ 0.2275 \\ 0.2063 \end{pmatrix}
\]

From this vector, it can be seen that the manager considers fragmentation to be the most important objective, while cost and grade are relatively the same. Flexibility is not a great concern according to this evaluation.

Comparisons can be inconsistent due to human discrepancies. A method was devised to check for inconsistencies. The solution consists of multiplying the pairwise comparison matrix by the score of the objectives. Therefore, from the example above, the following multiplication is made:
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Using the numbers from the vector \( w_{\text{consistency}} \), the following single value is calculated using the weighted objective values.

\[
\begin{align*}
2.0017 + & \frac{0.3414}{0.4811} + \frac{0.9346}{0.2275} + \frac{0.8446}{0.2063} = 0.0311
\end{align*}
\]

Using the value above, the consistency index (CI) is calculated using the equation below. The \( n \) variable is the number of objectives.

\[
CI = \frac{0.0311 - n}{n - 1} = \frac{0.0311 - 4}{3}
\]

The CI is then compared to an index value, obtained from the table below. Saaty derived the table.

<table>
<thead>
<tr>
<th>Table 4-16: Random Indices for Consistency Check(^\text{62})</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n )</td>
</tr>
<tr>
<td>RI</td>
</tr>
</tbody>
</table>

- if CI = 0, perfectly consistent
- if CI/RI < .10 then satisfactory consistency
- if CI/RI > .10 then serious inconsistencies exist

The solution is still not complete. All the steps above must be repeated for every option. Options 1 through 4 (No Tech, Drill, Shovel and All Techs) must be compared with each other, rated on the performance of each objective. Figure 4-6, represents the pairwise comparison matrix for comparing the options according to the fragmentation objective (on an Excel spreadsheet). The evaluator considers the Drill option to be moderately more important than the No Tech option for improving fragmentation (cell C13). Furthermore, according to the final scores, the Drill option is the best solution for fragmentation. Finally, it can be seen that the matrix has satisfactory consistency.

\(^{62}\) Winston, et. al., Ibid., pp.368
Figure 4-6: Pairwise Comparison Matrix of Options for Fragmentation for IOM Example

Once all score matrices have been completed, and they all have satisfactory consistency, the score matrix is multiplied by the weight matrix to obtain the final overall score matrix. The result is shown in the figure below. From the solution in Figure 4-7, both the Shovel and All Techs options satisfy the management at the iron ore mine.

<table>
<thead>
<tr>
<th>Pairwise comparisons among Options on fragmentation</th>
<th>Scores</th>
<th>Product Ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>No tech</td>
<td>Drill</td>
<td>Shovel</td>
</tr>
<tr>
<td>No tech</td>
<td>1</td>
<td>1/4</td>
</tr>
<tr>
<td>Drill</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Shovel</td>
<td>1</td>
<td>1/4</td>
</tr>
<tr>
<td>All techs</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

Normalized Matrix

<table>
<thead>
<tr>
<th></th>
<th>No tech</th>
<th>Drill</th>
<th>Shovel</th>
<th>All techs</th>
</tr>
</thead>
<tbody>
<tr>
<td>No tech</td>
<td>0.4943</td>
<td>0.0208</td>
<td>0.1905</td>
<td>0.0741</td>
</tr>
<tr>
<td>Drill</td>
<td>1.9672</td>
<td>0.0833</td>
<td>0.7619</td>
<td>0.2222</td>
</tr>
<tr>
<td>Shovel</td>
<td>0.4943</td>
<td>0.0208</td>
<td>0.1905</td>
<td>0.0741</td>
</tr>
<tr>
<td>All techs</td>
<td>1.4754</td>
<td>0.0833</td>
<td>0.5714</td>
<td>0.2222</td>
</tr>
</tbody>
</table>

|                  | 0.7587  | 0.3011| 0.6297 | 0.2275    |
|                  | 0.5881  | 0.9302| 0.1051 | 0.8280    |

|                  | 0.005544|       |        |           |

CMPI 0.00616

Figure 4-7: Final Solution for IOM Example

4.2.3 Option Pricing

This pricing technique was originally intended to formulate a fair, non-subjective price for stock options. Manufacturing has used this price model to determine the value of flexibility in manufacturing systems. The economic model has also been used in the mining industry for valuing the flexibility of design\(^\text{63}\).

This method’s power lies in its ability to quantify the flexibility of the technologies. In this section, the origin and mechanics of option pricing, as a justification method, will be given, with an example of its application as a justification tool. The technique can be applied to technologies that are level 2 or 3 since flexibility can be tactical or strategic in nature.

An example of tactical flexibility in mining is the ability to mine a ‘back-up stope’ in case the planned stope becomes unavailable (for example, due to a catastrophic cave-in of the planned stope). This flexibility can be purchased by undertaking advanced development\(^\text{64}\); however, the extra capital costs of undertaking advanced development must be larger than the cost of the loss of production that would be incurred in the event of losing a stope.

---

\(^{63}\) Samis, Mike, *Project evaluation using contingent claims analysis – an overview*, Master’s Thesis, University of the Witwatersrand, Johannesburg, 1994

\(^{64}\) Dunbar, W Scott; Sean Dessureault and Malcolm Scoble. *Analysis of Flexible Mining Systems*. CIM '98 CD-ROM, 1998

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An example of strategic flexibility is a mining company’s ability to increase production in the event of a price (of the mineral being mined) increase or shut down in the event of a price drop. Operating without a union contract and having extra capacity can purchase this type of flexibility.

Three methods are discussed: the Black-Scholes' method of valuing a European Call option, binomial method of computing the option price; Azzone’s method for direct application in the manufacturing industry.

4.2.3.1 Black-Scholes

A European call option on a stock gives the owner the option to buy (if the option is a call option) or sell (if the option is a put option) a given number of the stock at a specified price on a particular date. (There are many types of options such as American options or Asian options; however, their particularities will not be explained here.) The date at which the option is must be exercised is called the expiration date. The price at which the option holder is allowed to buy or sell the stock is called the exercise price. The reason one would buy a call option at an exercise price X, is that he/she believes that at the price of the stock will be higher than X. Therefore when he/she exercises the call option, he/she will obtain a stock for less than its current value. The inverse is true if it is a put option. One would exercise a put option if the exercise price is more than the current price of the stock, therefore the individual/company who sold you the put option must buy the stocks at a price higher than those that you would get on the open market.

The Black-Scholes option price is calculated using the following equation:

\[
\text{Black-Scholes option price} = SP \times N(d_1) - EP \times e^{-DUR \times IR} \times N(d_2)
\]

where

\[
d_1 = \frac{\ln(SP/EP) + (IR + VOL^2/2) \times (DUR)}{VOL \times \sqrt{DUR}}
\]

and

\[
d_2 = d_1 - VOL \times \sqrt{DUR}
\]

Equation 4-5: Black-Scholes option price

\(SP\) - stock price
\(EP\) - exercise price
\(DUR\) - duration of the option
\(IR\) - interest rate (risk free interest rate)
\(VOL\) - Volatility of the stock

In the securities industry, all of the above variables are usually known, except volatility. Volatility of the stock is its standard deviation (the amount of variation over time). This can...
be calculated from the stock's historical performance. The Black-Scholes method of valuing options is not used in determining the value of flexible manufacturing systems. Some consider it unusable because a number of basic assumptions, such as total divisibility, which are unacceptable for investments in manufacturing (and hence mining) systems\textsuperscript{65}. It is provided in this thesis as a basic example of how option on stocks were first determined in an analytical manner.

A real option to produce metal differs from a stock option in that instead of buying the option to buy (call) or sell (put) a stock at a certain price after a given amount of time, areas of ore can be mined, processed and sold as metal as price fluctuates. For example, buying the flexibility or option to mine a particular stope (by paying for the development costs or designing current excavation to accommodate this flexibility) would allow the mine to extract that ore, if the market price increases to make that stope profitable.

4.2.3.2 Binomial Options Theory

Binomial option pricing is a generalization of Black-Scholes. This method of calculating the value of an option is based on a binomial model of metal price fluctuations\textsuperscript{66}. For example, over a certain period the price of a metal can either increase or decrease from its value at the beginning of the period.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{binomial_fluctuations.png}
\caption{Binomial Fluctuations}
\end{figure}

Increasing the production from a mine is analogous to a call option (i.e., the mine operator has the right, but not the obligation to produce more metal at any time)\textsuperscript{67}. The option to increase production will only be exercised if \( P > X \) given that \( P \) is the price per unit and \( X \) is the cost of production per unit. The figure below simplifies this concept, where the payoff (option value) is governed by metal price.


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Payoff

Option Payoff = \max(P - X, 0)

Figure 4-9: Option Payoff

An example of the application of valuation of strategic flexibility is presented below, it has been adapted from an example provided by Dunbar\textsuperscript{68}. The example assigns a value to a technology/methodology that can allow a gold mine to increase capacity in the event of a price increase. The following variables are used in the example:

- Mine life: 10 years
- Production rate, \(M\): 10,000 oz/year
- Production cost, \(X\): $200/oz
- Risk-free discount rate: 5%
- \(Price\) \(P\): $300/oz
- \textit{Upward} \(u\): 1.1
- \textit{Downward} \(d\): 0.9

The lattice of gold prices below is calculated using binomials. For example, over the 10 year life of the mine, the price can either increase by 10% (\(u=1.1\)) or decrease at a rate of 10% (\(d=0.9\)). Hence, if in the first year the price of gold increases, from 300 to 330, then decreases in the following year, the price would fall to 297.

Table 4-17: Binomial price lattice for gold over a 10 year period

<table>
<thead>
<tr>
<th>Year</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>300</td>
<td>330</td>
<td>363</td>
<td>399</td>
<td>393</td>
<td>439</td>
<td>483</td>
<td>531</td>
<td>584</td>
<td>643</td>
<td>707</td>
</tr>
<tr>
<td>270</td>
<td>270</td>
<td>297</td>
<td>327</td>
<td>359</td>
<td>395</td>
<td>435</td>
<td>484</td>
<td>535</td>
<td>592</td>
<td>650</td>
<td>711</td>
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<td>243</td>
<td>243</td>
<td>267</td>
<td>294</td>
<td>323</td>
<td>357</td>
<td>392</td>
<td>438</td>
<td>485</td>
<td>541</td>
<td>598</td>
<td>655</td>
</tr>
<tr>
<td>218</td>
<td>218</td>
<td>240</td>
<td>264</td>
<td>291</td>
<td>320</td>
<td>352</td>
<td>387</td>
<td>426</td>
<td>470</td>
<td>520</td>
<td>571</td>
</tr>
<tr>
<td>196</td>
<td>196</td>
<td>216</td>
<td>238</td>
<td>262</td>
<td>288</td>
<td>317</td>
<td>348</td>
<td>387</td>
<td>426</td>
<td>470</td>
<td>520</td>
</tr>
<tr>
<td>177</td>
<td>177</td>
<td>194</td>
<td>214</td>
<td>235</td>
<td>259</td>
<td>285</td>
<td>310</td>
<td>348</td>
<td>387</td>
<td>426</td>
<td>470</td>
</tr>
<tr>
<td>159</td>
<td>159</td>
<td>175</td>
<td>192</td>
<td>212</td>
<td>233</td>
<td>254</td>
<td>278</td>
<td>307</td>
<td>337</td>
<td>368</td>
<td>401</td>
</tr>
<tr>
<td>143</td>
<td>143</td>
<td>157</td>
<td>173</td>
<td>191</td>
<td>210</td>
<td>231</td>
<td>254</td>
<td>278</td>
<td>308</td>
<td>339</td>
<td>371</td>
</tr>
<tr>
<td>129</td>
<td>129</td>
<td>142</td>
<td>156</td>
<td>173</td>
<td>191</td>
<td>210</td>
<td>231</td>
<td>254</td>
<td>278</td>
<td>308</td>
<td>339</td>
</tr>
<tr>
<td>116</td>
<td>116</td>
<td>127</td>
<td>142</td>
<td>156</td>
<td>173</td>
<td>191</td>
<td>210</td>
<td>231</td>
<td>254</td>
<td>278</td>
<td>308</td>
</tr>
</tbody>
</table>

The values of the gold mined (including all capital and operating costs) is presented in the table below.

Table 4-18: Value of gold production (Smillion) using gold price fluctuations and mine model

\textsuperscript{68} Dunbar, W. 1998, Ibid

Consider a technology or modification that allows a capacity expansion or contraction at any time. The cost of the technology is $1.2 million, with potential production rate increase to 12,000 oz/year and production costs increase to $215/oz. Assuming that the modification was in place, the previous table is re-calculated and presented below.

Table 4-19: Value of gold production with design modification

<table>
<thead>
<tr>
<th>Year</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>14.37</td>
<td>15.61</td>
<td>16.51</td>
<td>17.02</td>
<td>17.02</td>
<td>16.44</td>
<td>15.15</td>
<td>13.02</td>
<td>9.90</td>
<td>5.63</td>
<td>0.00</td>
</tr>
<tr>
<td>1</td>
<td>9.45</td>
<td>10.48</td>
<td>11.21</td>
<td>11.55</td>
<td>11.42</td>
<td>10.73</td>
<td>9.37</td>
<td>7.23</td>
<td>4.16</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>5.59</td>
<td>6.47</td>
<td>7.07</td>
<td>7.31</td>
<td>7.12</td>
<td>6.39</td>
<td>5.04</td>
<td>4.75</td>
<td>2.95</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>2.74</td>
<td>3.44</td>
<td>3.96</td>
<td>4.16</td>
<td>3.95</td>
<td>3.25</td>
<td>1.97</td>
<td>1.17</td>
<td>0.50</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>4</td>
<td>1.02</td>
<td>1.35</td>
<td>1.77</td>
<td>1.96</td>
<td>1.79</td>
<td>1.17</td>
<td>0.51</td>
<td>0.17</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>5</td>
<td>0.22</td>
<td>0.31</td>
<td>0.43</td>
<td>0.60</td>
<td>0.51</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>6</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>7</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>8</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>9</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>10</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

The value of the design modification is given by subtracting base case from the enhanced version, therefore: $14.37-$13.13=$1.24 million. This technology will (most likely) not be purchased since the $40,000 profit is marginal. See the appendices for the theory and equations behind the explanations above.

4.2.3.3 Azzone’s option-based model for Manufacturing systems

Azzone\textsuperscript{69}, developed a model that aims at evaluating the value of flexibility for manufacturing systems, based on the ability to mix or produce variable products. An example of this type of flexibility in mining is the blending that occasionally occurs in coal mines. Customers specify the various grades of coal according to their needs. If a coal mine has the ability to change its sequencing and dispatch to achieve this specific grade (product) from varying ore benches throughout the mine, it may be able to take advantage of price

\textsuperscript{69} Azzone, Ibid, p.134-135
fluctuation for certain products. In order to change from producing one product to another, a change or adaptation cost (AC) is incurred. This change cost may include removing waste rock to expose a specific grade of ore or building a haul road to access a specific grade of ore. If planned correctly, this product mix change will create a cash flow (CF). The product mix changes will be introduced (the option will be exercised) only if the cash flows are higher than the adaptation costs (CF > AC), creating a payoff CF - AC.

This flexibility can affect a system, according to this model, in two ways.

First, by reducing the AC, the company can afford to undertake more product mix changes that can potentially increase cash flow. For example, consider a technology such as an algorithm that is connected to the truck dispatch and geological database that can automatically allocate trucks so that the new blends are formed, optimizing profitability (a relatively simple problem that can be solved using linear programming). This increases the probability, p(CF) that these products will be the ideal product mix (Knowledge of the market place may be an unknown factor. In manufacturing this uncertainty is minimized by market research to determine which product is demanded by consumers).

Second, the net value of each acceptable product mix change increases the payoff (payoff is CF-AC, therefore if AC decreases, payoff increases). According to these assumptions, the value of flexibility can be calculated using the equation below:

\[ V = \int_{AC}^{\infty} (CF - AC) p(CF) dCF \]

Equation 4-6: Value of flexibility

The model may assume that the CF has a normal distribution, N(\( \mu \);\( \sigma \)) (the probability of a certain cash flow will vary according to a normal curve, according to mean \( \mu \) and a standard deviation of \( \sigma \)), as seen in the figure below. Using this assumption, the following equation can be derived by evaluation of the integral in Equation 4-6.
Figure 4-10: Normal Curve distribution p(CF) vs CF

\[ V = \frac{s}{\sqrt{2\pi}} e^{-\frac{(AC-a)^2}{2s^2}} \left[ 1 - F\left( \frac{AC-a}{s} \right) \right] \]

Equation 4-7: Value of flexibility assuming a normal distribution

\[ \text{a} = \text{mean} \]
\[ \text{s} = \text{variance} \]
\[ V = \text{value} \]

- And where \( F(X) \) is the cumulative probability at \( x \) of a normal distribution having a mean of \( a \) and a variance of \( s \). \( X = (AC-a)/s \)

A numerical example using the coal mine analogy, described above (with products that vary in grade), is demonstrated below. The increase in product flexibility could lead to a reduction in product change cost from $100 000 to $35 000. Preliminary discussions with metallurgical coal buyers show that the probability of annual demand of the new product mixes is 0.6 (the product may change 0.6 times per year). Based on records and expert market analysis by the marketing department, the company estimates that the cash flow from each new coal-mix opportunity can be described by a normal distribution \( N(175000; 70000) \). Using the equation above, and a spread-sheet, the value for the base case (operating as usual), was found to be:

\[ V = \frac{70000}{\sqrt{2\pi}} e^{-\frac{(175000-100000)^2}{2\times70000^2}} + (75000) \left[ 1 - F\left( \frac{75000}{70000} \right) \right] = 90264 \]
and the value of changing the product mix using the technology,

\[ V = \frac{70000}{\sqrt{2\pi}} e^{-\frac{(175000-21000)^2}{2\cdot70000^2}} + \left(\frac{154000}{70000}\right) \left[1 - F\left(\frac{154000}{70000}\right)\right] = \$155527 \]

Therefore, the difference between the base case and technological methods of changing the product mix is \$155 527 - \$90 264 = \$65 263. Considering an estimated probable annual demand of 0.6, the value of the technology's flexibility is \$39 158, or roughly \$40 000 per year. This value should be added to the cash flow analysis (the level 1 justification evaluation).

The assumptions made for the example above can be changed, as new or more precise information becomes available. For example, if the cash flow from new product mixes is not truly a normal distribution, its cumulative probability function, 'F(X)' would be changed.

### 4.3 Level 3 Justification Schemes - Risk & Analytic Methods

Analytic techniques are primarily quantitative and are more complex than economic approaches. The essential characteristic that makes analytic methods better suited for evaluating complex technologies is that they tend to capture more information. These methods can all, to a varying degree, quantify qualitative benefits and costs. Level 3 justification schemes also consider uncertainty and multiple causes and effects. A further advantage is that these methods are more realistic by taking more factors and subjective judgements into account\textsuperscript{71}.

The disadvantages of these methods are considerable, mainly due to the traditionalism embraced by managers in the mining industry. For instance, since the analysis is less easily comprehended and more time consuming, fewer managers use this method when justifying or considering approval of a project. A further disadvantage of this method is the large amount of data required when compared to economic methods.

At this level of justification, the approaches are called decision support. Most of these methods supply added information to the evaluation giving managers a more knowledgeable view to make better judgements on what avenue to pursue.

The methods that are to be described in this section are:

**Value analysis:** a method that can provide experience with the technology and empirical results that can be used in a financial analysis, thereby reducing risk.

\textsuperscript{70} Azzone, Ibid, p.136

\textsuperscript{71} Meredith and Suresh, Ibid, p. 1046
**Decision Analysis**: this method is similar to risk analysis, where probabilities are used to calculate the risk involved, the potential income and the possible outcomes. This method uses figures such as the certainty equivalent value (CEV) and utility functions that can be inserted into the financial appraisal in order to take into account a more realistic view of risk.

**Risk Analysis**: where a series of scenarios are simulated to determine which of several possible investment projects should be chosen.

Decision and risk analysis can be very involved, and so only simplified examples will be used here to illustrate these methods.

### 4.3.1 Value Analysis

This justification approach was used by Keen (1981) in the assessment of an advanced technology. The method involves two main stages.

The first stage, called the pilot stage, the investment is considered as a research & development project rather than an investment. The decision to proceed with the pilot stage is justified mainly on estimated quantified benefits. The pilot involves a scaled-down version of the proposed system that will allow some of the main benefits to be determined. The pilot phase costs are kept relatively low.

Once the pilot stage is finished, the expected and unexpected benefits are evaluated to confirm the project's value to the firm. This exercise also allows evaluators to determine the quantifiable benefits of the qualitative aspects of the project. If the costs and benefits are acceptable, and the riskiness (determined from experience with the limited system) is acceptable, then the full scale project would be accepted. This method also allows the reduction of risk since potential problems can be monitored or corrected once they are identified in the pilot stage. This second phase is known as the build stage.

This method, originally suggested for the manufacturing and information systems industry, can also be easily applied to mining. The difficulty lies in the ability of the supplier of the industry to sell a limited 'sample' of the technology for evaluation. A mining example of this evaluation method can be outfitting a single drill with a GPS drill monitoring platform at a mine where there are several drills in the fleet or modifying a single production train. The worth of the predicted benefits and the unpredicted effects of the qualitative benefits will become apparent. The synergistic benefits of the system could only be calculated once the entire drill fleet is outfitted with similar systems.

### 4.3.2 Decision Analysis

Decision analysis is used in many fields including: energy, manufacturing and service industries, medicine, sports, public policy, marketing and space exploration. Decision
analysis is defined as "...the study of how people make decisions, particularly when faced with imperfect or uncertain information, as well as a collection of techniques to support the analysis of decision problems."^{72}

Many of the models used in level 2 justification schemes identify best solutions or the optimal mix of products (in this case technology). These methods support the decision making however, little uncertainty can be introduced. In reality, people make decisions, where risk plays an important role in an individual's final decision. Another distinction between programming models and decision analysis is that a continuous range of solutions is possible for optimization models. Decision analysis studies a limited number of options available to the decision maker. The options and outcomes can be, to a certain extent, qualitative, where numerical values are placed on non-numeric benefits and costs.

Decision analysis requires a substantial amount of background information and an understanding of the system under study. Collecting the information provides another advantage: a blueprint for implementation. For complex, expensive projects, a team representing all the affected departments is usually assembled to ease the implementation. Decision Analysis (DA) requires the inter-departmental team to work as a group to solve and analyze the various decisions and options available to the situation. DA also requires information that can only be provided by that team. The analysis is also conducted with the team's input. Therefore member of the various business units are able to understand the vision and difficulties of the project, allowing a smoother integration into the overall process^{73}.

![Decision Analysis Process Diagram]

Figure 4-11: Decision Analysis Process

^{72} Camm, Jeffery D. and James R. Evans. Ibid, p.631

^{73} Winston, Ibid., p.392

Masters of Applied Science Thesis. Sean Dessureault
This section will investigate decision analysis as a CIA method. The diagram above represents the decision analysis process. This diagram is based on a suggested\textsuperscript{74} method of how to undertake a decision analysis. All these steps will not be explained or shown in an example, however, the tools necessary to complete the decision model, quantify judgements and calculate the expected value (EV) will be shown. Expected value (EV), is also commonly represented as expected monetary value (EMV). Decision trees and other forms of analyzing and interpreting decision analysis will be shown. Examples will be provided to explain some concepts.

4.3.2.1 Payoff Table
Payoff tables to conveniently represent monetary outcomes for a given situation. A payoff is the value of making a decision \(D\), having a state of nature \(S\). There are usually several different states of nature (possible outcomes). A payoff table is represented by the matrix below, where payoffs are represented by the expression \(V(D_i, S_j)\).

<table>
<thead>
<tr>
<th>States of Nature</th>
<th>(S_1)</th>
<th>(S_2)</th>
<th>(S_3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decisions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(D_1)</td>
<td>(V(D_1, S_1))</td>
<td>(V(D_1, S_2))</td>
<td>(V(D_1, S_3))</td>
</tr>
<tr>
<td>(D_2)</td>
<td>(V(D_2, S_1))</td>
<td>(V(D_2, S_2))</td>
<td>(V(D_2, S_3))</td>
</tr>
</tbody>
</table>

A numerical example of a payoff table: A gold mining company, PT, has 3 million dollars to invest. PT has three choices: put it into liquid reserves (treasury bonds, similar to a bank CD), reinvest it into the existing mines or spend it on exploration. These represent the decisions \(D_1\), \(D_2\) and \(D_3\). Each option has different levels of risk and profit. The value of each option is based on the price of gold. If the price gold can reduce, stay constant or increase (Low, no change and high), these are the states of nature \(S_1\), \(S_2\) and \(S_3\). The outcome were evaluated and shown in the payoff table below.

<table>
<thead>
<tr>
<th>Options</th>
<th>Low</th>
<th>no change</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reserves</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Reinvest</td>
<td>-1</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Exploration</td>
<td>-3</td>
<td>4</td>
<td>10</td>
</tr>
</tbody>
</table>

\textsuperscript{74} Schuyler, John R., \textit{Decision Analysis in Projects.}, Project Management Institute, 1996
4.3.2.2 Expected Value

In the payoff example above, risk was an inherent part of the problem, however, the payoff tables were not able to reflect the different probabilistic information. The uncertainties relating to the different states of nature can be taken into account by using the expected value approach. The expected values of each option can be calculated according to the equation below:

\[ S(D_i) = \sum_{j=1}^{n} P(S_j)V(D_i,S_j) \]

Equation 4-8: Expected Value

In the above equation, \( P(S_j) \) is the probability that the state of nature \( S_j \) will occur. The value \( V(D_i,S_j) \) is the payoff that occurs when decision \( D_i \) is made and state of nature \( S_j \) occurred. The example above is continued, using the probabilities 0.3, 0.55 and 0.15 for the probability that the price of gold decreases, stays the same, and increases, respectively. The problem can be solved as seen in the table below.

Table 4-22: Expected Value Example Results

<table>
<thead>
<tr>
<th>Outcomes ($000,000's)</th>
<th>Low</th>
<th>no change</th>
<th>High</th>
<th>EV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probabilities</td>
<td>0.3</td>
<td>0.55</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>Reserves</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Reinvest</td>
<td>-1</td>
<td>5</td>
<td>6</td>
<td>3.35</td>
</tr>
<tr>
<td>Exploration</td>
<td>-3</td>
<td>4</td>
<td>10</td>
<td>2.8</td>
</tr>
</tbody>
</table>

A sample calculation for the ‘reinvest’ expected value is:

\[(.3)(-3) + (.55)(4) + (.15)(10) = -0.9 + 2.2 + 1.5 = 2.8\]

Therefore the recommended decision would be the highest EV (for that decision). In the example above this would be the ‘reinvest’ option. The information can be better represented in a graphical structure called a decision tree.

