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Department of Mining and Mineral Process Engineering

The University of British Columbia
Vancouver, Canada

Date April 9, 2001

DE-6 (2/88)
ABSTRACT

This research contributes to understanding the interaction between ground-related problems and mining systems as a basis for the development of flexible mining systems. It has demonstrated that ground-related problems impose a significant operating risk factor that requires particular attention in proactive mine planning and design. A new philosophy for quantifying the impact of ground-related problems and assessing the links between mine planning and geomechanics was established. The various types of potential problems were classified based on review of case studies and the surveillance of ground failures in several underground hard rock mines of the Sudbury Basin. It was demonstrated that, despite serious efforts in the design of underground mines, ground-related problems still cannot be totally avoided.

A time-dependent internal risk model was established to quantify the impact of ground-related problems in mine production systems. Subjective probabilities provide the input for a reliability analysis, which derives the required input parameters for production simulation. Reliability analyses that are currently used to calculate the reliability of mine equipment were applied for the case of mine subsystems with ground-related problems. A cost impact model that is dependent on the parameters determined in a reliability analysis was introduced.

Flexibility needs in mine planning and design, with respect to ground-related problems, were analyzed through conventional discounted cash flow analysis, real options analysis, production simulation, and Monte-Carlo simulation. Approaches that are currently applied in investment science and decision making were evaluated in terms of their applicability to evaluate such flexibility needs in mining systems. A methodology that includes the applicability of project valuation analyses to assess flexible mining systems with respect to potential ground-related problems, along with a flexibility index, were introduced. Their applicability is demonstrated through test case studies. Contingency planning and flexibility assessment by such means can be integrated into future mine production systems to account for the potential risk of ground-related problems for more proactive mine planning and design.
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LIST OF SYMBOLS

A: cost to introduce alternative plan, additional cost;
B: Borrowed amount for equivalent portfolio;
C: Call option;
d: multiplicative down factor;
DCF: Discounted Cash Flow analysis;
E: Equivalent portfolio, investment opportunity value;
E₀: total value of the investment opportunity (NPV);
f(t): probability of failure;
F: increase in operating costs;
FC: Fixed Costs;
G: Annual ground-related problems;
GRPC: ground-related problem cost;
h(t): hazard function;
lₐ: potential cost savings;
l₀: initial outlay;
l': investment of additional amount;
IEC: initial excavation cost for the subsystem;
K: the stock price written on the option;
k: discount rate, rate of return;
k₁, k₂: hazard function constants;
λ: hazard function constant;
MTBF: Mean Time Between Failures;
MTTR: Mean Time To Repair;
NPV: Net Present Value;
N: number of shares;
O: reduction in cash inflows;
P: Put option;
p: risk-neutral probability;
q: probability;
r: risk-free rate;
R(t): reliability;
R⁺, R⁻: returns based on stock performance;
S: stock security;
S_p: stock price;
t₀: designed/scheduled operating life;
TC: Total Cost;
u: multiplicative up factor;
VC: Variable Costs;
V₀: gross project value;
V, V⁺, V⁻: cash flows;
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CHAPTER 1:
INTRODUCTION

1.1 CURRENT PRACTICES AND FUTURE TRENDS IN MINING

Low cost producing mines that comply with environmental regulations and maintain effective societal policies are the next generation mines, which will survive in the increasingly competitive world of metal markets. Today, mining companies are under pressure to re-engineer their operations, introduce new working philosophies, and develop and apply cost-effective mining technologies. It has been realized through years of operating underground mines that the greatest savings in such operations occur in the early planning stage, as part of the feasibility study. Here, the corporate team has the flexibility to explore alternatives and assess risk, using various technical and economic criteria. Once ground is broken, the alternatives that are available to the operator diminish exponentially as the mine matures. Although production and cost optimization are the constant objectives of the operator, it is a fact that many of the key design and planning decisions affecting these have already been made at the initial planning stage.

Minimization of cost is often the paramount objective in mining projects. However, the rigidity of a low-cost production system may eventually prove costly, unless the ability to respond to changes through time is built within the mine plan. In a world of widening competition and uncertainty, operating flexibility and strategic adaptability are increasingly critical to long-term success and survival of the mineral resources sector in Canada. New developments in management practices, including those that have been developed in the
manufacturing sector (Shingo, 1989), as well as evaluation methods for capital budgeting (Trigeorgis, 1998), should benefit mining significantly. However, the application of technologies from other industries faces several challenges unique to mining. These relate to the multidimensional aspects of mineral resource projects, coupled with the high degree of uncertainty that is usually present, and the traditional conservatism of the minerals sector. Today, there is a clear need for scientific, comprehensive, holistic planning and design approaches to be developed and applied to underground hard rock mines. The focus of this thesis will be on underground hard rock mining as opposed to surface mining, evaporite or coal mining.

1.2 RISK FACTORS IN MINING PROJECTS

The economic evaluation of a mineral project requires the integration of a great deal of diverse information. Prior to a mining project receiving financing, a bankable feasibility study needs to be prepared. The feasibility study analyzes the technical and economic viability of a project and the level of accuracy required for making an investment decision. Such a study includes the review of critical technical parameters and risk factors related to ore reserves, mine design, metallurgical testing, flow sheet, construction schedule, sales agreements, production rate, operating costs, product prices, and environmental and societal issues (Worth and Haystead, 1990, Smith, 1994, Goode, et al, 1991). A list of the parameters that need to be evaluated in a mining project is shown in Table 1.1 (Orr, 1992).

Risk in a mining project is evaluated with respect to internal (endogenous) and external (exogenous) conditions. Internal conditions are those that are dictated by the deposit itself, whereas external conditions are determined by outside considerations, such as business or
Table 1.1: Evaluation of parameters in mining projects, (Orr, 1992)

<table>
<thead>
<tr>
<th>Evaluation Parameter</th>
<th>Considerations</th>
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<tbody>
<tr>
<td>Geotechnical</td>
<td>- Lithology</td>
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<tr>
<td></td>
<td>- Groundwater</td>
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<td></td>
<td>- Geophysics</td>
</tr>
<tr>
<td></td>
<td>- Ore genesis</td>
</tr>
<tr>
<td>Mineral occurrence</td>
<td>- Continuity of ore zones within mineralized strata</td>
</tr>
<tr>
<td></td>
<td>- Occurrence of mineral within ore zone (geologic grade)</td>
</tr>
<tr>
<td></td>
<td>- Economic mineral occurrence within ore zone (mining grade)</td>
</tr>
<tr>
<td>Ore body configuration</td>
<td>- Dip</td>
</tr>
<tr>
<td></td>
<td>- Plunge</td>
</tr>
<tr>
<td></td>
<td>- Size</td>
</tr>
<tr>
<td></td>
<td>- Shape</td>
</tr>
<tr>
<td>Safety/regulatory</td>
<td>- Labor intensity of method</td>
</tr>
<tr>
<td></td>
<td>- Degree of mechanization</td>
</tr>
<tr>
<td></td>
<td>- Ventilation requirements</td>
</tr>
<tr>
<td></td>
<td>- Refrigeration requirements</td>
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<tr>
<td></td>
<td>- Ground support requirements</td>
</tr>
<tr>
<td></td>
<td>- Dust controls</td>
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<td></td>
<td>- Noise controls</td>
</tr>
<tr>
<td></td>
<td>- Gas controls</td>
</tr>
<tr>
<td>Environmental</td>
<td>- Subsidence potential</td>
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<tr>
<td></td>
<td>- Groundwater contamination</td>
</tr>
<tr>
<td></td>
<td>- Noise controls</td>
</tr>
<tr>
<td></td>
<td>- Air quality controls</td>
</tr>
<tr>
<td>Economic</td>
<td>- Minable ore tons</td>
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<td></td>
<td>- Ore body grade</td>
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<td></td>
<td>- Mineral value</td>
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<tr>
<td></td>
<td>- Capital costs</td>
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<td></td>
<td>- Operating costs</td>
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<tr>
<td>Labor/political</td>
<td>- Costs, influences</td>
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market requirements (Krantz and Scott, 1992). The internal conditions in a mining project relate to grade distribution, ground conditions, workforce, management/operating team, equipment and infrastructure. The external conditions relate to market prices, environmental conditions, political/country risk, community relations, industrial relations, stakeholder issues, legislation and government policy (Dunbar, et al, 1998; Smith, 1995). Depending on the type of analysis that is conducted, and the particular characteristics of a mining project,
certain conditions may be perceived as internal instead of external, or vice-versa. Common sources of risk in mining projects are presented in Figure 1.1.

**Figure 1.1:** Sources of uncertainty in mining projects

According to Worth and Haystead (1990), the risk factors evaluated in a feasibility study by a financial institute include: operational risk, technical risk, completion and cost overrun risk, market and price risk, country risk, legal risk and environmental risk.

The uncertainty related to the orebody characteristics imposes a geological risk in a mining project. The risk characteristics of the production schedule and cost estimates that are included in a feasibility study will be based on the ability of the mine plan to accommodate the variability in the geological characteristics of the orebody, and on the experience of the operating team. One of the objectives of a mine planning team is to minimize the risk that is associated with the forecasted schedule of production and costs included in a feasibility study. This risk can be minimized by obtaining additional information about a particular
parameter through further testing (for instance, by drilling more holes to improve the knowledge of the ore grade), or by building contingency to accommodate events that can significantly disturb the operating performance of the mine production system.

Minimizing the costs associated with a particular mining project alone is not adequate. As pointed out by Dunbar, *et al* (1998), the rigidity of a low-cost mining operation can prevent it from fluctuating the production rate efficiently, or introducing new technology and methods. In addition to minimizing the costs associated with a particular project, as part of risk management, the planning team needs to introduce measures that will enhance the operational capabilities to incorporate flexibility, adaptability and performance\(^1\). This is often achieved intuitively, when action plans are built to a cost structure in response to expected or unexpected changes. These objectives can be achieved only if the risk associated with a particular design has been properly evaluated and quantified.

In the manufacturing sector, proactive strategies of risk management are essential in a management philosophy that is based on total quality management (TQM). The internal characteristics of TQM focus on understanding and constantly improving the production process, with an emphasis put on quantifiable measures such as speed, amount of rework, and failure rate (Baldwin and Trigeorgis, 1992). Organizational capabilities include the ability to control all forms of delays and rework, as well as the ability to introduce incremental improvement and innovation in internal processes.

---

\(^1\) The thesis explores these issues below
Assessment and management of uncertainty is perhaps the most difficult aspect in a mining project. Since investments in the mineral resource sector are frequently associated with techno-economic and socio-economic risks, it is particularly important to introduce decisive measures that will mitigate or counterbalance that risk. Quantifying risk and building adaptability into a mining project is of strategic importance in meeting the present objectives and in sustaining growth in the mineral resource sector.

1.3 NEED FOR FLEXIBILITY IN MINING PROJECTS

As pointed out by Samis and Poulin (1998), the present value of individual project cash flows is influenced by the following considerations:

- The timing of the individual cash flows;
- The resolution of uncertainty regarding the economic and physical characteristics of the project;
- The ability of management to react to the resolution of uncertainty.

Mines are designed, in most cases, before, operating conditions are fully realized and appreciated. In cases where the uncertainty related to a particular parameter cannot be reduced through design improvisations, it is important that contingency be built within the mine plan to accommodate the factors that can seriously constrain production rate and costs, and to adapt to changing conditions over the life cycle of the operation. There are areas where the information necessary to make an accurate determination of conditions is not available. It is in these areas that flexibility is most important.
Introduction of flexibility in a mining operation is often performed intuitively by the design and planning team during the process of a feasibility study. This team has to rely on judgement and experience to determine the areas where flexibility has to be built into the production system and into the project as a whole. Flexibility is an integral part of mine planning and design. Here, flexible alternatives are evaluated and contingency plans are built, where this is judged to be necessary. The following comments can be made about the process to introduce flexibility in mine planning and design:

- Types of flexibility that have been identified include: the development of openings ahead of production, the prediction of dilution and oversize and the measures to contain the problem, the stope sequencing with the introduction of “back pocket” stopes, the bin capacity to accommodate production delays, the stockpiling of ore, the scheduling of mine production to accommodate quality and throughput requirements, the support of openings in anticipation of rehabilitation needs, the ability to blast out of sequence, the availability of spare equipment to maintain production levels, the use of alternative mine openings, the availability to external resources (contractors, consultants), the adequacy of inventory available in a warehouse, budgetary contingencies, the ability of personnel to recognize a problem and the breadth of training of mine personnel.

- There is no systematic method for introducing flexibility in mine planning and design. This procedure is not documented or formalized; rather it is subjective and dependent on

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2 Based on discussions and observations in mines of the Sudbury Basin, as well as on discussions with Paul Miller, Placer Dome Ltd., Kerry MacNamara, Goldcorp Inc. and Jane Alcott, Mine Sigma, CANMET.
the experience of the senior planner. Currently, there is no formalized process to quantify the value of flexible alternatives in a mine plan.

In a study of mining method selection, Krantz and Scott (1992) emphasize that the ultimate level of profitability of a mining project is enhanced by flexibility in the mine plan and by the choice of mining methods. A mine plan must have sufficient flexibility to allow the mining method to be changed and still meet the other goals of the project as defined by production scheduling, economic analysis, and manpower and equipment availability. In selecting a mining method, Singh and Rajala (1981) indicate that the method must be flexible enough to accommodate limitations imposed by existing mine facilities, such as the existing development, ore handling, compatibility with production schedule, fill and drainage systems, as well as to cope with different geological conditions. Bharti, et al (1983), emphasize that alternatives mining approaches should be sufficiently flexible to deal with difficult and unanticipated ground conditions.

Flexibility will be defined here as the ability of a mining system to sustain performance, preserve a particular cost structure, adapt to internal or external changes in operating conditions, and take advantage of new opportunities that develop during a mine’s life cycle by modifying operational parameters. Such a system will be defined in this thesis as a flexible mining system. In that sense, flexibility is a parameter that measures the ability of a mining system to respond to favourable or unfavourable changes (Dunbar, et al, 1998). It provides a means for the management team to improve its decision-making process and introduce appropriate measures in an uncertain environment with operating restrictions (Sagi, et al, 1995).
The concept of flexibility was first introduced in the manufacturing industry (FMS Handbook, 1983) where product flexibility became the focus of a flexible manufacturing system. This ability to switch from one product to another, depending on demand, is not usually an applicable type of flexibility in the mining industry (Dunbar, et al, 1998). An attempt to introduce the concepts of flexible manufacturing systems to the planning, design and equipment allocation in strip coal mines was made by (Singh and Skibniewski, 1991). The authors introduce various types of system flexibility with the emphasis given to equipment and product demand. The operating environment of a surface coal mine is significantly different from that of the underground hard rock mine. The techno-economic differences of these two mining systems limit the applicability of the proposed flexibility approach to an underground hard rock mine.

The design flexibility in construction projects was explored by Fredrickson (1998). He demonstrated that the design-builder flexibility is gradually reduced with increasing design completion. Although certain technical and economic aspects of construction projects are similar to the ones of mining projects, the fact that mines produce a marketable product imposes significant differences when examining flexibility needs in such projects.

The flexibility needs of mineral resource investments as related to market risk has been examined by several authors (Kajner and Sparks, 1992, Sagi et al, 1995, Trigeorgis, 1998, Samis and Poulin, 1997). The risk imposed by non-market related internal project factors is often not examined in such analyses.

Over the last decade, the valuation of flexibility in finance has attracted significant interest with the introduction of several mathematical models that are based on evaluation of options

Several types of flexibility have been identified for natural resource investments by Trigeorgis (1990 and 1998) that relate to the ability to defer investment, expand, contract, temporarily shut down, abandon, switch use, etc. In that sense, flexibility needs to be built into a project not only to act as “insurance” against adverse production performance, but also to enable the management team to take advantage of opportunities that may develop during the life cycle of the operation. Mining flexibility has been examined by Dunbar, et al (1998). The authors introduce a classification of tactical and strategic types of flexibility in an operating environment. This operational flexibility has been defined as the ability of the mining system to modify operational parameters to sustain performance. Such flexibility is often constrained by geological complexity and excavation geometry, layout, access, sequence and mining method.

1.4 MINE PLANNING AND DESIGN ASPECTS OF FLEXIBILITY

Mine planning and design precede the initiation of mining in an underground mine. Once the mine is in operating mode, production control becomes closely associated with ongoing planning and design of existing or new sectors of the mine. Mine planning and design are usually conducted by a team of specialists, in a proactive manner. Mine design is associated with the determination of design parameters in an underground mine, while mine planning determines the sequence of events and resources needed to ensure the cost-effective
extraction of an orebody. However, these two terms are often used interchangeably in the mining industry. Production control can require changes in the initial mine plan and design as a response to encountering different conditions than those anticipated.

The planning stage is defined here as the period between the initiation of the feasibility study and the first day of the mine going into operation. Subsequent planning operations aim to follow the developed production plans and introduce modifications where these are necessitated by financial markets, economic, technical, or geological problems. The objectives of underground mine design is to develop an extraction (depletion) strategy, which maximizes the economic benefits from the ore reserve. The engineering effort required to produce the optimum design is increased by constraints such as ground control or ventilation requirements, and often by a reduced level of information available on the geological, economic, and geotechnical aspects of the orebody at depth (Pelley, 1994). The effectiveness of mine design is greatly dependent on the ability of the initial plan to foresee and provide solutions to possible production-related problems that can occur once the mine is operational.

Strategic or tactical mine planning are both complex and involved processes. They are to some degree unique and dependent on the mine location, mine management’s experience, economic conditions, and local regulations. Therefore, each mine needs its own mine plan which includes particular features such as mining sequence and layout, production scheduling, geomechanical design, equipment and human resource deployment, ventilation, drainage etc. In effect, the uniqueness of a plan is based on the specific sequence of mining and the equipment used. The entire process can be summarized in a simple statement, that is, the determination of the optimum technical and economic system to extract the ore. The optimum mining system results in minimizing cost and maximizing profit. To minimize the
cost or maximize the ore recovery, one must be able to evaluate multiple alternatives in a short period of time, and have the ability to modify the assumptions used, based on the availability of new information.

Although the analyses conducted during the mine planning stage have a cost that is a very small percentage of the anticipated cash flow during the years of operation of a mine, the consequences that this plan can have on the whole operation are very significant, and may even result in the premature closure of the mine due to some underestimated or unanticipated factors. A mine plan must have enough flexibility built in at the start to accommodate a reasonable range of expected change.

The uncertainties that are due to the particular environment of an underground mine and the multi-functional, interrelated activities that take place, can result in significant disruptions in the production cycle. This, in turn, can impact on scheduled production levels and operating costs. Characterization of production problems that underground mine operations encounter tend to receive little formalized attention. The conditions that lead to a particular production problem are often not analyzed in great detail. The risk is that particular problems recur, since the lessons that are learned reside with particular individuals.

Optimization of a mine plan is an essential part of the planning process. In order to optimize the mine plan, the following individual objectives need to be met (Pelley, 1994):

- Maximize the overall percentage extraction of the mineral resource;
- Develop an optimum sustainable rate of extraction;
- Minimize the cost per unit extracted;
• Minimize the initial development time and cost;
• Provide a grade control strategy;
• Minimize ground control cost and problems.

These objectives are usually not complementary, and, to some degree, may be in conflict. A techno-economic feasibility study of a mining project focuses on the optimization of a complex set of variables through the long-range plan. Processes for managing project uncertainty with contingency planning have been examined by Roberts, et al (1996). According to them, although optimization based on existing project management tools can perform “what if” and risk analyses, the management of uncertain project environments is not well supported. In a contingency planning protocol, the following process steps are introduced:

• Identify and articulate the problems to be solved;
• Identify alternative solutions;
• Choose decision criteria;
• Justify alternatives;
• Plan contingencies;
• Enact contingency plans;
• Evaluate contingency plans;
• Evaluate conditional decisions.

One of the most important outcomes of the optimization process is a solution that allows the maximum degree of flexibility. The selection of the mining method in an underground mine is perhaps the most critical task of the planning team. The ability to adapt to unexpected
underground conditions or external considerations can go a long way towards determining the immediate and long-term success of a mining operation (Krantz and Scott, 1992). In an examination of flexibility of mining methods, the authors point out that: “…there is no one mining method that allows the mine operator to be able to accommodate all the known and unexpected conditions, but the mining method chosen should be the one that best accommodates the known and expected parameters at the lowest possible cost per ton mined, and still allows the flexibility to handle the unexpected”.

When choosing a mining method, Krantz and Scott (1992) introduce five types of flexibility associated with:

- Ore deposition (delineation, outline);
- Uniformity of mineralization (i.e., variation in ore grade);
- Scheduling and sequence of mining activity;
- Ground conditions of the deposit and the surrounding host rock;
- Working environment.

Proper method selection allows for mining areas with varying ground conditions without major changes in the mining method.

1.5 GROUND-RELATED PROBLEMS AS AN INTERNAL PROJECT RISK FACTOR

Among the factors that introduce uncertainty into a mining project is the behaviour of the ground during the development and ore extraction phases. This is of particular importance in flexibility assessment. As pointed out by Krantz and Scott (1992) and Bharti, et al (1983), a
mine must have the flexibility to modify mining methods in response to unexpected ground-conditions. However, although the need for flexibility in an underground mining environment was identified, no solutions were provided on how to identify and introduce flexibility in a mining system.

Geologic uncertainty is present in a mining project in terms of estimating the grade of an orebody, and, therefore, its in-situ economic value, the recovery that can be achieved using a particular mining method, and the production delays and cost overruns that can occur during the mine life cycle. The evaluation of the in-situ economic value of an orebody is the subject of geostatistical analyses that can provide ore grade estimates (including cut-off grades), as well as the global deposition of the orebody. However, the actual economic value of the mining project will be dependent on the final recovery of the metal that can be achieved. The overall geology and the selected mining method are the key factors that affect recovery. Uncertainty in ore estimation can be taken into account through geostatistical simulation. The remaining factor that relates to geologic uncertainty is the potential for ground-related problems during the life cycle of an underground production system. Internal project risk is present in any production or operating cost calculation conducted as part of mine planning and project valuation analyses.

The focus of this study will be the evaluation of the uncertainty related to internal project factors (as opposed to market uncertainty), and, in particular, the ground-related problems that can occur in an underground hard rock mining operation. The hypothesis of this study is that ground-related problems can be significant for the performance of a mining operation, and that flexible mining systems can be designed and planned with the methodology proposed.
Ground-related problems are those that can result in delays and cost overruns during the development and operating cycles of a mine due to geotechnical factors. Such problems can be related to falls of ground, development of unsafe conditions to personnel and equipment, deterioration of local conditions around mine openings, and, in general, all the problems that are subject to in-situ ground conditions and the response of the ground to mining. The science of rock mechanics and rock engineering provides design approaches that can be used to improve the design of underground mine opening and to minimize the likelihood of ground-related problems. The common rock mechanics objectives in the design of a mine are summarized by Brady and Brown (1994), as:

- Ensure the overall stability of the complete mine structure, defined by the main ore source and mined voids, ore remnants and adjacent country rock;
- Protect the major service openings throughout their designed duty life;
- Provide secure access to safe working places in and around the centres of ore production;
- Preserve the mineable conditions of unmined ore reserves;
- Minimize undue risk to operator.

Despite the best efforts to eliminate ground-related problems in mines through extensive research in the field of rock mechanics and geomechanical mine design over time, such problems still impede underground mining operations and impose both a safety as well as an operational hazard. This, in turn, creates both political and economic risks that can place a mineral resource investment in jeopardy.
1.5.1 Impact of ground-related problems in underground hard rock mines

The impact of ground-related problems is often characterized in terms of the health and safety aspects of underground mines. The impact on mine production performance is not always adequately appreciated and characterized. In a study of the impact of ground-related problems in South African mines, Wagner (1991) indicates that rock engineering design impacts on the recovery of the mineral deposits and the operating costs. In addition, rock-related hazards account for more than half of all fatalities in South African gold mines, and about one-third of all fatalities in coal mines. He argues that "...the economic wellbeing of a mine should not be measured in traditional rock mechanics terms, but in quantities which affect the bottom line of mining operations". The author also indicates that rock engineering decisions impact on the optimal utilization of the mineral resources; favourable and safe operating conditions; and operating costs and losses. In his conclusions, he states that "...present management structures on mines do not take full advantage of the potential contribution of rock engineering" and that "rock engineering is a means to an end and not an end in itself. This requires a change in culture of the rock engineering profession in the mining industry".

In an evaluation of costs and overall major losses as a result of rock deformation and failure in tunnels in South African gold mines, Jager and Wojno (1991) argue that good engineering practices that include mine layout and support are saving the industry hundreds of millions annually in tunnel costs and enable areas to be mined, which would be inaccessible or uneconomic without the rock engineering input. Furthermore, Buddery and Oldroyd (1991) provide a detailed description of the impact of rock engineering design in reducing costs, improving productivity, increasing extractable reserves and rectifying safety. In a review of
regional pillar design strategies, Goel and Page (1981) evaluate the contributing factors that make pillar extraction economically viable.