4.3.2.3 Decision Trees

A decision tree is a graphical representation of a decision situation\(^75\). The formal terminology of decision trees abide by the following conventions:

- Decision nodes are represented by squares
- Decision branches stem from decision nodes

\(^75\) Camm, Ibid, p.636
• State of nature nodes are represented by circles
• State of nature branches stem from state of nature nodes

The figure below represents a decision tree. There is no formal limit to the number of decisions or the structure of the decisions. For the purpose of clarity, a single layered decision tree is presented below. The value $V(D_i, S_j)$ is the payoff of the $D_i$ option for $S_j$ state of nature. $V(D_i)$ is the expected value of that decision. The optimal solution would be to select the decision with the highest expected value.

\[
V(D_i) = \sum_{j=1}^{n} V(D_i, S_j) \times S_j
\]

Equation 4-9: expected value of decision

To continue the example above, the values are entered into the tree. The resulting decision tree appears as shown below. In this example, the reinvestment decision is the should be chosen since it has the highest value (3.35).
4.3.2.4 Expected Value of Perfect Information (EVPI)

Perfect information is impossible, however, it is convenient to know how much money can be spent to improve the value of the decision, if such information existed. The term 'perfect information' relates to information that would reveal exactly what state of nature will occur. EVPI is defined as the difference between the expected payoff under perfect information and the expected payoff of the optimal decision without perfect information. If the example above is continued, the EVPI can be calculated as follows: using the below table,

Table 4-23: Data Required for EVPI calculation

<table>
<thead>
<tr>
<th>State of Nature</th>
<th>Decision</th>
<th>Payoff</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Reserves</td>
<td>3</td>
<td>0.3</td>
</tr>
<tr>
<td>no change</td>
<td>Reinvest</td>
<td>6</td>
<td>0.55</td>
</tr>
<tr>
<td>High</td>
<td>Exploration</td>
<td>10</td>
<td>0.15</td>
</tr>
</tbody>
</table>

The expected payoff under perfect information is found to be

\[(3)(0.3) + (6)(0.55) + (10)(0.15) = 5.7\]

and the expected value of perfect information is

\[5.7 - 3.35 = 2.35\]
4.3.2.5 Multistage Decisions

The example above is a situation where there is only a single decision to make. Most situations are more complex, in which several subsequent decisions can be made in a certain situation once the effects of the previous decisions are known.

Example:

An underground nickel mining company, UNMC, is considering investing in a fleet of Tele-guided LHDs. The technology is new so several non-quantifiable aspects may hinder the overall performance and make the investment unprofitable. Problems such as labor relations and maintenance may pose difficulties in calculating cost savings. There are qualitative benefits such as safety and flexibility, but they are not considered to be of prime importance. The mine management is familiar with advanced justification techniques, therefore a value analysis program is contemplated.

There are three initial decisions available: continue operating using the conventional LHD fleet, upgrade immediately to a fully Tele-operated fleet or test a single Tele-operated LHD in the mine to evaluate the attitudes of the workforce and maintenance requirements. Once the evaluation is completed (value analysis has been completed), the remaining options may be to abandon the Tele-operation and continue operating using the conventional LHD fleet, or to upgrade to a Tele-operated LHD fleet. A negative outcome of the value analysis does not automatically exclude the option of upgrading the fleet. The value analysis may have had some extraneous circumstances that would not affect the success of the Tele-fleet. The costs of the upgrades are presented in the table below.

<table>
<thead>
<tr>
<th></th>
<th>Values in '000,000's</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Costs</td>
</tr>
<tr>
<td>Tele-fleet</td>
<td>($4.5)</td>
</tr>
<tr>
<td>1 Tele-LHD</td>
<td>($1.5)</td>
</tr>
</tbody>
</table>

The decisions faced by management can be set up according to the decision tree seen below. Note that the different outcomes, 'success' and 'failure' represent the situation where the Tele-fleet performs up to expectations (in so far as cost savings) or fails to perform, in which case the cost of the modifications to the LHDs and the lost production is considered to be a loss. These final conclusions are not limited to only one or two outcomes. A 'moderate success' or 'moderate failure' or 'no change' outcome can be included if desired. If the value analysis is abandoned, the cost of a single alteration (installing equipment required to Tele-operate a conventional LHD) and training of a few operators is considered to be a loss.
It can be seen in the diagram above that the probabilities of success/failure for immediate implementation may be different from those that follow the value analysis due to information that will be received once the value analysis has been completed. These probabilities can be estimated accurately and realistically by using Baye’s Theorem.

4.3.2.6 Baye’s Theorem

Baye’s Theorem was developed by an 18th century British clergyman, Rev. Thomas Bayes77. The applicable aspect of the theorem is explained below, using the example that has been continued from the previous sub-section.

The situation in the example has three types of probabilities:

1. Probability of success/failure if immediate implementation is decided
2. Probability of positive/negative evaluation of the technology in the value analysis
3. Probability of success/failure of Tele-operation implementation once value analysis outcome is known.

From the diagram above, it can be seen that the value analysis branch attempts to evaluate whether or not the fleet should be committed to Tele-operation. In the decision where the fleet is committed immediately, the probabilities of success or failure will be different than in the decision that is made once information has been obtained from the value analysis. This additional information provides an indicator of which state of nature may occur. According to convention, the initial probabilities assigned to a state of nature are called 'prior probabilities'. Once information regarding the most likely state of nature has been obtained, the readjusted probabilities are labeled 'posterior probabilities'. In terms of statistical terminology, the following can be stated as a conditional probability:

77 Schuyler, Ibid, p.39
• $P(S_j|I_k)$ is the probability of the state of nature $S_j$ occurring given the indicator $I_k$.

Indicator information is not completely reliable. Some tests may not reveal the true state of nature. The indicator reliabilities are defined in statistical terms as follows:

• $P(I_k | S_j)$ is the probability that $S_j$ is the true state of nature given the indicator $I_k$.

Continuing the example we consider the following probabilities. After a preliminary analysis, there is a probability of .65 that the immediate implementation of the Tele-fleet will be a success. Therefore there is a probability of .35 ($1-.65$) that the Tele-fleet will fail upon immediate implementation. The probability of $P(I_k | S_j)$ (indicator reliability) can be determined through historical results.

Considering the example being used throughout this section, suppose UNMC has come across 34 different technologies into the mine over its previous 20 years of life. Of the 34 technologies, 30 were pre-evaluated using value analysis. The number of positive evaluations after the value analysis was 23. Of the 23 technologies that were deemed valuable, 21 were implemented. Of the 21 implemented, 19 were successes and two failures. Of the 7 technologies that were deemed unfit for further implementation, 3 were implemented due to various reasons. Of the 3 implemented, one was a success. This data is summarized in the table below.

Table 4-25: Historical Data

<table>
<thead>
<tr>
<th>Historical Data:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td># of Technologies implemented or tested</td>
<td>34</td>
</tr>
<tr>
<td># of implemented technologies</td>
<td>29</td>
</tr>
<tr>
<td># of Technologies succeeded</td>
<td>20</td>
</tr>
<tr>
<td># of Technologies failed</td>
<td>9</td>
</tr>
<tr>
<td># of Technologies evaluated using V.A.</td>
<td>30</td>
</tr>
<tr>
<td>Total # of successes</td>
<td>20</td>
</tr>
<tr>
<td>Total # of Failures</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Value Analysis Historical Data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted to be successful</td>
<td>23</td>
</tr>
<tr>
<td>Amount implemented</td>
<td>22</td>
</tr>
<tr>
<td>Successes</td>
<td>19</td>
</tr>
<tr>
<td>Failures</td>
<td>3</td>
</tr>
<tr>
<td>Predicted to be failures</td>
<td>7</td>
</tr>
<tr>
<td>Amount implemented</td>
<td>3</td>
</tr>
<tr>
<td>Successes</td>
<td>1</td>
</tr>
<tr>
<td>Failures</td>
<td>2</td>
</tr>
</tbody>
</table>

The prior probabilities can be calculated using this historical information. The table below shows the prior probabilities with sample calculations immediately below the table.
Table 4-26: Prior Probabilities

<table>
<thead>
<tr>
<th>Prob. of immediate implementation</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Success</td>
<td>0.69</td>
<td>Failure</td>
</tr>
</tbody>
</table>

If indicator ...  

gives positive evaluation  

<table>
<thead>
<tr>
<th>Success</th>
<th>0.86</th>
<th>Failure</th>
<th>0.14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implement</td>
<td>0.96</td>
<td>Abandon</td>
<td>0.04</td>
</tr>
</tbody>
</table>

gives negative evaluation  

<table>
<thead>
<tr>
<th>Success</th>
<th>0.33</th>
<th>Failure</th>
<th>0.67</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implement</td>
<td>0.43</td>
<td>Abandon</td>
<td>0.57</td>
</tr>
</tbody>
</table>

Sample calculation for immediate implementation probability: Since 9 of all 29 implemented technologies were considered failures probability that another technology is considered a failure is 9/29 = .31. Therefore probability of success is 1 - .31 = .69.

Sample calculation, indicator gives positive evaluation. Since 19 projects were considered successes after implementation and a value analysis evaluation of positive, the success probability given these conditions is calculated by 19/22 = .86.

It is clear from the historical data above, that value analyses conducted by UNMC is better at predicting successes than failures. Prior probabilities can be used to calculate the posterior probabilities using the Bayesian theorem as follows:

$$
Pr(B | A) = \frac{Pr(A | B) Pr(B)}{Pr(A | B) Pr(B) + Pr(A | B') Pr(B')}
$$

Equation 4-10: Equation showing Bayesian principle

In the equation above, $Pr(B | A)$ is read as the probability that $B$ will occur given $A$. For the purpose of this example, the value $B$ represents the state of nature that the project succeeds following implementation, while the variable $B'$ represents the state of nature where the project fails. The variable $A$ represents the state of nature that the value analysis renders a positive evaluation of the technology. The solution below calculates the probability that the project will succeed given a positive evaluation of the value analysis. The left side of the equation can be read: “the probability that the project will succeed given a positive evaluation.”

$$
Pr(B | A) = \frac{Pr(A | B) Pr(B)}{Pr(A | B) Pr(B) + Pr(A | B') Pr(B')} = \frac{(.86)(.69)}{(.86)(.69) + (.33)(.31)} = .59 \div .70 = .85
$$

The denominator of the above equation is equivalent to the probability of a positive evaluation of the value analysis. Therefore the probabilities of a successful evaluation is .70
while the probability of a negative evaluation is .3. The probability that the project will succeed given a negative evaluation is calculated:

$$
\Pr(B|A') = \frac{\Pr(A'|B) \Pr(B)}{\Pr(A'|B) \Pr(B) + \Pr(A'|B') \Pr(B')} = \frac{(.14)(.69)}{(.14)(.69) + (.77)(.31)} = \frac{.10}{.34} = .29
$$

The posterior probabilities are summarized in the table below. The discrepancies between the table and the sample calculations above are due to significant figures.

<table>
<thead>
<tr>
<th>Probability</th>
<th>Reads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pr(B</td>
<td>A)</td>
</tr>
<tr>
<td>Pr(B'</td>
<td>A)</td>
</tr>
<tr>
<td>Pr(B</td>
<td>A')</td>
</tr>
<tr>
<td>Pr(B'</td>
<td>A')</td>
</tr>
<tr>
<td>Pr(A)</td>
<td>0.70</td>
</tr>
<tr>
<td>Pr(A')</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Since all the probabilities have been calculated, the final decision tree can be formulated:

![Decision Tree for UNMC example](image)

**Figure 4-15: Decision Tree for UNMC example**

From the above diagram, it can be seen that UNMC should directly implement the Tele-fleet. However, the difference between the two decisions is not very important. The above analysis is only as accurate as the initial assumptions. As part of the decision analysis methodology, a sensitivity analysis should be conducted.
4.3.2.7 Sensitivity Analysis

Sensitivity analysis is useful in determining which variables in an evaluation are most influential. Project risk management depends on prioritizing uncertainties and options available. Once a decision tree is set-up on a spreadsheet, it is relatively easy to perform a sensitivity analysis. Sensitivity analysis is a method of determining the effect of varying certain variables. In this example, one of the most uncertain variables is the benefit predicted if the Tele-fleet implementation is successful. Instead of 15 million dollars, a total of 8 million will be used as the possible benefit of operating the mine with a Tele-fleet. Furthermore, the cost of abandonment will be raised to a cost of 2 million. The decision tree reflecting these new figures is presented below:

![Decision Tree](https://via.placeholder.com/150)

**Figure 4-16: Sensitivity Analysis Decision Tree**

From the decision tree presented above, the proper decision is the same decision as before: to invest directly in a Tele-Fleet. However, it is still very clear which decision to make. The EMV of the two automation decisions are very close and almost the same as the ‘do not invest decision’. Further study of the values will be required to ‘solidify’ the values of the probabilities, benefits and costs.

The decision, at marginal profit levels, as seen above, is subjective to the risk preference of the manager or corporation making the decision. Their risk characteristics being either risk takers or risk evaders will reflect on the final decision. A subjective way of measuring the risk preference of a corporation or individual can be calculated using utility theory.

4.3.2.8 Utility Theory

Utility theory was designed to quantify the inconsistencies in human nature where different decision-makers have varying views towards risk. There are many occasions in which people

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78 Camm, Jeffery D., Ibid, p. 20
make decisions that do not conform to basic expected values. This phenomenon can best be illustrated using a non-mining example. Consider individuals who purchase lottery tickets. The expected value is negative, however, the chance of winning a million dollars, even if it is highly unlikely, is more attractive than losing a dollar. Another example is in the case of insurance. Much more money is paid into insurance premiums than the calculated EV; however, it is much more unattractive to lose a thousand dollars than it is to possibly lose ten thousand. Therefore it can be seen that the worth of decisions include something other than the monetary value of the payoffs. This total worth of a particular payoff is called utility. When a rational person or organization chooses to select a decision that does not maximize the expected monetary value, he/she/they may be maximizing the expected utility. Using utility theory to reflect an individual or organization's attitude towards risk will help the individual to select the decision that maximizes the utility.

Assigning an individual or organization's utility is not easy. It involves asking the individual or individuals comprising the group a set of question that establishes their risk preference, being either risk averse, risk neutral, or risk seeker. An example of how to assess and apply utility is provided in an example below.

The example being used in the previous subsections is continued here. The manager of UNMC currently faces a decision to either invest in a Tele-fleet or continue to operate in the present manner. A decision analyst attempts to determine the manager's risk preference by asking a series of questions.

The first question is what the manager perceives as being the worst and best payoff possible. The manager responds by saying that a $-4.5$ and $10.5$ million dollars is the worst and best payoff possible. The decision analyst can now assign $-4.5$ million as having a utility value of $0$ and $10.5$ million a utility value of $1$.

The next questions would present the following situation: The manager has a choice between the following options:

1. payoff of $X$ or
2. the possibility of winning $10.5$ million with probability $p$ or losing $4.5$ million with a probability of $1-p$

Suppose the decision analyst chooses $9$ million dollars as $X$. A decision tree can be set up to better represent the options, as seen below. The manager must choose a value of $p$ such that he is indifferent as to which option to select. Suppose he decides on a probability of $0.8$.

---

Therefore he is indifferent between being paid 9 million dollars or gambling on the chance to win 10.5 at a probability of .8 or lose 4.5 million at a probability of .2.

The decision analyst then proceeds to ask the same questions, except substituting different values for X, such as 8.5 to -3.5 million dollars. The probabilities given by the hypothetical manager of UNMC are summarized in the table below. This data can be viewed in a chart called a utility curve, which can be seen below the table.

Table 4-28: Decision Analysis Example - Manager's responses

<table>
<thead>
<tr>
<th>Option 1 Payoff</th>
<th>Option 2 p</th>
<th>EMV</th>
</tr>
</thead>
<tbody>
<tr>
<td>-4.5</td>
<td>0</td>
<td>-4.5</td>
</tr>
<tr>
<td>-3.5</td>
<td>0.2</td>
<td>-1.5</td>
</tr>
<tr>
<td>-2.5</td>
<td>0.38</td>
<td>1.2</td>
</tr>
<tr>
<td>-0.5</td>
<td>0.58</td>
<td>4.2</td>
</tr>
<tr>
<td>1.5</td>
<td>0.7</td>
<td>6</td>
</tr>
<tr>
<td>4.5</td>
<td>0.8</td>
<td>7.5</td>
</tr>
<tr>
<td>6.5</td>
<td>0.85</td>
<td>8.25</td>
</tr>
<tr>
<td>8.5</td>
<td>0.92</td>
<td>9.3</td>
</tr>
<tr>
<td>10.5</td>
<td>1</td>
<td>10.5</td>
</tr>
</tbody>
</table>

Figure 4-17: Utility Curve for UNMC manager

The manager is considered a ‘risk averse’ decision maker. For example, he would rather pay 3.5 million dollars outright than risk the chance on a gamble with an expected monetary value of -1.5 million dollars. The risk curves for different preferences can be seen in the figure below.
Using the utility curves, a decision tree can be altered so that decisions are based on maximized utility. The example from the previous subsection can illustrate this procedure. The values of the payoffs in the decision tree are replaced by their utility equivalent, determined by using the manager’s utility curve. The utility values replace the payoffs in the decision tree. Once the decision tree is folded back, the decision tree with the highest utility is the ideal decision when considering the manager’s risk preferences. According to the figure below, the decision which most suits the manager’s risk profile is to avoid investing in technology altogether since the payoff of 0 has a utility of .6. This reduces the risk of the eventual outcome thereby maximizing the utility. If the company decides to invest in technology, the manager would first evaluate the Tele-operation technology by evaluating its performance through a value analysis procedure since it has the second highest utility value.

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Figure 4-18: Utility Curves for Various Risk Preferences

80 Hanna, Ibid., p.563
Figure 4-19: Decision Tree using Utility values

A measure called the Certainty Equivalent is sometimes worthy of consideration. The Certainty Equivalent of a situation is the value at which a company or individual would be indifferent between engaging in the project or paying (or being paid) a certain payoff. In the example used above, suppose the manager would rather pay 1.5 million dollars to avoid investing in Tele-operation technology. Hence, the certainty equivalent for this situation and this manager is −1.5 million dollars. If the manager were a risk seeker, perhaps the certainty equivalent would be closer to the highest EMV of 5.84 million dollars (for the pre-sensitivity analysis decision tree).

Determining the utility curves for certain groups or companies is difficult since the various individuals in the group or the people in charge of the company have different views on risk. Furthermore, the process requires the decision analyst to pose hypothetical alternatives involving uncertain outcomes which can be confusing for those being assessed. Some utility functions have been derived based on empirical evidence collected by Ronald Howard\(^\text{81}\). The equation has the following form:

\[
U(x) = 1 - e^{-x/R}
\]

Equation 4-11: Utility Function

The \(R\) parameter is risk tolerance, which measures the risk that the decision-maker is willing to tolerate. The \(x\) value is a monetary value that is positive if it is a payoff and negative if it is a cost. According to Howard's (same source) consulting experience, large companies have an \(R\) according to the following breakdown:

---

81 Winston, Ibid. p.445
Table 4-29: Percentages in the Calculation of R

<table>
<thead>
<tr>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.4% net sales</td>
</tr>
<tr>
<td>124% net income</td>
</tr>
<tr>
<td>15.7% equity</td>
</tr>
</tbody>
</table>

Therefore a company with a net equity of 200 million has a risk tolerance of 31.2 million dollars. These guidelines were derived from many years of experience in the manufacturing industry, but they do not apply well mining because of the industry's inconsistent attitudes towards risk. The risk preference of mining companies is discussed in the following subsection.

4.3.2.9 Mining Companies' attitudes toward Risk

A mining venture can be considered high risk. There is a great deal of financing required for exploration. Exploring for minerals is an uncertain field though necessary for to the survival of the mine or mining company: the mineral industry continually requires new deposits. A company can augment its reserves by acquiring claims; however, this too can be a risky venture (Bre-X was almost acquired by Freeport, then the company discovered that there were no reserves). Reducing costs is also an essential part of the mining business. But, new technology that promises to reduce costs is considered a very risky proposition, given mining's general reluctance to adopt new technology.

4.3.2.10 Discussion of Decision Analysis & Other methods

Formulating decision trees can be a lengthy process. Software does exist that aids in the creation of the graphical interface and calculation procedures required in decision trees; e.g.: Treeplan (for Excel 5.0); however, several decisions are required and each have multiple options and payoffs, the ends of the decision trees can become very 'bushy'. For example, consider a decision with 3 options which each lead to another decision and finally lead to four payoffs each. The final decision tree contains 24 payoffs. This decision tree would be difficult to see graphically due to its size. Furthermore, collecting and assessing the various probabilities, historical data and management characteristics is time consuming. Establishing accurate probabilities can be further complicated if the option under study is unprecedented. Some simple methods of decision making under uncertainty have been established such as the Laplace approach, Maximax (also known as the Optimistic Approach), Maximin (also known as the Pessimistic Approach) and the Minimax Regret. These methods can be used when probabilities are uncertain.
4.3.2.10.1 Laplace approach

The Laplace approach consists of taking Laplace’s principle of insufficient reason which states that if no reason exists for one state of nature to be more likely than another, then they should be treated as equally as likely\(^82\). Recall the first example discussed in the Decision Analysis section: the PT mine has 3 million to invest in bonds, operations or exploration. The solution can be determined using the equation shown below:

Select the \(\text{MAX}(D_i)\) given that

\[
D_i = \frac{\sum_{j=1}^{n} P_{ij}}{n}
\]

**Equation 4-12: Laplace Decision**

\(D = \) decision that must be taken, (in this case, bonds, operations or exploration) therefore since there are three decisions possible, \(i=1,2\ldots m\) (in this example, \(m=3\))

\(P = \) possible payoff. The various payoffs are in an array where three possible outcomes are possible, \(j=1,2\ldots n\) (in this example, \(n=3\)).

A numerical example is given below. According to the Laplace method, the three options would have the following values:

- Liquid Reserves: \(\frac{3+3+3}{3} = 3\)
- Operations: \(\frac{-1+5+6}{3} = 3.33\)
- Exploration: \(\frac{-3+4+10}{3} = 3.67\)

Therefore the exploration option would be chosen.

4.3.2.10.2 Maximax

An individual or company with a ‘risk seeker’ utility curve may choose this option because it chooses the options with the highest gains. In this example, again the exploration option would be chosen, followed by the operation option. The equation below would be used for this method.

Solution: choose \(D_i\) where \(i\) is \(\text{MAX}[P_{ij}]\)

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\(^82\) Hanna, Ibid. p.638
Equation 4-13: Maximax

4.3.2.10.3 Maximin

An individual that is risk averse may choose this method which consists of choosing the option with the most attractive worst case scenario. In this example, the PT mine would first consider investing in a low-yield (& low risk) bond followed by reinvesting the money in its operations.

Solution = choose MAX\[P_{ij}\] where \(j\) has MIN(AVERAGE\(P_{ij}\)), or worst case scenario

Equation 4-14: Maximin

4.3.2.10.4 Minimax Regret.

This approach attempts to quantify the decision maker's regret or opportunity loss, then suggests the option with the lowest regret. The following equation is used to determine the regret value.

\[ R_i = \sum_{j=1}^{m} MAX(P_j) - P_j \]

Equation 4-15: Minimax Regret

For example, consider the case of PT mine choosing to reinvest the money in its operations. If the price of gold lowers, the best decision would have been to invest in the bonds, a gain of 4 million dollars (the difference between 3 and -1 million). If the price of gold increased the exploration option should have been chosen, with a further lost opportunity of 4 million (the 'higher' price of gold result of exploration is 10 million while the 'higher' gold price result of reinvesting in the operation is 6, therefore the value is 10-6). Therefore the total regret for the 'reinvestment in the operation' opportunity is 8 million dollars (4+4). The initial values and Maximum opportunity loss is presented in the table below. The exploration opportunity has the lowest regret, followed by the reinvestment decision.

Table 4-30: Minimax Regret Solution

<table>
<thead>
<tr>
<th>Options</th>
<th>Outcomes ($000,000's)</th>
<th>Regret</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>no change</td>
</tr>
<tr>
<td>Reserves</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Reinvest</td>
<td>-1</td>
<td>5</td>
</tr>
<tr>
<td>Exploration</td>
<td>-3</td>
<td>4</td>
</tr>
</tbody>
</table>

83 Camm, Ibid. pp. 638
4.3.2.11 Conclusion to Decision Analysis

The methods above do not remedy decision analysis' weaknesses namely, the requirement for accurate probabilities and the inability to properly present decision trees with many options and payoffs. The decision tree is also subject to discrete outcomes, and is unable to easily represent time-based options. Schuyler (1996) considers Monte Carlo simulation as an alternative that can eliminate many of the problems facing the decision tree analysis approach to decision making. Some authors consider simulation as a topic within decision analysis while others consider it under the banner of risk analysis. Due to the importance of this subject, a separate section will be considered here.

4.3.3 Risk Analysis

Risk analysis was popularized by Hertz (1981), who used the method in capital investment. The method relies on simulation of probabilistic factors to both statistically and graphically determine the outcome of a situation. The initial probabilities for the variables can be obtained through historical records or by the subjective opinions of managers. Risk analysis is also known as simulation.

This section provides the reasoning for using simulation as a justification tool, then gives a brief history of simulation. A practical example is described and executed in the following two chapters, based on an actual level 3 technology application (the CAES enabled blending project).

4.3.3.1 Simulation as a Justification Tool

Simulation can be used as a justification scheme by revealing the true nature of the uncertainties through sensitivity analysis84 or by identifying potential problems (if the model is detailed enough). Important variables, that are not always evident, can be identified through sensitivity analysis. Inspecting scenarios that do not perform according to expectations can identify potential problems in the plan; however, the model must be detailed enough to be realistic.

A further advantage of using simulation in justification is its applicability to the risk factor. The risk factor, which is of prime importance in the economic justification schemes, can be reduced by simulation since it provides a more precise (if modeled correctly) estimate of the figures used in determining the economic benefits and costs. For example, a higher risk would be applied if guesses, based on instinct or experience, were used in the economic evaluation, instead of a model that can accurately predict the outcomes of the project based on historical data and statistical analysis.