In a study of Ontario mines, Pelley (1994) argues that “...the ability to control ground conditions affects the rate and level of extraction recovery, the operating and development costs, and the capability to control dilution. The inability to control the ground affects the safety of personnel and effectively causes the cessation of mining operations”. In a study of the significance of geomechanical mine design in Canada, Bawden (1993) argues that “...inadequate attention to the design of stope dimensions, support, etc., can quickly eliminate profitability from high productivity bulk mining methods”. He also emphasizes that the most critical cost elements that can be influenced by geomechanics include dilution, support costs, blast damage and safety (Bawden, et al, 1988). Although research has identified the significance of proper geomechanical design in mines, it has not provided a systematic approach to evaluate and measure the impact of ground-related problems on production performance.

Dilution has attracted a significant focus over the last decade in Canada. The impact on mine production has been evaluated (Elbrond, 1991, Scoble and Moss, 1994, Pakalnis, et al, 1995). As stated by Bawden, et al (1988), “... the most serious consequence of dilution is when this prevents the operator from milling ore. In such a case 10% dilution, for example, results in a direct 10% reduction in revenue”.

Loss of ore reserves (or even mines) as a result of gross miscalculation of potential ground-related problems are discussed by Tintor (1988). The author presents a number of cases where major losses occurred in Canadian mines as a result of inadequate evaluation of the in-
situ geological conditions. He emphasizes the value of sound technical information within a feasibility study. A deterioration in ground conditions can result in orebody losses and even premature closure of mines, as was the case of the Falconbridge, Macassa and Strathcona Mines (CRRP, 1995).

This study aimed to characterize the nature and intensity of production delays and economic losses due to ground-related problems in the hard rock mining industry. These can range from insignificant losses up to the loss of a whole year's production (Morrison and Galbraith, 1990). In a study of losses associated with sill pillar mining at the Williams Mine, LeBlanc and Murdock (2000) indicate that ground-related problems resulted in significant production delays, dilution, needs for rehabilitation, redesign and support. Production delays due to ground falls in a sill area were equivalent to over two million tonnes of production containing half a million ounces of gold. A single rockburst resulted in rehabilitation costs in excess of four million dollars. This event occurred despite efforts to optimize geomechanical mine design over time (Bronkhorst, et al, 1993) in that mine.

Lost opportunity costs are also evident in cases where ground-related problems cause production delays. Such delays will result in an overall lower rate of economic return than planned, based on the initial feasibility study for the particular project. This is due to the fact that the initial investment is "locked" in a project for longer time, therefore resulting in a devaluation of the overall return for the project.

Last, but not least, the safety implications that ground-related problems impose on underground hard rock mining operations should be emphasized. Despite efforts to ameliorate the danger that ground falls and rockbursts impose on the labour force, a number
of fatal accidents have occurred in Canadian Mines. The particular conditions that are associated with these incidences were the focus of public inquiries and intense research over recent years. Such incidents occurred, for example, at Elliot Lake (Hedley, 1992), Red Lake, Falconbridge and Macassa Mines (CRRP, 1995), with devastating effects on the mining companies and the image of the industry as a whole. The loss of life cannot be related to any form of economic loss. Fatalities and accidents in mines in many cases raise political and ethical issues for mining corporations with serious economic repercussions, in addition to the operational losses that are created.

This thesis does not attempt to conduct risk analysis that is associated with any threat to life or attempt to assess the economic impact of fatalities and accidents in mines. It will be inherently assumed that planning does not accommodate any form of injury to personnel, but, that rather, design approaches, training and safety measures are part of any professional mine planning practice and evaluation of alternatives. Therefore, the impact of ground-related problems will be examined only in terms of various forms of economic loss in a mine production system.

A literature review on the impact of ground-related problems has clearly indicated that the viability of an underground mining operation today is critically dependent on cost-effective solutions that can optimize the production cycle and simultaneously minimize the possible disruptions to that cycle. If decision making in mine planning is driven mostly by economics, the potential impact of ground-related problems cannot be ignored or left unrealized in lieu of inadequate information to assess them.
Ground-related problems that occur during the development or production cycles are classified in many cases as unforeseen or unanticipated. Their impact is usually not included in the original plan of the mining project, and in the best case, only rough estimates of the impact on ore recovery or dilution are made. The volatility of the operating cost due to ground-related problems is only realized once mining is underway and the mine planning alternatives have been diminished. Well-documented rock engineering design analyses (empirical, analytical, numerical) have been developed through time (e.g., Pakalnis and Vongpaisal, 1998). However, these were not developed by keeping in perspective the options that are available to a mine operator at a given time, and the degree of flexibility which is required in mine planning and design.

Anticipation and control of ground-related problems are critically important for the optimum performance of the mining operation and the satisfaction of the production targets set (Kazakidis, et al, 1999). In next generation mining, the overall mine design cannot afford to be defined on a trial and error basis, since this has a very high direct impact on the operational cost of a mine. Geomechanical mine design needs to become an integral part of mine planning at the early stages of a mining operation, when there is still time to consider favourable planning and design alternatives. A review of case histories indicates that there are many examples in which ground-falls or stress-induced failures resulted in ore dilution or closure of stopes, drifts, levels, ore passes or raises, which in turn significantly increased the operating cost of a mine. It is widely appreciated today that, although not every ground-related problem in an underground mine is foreseeable, many can be avoided when geomechanical principles, coupled with knowledge about the particular rock mass and past experience of its behaviour, are integrated fully into mine planning and design. Contingency planning and flexibility assessment will be directly impacted by ground-related problems.
1.5.2 Optimization philosophy and flexibility with respect to ground-related problems

The criterion that a planning team often sets for a new mining operation is a constant production level (e.g., tonnes per day) below a certain mining production cost (e.g., $ per tonne or $ per ounce). This, in itself, constitutes a planning and operating philosophy, since the whole mine, its personnel and equipment, will be designed to meet these particular criteria. Intuitively, the assumption here is that the variability in the production and cost will remain small enough, not to significantly affect the viability and profitability of the mining operation. In addition, it is often the case that there is no proactive plan addressing how the operators should deal with particular ground-related production problems, once these are encountered in the operating mine. Maintaining the production level as the first priority can often result in mining uneconomical, low grade parts of the deposit, or hoisting waste rock to feed the mill's tonnage requirements. On the other hand, if the operating cost becomes the first priority, then a mine theoretically may reach a cost level, which makes it preferable to stop production for a certain period of time. It is becoming apparent that introducing flexibility into the original mine plan, accounting for the risk and impact of potential ground-related problems, will be basic need for the next generation mine planning systems. Technological developments now provide the opportunity to introduce a new philosophy in mine planning and design.

The reasons for ground-related disturbances need to be evaluated, classified and prioritized. Means to calculate the economic cost of the particular disturbance and the cost of alleviating or minimizing the chance of it occurring, need to be evaluated through the analysis of particular case studies. The likelihood that a particular problem will occur, the potential
economic and production impact, and the cost to alleviate this problem are the three factors that should constitute the backbone of any flexibility-risk analysis.

1.6 JUSTIFICATION FOR RESEARCH

The comments made by Wagner (1992), about the need to introduce an approach to measure the contribution of rock engineering to mining in terms of economic rather than rock engineering parameters, contributed to the initiation of this research. Furthermore, the need to provide a methodology to assess internal project risk in long term mine planning due to ground-related problems became evident through my professional practice during the past ten years. The inadequacy of information availability to assess the economic impact of significant ground-related problems was an additional contributing factor to justify this research. Literature reviews have verified that little has been done to fill that gap. The need to formalize the integration of types of flexibility into mine plans, to anticipate and counterbalance production problems and operating losses due to ground-related problems justified the research. Identification of the tools available in other disciplines (other than the traditional DCF analysis) became an obvious goal. The link of the above design parameters to decision making as part of mine planning was an additional incentive to pursue this research topic. The concepts of flexible manufacturing systems and cellular manufacturing, together with the acceleration in enabling technology advances, also prompted the need to consider how flexible mining systems could be engineered. This research aims to contribute to the evolution of conceptual design of flexible mining systems, which account for the response of the rock mass to excavation.
The thesis introduces alternative processes in mine planning for the evaluation of the production disruptions that can occur in an underground hard rock mine due to ground-related problems. It focuses on field work mainly conducted in the mines of the Sudbury area of Ontario, Canada. It is considered, however, that the work has comparable value for underground hard rock mining in general. The introduction of operating flexibility during the planning stage of a mine then becomes the third dimension of the evaluation process, supplementing the attention given to production capacity and operating cost. The evaluation analyses and data requirements, as well as the interrelationship between flexibility, production capacity and operating cost, required to be examined conceptually. This was approached through case studies from underground hard rock mines with ground-related problems. The planning philosophy for flexible mining systems then becomes dynamic. Its objectives are not only the minimization of the production cost, the maximization of profit, or the maximization of the production rate, but also the maintenance of an appropriate level of flexibility throughout the mine life cycle.

1.7 RESEARCH OBJECTIVES

This thesis explores the means to quantify operational flexibility in underground hard rock mines. It focuses on the evaluation of internal project risk associated with ground-related problems, as part of the mine planning process. The impact of ground-related problems on the operating cost of a mine is considered, and mining system rationales are reviewed. The final outcome is a proposed planning methodology, which integrates flexibility analysis into the planning process through the evaluation of internal risk-related alternatives to minimize the impact of potential ground-related problems.
The research objectives of the study are to:

- Characterize the interaction between mine planning and mining geomechanics;
- Characterize internal risk and flexibility in mine planning;
- Classify the types of ground-related problems that occur in underground hard rock mines and their impact;
- Determine the means to evaluate the impact of potential ground-related problems in a mining project;
- Establish and evaluate analytical methodologies to assess internal risk;
- Apply concepts of reliability engineering to a risk model for mine excavations;
- Examine the applicability of flexibility analyses to evaluate the mine planning alternatives to potential ground-related problems;
- Establish a methodology to account for flexibility in planning to accommodate internal risk associated with ground-related problems.

1.8. RESEARCH METHODOLOGY

1.8.1 Linking mine planning and geomechanics

Although there is extensive literature on geomechanics analyses in general, very little has been done to establish direct links with the mine planning parameters. This gap has been filled through evaluation of mining practices in Sudbury Mines and communication with specialists in mine management, planning and ground control. The mine planning parameters whose derivation is dependent upon input from geomechanics analyses of ground-related problems were identified.
1.8.2 Classification of potential impact of ground-related problems

A classification of ground-related problems was conducted by keeping in perspective the mine planning needs, as well as the potential economic impact that ground problems can have on underground production. These sources of cost are tabulated in such a way that prioritization of potential incidents is enabled.

1.8.3 Case studies

The significance of ground-related problems to the overall planning strategy for an underground mine was demonstrated through representative case studies. The impact of particular types of problems on the operation and the flexibility implications were also evaluated.

1.8.4 Review of mine planning rationales

The current rationale that is followed during mine planning analyses with regard to evaluating potential ground-related problems was reviewed based on the analysis of field work, interviews with planning specialists, and a literature search.

1.8.5 Flexibility concept

An extensive literature review was conducted to evaluate flexibility analytical techniques developed in other fields. This aimed to determine those that can be used to evaluate mine planning alternatives that are associated with ground-related problems. The concept of developing contingency for mine planning was demonstrated through test case studies by applying a range of appropriate techniques, including DCF, production simulation and real options.
1.8.6 Testing and development of the methodology

A methodology that incorporates flexibility into mine planning systems was proposed and explored through analysis, systems flow charts, and appropriate demonstrative examples. The examples are based on field-survey data collected at mines.

1.9 THESIS STRUCTURE

This thesis consists of seven chapters in total. Chapter 1 introduces the nature of risk in mine planning, the significance of ground-related problems, the need for flexibility in mining, operational reality and planning practices. Chapter 2 analyzes the links between mine planning and ground-related problems in hard rock mines and introduces key case studies where the impact of ground-related problems and the significance of flexibility are demonstrated. Chapter 3 introduces an internal risk model. The impact of ground-related problems is classified and the means to conduct reliability analysis and cost assessment are introduced. Chapter 4 discusses the application of production simulation and project valuation analyses, such as the DCF analysis, in evaluating the impact of ground-related problems. Chapter 5 evaluates the application of real options in assessing flexibility in mining projects with respect to ground-related problems. Production, economic simulation and real options analyses are integrated, and their applicability is demonstrated through examples. Chapter 6 provides guidelines and a methodology to account for flexibility in planning that accommodates internal risk, such as the risk associated with ground-related problems. Finally, the results are synthesized and recommendations for further research and implementation are presented in Chapter 7.
1.10 SIGNIFICANCE AND CONTRIBUTIONS OF THE THESIS

The outcome of this study will benefit the mining world (industry and academia) by demonstrating a new philosophy for quantifying operational flexibility during the decision making process of planning and design for underground hard rock mine operations. The study will integrate research from the following disciplines: mine planning and design, scheduling, mining project valuation, decision making, simulation, investment science, finance, operations research, management science, reliability engineering, mine geomechanics, cost-benefit analysis, engineering economics and mining systems analysis.

This research is the first to attempt to quantify the reliability of mine excavations in terms of risk associated with ground-related problems. It considers ground-related problems as an internal project risk factor and proposes a methodology to introduce flexibility to counterbalance such problems in a mining system as part of proactive mine planning and design. The work documents the significance of ground-related problems in mine planning and design, and their potential economic impact on mine production and cost structure. Ground-related problems are considered as an operating risk factor. The thesis represents an important first step towards understanding how ground-related problems can be introduced and evaluated in terms of flexibility needs in an underground mine production system, in an effort to ensure the optimization of a predetermined cost and production structure.
CHAPTER 2:

MINE PLANNING AND GROUND-RELATED PROBLEMS

2.1 GENERAL ASPECTS

In Chapter 1, the significance of ground-related problems in mining operations through time was described and linked to key case studies. Design work has often focused on the avoidance of such problems or, in case they cannot be avoided, the introduction of contingency in a mine plan to alleviate or minimize their impact. Sources of risk in underground mining were introduced in Chapter 1. The emphasis of this thesis will be on the risk associated with ground-related problems that occur in underground mines. A flexible mine plan that introduces contingency to accommodate the risk imposed by ground-related problems is often critical. The links between the mine planning functions of an underground mine will be explored next. Finally, typical examples of ground-related problems that impaired mine production in underground mines will be analysed.

In an effort to analyse the geomechanics aspects of mine planning, as well as to introduce representative examples of ground-related problems in underground hard rock mines, a study was undertaken in several underground hard rock mines in Sudbury, Ontario. Mine personnel, including mine planners, mine engineers, ground control personnel, geologists, as well as mine management personnel, were interviewed. In addition, records pertaining to key case studies were analysed.

Mining geomechanics and geomechanical mine design are terms that refer to the evaluation and specialized design to account for ground-related problems in mines.
Underground operations contain several functions. Mine planning is a primary function of a mine. Here the design, layout, and schedule, of the mine or mining sector are performed. The knowledge of the orebody geology is vital for mine planning. Geomechanics have a significant input into mine planning. The emphasis in the analysis introduced here has been placed on three functions: geology, mine planning, and geomechanics.

Planning of mining operations, prior to development, can be separated into three stages:

- strategic planning (corporate-divisional);
- long-term planning; and,
- short-term planning.

Strategic and long-term planning precedes the initiation of operations in the mine. Once mining of the orebody is initiated, then short-term planning becomes a permanent function of the operation, while the mine updates its long-term plan on a routine basis (e.g., annually). Exploration of extension to reserves will generally still continue. Knowledge gained in the mine production control process in an operating mine provides a key input for both short and long-term planning.

Once new orebodies or extensions of existing ones are found, the strategic and long term planning will be initiated to evaluate the feasibility of the new mine sector. The concepts of the stages of planning and their interaction with mining control are illustrated in Figure 2.1. Although these stages of planning describe a well defined planning process, it is often the case that unanticipated problems during the mining of an orebody result in changes to the original long or short term plan, and the establishment of a new action plan to accommodate
the encountered problems. Ground-related problems often impose a need to deviate from the original mine plan, and to introduce a new, significantly altered, plan to accommodate the particular requirements of a mining operation.

Unfortunately, the particular geological setting of each orebody makes it impossible to duplicate a mine plan from one mine to another. Each orebody requires its own planning and design, customized to meet the requirements of the particular operation and the characteristics of the orebody.
In order to examine the information input that geomechanics provides to mine planning, it is necessary to:

i) establish the links between mine planning, geology and geomechanics; and,

ii) analyze the parameters of the particular planning stage and the required input from a geomechanics decision support system.

2.2 ESTABLISHED LINKS BETWEEN GEOLOGY, PLANNING AND GEOMECHANICS

Planning functions in an underground mine involve several specialists and include design work related to geology, mine planning, geomechanics, mining, environmental issues, electrical, mechanical, maintenance etc. Geomechanics issues are directly related to geology and mine planning. Information is shared between them, and decision making in each function will often require input from each of the others. An optimized view of the interaction among geology, mine planning and geomechanics is shown in the flow chart of Figure 2.2. Here, links among these three functions have been established, based on the requirement of the particular activities. These activities are described as data generation activities, or planning and control processing information. Databases for each of the three functions have been considered for storage and updating of the particular information. Interaction among the various activities is required in order to maintain the normal flow of the three functions considered here. Once the mine starts operating, various incidents provide feedback to all three functions, which enable the modification of the original plan, and the optimization of the planning process within existing or new mine sectors.
Figure 2.2: Links between geology, mine planning and geomechanics (Kazakidis, et al, 1999)
2.3 GEOMECHANICS INPUT INTO PLANNING ACTIVITIES

Each of the three planning activities (i.e., strategic, long and short-term planning) engages several techno-economic parameters. The parameters of long and short-term planning activities were analyzed in order to determine the input required from a geomechanics decision support system for each of the parameters. Figures 2.3 and 2.4 describe the parameters contained in long and short-term planning activities. It should be noted that the classification of mine planning parameters, shown in Figures 2.3 and 2.4, has been kept general enough to ensure that it covers the issues relevant to this study. Although the key parameters are considered to be representative of mine planning in general, specific functions and certain parameters may be different from site to site, depending on the particular requirement of the operation, company structure, legislation and analysis process. The geomechanics requirements of mine planning were kept as the focus of the critical review of the planning process presented here.

The need for geomechanics analyses becomes critical once long-term planning is initiated. Most of the key mine design decisions that can determine the efficiency of underground production systems are made during this stage. Design and planning related decisions (e.g., mining method, access, sequence) are not driven strictly by economic factors, but also by an evaluation of technological factors such as ground-related issues. Geomechanical mine design should now become a key player in the overall decision making of long-term mine planning. Here, the planning parameters are contained within four subactivities, which are linked with internal loops. Several of these parameters require input from geomechanics analyses as indicated in Figure 2.3. The four subactivities include:
- Global extraction strategy;
- Primary development and services;
- Method design and production scheduling;
- Resource planning.

Input from geomechanics is indicated throughout the components of the four subactivities in Figure 2.3. The purpose of this analysis is to delineate the parameters of long term planning for which design and decision making requires input from geomechanics. The extent and the type of input will be a function of the particular orebody characteristics (e.g., geology, geometry, depth), the mining method, the equipment used, and other factors that affect the decisions pertaining to the parameters of the four subactivities of long-term mine planning.

Confidence/risk analyses are usually conducted within each subactivity, or coincide with the completion of the long-term mine plan. These analyses include the evaluation of design alternatives and 'what if scenarios' of possible production delays or the development of opportunities during the mining process.

With the completion of the long-term plan and the financial evaluation, the developed mine plan must be evaluated, and reliability assurance carried out. The effectiveness of the constructed mine plan to handle problems throughout the mine life cycle, as well as the efficiency of the overall mining system, is evaluated. Key decisions pertaining to the flexibility needs of the overall mining system are also evaluated during this process. The final outcome includes a feasibility study with a production plan to mine the mineral resource inventory (MRI). A virtuous long-term plan will have assessed the potential for ground-
related problems to occur throughout a mine’s life, and will accommodate impact and counter measures within the production and cost schedules of the long-term plan and the overall design of the particular mining operation. In this way, flexibility needs to accommodate potential ground-related problems within a production system would be attended to at the long-term planning stage.

Similar analyses are required for short-term planning, as indicated in Figure 2.4. However, since the key mine design has already been performed as part of long-term planning, only tactical decisions can be performed here, some of which require input from geomechanics as indicated in Figure 2.4. The four subactivities include:

- Primary development and services;
- Delineation;
- Production and secondary development;
- Resource planning.

Mining control parameters require particular geomechanics input in terms of ground control, evaluation of hazard conditions (i.e., rockburst, ground falls), and overall production control. However, since the focus of this thesis is on the planning function of an underground mine, examination of geomechanics needs in mining control will not be discussed any further here.

Geomechanics input into mine planning requires the establishment of a process, which facilitates the execution of design analyses. Such a process, effectively, would comprise the following five main functions:
• established company guidelines (e.g., support guidelines);
• empirical design techniques (e.g., stope stability method);
• stress modelling (using numerical models such as MAP3D, EXAMINE3D, FLAC3D);
• structural analysis (e.g., rock mass classification, joint mapping, wedge stability analysis);
• past experience of personnel.

The applicability and the use of the particular function of a design process would be based on the design needs of the planning parameters (e.g., mining method, sequence, stope size etc.) that have already been described. Mine planning systems for the next generation of mining systems will require the establishment of an effective design process in which design expertise would be available to fulfil the requirements imposed by the long and short-term mine planning parameters.
Figure 2.3: Parameters in long-term mine planning (Kazakidis, et al, 1999)
Figure 2.4: Parameters in short-term mine planning
2.4 GROUND-RELATED PROBLEMS IN MINE PRODUCTION SYSTEMS

Although the input requirements of geomechanics into mine planning can be determined, it is often the case that during the mining cycle of an orebody, ground-related problems are encountered despite best efforts by the planning/operating team to avoid them. Classifications of ground instabilities are usually made in terms of their characteristics (i.e., fall of ground versus rockburst), failure mechanism (e.g., tensile versus shear failure), or location (stope failure, drift failure, pillar failure), rather than their impact on mine production (Ontario Government, 1986, Hedley, 1992, MASHA, 1998). Ground-related problems can impact on mine production by causing delays in the production system. Typical ground-related problems in mines can be associated with problems in individual stopes or series of stopes, pillars, and access drifts, as well as with delays in a prescheduled excavation sequence of mine openings. A comprehensive review of ground-related problems and applications of underground hard rock mine design in Canadian mines is given by Bawden (1993).

In geomechanics, ground instability is considered as a major concern primarily because of its implications for safety. Safety is of paramount importance in underground mining, and warrants the special focus and attention that it has been given by ground control over the years. Major tragedies in the mining industry [e.g., Falconbridge Mine (CRRP, 1995), Belmoral (Betournay and Mitri, 1995), Elliot Lake (Hedley, 1992)] are indicative of the devastating impact that ground instabilities can have on a mining operation. The focus of this thesis is not to add another analysis of these catastrophic failures, but rather to focus on the production impact that a ground-related problem (small or large) can have on an operating mining system. From that perspective, the risk for production losses or increment of
operating expenses due to ground-related problems are examined, as opposed to the risk for
disasters that can result in human loss. Therefore, the examples presented here and the
classification of the ground-instabilities, are focused on the evaluation of the impact of
ground-related problems on a production system. The author would like to stress that this
should not be seen to belittle or trivialize the link between ground instability and safety in
underground mines, which is and will be a very important function of a mining operation as
long as miners work underground.

Ground-related problems are a broad issue that has hampered underground mining operations
all over the world for many years now, as was discussed in Chapter 1. Such problems can
impose a real challenge to flexibility in an underground production system. Studies of actual
past ground-related problems and their impact on mine planning at mines were undertaken.
The lack of flexibility in the mine production system, necessary to maintain production levels
and operating costs at pre-scheduled levels, is also demonstrated. The case studies aim to
help assemble a sound knowledge base and understanding of the types and impact of ground-
related problems that need to be accounted for in planning for different mining situations.

While not all problems can be avoided, it is imperative that flexibility be built into the
mining system during the planning stage, when most options are still available, in order to
accommodate production losses or increments in operating costs. Accommodating ground-
related problems in underground mining operations can impose a real challenge in terms of
flexibility in the production system, since it is often difficult to foresee, design, and schedule,
production and costs around these problems. Nonetheless, the potential impact that they can
have is such that an early evaluation of the likelihood that they will be encountered is
necessary, as well as an evaluation of the means to minimize, alleviate, or control them. This
will result in the overall amelioration of mine planning quality and the introduction of flexibility into the performance of mine production systems.

2.5 CASE HISTORIES OF TYPICAL GROUND-RELATED PROBLEMS

Four case studies from underground hard rock mines in Sudbury, Ontario are presented to demonstrate the impact of several ground-related problems. These case studies describe typical ground-related problems such as those associated with stope, pillar and access drifts failures, as well as with delays in a mining sequence. The information presented here is based on collection of data through interviews of key mine personnel, as well as on a review of mine records and published literature.

The description of the case studies focuses on the impact that ground-related problems had on a mining system, rather than on the geomechanical analyses that were carried out prior to and after the occurrence of these problems. Effort was made to analyze these four studies in a way to facilitate:

- the demonstration of representative ground-related problems in underground mine production systems;
- an analysis of the interaction between geomechanics and mine planning;
- a classification of ground failures experienced in different mining situations;
- the demonstration of the significance of ground-related problems in underground mining systems;
- the development of links for future decision support systems.

The case studies were examined in terms of:
• type of ground problem;
• summary of the problem;
• historical review;
• economic/production impact;
• analysis of planning and design;
• flexibility implications.

The type of ground problem was described in terms of the problem characteristics. The problem summary comprised a description of the environment and events making up the case study. This was followed by an analysis in terms of a historical review and the economic impact. These were based on existing documentation for the case studies, examination of records, and discussions with personnel at the mine sites. The economic impact was expressed in terms of loss of ore reserve in tons, dilution, loss of production, or direct economic impact on production cost. Finally, the evaluation analysis for each case study focused on reviewing the decision making process during the planning and operating stages, the strategic and tactical mine design adopted, any modifications to the original plan, and the measures taken to overcome the problem. Alternative designs or layouts that could have alleviated or minimized the problem were also included. The geologic complexity, the unpredictability of the rock mass behaviour, and the impact that this had on the occurrence of case study events, was taken into account in the analysis of planning and design. The implication that the ground instabilities had on the flexibility of the mine production system is also discussed.
2.6 CASE STUDY A

2.6.1 Type of ground-related problem

Ground-related problems included:

- Loss of ore reserve due to uncontrolled slough of ore, overstressed pillars, and excess ground deterioration.
- Dilution due to unstable walls and need for rehabilitation due to regional deformation and static stress induced damage.

2.6.2 Summary of the problem

Longitudinal vertical retreat mining was designed to take place in a sequence of primary stopes and pillars. With the completion of primary stope extraction, bursting at the pillars was initiated as a result of their stiff nature and the high in-situ stresses. Two of the pillars became unminable due to heavy fracturing from stress redistribution. Inability to backfill the mined stopes, and the need to continue mine production, exacerbated the ground problems, by creating a 200 foot (61 m) wide open stope span and causing excessive sloughing of the hangingwall and the back that resulted in significant loss of ore and dilution.

2.6.3 Historical review

Mining at the 120 orebody between the 3600 and 3935 levels was initiated in 1984 using vertical retreat methods (Figure 2.5). The orebody in this area is subvertical and its thickness varies between 15 feet (4.5 m) and 80 feet (24.3 m). The 3835 sublevel was used to facilitate mining of the 335 ft (102 m) high stopes. The width of the stopes was determined by the ore contacts. The primary stopes were to be 40 feet (12.2 m) along strike and the pillars (i.e.,
secondary stopes) 80 feet (14.4 m) along strike. Primary stopes were to be filled with cemented fill, and the secondary stopes with straight fill. Such a design could fulfil the production requirements while minimizing the requirements for cement in backfill. The stope-pillar design was based on the current knowledge of the regional stress field and the experience for pillar design above the 2200 level at the same mine. It was assessed that the pillars, having an average strike length to width ratio of 4:1, would maintain an acceptable safety factor until pillar recovery. The design calculations indicated that the strong pillar layout could allow delays in backfilling of the primary stopes, provided that filling caught up prior to initiation of pillar mining.

Production at the 120 orebody was initiated in 1984. The total vertical height of the stopes was 335 feet (102 m), and mining was assisted by the sublevel that was developed on the 3835 foot level. By the end of 1985, mining of the primary stopes was near completion, with the 113 stope being extended. However, only three out of nine stopes had been completely filled and two others half-filled. The hydraulic fill system was not installed at the mine, and a system of placing dry rock fill from the surface which could be augmented with cement slurry was implemented instead. Rock passes and chutes were used to bring the rock fill from the surface to the main mine levels, an operation that encountered significant delays due to hang-ups in the passes. In January 1986, during mining of the last primary stope at the extreme south end of the orebody (113 stope), a crown blast at the 3835 sublevel triggered a major episode of seismic activity and rockbursting (Figure 2.5 and Table 2.1). Heavy fracturing and seismicity indicated that the 114 pillar adjacent to the stope, as well as the 115.5 pillar, were failing. There was significant damage to the 3835 sublevel access and to a lesser degree on the 3600 and 3935 levels. With the 114 and 115.5 pillar having failed, the loads were transferred to the 116.5 and 118 pillars in the middle of the zone. At least 110,000
tons (99,700 tonnes) of ore were lost due to the rockbursting activity at that time in the area. Due to the high levels of seismic activity, a microseismic system was installed to monitor the activity. Mining continued through 1986 with modest levels of seismic activity and few groundfalls. Dilution of open stopes was significantly increased while many of the primary stopes remained unfilled.

The transfer of load to the 116.5 and 118 pillars resulted in wall sloughing, gradual deterioration, and squeezing of the predrilled 6.5" (0.165 m) ITH holes in these pillars. Filling of the 117 primary stope located between these pillars was not completed. Although mining of the pillars was initially planned after filling of the 117 stope, production needs required that these pillars be blasted. The 118 and 116.5 pillars were blasted (slashed) into the open 117 stope in December 1986 and March 1987 respectively, creating a 200-foot (61 m) span along strike, east of the failed 115.5 pillar. Falls of grounds in the walls and back of this void, accompanied by seismic activity, started occurring. By the summer of 1987 the
initial hangingwall slough had expanded, with tension cracks developing as far as along the access drift. The caving in the back had progressed 200 feet (61 m) upwards, reaching the 3400 level. An estimated 170,000 tons (154,221 tonnes) of ore were lost due to sloughing. During the summer shutdown of 1987, filling of the cave began. The placement of 280,000 tons (254,010 tonnes) of backfill was completed in September 1987.

2.6.4 Economic impact

In addition to the quarter million tons of ore that were lost, significant dilution, rehabilitation of drifts, and remedial geomechanics work, arose as a result of the described ground failures.

2.6.5 Analysis

Ground failure initiation and propagation occurred due to unanticipated consequences of strategic design and tactical operational decisions.

a) Strategic design:

The initial pillar design as part of long-term (strategic) planning was based on an inaccurate assumption in terms of the stress field and the stiffness of the pillars. In order for numerical modelling to be successful, valid field stress measurements are an essential prerequisite, as later study carried out by Mines Research indicated. Lack of knowledge of a single parameter can dramatically affect the overall design. Some pillars proved to be stiff because of their overall shape, but also due to their stiff, siliceous nature. The reality was that the appropriate design turned out to be a weak (yieldable) pillar layout. Such a design was followed for mining above the 3600 level. It should be noted that yielding pillar, or pillarless stope
sequences, would have required fill placement to closely follow stope extraction. Therefore, it can be concluded that the root problem was the inadequacy of pillar design.

b) Tactical decisions:

The *filling delays* were not essential contributing factors to the cause of the problem, but rather to the inability to contain it and ultimately halt its uncontrolled propagation. The effect of backfill in open stopes is to restrict the amount of displacement, which can occur in the walls of the stopes. While the initial failure of the walls cannot be prevented by the presence of fill, it can prevent large progressive failures. Similarly, although the fill cannot control the onset of mining-induced seismicity, which is controlled by the stress-state around the stopes, it can control the seismicity, which results from a progressive failure of the walls. Once the pillars started failing prematurely, the fill placement became critical, since the propagation of failure and the seismic activity could not be halted by any other means.

With the onset of rockbursting, the mine was unable to modify its planning to fulfill extensive backfill requirements, since the backfill schedule was based on the assumption of fill not becoming critical until the initiation of pillar mining. It should be noted that the original plan called for fill to be placed in stopes as soon as these were empty. The inability to expedite filling of the empty stopes, and further delays in the backfill system, coupled with the fact that these stopes were the only ones available to maintain mine production, resulted in a further deterioration of the situation. The creation of the 200 foot (61 m) wide void, and the subsequent failure propagation and sloughing of the hangingwall and back to the 3400 level, was a direct outcome of tactical decisions made as a result of the requirements for production.
### Table 2.1: Case study A, rockbursting and major falls of ground in 1986

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
<th>Description</th>
</tr>
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| January 20 | Bursting >50 t | 3835 level major failure of 114 sill back blocked access  
3600 level spalling of shoulders, loss of ground in 1600 x-cut  
3835 level 1530 x-cut spalling damaged support  
3935 level 20 t of slough in 117 stope |
| February 14| Bursting < 5 t | 3600 level 113 drill sill spalling on corners and shoulders damaged bolts and screen |
| February 16 | Bursting     | 3935 level material in 113 drawpoint walls failed but contained by mechanical support |
| February 21-22 | Bursting | Bursting after 113 stope 3600 level crown blast  
3935-3600 level, 113-118 section, material expelled from walls of drifts and crosscuts  
Broken bolts, screen damaged and heavily bagged in some locations  
~20,000 t of slough from walls and pillars into 117 stope |
| April 29   | Fall of Ground ~1400 t | 3600 level 115.5 pillar, 115.5 sill back and 116 stope back sloughed into 116 stope |
| May 3      | Fall of Ground ~2000 t | 3600 level 121 stope back down after 121.5 crown blast |
| May 27     | Bursting >50 t | Detected by Microseismic System but not by national seismic network  
3600-3835 level, 116-118 section  
116.5 pillar and 118 pillar sloughed into 117 stope |
| Sept 27    | Bursting >50 t | 3600-3935 level, 114-122 section  
3835 level 1660 drift brow peeled at 116 stope |

### 2.6.6 Flexibility implications for the mining system

The mine had no means to replace the production lost as a result of the ground-related failure. Mine design did not take into account that, with backfill lagging behind production, an inflexible production system was created, where failure of a single pillar could hamper the production of the whole mine. The mine took a risk and paid dearly for it. Although it was not an easy task to initially estimate the likelihood of such a failure to occur, it was possible to estimate the consequences of such a failure on the mine production system. Once the mechanism and the extent of failure were established, there was no flexibility in the filling system to place fill in the created void in order to control the propagation of failure.
2.7 CASE STUDY B

2.7.1 Type of ground-related problem

A need for significant rehabilitation and redevelopment was caused by regional deformation, support deterioration, stress induced damage and ground deterioration. Production loss occurred due to ground falls and excess seismicity. The need for additional support arose due to the underestimation of anticipated rock mass conditions. Additional geomechanical analysis was required as a result of the encountered ground-related problems.

2.7.2 Summary of the problem

Ground related problems hampered production in an underground mine, contributing to its eventual closure in 1986. Such problems included: rockbursting, lateral closure due to squeezing, backfalls in bottom sills and top sills, squeezing of blastholes, corrosion of support, dilution from sandfill, and sloughing in bored raises and stope brows. Production delays and risk to personnel due to ground control problems contributed to the suspension of mine production. Understanding of the rock mass behaviour through a detailed analysis of incidents of prior ground failure, and the analysis of the structural geology, became necessary to develop appropriate mine design measures prior to the mine’s reopening in 1993 (Whiteway, 1993).

2.7.3 Geology

The orebody between the 3400 and 5500 levels consists of two parallel massive sulphide shear ore zones (#1 and #4), striking E-W and steeply dipping south, parallel to the footwall norite contact. The hangingwall consists of metasediments and metavolcanics. A strongly
foliated zone with a thickness of up to 60 feet (18.3 m), exists at the wall contact adjacent to the sulphides. All rock units are crosscut by two systems (North & South) of massive olivine diabase dykes which run obliquely at 15 degrees to the strike of the ore. A late stage fracturing system resulted in the formation of an E-W trending fault and NW-SE trending extension fractures that overprint the orebodies and offset the olivine diabase dykes.

2.7.4 Historical review

Rockbursting at several levels of the mine had been associated with the rolls in the sulphide stringers and with the massive olivine diabase dykes, particularly in the areas where these brittle dykes had been stressed by the late stage fault system (Figure 2.6). A rockburst that occurred in 1979 in the #2 shaft between the 3800 and 4000 levels next to a fault resulted in extensive damage to the shaft and the access openings. It should be noted that several large permanent excavations existed in the shaft area on the 4000 level. At other locations, seismic activity was associated with brittle bands of quartzite in the metavolcanics and sulphides. Rib or crown pillar areas within the orebody indicated a non-violent yielding behaviour by gradual deformation.

The wall rock of development drifts that were driven parallel to the sheared orebody gradually buckled over time, creating stability problems. In some cases, the high lateral stresses, coupled with the strongly foliated or fractured zones, resulted in gradual closure of the opening and consequent abandonment of the drift. Similar problems appeared in raises where sloughed zones enlarged the hole from 5 feet (1.5 m) up to 25 feet (7.62 m) in diameter.
With the total conversion to a vertical retreat bulk mining method in 1985, ground control problems were encountered in the back of both the top sills and bottom sills of the stopes. Ground conditions worsened as mining progressed deeper. A total of 5 rockbursts and 25 falls of ground were reported for the period between 1984 and 1986 (Figure 2.6). Generally, groundfalls and overbreak occurred in the roof of the sills in orebody areas where shear zones intersected extension fractures. These problems were a result of a gradual deterioration of the rock mass and the support system over time, rather than induced by blasting. Continuation of the groundfalls throughout 1986 resulted in suspension of production from 3400 to 4000 levels, and the initiation of a ground stabilization program in May of the same year. A fatality that occurred in August 1986 due to a fall of ground (the fall occurred during the process of drilling for cable bolt installation, 150 feet (45.7 m) ahead of the area already supported with cable bolts), as well as subsequent ground falls, prompted the decision to suspend operations. After the completion of a subsequent stabilization program in November 1987, the mine remained on a standby basis for seven years until its reopening in 1993, following a major mine design study carried out by the company.

2.7.5 Economic impact

In addition to the impact on the mining company of the mine closure in 1986, it has been estimated that the reopening of the mine in 1993 had a total cost of approximately $40 million. The re-opening cost included: a new mining plan, underground development, reconditioning, maintenance, introduction of a new fill system, refurbishing and geomechanical monitoring costs.
2.7.6 New mine design measures

Geomechanical analysis conducted as part of the mining plan package provided the following guidelines for the new mining plan:

a) Development:

- Use of cemented sandfill was required to fill all openings within the orebody in order to stabilize the ground prior to redeveloping.
- The crusher facilities were required to be relocated from 4000 level to a position closer to the orebodies on the 4400 level. This relocation was recommended in order to reduce the risk of a rockburst in the shaft at the same location as the 1979 event.
- Permanent service openings, including conveyor ramps, main access ramps, air raises, fill raises, ore and rock passes, were needed to be located away from the orebody and from any major structures such as diabase dykes, fracture zones and shear zones.
- Orebody accesses needed to be located in the footwall beyond the strongly foliated envelope adjacent to the ore. In general, tram drifts were to be located approximately 100 feet (30.5 m) away from the orebodies.
- Development through the olivine diabase dykes must be minimized, and extraction should be sequenced to mine away from the dykes on both sides. Crossing the dykes near the ore zone and where they were deformed must be avoided due to the high potential for rockbursting.
- Crosscuts should be developed perpendicular to the foliated footwall zones adjacent to the orebody, and in such a way that they are extended to the orebody only when required, so that the length of time over which these openings are required to be maintained would be minimized.
b) Support:

- Fully grouted support systems were required to be used to reduce the risk of deterioration due to corrosion.
- Screening was required to be installed at the base of the rail, and shotcrete was required to be used in areas where the rock mass was strongly foliated or extremely blocky.
- Drift intersections were required to be cable-bolted.
- The support systems were required to be tailored to suit the opening size, ground conditions, and the required life of the opening.
- Raises were required to be supported with cement grouted rebars, while passes would be supported with resin grouted fibre glass bolts.

c) Mining method & sequence:

- To minimize the potential for induced rockbursts, mining at the one shear zone was required to be conducted one lift ahead of the other shear zone at all times, as recommended in the geomechanical study. Stope sequencing should be optimized to reduce remnant panels to a minimum.
- Instead of the Vertical Retreat Mining (VRM) system, a modified slot-slash blasthole system was required to be used for mining with a slot raise to alleviate blasthole squeezing and sloughing. Stope width was limited to 24 feet (7.3 m), while the level interval was limited to 100 feet (30.5 m) to minimize the risk of wall failure. The hangingwall was required not to be overcut to provide increased drill access.
- Predrilling of adjacent stope panels was required to be avoided to minimize hole closure. The smallest drill hole size that is commensurate with drill accuracy was recommended to be used. The lowest possible powder factor was recommended to be used.

- A paste fill system was recommended to be used to backfill the panels. This system would enable the operator to fill entire stopes without waiting for water to drain from fill and mine ore immediately next to fill once it had been hardened after a week. Panels were required to be backfilled as soon as possible after excavation, and top sills were required to be filled tightly to reduce the span of adjacent sills.

- Pillar widths were recommended to be kept small to prevent stress build up and promote yielding.

The introduction and the implementation of the new mine plan in 1992 was able to provide effective solutions to the mine problems. These solutions resulted in an efficient mining operation, with minimal production disruptions due to ground related problems.

2.7.7 Flexibility implications for the mining system

The underestimation of the potential for instabilities to occur in the particular mine resulted in the design of a support system which was often unable to perform adequately. This resulted in production delays, since rework was needed on an ongoing basis. There was no flexibility built into the system to sustain production while rehab work was carried out in the mine. The redesign that took place later on focused on minimization of the possible delays in the mining system due to ground-related instabilities, making the production system less susceptible to potential disruptions.
Figure 2.6: Case study B, longitudinal sections indicating locations of rockbursts and falls of ground between 1981 and 1986
2.8 Case Study C

2.8.1 Type of ground-related problem

Ground-related problems included:

- Loss of production due to tight sequence schedule and backfilling delays;
- Additional geomechanical work and need for redevelopment.

2.8.2 Summary of the problem

Production scheduling problems were encountered in an orebody where mining was taking place with blasthole slot-slash and cut-and-fill mining methods. The production shortfall is attributed to the overall complexity and restrictions of mining sequence not reflected in the initial plan, the limited number of blocks that can be mined at any one time, and the change in fill type.

2.8.3 Historical review

Mining in an overall flat orebody commenced in 1991. The 1994 five-year production plan (Figure 2.7) called for the production to be scheduled at the rate of 2700 tons (2450 tonnes) per day until 1999. Pillarless mining retreating to a single footwall access was planned. A paste fill system was introduced to speed up the mining cycle and solve the quality problems in the existing alluvial hydraulic fill. In 1996, it was realized that the production targets set for the next two years could not be met. Not enough stopes could be mined at the same time, since the drilling-mucking-filling stope cycle and traffic congestion imposed constraints
2.8.4 Economic impact

The scheduling problems and the delays related to the paste fill system that were encountered at the mine resulted in a production loss that is estimated to be equivalent to approximately 6 millions lbs of nickel (2.7 million Kg) for the year 1997, 6 million for the year 1998, and 4 million (1.8 million Kg) for the year 1999. In addition to the cost of the production reduction, other costs included the necessary work for the re-evaluation of the mine plan, the extent of mine life, the cost of remedial work on the existing hydraulic fill system, the expense of attempting to make the paste system work, and the additional development for the revised sequence.

2.8.5 Analysis

The limits on production due to bottlenecks in the mining sequence, which retreated to a single footwall access, were underestimated. As a result, the production plan was unattainable. Problems with the paste fill system exacerbated the situation. Alternative mining sequences were evaluated in an attempt to maximize production. Ground control analyses of the stability issues were an integral part of the assessment of sequence alternatives.

2 This is a term often used in mining operations to describe production constraints.
It is evident that if a process had originally been in place to accurately foresee future production bottlenecks due to the mining sequence, the problems encountered could have been minimized. Evaluation of alternative sequences would have improved communication between the different parties involved in the decision making process of long-term mine planning, and more accurate estimations of future mining production in five year plans could be ensured. The reliability assessment of such a process is imperative in order to minimize the risk of sequencing problems. The modification of the mining plan in terms of sequence, access, and filling system, proved to be a troubling task once the extraction of the orebody was initiated. Clearly, there is a need to understand the impact of production delays and poor quality fill problems on the overall production cycle. In conclusion, the establishment of early diagnostic tools and processes for long-term mine planning alternatives assessment is imperative. Such a methodology would be able to provide cost-effective solutions, improve the reliability of the long-term mine planning and design, and help the communication and the demonstration of the potential problems, concepts, and feasible alternatives, among all people involved in mine planning.

2.8.6 Flexibility implications for the mining system

If the potential production bottlenecks had been foreseen, redundancy could have been built in to accommodate them and maintain the prescheduled production levels. The fact that only one footwall access was available created an inflexible mining system unable to accommodate sequencing problems that were encountered due to backfill delays and ground instability problems. At a small additional cost premium, a second access to the ore zone would have created a flexible mining system able to accommodate certain potential sequence delays, when these were encountered.
Figure 2.7: Case study C. Mine layouts and production plans from 1994 to 1997
2.9 Case Study D

2.9.1 Type of ground-related problem

Ground-related problems included:

- Dilution due to unstable wall, excess blast damage and rockbursting;
- Production delays related to backfilling the stope;
- Drilling and mucking delays in adjacent stopes.

2.9.2 Summary of the problem

Mining of an orebody with vertical retreat methods was designed to take place with a longitudinal, bottom-up extraction sequence. Until 1992, 1-3-5 and 1-4-7 sequences were followed at the mine. These sequences were confronted by significant ground-related problems. In 1992, during mining of the 4020 stope, stress induced failure and excessive hangingwall sloughing problems were encountered. Evaluation of sequencing problems resulted in the adoption of a centre-out, pillarless sequence (Figure 2.8).

2.9.3 Historical review

Excavation sequences at the mine until the end of 1992 were designed to be with 1-3-5 or 1-4-7 bottom up sequences. Although such sequences are favourable from the operational point of view, since they enable several alternative production sources at any given time, they encountered significant ground problems at several instances.
At the end of 1991, the production schedule included mining of the 4020 stope that was located at a distance from the mined stopes, within a high stress area. The vertical height of this stope is 200 (61 m) feet, and its strike length was 50 feet (15.2 m). The orebody in this area consisted of massive sulphides, with a dip of 66 degrees, and a thickness of approximately 45 feet (13.7 m). The hangingwall of the stope, which consisted of metabreccia, was overcut to provide increased drill access. Overcut and undercut drifts were supported with conventional support. During VRM mining of the stope, high stresses were observed in the stope area. The problem was accelerated by the crown blast, which took place in April 1992. Caving of the hangingwall was initiated, and was accelerated by the fact that some of the holes in the hangingwall had been blasted, causing additional damage to the rock. This resulted in excess dilution. Attempts to fill the stope with cemented sandfill in April and May 1992 were unsuccessful, due to the fact that the fill barricade was being damaged by rock blocks falling from the hangingwall of the stope. Filling of the stope was finally completed in October 1992. By that time, the slough of the hangingwall had reached 20 feet deep across the middle of the stope.

2.9.4 Economic impact

The rock dilution at the stope was estimated to have been approximately 11,600 tons (10,520 tonnes), which was 30% of the ore tonnage produced out of this stope. In addition, the ground problems resulted in production scheduling delays. Adjacent panels were also affected by this ground failure, something that slowed down drilling and mucking operations when these panels were mined.
2.9.5 Analysis

Ground failure initiation and propagation occurred as a result of planning and tactical operational decisions. The ground failure that resulted in excess dilution and further scheduling problems were a result of the original excavation sequence, blasting of holes in the hangingwall of the stope, and overcutting the hangingwall. It has been estimated that the benefits of the centre-out pillarless sequence outweigh the operational constraints that this sequence imposes. Such a sequence gradually forces the high stress concentrations, that otherwise would be in the vicinity of active stopes, outwards. Since the end of 1992, the centre-out pillarless sequence has been incorporated into the mine’s ground control and planning guidelines.