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84 Kulatilaka, Nalin., Ibid., pp. 959

4.3.3.2 History of Simulation

The most common form of simulation is Monte Carlo simulation. John Von Neumann has been credited for naming and popularizing Monte Carlo techniques while participating in the development of the atomic bomb\textsuperscript{85}. He recognized that random sampling of unknown variables could be used to solve mathematical problems that are otherwise impossible to solve. The simulation process involves two main elements: a model that can project the outcome value and a method of repeatedly generating scenarios through randomly sampled probabilities\textsuperscript{86}. Simulations can be either discrete or continuous. Several simulation software packages are available such as Extend or AweSim. Simulation can even be performed on spreadsheets.

\textsuperscript{85} Schuyler, Ibid., p.43
\textsuperscript{86} Hurrion, R.D., \textit{Simulation.}, IFS (Publications) Ltd., UK., 1986
5 Background to Practical Examples

The thesis has so far reviewed the management science theory considered to be applicable to the justification of new technology to the mining industry. The CIA methods were applied to the various technologies used or being contemplated for use at the Highland Valley Copper Mine. This chapter focuses on the background information required to understand the mine environment, how the technology is applied, and the financial and managerial realities at HVC. The results of the application of these justification techniques are presented in the next chapter.

This chapter begins by providing the chronology of the data collection and interpretation phase of the study. A general description of the mine familiarizes the reader with the key factors influencing the mine. The focus of this introduction is to present the background information required to explain the technologies under study and understand their impact on the mine.

There are two technologies that will be used to present the three levels of CIA methods. The first, the AQUILA drill monitoring technology, is used as an example of the application of the level 1 and 2 justification techniques that apply in that particular situation. Therefore a detailed review of the drilling and blasting procedures at HVC will be presented. Since this technology has largely been implemented, the discussion in the next chapter provides a comparison between pre and post implementation engineering and operational procedures of drilling and blasting. This chapter describes the pre-implementation situation and concludes by providing the reasoning behind the level 2 classification.

The second new technology, Caterpillar's CAES, will be analyzed so that the appropriate justification methods are applied. The technology is a key part of a larger project to design the mine output to conform to the ideal mill feed. A complete description of the current mine-mill planning and design interface is provided along with a description of the current flows of information and ore within the mine.

5.1 Chronology of Research

Direct observations and raw data were collected over a period of seven months in three field study periods.

An initial investigation period, in March 1998, presented the project to the mine management to gain formal approval, collect primary data and to organize subsequent field work during the summer. The summer data collection period was throughout the month of July. Senior HVC engineering staff requested that the UBC study include a post-audit on the Application of Financial Expenditure (AFE) relating to the AQUILA drill technology. This data was
needed for the management science CIA methods. Some of the justification techniques were discussed and a formal example of the techniques presented in the AFE audit.

The engineering and mill planning staff at HVC were also evaluating a second, more integrated technology. Caterpillar's Computer Aided Earth-moving System (CAES) was a technology that was seen as beneficial to both mill and mine since it could be used in the mine to improve feed characteristics to the mill, as explained later in this chapter. The AFE for this technology had been already written, evaluated, and declined by the upper management of the mine. (A copy of the original AFE is included in an appendix.) The AFE for the CAES used level 1 justification schemes to justify a level 3 technology. Level 1 justification schemes were used to justify the technology since these were the only techniques known to both the author of the AFE (the senior mine engineer) and mine management at the time. The UBC study proposed to re-evaluate the technology using the appropriate justification schemes and present the results to mine management. This prompted a third visit in September to collect the data required to apply the level 3 justification schemes. This data was therefore collected with the intention of completing a simulation for justification purposes.

5.2 Highland Valley Copper Mine: Background Information

This section presents the basic characteristics of the mine. This will allow the reader to be familiar with the main engineering and operating variables governing the mine performance.

5.2.1 Location

The Highland Valley Copper mine is located in south central British Columbia. The mine is accessed by Highway 97C, 17 kilometers west of the town of Logan Lake and 75 km southwest of Kamloops.
5.2.2 Production Statistics

Two pits, the Lornex and Valley, are mined using a truck and shovel fleet. There are 3 49R rotary drills, each equipped with AQUILA monitoring systems. There are 7 shovels, 1 front-end loader, 34 haulage trucks (all of common capacity) and various service equipment. Two ore shovels operate in the Valley pit and a single ore shovel services the Lornex pit.

The stripping ratio is approximately 1:1, where 261,000 tons of rock are mined daily. There are two semi-mobile in-pit crushers in the Valley pit, side-by-side feeding a twin conveyor system that is capable of conveying 6000 tons per hour and which deposits all ore onto three surge piles, which are drawn into the mill using conveyor systems. The exact network of this system is an important part of the CAES project and will be further discussed in the next section.

The HVC mill processes about 130,000 tons per day. In 1997, HVC produced 391,951 tons of copper sulfide concentrates containing 346 million pounds of copper. Concentrate of 1100 tons, with a copper grade of 40% is produced daily, which is trucked out to a rail line, that services a port facility, where the concentrate is shipped to smelters in Japan, Pacific Rim Countries and Canada. The mine also produces 1.8 million kilograms of molybdenum a year. HVC has long-term contracts for over 90% of its copper-concentrate. Annual or biennial re-negotiation of smelter terms are conducted to reflect market conditions.

Some of the major costs include labor, which is approximately $98 million annually, or about 39% of 1997's budget. Energy is another major cost, including diesel fuel/gasoline, natural gas and electricity. In 1997, $46 million, or 18% of the budget was spent on energy.

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87 Getty Copper Corp., Information Pamphlet
89 “HVC mini fact sheet”, internal publication (1998)
Electricity costs alone amounted to $36 million, making HVC BC Hydro's third largest customer.

5.2.3 Maintenance
A great deal of emphasis is placed on maintenance at HVC. An organized and intensive preventative maintenance program has allowed shovel availability of 96% to be attained\(^90\) (excluding the PM downtime). Each shovel undergoes a 12-hour maintenance check every week.

5.2.4 Environment
Tailings disposal is conducted on the valley floor, northwest of the Valley pit. Two tailings dams were erected, sealing the valley along a length of approximately 10 km. The water is in a closed system with a flow rate of 153,000 liters per minute.

5.2.5 Human Resources
The mine employs approximately 1,050 people. Employees have a cost-reduction bonus pay scheme where employees get a bonus in their paychecks tied to reductions in operating costs. There is also a profit-sharing scheme that is based on copper price. HVC is engaged in a recognized safety program and had won the award for being the safest large mine in BC several times.

5.2.6 Ownership & Hierarchy
Several different companies are partners in the mine. The following table is a breakdown of the ownership.

Table 5-1: Percent Ownership of HVC

<table>
<thead>
<tr>
<th>Company</th>
<th>Percent Ownership</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cominco</td>
<td>50</td>
</tr>
<tr>
<td>Rio Algom Lim.</td>
<td>33.6</td>
</tr>
<tr>
<td>Teck Corp.</td>
<td>13.9</td>
</tr>
<tr>
<td>Highmont mining</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

The mine hierarchy is presented in the diagram below. For AFEs of lower than $CAN150000, the mine manager has the ability to accept or reject proposals. The HVC management committee must make the decision for capital purchases above this value. The committee is made up of 3 people from Cominco and Rio Algom, for a total of 6, who are

\(^90\) Amon, Frank. *HVC mine budget, 1998*, internal document
effectively the HVC directors. Therefore, this committee could be the focus of study once the advanced justification schemes had been applied to the CAES AFE, which is above the $150,000 threshold.

Figure 5-2: HVC Management Hierarchy

5.3 Case Study 1: AQUILA Drill Technology & Fragmentation Optimization

The initial research proposal was to study the financial and qualitative benefits of the GPS based AQUILA technology at HVC. During the summer data collection period, the case study was a post justification exercise of the AQUILA drill technology. The HVC engineering staff considered fragmentation optimization as being the most important aspect of the drill technology. This aspect was also considered to be one of the most challenging to justify financially.

Before the results from the study are presented, background information must be provided so that the reader is familiar with the key variables that affect and were affected by the technology. This section begins by describing the AQUILA technology in detail. The blast planning, drilling and resulting fragmentation before and after technology implementation will also be described in this section. The technology was justified in this case study using

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91 Richards, Mark “Hierarchy” personal email (October 8, 1998)
92 Richards, Mark. Ibid, (October 8, 1998)
both level 1 and level 2 justification schemes. Finally, the reasoning for classifying this technology as level 2 will conclude this section.

5.3.1 AQUILA technology

AQUILA Mining Systems Limited is a Montreal-based company, with a controlling interest owned by Caterpillar Inc. AQUILA Mining Systems Limited, Caterpillar Inc., Mincom and Trimble Navigation have formed a strategic alliance to develop and market GPS and software tools for the mining industry. AQUILA pioneered the development of advanced computer based monitoring, control and guidance systems for drills and cable shovels\(^93\). AQUILA had two main product lines, a drill monitoring, control and GPS based guidance systems and a shovel and GPS-based guidance system up until 1998, it now focuses solely on drill systems. Both technologies use an Advanced Monitoring Platform (AMP). The AMP is a 32-bit computer system, which consist of a display, hand-held terminal and an electronic card housing. Two GPS receivers are required on the equipment. The receivers can be seen on the top of the mast of the drill in the diagram below.

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\(^93\) AQUILA; *Paving the way for total mining systems*, promotional pamphlet, 1997


Sean Dessureault
production monitoring system (DM-1) mainly consists of an operator interface, which provides the operator with immediate feedback on drill performance.

The DM-2 Material Recognition system uses vibration sensors and pattern recognition algorithms to determine characteristics of the material that is being drilled. The technology can determine a hardness index and geological interface locations all in real time. This information is stored on files, which can then be uploaded into a laptop from the drill computer then downloaded into the mine LAN at the engineering office. An example, seen below, of the VGA screen seen by the operator, shows the progress of the drill bit as drilling progresses. From the left-hand side of the screen, it can be seen that the bit is 5.883 meters deep (from the collar) and the design depth is 15.45 meters. The next two figures show the process of uploading the data to a laptop on the drill (note: the drill is still in operation) and downloading the files into a computer. The file transfer process takes no longer than a few minutes (via serial link).

Figure 5-4: Screen Shot - Operator's Status Screen
The DM-3 drill control technology is used in conjunction with a programmable logic controller (PLC) and electro-hydraulic actuators to allow automatic drilling. This allows the hole to be drilled without operator control to ensure the hole is drilled from collar to design depth. The drill control system ensures that the pulldown pressure and rotary speed are within limits for torque and vibration rates. This system is not used at HVC.

A DM-4 maintenance monitoring system is commercially available but is not being used at HVC.

The DM-5 Guidance system is the primary feature of the Trimble GPS system. Using high-resolution, kinematic GPS receivers and an AMP platform, the system provides the three-dimensional location of the drill in real-time. An AQUILA Moving Map Display (MMD), located in the operator's booth on the drill, displays the designed location of the blastholes along with the icon representing the position of the drill. As the drill approaches the hole, the view is automatically zoomed, allowing the operator a closer perspective of the hole position and approaching bit position. The operator can navigate throughout the drill pattern without stakes or surveying and with much greater accuracy than is possible with conventional line of sight navigation. Collar elevation is also taken into account so that the hole is always drilled to the designed depth. Figure 5-6 is a screen capture of the operator's navigation screen.
Figure 5-6: Drill Navigation Screen

The AQUILA system can provide instructions to the operator relating to a specific hole. For example, if a certain blasthole requires a sample to be taken, a message attached to the particular hole is given. The operator then places a sample bag with a barcode that contains the specific location and number of the hole in the code. This facilitates the assay lab’s activities when testing the sample.

5.3.2 Blasting Methodology Pre-Technological Improvement

Before the AQUILA technology was added to the drills, two teams of up to three surveyors would have to design, stake and survey the drill pattern on-site. The general procedure was undertaken as described below. Problems faced in these situations will be explained where details are needed.

1. A general area is outlined by the daily planner as to where the next blast should be located. The burden and spacing is set for certain areas within the pit so that the survey team knows, before venturing into the field, what the approximate burden and spacing should be. Hence, engineering considerations such as vibration or blast optimization were limited when using this method of blast design.

2. A team of two surveyors proceeds to the area. Once on site, the blast pattern is conceived, from the on-site characteristics in the field. Exact field conditions are

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94 Description of procedure received in month of July from Ken Anderson, Mine technician currently in charge of blast design, former surveyor of blast patterns.

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frequently unknown in the engineering office. Furthermore, obstructions may impose limitations upon the design or implementation of the design.

3. The blast pattern is laid out using a Total-Station, colored tape, stakes and spray paint. A large amount of survey consumables are used to delineate the pattern.

4. Climatic conditions and adverse weather affects impede the design and implementation. Weather can also blow down the stakes, wash out the paint marks or drop snow over the pattern.

5. Location of the trim holes varies, depending on the survey team. Therefore there is little consistency in design.

6. Laying out three patterns whose blasts result in 400 000 tons of broken rock requires 16 hours. A single pattern required eleven man-hours of labor.

7. The drill operator requires great skill in positioning the drill bit over the indicated hole. The operator aims the drill rig according to azimuth lines laid out by the surveyors. A small 2x1-foot window on the floor of the rig reveals to the operator the position of the bit.

8. Occasionally, the pattern is not completed in time and during the drilling process, the stakes are commonly knocked down. Consequently, there are situations where the operator is required to line-up the drill visually, according to stakes on the periphery of the pattern.

9. Once the holes are completed, a survey team returns to the site to re-survey the drilled blasthole locations. The law requires this so that in the event of a misfire, the exact position of the misfire is known.

10. Occasionally, a ‘split’ is required due to time constraints in the pit. A ‘split’ is when a large blast pattern is divided into two blasts. A split is implemented if the shovel would run out of muck before the large blast could be drilled and blasted. In this situation, the surveying and marking of the blast pattern would be remade to suit the requirements of the pit. This effectively forces the surveyors to remark the same bench twice.

**Resulting Performance:**

In some instances, the drill rig deviates from the drill pattern by over a meter. Furthermore, the lack of precision of the drill rig is compounded by the poor accuracy of the surveyor-marked pattern. The misalignment of the blast holes induces poor fragmentation: very large blocks are present within the muck pile. Engineering staff consider these large boulders a cause of increased wear on shovels, trucks, and crushers. It was also observed that poor
fragmentation would also adversely affect the mill performance. Throughput would fluctuate resulting in decreased recovery.

### 5.3.3 Chronology of Technology Acquisition

In 1995, HVC purchased a Bucyrus Erie 49R-drill rig to begin replacing its aging 45 R drills. The 49R drill was in operation by July 1995. A second 49 R was purchased and operating by June 1996. In the AFE for the second drill, the senior mine engineer added the price of the AQUILA technology to the overall price. The comparatively small price of $US100 000 was less than 5% of the purchase price of the drill. The AQUILA technology was installed and implemented by May 1997. Results from the technology and the observed drill performance persuaded management to purchase an AQUILA system for the first 49R drill.

An AFE was submitted for approval before the AQUILA system could be purchased. Primary economic and qualitative benefits were listed. Financial statistics were calculated such as a 2 year payback and an IRR of 75.1%. A comparison of predicted financial statistics and actual financial statistics will be provided in the next chapter. A third 49R was purchased with the AQUILA system, which was installed when the drill was being built (seen completed on Figure 5-3: 49R Drill rig showing GPS receivers). Throughout this process, the old 45R drills were being retired as fast as the mine plan could afford. Currently, a single operational 45R drill is kept on site in the event of catastrophic failure of a 49R drill. Generally, two drills work in the Valley pit while the remaining drill operates in the Lornex pit.

### 5.3.4 Changes Anticipated

The following two lists represent the analytical and financial benefits that were anticipated based on the AFE (mentioned previously, in 5.3.3: Chronology of Technology Acquisition).

#### 5.3.4.1 Anticipated Analytical benefits

The words in the square brackets will be used in a comparative table (benefits anticipated vs. achieved) presented in the next chapter:

1. The ability to drill patterns more accurately both by position and depth. Thus, drill operators will be more accountable for deviating from the drill plan as a result of quicker hole pickups. [accuracy] & [operator accountability]

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95 Richards, Mark, "information requests" personal email, (October 27, 1998)
96 Mark Richards, "GPS drill Technology Acquisition- AFE", internal Highland Valley Copper Report
2. An accurate collar elevation is obtained from each hole and the hole depth can be adjusted, producing more even benches resulting in improved operating conditions for shovels and trucks. [more even benches]

3. Explosive strength can be adjusted according to the measured drillability, thus improving explosives consumption and fragmentation. Optimizing fragmentation will improve diggability, reducing wear on the shovels, trucks and crushers while improving mill throughput. [less explosives consumption] & [better fragmentation]

4. Drill navigation is an essential step towards single operator-multiple drill operations and automation. [automation option]

5. Automated drill hole surveying and material recognition will provide information for blast design and provide opportunity for a more automated and productive explosives loading system. [material recognition] & [improved explosives loading]

5.3.4.2 Anticipated Financial benefits
The following financial benefits were calculated for the A.F.E.

1. discounted payback period of 1.3 years
2. IRR of 75.1%
3. projected annual operating savings of $146,000
4. 0.01% improvement in throughput ($30,000/yr. at 90 ε/llb.)
5. Reduced shovel costs of $30,708/yr.
6. Reduced drill & blast costs of $104,470/yr.
7. A reduction in survey overtime for pattern staking and hole pickups
8. A reduction in the consumption of survey materials

The above analytical and financial benefits will be used in a comparison with the actual results achieved. Discussion and application of the various justification schemes, are the subjects of the next chapter.

5.3.5 Reasoning Behind Level 2 Classification.
A method of classifying technologies into three levels is used, as discussed in chapter 3, as a means of determining which justification schemes are appropriate. Classification mainly depends on the level of integration into the overall system. The AQUILA technology is heavily integrated into the drill operation and blast pattern design of the mine; however, it
Chapter 5 – Background to Practical Examples

does not directly influence planning, scheduling or any other department in the mine. The technology has radically changed a certain component of the process, namely the design and implementation of blast design. This process can be considered a ‘cell’ of the overall system; this integration on a cell basis corresponds to a level 2 technology. Therefore a more intense economic analysis is required, coupled with portfolio analysis. These justification schemes will be presented in the following chapter.

5.4 Case Study 2: CAES technology & Ore Blending

This case study was initiated out of the requirement to provide a field example of level 3 CIA methods. During the summer study, the mine-engineering department was attempting to justify, mainly in basic financial terms (level 1-justification schemes), a technology that was clearly level 3. This presented an opportunity to apply a level 3 justification scheme in a practical example. The technology was to be used as intended by the designers, Caterpillar, but also for a larger purpose, as a blending tool. The most important financial benefit was difficult to justify because the technology would be integrated, with a series of other new technologies, into both mine and mill to create a comprehensive ore-tracking tool. This tool would be used to optimize ore blending to the mill. (Initial estimates of the return on such a project was approximately $12 million/year). The complexity, risk and integrated nature of this ore blending project would generate the need for level 3 justification schemes to provide a realistic forecast of the benefits. The next chapter describes the application of Level 3 justification schemes to this project. This section provides the background information required.

This subsection begins by providing a description of CAES technology. The ore-blending project developed following a series of experiences at HVC. The chronology and details of these experiences are discussed. The current system in place at HVC will be described so that the reader is familiar with the variables and constraints affecting the project. Finally, a description of the ore blending project is provided.

5.4.1 CAES Technology

CAES is based on GPS technology, software and digital wireless communication. The basic components include a digital bi-directional radio, on-board 486 computer and software. CAES is part of a series of products called Mining and Earthmoving Technology Systems (METS). These products were developed by Caterpillar Inc. and its partners; AQUILA Mining Systems Limited, Trimble Navigation Limited, and Mincom to supply a perceived demand for systems that use new technologies to improve operations efficiency.\(^{97}\)

\(^{97}\) Caterpillar – “CAES”, Promotional paper submitted to HVC by Finning Inc.
A mine plan, based on any planning software, is exported into a software package called METSmanager, in AutoCAD format (DXF) (there is a series of software offered that help in planning & design called METSoffice). The plan is transmitted to the machine via digital radio link using simple ‘drag and drop’ procedures typical for Windows-based programs. The on board system is known as CAES. The design can be instructions for a shovel, loader, grader or dozer. RTK GPS technology provides the position and orientation of the vehicle to the operator so that he can see his position with respect to the mine plan and pertinent geological features. Figure 5-7 shows the view that a front-end loader operator has on the CAES screen. The view allows the operator to load specific volumes of ore (in the case of a shovel or loader), cut and fill an area precisely to design (dozer, shovel or loader) or sculpt roads to design specifications (grader). CAES transmits estimated changes in the real-world situation incurred by the vehicle’s earthmoving activities (it updates the topographical maps), to close the loop between planning and production.

![Figure 5-7: Front-end loader operator's view of the CAES screen](image)

There are many possible benefits quoted for this system. The following list enumerates these benefits and explains the reasoning behind them\(^98\).

1. Information
   1. Real-time radio link between planning and operations can provide
      - Timely topography & pit face status
      - Faster reaction time to pit events
      - Faster plan updates
      - Improved quality and speed in production statistics

\(^98\) Information received from photocopy of slides received by HVC from Finning during sales presentation

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• Improved blending at the face

2 Better documentation via METS Office can provide the following advantages:
  • Production tracking by ore grade
  • Improved reconciliation, in the mine and mill relationship
  • Royalty tracking
  • Reduced record-keeping inconsistencies from reduced transcribing

3 Cost elimination
  • Many survey costs eliminated (CAES can update the plans automatically
  • Partial elimination of fly-overs

4 Increased precision/visual awareness
  • Timely, virtual markers for ore contacts
  • Bench elevation control
  • Poor visibility environments no longer a detriment

5 Ore Control Systems
  • Elimination of erroneous ore routing following loading
  • Reduced dilution
  • Improved stockpile blending

6 Sloping applications
  • Ramps/roads
  • Leach pad construction
  • Pre-stripping
  • Reclaim contouring

The above list is an example of the type of advantages possible using this type of technology. The list is comprised mostly of qualitative benefits that are difficult to quantify in economic terms. Caterpillar representatives, in a sales presentation to HVC, calculated the economic advantage of eliminating erroneous ore routing. Using a case study at another copper mine, it was determined that 7% of truckloads were sent to the incorrect destination. For example, a truck loaded with ore went to the waste dump while a truck loaded with waste was dumped into the crusher. It was calculated that with a 240 Ton truck and an ore grade of .5% Cu, a truckload of misidentified ore would cost a mine 30000 $/day. To the author’s knowledge, this is the only formal justification of this technology. Other advantages such as facilitated leach pad construction or better documentation are difficult to justify using conventional justification techniques.

It is important to note that more uses will became apparent as other operations consider and implement the technology. Improved stockpile blending is considered to be an advantage of this system; however, the HVC implementation plan to accomplish this difficult task has not yet been devised. The mill and mine planners at HVC have proposed a project that would use a combination of blending at the face, on the conveyors and on the stockpile to achieve a
desired grade, hardness and fragmentation distribution. This would involve both mine and mill. This project would use the ore tracking abilities of CAES and conveyor and mill modeling and monitoring to track ore throughout the entire system. The details of this project will be discussed in the following subsection. Despite the many other benefits obtained when using CAES, blending will be the only qualitative benefit justified in this thesis and will be used as an example of level 3 justification. In order to determine the true value of this technology, all the uses for the technology, to be used in the particular operation, should be ascertained.

5.4.2 Chronology

In early 1996\textsuperscript{99}, the mine engineering department planned to increase efficiency and decrease costs by increasing their drill bit size and thereby the required burden and spacing. This induced a fragmentation distribution with much larger fragments\textsuperscript{100}. As predicted, mining costs were reduced, however, mill throughput greatly decreased. Savings incurred in the mine were greatly offset by the increased maintenance costs and decreased copper concentrate production from the mill. These experiences revealed to the mine and mill planners the importance of fragmentation to the overall profitability of the company. Planning procedures were changed at HVC to reflect a more cooperative rapport between the mine and mill planners. Currently, staff from the mill go to the weekly mine planning meetings and mine engineering staff go to biweekly ore quality meetings at the mill.

The revelation of the importance of fragmentation prompted mine management to hire a consultant, JKMRC of Australia, to devise a methodology to determine;

1. The optimum fragmentation for the mill;

2. An empirical formula to determine fragmentation during blast design phase.

The study is considered proprietary information of the mine therefore the details will not be discussed herein.

One of the main conclusions derived from the report is that ore hardness is not one of the main structural variables influencing fragmentation, as previously thought. The rock quality designation RQD, or the frequency and number of joints was considered to be the most influential variable on blastability. Size distribution (whose result is a variable of blast design) and hardness were determined to be the most influential variables governing mill throughput. This study prompted a suggestion, from the Senior Control Metallurgist, to improve the current system of fragmentation forecasting and blending.

\textsuperscript{99} Richards, Mark, Ibid (October 27\textsuperscript{th})

\textsuperscript{100} Derived from discussion with Frank Amon, Engineering superintendent and Mark Richards, senior mine engineer, during summer visit in 1998.

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5.4.3 Current System

Currently, and in the past, HVC has been estimating ore hardness, for the purposes of blast design and throughput forecasting using knowledge of the geological conditions combined with personal experience and intuition. A ‘Nelson Number’, also known as ‘A line equivalent hardness number’, is used to classify different regions within the pit. The number is an indexed figure based on the experience of the Senior Geologist in charge of ore quality, Nelson Holowachuk. The index number is known as A-line equivalent because the index is based on the throughput of the A line semi-autogenous (SAG) mill, a 10 m diameter SAG with a standard ball charge\footnote{Simkus, Ron and Dance, Adrian., \textit{Tracking Hardness and Size: Measuring and Monitoring ROM Ore Properties at Highland Valley Copper.}, Mine to Mill – 98, paper Submitted for AIMM conference, Brisbane, 1998}. 