2.9.6 Flexibility implications for the mining system

Although the centre out sequence may be considered to be an inflexible system, since not many stopes are available to mine at any given time, the potential problems that are associated with an alternative mine sequence (e.g., with pillars) results in significant ground instabilities, which create an even more inflexible system. This is despite the fact that theoretically more stopes can be available to the operator at any given time with a sequence other than a centre out one. Underestimation of the ground-related problems associated with sequences with pillars, can result in erroneous estimates of mining flexibility for a particular mine system. The selection of a proper mine sequence needs to take into account the likelihood for certain ground-related problems to occur prior to assessing the flexibility of a mine production system. Availability of stand-by stopes is the other parameter that should be included when assessing flexibility.
Figure 2.8: Case study D, Longitudinal section indicating the location of the 4020 stope
CHAPTER 3:

INTERNAL RISK MODEL FOR GROUND-RELATED PROBLEMS

3.1 GENERAL

It was demonstrated in Chapters 1 and 2 that ground-related problems can cause a significant disruption to the production system of an underground mine. Therefore, the planning/design engineer has to minimize the risk of such disruptions in order to maintain the scheduled production levels throughout the mine life. The risk can be minimized by planning to avoid causative situations, and/or by building the flexibility to contend with occurrences of problems. The significance of operating flexibility and its relationship with ground-related problems in mines has been presented in previous chapters.

Operating risk (also termed here internal project risk or private risk) can relate to grade control, equipment performance, safety considerations, environmental control, ground problems etc. The operating risk model that will be considered herein will focus on the examination of risk associated with ground-related problems.

Today, there is no risk model available that deals with the operating risk of underground mines for planning issues such as those associated with ground-related problems. Such problems are often examined “in isolation” only during the operating stages of an underground mine. In the best case, they are part of the contingency built into a mine’s budget as part of the initial long-term plan or the feasibility study. However, the degree of that contingency is often unrelated to the operating risk associated with a particular project.
Initial feasibility studies, set in a scenario of information inadequacies, often set the tone for the ultimate planning.

Normally, a great deal of effort is made to properly quantify the risks associated with the external factors of a mining project, such as the price of gold, inflation, etc. However, when it comes to the evaluation of the risk associated with the internal factors related to the operating environment of an underground mine, little has been done to quantify such risk. This is due to the difficulty of pre-assessing the likelihood of a great variety of potential production disruptions. Another factor is the result of current accounting practices, followed in most underground operations, which fail to capture the activity-based costs that could be used to give a precise estimate of the cost impact of operating problems.

Once the impact of an operating delay is fully realized during the production cycle of a mine, it is often very difficult to alleviate the production constraints without significantly deviating from the original mine plan. Such deviations, often known as "redesigns", can disturb mine production and significantly increase the capital and operating costs of a mine. They can also prolong the time required to mine a particular orebody, therefore imposing an additional cost, due to delayed cash inflows and the need to maintain the mine infrastructure for a longer time period than the one included in the original design.

Flexibility needs in an underground mining system were defined in Chapter 1. These can be assessed based on the operating risk that is associated with the particular project. Therefore, flexibility assessment will require an assessment of the internal operating risk against certain types of potential production disruptions. These disruptions can have an additional cost impact on the initially assessed operating cost.
This approach may not be the only one that can be followed for flexibility assessment in underground mines. However, when it comes to assessing the cost impact of ground-related problems, an appropriate customized internal-risk model will need to be set, prior to utilizing existing financial models to conduct flexibility assessment. The classification of the impact of ground-related problems needs to relate to the rationale of flexibility analysis. This type of classification will facilitate the key links between ground-related problems in general, operating risk, and cost/impact assessment. Once ground-related problems have been recognized, then they can be related to time and cost impact. The stages of the approach that should be followed, in order of sequence, will then be:

- Tabulation of subsystems in an underground mine setting;
- Classification of ground problem impact;
- Evaluation of probability of occurrence for certain types of ground problems to occur;
- Calculation of reliability parameters;
- Calculation of cost impact;
- Application of reliability parameters on production simulation;
- Selection of the appropriate financial model;
- DCF calculations;
- Establishment of the flexibility model;
- Flexibility assessment analysis;
- Final decision making.

In this chapter a methodology will be presented to:

- classify the ground-problems that are associated with operating risk and production disruptions in an underground mine;
introduce a risk model to derive failure probabilities; and,
conduct a cost impact assessment of these problems.

3.2 GROUND-RELATED PRODUCTION DISRUPTIONS

3.2.1 Mine subsystems

An underground hard rock mine constitutes a production system that consists of several excavations. These excavations are the components/subsystems of the mine production system. Such subsystems can be the stopes, the drifts, the orepasses etc. These include primary development, secondary development, and ore extraction. In order to analyze the types of ground-related problems that are observed in these subsystems, they were classified into the five general categories shown in Table 3.1. The criteria developed for the classification were based on the function of the particular subsystem within the mine, the

<table>
<thead>
<tr>
<th>Mine Subsystems</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A</strong> STOPE</td>
</tr>
<tr>
<td>O/C, U/C, open stope</td>
</tr>
<tr>
<td>(All mining methods)</td>
</tr>
<tr>
<td><strong>B</strong> DRIFT</td>
</tr>
<tr>
<td>(includes: crusher room, haulage drift, level, drift access drift, crosscut, intersections, service openings)</td>
</tr>
<tr>
<td><strong>C</strong> PASS</td>
</tr>
<tr>
<td>Orepass, rock pass, fill raise, ore transfer raise, chute, bin</td>
</tr>
<tr>
<td><strong>D</strong> VENT RAISE</td>
</tr>
<tr>
<td><strong>E</strong> SHAFT</td>
</tr>
</tbody>
</table>
special characteristics of the subsystem (e.g., gravitational flow of material, inlet or outlet of air flow), the duration of the opening life, as well as the overall types of ground-related problems that can develop.

3.2.2 Classification of ground-related problem impact in mine subsystems

A survey of ground-related problems in underground hard rock mines was conducted based on interviews with mine operators, mine planners, and ground control engineers at underground hard rock mine operations in Sudbury, Ontario. The reasons for the consideration of an approach that focuses more on the consequences (i.e., impact) of ground-related problems, rather than on the geomechanical reasons for their occurrence, were analyzed in Chapter 2. The ground-related problems were classified for each of the five subsystem categories shown in Table 3.1.

The potential ground-related problems that can develop in a particular subsystem were tabulated based on the impact and cause of the ground problem. A description for each of the five subsystem categories is introduced in Tables 3.2 to 3.6. The description, included in this generic classification, is general enough to include several ground problem subcategories. There can be more than one cause that contributes to a particular ground problem. For example, if a particular groundfall that requires rehabilitation in a stope’s undercut (u/c) is attributed to adverse geology and blast-induced damage, the problem will be classified as A5-A7. Similarly, the same cause of a ground-related problem can result in various types of impact in one or more subsystems.
It should be kept in perspective that the consequences of ground-related problems normally fall into one or more of the following four main categories:

- production/time delays;
- increases in costs due to repairs;
- ore dilution;
- ore reserve losses.

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Redrilling is required due to hole squeezing.</td>
</tr>
<tr>
<td>2</td>
<td>Delays due to secondary blasting of oversize muck</td>
</tr>
<tr>
<td>3</td>
<td>Delays related to backfill placement</td>
</tr>
<tr>
<td>4</td>
<td>Regional deformation requiring rehabilitation at o/c, u/c</td>
</tr>
<tr>
<td>5</td>
<td>Adverse geology – related damage requiring rehabilitation at o/c, u/c</td>
</tr>
<tr>
<td>6</td>
<td>Static mining induced stress damage requiring rehabilitation at o/c, u/c</td>
</tr>
<tr>
<td>7</td>
<td>Blast induced damage requiring rehabilitation at o/c, u/c</td>
</tr>
<tr>
<td>8</td>
<td>Seismic induced damage requiring rehabilitation at o/c, u/c</td>
</tr>
<tr>
<td>9</td>
<td>Groundwater induced damage requiring rehabilitation at o/c, u/c</td>
</tr>
<tr>
<td>10</td>
<td>Support deterioration due to support corrosion, machine impact requiring rehabilitation at o/c, u/c</td>
</tr>
<tr>
<td>11</td>
<td>Delays due to muck oxidation/sulphide fires/ dust explosions requiring rehabilitation</td>
</tr>
<tr>
<td>12</td>
<td>Delays for ground inspection/quality control purposes</td>
</tr>
<tr>
<td>13</td>
<td>Loss of ore reserve</td>
</tr>
<tr>
<td>14</td>
<td>Unplanned dilution due to unstable rock wall/back or unstable fill</td>
</tr>
<tr>
<td>15</td>
<td>Unplanned dilution due to blast hole deviation/blast design</td>
</tr>
<tr>
<td>16</td>
<td>Other</td>
</tr>
</tbody>
</table>

The classification introduced here provides a means to eventually derive time and costs impact, associated with ground-related problems, for use in production flexibility analysis.

Some of the ground-related problems can occur on a frequent basis and have only minimal effects on the mining operation, while others rarely occur, but may result in significant damage to a subsystem. It can be seen that the subsystems falling into category A (i.e.,
stopes) have a greater variety of ground-related problems than the rest of the subsystems. This can be attributed to two causes. Firstly, most of the production activities in an underground mine occur in the stope areas. Secondly, the disturbance of ground is greatest where mining is taking place, which is where ore is extracted.

<table>
<thead>
<tr>
<th>Table 3.3: Ground-related problem description for subsystem category B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Category</strong>: B</td>
</tr>
<tr>
<td><strong>Type</strong></td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
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<tr>
<td>6</td>
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<tr>
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<tr>
<td>9</td>
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<tr>
<td>10</td>
</tr>
<tr>
<td>11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3.4: Ground-related problem description for subsystem category C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Category</strong>: C</td>
</tr>
<tr>
<td><strong>Type</strong></td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
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<tr>
<td>5</td>
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<tr>
<td>6</td>
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<tr>
<td>7</td>
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<tr>
<td>8</td>
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<tr>
<td>9</td>
</tr>
</tbody>
</table>
### Table 3.5: Ground-related problem description for subsystem category D

<table>
<thead>
<tr>
<th>Category: D</th>
<th>Subsystem: Air raise</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td><strong>Description</strong></td>
</tr>
<tr>
<td>1</td>
<td>Hang-ups caused by major geological structure or weak rock wall material.</td>
</tr>
<tr>
<td>2</td>
<td>Hang-ups caused by damage on vent raise walls due to mining induced stress (pass near mining) or major seismic events or blast induced damage.</td>
</tr>
<tr>
<td>3</td>
<td>Delays due to sulphide dust explosion</td>
</tr>
<tr>
<td>4</td>
<td>Delays due to dislocation of support/lining and need for repair.</td>
</tr>
<tr>
<td>5</td>
<td>Delays for inspection/quality control purposes</td>
</tr>
<tr>
<td>6</td>
<td>Other</td>
</tr>
</tbody>
</table>

### Table 3.6: Ground-related problem description for subsystem category E

<table>
<thead>
<tr>
<th>Category: E</th>
<th>Subsystem: Shaft</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td><strong>Description</strong></td>
</tr>
<tr>
<td>1</td>
<td>Regional deformation requiring rehabilitation</td>
</tr>
<tr>
<td>2</td>
<td>Adverse geology – related damage requiring rehabilitation</td>
</tr>
<tr>
<td>3</td>
<td>Static stress – induced damage requiring rehabilitation</td>
</tr>
<tr>
<td>4</td>
<td>Blast induced damage requiring rehabilitation</td>
</tr>
<tr>
<td>5</td>
<td>Seismic induced damage requiring rehabilitation</td>
</tr>
<tr>
<td>6</td>
<td>Groundwater induced damage requiring rehabilitation, redevelopment or development slow down</td>
</tr>
<tr>
<td>7</td>
<td>Support deterioration due to corrosion or equipment, material impact requiring rehabilitation</td>
</tr>
<tr>
<td>8</td>
<td>Delays for inspection/quality control purposes</td>
</tr>
<tr>
<td>9</td>
<td>Other</td>
</tr>
</tbody>
</table>

### 3.3 RISK MODEL FOR GROUND-RELATED PROBLEMS

#### 3.3.1 Risk and reliability analyses

Risk is often defined as a parameter, relating two basic aspects, uncertainty and consequence (Davies, 1997, Smith, 1995, Foster and Edwards, 1995). Uncertainty is expressed as the probability of an event to happen, while consequence is a measure of the effect, usually associated with the economic impact of that event. Combining uncertainty and consequence gives a measure of risk. Mining risk analysis has been used in feasibility/ cost estimation (O’Hara, 1982), as well as in geomechanical design (Brummer, et al, 1993, Carter 1994,
Diederichs and Kaiser, 1996, Einstein, 1996). However, it has not traditionally been of widespread or routine use.

When examining the probability of uncertainty in risk analysis it is often the case that the reliability of the system or the event under consideration is examined instead. Reliability of an item has been defined (Hosseini, 1999, Harr, 1987) as the probability that the item will perform a specified function under specified operational and environmental conditions, at and through a specified time. In that context, reliability is related to the probability of failure through the equation:

{Reliability} = 1 − {Probability of Failure}

The concept of reliability engineering in mining was first introduced by Dotson (1966). Reliability models were later introduced to the design, planning and operation of mine systems by Kumar and Granholm (1988). The authors describe the models applicable in reliability investigation, and introduce the applicability of reliability techniques and their economic implications to identify systems with low reliability.

The calculation of reliability, maintainability and availability parameters for longwall mining systems was discussed by Ramani, et al (1989). In the examination of a similar longwall mining system, Ercelebi and Yegulalp (1993), included the production delays due to geology as a separate component of the mining system. This is due to the fact that delays related to geology are different in nature from equipment-related failures, and may bring production to a halt. Exponential and lognormal distributions, traditionally used for Mean Time Between
Failure (MTBF)\(^1\) and Mean Time To Repair (MTTR)\(^2\) respectively in maintenance, have been adopted for unscheduled delays due to ground-related problems in this thesis.

Hall, *et al* (1999) present an example of the determination of system reliability for the case of a fleet of diamond drills. Here failure and repair time distributions are determined from available maintenance data. Simulation enables the determination of drill system reliability and availability for different scenarios.

Risk analysis traditionally evolved for civil/geotechnical design of earth structures. Londe (1993) introduced a methodology to evaluate safety in dam design using reliability analysis. A review of the basic aspect of reliability, risk analysis, and its application to decision making in tunnelling, is presented by Einstein (1996 and 1991) and Einstein, *et al* (1987). A tunnel excavation decision support system using Bieniawski's design methodology for rock engineering is introduced by Kalamaras (1997). A reliability assessment for building over abandoned mines based on a qualitative assessment of consequences arising from hazards is given by Cole (1993). The author classifies the events that can impact on relative risk assessment in three categories: events causing total loss, impairment and inconvenience. The degree of risk and the attitude to reliability are classified for each of the three event categories.

A decision making procedure, based on a risk-cost-benefit analysis, for selecting rockburst-resistance drift support is introduced by Brummer, *et al* (1993). The procedure enables the

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\(^1\) Mean time between failures (MTBF) or mean time to failure (MTTF) is defined as the expected value of the time that a particular system or component will be performing adequately.
selection of risk for certain damage levels and the calculation of the risk costs (e.g., rehabilitation, production cost, equipment loss etc) associated with a particular support system. These costs can then be compared with the installation cost of support systems with different reliability, therefore providing a means to evaluate the alternatives that are available to a mine engineer when selecting support systems.

The literature review has indicated that the available approaches to evaluate mining equipment reliability are based on initial statistical analysis of collected data. Once time failure parameters are determined for each subsystem/component of a mining system, then the total reliability and availability of the system can be determined. Reliability analyses for tunnelling focus on probabilistic assessment of the rock mass parameters prior to and during the excavation of the opening. There is no examination of expected ground-related failures that may occur once the opening is completed, which is the case in many mining openings. This is, in essence, the difference between civil tunnel construction and mining. Generally, there is no tendency for interaction with subsequent tunnelling in the vicinity, as may be the case in mining. In addition, the ground conditions around a civil tunnel are assumed to remain the same once its excavation is completed, while a mining opening normally will be exposed to different conditions (e.g., mining induced stress, excess deformation, blast damage) during its operating life.

Although mining equipment reliability analysis and risk/reliability analysis in tunnelling contain elements that can be used in a reliability analysis for mine openings with ground-related problems, it needs to be adapted and validated. Also, it is essential that a practical

\(^2\) Mean time to repair (MTTR) is defined as the expected value of the time that is required for a particular failed system or component to be restored or repaired to a specified condition.
methodology be developed to properly determine time dependent reliability and availability of mine openings, particularly when no or limited performance data records are available. This approach will need to take into account the consideration of the mine as a production system, the time-dependency in the performance of underground mine openings, and the various types of ground-related problems that occur in mine subsystems.

3.3.2 Mine subsystem risk

The actual risk associated with a particular subsystem through design analysis will be a function of:

- The in-situ conditions (e.g., rockmass, stress);
- The local subsystem geometry (e.g., the size, shape and orientation of an opening);
- The overall mine geometry (e.g., mining induced stresses);
- The excavation method;
- The support system used in the particular subsystem;
- Muck flow characteristics (for orepasses and stopes);
- Available operating experience (e.g., accuracy in long hole drilling);
- Know-how/expertise within the design team in minimizing/controlling ground-related problems.

Today, there are no guidelines on how to quantify risk parameters during the design of a particular mining subsystem that consider all of the above parameters. Some attempts to quantify risk in particular stope design analysis have been made in the past without linking all of the key design parameters (e.g., Diederichs & Kaiser, 1996; Pakalnis, et al, 1995). In
addition, these methods are linked more to the problem of dilution in an underground mine, rather than to the delays due to ground-related problems and the potential loss of ore. Overall, the emphasis of ground control in mines is on safety rather than on production control.

Today, qualitative risk evaluation is routinely conducted by mine design teams as part of long and short term planning. The variability of the nature of the ground-related problems in a mining environment, coupled with lack of knowledge of potential controlling mechanics and the limitation of the existing design tools, make it very difficult to attempt to directly derive quantifiable risk values through the use of existing design tools in underground hard rock mines.

3.3.3 Time-dependent reliability analysis model

A model that allows the evaluation of the frequency of ground-related problems needs to be established. Although probabilistic analyses for a single anticipated failure are available in the literature for civil engineering geotechnical applications, the fact that multiple failures can occur in the same mining subsystem over its life, make imperative the application of a time-dependent reliability analysis. Time dependency in the performance of underground mine openings is attributed to reasons such as the deterioration of the rock mass integrity, change in stress distribution, blasting in the vicinity of openings, corrosion of support systems, etc.

One analysis that could be used to describe time-dependent reliability can be based on the *bathtub-shaped* hazard function shown in Figure 3.1 (Harr, 1987). This hazard function
enables the consideration of repetitive failure incidents (as opposed to single catastrophic events), as well as the evaluation of deteriorating conditions, which are both key elements of ground-related problems in underground hard rock mines (as opposed to ground-related problems in civil engineering projects).

The hazard function $h(t)$ is defined as the failure rate, that is, the rate of change of the conditional probability of failure given that the system has survived to time $t$. The hazard function is related to the probability of failure $f(t)$ and the reliability $R(t)$ with the following equation:

$$h(t) = \frac{f(t)}{R(t)}$$

The hazard function of a typical mining system can be represented by the *bathtub* distribution shown in Figure 3.1. It is assumed that a system that is perfect initially will fail progressively. The general equations that link reliability with the hazard function and probability of failure are given by Harr (1987) and are shown in Table 3.7.

<table>
<thead>
<tr>
<th>Period</th>
<th>Description</th>
<th>Hazard function, $h(t)$</th>
<th>Probability distribution of failure, $f(t)$</th>
<th>Reliability, $R(t)$</th>
<th>$MTBF = \frac{\pi}{2\kappa}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Initial period of operation, breaking in failures</td>
<td>$h(t) = -\kappa t$</td>
<td>$f(t) = -\kappa t e^{\kappa t^2 / 2}$</td>
<td>$R(t) = e^{\kappa t^2 / 2}$</td>
<td>$MTBF = \frac{\pi}{2\kappa_1}$</td>
</tr>
<tr>
<td>II</td>
<td>Chance/random failures – constant rate of failure</td>
<td>$h(t) = \lambda$</td>
<td>$f(t) = \lambda e^{-\lambda t}$</td>
<td>$R(t) = e^{-\lambda t}$</td>
<td>$MTBF = 1/\lambda$</td>
</tr>
<tr>
<td>III</td>
<td>Wearing out failures – increasing rate of failure</td>
<td>$h(t) = \kappa_2 t$</td>
<td>$f(t) = \kappa_2 t e^{-\kappa_2 t^2 / 2}$</td>
<td>$R(t) = e^{-\kappa_2 t^2 / 2}$</td>
<td>$MTBF = \frac{\pi}{2\kappa_2}$</td>
</tr>
</tbody>
</table>
A mine opening (e.g., stope, drift, pass) is designed to perform a particular function within a certain time interval. The excavation period is followed by an operational period. A certain performance is anticipated from the mine opening in terms of the type and the frequency of ground-related problems that may be encountered during the operating lifetime of the particular mine opening. In certain cases, the operational period may exceed the originally assigned operating lifetime of a particular opening. Then, the ground-related problems may escalate due to the original design of the ground support system, the proximity of mining to the particular opening, or other reasons.

Three distinct periods are part of a typical bathtub distribution, namely the initial breaking-in period, the chance failure period, and the wearing-out period (Ayyub and McCuen, 1997, Amstadter, 1971, Harr 1987, Ang and Tang, 1984). The use of the bathtub distribution to evaluate the ground-problem hazard function is examined below.
The initial period of the bathtub distribution is representative of construction or planning errors related to deviation from standards, poor quality in construction/planning, and human factors that may cause an initial high failure rate. The ground fall during the newly excavated drift due to improper installation of cement grouted cablebolts, or after the inappropriate support of an orepass with mechanically anchored rockbolts, are examples of initial period failures. Mining companies usually try to ensure that such errors are avoided through quality control programs, training, peer reviews, and due diligence, both at the feasibility and operating stages of a mine operation. Such processes can eliminate potential early failures and indicate appropriate corrective measures. In many cases, corrective measures against "infant mortalities" (Amstadter, 1971) are taken during the excavation stage due to a change in anticipated in-situ conditions or use or life span of the particular mine opening. It is thought appropriate that "infant mortalities" be considered separately from the reliability analysis conducted for a mining subsystem.

The second period of the bathtub distribution represents the main operating period of the mine opening/subsystem. Ground-related failures here can occur at random and tend towards some constant failure rate, which corresponds to a certain mean time between failure, $MTBF$ (Harr, 1987). The reliability of the subsystem is dependent only on time, and it progressively decreases. The assumption of a constant failure rate for the operational period of a certain subsystem is a reasonable one, if there are no changes in the in-situ rock mass conditions around the opening (e.g., support is still functioning adequately, mining-induced stresses are not progressively affecting the subsystem, orepass walls are not sloughing). Conditions often cumulatively worsen as a rock mass degrades, although stress redistribution can counteract as well as worsen the degradation of conditions.
The second period of the hazard function does not consider delays as a result of potential wearing out failures in the orepasses, which are commonly encountered in unlined passes. These can be considered in the third period of failures in the bathtub distribution. The failure rate increases here as a result of aging or change of the in-situ conditions in the particular subsystem. This failure rate can reach a point beyond which operation of the particular subsystem is no longer feasible. Orepasses with extensive sloughing of their walls or drifts with rusted bolts or cablebolts are examples of subsystems where wearing out failures can occur.

When assessing the “lifecycle” of a subsystem, the excavation period has to be considered separately from the operating period of that opening. In such cases, one or more periods of the bathtub distribution will be included in the excavation lifetime, while a separate distribution with one or more periods of the bathtub distribution will be used for the operating lifetime. This approach has the advantage of allowing the reliability of a mine opening to be low during the excavation stage, and, once this is completed, to increase at the beginning of the start life of the operating period. This is something that could not be achieved using a single bathtub distribution for both the excavation and the operating periods, since by definition the reliability will be decreasing with time for all periods. For certain openings (e.g., shaft), the operating stage is the critical one for a production analysis, while for others, both excavation and operating stages (e.g., stope) are critical.

The basic reliability analysis model that will be considered for ground-related problems of mining subsystems in this work will include two distinctive periods:
• The excavation/operating period, with chance failures represented by a presumed constant rate of failure; and,
• The wearing out period with a presumed linearly increasing rate of failure.

This model (Figures 3.2 and 3.3) has the advantage of including the two key time periods of a bathtub distribution that are representative for ground-related problems. Either period can be excluded from the model, if this is justifiable based on the behaviour of the particular subsystem, by adjusting accordingly the times $t_2$ and $t_3$.

![Figure 3.2: The hazard function in the reliability analysis model considered for mining subsystems with ground-related problems](image)

![Figure 3.3: The reliability function in the reliability analysis model considered for mining subsystems with ground-related problems.](image)
Man entry openings usually have a medium to long period of chance failures depending on the type of the opening (e.g., crusher, overcut). Non-man entry openings, such as stopes, can have a very short period of chance failures, followed by an equally short period of wearing out failures. Orepasses and ore transfer raises can have a short or long chance failure period, depending on support/ground type, followed by a wearing out period, which can be even longer than the chance failure period. Shafts are considered to have a very long chance failure period, with no wearing out failure period due to ground-related problems.