![Figure 5-8: Grinding at HVC\textsuperscript{102}](image)

The HVC mill has five separate grinding lines labeled A through E (as seen in Figure 5-8: Grinding at HVC). These are fed by three storage piles, labeled pile 1 through 3. They can be seen in Figure 5-10. In the overhead photo, the mill can be seen in the north east quadrant. Three conveyor belts can be seen conveying the ore onto the piles. It can also be seen that there are inactive portions of the piles. These are the outer truncated cones seen most clearly on coarse pile 3 (left most pile). The ore is drawn into the mill through underground feeders. If the piles are reduced to 30% of their capacity, the outer cones begin to be drawn into the

\textsuperscript{102} Highland Valley Copper, “\textit{A world Class Mine}.”, Corporate Mission Statement, p.15

\footnote{Simkus, Ron and Dance, Adrian., \textit{Tracking Hardness and Size: Measuring and Monitoring ROM Ore Properties at Highland Valley Copper.}, Mine to Mill – 98, paper Submitted for AIMM conference, Brisbane, 1998}
mill. The outer cones are typically more coarse since large fragments tend to ravel down the active cone.
Figure 5-9: Conveyor Belt Flowsheet, HVC, June, 1998
Figure 5-10: Coarse Ore Storage Piles

A network of conveyors feeds the piles. The network can be seen in the Figure 5-9.

From ‘Figure 5-9: Conveyor Belt Flowsheet’, it can be seen that the 2-1 conveyor, leading from the Lornex pit, can be combined with the feed coming from the surge pile on conveyor L2A. Conveyors L1A and L1B, attached to crushers 4 and 5 respectively, feed the surge pile. Conveyor L2B also draws from the surge pile and can be blended with conveyor L2A feed, to supply pile 3 or with feed from the Lornex pit to supply pile 1.
Figure 5-11: Surge Pile

Figure 5-11 shows the surge pile which is fed from the L1A conveyor and L1B conveyor, however, the feeds can remain segregated if the feeder rates beneath the surge pile are similar. The diagram and table below provides a schematic of the possible blends. These diagrams reflect the assumption that the ore on the surge pile remains segregated.

Table 5-2: Material Flow

<table>
<thead>
<tr>
<th>Origin</th>
<th>Destination / Pile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lx</td>
<td>1 or 2</td>
</tr>
<tr>
<td>Crusher 4</td>
<td>2 and/or 3</td>
</tr>
<tr>
<td>Crusher 5</td>
<td>1 and/or 3</td>
</tr>
</tbody>
</table>

Figure 5-12: Material Flow

This method of blending has been successful in the past, however, it depends highly on the senior geologist’s experience. A more scientific and automated methodology, currently under consideration at HVC, will be presented in the next section.
5.4.4 Optimization of Ore Blending

Using various technologies used in mills and available for mining equipment, it may be possible to track ore properties through the entire system\textsuperscript{103}. Some studies or interpolations of certain key aspects must also be ascertained, such as the blending behavior of the surge pile, crusher and storage piles. The general plan and assumptions have been interpreted as follows.

Ore hardness, grade and other properties for a particular volume of ore can be determined through geological databases or from drill data logs that are automatically created from AQUILA drill monitoring systems. Figure 5-12 provides an example of the hardness contours.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure5-12.png}
\caption{Hardness Contours}
\end{figure}

Spatial polygons could be interpreted so that following a blast, the ore properties and mechanical properties for every volume of the blasted muck would be known. Using the CAES technology the ore could be tracked from the bench to a crusher. This technology has made the project possible since most of the other technologies and infrastructure needed for the project, have been available and implemented at HVC.

Once the ore has been dumped into one of the two in-pit gyratory crushers, it can be tracked through the system using the existing monitoring system. Figure 5-14 graphically represents the information viewed by the mill monitoring system. The crusher CR1 represents the crusher that services the Lornex pit and CR4 & 5 represent the two crushers in the Valley pit. Blending occurs in the crushers. Each crusher has two dumping bays so that two trucks can dump simultaneously as seen in Figure 5-15.

\textsuperscript{103} Ron, Simkus et. al. Ibid., p.3
Trucks dump onto an apron feeder that has a capacity of approximately 500 tons, equivalent to approximately 3 truck loads (for standard 172 ton Cat haul trucks). Three truckloads are blended together in the crusher, making it possible to control the blend of the ore through dispatch.

Figure 5-14: Monitoring screen of muck flow from pit to pile, HVC

Figure 5-15: Gyratory, semi-mobile, in-pit crusher at HVC

Figure 5-14 shows that crushers 4 and 5 feed the same surge pile. Ore remains segregated as long as the feeder rate of feeders F1A and F1B remain the same.

104 Dance, Adrian “pictures” personal email (July 15th, 1998)
The senior control metallurgist developed a stockpile model, Figure 5-16. As ore falls upon the pile, blending occurs. According to the model, virtual 'slabs' of approximately 1500 tons (depending on the capacity of the pile) are blended together. Two virtually separate cones, containing several ‘slabs’ of ore are fed onto the conveyor belts leading to the storage piles as long as the feeder rates drawing from the piles are the same and the feed onto the two piles is the same. When the feeder rates of the feeders vary, blending between the two cones can occur. The algorithm below determines the resulting blend.

**Figure 5-16: Surge Pile Diagram**

If \( P1 < 50\% \) of the total tons of the surge pile

\[
WT = \left( \frac{P1}{P2} \right) \left( \frac{F2}{F1} \right)
\]

where \( 0.1 < P1/P2 < 1 \) and \( .5 < F2/F1 < 1 \)

If \( P1 < 20\% \) of the total tons of the surge pile

\[
WT = \left( \frac{P1}{P2} \right) \left( \frac{F2}{F1} \right)
\]

where \( 0.1 < P1/P2 < 1 \) and \( .8 < F2/F1 < 1 \)

If \( P1 \geq 50\% \) of total tons of surge pile

\[
WT = \left( \frac{F2}{F1} \right)
\]

where \( 0.5 < F2/F1 < 1 \)

Where:

- \( P1 \) = above the feeder
- \( P2 \) = above the opposing feeder
- \( F1 \) = feed rate of the feeder of the pile
- \( F1 \) = feed rate of the feeder of the opposite pile
- \( WT \) = the fraction of the feed not blended into other feeder

**Figure 5-17: Surge Pile Blending Algorithm**

The blending algorithm has yet to be validated. A physical model of blending will allow the mine to manipulate the blend using the surge pile feeders.
From the surge pile, the ore continues to the storage piles 1-3. The mill has the ability to blend on the conveyor by increasing the feed rate on the various feeders or by using a rock box. On Figure 5-9, it can be seen that feed from the Lornex pit can be directed to pile 1 by increasing the feed rate, or to pile 2 by decreasing the feed rate. Therefore controlled blending is possible at these junctions.

Further blending occurs once the ore lands on the storage piles, similar to the blending that occurs on the surge pile. Slabs of 1500 tons are blended, producing virtually homogeneous volumes of ore. As discussed previously, if the active cones are reduced in volume to 30% of their capacity, the inactive section of the cone begins to feed into the mill. The inactive sections of the storage piles are usually more coarse than the average feed, because larger rocks tend to roll down the pile to the outside. Table 5-3 summarizes these blending methods and describes their degree of control.

Table 5-3: Blending Summary

<table>
<thead>
<tr>
<th>Area</th>
<th>Blending control</th>
<th>Constraints/variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-crusher</td>
<td>(high degree of control)</td>
<td>• Production</td>
</tr>
<tr>
<td>(face blending)</td>
<td>• Truck dispatch</td>
<td>• Properties of blasted ore</td>
</tr>
<tr>
<td></td>
<td>• Drill data database</td>
<td>• Preventative maintenance (PM) on shovels</td>
</tr>
<tr>
<td></td>
<td>• Optimization algorithm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Wireless radio-link-LAN</td>
<td></td>
</tr>
<tr>
<td>Crusher</td>
<td>(No control)</td>
<td>• Feed from trucks</td>
</tr>
<tr>
<td>Surge Pile</td>
<td>(Semi-control)</td>
<td>• PM - shovels</td>
</tr>
<tr>
<td></td>
<td>• Variable feed rates of draws</td>
<td>• PM - crushers</td>
</tr>
<tr>
<td>Conveyors</td>
<td>(high degree of control)</td>
<td>• PM - conveyors</td>
</tr>
<tr>
<td>blending</td>
<td>• feeder rates</td>
<td>• PM - feeders</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• PM - mill</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Storage pile capacity</td>
</tr>
<tr>
<td>Storage Piles</td>
<td>(No control)</td>
<td>• PM - mill</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Storage pile capacity</td>
</tr>
</tbody>
</table>

5.4.5 Associated Technologies

Whipfrag™, a product that uses imaging technology, can determine the size distribution of ore moving along the conveyor belt. The product consists of a digital camera that takes a picture of ore moving by on a conveyor belt (as seen in the Figure 5-18) or in a shovel bucket. HVC is in the process of installing 9 Whipfrag cameras, placed at strategic locations throughout the are handling system.

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Once an image is captured, Whipfrag software delineates the ore into various size fragments as seen in the figure below. The fragments are counted and their size analyzed. A particle size distribution can be provided. The most common problems encountered are the virtual fusion of fine particles into larger fragments and the virtual disintegration of large particles into smaller fragments. HVC currently records the distribution of the particles in three categories; fine, medium and coarse, as seen in Figure 5-19. A single Whipfrag camera can sample the ore on the conveyor belts four times per minute.\footnote{Dance, Adrian. From conversations during July visit}

**Figure 5-18:** A) Whipfrag image capture  
B) Whipfrag Delineation

**Figure 5-19:** Whipfrag results

Fragmentation monitoring technology, such as Whipfrag, can be used to optimize mining systems since blast design models can then be tested for accuracy. For example, HVC received a blasting design model from JKMRC, based on empirical data. The model predicts [insert details].

\footnote{Dance, Adrian. From conversations during July visit}
fragmentation based on rock properties and blast design. The senior metallurgist confirmed the results of the JKMRC results using Whipfrag and developed his own model that can anticipate the effect of the fragmentation on the SAG mill throughput. Attempts were made to determine the accuracy of the model using Whipfrag. Figure 5-20 compares the predicted and actual values of the throughput versus time. From the accuracy of this model, it was deduced that optimum blending design is possible using modeling.

![Figure 5-20: Actual vs. Predicted throughput over time](image)

**5.4.6 Financial Reasoning for CAES/Blending project**

Considering the low grade of the HVC ore and size of the mill, throughput is an important process variable for the mine. The SAG mill is considered by some as the bottleneck of the entire mine-mill system. The purpose of the blending project is to devise an automated methodology of blending the ore so that throughput will be relatively constant. Fewer power spikes and less maintenance are minor cost savings that may be derived from a constant throughput.\(^{106}\) The major motivation from this project is the increased recovery that would be derived from a constant throughput.

The advantage of automatic blending comes from basic mineral processing theory. The major economic benefit from blending the ore is the decrease in the variability of the throughput in the SAG mill. Constant throughput increases recovery. Recovery is defined as (in the case of metallic ores), “the percentage of the total metal contained in the ore that is

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\(^{106}\) Richards, Mark, Ibid, (October 27th, 1998)
recovered in the concentrate\textsuperscript{107}, see Figure 5-21. According to mineral process theory and practice, recovery increases with residence/retention time. However, due to economic constraints, the feed cannot stay in the flotation circuit for the amount of time it takes to approach 100% recovery. Consumables such as energy for the system components and chemicals needed for flotation must be balanced economically. There is an optimal overall retention time (time period that the mineral remains in the system). The SAG mill governs the retention time of the system at HVC\textsuperscript{108}. For example, if fine, soft ore enters the SAG mill, the ore passes through the mill quickly. Throughput thus can greatly increase whilst the retention time decreases. Recovery will decrease if the time spent in the system decreases.

Comparatively, if very coarse, hard ore suddenly enters the system, throughput decreases, which increases the retention time of the ground mineral, but not consuming the designed amount of chemicals and energy. In this case, too much effort (hence money) is expended to obtain the metal. A controllable throughput allows the optimal retention time to be achieved.

![Figure 5-21: Recovery vs. time\textsuperscript{109}](image)

The estimated increase in recovery at HVC is currently estimated to be equivalent to 12 million pounds of copper per year\textsuperscript{110}.

\section*{5.4.7 Blending Summary}

This project requires level 3 justification schemes due to the deep integration of the technology within the mining system and the large degree of risk. The calculated economic benefits would be greatly underestimated due to the high hurdle rate normally used for such a high risk application. Simulation of the system can be used to demonstrate that the system

\textsuperscript{107} Wills, Barry A., \textit{Mineral Processing Technology}, 5\textsuperscript{th} ed., Pergamon Press, 1992, p.31
\textsuperscript{108} Dance, Adrian from personal conversation during September visit
\textsuperscript{109} Wills, Ibid p.539
\textsuperscript{110} Dance, Adrian from personal conversation during September visit.

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will be capable of decreasing the variability of the mill feed. Such a demonstration would provide justification for decreasing the hurdle rate. A simulation of the system for this purpose is presented in the following chapter.

The proposed blending project integrates several technologies and a large flow of information that will span the entire mine. More importantly, a fundamental change of the way the mine operates will be required if the project is to be successful. More communication between the mine and mill, an open collective outlook of the workforce, and managerial commitment are needed. As mentioned previously, communication between the mill and mine has greatly expanded since the realization that the characteristics of the mine feed has such a direct effect on the performance of the mill and hence, overall profitability.

The workforce at HVC has demonstrated that technological change is possible through its acceptance of highly technical innovations, such as the use of GIS and drill monitoring. Managerial support will have to be won through appropriate justification of the project, which is the focus of the next chapter.
6 Practical Examples of the Justification Schemes

This chapter presents the application of new CIA methods to the two case studies described in the previous chapter. The examples will be presented in increasing complexity; the AQUILA drill technology, followed by the blending project.

6.1 Case Study 1: AQUILA Drill Technology & Fragmentation Optimization

This section presents a practical example of the proper application of level 1 and 2 CIA methods for a level 2 technology. The first sub-section presents the current state of the AQUILA technology at HVC in terms of its relation to planning, surveying, maintenance and blast design. The second sub-section presents the financial and qualitative benefits derived from using the AQUILA technology in that particular configuration. Comparisons are made between the anticipated and actual benefits and costs. This is followed by an analysis of how the original justification of the technology was performed. Finally, non-economic CIA methods that are applicable to this situation are presented.

6.1.1 Current Blasting Methodology

The current blasting methodology at HVC are described in three main steps: preliminary surveying, blast design and plan execution.

6.1.1.1 Preliminary Surveying

Conventional surveying of the area to be blasted is performed prior to design using a highly accurate GPS surveying instrument (the instrument is used as the main surveying instrument of the mine). A single surveyor performs a toe and crest pick-up to ensure that the plans in the computers have accurately delineated the position of the crest and width of the bench to be blasted. Once the mine plans have been updated (all mine plans are computerized, and are available on the mine-wide LAN), the blast design phase begins. (Preliminary surveying and data entry require approximately 2 hours.)

6.1.1.2 Blast Design

One mine technician designs the blast pattern using a planning and CAD software package called MicroStation from Bentley (Gemcom is used as the general mine design software while MicroStation is used for CAD, GIS and the production of maps\(^\text{111}\)). The technician begins by summoning a plan view of the updated bench plan. The long-term bench plan (the position of the next bench crest) is also brought into view with the locations of the bootlegs from the blast that uncovered the present bench. The software has several grids available to

\(^{111}\) Richards, Mark. “More information”, personal email, (November 18th, 1998)
place the bench to represent the burden and spacing for regions of a certain hardness. The mine currently uses the "A line equivalent hardness" index in its blast design. The planner then repositions the holes on the periphery of the blast to ensure a clean, flat, new bench face. The tie-in is added and every hole and tie-in are numbered and labeled. Holes that require sampling are indicated. A special printer then prints out bar-code labels that are used to label the bags that the operator uses when collecting samples. Labeling simplifies the work of the lab technician, where the hole position and number are automatically recorded with the results of the lab tests, using a bar code reader.

A copy of the blast plan is printed out and given to the foreman of the drill operators. Once the technician supervisor and the mine superintendent approve the plan\(^\text{112}\), positions of the holes are saved in AQUILA readable data format on a laptop. Finally, the design technician drives to the drill(s) and downloads the plan into the AQUILA computer on the drill. Data stored on the AQUILA computer can be uploaded at the same time to retrieve the data provided by the various AQUILA products (geological data such as hardness that can be used in updating hardness contours or actual drilled blasthole position that is required by law to locate possible bootlegs). A technician requires 3 hours to design a plan that would produce half a million tons of broken rock. (Note: the upload/download step could be automated with a wireless communications network. This is one of the benefits that can be achieved using the CAES technology described previously.)

6.1.1.3 Plan Execution

The operator must determine the most efficient manner of navigating the drill to the various hole positions. The operator navigates the drill using the Moving Map Display (MMD) on board, then engages the automatic collaring and drilling mechanism once the bit is in position. The burden and spacing can vary between 6.6 x 7.6 (753 t per hole) to 13.3 x 15.3 meters (3050 t. hole). Drilling time per hole varies from 15 min to 1hr 15min. The bigger patterns tend to be softer and thus quicker to drill. Engineering staff estimate that a blast that produces half a million tons takes 7 or 8 shifts.\(^\text{113}\)

6.1.2 Qualitative Benefits

The final costs and benefits assembled as part of this thesis are presented in this subsection. The benefits promised in the AFE are analyzed and the benefits not anticipated are listed. The financial benefits are estimated, according to conventional, level 1 techniques for the AFE.

\(^{112}\) Richards, Mark. Ibid, (November 18\textsuperscript{th}, 1998)
\(^{113}\) Richards, Ibid (November 18\textsuperscript{th}, 1998)
6.1.2.1 Predicted Qualitative Benefits

The qualitative benefits indicated in the AFE and their outcome are presented in Table 6-1.

Table 6-1: Qualitative Benefits Promised in the AFE vs. Actual Outcome

<table>
<thead>
<tr>
<th>Promised</th>
<th>Final result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>There has been a distinct improvement in blasthole position. Previously, both surveyors and drill operators were responsible for positioning the hole correctly. Now only the drill operator is responsible and has been given the tools to easily and accurately position the hole. Hole position went from an accuracy of ±1-2 meters to the current accuracy of ±10 cm.</td>
</tr>
<tr>
<td>Drill operator accountability</td>
<td>Drill operators can be held more accountable for deviating from the pattern. Recording the position and time for each hole is a form of constant supervision, ensuring high quality.</td>
</tr>
<tr>
<td>More level benches</td>
<td>Clean-up crews, the first workers to re-enter a newly blasted area, have reported an improvement on the amount of clean up required compared with the period before the technology was implemented. Furthermore, shovels have reported less hard toes while truck drivers have noticed smoother bench levels.</td>
</tr>
<tr>
<td>Less explosives consumption</td>
<td>There has been no distinguishable improvement in explosives consumption that can be attributed to the technology. This is mainly due to the lack of resources to take advantage of all the information provided by the monitoring system. A great deal of data is recorded by the monitoring system that can be used to optimize aspects of the operation involving drilling.</td>
</tr>
<tr>
<td>Improved fragmentation</td>
<td>Fragmentation affects the operation in many respects. Reportedly, shovels require less ground engaging consumables. The mill has also reported an improvement in fragmentation, (of the many variables involved in the improvements mentioned above, fragmentation is assumed to be one of the most important). Mill throughput has increased by 7.4% in 1998. This value is considered to be qualitative since only a fraction of that increase may be attributable to improved fragmentation.</td>
</tr>
<tr>
<td>Automation option</td>
<td>No further autonomy has been adapted to the drill. A radio link is proposed; however, due to the current price of copper, it is an unlikely purchase.</td>
</tr>
<tr>
<td>Material recognition</td>
<td>The material recognition software provides an index that is related to the hardness of the material being drilled. Software adjustments have been requested to take jointing and blocks into account, since according to extensive materials testing it was determined that the different 'hardness zones' are not very distinct. However, a project has been proposed to compare the hardness index results from the technology with the mine's hardness contours, to find the exact correlation.</td>
</tr>
<tr>
<td>Improved explosives loading</td>
<td>There has been no change in explosives loading practice due to the presence of drill monitoring technology. However, it does improve the blast pattern initiation sequence due to design consistency, and the ability to make more informed decisions (the pit foreman sometimes cannot see 'the whole picture' from the ground).</td>
</tr>
</tbody>
</table>
6.1.2.2 Unpredicted Benefits

The unpredicted qualitative benefits were numerous. There are two types of benefits discussed here. The first deals with potential projects, where this specific technology is only a link in a long value chain of technologies that will eventually induce an overall economic outcome. The second type of benefits listed in this section are direct qualitative benefits that have been mentioned or expressed by the respective affected individuals or departments.

6.1.2.2.1 Potential Projects:

1. *Upgrading pit hardness contours*

The technical supervisor plans to update the current pit hardness contours using the hardness index, which is automatically measured by the drill monitoring technology. The potential benefit of better knowledge of the bench is to improve fragmentation through optimal pattern design. Once the exact contours are laid out, the hardness of other areas may be interpreted so that the appropriate burden and spacing or powder factor can be applied to the blast plan according to hardness.

2. *Automatic determination of local jointing*

AQUILA Mining Systems claims to have the potential to detect the presence of joints through drill string monitoring. The ability to make these measurements would allow an improved prediction of the fragmentation since jointing has been identified as the most important parameter governing fragmentation\textsuperscript{114}.

3. *Tracking bit & string performance*

The current method of tracking bit and string performance is rudimentary and does not have the desired detail. The current method consists of having the drill operator alert the dispatch center that the bit or string is being changed. Using the data automatically generated from the monitoring platform, it is possible to track the overall operating time of a particular drill bit, where the largest amount of penetration occurred, and other variables. Tracking bits ensures that the drill bit suppliers conform to contract specifications.

4. *Overall throughput increase at mill*

The objective of the drill monitoring platform is to improve fragmentation, a precondition of improved recovery. One of the key technologies required for the ore blending project is the AQUILA drill technology. This project is described as the ore blending project in the previous chapter. The ore blending project would not be feasible without drill technology.

\textsuperscript{114} JKMRC, confidential report prepared for HVC mine; *Optimizing Fragmentation at Highland Valley Copper with respect to Mining & Processing Operations*, June 1998

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6.1.2.2 Unpredicted Qualitative benefits

Various employees and departments noticed several unpredicted benefits. The most important are listed below. These benefits may be quantified after considerable study and analysis.

1. Split implementation

In the event of a requirement to split the blast design, the blasting technician simply changes the design on the computer, and updates the drill computer. Previously, surveyors had to go into the field, erase the painted lines then redraw a new pattern (the second phase of the split). This also resulted in a significant rework for the surveyors and was a source of contention between the blast foreman, drill operators and surveyors.

2. More informed design

The methodology of design was changed to take advantage of the drill positioning systems, which resulted in an important benefit in terms of consistency and flexibility. By having a single methodology of design, there was less confusion, more consistency and improved operations-engineering relations. Designing a blast in this manner also allowed the design to include variables that were previously unavailable, because design of the blast was done in the field instead of the engineering office, and took into account geological, hardness and future plans.

3. Improved safety

First aid incidents have dramatically reduced since the implementation of the AQUILA Drill technology. This is due in large part to the reduced amount of survey time technicians now spend in the pit, performing hazardous or strenuous tasks such as pounding stakes (which can induce hammer accidents such as accidentally hitting one’s knee) and walking around on a drilled bench in the winter (drill holes, covered with snow have caused many sprained ankles when walked upon).

4. Operator acceptance

Operators have expressed approval of the system since “it makes the job easier”. The resulting improvement in operator enjoyment of the system, due in large part to its ‘video game’ type qualities, may impact on productivity and a better working atmosphere.

5. Clean-up time

Following a blast, benches must be cleaned using dozers or front-end loaders. After a shovel has finished clearing a bench of blasted muck, the floor of the bench must be leveled so that further operations upon the bench can progress. Due to the improved blast design and drill hole accuracy, clean-up time has substantially reduced. The operations foreman has
estimated a fifty percent reduction in the amount of clean-up time needed following a blast. This benefit is difficult to quantify since the same workforce is used (no direct financial benefits are accrued from less labor). Less clean up time allows the operators involved more time to improve road conditions.

6. **Less Oversize**

Increased accuracy has resulted in less oversize and a substantial reduction of secondary blasting. The benefits from the two improvements above is secondary blasting costs (or less time) and less wear on the crushers.

7. **Less Blaster Time**

Since blast tie-ins are designed in the engineering office, blasters no longer require the time to ‘figure out the blast layout’.

Caved Holes

### 6.1.3 Financial Benefits

The financial benefits were determined while taking several influential factors into account, primarily the chronology of events relating to:

- which drills had the technology
- size of bit, pattern & spacing along with the resulting fragmentation

The calculations and raw data used to determine the values in this section are provided in the appendices. Some of the results are discussed below.
Table 6-2: Financial Benefits - Results

<table>
<thead>
<tr>
<th>Variables</th>
<th>Predicted $/year</th>
<th>Actual $/year</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less surveyor o/t</td>
<td>$10,800</td>
<td>$33,866</td>
<td></td>
</tr>
<tr>
<td>Less surveyor materials</td>
<td>$4,200</td>
<td>$37,705</td>
<td></td>
</tr>
<tr>
<td>Less 'caved' holes</td>
<td></td>
<td>$48,804</td>
<td>cost of drilling caved holes</td>
</tr>
<tr>
<td>Design time for pattern</td>
<td></td>
<td>$50,794</td>
<td>extra technician time</td>
</tr>
<tr>
<td>Shovel productivity</td>
<td></td>
<td>$125,936</td>
<td>($/hr. value added - calculated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$142,721</td>
<td>using Budget'98)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variables</th>
<th>Estimated $/year</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mill throughput</td>
<td>$32,000</td>
<td>$32,000 none directly attributable (NDA)</td>
</tr>
<tr>
<td>Drill &amp; blast costs</td>
<td>$104,470</td>
<td>- (explosives &amp; bits) - NDA</td>
</tr>
<tr>
<td>Shovel maint.</td>
<td>$30,708</td>
<td>$78,000</td>
</tr>
<tr>
<td>Total</td>
<td>$15,000</td>
<td>$439,826</td>
</tr>
<tr>
<td>Total incl. estimated</td>
<td>$182,178</td>
<td>$549,826</td>
</tr>
</tbody>
</table>

There are several values in the above table that require explanation. First, it should be noted that the overall precision of the estimates is higher, due to the quantification of benefits that were previously listed as qualitative. The values in the ‘Estimated’ category were provided by the experts of various departments, based on quantitative data and experience. Reduced shovel maintenance savings are the reduced cost of ground engaging consumables and shovel cables.

The benefits in the ‘unanticipated’ category are explained below.

1. **Caved holes**

   There were situations, discovered when explosives were being loaded, that some holes had ‘caved’. This can occur by drilling through bad ground or by the hole not being drilled to design depth. The monitoring system allows supervisory control where the drill logs record the depth and position the hole was drilled. Therefore operators are more observant of design parameters.

2. **Design time**

   In the original estimates, design time was not taken into account. This value is the savings in the amount of time required to design and approve a blast plan.

3. **Overtime reduction**
Occasionally, mine engineering staff were required to stay longer than the regular hours to finish implementing a blast pattern. This no longer occurs.

4. Utilization

The amount of holes drilled per shift has dramatically improved (listed in table as ‘utilization’). This is mainly due to the drill operator’s ability to quickly move from one hole to another. Operator attitude has also improved resulting in increased productivity.

6.1.4 Costs & Financial Assessment

The final costs are proprietary and will not be presented here. However, financial variables such as the payback period will be presented. Benefits and costs reflect the combined values for all variables of the 3 drills and technology platforms, because calculations were made by comparing the variables before the drill monitoring technology was implemented with the variables after all drills were outfitted with the technology.

The final financial evaluation variables are presented below. The calculations and HVC discounted cash flow sheets are provided in the appendices (except public versions of this thesis).

Table 6-3: Final Financial Outcome

<table>
<thead>
<tr>
<th></th>
<th>AFE</th>
<th></th>
<th></th>
<th>Single unit Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payback Period (using DCF $)</td>
<td>1.3</td>
<td>1.2</td>
<td>1.3</td>
<td>0.0</td>
</tr>
<tr>
<td>Payback Period (using Real $)</td>
<td>1.3</td>
<td>1.2</td>
<td>1.3</td>
<td>0.0</td>
</tr>
<tr>
<td>I.R.R. (%) (Using Real $)</td>
<td>75.1</td>
<td>77.0</td>
<td>44.5</td>
<td>-1.9</td>
</tr>
<tr>
<td>R.O.I. (%) (NPV / Investment)</td>
<td>228.1</td>
<td>235.2</td>
<td>246.8</td>
<td>-7.1</td>
</tr>
<tr>
<td>N.P.V. @ Prescribed Rate</td>
<td>$335,310</td>
<td>$341,561</td>
<td>$1,010,064</td>
<td>$(6,251)</td>
</tr>
</tbody>
</table>

6.1.5 Analysis of Results

The analysis begins by discussing the original justification conditions and the subsequent decision. This allows the reader to understand why the original technology assessment was so thorough and precise (compared to the actual outcome). The second step in the analysis considers issues raised discussed in Chapter 3. Ashford discusses the main criticisms of formal justification schemes and makes suggestions on how to alleviate some of the weaknesses of these techniques. The analysis applies these suggestions to the above situation.

115 from personal communication: R. Dhaliwal for maintenance, A. Dance for milling information and Steve Gapp for mine operations
6.1.5.1 Original Justification Circumstances

As discussed previously (Chapter 5), the senior mine engineer was able to have the first system approved by 'being included in the cost of the technology in the original price of the second 49R purchase. The performance of the technology was observed over a few months. The blast design methodology was re-evaluated and then restructured to take advantage of the many benefits observed from the technology. Engineering staff concluded that the technology was valuable and decided to purchase the same drill monitoring system for the first 49R drill.

This system had to be procured using a formal AFE. The anticipated benefits were estimated with a high degree of accuracy because the system on the second 49R had shown the possible benefits. Management had also heard of the numerous qualitative benefits derived from the system and had a favorable view of the technology before the AFE had even been submitted. It is uncertain whether the mine management would have approved the purchase of a drill monitoring system and what the anticipated estimates would have been. Hurdle rates may have been applied by decision-makers in the original assessment, but a bias in favor of the technology was present due to its successful implementation in the second 49R drill.

6.1.5.2 Financial Assessment

This section describes the financial assessment that was undertaken following the implementation of the drill monitoring technology. Suggestions of information that should have been included in the original technology assessment are discussed. The post-implementation financial justification uses hard data and estimates provided by mine records and staff. This discussion focuses on the variables listed, not the values of the variables since these would be unknown if the technology had not been implemented previously (as was the case in this example).

Ashford (from chapter 3) has acknowledged that the usual methods of applying traditional financial techniques are not suitable to new technologies; however, he insists that the basic axioms of the methods are sound. Ashford’s suggestions on how to properly apply traditional financial justification techniques to the AQUILA technology.

6.1.5.2.1 Taking into account the long-term effects.

As discussed in the literature review, traditional appraisal methods undervalue long term effects for several reasons. First, the payback method is highly criticized for its preference

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for projects which focus on short term benefits. Discounting methods also tend to undervalue the long term effect, if the discounting rate used is unrealistically high. Standard discount rates should reflect market realities, not a corporate-wide figure that has been standardized to apply to any investment proposal. Finally, Ashford condemns the widespread tendency for management to blindly apply blanket hurdle rates such as minimum payback period or ROI.

HVC uses a discount rate of 10%. Corporate wide hurdle rates are also used in capital asset budgeting. A minimum payback period of two years is the norm.

These managerial practices should not be overly criticized just because they are the only methods well known to mine management. Recommendations on how to change these practices are not an objective of this thesis; however, it is important to comment that management should scrutinize these methods when evaluating new technology. Recognizing the various technology levels also aids in knowing what the limits of the CIA methods are with respect to the technology under evaluation. Therefore several of the conclusions that can be derived from this step in the analysis are as follows:

1. Foster a greater understanding by management of the difference between technologies and the limits of the CIA methods used;

2. Make management aware of other CIA methods and which technology would best apply;

3. Question the use of blanket hurdle rates;

4. Consider using a discount rate that reflects reality, avoid company-wide standard rates.

6.1.5.2.2 Assumptions about the Future

Commodity markets are dynamic. Demand for mining products fluctuates. Activities within operations have many variables that govern the mine’s performance. The entire mining process is dynamic, from the planning stage to the customer. For example, the assumptions made when first designing a mine may not be applicable to the same mine after five years of operation, therefore what was considered to be the optimum operating procedures may no longer be optimal. Unfortunately, level 1 CIA methods rarely take this dynamic nature of the mining system into account.

An appropriate response to the inherent weakness of these methods is to make forecasts or scenarios of the environment and incorporate this data into both the base-case and new technology appraisals. Historical data, expert opinions and personal experience can be used in these forecasts to reflect reality more accurately. For example, during the original evaluation, the increased drill utilization was unpredicted and therefore remained unquantified. Furthermore, the value of operator satisfaction was undervalued.
Operators expressed enjoyment in navigating with the AQUILA system because it was 'like playing a video game'. Therefore operators wanted to work faster and more efficiently so that the navigation segment of the drilling cycle would happen sooner. Figure 6-1 shows drill productivity before and after the technology was implemented. Drill productivity for the 49Rs was decreasing; however, once the technology was implemented, the productivity increased and continues to increase. The eventual production rate when stabilized will likely be much higher than prior to the technology implementation.

Figure 6-1: Meters drilled per drill over the time scale

This decreasing trend before the technological implementation could have been detected using monthly drill reports. The increased productivity of the drill fleet could have been predicted by knowing the drilling process (the ease of navigating onto a staked marker vs. GPS positioned virtual marker) and understanding the psychology of the operators.

A more strategic example of making forecasts can be based on the fluctuating market values of some commodities. A production increase that occurs due to the implementation of the technology coupled with an increase in demand (hence price) of the commodity would greatly alter the NPV of a project. A negative example of disregarding future conditions could be making an evaluation during an economic boom (hence using those current values) but then witnessing when the technology is implemented that the market demand drops.

There are several reasons why evaluators (including the HVC staff) currently do not include the dynamic nature of the mining industry in justifications. The uncertainty of making future assumptions can be challenging for the individual undertaking the evaluation because these assumption may be wrong or strongly contrary to the view of the decision maker.

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This problem can be avoided by presenting several scenarios and documenting evidence for the probabilities of each case, based on expert opinion or hard data. Unfortunately, decision makers commonly rely on single number comparisons (such as payback period, NPV, ROI, etc.) that are compared to the base case single value (e.g. payback period, NPV...).

A second impediment for including the dynamic nature of the mining industry is time. Those individuals whose task is to evaluate the technology are commonly employees who have many other responsibilities. Researching possible scenarios and the links between the many variables that new technology tends to influence is very time consuming; furthermore, individuals who are not on-site may be unaware of several of the affected variables, and yet are responsible for the evaluation. Finally, management flexibility and the time to absorb a complex evaluation that includes several scenarios is one of the most significant impediments to using dynamic CIA methods. Corporate culture may not readily allow such evaluations.

Several conclusions can be summarized from this step in the analysis:

1. Justification of new technology whose benefits may be long term or can affect dynamic trends should be valued using methods that are dynamic. This can be accomplished by researching and presenting various scenarios that are perceived to be feasible.

2. Appropriate time and resources should be devoted to evaluating technologies whose value may alter over time.

3. An individual who fully understands the system should undertake the evaluation.

4. Decision-makers should be flexible enough to evaluate a dynamic justification.

6.1.5.2.3 Benefits Ignored

New technology offers many qualitative benefits that are often difficult to quantify. Financial CIA methods in particular have difficulty in taking these benefits into account. Some benefits can be estimated using hard data and expert opinion, but the individual justifying the technology must put the effort into analyzing all of the affected variables.

Once the system has been defined, the system’s response to the new technology must be ascertained. This may involve increased vigilance and take much longer than traditional financial justification methods. The resulting evaluation will contain many more variables and take more time with greater uncertainty. The decision-maker may not agree with the assumptions or analysis of the situation, creating a negative bias against the technology. Documented proof and direct opinions of experts who are willing to support their opinions would aid in the credibility and reliability of the justification.
An example of qualitative benefits that can be assessed in quantitative terms through in-depth investigation is the cost savings incurred by altering the design methodology. The engineering department was planning to restructure the blast design methodology following the implementation of the technology; hence, design costs would also change following the restructuring. Estimates could have revealed the $51,000 dollar savings (per year) that occurred. The table below summarizes these calculations. The design production rate estimates were provided by the individual who currently (and previously) designs the patterns\textsuperscript{117} and the salary rates were obtained from the HVC union contract.

Table 6-4: Design Costs

<table>
<thead>
<tr>
<th></th>
<th>Cost of pattern implementation &amp; design (in man-hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># of patterns</td>
</tr>
<tr>
<td>pre-tech</td>
<td>16</td>
</tr>
<tr>
<td>post-tech</td>
<td>3</td>
</tr>
<tr>
<td>difference</td>
<td>13</td>
</tr>
<tr>
<td>% decrease</td>
<td>81%</td>
</tr>
</tbody>
</table>

There was no reduction in staff following the technology acquisition. The surveyors that formerly undertook the design and implementation of blast patterns were placed in other profit or quality generating positions (for example, one such technician currently maintains the GIS database, which has greatly improved many other aspects of mine design). This evaluation has not quantified this benefit, as the uncertainty of such an estimate would weaken the evaluation.

It should be noted that undertaking a more in-depth investigation should result in increased accuracy for those variables that are anticipated. For example, the quantitative benefit of using less surveyor materials were determined much more accurately during the second justification process than in the original AFE. The reduction in survey material produced a cost saving of $38,000, which is much higher than the original estimate of $4,200 per year. It is understandable that the original AFE did not require as much scrutiny as a technology completely new to the operation since, as discussed previously, a system had already proved itself to be worthy before the AFE was commissioned. The increased accuracy may reveal some costs that were unanticipated.

From the above analysis the following conclusions can be drawn:

\textsuperscript{117} Ken Anderson, Mine technician, formerly part of a group of 6 field surveyors, has undertaken the design and implementation of the design patterns.
1. Decision-makers should maintain an open mind when evaluating the justification documents.

2. Those who undertake the justification should document the opinions and support the assumptions made with hard data and reasoning. Adequate time should be allocated to ensure the justification is accurate and complete.

3. The qualitative benefits should be quantified to the best of the evaluator’s abilities.

4. The believability of the justification should be taken into account. Estimates should not be included that appear unsubstantiated.

5. The un-quantifiable costs should also be included.

6.1.5.2.4 Management Control
Ashford (1988) condemned organizational reward systems that reward managers for supporting projects that yield clear short term rewards against long term profitability. This may not be a problem at HVC since the management culture is very personalized. Individuals relate to each-other on a first name basis and live in a relatively small community. Furthermore, the reward system at HVC was not included in this research for confidentiality reasons. For large projects, where the expenses are above $150,000, the decision to proceed is made by a committee that is far removed from the community and the mine. In this case, the upper management may have a short-term profitability outlook on the mine.

6.1.6 Selection of Level 2 Justification Scheme(s)
The technological and justification classification of the AQUILA drill technology has been discussed previously in this thesis and it has been concluded that it is a level 2 technology. Nevertheless, not all level 2 justification schemes apply. For example, programming models are ideal for situations where a mix of technologies is being considered. Another example is growth options, where the value of a technology that would produce financial benefits only under certain conditions (dependent on an independent fluctuating variable such as price) can be evaluated. Thus programming models and growth options are not viable CIA methods for this technology since it is a single technology and it always exhibits its value. Scoring methods are appropriate for this technology, since it has many qualitative benefits that can be rated by the decision-makers. AHP was considered to be a valuable justification method. The method was presented to the person responsible for the decision regarding the AQUILA technology acquisition.
6.1.7 Application of AHP at HVC

During the second HVC visit, the analytical hierarchy process was explained to the Chief of Engineering. He was asked to list the objectives that were needed at the time the drill technology was being contemplated. The responses are listed Table 6-5; possible solutions to achieve the objectives (selected by the engineer) are also listed. Other objectives, such as surveyor safety, fragmentation, and bench grade (level), were not considered.

Table 6-5: Data Required for AHP application

<table>
<thead>
<tr>
<th>Objectives</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>accuracy</td>
<td>accu</td>
</tr>
<tr>
<td>efficiency of drilling</td>
<td>drl_eff</td>
</tr>
<tr>
<td>efficiency of blasting</td>
<td>blst_eff</td>
</tr>
<tr>
<td>ease of design</td>
<td>design</td>
</tr>
<tr>
<td>cost of option</td>
<td>cost</td>
</tr>
<tr>
<td>simplicity of option</td>
<td>simp</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Options</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>drill monitoring</td>
<td>techno</td>
</tr>
<tr>
<td>re-training/restructuring</td>
<td>Train</td>
</tr>
<tr>
<td>status quo</td>
<td>Quo</td>
</tr>
</tbody>
</table>

The HVC decision-maker then evaluated the various objectives according to the AHP rules (the actual spreadsheet is included in the appendices). Table 6-6 represents the evaluator's responses and Table 6-7 are the results of the AHP analysis. The consistency index was deemed satisfactory for all tables.

Table 6-6: Results from the AHP evaluation

<table>
<thead>
<tr>
<th>Results</th>
<th>accu</th>
<th>drl_eff</th>
<th>blst_eff</th>
<th>design</th>
<th>cost</th>
<th>simp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tech</td>
<td>0.71</td>
<td>0.56</td>
<td>0.25</td>
<td>0.65</td>
<td>0.06</td>
<td>0.19</td>
</tr>
<tr>
<td>Train</td>
<td>0.21</td>
<td>0.32</td>
<td>0.50</td>
<td>0.25</td>
<td>0.24</td>
<td>0.08</td>
</tr>
<tr>
<td>Quo</td>
<td>0.08</td>
<td>0.12</td>
<td>0.25</td>
<td>0.10</td>
<td>0.70</td>
<td>0.74</td>
</tr>
</tbody>
</table>

Table 6-7: Final Score for HVC-AHP example

<table>
<thead>
<tr>
<th>Overall Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tech</td>
</tr>
<tr>
<td>Train</td>
</tr>
<tr>
<td>Quo</td>
</tr>
</tbody>
</table>
The decision-maker’s assessment coincides with the decision that was taken. The status quo option scored close to the technology option, most likely due to its high score in the heavily weighted ‘cost’ variable.

When asked, the decision-maker considered this CIA methodology to be applicable to the AQUILA technology. It was considered to be ‘very useful’; however, apprehension was expressed as to the acceptability of the method at higher management levels since the method requires a lengthy (1 hr.) explanation before the decision maker has confidence in using the method.

### 6.2 Case Study 2: CAES Technology & Ore Blending

This section presents the practical application of a level 3 CIA method for a level 3 technology. This case study was not intended to justify the technology, but rather to consider some alternative CIA methods. The discussion focuses on a single aspect of the ore blending project. The first subsection discusses the reasoning for selecting the single aspect of the project for justification. The second step in this case study is to present the methodology behind the justification. This will be followed by the interpretation of the results and the conclusions that can be derived from the study.

#### 6.2.1 Weakness in Current Justification of Ore Blending project.

The ore-blending project was never directly explained to the decision-makers who are responsible for the CAES technology acquisition. The AFE, entitled ‘Digital Radio Network’ (a copy is in the appendices) justifies the technology in terms of benefits to the mine. The benefits listed in the AFE are presented below.

- Reduction in data collection time (data collected automatically)
- Flexibility to expand up-coming technological tools
- Optimization of explosives loading
- Optimization of the planning and updating cycle between field and office systems.
- Better use of technical manpower for production control, geotechnical monitoring and evaluation, and blasting optimization.
- Improvement of data integrity as data will be accessible through CAES office wherever it is required. Visual interpretation of data allows the user to better inspect data for accuracy and integrity.
- Reduction in record keeping errors due to the fewer translations of data.
- Elimination of shovel delays due to data transfers.

The system was evaluated only on the benefits that would be achieved for the mine, not the mill. This is a significant limitation considering that the proposed ore-blending project would generate substantial savings. It is not known if this is a company-wide limitation (to restrict
capital asset purchases based on departmental needs), or if it was imposed on the evaluation due to the uncertainty of the ore-blending project.

The blending project, as discussed in the Chapter 5, was a proposal from the senior metallurgist, working in the mill. The senior metallurgist was unable to provide data or other expert opinion to support the assumptions. Therefore there may have been too much uncertainty in the project to be included in the AFE. This case study attempts to reduce some of the uncertainty concerning the assumptions of the project.

The uncertainties of new technology also encouraged management to be apprehensive about the acquisition of a radio network. Few such radio networks are currently used in mines. Site visits to a similar mine using the technology (Phelps Dodge's Morency mine) were planned for the senior mine engineer in November. An agreement between the Caterpillar supplier, Finning, has also been formed where the technology will be installed on a limited scale and as an evaluation. This would be similar to the suggestion of using value analysis, as discussed in chapter 3. The details of the commercial arrangements are understandably unavailable for publication; however, it can be mentioned that HVC will pay for this limited technological exposure.

The justification presented in this case study is incomplete. The full benefits of this technology to the company (including the mine, mill, overhead and environmental benefits) were not assessed. The purpose of this thesis was not to justify any particular technology, but rather to identify and evaluate the CIA methods that would be appropriate and to give examples. Therefore only some variables in the ore-blending project will be investigated in this case study.

The previous chapter described the ore-blending project. From the description, it can be seen that the nature of the ore is a variable that is uncontrollable. The ability to control blending, considering the current conveyor network, is also an uncertain variable. These two variables are discussed below.

Variability of the ore: Current ore hardness contours shows that the hardness of the ore is highly variable. However, if the variability in hardness in later stages of the mine life becomes much less (ore becomes of uniform hardness), then the benefits of a blending system will be eliminated. The minimum variability of the ore may be an important value to determine although for the purposes of this case study, average variability and hardness values are used.

Blending ability. Due to copper prices and the uncertainty of this project, little capital expenditure will be spent on the mine's blending ability (no capital purchases are planned for the next 2 years: the company predicts that the copper prices will increase at that time). The project must be justified using the equipment that is currently in-place. The network of
conveyors, trippers, surge piles, storage piles and dispatch systems have limitations that will not allow any possible blend. Considering the average (or most likely) hardness variability and values, an important question is: what is the best possible reduction in feed variability using the current materials handling network? This uncertain element will be the focus of the following study.

6.2.2 Simulation Description

Object-based simulation software (Extend4™ from Imagine That) and spreadsheets (Microsoft Excel™) were used to study the two uncertainties described above. Raw data was collected pertaining to the materials handling network. Due to the complexity of the network, the simulation was designed and constructed in ‘modules’. Some of the important assumptions within each module are described here.

6.2.2.1 Ore Generating Module

The ore generating module can be seen in Figure 6-2. This group of nodes generates discrete blocks of ore that represent 172 tons, i.e. one truck load. The module was linked to a spreadsheet where data could be easily changed as more accurate information was added to the model. The data entry table is seen in the figure below.

<table>
<thead>
<tr>
<th></th>
<th>Valley 1 &amp; 2</th>
<th>Lornex</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>Hardness</td>
<td>27.5</td>
<td>52.5</td>
</tr>
<tr>
<td>Block size</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Grade</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Block size</td>
<td>20</td>
<td>50</td>
</tr>
</tbody>
</table>

Random number generator nodes vary the ore grade based on known data such as ‘L1 Gr Min’, which represents the first ore loading station (a virtual shovel) in the valley pit (L1). The grade and hardness are varied independently; however, since grade was not an important variable to the success of the project, the relationship between the grade and hardness of the ore in the valley pit was not considered. The hardness of the ore was determined through the variables ‘L1Hr Gr Min’, ‘L1Hr Gr Max’, ‘L1 Hr Min’ and ‘L1 Hr Max’ that represent the minimum and maximum number of consecutive ore blocks with similar hardness and the minimum and maximum hardness of the ore blocks. These are connected to random number generators that use these parameters to create an entire blasted bench of single truck loads (when initially generated, one entity represents a 172 ton truck load, several thousand entries can be created, representing blasted muck).
6.2.2.2 Alternating truck allocations module

As discussed in the previous chapter, trucks have a tendency to dump into the same crusher despite the mill’s request for trucks to dump into both crushers in an alternating fashion. For example, a truck loading at a particular ore shovel would dump first into crusher 4, then on the next trip, into crusher 5. The ore blending project will use truck dispatch as the first stage of blending, where an algorithm would determine where each truck should dump (crusher 4 or crusher 5). Due to the complexity of such an algorithm, a simple alternating network of nodes was designed. Trucks leading from Valley shovel 1 first dump into crusher 4, then into crusher 5 on the next load. Figure 6-3 depicts these activity nodes on the model.

Figure 6-3: Alternating truck allocation, Extend™ Simulation

In developing such a model, several of the project’s potential difficulties were made evident. A simple optimization algorithm was unable to determine the optimum truck allocation and
ore blend simultaneously. There are several reasons for this difficulty. The first deals with the delayed outcome of altering the blend at the face. A delay will occur between the time of excavation and entry into the mill; therefore predictions must be made as to where the shovel will excavate the next ore block so that an appropriate blend can be computed. Other differences may occur due to feed rates along the network as the feed rate may change from the time of calculation and movement from the crusher to the surge pile.

6.2.2.3 Blending on Crusher Apron Feeder Module

As discussed in the previous chapter, the feeder apron capacity on the in-pit crushers is 500 tons (3 truck loads). The simulation assumes that the crushing and feeding action blends the ore. A ‘hierarchical’ (a node that contains several other nodes within it, a space saving technique) node was developed. The node is represented in the model as a white square and its contents appear as seen in the figure below.

![Diagram of Blending on Crusher Apron](image)

Figure 6-4: Blending on Crusher Apron, Extend™ Simulation

This network of nodes calculates the average grade and hardness of each block, then resets the value of each block’s attributes to the calculated averages. The ‘select’ node is used to route the elements into the three branches so only 3 consecutive truckloads of ore are blended. The ‘info’ nodes were used for debugging purposes. The ‘Get A’ nodes read the attributes of the entities passing through the node. The ‘Eqr’ nodes, in the blending module, calculates the average hardness and grade for the three elements passing through, then sends this value to the ‘SetA’ node where the average ‘Hardness’ and ‘Grade’ attributes are set to the 3rd element passing through. The ‘Batch’ node (the block with ‘demand’ written underneath) batches 3 element together and sets their attributes according to the values of the last element (whose attributes were set to the average values).
A similar node is used to blend the ore on the surge pile. Limited blending control is possible on the surge pile, where the controlling variables are the draw rates of the feeders below the pile. This form of blend optimization was not simulated.

6.2.2.4 Optimization of Feed onto Storage Piles Module

As discussed in the previous chapter, the run-of-mine from various crushers can be blended together so that an optimum blend is deposited on the three storage piles. There are limitations to the possible distributions. These possible blends are seen in the figure below.

An optimization algorithm was used to determine the X, Y, and Z variables. These represent the percentages of feed from each crusher to each pile.

![Figure 6-5: Distributions of X, Y and Z, for piles 1, 2 and 3](image)

Programming was required to calculate the X, Y and Z values in real time, using the hardness values of the ore blocks that were drawn from the surge pile or Lornex pit. To the author’s knowledge, no real-time optimization node exists for Extend4™. An optimization program on Excel™ was developed for a series of hardness values on a three dimensional array. The optimum blend distributions for five possible hardness values for crushers 4 and 5 and 2 possible hardness values for Lornex were calculated. The table below represents the array. The six digit figures in the table represent the X, Y and Z values for the blend distributions. Once this 6-digit value was determined, a calculation within the simulation separates the three values using a modulus function. An example is presented below the table.

<table>
<thead>
<tr>
<th>Lornex Pit 17 Hardness</th>
<th>Lornex Pit 22 Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>10150</td>
</tr>
<tr>
<td>35</td>
<td>120122</td>
</tr>
<tr>
<td>40</td>
<td>100108</td>
</tr>
<tr>
<td>45</td>
<td>180902</td>
</tr>
<tr>
<td>50</td>
<td>383801</td>
</tr>
</tbody>
</table>

Example of crusher 4 (45 Hardness Hd.), crusher 5 (35 Hd.) and Lornex (17 Hd.), and ideal blend figure (IBF - 383874), using equation;

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X = (IBF - MOD(IBF,10000))/1000000
Y= (MOD((IBF - MOD(IBF,100)),10000)/10000
Z= MOD(IBF,100)/100

Equation 6-1: Extraction of X,Y and Z figures from IBF

X = (383874 - MOD(383874,10000))/1000000 = 0.38
Y= (MOD((383874 - MOD(383874,100)),10000)/10000 = 0.38
Z= MOD(383874,100)/100=0.17

Using the X, Y and Z values, the hardness values of the resulting pile feed was calculated using the equations below.