3.3.4 Subjective probabilities for reliability assessment

When mine records or databases that relate to ground-related delays are available, statistical analyses can be used to determine reliability parameters associated with the frequency of failures in a particular subsystem. Such analyses are routinely carried out to determine the reliability and maintainability of underground mobile mining equipment (Vagenas, et al, 1997). Unfortunately, efforts to obtain such records in hard rock underground mines, particularly in Sudbury, were not successful. Records are not kept with the information required to conduct reliability/maintainability analyses. Fall of ground databases, usually maintained by ground control engineers, do not record the impact that ground-problems have on production and the time required to repair damages, which are essential to calculate reliability and availability parameters. Nonetheless, once statistically significant records are available, a statistical analysis can be used to derive the reliability-associated parameters, as shown in the right section of Figure 3.4.

\[ \text{Availability} = \frac{MTTF}{MTTF + MTTR} \]

where, \( MTTF \) and \( MTTR \) are the mean time to failure and mean time to repair respectively.
Figure 3.4: Reliability analysis for mining systems accounting for ground-related problems
Although quantification of risk has not been traditionally part of a standard mine design analysis, the planning engineer conducts a qualitative evaluation of risks associated with the design of a particular subsystem and observes its behaviour once the subsystem is excavated and operating. This practice may be implicit, but it does create knowledge that could be transferred to future designs of subsystems, and to reevaluation of the anticipated performance of mining subsystems. Therefore, an experienced mine design specialist has a good idea of the risk of damage to a subsystem due to ground-related problems and its impact on the overall production of an underground mine. This knowledge is often based on personal professional experience gained from particular operations. A person with such experience can provide key input towards establishing subjective probabilities for certain types of production interruptions due to ground-related problems at particular subsystems. In this way, local knowledge and experience can provide the basis for assessing the reliability parameters for mining subsystems, and ensure that the quality of mine design and planning improves with time.

In order to assess the reliability parameters of subsystems that are not based on statistical analysis of data records, a new methodology that is based on a subjective probability analysis needs to be sought. Subjective probabilities that capture the experience of specialists have been used for decision making in economic and technological environments in the past twenty years (Saaty and Vargas, 1994).

The methodology introduced in this thesis is summarized in the flowchart of Figure 3.4, and consists of four distinct stages:
• Subsystem classification;
• Determination of the likelihood of ground-related problems occurring;
• Identification of chance/wearing out failure time periods;
• Calculation of reliability parameters based on bathtub distribution.

Repair times due to ground-related problems in mining subsystems can also be determined through the same methodology. Figure 3.5 provides a demonstrative example for the calculation of reliability parameters for mine subsystems.

Once the mining subsystem is selected, the quantification of the frequency of the ground-related problems described in Tables 3.2 to 3.6 can be conducted. An experienced mine planning and design specialist can then select the frequency of the interruptions for each of type of ground-related problems. Most likely, minimum, and maximum values can be specified, as shown in Figure 3.5. The same process can be followed for the estimation of the repair time required for each type of failure. The time length of the chance failure and wearing out failure periods can also be specified. A rate of problem escalation (if any) during the wearing out period can be selected.

Once these input data are provided, the average, minimum, and maximum reliability values for the chance and wearing out failure periods are determined for the subsystem using the equations provided in Table 3.7. Mean time between failure (MTBF) and mean time to repair (MTTR), availability and reliability are determined, as shown in Figure 3.5. The reliability is plotted versus time for chance and wearing out failure periods, as indicated in the same Figure.
Subsystem classification: B
Classes: A, B, C, D or E

1 day = 1 month = 60 shifts

Likelihood and frequency of ground-related problems (chance failures only)

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Inadequate performance (Failure) occurs every...</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B1</td>
<td>Day, Week, Month, 3M, 6M, 1yr, 2 yrs, 3 yrs</td>
</tr>
<tr>
<td>2</td>
<td>B2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>B3</td>
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<td>B6</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>B7</td>
<td></td>
</tr>
</tbody>
</table>

Min | Likely | Max
---|--------|---
6   | 9      | 12
8   | 16     | 24
10  | 19     | 33
12  | 24     | 48
14  | 33     | 66
16  | 33     | 66
18  | 33     | 66

Designated operating life with chance failures only: 3 months

Maximum operating life (time for the subsystem to be considered in the analysis): 6 months

Rate of problem escalation after the end of the designated operating life: 3

Repair-excavation time required (down time until subsystem becomes operational again)

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>The subsystem will be operational after...</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B1</td>
<td>Day, Week, 2 wks, 1M, 3M, 6M, 12M</td>
</tr>
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<td>6</td>
<td>B6</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>B7</td>
<td></td>
</tr>
</tbody>
</table>

Min | Likely | Max
---|--------|---
1   | 5      | 10
2   | 6      | 15
3   | 4      | 5
4   | 10     | 20
5   | 4      | 8
6   | 6      | 12
7   | 8      | 16

Subsystems probabilities

Period: Chance failures

<table>
<thead>
<tr>
<th>AVER</th>
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<th>MAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTBF</td>
<td>180</td>
<td>2160</td>
</tr>
<tr>
<td>MTTR</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>lambda</td>
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<td>0.5</td>
</tr>
<tr>
<td>Availability</td>
<td>99.54</td>
<td>97.3</td>
</tr>
<tr>
<td>Reliability, R</td>
<td>77.88</td>
<td>60.65</td>
</tr>
</tbody>
</table>

Period: Wearing out failures

<table>
<thead>
<tr>
<th>AVER</th>
<th>MIN</th>
<th>MAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTBF</td>
<td>360</td>
<td>720</td>
</tr>
<tr>
<td>MTTR</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>lambda</td>
<td>14.14</td>
<td>15.55</td>
</tr>
<tr>
<td>Availability</td>
<td>98.63</td>
<td>93.21</td>
</tr>
<tr>
<td>Reliability, R</td>
<td>77.88</td>
<td>60.65</td>
</tr>
</tbody>
</table>

Figures 3.5: Sample form used for calculation of reliability parameters for mine subsystems
3.4 COST IMPACT MODEL

Until now the probability of uncertainty, which is one of the two key risk parameters, was examined through the introduction of a reliability analysis model. The consequence that describes the economic impact of an event will be examined next for the case of ground-related problems. In order to describe the economic impact, a cost model needs to be developed based on cost parameters that are available in mining operations.

3.4.1 Fixed and variable costs

The cost impact that ground-related problems can have on a mining operation is a function of fixed and variable costs. Fixed costs include those costs that are independent of the volume of production. Such costs can be:

- The cost of rehabilitation, maintenance or replacement of a subsystem due to ground-related problems.
- Ore loss due to ground-related problems (e.g., bursting activity in a sill, uncontrolled caving, excessive dilution).
- The loss of the initial investment to excavate the particular subsystem, at least in part, depending on the remaining lifetime of the subsystem.
- Any damage or loss of mobile equipment that was associated with the ground-related problem in the particular subsystem (e.g., damage to drill rod, scoop tram etc).

These costs can result in increased mine capital and operating costs, unless they were included in the original budget of the feasibility study. Variable costs are those that vary directly with the volume of production and can be related to:
• Delays, causing production loss due to ground-related problems that can occur in a stope, drift, pass.

• Milling costs related to dilution occurring within the underground mine (e.g., unplanned stope dilution due to hangingwall failure). If such costs are expressed as a total number instead of on a per shift basis, then they should be treated as fixed costs.

• Labour and operating costs related to a decrease in production or mine closure for a certain time period.

• Lost opportunity costs, since the investment in the mine yields a rate of return lower than the one of the next best opportunity for the company or the expected rate of return for the particular project.

It should be noted that in certain cases, variable costs can be expressed as fixed ones, and vice-versa, depending on the accounting system of a particular mine. Generally, all costs that can be expressed on a per shift basis are variable costs, while those which are expressed as total costs are fixed.

3.4.2 Cost model

The methods to determine each of fixed and variable costs are dependent on the costing procedure (e.g., activity based costing – Baiden and Zanibbi, 1999) followed in the particular mine, and are beyond the scope of this work. Although activity-based costing would be the preferable method to evaluate costs related to production interruptions due to ground-related problems, such an accounting method is not yet being used routinely in mining operations.
A methodology that examines the cost impact of ground-related problems is presented, based on crude estimates of the order of magnitude of fixed and variable costs. The cost model that is introduced here to describe the impact of ground-related problems resulting in production interruptions is based upon the following model (Ebeling, 1997):

\[
GRPC = \frac{t_d}{MTBF} \left[ FC + (VC \times MTTR) \right],
\]

where:

- **GRPC**: the ground-related problem costs;
- **td**: the designed/scheduled operating life;
- **MTBF**: the mean time between failures;
- **FC**: the fixed costs for a single ground-related failure;
- **VC**: the variable costs for a single ground-related failure per shift of down time;
- **MTTR**: the mean time to repair the subsystem and bring it to its previous capacity.

The model captures the effect of both **MTBF** and **MTTR** on costs. It should be noted that the \( \frac{t_d}{MTBF} \) ratio describes the number of anticipated failures in the subsystem, which can be less than one. All cost values included in the model are net present values. In the case that the operating period for a subsystem includes both chance and wearing out failure periods, the GRPC should be calculated for each period separately, and then summed up to give the total GRPC:

\[
GRPC_{\text{total}} = GRPC_{\text{chance failure period}} + GRPC_{\text{wearing out failure period}}
\]

The total cost for the excavation and operation of a subsystem to be included in the initial budget will then be:

\[
TC = IEC + GRPC_{\text{total}}
\]
TC: the total cost for the subsystem; and,

IEC: the initial excavation cost for the subsystem

It should be emphasized that GRPC can be significantly higher than the IEC in many instances, as was demonstrated in the case studies analyzed in Chapter 2. For instance, a single failure in an access drift to a level with an excavation cost of $200,000 can have an overall impact of millions of dollars if ground failures cause significant mine-wide production interruptions. Focusing on the excavation cost of a subsystem as the single parameter in long term mine planning can be deceiving, since it ignores the consequences that the particular decision has on other subsystems and the anticipated production rates. GRPC provides a means to calculate the potential consequences of a mine planning decision that can result in ground-related problems.

3.4.3 Cost impact assessment

The ground-related problems per mine subsystem have been analyzed in section 3.2 and subsystem reliability parameters for such problems have been determined in section 3.3. A proposed methodology for cost impact assessment is summarized in Figure 3.6, and consists of four distinct stages:

- Calculation of reliability parameters ($MTBF$, $MTTR$);
- Assessment of subsystem fixed cost impact for various ground-related problems;
- Assessment of subsystem variable cost impact for various ground-related problems;
- Calculation of total ground-related problem costs.
Once these costs are calculated, then the total cost of the subsystem, which includes its excavation, can be estimated. If this cost is unacceptably high, changes in the original mine plan may be sought, that improve the $MTBF$ and $MTTR$ values and, therefore, the overall cost due to potential ground-related problems.

Figure 3.7 shows the process used to conduct cost impact assessment. The example is a continuation of that considered in Figure 3.5. Once the subsystem reliability parameters are calculated, the quantification of the fixed and variable costs associated with particular ground-related problems could be conducted. It should be emphasized that the method for determining the exact fixed and variable costs may vary from site to site. Here, only the order of magnitude is specified to identify the scale of the potential problem. However, if exact values are known for ground-related problems in a particular subsystem, these can be used in a similar manner. Most likely, minimum and maximum values for fixed and variable costs can be specified, as shown in Figure 3.7. The operating time with chance and wearing out failures has already been specified as part of the reliability analysis.

Once these input data are provided, the ground-related problem costs (GRPC) can be calculated for chance and wearing out failure periods using the analysis introduced in section 3.4.2. Then, the sum up of the costs for the two failure periods can provide a total estimate of the GRPC, as indicated in the same figure.
Calculate subsystem reliability parameters 
\( (MTBF, MTTR) \)

Assess cost impact for potential ground-related problems in the subsystem

Fixed costs, FC $/shift

Variable costs, VC $/shift

Redesign subsystem to improve \( MTBF, MTTR \)

Calculate ground-related costs,
\[ GRPC = \frac{t_f}{MTBF} (FC + VC \times MTTR) \]

\( t_f \) designed/scheduled operating life

Decision making

Satisfactory?

\[ TC = IEC + GRPC \]

IEC: Initial excavation cost

\( TC = IEC + GRPC \)

Figure 3.6: Methodology for cost impact assessment
RELIABILITY ANALYSIS FOR SUBSYSTEM

<table>
<thead>
<tr>
<th>PERIOD</th>
<th>AVERAGE</th>
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</thead>
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<tr>
<td></td>
<td>lifespan</td>
</tr>
<tr>
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</tr>
<tr>
<td>Wear our failures</td>
<td>3</td>
</tr>
</tbody>
</table>

SUBSYSTEM CLASSIFICATION: B

CROSSCUT

FIXED COST IMPACT (ORDER OF MAGNITUDE) - FC

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
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</tr>
<tr>
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VARIABLE COST IMPACT (ORDER OF MAGNITUDE) - VC

<table>
<thead>
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</table>

TOTAL GROUND-RELATED PROBLEM COST - GRPC (ORDER OF MAGNITUDE)

<table>
<thead>
<tr>
<th>PERIOD</th>
<th>COST IMPACT $</th>
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<td></td>
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<tr>
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<tr>
<td>Wear our failures</td>
<td>$22,875</td>
</tr>
<tr>
<td>TOTAL $</td>
<td>$30,500</td>
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</tbody>
</table>

INITIAL EXCAVATION COST, IE $40,000

TOTAL SUBSYSTEM COST - TC (ORDER OF MAGNITUDE)

<table>
<thead>
<tr>
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<th>COST $</th>
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<td>AVRG</td>
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<tr>
<td>TC=IEC+GRPC</td>
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</table>

Figure 3.7: Calculation for ground-related problem cost impact based on MTBF and MTTR
CHAPTER 4: PRODUCTION SIMULATION AND DCF ANALYSIS

4.1 INTRODUCTION

Production simulation, discounted cash flow (DCF) analysis, and Monte Carlo simulation are some of the conventional methods, which are used to establish financial models, and to conduct business analyses for decision making in mineral resource industries. The ability of each of these analyses to incorporate risk associated with ground-related problem and to evaluate planning and design alternatives in a mining system, will be explored in this chapter. It should be noted that production simulation and DCF analysis are now used extensively in the mining industry to conduct feasibility studies, determine optimum mine plans and evaluate design alternatives.

4.2 PRODUCTION SIMULATION

4.2.1 General concepts

In order to study and evaluate the quality of planning and design built into a proposed mining system, it is important to apply the appropriate engineering tools. A key tool is software to realistically simulate the performance of a given mining system under a specified range of operating conditions. This process simulator represents an evolution of a process over time under certain constraints related to layout, resources and equipment. A review of the state of
practice in simulation and its application in the mining industry is given by Sturgul and Li (1997).

The simulation tools that are currently in use in mining were largely created to contribute to (Kazakidis, et al., 1999):

- understanding and improvement of individual processes within the production and development cycles;
- determination of suitable mine planning strategies and mining methods related to stope size and geometry, rock fragmentation and sequence of excavation;
- understanding of the infrastructure required to support the development and production processes;
- understanding of the system requirements (hardware and software) of mine orebodies using advanced mining technologies.

A simulation tool that is gaining acceptance in the Canadian mining industry today is AutoMod™ (developed by AutoSimulations Inc.). This is a discrete-event 3-D simulation/animation tool that is used to evaluate the performance of complex mining systems and to examine operational alternatives and what-if scenarios (Vagenas, et al., 1996).

In a discrete event simulation, the variables of a model change at discrete points in time. The state of the model can be altered by events scheduled to occur in future time. A simulation clock is used to keep track of events and the current value of time as the simulation proceeds. The occurrence of an event causes the execution of logics for changing the status of the model variables, updates the simulation time and animation sequence and collects statistics
of interest. One key parameter for which statistics are usually kept is the fluctuation of the
daily, weekly, or monthly production in an underground mine production system.

Other process simulation tools that enable the analysis of simpler mining layouts include
Extend™ (developed by Imagine That Inc.) and Simul8™ (developed by Palisade Inc.).
However, the fact that a mine geometry is a complex three dimensional production system
with multiple variables that need to be included in order to provide realistic outputs,
significantly limits the application of these tools to simplified geometry layouts or sensitivity
analyses of certain constraining variables.

It is currently common practice for production simulation to precede cost analysis. In order
for such analysis to be included in production simulation, activity-based costing data (Baiden
and Zanibbi, 1999) would need to be available in the mining operation. Activity-based
costing is a type of costing where each activity and overhead cost associated with production
consume resources such as labour, equipment, time or energy, (Dunbar, et al, 1998).
However, the accounting methods, currently followed in mines, do not generally provide
such data. As an alternative, the practice is first to conduct production simulation and, once
certain alternatives are evaluated in terms of satisfying production criteria, to conduct cost-
market analyses in order to evaluate the mining project or a certain scenario.

The production simulation considered here excludes cost-market analysis and it focuses on
forecasting production in time or an evaluation of certain mine design alternatives available
to the mine engineer based on production output.
4.2.2 Simulation of production affected by ground-related problems.

Ground-related problems result in production/schedule delays, increases in costs due to repairs/replacements, ore dilution, and ore reserve losses. Production simulation can be used to simulate delays, ore dilution, and ore reserve losses.

Delays due to ground-related problems in a particular mining subsystem can be simulated similarly to delays related to equipment breakdowns. Simulation of equipment breakdowns has been conducted routinely in the mining industry over the past twenty years (Vagenas, et al, 1996, Hall, et al, 1999). A methodology to derive the frequency of interruptions due to ground-related problems has already been introduced in the reliability analysis of Chapter 3.

In addition to frequency of occurrence, production simulation models provide the ability to control the material flow from the stope to the crusher station or the shaft collar. Ore dilution can result in an increase of the amount of material flow in a mining system due to excess bear rock that needs to be mucked and an increase in the utilization of resources (e.g., personnel, equipment, energy) that are required for such operation.

A particular mining sequence may often result in ground-related problems that can force the mine engineer to abandon a stope or a section of a mine. This will result in a reduction of the mineral resource inventory and a shortage of production scheduled to be mined within a particular time period. Depending on the capacity of the hoist system to accommodate increases in the production rate and changes in the mine layout, the shortage of production may or may not be replaceable. If the production is not replaceable, then this will result in an
increase of the time required for a particular mine infrastructure to remain active in order for
the prescheduled ore extraction to be completed.

The simulation models that are currently used in the mining industry are not customized to
accommodate the impact of ground-related problem on mine production. Examples of
simulation of ground-related problem delays as discrete events are given by Dunbar, et al
(1999) and Kazakidis, et al (1999). These delays result in a shutdown of the production in the
simulation model that requires certain repair time in order to bring the production back to
normal. These time intervals correspond to the mean time between failure (MTBF) and mean
time to repair (MTTR) that can be determined using the reliability analysis introduced in
Chapter 3.

Dunbar, et al (1998) introduced values for MTBF and MTTR in a stope layout to evaluate
the significance of the availability of a “stand-by stope” in the daily production of a
simplified mining system consisting of stopes (Figure 4.1). The stope production problems
considered in the analysis may well be related to ground problems such as those described
for subsystem A in Chapter 3. The introduction of contingency in a mining layout is a form
of flexibility. This analysis provides a means to evaluate the fluctuation (or stability) of daily
production over time. However, unless preset criteria are established by the mine engineer on
what constitutes acceptable levels of production, the benefit of the “stand-by stope” versus
the cost of developing it can only be assessed through a complete economic analysis.

A simulation model to analyze open stopes mined with vertical retreat mining was developed
by Laurentian University’s Mining Automation Laboratory (Vagenas, et al, 1996). The
model included eight stopes along strike, access drifts, a ramp, a fleet of mining equipment
and crews. The mining sequence is a pillarless retreat system. This model was adapted to examine the impact of ground-related problems on mine production (Kazakidis, et al, 1999). It was determined, based on the likelihood of ground-related problems in access drifts, that the production interruptions will have a frequency of one failure every month. Each failure will require one day of rehabilitation in order for production to commence. Two simulations were carried out; one that considered the ground-related problems and one that ignored them. The results of the simulation were examined in terms of the predicted fluctuations of daily production over time. Figure 4.2 displays the tail end of the production at the VRM stopes. It can be seen that the ground-related problems in the access drifts result in an extension of the mining period by eight days. This may be considered as insignificant compared to the total number of days that is required to develop and mine the particular stope layout. However, no
ground-related problems were considered in this example in subsystems other than the access drifts. Nonetheless, this demonstrative example introduces the concept of utilizing delays due to particular ground-related problems in production simulation.

**Figure 4.2:** Comparison of production simulation results with and without interruptions due to ground-related problems in access drifts (one failure per month, resulting in one day system interruption) (Kazakidis, et al, 1999)

### 4.2.3 Evaluation of alternatives through production simulation

Production simulation can be used to assess the impact of ground-related problems in terms of tonnage shortage over the life of a mining system. A process to include ground-related problems in production simulation through reliability analysis is shown in Figure 4.3. Production simulation can include time delays, as well as needs for excess mucking of material due to dilution and loss of mineral resource inventory due to ground-related problems. However, when evaluating alternatives that will introduce flexibility in the overall mining system to accommodate the ground-related problems, the cost of a potential alternative is not examined. For instance, in the example with the “stand-by stope”, examined
Figure 4.3: Input of ground-related problems into production simulation analysis and evaluation of a mine plan over the production life of a mining system.
earlier, the cost of developing the extra stope should not outweigh the benefit for not losing the production over a certain time period. This will be dependent on the frequency of ground-related problems in stopes. Nonetheless, the analysis is valid in cases where the order of magnitude of impact on production versus rehabilitation costs are known.

In underground hard rock mines, decisions are often made based on the ability of the mining system to maintain certain production levels over time, as long as the additional costs related with this do not exceed a certain threshold. On that basis, production simulation alone can be used to determine the ability of the mining system to sustain production levels, while accommodating delays related to ground-related problems. Alternative scenarios can be evaluated and additional flexibility can be introduced in the production system.

Once it is determined through simulation that ground-related problems are likely to impair the scheduled production levels beyond acceptable levels, three options become available:

- Alter the mine plan to introduce contingency in the production system that can accommodate delays related to ground-related problems in certain subsystems (i.e., modify mine wide design and production scheduling);
- Find ways to decrease the frequency and duration of delays that are anticipated in certain subsystems (i.e., modify subsystem design);
- Introduce a combination of the above two options.

Examples of mine wide design can include the introduction of a second orepass to the production system, earlier initiation of development in other mining zones, or the introduction of “stand-by stopes”.
Subsystem design can include, for example, the decrease of span or height in a stope, the introduction of different support systems, drilling with different diameter holes, destressing, and the introduction of stand-by rehabilitation crews.

Determining acceptable levels of production decreases is often not adequate to access the flexibility needs of an underground operation and the alternatives that are available to a mine engineer. In many cases, decision making cannot be based solely on the evaluation of the production impact of a particular problem. Evaluation of alternatives, options or opportunities when assessing a flexible mining system will require the determination of the cost to introduce the particular alternative in the mine plan and the assessment of the economic impact of the particular problem over time. In such cases, production simulation alone can result in erroneous decisions. Therefore, although production simulation is part of a process to evaluate the volatility of production in an underground mining operation, it is often the case that economic analyses will be required to properly assess the alternatives that are worth pursuing at a given time. These alternatives will introduce the required flexibility in the mining system to accommodate the anticipated ground-related problems.

4.3 DISCOUNTED CASH FLOW ANALYSIS

4.3.1 Traditional Project Evaluation Criteria

The economic evaluation of investment opportunities is intended to facilitate the comparison between the return on investment and the cost of capital. Discounted cash flow (DCF) analysis has been routinely carried out for mining project evaluation and mine investment analysis. The DCF analysis is usually based on the determination of annual cash flows
throughout the lifetime of a mining project. The fundamentals of the analysis are described in
detail in standard textbooks (e.g., Gentry and O’Neil, 1984, Bilodeau, 1998). The process of
economic and financial analysis of engineering projects and the relevant terminology are
analyzed by Nilsson (1982) and Benzimra (2000). Once the cash flows for a particular
mining project or economic scenarios are assessed, then, two key performance indicators are
usually used to evaluate its feasibility and potential alternatives: the net present value (NPV)
and the rate of return (ROR).