Pile 1 Hardness = Lx*(1-Z)/(2-Z-X)+C5(1-X)/(2-Z-X)
Pile 3 Hardness = C4*(Y)/(X+Y)+C5*X/(X+Y)

Equation 6-2: Pile Hardness Equations

Where:

Lx – Lornex feed,
C4 – crusher 4 feed
C5 – crusher 5 feed

Pile 1 Hardness = 17*(1-0.17)/(2-0.38-0.17)+35(1-0.38)/(2-0.38-0.17)=29.75
Pile 2 Hardness = 17*(1-0.38)/(1-0.38+0.17)+45*0.17/(1-0.38+0.17)=29.75
Pile 3 Hardness = 45*(0.38)/(0.38+0.38)+35*0.38/(0.38+0.38)=40

The Excel™ optimization algorithm attempts to alter the distributions so that the piles conform to the average hardness possible in the hardness range. The equations below calculate how the average hardness of pile 1:

average ore hardness from source X = (Minimum. Hardness + Maximum Hardness)/2
(assuming uniform distribution)
average ore hardness to Storage Pile X = (Average from source 1 + Average from source 2)/2
(assuming identical production rates from both sources)

Equation 6-3: Average Ore hardness for Storage Pile X

Example: Storage Pile 2

average ore hardness from crusher 4 = (27.5 + 52.5)/2=40
average ore hardness from Lornex = \( (14.5 + 24.5)/2 = 19.5 \)

average ore hardness to storage pile 2 = \( (40 + 19.5)/2 = 29.75 \)

The node structure for the blend distributions and final pile hardness calculations are shown in Figure 6-6. The values of 500-ton (size of the elements following the blend at the crushers) slices of the storage pile are recorded onto an output file. The output file is read by an Excel™ spreadsheet that subsequently calculates the average deviation of the 500 ton elements for the entire simulation run. The simulation run is 1000 time units. The factor of time was not a consideration in this simulation since the variable under study was the variability of the storage piles. The simulation was run 100 times using the optimized distributions of X, Y and Z and a distribution where the X, Y and Z values were all 50, no matter what the hardness (this was to simulate the current methodology of blending the ore). The average deviations of the optimized and manual adjustment from the 100 runs and 3 piles were averaged and compared, see Figure 6-7 (data can be found in the appendix 6). The optimized blending was determined to have 11% lower variability than the assumed base case.

**Figure 6-6: Decision and Calculation Module for ideal blend**
6.2.3 Simulation Results

The simulation determined that an 11% reduction of variability would result from using an optimized blending algorithm. For each percentage reduction in variability, it was determined that it would result in increased recovery that may, in turn, could be considered an economical return. The chief metallurgist estimated a possible $12 million dollar increase in revenue; however, these are only preliminary estimates. More study would have to be conducted to determine the economic impact of each percentage reduction in ore variability.

6.2.4 Validity of the results

There are several major deficiencies in this particular simulation. The following sections describe these weaknesses.

6.2.4.1 Lack of real-time optimization algorithm

As discussed previously, the simulation software package, Extend4™, did not have an optimization algorithm within its object libraries. The simulation used a three dimensional array to determine the optimum blend. Due to the limitations of the simulation software, the distributions were calculated for hardness in 5 index point increments, as seen in Table 6-9, where the crusher 4 and 5 hardness values range from 30, to 50 in 5 point increments. Hardness values are rarely exact values once they reach the decision module of the simulation, introducing significant error as shown in Table 6-10. An optimization algorithm must be integrated into the system that is capable of pooling all available data. This source of
error increases the variability in the calculations, signifying that the estimates were an underestimate of the potential revenues.

Table 6-10: Example of Possible errors given 5 hardness increments

<table>
<thead>
<tr>
<th>Crusher Values</th>
<th>C4</th>
<th>C5</th>
<th>Lx</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>actual</td>
<td>32.2</td>
<td>47.0</td>
<td>23.0</td>
<td>5.57</td>
</tr>
<tr>
<td>Simulation</td>
<td>30.0</td>
<td>45.0</td>
<td>22.0</td>
<td>0.00</td>
</tr>
</tbody>
</table>

6.2.4.2 Lack of other blending control mechanisms

Due to the limited time and scope of this simulation justification, not all of the blending control mechanisms were designed and simulated. Several other blending mechanisms with limited or full control were listed in the previous chapter. Had these been added to the simulation, it is highly probable that the ore hardness variability would further decrease, thereby increasing potential revenue.

6.2.4.3 On-site characteristics not fully modeled

The effect of preventative maintenance (PM) and incidental shutdowns were not modeled in the simulation. Furthermore, production rates from each ore source were assumed to be equal in the simulation. Consumption rates from the various ore processing lines were neglected. These factors should be considered when designing the final blending project. Since, these factors reduce the amount of control over the ore blends, they will reduce the project's ability to blend better than the existing system (for example, the reduction in variability will be reduced from 10% to 7%).

6.2.4.4 Milling Characteristics

The simulation assumes that every grinding line processes ore at the same rates given identical hardness. Studies should be conducted to determine the optimal variability (or lack thereof) for each grinding line, based on maximizing profit. For example, if it is more profitable to grind variable ore on line B than line C, line C should receive the more variable blend. This study may increase the complexity of the final algorithm but a definite increase in profit should be expected.

6.2.4.5 Ore Variability

The ore on-site does not have a truly uniform distribution of ore hardness between the values 27.5 and 52.5. At the time of the simulation development, limited information was available on ore hardness, since the ore hardness contours were not yet fully available. Current information suggests that the ore hardness in the Valley pit varies between 5 and 65. The
mean hardness is found to be around 40 and the distribution resembles a flat normal curve skewed to the right. This new information could be added to the simulation; however, significant changes to the blending module would be required, which may decrease the ability to provide the optimal blend. For example, not all ore hardness blends would provide the ideal hardness at the storage pile. At extreme values, errors (differences between the ideal 29.75 for Pile 1 & 2 and 40 for Pile 3) would appear. Table 6-11 reveals the errors that result on the various storage piles, despite having an optimal mix (the least amount of error possible).

Table 6-11: Divergence from ideal blend at extreme feed hardness values

<table>
<thead>
<tr>
<th>Lornex Pit: 17 Hardness</th>
<th>Lornex Pit: 22 Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 35 40</td>
<td>30 35 40</td>
</tr>
<tr>
<td>30 30 30</td>
<td>30 30 30</td>
</tr>
<tr>
<td>35 35 35</td>
<td>35 35 35</td>
</tr>
<tr>
<td>40 40 40</td>
<td>40 40 40 40 40</td>
</tr>
<tr>
<td>45 45 45</td>
<td>45 45 45 45 45</td>
</tr>
<tr>
<td>50 50 50</td>
<td>50 50 50 50 50</td>
</tr>
</tbody>
</table>

From the table above, it can be seen that when the Valley sources (crusher 4 and 5 feed) are at extremes, divergence from the ‘ideal’ blend increases. When considering on-site hardness values of 65, it is reasonable to assume that a great deal of divergence from the ideal blend would occur, given a similarly high hardness from the other Valley sources. This may reduce the reduction in variability possible (hence the value of the enabling technologies).

6.2.4.6 Limitations of the Hardware

Large conveyor belts, rock boxes and conveyor belts may not be able to vary their speeds, flows or feed rates as easily as represented in the simulation. With increased use comes increased maintenance costs. Therefore the limitations of the hardware should be considered when the project is being designed.

Examples of the simulation’s weakness in overestimating the hardware’s capacity can be related to conveyor belts and storage piles. In some cases, the ideal mix would be achieved by sending a great deal of ore onto a single belt, while leaving another empty. For example, consider the ‘ideal’ blend when the feeds are at values: C4-35, C5-50 and Lx-22. The resulting blend sends 60% of the feed from crusher 4 and almost all of the crusher 5 feed onto the belt leading to pile 3. The belt may not have the capacity to hold this amount of ore. A further problem occurs if the situation lasts longer than the active cone on pile 2 because relatively little ore is being sent to that pile. The ‘ideal’ blends that choke off ore to certain piles are presented in the table below.

Masters of Applied Science Thesis. Sean Dessureault
Table 6-12: Neglected Storage Piles

<table>
<thead>
<tr>
<th></th>
<th>Lornex Pit 17 Hardness</th>
<th>Crusher 4 hardness</th>
<th>Lornex Pit 22 Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30 35 40 45 50</td>
<td>30 35 40 45 50</td>
<td>30 35 40 45 50</td>
</tr>
<tr>
<td>30 P3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35 P3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>P1 P1</td>
<td>P1 P1</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>P2 P2 P1 P1</td>
<td>P2 P2 P1 P2 P1</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This situation may reduce the project's ability to reduce the ore variability. The simulation did not take these hardware characteristics into account; however, the final project design should.

6.2.5 Application of Simulation Results

The simulation results would normally not be applicable at this stage since financial costs and benefits have not been determined. The simulation results would apply to the financial results by decreasing the uncertainty thereby allowing the hurdle rates to be decreased. The financial benefits estimated by the simulation (once a value per percentage reduction in ore variability has been determined) may be included in the financial appraisal of the project if management is satisfied with the results. These results can be further analyzed using decision trees. This technology may enable similar projects to be implemented that would produce other benefits. The example below considers all the possible projects that the technology would enable. Probabilities were estimated based on the author's assumptions.

Table 6-13: Decision Tree Probabilities for Blending project

<table>
<thead>
<tr>
<th></th>
<th>Prob. of immediate implementation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Success 0.40</td>
<td>Failure 0.60</td>
</tr>
<tr>
<td>If indicator ...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>gives positive evaluation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Success 0.70</td>
<td>Failure 0.30</td>
<td></td>
</tr>
<tr>
<td>Implement 0.90</td>
<td>Abandon 0.10</td>
<td></td>
</tr>
<tr>
<td>gives negative evaluation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Success 0.10</td>
<td>Failure 0.90</td>
<td></td>
</tr>
<tr>
<td>Implement 0.10</td>
<td>Abandon 0.90</td>
<td></td>
</tr>
</tbody>
</table>
Table 6-14: Decision Tree Numerical Values for Blending Project

<table>
<thead>
<tr>
<th>Values in '000,000's</th>
<th>Costs</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project</td>
<td>($2.00)</td>
<td>$7.0</td>
</tr>
<tr>
<td>Radio sample</td>
<td>($0.03)</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 6-8: Decision Tree for Blending Project

The decision tree above predicts that the project should be accepted, given the assumptions; however, when considering the estimated utility curve for HVC (derived from conversation with the superintendent of engineering), this conclusion may not be as certain. The utility curve and subsequent utility decision tree below show the inconclusive results of the evaluation, given the assumptions.

Figure 6-9: Utility Curve for blending project
6.2.6 Conclusion and Recommendations for Case Study 2

Several conclusions can be drawn from the above discussion of case study 2.

- The analysis of the simulation revealed several weaknesses of the simulation. These weaknesses must be identified prior to submission of the appraisal to the decision-maker. Failure to identify the shortcomings of the justification may weaken the appraisal and thereby reduce certainty.

- Uncertainty is one of the most important characteristics that the above simulation attempts to reduce. Revealing some of the shortcomings of the project, analyzing the potential benefits, and documenting these findings reduce the uncertainty of the project, which in turn increases its value. The simulation above, when presented to HVC decision makers and project evaluators, considered it ‘very useful’. Knowledge of the value of some variables would allow the evaluators to speak to the decision-makers, through HVC’s sound management relations, about the potential benefits of the project.

- Despite the positive assessment from HVC staff, some apprehension was expressed as to the validity of the simulation results. Since this is their first exposure to this form of justification, it is understandable that some apprehension was expressed. Through further dissemination of these techniques throughout the industry, increased credibility would be attributed to the conclusions derived from these CIA methods.

- As discussed previously, the justification of the CAES technology is incomplete. Nevertheless, at this stage in the evaluation of such a technology, no further simulation
was required. The justification simulation should focus on justifying further study of the benefits and costs of the system. More in-depth study and evaluation should be the result of a positive judgment (by the decision-makers) of the above justification. The simulation revealed many of the potential costs and benefits attributable to the project and these observations can be used as a template for further study.

- HVC management has decided to continue studying the ore blending project; however, considering the current price of copper, little hope is expressed in being allowed to purchase capital equipment.

- As can be seen from most of the conclusions above, the perception of uncertainty is a major concern. No psychological experimentation or studies were conducted relating to decision-maker’s perceptions of risk; however, this is an important topic and should be mentioned. The techniques presented in this paper attempt to dispel prejudices against new technologies through analytical justification tools.
Chapter 7 – Conclusions and Recommendations

7 Conclusions and Recommendations

7.1 Summary of the Investigation

The primary objective of this thesis is to identify, evaluate, and demonstrate the usefulness of various decision-making tools for the justification of advanced technologies in the mining industry. It has focused particularly on the technologies that relate to the evolution of automation in surface mining. The work nonetheless is considered applicable to all forms of mining. This investigation has addressed this objective by:

1. Identifying the need for new technology (Chapter 1);

2. Identifying the need for CIA methods that are better suited for advanced technology (Chapter 2-3);

3. Recognizing the requirement for less reliance on single value comparative justification schemes that incorporate too little information (Chapter 1-3);

4. Discussing the need to focus on long term profitability as opposed to short-term gain (Chapter 3);

5. Identifying CIA methods and technology classification schemes based on manufacturing operations management theory and practice, and adapting these for the mining industry (Chapter 3–4);

6. Discussing the applicability of manufacturing operations management in the mining industry (Chapter 3);

7. Identifying weaknesses in current capital appraisal approaches when applied to new technology (Chapter 3-4);

8. Providing the theory and mining-based hypothetical examples of several key CIA methods (Chapter 4);

9. Providing practical examples of some of the key assessment approaches based on open pit technologies (Chapter 5);

10. Determining management’s impression of the evaluation methods for the practical examples (Chapter 5).
7.2 **Significant contributions made by this thesis include:**

1. A comparative review of both manufacturing and mining to show the similarities of the two industries in an attempt to facilitate the flow of innovation from manufacturing into mining (Chapter 3);

2. The development of a classification scheme to allow technology evaluators to apply the correct justification method to an appropriate level of technology (Chapter 3).

3. A comprehensive simulation of a material handling network that reveals the usefulness of simulation as an analytical tool design and justification tool (Chapter 5);

4. The identification of the need to integrate the mine and the mill operations (Chapter 6).

7.3 **Conclusions**

7.3.1 **Thesis Stimulus**

The area of study of this thesis was the application of new capital appraisal techniques for advanced technology in the mining industry. This subject was inspired by the need for the mining industry to use more technology that increases efficiency, environmental conservation, safety and responsible use of resources. These technologies usually have benefits that are qualitative or difficult to account for financially. Such technology need to be appraised using methods that can account for all costs and benefits. The manufacturing industry was faced with similar problems justifying technologies whose benefits were mostly qualitative. Tools were developed by the manufacturing industry that can be used to accurately appraise all costs and benefits of new technology currently available for use in the mining industry.

7.3.2 **Review of the CIA methods**

A classification scheme was suggested that aids those undertaking the appraisal to select the methods that best suit a particular technology. Therefore, as the complexity and integration of the technology increases, the complexity and involvement (time required, expense, etc....) of the method most suitable for that particular technology similarly increases. Level 1 technology’s benefits are well understood and usually quantitative. Traditional appraisal techniques such as NPV and IRR can be used to accurately appraise this level of technology. Level 2 technology integrates the activities within a process. For example, integrating the GIS with the engineering LAN allows the integration of survey and engineering activities into a single engineering design process. These benefits are more qualitative such as increased efficiency, design quality, safety, and flexibility. Methods such as programming models, options pricing and scoring models are ideal for this level of complexity. Level 3 technology integrates entire processes. Since mining processes are large, information
intensive and complex, level 3 CIA methods are used to understand and predict the effects of certain changes on the overall system. Level 3 CIA methods, such as simulation and decision analysis, capture large amounts of information, and are more useful for modeling these complex systems. All appraisals require the application of financial appraisal methods, although, the importance of the conclusions should decrease with each increase in technology level. Improvements in the accuracy of these methods can be made by knowing the weaknesses of these methods such as the tendency to ignore qualitative benefits, making false assumptions about the future, focusing on the short term, and management’s tendency to rely on hurdle rates. Managerial practice is a key issue in CIA. Managers must understand and trust the appraisal method before basing a decision on the data that the method provides. Examples of these methods, both hypothetical and practical were provided in this thesis to help advance the credibility of these CIA techniques.

7.3.3 Review of the Main Conclusion of the Practical Applications

The practical application of new technology-oriented appraisal techniques has set the industrial context of this work with respect to past initiatives in the manufacturing industry and future directions in the mining industry. Several key issues, based on managerial practice, were identified in the application of these techniques in the context of the case studies.

The issue of managerial acceptance of these appraisal methods is prevalent since, without the understanding or recognition of the decision makers, the tools described in this thesis will not be used in the mining industry. Managerial attitude further impacts on the level of effort that should be applied to an evaluation. The effort and expense of an appraisal should be directly proportional to the perceived level of complexity and stage of development of the project under evaluation.

The second issue of managerial practice that is prevalent throughout every stage of design and implementation of a new mining technology is the over-reliance on empirical techniques. Scientific management tools have become much more accessible due to new inexpensive software packages such as spreadsheets and simulation programs. More accessible and user-friendly programs should facilitate mining’s divestiture of the rule-of-thumb.

Finally, managerial reliance on single value comparative appraisal methods such as the NPV are still useful; however, their perceived relevance should be reduced. Uncertainties should not be taken into account by the application of blanket hurdle rates that do not take in account various scenarios or the true situation.

Middle management interest and response to the case study results at HVC, show that the methods described in this thesis are applicable for advanced technology assessment.
Management at HVC recognizes the new technology's benefits such as increased competitiveness, safety, efficiency, environmental conservation and intelligent planning and design. This thesis has aimed to advance the ability of the mining industry to adopt new technologies so that the benefits received will revitalize the mining industry.

### 7.3.4 Validity of the Approach

The ultimate purpose of this thesis is to provide current mine management with the will and knowledge required to accurately appraise new technologies. The methodology of the thesis intended to provide purpose, reasoning, theory, and, examples. This thesis began by discussing the purpose and reasoning behind why this topic should be explored. Definitions were provided to clarify terms that were used repeatedly throughout the thesis. The classification scheme and appraisal methods described in this thesis were originally developed for the manufacturing industry. A discussion of the validity of such methods in a mining context was needed. The methods and examples were provided to illustrate the usefulness of these methods. Finally, practical examples of these methods, in the appraisal of advanced technologies, provided evidence that these methods can be used in a mining context. The challenge of communicating this message to industry decision-makers still remains.

The methodology of this thesis is lacking in promoting these CIA methods to the industry. Marketing these methods to decision-makers and project evaluators in venues, such as workshops, would have allowed a greater appreciation of the problems involved in evaluating the true value of new technology. Advancing the skill level of management skills in mining to levels equal to those found in other industries should have been part of the final plan of the thesis.

### 7.4 Recommendations

Future work should include the following:

1. Efforts should be made to expose these CIA methods to the mining industry, especially to higher level decision-makers, in order to promote awareness of appraisal methods for advanced technologies;

2. The analytical tools employed in this study, i.e. Decision Analysis and AHP, justify further refinement. This should be achieved through further practical applications. For example, using Azzone's options approach, linear optimization, valuation of flexibility, and decision analysis in various other applications will allow refinements of the procedures to be made;
3. The confidence intervals relating to the validity of simulation results should be identified: the precision of the results of the simulation should be relative to the amount of money that is to be invested in the next step of evaluation or implementation.

4. Alternative CIA methods should be introduced into tertiary mining education, identifying the weaknesses of traditional methods in their application to new technologies;

5. A valuable step in the development of appraisal technique could be to evaluate alternative techniques in differing corporate cultures or social contexts, for example as would be found in other countries.
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9 List of Appendices

Appendix 1: Integer Programming
Appendix 2: Goal Programming
Appendix 3: AFE for GPS drill
Appendix 4: AFE for Radio Network
Appendix 5: HVC Drill monitoring audit & associated appendices
Appendix 6: Simulation Results
Appendix 7: Options Pricing theory (from Luenberger, 1998)
9.1 Appendix 1: Integer Programming

Optimization models where some or all of the variables must be integers are called integer programming (IP) models. IP uses math similar to LP modeling. The complex and intricate math involved in IP is not a key aspect of this thesis and therefore will not be explained or presented. An example of how to build and execute a model on a modern spreadsheet tool is provided. Microsoft's Excel program is used to formulate and solve the IP model.

Given the following situation: Minecomp, an underground base metal mine, is considering investing in several different technologies. Mine comp is considering upgrading its communications system to provide possible automation. The monetary values of both the investment and estimated return are provided in the table below. Some restrictions are imposed on the model due to technology incompatibilities. These restrictions are also presented below.

Table 9-1: Data for Minecomp Example

<table>
<thead>
<tr>
<th>Investment</th>
<th>Description</th>
<th>Abbreviation</th>
<th>Cash Required (in thousands)</th>
<th>NPV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Leaky feeder (low capacity)</td>
<td>LFL</td>
<td>$150</td>
<td>$200</td>
</tr>
<tr>
<td>2</td>
<td>Leaky feeder (high capacity)</td>
<td>LFH</td>
<td>$250</td>
<td>$400</td>
</tr>
<tr>
<td>3</td>
<td>Distributed antenna system</td>
<td>DAS</td>
<td>$400</td>
<td>$600</td>
</tr>
<tr>
<td>4</td>
<td>Radio tech 1</td>
<td>R1</td>
<td>$150</td>
<td>$500</td>
</tr>
<tr>
<td>5</td>
<td>Radio tech 2</td>
<td>R2</td>
<td>$100</td>
<td>$1,750</td>
</tr>
<tr>
<td>6</td>
<td>Both Radio techs</td>
<td>RR</td>
<td>$250</td>
<td>$3,500</td>
</tr>
</tbody>
</table>

Table 9-2: Restrictions for Minecomp Example

<table>
<thead>
<tr>
<th>Restrictions:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio tech 1 cannot function with LFL</td>
</tr>
<tr>
<td>DAS cannot function with LFL</td>
</tr>
<tr>
<td>Budget of $730,000</td>
</tr>
</tbody>
</table>

The main components to this assessment are:

- The investments chosen
- The cash required for the investments
- Total NPV of the chosen investments

This model was developed on Microsoft Excel for Office 97. It can be developed on any version of Excel from Excel 5 to the most recent. The data was entered into the spreadsheet as seen in the figure below. Enter any value in the range from B2: G2. (The values shown in

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118 Winston, et. al., Ibid., pp.214
the figure is the optimal solution.) The total cost value is the total cost of investing in the selected investments, therefore in cell B8, enter the formula

=SUMPRODUCT (B2:G2,B4:G4)

This function multiplies the array representing the selected investments with the array representing the investment costs. The total NPV of the accumulated projects can be calculated using the same function, except the range B4:G4 is replaced by the range B6:G6.

**Figure 9-1: Optimal Solution for Minecomp Example**

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Investment decision</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Restrictions</td>
</tr>
<tr>
<td>4</td>
<td>Investment Cost</td>
<td>$150</td>
<td>$250</td>
<td>$400</td>
<td>$150</td>
<td>$100</td>
<td>$250</td>
<td></td>
<td></td>
<td>RR x R1 0</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RR x R2 0</td>
</tr>
<tr>
<td>6</td>
<td>NPV</td>
<td>$200</td>
<td>$400</td>
<td>$600</td>
<td>$500</td>
<td>$1,750</td>
<td>$3,500</td>
<td></td>
<td></td>
<td>DAS x LFL 0</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>R1 x LFL 0</td>
</tr>
<tr>
<td>8</td>
<td>total cost</td>
<td>$650</td>
<td>&lt;=</td>
<td>$730</td>
<td>Budget</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>total NPV</td>
<td>$2,550</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The solver is activated by selecting ‘Solver...’ from the ‘Tools’ menu. When the solver window appears, enter the following:

1. Objective, Choose cell B10 as the objective to maximize
2. Changing cell. Select the range B2:G2 as the changing cell
3. Constraints. Select range B2:G2 as binary entries. Next, make the budget constraint by making total costs (B8) equal or less than (D8). The restrictions in the table below represents the products of the two binary values. In order to have either RR or R1 (and not both), the product of the two integers must be equal to zero.
As can be seen from the previous figure, the solution to the problem would be to invest in a DAS, while using radio technologies 1 and 2.
9.2 Appendix 2: Goal Programming

Goal programming is ideal for situations where a company wants to achieve several objectives, given limited resources. Sometimes it is impossible to realize all the objectives simultaneously, but in the solving process, the solution is usually optimized. If the company cares to prioritize its objectives, goal programming can still be used. This method of prioritizing objectives is called a preemptive goal programming approach (will not be explained here but readers are encouraged to review the references).

Given the following example:

An open pit mining company, OPMC, would like to improve its drilling operations. Management identified three key variables that measure drill performance. The mill would like specific size distribution, therefore fragmentation is a key variable. Due to the geological conditions, accurate drill position is another important variable. Finally, the drilling operation is taking too much time to set-up the drill and begin drilling therefore set-up time is the final variable.

Management has identified two possible solutions. The first is to undertake an intensive operator-training program. There is an incremental improvement in the three key variables governing drill performance, as seen in the table below. The second solution is the purchase of a drill navigation package offered by Aqmod, a fictional mining technology provider. Each navigation package purchased, provides an incremental improvement in the three drill improvement variables. This data is summarized in the tables below.

Table 9-3: Goals for OPMC Example

<table>
<thead>
<tr>
<th>Description</th>
<th>Abreviation</th>
<th>% improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>goal 1: improve fragmentation</td>
<td>Frag</td>
<td>31%</td>
</tr>
<tr>
<td>goal 2: improve blast hole position</td>
<td>Pos</td>
<td>20%</td>
</tr>
<tr>
<td>goal 3: decrease set-up time</td>
<td>S-t</td>
<td>30%</td>
</tr>
</tbody>
</table>

Table 9-4: Improvement Methods for OPMC Example

<table>
<thead>
<tr>
<th>Description</th>
<th>Abreviation</th>
<th>Frag</th>
<th>Pos</th>
<th>S-t</th>
<th>Cost/unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>method 1: Higher level of training</td>
<td>Training</td>
<td>1%</td>
<td>2%</td>
<td>3%</td>
<td>$ 3,300</td>
</tr>
<tr>
<td>method 2: Aqmod drill platform</td>
<td>Aqmod</td>
<td>17%</td>
<td>8%</td>
<td>11%</td>
<td>$80,000</td>
</tr>
</tbody>
</table>

A spreadsheet model, similar to the integer programming model above, will be formulated. The main components to this model are listed below:

- Number of improvement method units purchased

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Winston, et. al., Ibid., pp. 338
Appendix 2: Goal Programming

- Cost of the methods
- Overall improvement

The spreadsheet model was formulated as shown in the figure below. (The values represent the optimized solution.) The only computations necessary are total cost and overall improvement. The total costs are calculated using the following function:

\[\text{=SUMPRODUCT($B$8:$C$2,B6:C6)}\]

The overall improvement is also calculated in the above fashion, where B6:C6 replaced by B2:C2 and the function is copied to the cells below, so that all the improvements can be calculated.

**Figure 9-3: Optimal Solution for the OPMC Example**

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Fragmentation</td>
<td>1%</td>
<td>17%</td>
</tr>
<tr>
<td>3</td>
<td>Position</td>
<td>2%</td>
<td>8%</td>
</tr>
<tr>
<td>4</td>
<td>Set-up time</td>
<td>3%</td>
<td>11%</td>
</tr>
<tr>
<td>6</td>
<td>Cost/Unit</td>
<td>$3,300</td>
<td>$80,000</td>
</tr>
<tr>
<td>8</td>
<td>number purchased</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>Cost constraint</td>
<td>total cost</td>
<td>Budget</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>$169,900</td>
<td>$170,000</td>
</tr>
<tr>
<td>13</td>
<td>Improvement</td>
<td>Goal</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Frag</td>
<td>37%</td>
<td>&gt;=</td>
</tr>
<tr>
<td>15</td>
<td>Pos</td>
<td>22%</td>
<td>&gt;=</td>
</tr>
<tr>
<td>16</td>
<td>S-t</td>
<td>31%</td>
<td>&gt;=</td>
</tr>
</tbody>
</table>

The solution is found using the Solver tool provided with Excel.

As in the previous problem, the optimal solution is found using the Excel Solver, activated through the ‘Tools’ menu. When the solver window appears, enter the following (the final solver window should look like the figure below):

1. Objective; there is no target cell for this problem. An optimum solution will be solved automatically, taking into account all the constraints.

2. Changing cells; select the range B8:C8 as the changing cells, and constrain the range to non-negative values

3. Improvement constraint: select the column B14:B16, as greater or equal to the goal column, in this case being E14:E16.
4. Budget Constraint: select the cell B11 as being less than or equal to cell E11.

Figure 9-4: Solver Window for OPMC Example

The solution obtained is shown in the figure at the beginning of the example. The optimal solution is to train three operators, while purchasing two Aqmod drill packages. Changing the estimated improvement values incurred from the two methods can alter the solution. Therefore this solution is only as valid as the estimates.
9.3 Appendix 3: Original AFE

DRILL NAVIGATION AND MATERIAL RECOGNITION SYSTEM

PROPOSAL:

It is proposed to purchase a drill navigation and material recognition system for #20-10 Drill at a cost of $147,000.

JUSTIFICATION:

The newest BE49RII drill, #20-11 has recently been equipped with the Aquila drill navigation system. This enables real time location of the drill in three dimensions. Displaying the positional data on a moving map display, the operator can navigate the drill to within 30cm. of the desired location. Once the drill is leveled and the hole begun, the system automatically determines the collar elevation and corrects drill hole depths to achieve consistent bench heights. The use of traditional surveying is minimized for both staking and actual hole pick ups.

At Highland Valley Copper, one of the greatest demands on surveyor’s time is laying out blast holes and picking up actual drill hole locations. The actual drill hole is sometimes up to 0.5m or so away from the planned location; this is partly because of the terrain on the blast pattern and partly because of the difficulty in seeing the stakes as the drill moves over the stake. Stakes tend to be knocked over by the trailing electric cable and by vehicles such as water tankers and service vehicles driving on the pattern. Stakes also get lost in the snow and mud, thus actual locations may easily differ from those planned. There are considerable advantages to be achieved in locating drill holes by an “on drill” computer. GPS provides the locating ability for such a tool. Precise drill positioning and the ability to accurately determine the hole location in three dimensions offers many benefits. Tests at the Fording River Mine have shown that accuracies of better than 30cm. are possible. This is less than a hole diameter and better than a drill operator generally achieves by eye.

Currently, the Modular Mining System records the time to drill each hole from which maps of penetration rate are drawn. This is a very coarse measurement of hardness, since the penetration rate is affected by such variables as pulldown pressure, bailing air velocity and rock hardness. An accurate knowledge of the ore hardness is important for correct blast design, fragmentation and crusher/mill throughput. By monitoring a number of variables and using an expert system, real time automated analysis of drill variables is possible. Thus, hard versus soft ground or fractures can be displayed and mapped, resulting in optimum blasting and accurate information for hardness blending.
Highland Valley Copper has a fleet of two BE 49RII-120 Drills, one of which is already equipped with a drill navigation system. This drill is equipped with two Trimble 7400 MSI GPS receivers, to give drill position and heading. The attitude of the drill is measured by the BE Programmed Drill Control System. An Aquila Advanced Monitoring Platform (AMP), located in the drillers cabin, processes this data to enable real time location and positioning of the drill. An operator's screen displays a moving map which shows the drill's location relative to the blasthole locations.

The expected benefits of a drill navigation and materials recognition system are:

- a reduction in survey overtime for pattern staking and hole pickups. Manpower reductions have already been made in the mine technical group in anticipation of labour savings from the GPS drill system.
- a reduction in the consumption of survey materials.
- the ability to drill patterns more accurately both by position and depth. Thus, drillers will be more accountable for deviating from the drilling plan as a result of quicker hole pickups and on-line reports.
- each hole gets an accurate collar elevation and the hole depth can be adjusted, producing more even benches and less wear and tear on shovels and trucks.
- explosive strength can be adjusted according to the measured drillability, thus improving explosives consumption and fragmentation. Optimizing fragmentation will improve diggability reducing wear on shovels, trucks and crushers and improve mill throughput.
- drill navigation is an essential step on the route to one man, multiple drill operation and automation.
- being able to better measure rock hardness will improve the ability to blend the ore feed to the mill.
- automated drill hole surveying and material recognition will provide information for blast design and provide an opportunity for a more automated and productive explosives loading system.

COST ESTIMATE:

The cost of drill navigation and materials recognition is as follows:

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill navigation hardware and software</td>
<td>US$ 70,000</td>
</tr>
<tr>
<td>Materials recognition hardware and software</td>
<td>US$ 13,000</td>
</tr>
<tr>
<td>Installation, commissioning and training</td>
<td>US$ 12,000</td>
</tr>
<tr>
<td>Total Aquila Costs</td>
<td>US$ 95,000</td>
</tr>
<tr>
<td>Bucyrus International modifications</td>
<td>US$ 7,000</td>
</tr>
<tr>
<td>Sub-Total</td>
<td>US$102,000</td>
</tr>
<tr>
<td>Exchange rate CDN $1.34 = US$1.00</td>
<td></td>
</tr>
<tr>
<td>Sub-Total</td>
<td>$137,000</td>
</tr>
<tr>
<td>P.S.T.</td>
<td>$10,000</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$147,000</td>
</tr>
</tbody>
</table>
Justification

Page 3

FINANCIAL ANALYSIS:

The drill navigation and materials recognition system can be purchased for $147,000. It is recommended for the following reasons:

- A discounted payback period of 1.3 years (see Appendix I)
- An IRR of 75.1%
- Projected annual operating savings $146,000 (see Appendix II)
- The opportunity to improve the fragmentation of the blasted rock and thus crusher and mill throughput.
- The opportunity to reduce drilling and blasting costs and shovel, truck and crusher maintenance costs.

The cost estimate exceeds the original $100,000 budgeted, as the budget was set prior to the system being available in its present form. A total of $354,000 has been budgeted for GPS related projects, with a remaining balance of $209,000 unspent. It is planned to initiate this project prior to the end of 1996, with commissioning planned by the end of the first quarter of 1997.

ENG/MR96080
November 1996
9.4 Appendix 4: CAES AFE

DIGITAL RADIO NETWORK

PROPOSAL:
It is proposed to purchase a digital radio network to provide a high capacity data radio link between the Engineering office and field equipment.

JUSTIFICATION:
Like many mines worldwide, Highland Valley Copper continually seeks tighter integration between mine planning and mine operations. A tremendous reduction in computational costs and advances in software capability have led to the widespread use of distributed computer systems in mine planning. Excavation plans and blast designs are all in digital form and many "earthwork" projects such as ramps, dumps and reclamation are also being designed digitally.

Until recently, transferring these plans to mine operations required costly, manpower-intensive surveys and staking to ensure the mining equipment worked to plan. In turn, acquiring sufficient "as built" information for the next planning stage required additional surveying, often becoming a process delay. In both cases, the transfer from office to pit and vice versa, introduces time delays which tend to promote reactive, rather than proactive decisions. Each manual translation step introduces "opportunities" for error and "filtering" by less informed individuals. In addition, surveying is made more difficult by climate and terrain. Stakes can be obscured or displaced during the mining process.

The same computational cost and technological advances which have led to digital mine planning have also enabled the break away from manual surveying and staking. Significant breakthroughs in sub-centimetre, high speed GPS receivers has allowed kinematic GPS survey instruments to replace optical total stations in many situations. This technology now enables mining machinery to accurately determine their position relative to plan in real time, without survey stakes.

Over the past 18 months, the mine has invested a considerable amount of money in GPS based navigation systems for the three 49R drills and the new P & H 2800 shovel. During 1998, it is planned to extend this technology to the rest of the P & H 2800 fleet and two or three Cat D10 track dozers. In addition, two of the drills are equipped with rock recognition software that operates in conjunction with the navigation system.

Currently, data is uploaded and downloaded manually via a laptop computer. This is a labour intensive process that also negatively impacts on the machine production. New bi-directional, high speed wireless data communications enable a real-time link between mine plans and current field status, thus keeping engineering and operations "in sync".

The Caterpillar digital radio is a part of the new "Computer Aided Earthmoving System" (CAES), that has been developed in partnership with Trimble Navigation - a leading GPS and radio technology company. This system provides near real-time integration of planning and operations and takes advantage of state-of-the-art digital, spread spectrum radio. The high bandwidth radio provides a wireless Local Area Network (LAN), able to download current plans direct from the office. The bi-directional radio also allows Managers, Supervisors, and Engineers to access data from connected machines across the entire mine. The focal point of the software is METS Manager (see fig. 1). Data is seamlessly translated from mine plan to CAT format for transmittal to the pit. The METS Manager also manages the radio system.
scheduling and executing all data radio transmissions. After conversion to CAT format, the METS Manager downloads plans to machines. A comprehensive Digital Elevation Model is maintained in CAES office. To ensure currency of data, METS Manager periodically polls machines for new data and updates CAES office. The updated topography can be exported back to the mine planning software as required to ensure synchronization of planning with operations.

Figure 1: Schematic of the METS System

The installation of a digital radio network enables the mining equipment to become concurrent production measurement tools, tracking excavated and filled areas, blast patterns and rock hardness. CAES office is available to any authorized persons on the mine’s LAN to view exactly what is happening in the pit.

The expected benefits of a digital radio network are:

- To provide supervision with better monitoring tools and thus reduce losses such as ore/waste reversals.
• Dramatically reduce the time required to collect data.

• The provision of a digital radio network is an essential step if the use of high tech tools such as GPS and rock recognition are to be continued and expanded.

• To provide an essential step in the optimization of explosive loading using actual drilled results.

• To optimize the cycle between field and office systems.

• To leverage existing investments in technology. The Partnership has already made a significant investment in mine planning software, GPS and other monitoring and control systems. The proposed system will provide access to important information for those who need it when they need it.

• To promote better use of technical manpower for production control, geotechnical monitoring and evaluation, and blasting optimization.

• Improvement of data integrity as data will be accessible through CAES office wherever it is required. Visual interpretation of data allows the user to better check data for accuracy and integrity.

• A reduction in record keeping errors as there are fewer translations of data.

• Elimination of delays to shovels due to data transfers.

**COST ESTIMATE:**

The cost for the digital radio system is as follows:

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spread Spectrum radios</td>
<td>US $35,000</td>
</tr>
<tr>
<td>METS Manager software</td>
<td>US$30,000</td>
</tr>
<tr>
<td>CAES Office software</td>
<td>US$30,000</td>
</tr>
<tr>
<td>Shovel and Drill Upgrade</td>
<td>US$33,000</td>
</tr>
<tr>
<td>Installation &amp; Training</td>
<td>US$25,000</td>
</tr>
<tr>
<td>Sub-total</td>
<td>US$163,000</td>
</tr>
<tr>
<td>Exchange Rate US$1.00 = Cdn</td>
<td>$1.42</td>
</tr>
<tr>
<td>Sub-total</td>
<td>Cdn$231,000</td>
</tr>
<tr>
<td>Repeater Installation hardware</td>
<td>$15,000</td>
</tr>
<tr>
<td>Office PC</td>
<td>$3,000</td>
</tr>
<tr>
<td>Total</td>
<td>$249,000</td>
</tr>
<tr>
<td>PST @ 7%</td>
<td>$17,000</td>
</tr>
<tr>
<td>Total Including Tax</td>
<td>$266,000</td>
</tr>
</tbody>
</table>
FINANCIAL ANALYSIS:

The digital radio system can be purchased for $266,000, and is recommended for the following reasons:

- A discounted payback period of 1.0 years (see Appendix I)
- An IRR of 92.8% and a net present value of $659,000.
- Projected annual operating savings of $412,000. (See Appendix II)
- Digital radio is essential for the effective use of GPS, rock recognition, etc. in the mine. It will also provide an important link in the ongoing mine-mill optimization plans.
- Although difficult to quantify, the value of better and more immediate information to Management, Engineering and Supervision is very important if the quality of decisions is to be improved.
- With the implementation of stakeless blast patterns and digital maps for shovels, there is a need for field supervision to have access to the digital maps in the field for both supervisory and safety reasons.
Highland Valley Copper
Drill Navigation and Material Recognition System
A.F.E. post audit 96-065

July, 1998
1 Executive summary

At the suggestion of Mark Richards, a post audit was undertaken on AFE 96-065 (Purchase of a Drill Navigation and Material Recognition System for Drill #20-10). In order to properly assess the effect of the drill monitoring system, the effect of all similar systems on the mine was evaluated for the audit. A per-unit final summary is included in this audit that presents the final outcome of the overall costs and benefits of the 3 systems on a per-unit basis.

This audit includes the following items:

- comparison of projected and achieved qualitative benefits
- list of unpredicted benefits
- comparison of projected and achieved financial benefits
- actual financial costs
- unprejudiced cost savings
- addenda: non-numeric justification technique expressing the justified acquisition of the technology

After studying the effect of the drill technology on the mine’s finances and methodologies, it was concluded that the acquisition was within AFE parameters and even out performed the expectations even though some cost saving practices mentioned in the AFE were not implemented. The financial results are summarized in the tables below:

Table 9-5: Actual vs. Predicted Costs

<table>
<thead>
<tr>
<th>Description</th>
<th>Actual (US$)</th>
<th>Predicted (US$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill navigation and software</td>
<td>70,000 $</td>
<td>-</td>
</tr>
<tr>
<td>Materials recognition hardware and software</td>
<td>13,000 $</td>
<td>-</td>
</tr>
<tr>
<td>Installation, commissioning and training</td>
<td>12,000 $</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total Aquila Costs</strong></td>
<td>95,000 $</td>
<td>-</td>
</tr>
<tr>
<td>Bucyrus International modifications</td>
<td>7,000 $</td>
<td>-</td>
</tr>
<tr>
<td><strong>Sub-total (US$)</strong></td>
<td>102,000 $</td>
<td>101,290 $</td>
</tr>
<tr>
<td>Subtotal (C$AN - $1.34=US$1)</td>
<td>136,680 $</td>
<td>135,728 $</td>
</tr>
<tr>
<td>PST</td>
<td>9,568 $</td>
<td>9,501 $</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>146,248 $</td>
<td>145,229 $</td>
</tr>
<tr>
<td><strong>3 units</strong></td>
<td>438,743 $</td>
<td>435,688 $</td>
</tr>
</tbody>
</table>
Table 9-6: Predicted vs. Financial benefits

<table>
<thead>
<tr>
<th>Variables</th>
<th>Predicted $/year</th>
<th>Actual $/year</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less surveyor o/t</td>
<td>$10,800</td>
<td>$33,866</td>
<td></td>
</tr>
<tr>
<td>Less surveyor materials.</td>
<td>$4,200</td>
<td>$37,705</td>
<td></td>
</tr>
<tr>
<td>Red. drill &amp; blast costs</td>
<td>$104,470</td>
<td>-</td>
<td>none directly attributable</td>
</tr>
<tr>
<td>Reduced shovel costs</td>
<td>$30,708</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unanticipated Benefits</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Less 'caved' holes</td>
<td>-</td>
<td>$48,804</td>
</tr>
<tr>
<td>Design time for pattern</td>
<td>-</td>
<td>$50,794</td>
</tr>
<tr>
<td>Shovel productivity</td>
<td>-</td>
<td>$125,936</td>
</tr>
<tr>
<td>Drill utilization</td>
<td>-</td>
<td>$142,721</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Estimated Benefits</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced shovel maint.</td>
<td>-</td>
<td>$78,000</td>
</tr>
<tr>
<td>Mill throughput</td>
<td>$31,105</td>
<td>$32,000</td>
</tr>
</tbody>
</table>

| Totals less estimated            | $150,178       | $439,826       |                                         |
| Totals                           | $181,283       | $549,826       |                                         |

* overall improvement over time period is much higher
but drill monitoring may not be the only factor
** values roughly estimated by experts in their respective fields
*** Mainly in terms of ground engaging and cable rope

Table 9-7: Summary of Financial Results, using calculated, total Benefits

<table>
<thead>
<tr>
<th></th>
<th>AFE</th>
<th>Actual</th>
<th>Single unit</th>
<th>Chronological</th>
<th>Single unit Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payback Period (using DCF $)</td>
<td>1.3</td>
<td>1.2</td>
<td>1.3</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Payback Period (using Real $)</td>
<td>1.3</td>
<td>1.2</td>
<td>1.3</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>I.R.R. (%) (Using Real $)</td>
<td>75.1</td>
<td>77.0</td>
<td>44.5</td>
<td>-1.9</td>
<td></td>
</tr>
<tr>
<td>R.O.I. (%) (NPV / Investment)</td>
<td>228.1</td>
<td>235.2</td>
<td>246.8</td>
<td>-7.1</td>
<td></td>
</tr>
<tr>
<td>N.P.V. @ Prescribed Rate</td>
<td>$335,310</td>
<td>$341,561</td>
<td>$1,010,064</td>
<td>($6,251)</td>
<td></td>
</tr>
<tr>
<td>Initial cost</td>
<td>$147,000</td>
<td>$145,229</td>
<td>$409,282</td>
<td>$1,771</td>
<td></td>
</tr>
</tbody>
</table>
2 A.F.E. justification

The following represents a summary of the justification section of the A.F.E. (Appendix A). The A.F.E. contained both economic and analytical justification. Both will be presented.

Analytical

The analytical benefits from the drill navigation and materials recognition system that were foretold in the A.F.E. included:

1) The ability to drill patterns more accurately both by position and depth. Thus, drillers will be more accountable for deviating from the drill plan as a result of quicker hole pickups. [accuracy] & [driller accountability]

2) Each hole gets an accurate collar elevation and the hole depth can be adjusted, producing more even benches resulting in improved operating conditions for shovels and trucks. [more even benches]

3) Explosive strength can be adjusted according to the measured drillability, thus improving explosives consumption and fragmentation. Optimizing fragmentation will improve diggability, reducing wear on the shovels, trucks and crushers while improving mill throughput. [less explosives consumption] & [better fragmentation]

4) Drill navigation is an essential step towards single operator-multiple drill operations and automation. [automation option]

5) Automated drill hole surveying and material recognition will provide information for blast design and provide opportunity for a more automated and productive explosives loading system. [material recognition] & [more informed design] & [improved explosives loading]

The success and validity of the benefits mentioned above will be assessed in a further section. Additional benefits, not mentioned in the A.F.E, will be discussed.

Financial benefits

The following financial benefits were calculated in the A.F.E. (Appendix A)

- discounted payback period of 1.3 years
- IRR of 75.1%
- projected annual operating savings of $146,000
- 0.01% improvement in throughput ($30,000/yr. at 90 €/lb.)
- reduced shovel costs of $30,708/yr.
- reduced drill & blast costs of $104,470/yr.
- A reduction in survey overtime for pattern staking and hole pickups
- A reduction in the consumption of survey materials

The financial estimates calculated in the A.F.E. will be compared to the actual savings. Additional financial benefits will also be calculated to supplement the actual financial estimates.

3 Capital Expenditures

The capital outlay for the GPS system and software was listed as a single expense in the accounting ledger. It is unclear if the training and installation of the equipment is included in the price. However, installation and training was not seen as a major expense, considering the operators easily adapted to the new navigation method, within days of its implementation.
Appendix 5: HVC Drill Audit Appendices

Figure 9-5: Planned vs. Actual expenditure

Benefits Achieved

The Drill monitoring technology revealed both qualitative and quantitative benefits. The qualitative benefits are difficult to quantify. In order to accomplish the difficult task of quantifying quality improvements, new justification techniques will be carried out, based on techniques developed by the manufacturing industry for the purpose of justifying advanced technology. An example is presented at the end of this section. The theory behind this method is contained in the appendices, however the basic axioms of the methods will be presented in the main text. Initially, qualitative and financial comparisons will be made between the estimated cost savings and the quantifiable actual savings.

4 Qualitative Benefits

The qualitative benefits promised in the AFE and the outcome are presented in the table below:
Appendix 5: HVC Drill Audit Appendices

Table 9-8: Comparison of Qualitative Benefits Promised AFE vs. Actual Outcome

<table>
<thead>
<tr>
<th>Promised</th>
<th>Final result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>There has been a distinct improvement in hole position. Previously, both surveyors and drillers were responsible for positioning the hole correctly. Now only the driller is responsible and has been given the tools to easily and accurately position the hole. Hole position went from an accuracy of ±1-2 meters to the current accuracy of ±10 cm</td>
</tr>
<tr>
<td>driller accountability</td>
<td>Drillers can be held more accountable for deviating from the pattern. Recording the position and time for each hole is a type of constant supervision, ensuring high quality</td>
</tr>
<tr>
<td>more level benches</td>
<td>Clean-up crews, the first workers to re-enter a newly blasted area, have reported an improvement on the amount of clean-up required compared with the period before the technology was implemented. Furthermore, shovels have reported less hard toes while truck drivers have noticed smoother bench levels.</td>
</tr>
<tr>
<td>less explosives consumption</td>
<td>There has been no distinguishable improvement in explosives consumption that can be attributed to the technology. This is mainly due to the lack of resources to take advantage of all the information provided by the monitoring system. A great deal of data is recorded by the monitoring system that can be used to optimize aspects of the operation involving drilling.</td>
</tr>
<tr>
<td>improved fragmentation</td>
<td>Fragmentation impacts the operation on many aspects. Reportedly, shovels require less ground engaging consumable. The mill has also reported an improvement in fragmentation. (many variables involved in the improvements mentioned above, fragmentation is assumed to be one of the most important). Mill throughput has increased by 7.4% in 1998, some of that increase may be attributable to improved fragmentation</td>
</tr>
<tr>
<td>automation option</td>
<td>No further autonomy has been adapted to the drill. A radio link is proposed, however, due to the current price of copper, it is an unlikely purchase.</td>
</tr>
<tr>
<td>material recognition</td>
<td>The material recognition software provides an index that is assumed to be related to the hardness of the material being drilled. Software adjustments have been requested to take jointing and blocks into account, since according to extensive materials testing it was determined that the different 'hardness zones' are not very distinct. However, a project has been proposed to compare the harness index results from the technology with the mine’s hardness contours, to find the exact correlation.</td>
</tr>
<tr>
<td>improved explosives loading</td>
<td>There has been no change in explosives loading due to the presence of drill monitoring technology. However, it does improve the blast pattern initiation sequence due to design consistency, and the ability to make more informed decisions based on observed performance.</td>
</tr>
</tbody>
</table>

Sean Dessureault
Masters of Applied Science
5 Unpredicted Qualitative Benefits

The unpredicted qualitative benefits were numerous. There are two types of benefits discussed here. The first deals with potential projects, where this specific technology is only a link in a long value chain of technologies that will eventually induce an overall economic outcome after a series of such projects. The second type of benefits listed in this section are direct unpredicted qualitative benefits that have been mentioned or expressed by the respective affected individuals.

**Potential Projects:**

1. **Upgrading pit hardness contours**
   The technical supervisor plans to update the current pit hardness contours using the hardness index which is automatically measured by the drill monitoring technology. The potential benefit of better knowledge of the bench is to improve fragmentation through optimal pattern design. Once the exact contours are laid out, the appropriate burden and spacing can be applied to the pattern.

2. **Automatic determination of local jointing**
   Aquila Mining Systems claims to have the potential to detect the presence of joints through drill string monitoring. Acquiring the software required to make these measurements would allow a better prediction of the fragmentation since jointing has been identified (JKMRC, 1998) as the most important parameter governing fragmentation.

3. **Tracking bit & string performance**
   The current method of tracking bit & string performance is rudimentary and does not have the desired detail. The current method costs of having the driller alert the dispatch center that the bit or string is being changed. Using the automatically generated data from the monitoring platform, it is possible to track a single bit's overall operating time, where it did most of its penetrating and a host of other variables.

4. **Overall throughput increase at mill**
   The objective of the drill monitoring platform is to improve fragmentation. The ideal fragmentation is governed by the requirements of the mill. An ambitious plan is being contemplated by the mill to improve throughput by decreasing the varying size distribution arriving at the SAG mills. This will allow a less varying throughput. It has been established that having a constant throughput will increase copper recovery. The project is composed of many levels of monitoring and control devices that will allow the mill to blend the ore being fed to the mill. The drill monitoring platform will be used to calculate a polygon of potential fragmentation distribution through efficient use of the joint detecting and hardness index values, for an area around each blasthole. Therefore, as the polygon of material is being tracked through the system, the mill can plan to alter its processes to better handle the material.

**Unpredicted Benefits**

1. **Split implementation**
   In the event of a requirement to split the blast design, the blasting technician simply changes the design on computer, and update the drill computer. Previously, surveyors had to go into the field, erase the painted lines then redraw a new pattern (the second phase of the split). This induced tension between the individuals involved, such as the blast foreman, drillers and surveyors and resulted in significant rework for the surveyors.