The net present value (NPV) method converts the anticipated time distribution of cash flows
(CF) for an investment opportunity into an equivalent value at the present point of time (time
zero). Therefore, each year’s cash flow is discounted to a present value using the cost of
capital as the predetermined discount rate. The sum of the present value components then
yields the NPV of the economic scenario under evaluation:

\[ NPV = \sum_{t=0}^{T} \frac{CF_t}{(1 + r)^t} - I_o \]

where,

- \( CF_t \): the cash flow in year \( t \) (inflow minus outlays: \( CF_t = C_t - Q_t \));
- \( r \): the discount rate for the particular project;
- \( I_o \): the initial investment outlay;
- \( T \): the total project life;
- \( t \): a point in time (usually the beginning or the end of a year);
- \( C_t \): the present value of benefits;
- \( Q_t \): the present value of costs.
A different way to calculate the NPV is by calculating the present value of benefits, $C_t$, and the present value of costs, $Q_t$. The difference of the two is the NPV for the particular project alternative:

$$NPV = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} - \sum_{t=0}^{T} \frac{Q_t}{(1+r)^t} - I_o$$

Since NPV is dependent on the discount rate selected, the results are dependent on the assumed cost of capital. The rate of return (ROR) of an investment opportunity is defined as the discount rate that results in a zero NPV. In other words, it is the discount rate, which equates the present value of the positive cash flows with the present value of the negative cash flows:

$$ROR = r, \quad \text{where: } \sum_{t=0}^{T} \frac{CF_t}{(1+r)^t} - I_o = 0$$

The rate of return (ROR) measures the average annual percentage return on investment that an alternative is expected to yield over the total project life.

In general terms, and for simple financial analyses, when using the NPV and ROR methods the project or the alternative with the highest values is preferred. However, these methods are not the only criteria for evaluating investment opportunities in the mining industry and for assessing available options in the decision making process. Criteria based on annual cash flow, operating cost, total return, benefit-cost ratio, payback period and present value ratio are also still in use by planning engineers and management executives. Nonetheless, the NPV and ROR methods have dominated project evaluation methods for mining projects.
4.3.2 NPV under uncertainty

The NPV is often adopted as the best available valuation measure consistent with a firm’s objective of maximizing its shareholders wealth, using as a discount rate the rate of return offered by comparable investment opportunities in the capital market, i.e., the opportunity cost of capital. The risk-free rate of return is determined from similarly traded assets without risk, such as government bonds (Luenberger, 1998, Smith 1995).

However, investments are characterised by risk and uncertainty. Risk in business decision making arises from forecasts of primary variables such as the costs of labour and materials, the prices and quantities of products sold, assumptions about competition, the firm’s market shape, the size and growth of the market, effective tax rates, expected inflation rate, and the project’s lifetime. Risk components that are commonly evaluated in mining projects in particular include: operational risk, technical risk, competition and cost overrun risk, market and price risk, political risk, legal risk, environmental risk and social risk.

The fundamentals of the approach for calculating NPV under certainty were analysed in the previous section. Once risk needs to be included in a DCF analysis, three approaches can usually be applied (Trigeorgis, 1998, Luenberger, 1998):

- Risk-adjusted discount rate approach;
- Certainty-equivalent approach;
- Capital Asset Pricing Model (CAPM) approach.
4.3.3 Cash flow calculations for ground-related problems

The annual cash flows in a mining project are determined from cash inflows and cash outlays. The cash flows in a mine will be a function of:

- The metal market;
- The production rate;
- The quality of ore;
- The operating and capital costs (include all operating factors and environmental, social and political costs); and,
- The problems and delays that occur during the lifetime of a mine.

Cash inflow calculations are usually based on the production rate (e.g., tonnes per year), the quality of ore (e.g., oz/tonne or Ni lb/tn) and the metal market (e.g., $/oz or $/Ni lb):

\[
\begin{bmatrix}
\text{CASH INFLOWS} \\
\$/yr
\end{bmatrix} = \begin{bmatrix}
\text{PRODUCTION RATE} \\
\text{tonnes/yr}
\end{bmatrix} \times \begin{bmatrix}
\text{ORE QUALITY} \\
\text{oz/tonne}
\end{bmatrix} \times \begin{bmatrix}
\text{METAL MARKET} \\
\$/oz
\end{bmatrix}
\]

Ground-related problems that affect orebody recovery for the particular year can result in lowering the production rate. Dilution related problems would lower the quality of the ore that is hoisted, while at the same time influencing the production rate.

The cash outlays can be based on a calculation of the operating cost (e.g., $/tonne or $/oz) or the variable and fixed costs at the particular mine. For the case of the calculation of operating cost, the cash outlays will be:
It is often the case that extra costs are included in the operating cost of a particular mine in order to obtain a comparative cost basis (cash cost). Ground-related problems could affect the production rate, the operating cost, as well as the extra costs. A methodology for cost impact assessment of production interruptions due to ground-related problems was introduced in Chapter 3. Amortization, depreciation, and corporate expenses are not included in the above calculations, and are added when total cost calculations are conducted at the corporate level.

For the case of calculation of variable costs on a per shift basis, the cash outlays will be:

\[
\begin{bmatrix}
\text{CASH} \\
\text{OUTLAYS}
\end{bmatrix}
= \begin{bmatrix}
\text{VARIABLE} \\
\text{COSTS}
\end{bmatrix}
\times \begin{bmatrix}
\# \text{of} \\
\text{SHIFTS}
\end{bmatrix}
+ \begin{bmatrix}
\text{FIXED} \\
\text{COSTS}
\end{bmatrix}
+ \begin{bmatrix}
\text{EXTRA} \\
\text{COSTS}
\end{bmatrix}
\]

Extra costs are all those which are not normally included as fixed and variable costs, and can include costs related to (unanticipated) production delays. Ground-related problems can affect variable, fixed, and extra costs in a particular mine.

Once the cash inflows and the cash outlays are determined (positive values), then the net annual cash flows for the particular year can be determined as follows:
\[
\begin{bmatrix}
CASH \\
FLOW \\
$/ yr$
\end{bmatrix}
= 
\begin{bmatrix}
CASH \\
INFLOWS \\
$/ yr$
\end{bmatrix}
- 
\begin{bmatrix}
CASH \\
OUTLAYS \\
$/ yr$
\end{bmatrix}
\]

The internal project risk (or private risk) of a mining project will be dependent on all of the above cost/revenue parameters with the exception of the metal price which is determined by the metal market. The metal market can be considered as independent from the particular project. Political or social project risks can be considered as external project risk factors, as was discussed in Chapter 1.

### 4.3.4 Evaluation of alternatives using DCF

Alternatives in underground mines are often evaluated through standard discounted cash flow (DCF) analyses that are routinely conducted as part of long term planning, budgeting and feasibility studies. Evaluation of managerial/operational flexibility through DCF analysis is presented here through conceptual examples from underground operations. However, it should be emphasized that the difference in NPV of two alternatives, with one containing a flexibility component, is not equal to the value of flexibility, as it will be shown later on in Chapter 5. Nonetheless, comparison of the NPV of two alternatives is commonly used as a means for decision making.

#### 4.3.4.1 Example with DCF analysis and ground-related problems

A small nickel orebody is being considered for development. Geological reserves total 1,000,000 tonnes at 3% nickel and 3.5% copper. If the mine is developed with a particular mining method, a mine recovery factor of 85% and a dilution of 20% are anticipated. The
mine recovery factor is the complement of that part of geological reserves which is left behind in pillars and remnants, and is assumed to be unrecoverable. The dilution factor accounts for the waste rock adjacent to the orebody itself that is inevitably extracted in the mining method. Dilution increases the tonnage mined but reduces the quality of recoverable reserves. The diluting waste-rock contains no recoverable metal values.

The deposit will be brought to production at a capacity of 255,000 tonnes per year, based on the capacity of the mine’s hoisting system. Capital expenditures of $45 million per year will incur over a two-year pre-production period. Operating costs are estimated at $60 per tonne. Long-term market price estimates are $2.5/lb for nickel and $0.9/lb for copper. All prices are in US dollars. The company’s cost of capital is 10%. It is assumed that cash inflows and outlays occur at the end of the year.

Before the examination of flexibility is considered, the net present value and the rate of return of the project are determined, as is normally done in DCF analysis.

The recoverable geological reserve will be: 1,000,000 x 0.85 = 850,000 tonnes.

The waste rock that will be mined as a result of dilution will be:

\[ 1,000,000 \times 0.85 \times 0.2 = 170,000 \text{ tonnes} \]

The hoisted rock (ore and waste) will be: \[ 1,000,000 \times 0.85 \times 1.2 = 1,020,000 \text{ tonnes} \]

The ore reserves will be: 850,000 tonnes @ 3% Ni and 3.5 % Cu:

- Nickel content: \[ 25,500 \text{ tonnes} \times $2.5/\text{lb} \times 2200 \text{ lb/tonne} = \$140.25 \text{ million} \]
- Copper content: \[ 29,750 \text{ tonnes} \times $0.9/\text{lb} \times 2200 \text{ lb/tonne} = \$58.905 \text{ million} \]

The total ore value will be: \$199.155
The mine life, after development, is: \( \frac{1,020,000}{255,000} = 4 \) years.

During the first two years, there is a negative cash flow of $45 million per annum. The annual cash flows during the years 3-6 will be:

\[
[\text{Annual cash flows}] = [\text{Total revenues}] - [\text{Total operating costs}] = \\
= \frac{199.155}{4} - \frac{1.02}{4} \times 60 = \frac{49.78}{4} - \frac{15.3}{4} \equiv \frac{34.5}{4} \text{ million}
\]

The net present value of the project will then be:

\[
\text{NPV} = -45 \times (1 - 1.1^{-2})/0.1 + 34.5 \times (1 - 1.1^{-4})/0.1 \times (1.1)^{2} = -78.10 + 90.38 = 12.28 \text{ m}
\]

Through trial and error it is found that the rate of return is ROR = 15.7%. Next, the need for flexibility in the project will be evaluated. Although the above analysis appears to be favourable, the operating team is concerned about the potential of ground-related problems to disturb production due to ground falls at the stope access drifts. Production losses observed in a similar mining scenario were found to average 51,000 tonnes per year, depending on ground conditions. In such a case the operating cost will increase by 10%, due to the needs for rehabilitation or driving new access drifts.

The operating team is considering a modified plan to place a second access drift to the stopes at an extra cost of $1 million per year (years 3-6) that could be used in case ground falls or rockbursting occur in the first access drift. The extra drift gives the flexibility to maintain production at the planned levels.

The impact of the potential ground problems will be:
i) decrease in the annual production by 51,000 tonnes;

ii) increase in the total operating costs by 10%;

iii) prolongation of the mine life, due to annual production losses, by \( \frac{1,020,000}{(255,000 - 51,000) - 4} \) = 1 year, causing delay of expected cash inflows.

The new annual cash flows for the case with ground-related problems, and for the case of the modified plan, needs to be calculated. When ground problems occur, the annual cash flow for the years 3 to 7 will be:

\[
[\text{Annual cash flows}] = [\text{Total revenues}] - [\text{Total operating costs}] =
\]

\[
= \frac{199,155}{5} - \frac{1.02}{5} \times 60 \times 1.1 = 39.83 - 13.46 \equiv 26.37 \text{ million}
\]

The net present value of the project will then be:

\[
\text{NPV} = -45 \times (1 - 1.1^{-2})/0.1 + 26.37 \times (1 - 1.1^{-5})/0.1 \times (1.1)^{-2} = -78.10 + 82.61 = 4.51
\]

It is found that the rate of return is \( \text{ROR} = 11.9\% \). The cash flow with the modified plan will be:

\[
[\text{Annual cash flows}] = [\text{Total revenues}] - [\text{Total operating costs}] =
\]

\[
= \frac{199,155}{4} - \frac{1.02}{4} \times 60 - 1 = 49.78 - 16.3 \equiv 33.5 \text{ million}
\]

The net present value of the project will then be:

\[
\text{NPV} = -45 \times (1 - 1.1^{-2})/0.1 + 33.5 \times (1 - 1.1^{-4})/0.1 \times (1.1)^{-2} = -78.10 + 87.76 = 9.66
\]
It is found that the rate of return will now be ROR = 14.6%

It can be seen that the modified plan increased both the net present value and the rate of return of the project. The modified plan gives the mine engineer the flexibility to avoid losses related to ground-related problems that could make the whole project non-feasible. It is evident in this case that, unless there is low risk for the particular production losses, it is considered favourable for the mine engineer to follow the flexible modified plan instead of the original one. However, if the production losses were significantly lower, that decision could be reversed. The above analysis can be used as a basis to examine production losses due to excess dilution and orebody losses, as well as support costs, orepass costs, backfill costs, sill mat costs etc. It can also be used to evaluate alternative mining methods.

4.3.4.2 Example with DCF analysis and risk associated with ground-related problems

In the example considered above, the net present value of the project will now be evaluated, when the probability of annual cost impact due to ground-related problems during the mine's life is as shown in Table 4.1:

<table>
<thead>
<tr>
<th>Probabilities</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>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum impact: 10%</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Most Likely impact: 70%</td>
<td>0</td>
<td>0</td>
<td>0.3</td>
<td>0.3</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Maximum impact: 20%</td>
<td>0</td>
<td>0</td>
<td>0.4</td>
<td>0.4</td>
<td>1.7</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Table 4.1: Probabilities for annual cost impact of ground-related problems

In million dollars
The higher cost impact during years 5 and 6 is attributed to sill pillar problems¹ that will cause loss of ore, excess dilution, and the need for rehabilitation. The mine engineer considers the high potential costs for years 5 and 6 unacceptable. There is a need to evaluate an alternative design in which, by placing strong sill mats² at an additional cost of $0.15 million per year during years 3 and 4, the probabilities of cost impact, due to ground problems during the last two years, can be reduced to the levels of years 3 and 4. The new design will also allow the mine engineer to drive overcuts (topsills) in the sills during years 5 and 6 and avoid orebody losses and excess dilution due to improved drilling conditions. The extra cost for driving the overcuts is estimated to be $0.1 million per year during the years 5 and 6. The benefit of the new design now requires to be analyzed.

The cash flows for the basic case when high cost impact is expected during years 5 and 6 due to ground-related problems will be evaluated first. If \( G \) is the annual ground-problem related cost, the annual cash flow for the years 3 to 6 will be:

\[
[\text{Annual cash flows}] =
\]
\[
= [\text{Total revenues}] - [\text{Total operating costs}] - [\text{Ground-problem cost}] =
\]
\[
= \frac{199,155}{4} - \frac{1.02}{4} \times 60 - G \geq \$34.5 - G \text{ million}
\]

The cash flow distribution over time for different cost impacts due to ground-related problems, and the NPV for each of the three probability cases, are shown in Table 4.2.

---

¹ For examples of sill pillar problems in hard rock mines, see Kazakidis, 1998.
² Sill mats are structures built by screen, bolts, fill or timber at the floor of a stope (sill cut) to reinforce the floor so it does not cave when the stope underneath is mined.
Table 4.2: Cash flow distribution and NPV for probable cases of ground-related problems

<table>
<thead>
<tr>
<th>NPV</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>
</tr>
</thead>
<tbody>
<tr>
<td>$11.52</td>
<td>-45</td>
<td>-45</td>
<td>34.3</td>
<td>34.3</td>
<td>34.1</td>
<td>34.1</td>
</tr>
<tr>
<td>$10.90</td>
<td>-45</td>
<td>-45</td>
<td>34.2</td>
<td>34.2</td>
<td>33.7</td>
<td>33.7</td>
</tr>
<tr>
<td>$9.69</td>
<td>-45</td>
<td>-45</td>
<td>34.1</td>
<td>34.1</td>
<td>32.8</td>
<td>32.8</td>
</tr>
</tbody>
</table>

The net present value for the project will then be:

\[ \text{NPV} = 0.1 \times 11.52 + 0.7 \times 10.90 + 0.2 \times 9.69 = 10.72 \]

The rate of return is found to be \( \text{ROR} = 15.1\% \).

The cash flow distribution for the alternative design are calculated as shown in Table 4.3:

Table 4.3: Cash flow distribution and NPV probable cases of ground-related problems for an alternative design scenario

<table>
<thead>
<tr>
<th>NPV</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>
</tr>
</thead>
<tbody>
<tr>
<td>$11.42</td>
<td>-45</td>
<td>-45</td>
<td>34.15</td>
<td>34.15</td>
<td>34.20</td>
<td>34.20</td>
</tr>
<tr>
<td>$11.16</td>
<td>-45</td>
<td>-45</td>
<td>34.05</td>
<td>34.05</td>
<td>34.10</td>
<td>34.10</td>
</tr>
<tr>
<td>$10.90</td>
<td>-45</td>
<td>-45</td>
<td>33.95</td>
<td>33.95</td>
<td>34.00</td>
<td>34.00</td>
</tr>
</tbody>
</table>

The alternative design provides a higher NPV ($11.14 million) than the one determined without the managerial flexibility. It is therefore preferable to introduce the alternative design. In this analysis, the probabilities associated with ground-related problems were considered. In the case that uncertainty existed for other project components such as grade, operating cost, production and metal market, the problem would be more complex, and could be assessed more effectively by probabilistic simulation, for example, through a Monte Carlo simulation.
4.3.5 Monte Carlo simulation analysis of operating risk using DCF

Whenever a proposed project may significantly impact on profit or loss for a corporation, an evaluation of the financial risks is advisable before making a final decision to proceed with the project. Risk analysis is especially important whenever one or more of the variables affecting profit or loss is difficult to determine with certainty. Such variables may include the metal price, the operating cost of a mine, the orebody grade or the anticipated production disruptions due to equipment or ground-related problems throughout a mine’s life. These variables define the external and the internal risk associated with a particular project, as was discussed in Chapter 1. Ultimately, the profit or loss for the project will depend upon the future values of these variables. The term risk focuses on the potential for loss, as was discussed in Chapter 3. The Monte Carlo method is a method of finding the probability distribution of the possible outcomes of a process or experiment by simulation (Anderson, et al, 1997, Harr, 1987). Monte Carlo spreadsheet simulation, using Insight™ (Savage, 1998), is used here to conduct internal risk analysis for mining projects. In the process, the way in which risk analysis can be used to assess flexibility requirements, evaluate alternatives, and conduct decision making in an underground mine operation will be demonstrated.

4.3.5.1 Example with Monte Carlo simulation and ground-related problems

The example of the small nickel mine, considered in the previous section, will also be used to demonstrate Monte Carlo simulation analysis. There is uncertainty in this mining project in terms of revenues, operating costs, and ground-related problems. It is assumed that the values of revenues and operating costs are those of the example 4.3.4.2. These are assumed to be normally distributed around their estimated values with standard deviations equal to 15% of the estimated values. The annual costs associated with ground-related problems, shown in
Table 4.4, follow a triangular distribution with minimum, most likely (mode) and maximum values (Figure 4.4).

Table 4.4: Annual cost associated with ground-related problems (triangular distribution)

<table>
<thead>
<tr>
<th>Values</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>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Most Likely (mode)</td>
<td>0</td>
<td>0</td>
<td>0.3</td>
<td>0.3</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Maximum</td>
<td>0</td>
<td>0</td>
<td>0.4</td>
<td>0.4</td>
<td>1.7</td>
<td>1.7</td>
</tr>
</tbody>
</table>

In million dollars

Figure 4.4: Triangular distribution for ground-related problems used for sampling in Monte Carlo simulation (please note that the most likely value of the distribution is not the average in this case, because the distribution is not symmetrical around its value).

The objectives that will be evaluated are:

(a) to determine the NPV distribution for the mining project using Monte Carlo simulation;
(b) to evaluate the options that are available to the mine engineer to alleviate or minimize production disruptions due to ground-related problems.

The cash flow distribution for the years 1 to 6 and the calculation of the average NPV using Monte Carlo simulation is shown in Table 4.5.
Table 4.5: Cash flow distribution and average NPV (in million $)

<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>
</tr>
</thead>
<tbody>
<tr>
<td>Revenues</td>
<td>0</td>
<td>0</td>
<td>49.8</td>
<td>49.8</td>
<td>49.8</td>
<td>49.8</td>
</tr>
<tr>
<td>Oper. Costs</td>
<td>45</td>
<td>45</td>
<td>15.3</td>
<td>15.3</td>
<td>15.3</td>
<td>15.3</td>
</tr>
<tr>
<td>Ground-prob.</td>
<td>0</td>
<td>0</td>
<td>0.3</td>
<td>0.3</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Cash flow</td>
<td>-45</td>
<td>-45</td>
<td>34.2</td>
<td>34.2</td>
<td>33.7</td>
<td>33.7</td>
</tr>
</tbody>
</table>

Monte Carlo simulation

<table>
<thead>
<tr>
<th></th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Year 4</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Revenues</td>
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<td>0</td>
<td>52.76</td>
<td>36.28</td>
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<tr>
<td>Ground-prob.</td>
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<td>0.36</td>
<td>0.30</td>
<td>0.74</td>
<td>1.19</td>
</tr>
<tr>
<td>Cash flow</td>
<td>-45</td>
<td>-45</td>
<td>34.82</td>
<td>19.58</td>
<td>22.09</td>
<td>28.99</td>
</tr>
</tbody>
</table>

NPV (average) = $ 10.84
deviation = $ 10.34

The new cash flow distribution and the calculation of the average NPV using Monte Carlo simulation, for the case where sill mats are built, is shown in Table 4.6.

Table 4.6: Cash flows and average NPV for the case of alternative design (in million $)

<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>
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</thead>
<tbody>
<tr>
<td>Revenues</td>
<td>0</td>
<td>0</td>
<td>49.8</td>
<td>49.8</td>
<td>49.8</td>
<td>49.8</td>
</tr>
<tr>
<td>Oper. Costs</td>
<td>45</td>
<td>45</td>
<td>15.3</td>
<td>15.3</td>
<td>15.3</td>
<td>15.3</td>
</tr>
<tr>
<td>Sill mats</td>
<td>0</td>
<td>0</td>
<td>0.15</td>
<td>0.15</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ground-prob.</td>
<td>0</td>
<td>0</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Cash flow</td>
<td>-45</td>
<td>-45</td>
<td>34.35</td>
<td>34.35</td>
<td>34.2</td>
<td>34.2</td>
</tr>
</tbody>
</table>

Monte Carlo simulation

<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>
</tr>
</thead>
<tbody>
<tr>
<td>Revenues</td>
<td>0</td>
<td>0</td>
<td>46.35</td>
<td>56.14</td>
<td>55.59</td>
<td>41.54</td>
</tr>
<tr>
<td>Oper. Costs</td>
<td>45</td>
<td>45</td>
<td>15.92</td>
<td>14.50</td>
<td>14.82</td>
<td>14.52</td>
</tr>
<tr>
<td>Ground-prob.</td>
<td>0</td>
<td>0</td>
<td>0.30</td>
<td>0.30</td>
<td>0.31</td>
<td>0.28</td>
</tr>
<tr>
<td>Cash flow</td>
<td>-45</td>
<td>-45</td>
<td>30.13</td>
<td>41.33</td>
<td>40.47</td>
<td>26.75</td>
</tr>
</tbody>
</table>

NPV (average) = $ 11.17
deviation = $ 10.33

As before, the alternative design provides a higher average NPV than that determined without the managerial flexibility. The benefit, which is the difference between the two, is of the same order of magnitude as that determined from the conventional DCF analysis in
section 4.3.4.2. This is due largely to the fact that this model is linear, based on the volatility that is introduced in the project variables.

The distribution of risk associated with the impact of ground-related problems versus time can also be evaluated, through a parameterized simulation, as can be seen in Figure 4.5. Here, the average annual impact of ground-related problems is plotted, along with 95% and 5% percentiles (90% confidence limits). Note the increase in impact for the case with no sill mats during the last two years of mining, as well as the increase in uncertainty. The option with sill mats reduces the impact of potential ground-related problems in the mine, as well as the uncertainty, whilst improving the project NPV.

The ground problem-related costs, assumed in this example, were relatively minor. It is often the case, however, that, catastrophic failures can have devastating effects on a mining operation. How would such an event be simulated? If it is assumed that the total impact of damage to a crusher station, for example, at the end of the fifth year is estimated to be $20
million, then the value of cost impact can rise from $1.7 to $20 million for that year. Therefore, the triangular distribution (Figure 4.4) is now skewed to the right to incorporate the acute problems of crusher station damage, while the minimum and most likely values are maintained. It is assumed that all of the other model parameters remain the same and that the mine manages to maintain the scheduled annual production levels after the crusher station is rehabilitated. When the new model is run, the average NPV is reduced to $7.16, incorporating the chance of failure in the crusher station.