2. **More informed design**
   The blast design methodology has changed dramatically. Previously, the design and implementation of a blast pattern was a vague and unstructured exercise. It was subject to frequent confusion and resulting in delays in the pit. The methodology of design was changed to take advantage of the drill positioning systems, which resulted in an important benefit in terms of consistency and flexibility. By having a single methodology of design, there is less confusion, more consistency and improved operations-engineering relations.

3. **Improved safety**
   The first aid incidents have dramatically reduced since the implementation of the Aquila Drill technology. This is due in large part to the amount of time technicians now spend in the pit. Previously, it was customary that the survey technicians remain in the pit, performing such...
hazardous or strenuous tasks such as pounding stakes (hammer accidents) and walking around on a drilled bench in the winter (drill holes, covered with snow may induce a sprained ankle when walked upon).

4. **Operator acceptance**
Operators have expressed much approval of the system since "it makes the job easier". The resulting improvement in operator enjoyment of the system, due in large part to its 'video game' type qualities, may impact on productivity improvements and a better working atmosphere.

## 6 Financial Benefits

The financial benefits were determined while taking several influential factors into account, primarily the chronology of events relating to:
- which drills had the technology
- size of bit, pattern & spacing along with the resulting fragmentation

The calculations and raw data used to determine the values in this section are provided in the appendices.

### Table 9-9: Financial Benefits - Results

<table>
<thead>
<tr>
<th>Variables</th>
<th>Predicted</th>
<th>Actual</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less surveyor o/t</td>
<td>$10,800</td>
<td>$33,866</td>
<td></td>
</tr>
<tr>
<td>Less surveyor materials.</td>
<td>$4,200</td>
<td>$37,705</td>
<td></td>
</tr>
<tr>
<td>Reduced drill &amp; blast costs</td>
<td>$104,470</td>
<td>-</td>
<td>none directly attributable</td>
</tr>
<tr>
<td>Reduced shovel costs</td>
<td>$30,708</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td><strong>Unanticipated Benefits</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Less 'caved' holes</td>
<td>-</td>
<td>$48,804</td>
<td>cost of drilling caved holes</td>
</tr>
<tr>
<td>Design time for pattern</td>
<td>-</td>
<td>$50,794</td>
<td>extra technician time</td>
</tr>
<tr>
<td>Shovel productivity</td>
<td>-</td>
<td>$125,936</td>
<td></td>
</tr>
<tr>
<td>Drill utilization</td>
<td>-</td>
<td>$142,721</td>
<td></td>
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<tr>
<td><strong>Estimated Benefits</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduced shovel maint.</td>
<td>-</td>
<td>$78,000</td>
<td></td>
</tr>
<tr>
<td>Mill throughput</td>
<td>$31,105</td>
<td>$32,000</td>
<td>none directly attributable</td>
</tr>
<tr>
<td><strong>Totals less estimated</strong></td>
<td>$150,178</td>
<td>$439,826</td>
<td></td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td>$181,283</td>
<td>$549,826</td>
<td></td>
</tr>
</tbody>
</table>

* Overall improvement is much higher, however, drill monitoring resulting in better fragmentation is not the only variable that was altered in the time period under evaluation.
** Estimated benefits were rough appraisals made by experts in their respective departments. (example, A. Dance for milling information, R. Dhaliwal for maintenance)
*** Based on savings incurred from less ground engaging costs and shovel cables.

## 7 Unquantified Qualitative Benefits

Several qualitative benefits that remain unquantified are discussed in the list below. These benefits would have a financial impact however, due to their highly integrated nature, they are impossible to quantify accurately.

- less clean-up time: Better fragmentation and improved design would result in less clean-up time
Appendix 5: HVC Drill Audit Appendices

- less crushing of oversize: More of the explosive energy is used in breaking rock when holes are positioned correctly. Therefore there will be less big boulders which require secondary blasting and less wear on the crusher since less rock will require crushing.
- less blaster time required: Since blast tie-ins are designed in the engineering office, blasters no longer require the time to ‘figure out the blast layout’.
- potential projects that have yet to be realize but will potentially induce large financial benefits

8 Costs & Final Outcome

The final costs are based only on the final ledger account. Benefits were calculated by comparing the variables before the drill monitoring technology was implemented with the variables after all drills were outfitted with the equipment. Therefore the benefits and costs reflect the combined values for all variables of the 3 drills and technology platforms.

The final financial evaluation variables are presented below. The chronological column represents the true value of the investment over a period of 1.5 years (implementation of the drill monitoring platforms for the entire fleet of 49R drills). The calculations and official HVC discounted cash flow sheets are provided in the appendices.

Table 9-10: Final Financial Outcome

<table>
<thead>
<tr>
<th></th>
<th>AFE</th>
<th>Actual</th>
<th>Single unit</th>
<th>Chronological</th>
<th>Single unit variance</th>
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</thead>
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<tr>
<td>Payback Period (using DCF $)</td>
<td>1.3</td>
<td>1.2</td>
<td>1.3</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Payback Period (using Real $)</td>
<td>1.3</td>
<td>1.2</td>
<td>1.3</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>I.R.R. (%) (Using Real $)</td>
<td>75.1</td>
<td>77.0</td>
<td>44.5</td>
<td>-1.9</td>
<td></td>
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<tr>
<td>R.O.I. (%) (NPV / Investment)</td>
<td>228.1</td>
<td>235.2</td>
<td>246.8</td>
<td>-7.1</td>
<td></td>
</tr>
<tr>
<td>N.P.V. @ Prescribed Rate</td>
<td>$335,310</td>
<td>$341,561</td>
<td>$1,010,064</td>
<td>$ (6,251)</td>
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<tr>
<td>Initial cost</td>
<td>$147,000</td>
<td>$145,229</td>
<td>$409,282</td>
<td>$ 1,771</td>
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9 Addenda: Non-financial Justification

The purpose of this section is to raise awareness of the benefit of using non-financial justification techniques when evaluating technologies that involve many benefits and costs that are difficult to quantify. The manufacturing industry has developed many methods to evaluate projects involving integrated technology (where financial costs and benefits would be difficult to assess). One method of justification that is appropriate for this level of integration is called the Analytical Hierarchy Process (AHP). It is a scoring method that allows the evaluator to be more consistent in the evaluation than conventional scoring methods. Consistency is a major barrier to the proper use of scoring methods. Human thinking is usually inconsistent. When using AHP a consistency index is calculated through a series of matrix calculations. This method can be greatly simplified when using a spreadsheet. An example of the results of this method is presented below. It was completed according to the sentiments of the mine superintendent. A second example of the calculations and a more in-depth explanation of this method is presented in the appendices.

AHP begins by listing a series of objectives and options. The mutually exclusive options must reach, to a varying degree, the objectives specified. The list below represents the objectives and options that the mine faced when deciding whether or not to invest in the drill monitoring technology.

Table 9-11: Objectives and options at time of justification

Masters of Applied Science Thesis. Sean Dessureault
## Objectives

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>accu</td>
<td>accuracy</td>
</tr>
<tr>
<td>drl_eff</td>
<td>efficiency of drilling</td>
</tr>
<tr>
<td>blst_eff</td>
<td>efficiency of blasting</td>
</tr>
<tr>
<td>design</td>
<td>ease of design</td>
</tr>
<tr>
<td>cost</td>
<td>cost of option</td>
</tr>
<tr>
<td>simp</td>
<td>simplicity of option</td>
</tr>
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</table>

## Options

<table>
<thead>
<tr>
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<th>Description</th>
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<tr>
<td>Tech</td>
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</tr>
<tr>
<td>Train</td>
<td>re-training/restruct</td>
</tr>
<tr>
<td>Quo</td>
<td>status quo</td>
</tr>
</tbody>
</table>

The process first involves comparing objectives, a pair at a time, and scoring them according to which objective is more important. Secondly, the options are compared, again two at a time, according to how well they accomplish each objective. During the comparison process, the consistency index must be below a certain value to remain satisfactory. The results from the evaluation are presented below. It can be seen that investing in the technology was a good choice, when compared with the other options.

### Figure 9-6: Results from AHP evaluation

<table>
<thead>
<tr>
<th>Results</th>
<th>accu</th>
<th>drl_eff</th>
<th>blst_eff</th>
<th>design</th>
<th>cost</th>
<th>simp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tech</td>
<td>0.71</td>
<td>0.56</td>
<td>0.25</td>
<td>0.65</td>
<td>0.06</td>
<td>0.19</td>
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<td>Train</td>
<td>0.21</td>
<td>0.32</td>
<td>0.50</td>
<td>0.25</td>
<td>0.24</td>
<td>0.08</td>
</tr>
<tr>
<td>Quo</td>
<td>0.08</td>
<td>0.12</td>
<td>0.25</td>
<td>0.10</td>
<td>0.70</td>
<td>0.74</td>
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</table>

CI: consistency index: all satisfactory

<table>
<thead>
<tr>
<th>Weigh</th>
<th>accu</th>
<th>drl_eff</th>
<th>blst_eff</th>
<th>design</th>
<th>cost</th>
<th>simp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tech</td>
<td>0.319</td>
<td>0.118</td>
<td>0.118</td>
<td>0.078</td>
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<td>####</td>
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</table>

### Overall Score

<table>
<thead>
<tr>
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<th>Quo</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.404</td>
<td>0.260</td>
<td>0.336</td>
</tr>
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</table>

**10 Recommendations**

Several recommendations regarding the use of the drill monitoring technology was raised during the collection phase of this audit:

- better utilization of the information provided by the Aquila Monitoring Platform is required
- increased integration of hardness information with explosives use is necessary
- purchase of a radio link to take advantage of more technician time and other optimization projects, should be reviewed


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Dave Assmus
Dave Ayres
Dave Westfall
Brad Aie
Colin Murray

11 Table of Appendices
Appendix A: Official Highland Valley Copper discounted cash flow analysis results
Appendix B: Shovel utilization calculation
Appendix C: Drill utilization calculation
Appendix D: Caved hole cost saving calculation
Appendix E: Design cost saving calculation
Appendix F: Mine engineering overtime cost saving calculation
Appendix G: Survey material consumption cost saving calculation
Appendix H: AHP - calculations relating to the conclusions expressed in the text
Appendix H: AHP - in-depth explanation and example

Texts Utilized
JKMRC, Report: Optimizing Fragmentation at Highland Valley Copper with respect to Mining & Processing Operations, June 1998
Appendix A: Official Highland Valley Copper discounted cash flow analysis results

**Highland Valley Copper**

**Discounted Cash Flow Analysis**

*Aquila Mining Systems Drill Monitoring Technology Acquisition AFE Values*

<table>
<thead>
<tr>
<th>(CAPITAL PURCHASE MODEL)</th>
<th>YEAR 1</th>
<th>YEAR 2</th>
<th>YEAR 3</th>
<th>YEAR 4</th>
<th>YEAR 5</th>
<th>YEAR 6</th>
<th>YEAR 7</th>
<th>YEAR 8</th>
<th>YEAR 9</th>
<th>YEAR 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Investment</td>
<td>147,000</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Inventory Changes (increase)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cost Savings</td>
<td>181,000</td>
<td>182,000</td>
<td>184,000</td>
<td>178,000</td>
<td>163,000</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Change in Cash Before Taxes</td>
<td>34,000</td>
<td>182,000</td>
<td>184,000</td>
<td>178,000</td>
<td>163,000</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Taxable Operating Savings</td>
<td>181,000</td>
<td>182,000</td>
<td>184,000</td>
<td>178,000</td>
<td>163,000</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Corporate Tax on Savings</td>
<td>-65,050</td>
<td>-59,938</td>
<td>-63,963</td>
<td>-63,963</td>
<td>-69,774</td>
<td>4,070</td>
<td>3,052</td>
<td>2,289</td>
<td>1,717</td>
<td>1,288</td>
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<tr>
<td>Net Cash (Outflow)</td>
<td>-31,050</td>
<td>122,063</td>
<td>120,047</td>
<td>114,035</td>
<td>103,226</td>
<td>4,070</td>
<td>3,052</td>
<td>2,289</td>
<td>1,717</td>
<td>1,288</td>
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<tr>
<td>Cumulative Cash Flow</td>
<td>-31,050</td>
<td>91,013</td>
<td>211,059</td>
<td>325,095</td>
<td>428,321</td>
<td>432,391</td>
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<td>437,732</td>
<td>439,449</td>
<td>440,737</td>
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<td>D.C.F. @ Prescribed Rate</td>
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<td>110,966</td>
<td>99,212</td>
<td>85,676</td>
<td>70,506</td>
<td>2,527</td>
<td>1,723</td>
<td>1,175</td>
<td>801</td>
<td>546</td>
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</table>

Payback Period (using DCF $) 1.3 Years
Payback Period (using Real $) 1.3 Years
I.R.R. (%) (Using Real $) 75.1 %
R.O.I. (%) (NPV / Investment) 228.1 %
N.P.V. @ Prescribed Rate $ 335,310
Highland Valley Copper
Discounted Cash Flow Analysis
Aquila Mining Systems Drill Monitoring Technology Acquisition Actual Values, (considering a single unit)

(CAPITAL PURCHASE MODEL)

<table>
<thead>
<tr>
<th></th>
<th>YEAR 1</th>
<th>YEAR 2</th>
<th>YEAR 3</th>
<th>YEAR 4</th>
<th>YEAR 5</th>
<th>YEAR 6</th>
<th>YEAR 7</th>
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<th>YEAR 9</th>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Inventory Changes (Increase)</td>
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<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Cost Savings</td>
<td>183,275</td>
<td>184,268</td>
<td>185,289</td>
<td>177,299</td>
<td>167,831</td>
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<td>Change in Cash Before Taxes</td>
<td>38,046</td>
<td>184,268</td>
<td>185,289</td>
<td>177,299</td>
<td>167,831</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Taxable Operating Savings</td>
<td>183,275</td>
<td>184,268</td>
<td>185,289</td>
<td>177,299</td>
<td>167,831</td>
<td>0</td>
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<td>Net Cash (Outflow)</td>
<td>-28,003</td>
<td>123,280</td>
<td>129,704</td>
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<td>106,059</td>
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<td>3,016</td>
<td>2,262</td>
<td>1,696</td>
<td>1,272</td>
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<td>Cumulative Cash Flow</td>
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<td>D.C.F. @ Prescribed Rate</td>
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<td>112,073</td>
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<td>791</td>
<td>540</td>
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<td>Cum. Discounted Cash Flow</td>
<td>-28,003</td>
<td>84,070</td>
<td>183,826</td>
<td>269,121</td>
<td>341,561</td>
<td>344,057</td>
<td>345,759</td>
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<td>347,711</td>
<td>348,251</td>
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<tr>
<td>Payback Period (using DCF $)</td>
<td>1.2 Years</td>
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<td></td>
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<td></td>
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<tr>
<td>I.R.R. (%) (Using Real $)</td>
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<tr>
<td>R.O.I. (%) (NPV / Investment)</td>
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<tr>
<td>N.P.V. @ Prescribed Rate</td>
<td>$ 341,561</td>
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</table>
# Highland Valley Copper

**Discounted Cash Flow Analysis**

**Drill Monitoring Technology Acquisition Actual Values, Considering Chronology of Events**

<table>
<thead>
<tr>
<th>(CAPITAL PURCHASE MODEL)</th>
<th>YEAR 1</th>
<th>YEAR 2</th>
<th>YEAR 3</th>
<th>YEAR 4</th>
<th>YEAR 5</th>
<th>YEAR 6</th>
<th>YEAR 7</th>
<th>YEAR 8</th>
<th>YEAR 9</th>
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<td>549,826</td>
<td>549,826</td>
<td>549,826</td>
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<td>Change in Cash Before Taxes</td>
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<td>C.C.A. on Investment</td>
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<td>-81,588</td>
<td>-61,191</td>
<td>-45,893</td>
<td>-34,420</td>
<td>-25,815</td>
<td>-19,361</td>
<td>-14,521</td>
<td>-10,891</td>
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<td>Gross Savings Taxable</td>
<td>165,122</td>
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<td>488,634</td>
<td>503,952</td>
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<td>-19,361</td>
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<tr>
<td>Net Cash (Outflow)</td>
<td>-28,003</td>
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<td>362,531</td>
<td>354,372</td>
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<td>Cumulative Cash Flow</td>
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<td>237,861</td>
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<td>5,829</td>
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<td>Cum. Discounted Cash Flow</td>
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<td>1,016,748</td>
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<tr>
<td>Payback Period (using Real $)</td>
<td>1.3 Years</td>
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<tr>
<td>I.R.R. (%) (Using Real $)</td>
<td>44.5 %</td>
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<tr>
<td>R.O.I. (%) (NPV / Investment)</td>
<td>246.8 %</td>
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<tr>
<td>N.P.V. @ Prescribed Rate</td>
<td>$ 1,010,064</td>
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Appendix B: Shovel utilization calculation

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<td>1643</td>
<td>1789</td>
<td>2470</td>
<td>2652</td>
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<td>Mar</td>
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<td>1844</td>
<td>2267</td>
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<td>total fleet</td>
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<td>7376.5</td>
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<td>1857</td>
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<td>1758</td>
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<td>2514</td>
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<td>Aug</td>
<td>1507</td>
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<td>2793</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Nov</td>
<td>1708</td>
<td></td>
<td>2695</td>
<td></td>
<td></td>
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<tr>
<td>Dec</td>
<td>1545</td>
<td></td>
<td>2556</td>
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<tr>
<td>Average</td>
<td>1727</td>
<td>1841</td>
<td>2560</td>
<td>2633</td>
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Used in calculations for average t/man hour:
- average t/man hr - per drill
- Month ends 1998
- P & H 2800 b

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<th>Ytd</th>
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<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Total</th>
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* for calculation of weights
average: 2903.167

Masters of Applied Science Thesis. Sean Dessureault
Appendix C: Drill utilization calculation

<table>
<thead>
<tr>
<th>Year</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
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<td>1998</td>
<td>25,440</td>
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<td>26,288</td>
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<td>1.150087</td>
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\%
of plan

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<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
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</thead>
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<td>1996</td>
<td>0.873406</td>
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<td>0.947119</td>
<td>0.660151</td>
<td>0.815653</td>
<td>0.784667</td>
<td>0.691149</td>
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<td>1997</td>
<td>1.023222</td>
<td>0.80242</td>
<td>0.988045</td>
<td>0.919672</td>
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<td>1.023864</td>
<td>1.053361</td>
<td>1.316895</td>
<td>1.046687</td>
<td>1.147697</td>
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<tr>
<td>1998</td>
<td>1.205539</td>
<td>0.9652</td>
<td>1.257114</td>
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Meters drilled per drill

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<th>Feb</th>
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<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
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<td>1995</td>
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<td>115</td>
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<td>10023</td>
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<td>11377.18</td>
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<td>14134</td>
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<td>10030.95</td>
<td>13203.25</td>
<td>11496.7</td>
<td>12563.88</td>
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<td>13622</td>
<td>17030</td>
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Chronology

<table>
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<th>Event</th>
<th>Effect on calculation</th>
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<tr>
<td>Jul-95</td>
<td>49 R commissioned</td>
<td>Pre-tech period begins</td>
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<tr>
<td>Jun-96</td>
<td>2nd 49 R commissioned</td>
<td>Meters drilled divided by 2 (2 drills)</td>
</tr>
<tr>
<td>Jan-97</td>
<td>single 49R with tech.</td>
<td>Pre-aquila period ends, Indecisive period begins</td>
</tr>
<tr>
<td>May-97</td>
<td>second 49R tech added</td>
<td>Indecisive period ends, Post-tech period begins</td>
</tr>
<tr>
<td>Apr-98</td>
<td>3rd 49R with tech commissioned</td>
<td>3rd drill added, with tech (divide by 3)</td>
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<table>
<thead>
<tr>
<th>Average meters drilled per drill</th>
<th>Pre-tech</th>
<th>Post-tech</th>
<th>Difference</th>
<th>% increase</th>
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<td>12219.25</td>
<td>14614.35</td>
<td>2395.096</td>
<td>20%</td>
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### Table 1: Key Performance Indicators

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<th>1998</th>
<th>Normalizing Value</th>
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<td>Price of copper ($ CAN)</td>
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<td>Annual revenue</td>
<td>$ 352,048,000</td>
<td>$ 341,616,000</td>
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<tr>
<td>Normalized revenue</td>
<td>$ 283,701,583</td>
<td>$ 341,616,000</td>
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<tr>
<td>Annual profit</td>
<td>$ 107,389,000</td>
<td>$ 58,546,000</td>
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<tr>
<td>Normalized profit</td>
<td>$ 89,590,963</td>
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<tr>
<td>Total costs</td>
<td>$ 234,400,000</td>
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<tr>
<td>Mine costs</td>
<td>$ 86,300,000</td>
<td>$ 132,500,000</td>
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<tr>
<td>Mine's Impact on Costs</td>
<td>37%</td>
<td>54%</td>
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<td>Mine costs, $ per ton</td>
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<tr>
<td>Excavation costs, $ per ton</td>
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<td>Percentage of excavation costs</td>
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<td>13%</td>
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<td>Drilling costs, $ per ton</td>
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<tr>
<td>Percentage of drilling costs</td>
<td>2%</td>
<td>3%</td>
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<tr>
<td>Value of shovel fleet's contribution to revenue</td>
<td>$ 19,322,377</td>
<td>$ 24,700,937</td>
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<tr>
<td>Value of shovel fleet's contribution to profit</td>
<td>$ 5,884,113</td>
<td>$ 4,233,380</td>
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<td>$ 2,640,325</td>
<td>$ 6,403,947</td>
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<td>Value of drill fleet's contribution to profit</td>
<td>$ 805,407</td>
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### Table 2: Average Drilling Performance

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<th>Average Meters Drilled per Drill per Month</th>
<th>Drill</th>
<th>Shovel</th>
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<td>Post Tech</td>
<td>Difference</td>
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<td>------------</td>
<td>-------------</td>
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<td>2395.1</td>
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**Main Causes:**
- Easily manoeuvred accurately into position
- Winter or environmental conditions have no effect

**Difference:** $190,295

---

Sean Dessureault
Appendix D: Caved hole cost saving calculation

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<td>44</td>
<td>53</td>
<td>49</td>
<td>4</td>
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<td>Mar</td>
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<td>10</td>
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<tr>
<td>Apr</td>
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<td>106</td>
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<td>May</td>
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<td>Jul</td>
<td>98</td>
<td>77</td>
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<td>Aug</td>
<td>53</td>
<td>32</td>
<td>19</td>
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<td>Sep</td>
<td>59</td>
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<td>16</td>
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<tr>
<td>Oct</td>
<td>103</td>
<td>43</td>
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<tr>
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<td>8</td>
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<td>Dec</td>
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<td>22</td>
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\[
\begin{array}{lllll}
\text{per month} & 57.5 & 52 & 23.2 & 6.3\\
\text{per year} & 690 & 624 & 278 & 76
\end{array}
\]

<table>
<thead>
<tr>
<th>year</th>
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<th>Actual</th>
<th>Budgeted</th>
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<td>1996</td>
<td>624</td>
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<td>$45,602</td>
<td>$52,416</td>
<td>pre-tech</td>
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<td>278</td>
<td>3336</td>
<td>$20,316</td>
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<tr>
<td>1998</td>
<td>76</td>
<td>912</td>
<td>$5,554</td>
<td>$6,384</td>
<td>estimated from 1998 values, unit June</td>
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</tbody>
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\[
\begin{array}{ll}
\$1/meter & \\
\text{Actual:} & $6.09 \\
\text{Budgeted:} & $7.00
\end{array}
\]

\[
\text{12 meters of} \text{drilled before 'caved'}
\]

- pre-aquila tech o/t costs (average) $55,188
- post-aquila tech o/t costs (estimate) $6,384
- difference - savings $48,804
- % decrease 88%

* almost all in valley pit
Appendix E: Design cost saving calculation

<table>
<thead>
<tr>
<th></th>
<th>Cost of pattern implementation &amp; design (in man-hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># of patterns</td>
</tr>
<tr>
<td>pre-tech</td>
<td>16</td>
</tr>
<tr>
<td>post-tech</td>
<td>3</td>
</tr>
<tr>
<td>difference</td>
<td>13</td>
</tr>
<tr>
<td>% decrease</td>
<td>81%</td>
</tr>
</tbody>
</table>

patterns/week 4
patterns/year 208

cost of technician / hour $ 26.64

Appendix F: Mine engineering overtime cost saving calculation
Appendix G: Survey material consumption cost saving calculation
Total consumables for Field Control

<table>
<thead>
<tr>
<th>Year</th>
<th>Total</th>
<th>Deductions</th>
<th>Consumables</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>$554,917</td>
<td>$488,306</td>
<td>$66,612</td>
<td>pre-aquila</td>
</tr>
<tr>
<td>1996</td>
<td>$90,531</td>
<td>$39,194</td>
<td>$51,338</td>
<td>pre-aquila</td>
</tr>
<tr>
<td>1997</td>
<td>$55,331</td>
<td>$19,945</td>
<td>$35,386</td>
<td>tech present, not exclusive</td>
</tr>
<tr>
<td>1998</td>
<td>$63,034</td>
<td>$41,764</td>
<td>$21,269</td>
<td>tech almost exclusive, based on estimates up to August 2nd</td>
</tr>
</tbody>
</table>

Summary

- Pre-aquila tech: $58,975
- Post-aquila tech: $21,269
- Difference: $37,705
- % Decrease: 36%

[Bar chart showing the consumption for different years]
Appendix 6: Simulation Results

### 9.5 Appendix 6: Simulation Results

<table>
<thead>
<tr>
<th>Optimized</th>
<th>505050</th>
</tr>
</thead>
<tbody>
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<td>P1</td>
<td>P2</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>3.75223</td>
<td>1.482668</td>
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<tr>
<td>3.939004</td>
<td>1.454626</td>
</tr>
<tr>
<td>2.514596</td>
<td>1.348117</td>
</tr>
<tr>
<td>4.134569</td>
<td>1.292778</td>
</tr>
<tr>
<td>3.101222</td>
<td>1.185773</td>
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<tr>
<td>2.994083</td>
<td>1.287824</td>
</tr>
<tr>
<td>3.737894</td>
<td>0.950048</td>
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<tr>
<td>3.314563</td>
<td>1.534087</td>
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<tr>
<td>3.648315</td>
<td>1.213184</td>
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<tr>
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<tr>
<td>3.4577</td>
<td>1.318587</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Optimized</th>
<th>505050</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>P2</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>4.109524</td>
<td>3.045637</td>
</tr>
</tbody>
</table>

| Improvement | 11% |


Sean Dessureault