The above discount rate of 10%, however, may not be reasonable in the presence of risk. Results of a sensitivity analysis of the average NPV with respect to different discount rates is given in Figure 4.6. The discount rate can have a significant impact in determining the profitability of a mining project. The DCF method will require the determination of a proper discount rate in order for internal project risk to be included in the analysis. Determining the
appropriate discount rate for a DCF analysis is not a trivial task (Trigeorgis, 1998). The options theory through the concept of risk neutral probability is more advantageous in handling the project risk associated issues, as discussed in the next Chapter.
5.1 INTRODUCTION

Flexibility in a mining system, defined in Chapter 1, is the ability of that system to sustain performance, preserve a particular cost structure, adapt to internal or external changes in operating conditions, and take advantage of new opportunities that develop during a mine's life by modifying operational parameters. In that sense, flexibility is a parameter that measures the ability of a mining system to respond to both favourable and unfavourable changes.

As was discussed in Chapter 1, the operating flexibility is influenced by several factors, one of which is the ability to control ground-related problems throughout the life of a mining operation. This is a form of internal project flexibility, which is required to counterbalance the internal project risk or the volatility of a certain design parameter. The impact of lack of flexibility in mines due to ground-related problems was explored through the case studies presented in Chapter 2. A direct relationship between mine planning and ground-related problems was established in the same chapter. Methods to measure the impact of ground-related problems on a mine production system were introduced in Chapter 3. It was shown that the consequences of ground-related problems in mines normally are related to production/time delays, increases in costs due to repairs/replacements, ore dilution, and ore reserve losses. Production simulation and conventional DCF analysis can incorporate ground-related problems to determine the impact on mine production or on the NPV of a
project. However, they don’t provide the appropriate vehicle to determine the value of flexibility available within a particular alternative.

The applicability of real options to assess the flexibility of a mining system (or a component of it) that contains risk/volatility due to production delays associated with ground-related problems, will be explored in this chapter. Once the concept of real options is explained, operating flexibility options associated with ground-related problems are discussed and demonstrated through examples. Binomial lattices and Monte Carlo simulation are used to determine the value of flexibility (option value) within a particular cash flow structure. Criteria for selecting the appropriate approach to examine flexibility and links to production simulation and DCF analysis are also reviewed in this chapter. The main intent of this chapter is to show through relatively simple examples that the value of flexibility can be quantified.

5.2 CALLS AND PUTS

The investment and financial sectors are particularly familiar with the fundamentals of options theory and the applications of calls and puts. The options theory has recently found application in managerial decision making. Real options became the subject of research to establish a process, which required evaluating flexibility in manufacturing and the resource sectors. Prior to analyzing the application of options in evaluating operating flexibility in mining projects, the definitions of the key parameters of the options theory are introduced. An option is defined as the right, without an associated symmetric obligation, to buy (if a call) or sell (if a put) a specified asset by paying a pre-specified price (the exercise or strike price) on or before a specified date (the expiration or maturity date).
Call options increase in value with favourable movements in the underlying asset price (i.e., are more valuable on the upside). Put options pay off when the asset drops in value (i.e., are more valuable on the downside). Put options can be used like insurance to provide protection against a decline in the value of the underlying asset. Put options can also be used to hedge risk (i.e., portfolio insurance).

If $K$ is the stock price written on the option and $S_P$ the stock price at the expiration date then the value of the options will be:

$$\text{Call option: } C = \max (0, S_P - K) \quad \text{Put option: } P = \max (0, K - S_P)$$

An *American option* allows exercise at any time before and including the expiration date. A *European option* allows exercise only on the expiration date. The value of an option for different stock prices is shown in Figure 5.1.

![Figure 5.1: Value of call and put options](image)

A discrete type of option that is of particular interest is the *barrier option*. Barrier options are standard calls or puts except that they disappear or appear if the underlying asset price is found to have crossed a predetermined (barrier) level, on a predetermined set of fixing dates (Clewlow and Strickland, 1998; Hull, 1997; Wilmott, *et al*, 1997). Therefore, the payoff depends on whether the underlying asset’s price reaches a certain level during a certain period of time.
5.3 SYNTHETIC OPTIONS

An option can be evaluated by determining the cost of constructing its equivalent replicating portfolio, that is the cost of a synthetic option equivalent. One can construct an equivalent portfolio consisting of N shares of a security S, partly financed by borrowing of amount $B at the risk-free rate, r, that would exactly replicate the future returns of the option in any state of nature (Trigeorgis, 1998).

Suppose that the price of the underlying stock, S, can move over the next period either up to $S^+$ (with a multiplicative up factor $u > 1$) or down to $S^-$ (with a multiplicative down factor $d < 1$), with probabilities $q$ and $(1-q)$, respectively, i.e.,

$$
\begin{align*}
S & \quad q \quad S^+ = u \cdot S \\
& \quad 1-q \quad S^- = d \cdot S
\end{align*}
$$

If $E$ is the exercise or strike price, then the value of a call option will be:

$$
\begin{align*}
q & \quad C^+ = \max (S^+ - E, 0) \\
1-q & \quad C^- = \max (S^- - E, 0)
\end{align*}
$$

Where $C^+$ and $C^-$ are the values of the call option at the end of the period if the stock moves up or down respectively.

A constructed equivalent portfolio for put and call options consists of:

Call option ≈ Buy N shares at S & Borrow $B at r ⇒ C = N \cdot S - B

Put option ≈ Sell N shares at S & Lend $B at r ⇒ P = N \cdot S - B
Let us examine the case of a call option based portfolio. After one time period (e.g., one year) the portfolio will be:

\[ q \rightarrow NS^+ - (1+r)B \]

\[ 1-q \rightarrow NS^- - (1+r)B \]

If the portfolio is to offer the same return in each state at the end of the period as the option, then:

\[
\begin{align*}
NS^+ - (1+r)B &= C^+ \\
NS^- - (1+r)B &= C^-
\end{align*}
\]

\[ \Rightarrow \frac{N}{B} = \frac{C^+ - C^-}{S^+ - S^-} \]

\[ \Rightarrow C = \frac{pC^+ + (1-p)C^-}{1+r} \]

where, \[ p = \frac{(1+r)S^- - S^+ - S^-dS}{uS - dS} = \frac{(1+r) - d}{u-d} \]

The factor, \( p \), is defined as the risk-neutral probability, which is the probability that would prevail in a risk-neutral world where investors are indifferent to risk. In such a world, all assets (including stocks, options etc) would earn the risk free return, and so expected cash flows (weighted by the risk-neutral probability) could be appropriately discounted at the risk-free rate. Note that the actual probability of up and down movements, \( q \), does not appear in the formula given for \( p \).

Denoting that the expected return will be:

if the stock moves up: \[ R^+ = \frac{S^+}{S} - 1 = u - 1 \]

if the stock moves down: \[ R^- = \frac{S^-}{S} - 1 = d - 1 \]
The risk-neutral probability, \( p \), can then be written as:

\[
p = \frac{(1 + r)S - S^-}{S^+ - S^-} = \frac{(1 + r)S^-}{S^+} = \frac{(1 + r) - (R^- + 1)}{S^+ - S^-}
\]

\[
= \frac{R^+ - R^-}{u - d}
\]

In order for \( p < 1 \), it must be that: \( d < 1 + r < u \).

A put option can be valued similarly, except that shares of the underlying stock will need to be sold (instead of bought) and there will be the need to lend instead of borrow money.

### 5.3.1 Generic example with synthetic options

The initial outlay for a mining project is calculated to be \( I_o = $105 \) million. There is an equal probability \( (q = 0.5) \) that a year later the project’s cash flows will be $150 million if the metal price moves up and $90 million if the market moves down. The value of this project, \( V_o \), (gross project value) is required to be determined.

The binomial lattice for the cash flows will be:

\[
\begin{align*}
V & \quad q \quad V^+ = $150 \\
& \quad 1-q \quad V^- = $90
\end{align*}
\]

In order to estimate the project’s opportunity cost of capital, a “twin security” with the same risk characteristics as the project under consideration is used. The security is currently priced in the market at \( S = $20 \). It is found that the security characteristics are described by the decision tree shown below:
The binomial multiplication factor for the security are $u=1.5$ and $d=0.9$. The required rate of return (discount rate), $k$, for the security will be:

$$\text{rate of return: } k = \frac{0.5 \times 30 + 0.5 \times 18}{20} - 1 = \frac{24}{20} - 1 = 0.20 = 20\%$$

The risk-free interest rate is estimated to be 5%.

Using the traditional DCF approach, the gross value of the project can be calculated by the equation:

$$V_0 = \frac{qV^+ + (1-q)V^-}{1+k} = \frac{0.5 \times 150 + 0.5 \times 90}{1 + 0.20} = 100$$

The net present value for the proposed investment can be calculated by subtracting the initial investment from the gross value of the project:

$$\text{NPV} = V_0 - I_0 = $100 - $105 = - $5\ million$$

This means that the proposed investment is not feasible and, in the absence of managerial flexibility, the investment should be rejected.

The same generic example will now be examined using the options-pricing hedging strategy. The binomial trees for the gross project value and the twin security have already been...
determined. The equivalent portfolio \( E \) consisting of \( N \) shares of the “twin security” \( S \), partly financed by borrowing of amount \( B \) at the risk-free rate, \( r \), will be:

\[
E = NS - B
\]

\[
E^+ = NS^+ - (1+r)B
\]

\[
E^- = NS^- - (1+r)B
\]

The equation for risk neutral probability will be applied for expected cash flows determined from the previous section:

\[
p = \frac{(1 + r)S - S^-}{S^+ - S^-} = \frac{(1 + 0.05)20 - 18}{30 - 18} = \frac{21 - 18}{12} = \frac{3}{12} = 0.25
\]

The gross project value will then be:

\[
V = \frac{pV^+ + (1-p)V^-}{1+r} = \frac{0.25 \times 150 + 0.75 \times 90}{1 + 0.05} = \frac{37.5 + 67.5}{1.05} = 100
\]

The value that is found using the options approach is identical to the one of the traditional DCF. This is due to the fact that no flexibility in response to changes in cash flow was introduced in this example.

In the case that the duration of the project is expected to be more than one year, the binomial lattice will include a year-by-year forward calculation for the underlying stock, \( S \), and then a backward calculation of the value of the cash flows appropriately discounted back to that year. The binomial lattice for a three-year operating period is shown in Figure 5.2:
Figure 5.2: Binomial lattice for a three-year operating period

The calculation process for multiyear projects can be performed through spreadsheets, as shown by Luenberger (1998).

5.4 REAL OPTIONS VERSUS DCF FOR FLEXIBILITY ANALYSIS

Flexibility may be provided from a collection of options associated with an investment opportunity, financial or real. Real options involve discretionary decisions or rights, with no obligation, to acquire or exchange an asset for a specified alternative price. The owner of a discretionary investment opportunity has the right – but not the obligation – to acquire the (gross) present value of expected cash flows by making an investment outlay on or before the anticipated date when the investment opportunity will cease to exist. Flexibility gives a manager the right to wait until more information is available and make the investment only if the value of the project turns out to exceed the necessary outlay, without imposing any symmetric obligation to invest and incur losses if the opposite scenario occurs.

The basic inadequacy of the DCF approaches to capital budgeting is that they ignore, or cannot properly capture, the flexibility of a management team to adapt and revise later
decisions. The traditional NPV approach in particular, makes implicit assumptions concerning an “expected scenario” of cash flows and presumes management’s commitment to a certain “operating strategy” from which it cannot depart, whether nature remains faithful to or deviates from the expected scenario of cash flows. When dealing with the valuation of investment opportunities, whose claims are not symmetrical or proportional, the traditional DCF approaches are inadequate.

In the real world of uncertainty and competitive interactions as new information arrives, the management needs to be able to defer, expand, contract, abandon, or alter a project at various stages during its operating life. NPV is based on a passive approach to management, as if market developments were unfolding in an event tree without any contingent response on the part of management. Clearly, using expected cash-flow estimates does not capture the dependence of future cash flows on future management decisions, since the cash-payoff structure of a flexible project changes, asymmetrically, in the presence of real options. Nor can the use of a single-risk adjusted discount rate capture the complex changes in risk that result from management’s flexibility to capitalise on success or to cut losses in the case of failure.

Trigeorgis (1998), indicates that, using an options-based approach (option pricing or contingent-claims analysis), an expanded (strategic) NPV can be calculated that includes the standard static (passive) expected NPV plus an option premium that reflects the value of strategic options from active management and interaction effects of competition, synergy and inter-project dependence:

\[
\text{Expanded NPV} = \text{Static NPV} + \text{Option Premium}
\]
The motivation for using an options-based approach to capital budgeting arises from its potential to conceptualise and quantify the option premium or flexibility component of value. Traditional static (passive) NPV should be seen as a crucial and necessary input to an options-based "expanded NPV" framework.

The options-based (i.e., expanded-NPV) analysis bypasses the discount-rate problem by relying on the motion of a comparable security to properly price risk, while still being able to capture the dynamic interdependencies between cash flows and future optimal decisions. According to Trigeorgis (1998), such analysis combines the best features of decision tree analysis and NPV without their drawbacks.

5.5 OPERATING FLEXIBILITY OPTIONS RELATED TO GROUND PROBLEMS

The flexibility of management in mining operations represents the ability to adapt to internal or external changes in operating conditions. These changes were described in Chapter 1. Ground-related problems are related to internal operational changes. Operational flexibility has been defined by Dunbar, et al (1998) as the ability within a mining system to modify operational parameters to sustain performance. The greater the flexibility in a mining system, the greater will be the risk reduction, the ability to maintain low operating costs, and the preservation of a particular cost structure. A project often permits management to choose among alternative courses of action. Each of these alternatives derives its value from its own particular cash flow series and from any possible future project opportunities associated with it (Samis and Poulin, 1998).
In a mining environment, operational flexibility is most constrained by geological complexity and excavation geometry, layout and access. These parameters are inter-linked to geomechanical mine design and mine planning (strategic or tactical) as was shown in Chapter 2. The uncertainty here is not attributed to the metal price, but, instead, to the geological uncertainty, which is reflected in the quality and cost of the produced ore, as well as the impact of potential problems that are associated with ore extraction and the maintenance of a certain production rate. Types of operational flexibility have been analysed by Trigeorgis (1998), Trigeorgis (1990), Copeland, et al (1990), and Dunbar, et al (1998).

Not all of these types can be associated with ground-related problems. Needs to introduce and measure operational flexibility with respect to ground-related problems can be related to the:

- ability to introduce an alternative plan (option to switch use);
- option to expand;
- option to maintain planned levels of production and costs.

Inflexibility can also arise if there is a lack of reliability in the performance of ground support systems in a mine system, lack of quality control in backfill placement or inadequate flow of material through orepass subsystems.

### 5.5.1 Ability to introduce alternative plans

This option, often described as the option to switch use, is a type of operational flexibility that is not related to the ability to introduce alternative plans because there is a need to increase mine production or the quality of the produced material. It is, rather, related to a need to maintain the prescheduled production levels in the particular mine when the
production cycle is disturbed by ground-related problems. Such problems are often unavoidable even if the best possible design is made up front.

Introduction of the “stand-by stope” concept in underground mines where ground-related problems are anticipated is an example of this type of flexibility. Although a particular stope was not scheduled to be an active producing stope at the given time, it has been developed to compensate for the risk of experiencing production delays in an active stope due to ground-related problems. The “stand-by stope” may not be used. However, in order for it to be used, it has to be developed and ready for production. The extra cost that is required to develop more than the exact number of stopes that are required for the pre-specified mine production. These may or may not be used, depending on the ground-related problems that will be encountered. The benefit is that mine production can be maintained at a certain level. This can be represented as a put option:

\[
\text{Option to switch use: } \max (0, I_c - A)
\]

where:

- \(I_c\): the potential cost savings;
- \(A\): the cost to introduce alternative plan.

In the generic example examined in section 5.3.1, the flexibility provided to the mine engineer through an extra stope for production drilling at any time will be evaluated. Mine management will exercise the option to introduce mining of the extra stope, if ground problems that can delay mine production appear in other stopes. Otherwise, the mine engineer will not exercise the option. The mining costs associated with developing such a stope during the first year are estimated to be \(A = \$5\) million. The impact on production loss,
however, that will occur in the particular mine due to production interruptions during that year are estimated to be between $3 and $15 million. Therefore, the savings that will occur as the “stand-by stope” plan is implemented will be: $I^+ = 15$ and $I^- = 3$. The value of the option to switch in this project now requires to be analyzed.

The minimum and maximum values of the investment opportunity will be:

\[
E^+ = V^+ + \max(0, I^+ - A) = 150 + \max(0, 15 - 5) = 150 + 10 = 160 \text{ (accept option)}
\]

\[
E^- = V^- + \max(0, I^- - A) = 90 + \max(0, 3 - 5) = 90 + 0 = 90 \text{ (do not accept option)}
\]

The total value of the investment opportunity with the “stand-by stope” option will then be:

\[
E_0 = \frac{pE^+ + (1-p)E^-}{1+r} - I_0 = \frac{0.25 \times 160 + 0.75 \times 90}{1 + 0.05} - 105 = \frac{40 + 67.5}{1.05} - 105 = -2.62
\]

The NPV for the project has improved, but is still negative. The value of the flexibility option however, to have the “back-pocket stope” available will be:

\[
[\text{Extra stope option}] = [\text{Expanded NPV}] - [\text{Static NPV}] = -$2.62 - (-$5) = $2.38
\]

Since this option has a positive value, it means that the option is desirable. Generally, if the potential cost savings are larger than the cost of introducing the alternative plan, then it will be worthwhile to build this type of flexibility into the particular mining system. In the “stand-by stope” example, the potential cost savings are related to the production loss for a certain time period, which is until the next-in-line stope starts producing ore. The cost to introduce
an alternative plan is the cost to have an extra stope developed and standing by in case a ground problem develops in one of the scheduled production stopes.

The ability to switch between different mining sequences is another form of flexibility. Mining with such flexibility is analogous to a flexible manufacturing system that can change its production mix over time (Triantis and Hodder, 1990). Other examples in mine planning, found in practice that are related to the need for options to switch use, can be: the introduction of additional passes between two levels where ground-related problems are anticipated to cause production delays; the maintenance of alternative accesses in a particular level or zone; the ability to re-route production; and the introduction of two backfill lines or types of backfill in a mine.

5.5.2 Option to expand

Once a project is initiated, then management may choose to retain flexibility by maintaining the option to expand production to other sectors that currently may be considered non-feasible or marginal. This type of flexibility is related to the ability to expand current or future production, with ground issues playing a dominant role in the possible expansion scheme. Increasing the recovery of an orebody by mining the pillar stopes near the end of a mine's life (when significant ground-related problems are often encountered), is a typical example of this type of flexibility. Another example is the placement of a shaft hoist with larger capacity than the one that is currently required, so that future production increases can be accommodated. Mines are frequently constrained by shaft capacity as a result of a minimized capital approach, as an outcome of the initial design.
One factor affecting options to expand, linked to ground-related problems, is the ultimate condition of remnant areas, pillars, and sill pillars, disregarding the eventual need to return to the same areas in the future to recover them. When some years later it is proven feasible to mine these areas because of new economic conditions, it is found that there are particular problems (causing higher than usual operating costs) that are associated with no placement of backfill in the adjacent mined panels, or inadequate sill mats that could cause dilution problems. Another opportunity to expand may be associated with maintaining access to mine openings for a longer time than was initially planned. This would require the placement of a different support system in the particular openings up-front.

The application of these types of options to the evaluation of mine planning alternatives with ground-related problems is generally limited. If such flexibility needs develop, these can be modelled like American call options on a future opportunity (Trigeorgis, 1998). In this way, the option with additional development leading to growth versus the standard one with no additional development are evaluated. Mine management will exercise its option to expand if ground or market/cost conditions turn favourably, but will otherwise let the option expire unexercised.

It is assumed that, in a particular year, mine management has the option to invest an additional amount $I'$ in addition to the originally proposed amount $I_0$. That would increase the reserves in a particular mine and increase the orebody extraction bringing a 20% additional value to the project. The total value of the project will then be $1.2V$. This can be represented as a call option as follows:
Option to expand: $E = \max (V, 1.2V - I') = V + \max (0, 0.2V - I')$

where $E$ is the investment opportunity value.

The generic example examined in section 5.3.1 with a flexibility to expand option becoming available a year after the initial investment will be considered. Based on this option, the mine engineer can modify the original design to place cemented backfill in the primary stopes and build reinforced sill mats in order to expand mining and increase the orebody extraction, at an additional cost $I'$ of $75$ million. The additional cost includes the cost for placing the fill and the sill mats and mining the pillar stopes. This will increase the value of the project, $V$, by 80%. The minimum and maximum investment opportunity values will then be:

- $E^+ = V^+ + \max (0, 0.8V^+ - I') = 150 + \max (0, 0.8 \times 150 - 75) = 150 + 45 = 195$ (expand)
- $E^- = V^- + \max (0, 0.8V^- - I') = 90 + \max (0, 0.8 \times 90 - 75) = 90 + 0 = 90$ (no expansion)

This means that only in the case where market conditions turn out favourably is it worthwhile to expand the project. In such a case, the total value of the investment opportunity (expanded NPV), $E_o$, that includes the option to expand, will be:

\[
E_o = \frac{pE^+ + (1-p)E^-}{1 + r} - I_0 = \frac{0.25 \times 195 + 0.75 \times 90}{1 + 0.05} - 105 = \frac{48.75 + 67.5}{1.05} - 105 = 5.71
\]

The value of the option to expand (or option premium worth paying for) will then be:

\[
\text{[Option to expand]} = \text{[Expanded NPV]} - \text{[Static NPV]} = 5.71 - (-5) = 6.71
\]
Since this option has a positive value, it means that the option to expand is desirable in the particular project. Although the original project per se has a negative (passive) NPV of $5 million, the investment proposal should not be rejected. The opportunity to expand the project within a year (expanded NPV) is actually worth a positive amount of $5.71 million or approximately 6% of the project’s gross value. This option can make it worthwhile to undertake a project that would otherwise be considered unprofitable (on the basic of static NPV).

This analysis can also be used to compare an option premium to the cost of the implementation processes, design, and facilities installation, that would provide the mine engineer with the option to expand operations.

5.5.3 Option to maintain a planned level of production and costs

In addition to safety considerations, geomechanical mine design and ground control have as their focus the minimization of disruptions to the mine production and the maintenance of the operating cost below a certain threshold. Once ground-related problems begin, this will lead to a loss of the production scheduled from certain stopes at a certain time, as well as an increase on the operating cost due to requirements to rehabilitate, reinforce, re-drill, re-excavate, or replace damaged mine openings. Ground-related problems can also create delays due to dilution or ore losses that can cause reduced production and lower orebody recovery.

When evaluating mine planning alternatives, the consideration of potential ground-related problems becomes paramount. The ability to maintain planned levels of production and costs
throughout the period for which planning is conducted is a function of the mine design parameters selected in the particular design. These include the mining method, stope geometry, drift layout, orepass system, backfill system and support/reinforcement applied in different mine sectors.

Minimizing the risk for ground-related problems is necessary in order to improve the overall production reliability, to preserve a particular cost structure and to sustain performance. Therefore, certain mine planning alternatives can be evaluated on the basis of the flexibility provided to the overall mine operation in maintaining a certain plan/schedule. This can be analysed using a real options approach. The option lies in the ability to continue production or to maintain a cost structure. This is a put option or a form of insurance policy. The option value lies in the loss avoided.

Assuming that the cash inflows of a mining project in a particular year are scheduled to be V, while the project associated costs are I. For example, ground-related problems at the stope access drifts are anticipated in a particular mine, when intersecting fractured dykes. It is estimated that, with the originally proposed support system, ground-related problems associated with these dykes will have an impact on the scheduled mine production and, therefore, reduce the cash inflows by an amount I_c. The production losses can be avoided, and the cash inflows maintained by installing an improved ground support system at an additional cost A. This will require the design in advance of specialized ground support as well as testing and training of personnel to install the new support system. This can be represented as a put option to maintain the cash inflows by paying the additional cost to install the improved support system and train the workforce:
Option to maintain production: \( E = \max (V - I_c - I, V - I - A) = V - I - \min (I_c, A) \)

where:

- \( V \): the project cash inflows (revenue);
- \( I \): the project associated costs;
- \( I_c \): the reduction in cash inflows;
- \( A \): the additional cost to place the improved support system;
- \( E \): the investment opportunity value.

An example in which the initial project outlay for capital expenditures in a mine are \( I_0 = $10 \) million is considered. At the end of the year, depending on the metal market, the cash inflows in a particular mine are estimated to be at least $50 million and no more than $80 million, while the operating costs will be \( I = $40 \) million. The “twin security” used in example 5.3.1 can be considered to estimate the cost of capital. Ground-related problems are anticipated to be encountered in this particular mine and reduce the cash inflows by 10%. If a new support system is introduced in stope access drifts that are intersected by dykes, at an extra cost of \( A = $6 \) million, this can minimize ground problem-related delays, and, as a result, maintain the scheduled cash inflows. Is it worthwhile to introduce the new support system in the mine in the future?

The net present value of the proposed project (passive NPV) will be:

\[
NPV = \frac{p(0.9 V^+ - I) + (1 - p)(0.9 V^- - I)}{1 + r} - I_0 =
\]

\[
= \frac{0.25 \times (0.9 \times 80 - 40) + 0.75 \times (0.9 \times 50 - 40)}{1 + 0.05} - 10 = \frac{0.25 \times 32 + 0.75 \times 5}{1.05} - 10 = \frac{8 + 3.75}{1.05} - 10 = 1.19
\]
The cash inflow loss due to ground-related problems will be $I_c = 0.1 V$. The minimum and maximum values of the investment opportunity will be:

- $E^+ = V^+ - I^+ \min(0.1V^+, A) = 80 - 40 - \min(8, 6) = 40 - 6 = 34$ (accept option)
- $E^- = V^- - I^- \min(0.1V^-, A) = 50 - 40 - \min(5, 6) = 10 - 5 = 5$ (do not accept option)

This means that only when the market conditions are favourable is it worthwhile to introduce the new support system. In such a case, the total value of the investment opportunity (expanded NPV), $E_o$, for the losses avoided with the “new support system option” will be:

$$E_o = \frac{pE^+ + (1-p)E^-}{1 + r} - I_o = \frac{0.25 \times 34 + 0.75 \times 5}{1 + 0.05} - 10 = \frac{8.5 + 3.75}{1.05} - 10 = 1.66$$

The value of the option will then be:

$$[\text{Option value}] = [\text{Expanded NPV}] - [\text{Static NPV}] = 1.66 - 1.19 = 0.47$$

This means that it is worthwhile to spend up to $470,000 to redesign, test and prepare the workforce, in order to have the flexibility to introduce the new ground support system in the mine. This analysis considers cash flows for a single operating year, something that is not representative of a typical mine. The intention of this example is only to demonstrate the methodology for calculating the value of options for the particular type of flexibility. Depending on the market price, the management team may decide to install a different support system at different years in stope access drifts.
It should be noted that the option to switch use, a put option examined earlier, can also be evaluated in a similar way as the option to maintain production and costs, shown above. Options to introduce alternative plans or undertake actions that could maintain the reliability/performance of a mining operation could be treated similarly.

A different example will be examined now, where the expected cash inflows at the end of the year are expected to be $V$, while the total operating cost is $I$. Depending on the ground conditions that will be encountered, ground-related problems could change the cash inflows from $F^+$ to $F^-$ and the operating cost from $O^+$ to $O^-$. At an extra cost, $A$, the management team can introduce ground control measures that could minimize ground-related problems and maintain the same production and cost structure in the particular mine. This can be represented as a put option to maintain the particular cash inflows (production level) and cost structure by implementing the additional ground control measures at a cost $A$.

Option to maintain cost structure: 
$$E = \max (V - I - O - F, V - I - A) = V - I - \min (O + F, A)$$

where:

$V$: project cash inflows;

$I$: project associated costs;

$O$: reduction in cash inflows;

$F$: increase in operating cost;

$A$: additional cost to place the improved support system;

$E$: investment opportunity value.
In this example, it is assumed that $V = $60 million, $I = $40 million, $I_o = $5 million and $A = $10 million. The reduction in cash inflows, due to ground-related problems, is 8-18% and the increase in operating cost 5-15%.

The risk characteristics here are not related to the metal market, but rather to the inherent project risks. It is assumed that the following information is known from cost analysis: the project net cash flows (i.e., expected cash inflows minus operating costs) are expected to increase by a factor of 1.5 or decrease by a factor of 0.9. The risk-free interest rate is assumed at 5%. Therefore, the risk-neutral probability for inherent project risks (independent of the metal market trends) can then be calculated as follows:

$$p = \frac{1 + r - d}{u - d} = \frac{1 + 0.05 - 0.9}{1.5 - 0.9} = 0.25$$

The static NPV of the particular project will then be:

$$\text{NPV} = \frac{p (V - I - 0.08V - 0.05I) + (1-p)(V - I - 0.18V - 0.15I)}{1 + r} - I_o =$$

$$= 0.25 \times (20 - 0.08 \times 60 - 0.05 \times 40) + 0.75 \times (20 - 0.18 \times 60 - 0.15 \times 40) - 5 =$$

$$= \frac{0.25 \times 13.2 + 0.75 \times 3.2}{1.05} - 5 = \frac{3.3 + 2.4}{1.05} - 5 = 0.43$$

The minimum and maximum values of the investment opportunity will be:

$$E^+ = V - I - \min(O^+ + F^+, A) = 20 - \min(0.08V + 0.05I, 10) = 20 - \min(6.8, 10) = 20 - 6.8 = 13.2$$

$$E^- = V - I - \min(O^+ + F^-, A) = 20 - \min(0.18V + 0.15I, 10) = 20 - \min(16.8, 10) = 20 - 10 = 10$$
This means that only when acute ground conditions (e.g., heavily fractured rock mass with water inflow) are anticipated is it worthwhile to introduce the new support system. In such a case, the total value of the investment opportunity (expanded NPV), $E_o$, for the losses avoided with the "new support system option" will be:

$$E_o = \frac{pE^+ + (1-p)E^-}{1 + r} - I_o = \frac{0.25 \times 13.2 + 0.75 \times 10}{1 + 0.05} - 5 = \frac{3.3 + 7.5}{1.05} - 5 = 5.28$$

The value of the option will then be:

$[\text{Option value}] = [\text{Expanded NPV}] - [\text{Static NPV}] = 5.28 - 0.43 = 4.85$

Since the option has a positive value, this means that the particular option is desirable. The option to maintain the scheduled production and cost structure has significantly improved the value of the mining project.

5.6 INTEGRATION OF INTERNAL PROJECT RISK WITH REAL OPTIONS

Internal project risk is often the only concern of a mine engineer, while external project risk factors are examined by a separate team at a corporate level. The mine engineer traditionally evaluates the flexibility that is needed within a mine plan, assuming a constant metal price. Production and operating cost optimization are the responsibilities of long term planning. The examples presented here introduce the tactical means to evaluate operating flexibility.
5.6.1 Example with cash flow fluctuation

For a fixed metal price, the cash flows that will be determined for a particular mining project will be subject to internal project risk. The initial cash outlay at time zero to acquire the particular mine is $140 million and the risk-free discount rate is estimated to be $r = 5\%$. It is assumed that risk analysis has indicated annual cash flows of $20$ million over a ten-year period (end of mine life), with an equal probability that they will increase by a factor of 1.1 or decrease by a factor of 0.8. It is assumed that the cash flow of a particular year will be dependent on the original estimate of the cash flow, as well as on the fluctuation of the cash flows in the previous year. It is also assumed that annual cash flows occur at the end of a particular year. The resultant lattice (Luenberger, 1998) for the cash flows is shown in Table 5.1:

<table>
<thead>
<tr>
<th></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>$20$</td>
<td>$22$</td>
<td>24.2</td>
<td>26.62</td>
<td>29.282</td>
<td>32.21</td>
<td>35.431</td>
<td>38.974</td>
<td>42.872</td>
<td>47.159</td>
<td>51.875</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>17.6</td>
<td>19.36</td>
<td>21.296</td>
<td>23.426</td>
<td>25.768</td>
<td>28.345</td>
<td>31.179</td>
<td>34.297</td>
<td>37.727</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.8</td>
<td>14.08</td>
<td>15.488</td>
<td>17.037</td>
<td>18.74</td>
<td>20.615</td>
<td>22.676</td>
<td>24.944</td>
<td>27.438</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.243</td>
<td>5.767</td>
<td>6.344</td>
<td>6.978</td>
<td>7.676</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cash flow (million of dollars)</td>
<td>4.194</td>
<td>4.614</td>
<td>5.075</td>
<td>5.583</td>
<td>3.355</td>
<td>3.691</td>
<td>4.060</td>
<td>2.684</td>
<td>2.953</td>
<td>2.147</td>
<td></td>
</tr>
</tbody>
</table>

The calculation of the NPV as shown in the generic example for synthetic options, will be conducted. In this case the value of a year node is added to the gross project value determined by the equation:

$$
\nu = \frac{pV^+ + (1-p)V^-}{1+r}
$$

where, $p$ is the risk-neutral probability. For this example, the risk-neutral probability will be:
\[ p = \frac{1+r-d}{u-d} = \frac{1+0.05-0.8}{1.1-0.8} = 0.833 \Rightarrow 1 - p = 0.167 \]

At the end of year 10, the remaining expected project values will be zero. Expected values for year 9 will be: \( \frac{51.875}{1.05} = 49.405 \). For the previous year, the remaining expected value of the project will be the sum of the next year’s cash flows, discounted one year back, plus the risk-neutral expected value of the project in the next period, also discounted back one period.

For example, the top value at year 8 can be calculated as follows:

\[ \frac{47.159}{1.05} + \left( 0.833 \times 49.405 + 0.167 \times 35.931 \right) / (1+0.05) = 89.827 \]

The binomial lattice values can then be calculated, using the risk-neutral probability \( p \), as shown in Table 5.2.

<table>
<thead>
<tr>
<th></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>209.52</td>
<td>207.43</td>
<td>202.82</td>
<td>195.21</td>
<td>184.06</td>
<td>168.72</td>
<td>148.47</td>
<td>122.49</td>
<td>89.827</td>
<td>49.405</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>150.86</td>
<td>147.5</td>
<td>141.97</td>
<td>133.86</td>
<td>122.71</td>
<td>107.98</td>
<td>89.084</td>
<td>65.328</td>
<td>35.931</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>107.28</td>
<td>103.25</td>
<td>97.353</td>
<td>89.24</td>
<td>78.532</td>
<td>64.789</td>
<td>47.512</td>
<td>26.131</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>75.093</td>
<td>70.802</td>
<td>64.902</td>
<td>57.114</td>
<td>47.119</td>
<td>34.554</td>
<td>19.005</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>-140</td>
<td>51.493</td>
<td>47.202</td>
<td>41.537</td>
<td>34.268</td>
<td>25.13</td>
<td>13.822</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>NPV</td>
<td>34.328</td>
<td>30.209</td>
<td>24.922</td>
<td>18.276</td>
<td>10.052</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>69.524</td>
<td>21.970</td>
<td>18.125</td>
<td>13.292</td>
<td>7.311</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>13.182</td>
<td>9.667</td>
<td>5.317</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>8</td>
<td></td>
<td>7.030</td>
<td>3.867</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>
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<tr>
<td>9</td>
<td></td>
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<td></td>
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<td></td>
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<td></td>
<td></td>
<td>2.812</td>
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<td>10</td>
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<td>0</td>
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</tbody>
</table>

| Net present value (millions) - Passive NPV | 2.812 | 0    | 0    |

It can be seen that, without any flexibility, the passive net present value is calculated to be

\[ NPV = V - I_0 = 209.5 - 140 = $69.5 \text{ million} \]
The alternative for the mine engineer to improve the orepass system of the mine at any time by an additional lined orepass at a cost of $5 million to the initial capital investment will be examined now. This gives an equivalent initial investment of $145 million. The risk factors for the cash flows are assumed to remain the same. The benefit will be an improvement in the anticipated cash flows by 4% (instead of $20 million they are now estimated to be $20.8 million). The binomial lattice for the net present value can then be recalculated as shown in Table 5.3.

### Table 5.3: Calculation of NPV for the case of additional capital investment on orepasses

<table>
<thead>
<tr>
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<th>8</th>
<th>9</th>
<th>10</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>217.9</td>
<td>215.73</td>
<td>210.93</td>
<td>203.02</td>
<td>191.42</td>
<td>175.47</td>
<td>154.41</td>
<td>127.39</td>
<td>93.42</td>
<td>51.381</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>156.89</td>
<td>153.4</td>
<td>147.65</td>
<td>139.21</td>
<td>127.61</td>
<td>112.3</td>
<td>92.648</td>
<td>67.942</td>
<td>37.368</td>
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<td></td>
</tr>
<tr>
<td>2</td>
<td>111.57</td>
<td>107.38</td>
<td>101.25</td>
<td>92.81</td>
<td>81.673</td>
<td>67.38</td>
<td>49.412</td>
<td>27.177</td>
<td>0</td>
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</tr>
<tr>
<td>3</td>
<td>78.097</td>
<td>73.634</td>
<td>67.498</td>
<td>59.398</td>
<td>49.004</td>
<td>35.936</td>
<td>19.765</td>
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<tr>
<td>4</td>
<td>-145</td>
<td>53.552</td>
<td>49.09</td>
<td>43.199</td>
<td>35.639</td>
<td>26.135</td>
<td>14.374</td>
<td>0</td>
<td></td>
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</tr>
<tr>
<td>5</td>
<td>NPV =</td>
<td>35.702</td>
<td>31.417</td>
<td>25.919</td>
<td>19.007</td>
<td>10.454</td>
<td>0</td>
<td></td>
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<tr>
<td>6</td>
<td>72.905</td>
<td>22.849</td>
<td>18.85</td>
<td>13.824</td>
<td>7.603</td>
<td>0</td>
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<tr>
<td>7</td>
<td>13.709</td>
<td>10.054</td>
<td>5.529</td>
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<td>8</td>
<td>7.312</td>
<td>4.021</td>
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<tr>
<td>9</td>
<td>2.925</td>
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<tr>
<td>10</td>
<td>0</td>
<td>0</td>
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</table>

It can be seen that the additional orepass system improves the NPV of the project by 72.905 - 69.524 = $3.381 million. Therefore, based on this analysis, the modification is beneficial to the project and should be implemented.

The examples considered until now were focused on explaining the analysis that can be carried out using binomial lattices. Luenberger (1998) and Dunbar, et al (1998) analysed the option to cancel production using similar examples. This option is not considered directly relevant to ground-related problems, so it is not examined here. The next example is truly in the spirit of real options as applicable to ground-related problems.
5.6.2 Example of real options with ground-related problems

Suppose that ground-related problems are expected to have a significant impact on annual cash flows. There is the possibility to invest an additional $3 million capital up front, providing the option to improve annual cash flows that are below $20 million by 50%, to a maximum of $20 million, at an additional annual cost of $0.5 million for extra development, support, rehabilitation and improved stope sequencing. It can be examined if this is a worthwhile option. By paying the initial additional capital cost (for design, training and equipment), the mine engineer has the option, but not the obligation, to introduce the modified design when the cash flows fall due to ground-related problems. The mine engineer does not exercise the option unless the cash flows are under $20 million and only if the modified design introduces an improved cash flow. This is equivalent to a conditional American put option. The initial additional capital cost is the "insurance premium" that is paid to acquire the particular option.

The cash flow lattice, shown in Table 5.1, will be reconstructed by including the conditional statement:

\[
\text{IF}\{(\text{cash flow}<20, \text{then MIN}\{\text{MAX}\{\text{cash flow}, 1.5 \times \text{cash flow} -0.5\}, 20\}, \text{ELSE cash flow}\}\}
\]

The initial capital cost will now be: $140 + $3 = $143 million. The binomial lattice for the new cash flows is shown in Table 5.4.
Table 5.4: New cash flows with the placement of a real option

<table>
<thead>
<tr>
<th></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>$20</td>
<td>22</td>
<td>24.2</td>
<td>26.62</td>
<td>29.282</td>
<td>32.21</td>
<td>35.431</td>
<td>38.974</td>
<td>42.872</td>
<td>47.159</td>
<td>51.875</td>
<td></td>
</tr>
<tr>
<td>18.7</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>5.791</td>
<td>6.421</td>
<td>7.113</td>
<td>7.874</td>
<td>4.533</td>
<td>5.036</td>
<td>5.590</td>
<td>3.527</td>
<td>3.929</td>
<td>2.721</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The new cash flows are now shown in bold. The NPV can now be calculated, based on these new cash flows. The risk-free interest rate and the risk neutral probabilities are the same as before. The binomial lattice for the NPV is shown in Table 5.5:

Table 5.5: Calculation of expanded NPV with real option

<table>
<thead>
<tr>
<th></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>211.98</td>
<td>208.59</td>
<td>203.32</td>
<td>195.4</td>
<td>184.11</td>
<td>168.73</td>
<td>148.47</td>
<td>122.49</td>
<td>89.827</td>
<td>49.405</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>160.52</td>
<td>152.34</td>
<td>144.19</td>
<td>134.79</td>
<td>122.99</td>
<td>108.05</td>
<td>89.085</td>
<td>65.328</td>
<td>35.931</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>129.58</td>
<td>118.76</td>
<td>106.7</td>
<td>93.638</td>
<td>79.999</td>
<td>65.212</td>
<td>47.518</td>
<td>26.131</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>102.58</td>
<td>94.71</td>
<td>84.000</td>
<td>69.922</td>
<td>54.246</td>
<td>37.188</td>
<td>19.048</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-143</td>
<td>74.32</td>
<td>68.158</td>
<td>59.929</td>
<td>49.28</td>
<td>35.806</td>
<td>19.048</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NPV =</td>
<td>49.328</td>
<td>43.54</td>
<td>36.022</td>
<td>26.485</td>
<td>14.602</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>68.983</td>
<td>31.182</td>
<td>25.826</td>
<td>19.008</td>
<td>10.490</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18.412</td>
<td>13.571</td>
<td>7.499</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.616</td>
<td>5.324</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Net present value (millions) - Expanded NPV with real option 3.742 0

It can be seen that the resultant NPV of $68.983 is lower than that calculated earlier ($69.524) without the particular option in Table 5.2. Therefore, under these conditions, the option is not desirable.
Suppose now that deterioration of ground conditions in the mine is anticipated. As a result, the cash flows decrease from a factor of 0.8 to a factor of 0.7. When the cash flows are calculated, the following binomial lattice for the remaining project values are found, as shown in Table 5.6.

Table 5.6: Calculation of expanded NPV with real option and a down factor of 0.7 instead of 0.8.

<table>
<thead>
<tr>
<th></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></td>
<td>213.66</td>
<td>209.91</td>
<td>204.16</td>
<td>195.87</td>
<td>184.37</td>
<td>168.83</td>
<td>148.5</td>
<td>122.49</td>
<td>89.827</td>
<td>49.405</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>149.33</td>
<td>140.54</td>
<td>130.88</td>
<td>120.52</td>
<td>109.19</td>
<td>95.243</td>
<td>78.134</td>
<td>57.162</td>
<td>31.439</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>110.57</td>
<td>104.41</td>
<td>95.731</td>
<td>84.08</td>
<td>70.093</td>
<td>54.685</td>
<td>37.937</td>
<td>20.007</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>72.567</td>
<td>68.61</td>
<td>63.054</td>
<td>55.62</td>
<td>45.987</td>
<td>33.793</td>
<td>18.621</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-143</td>
<td>42.738</td>
<td>39.338</td>
<td>34.75</td>
<td>28.770</td>
<td>21.166</td>
<td>11.677</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NPV =</td>
<td>24.246</td>
<td>21.469</td>
<td>17.813</td>
<td>13.132</td>
<td>7.2575</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>70.657</td>
<td>13.017</td>
<td>10.840</td>
<td>8.018</td>
<td>4.445</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.404</td>
<td>4.765</td>
<td>2.656</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>down factor = 0.7 instead of 0.8</td>
<td>2.700</td>
<td>1.517</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net present value (millions) - Expanded NPV with real option</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.846</td>
</tr>
</tbody>
</table>

It can be seen that now the resulting NPV is larger than the passive one. It is interesting to point out that the passive NPV does not need to be recalculated with the different down factor, since it results in the same final value of NPV. The value of the real option to control low cash flows will then be:

\[
\text{[Option to control cash flows]} = \text{[Expanded NPV]} - \text{[Passive NPV]} = \\
= 70.657-69.524 = \$1.133 \text{ million}
\]

Therefore, if ground conditions are expected to deteriorate, the modified design is beneficial to the project, since it improves its NPV. Increased deterioration of ground conditions will further improve the value of the real option and the project’s NPV.

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In the real option examined above, it is assumed that the internal project risk is the same throughout the mine's life. In addition, cash flows of $20 million, over a ten-year period, that are dependent on the previous year's cash flow, are assumed. It is often the case that the internal project risk increases as the mine matures, while the annual cash flows can also vary from year to year. However, the analysis that was introduced in this example could apply through simulation to the case of more complex cash flow distribution and risk.

5.6.3 Example with cost fluctuation

The former example considers that the ground-related problem costs are fixed for the evaluation of flexibility. Consider now the case where the potential for ground-related problems has been evaluated and the cost impact that these would have on the mine were determined based on the reliability-cost analysis introduced in Chapter 3. The cost impact is described as minimum, average or maximum. Each year, there is a 50% probability that the cost impact will remain on the same level, while another 50% probability that it will drop to the lower level (i.e., from minimum to average etc). For the calculation of the final cost value, it is assumed that there is an 80% probability for the cost to be the one corresponding to average conditions, while there is a 10% probability for minimum or maximum cost impact conditions. The internal project risk tree with respect to ground-related problems for a three-year period is shown in Figure 5.3.

The anticipated minimum, average and maximum cost impact values for ground-related problems at the end of each year are shown in Table 5.7.
The present value of the total cost impact estimate, discounted back to time zero, can then be estimated, based on the risk tree determine earlier. The risk-free discount rate is assumed to be 5%. It is estimated (Table 5.8) that the present value of future cost impact due to ground-related problems is $2.28 million. This value can be compared against potential measures that could be taken to reduce the cost impact due to ground-related problems or can be deducted from the NPV of the project, as in conventional DCF analysis. In this analysis, the method to determine the present value of the cost impact of ground-related problems was presented.

Table 5.8: Present value of total cost impact

<table>
<thead>
<tr>
<th>Year</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.28</td>
<td>$2.39</td>
<td>$1.55</td>
<td>$0.70</td>
</tr>
<tr>
<td>$3.31</td>
<td>$2.43</td>
<td>$1.50</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.7: Cost impact for ground-related problems

<table>
<thead>
<tr>
<th>Year</th>
<th>Min</th>
<th>Average</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year 1</td>
<td>$0.30</td>
<td>$0.50</td>
<td>$1.00</td>
</tr>
<tr>
<td>Year 2</td>
<td>$0.40</td>
<td>$0.50</td>
<td>$1.00</td>
</tr>
<tr>
<td>Year 3</td>
<td>$0.50</td>
<td>$0.70</td>
<td>$1.50</td>
</tr>
</tbody>
</table>

The value of the total cost impact estimate, discounted back to time zero, can then be estimated, based on the risk tree determined earlier. The risk-free discount rate is assumed to be 5%. It is estimated (Table 5.8) that the present value of future cost impact due to ground-related problems is $2.28 million. This value can be compared against potential measures that could be taken to reduce the cost impact due to ground-related problems or can be deducted from the NPV of the project, as in conventional DCF analysis. In this analysis, the method to determine the present value of the cost impact of ground-related problems was presented.
The cost impact values are discounted for ground problem risk and then also discounted at the risk-free discount rate.

Although the above analysis is adequate to provide one single value of cost impact of ground-related problems, it cannot be used to conduct a real options evaluation, in conjunction with fluctuating cash flows.

Consider now that the cash flows at the end of the year in the same mine can be described through a binomial lattice based on the upward and downward multiplicative factors, \( u = 1.1 \) and \( d = 0.8 \). The risk-neutral rate can then be determined as follows:

\[
p = \frac{1 + r - d}{u - d} = \frac{1 + 0.05 - 0.8}{1.1 - 0.8} = 0.833 \Rightarrow 1 - p = 0.167
\]

The cash flow lattice is shown in Table 5.9.

<table>
<thead>
<tr>
<th>Year</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5</td>
<td>$5.50</td>
<td>$6.05</td>
<td>$6.66</td>
</tr>
<tr>
<td>$4.00</td>
<td>$4.40</td>
<td>$4.84</td>
<td></td>
</tr>
<tr>
<td>$3.20</td>
<td>$3.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cash flows in million of $</td>
<td>$2.56</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Before real options are introduced in the analysis, the project’s present value will be examined, in a way that encompasses the ground-related problems by including the ground-problems related risk in the calculation of the annual cash flows. The methodology presented by Luenberger (1998) in an oil well example with private risk will be followed. The calculations of the overall project risk will be combined with the ground-problems cost
impact risk. At the final year there are 12 possible states, corresponding to four cash flow values and the three cost impact values due to ground-related problems. These are considered as being laid out in a 4 by 3 array. At the previous period there are the same three cost impact values for ground-related problems and three cash flow values, forming a 3 by 3 array. This pattern progresses backward to time zero. All arrays are shown in Table 5.10.

The values at the end of year 3 have been determined by straight subtraction of the ground problem cost impact values from the cash flows. The rest of the values contain the difference between cash flow and ground problem cost impact values plus the next year’s cash flows, discounted back one year both for ground problem risk and the risk-free discount rate. For example, the top right-hand corner value in the array at Year 2 is:

\[
[\text{Remaining project value}] = (6.05 - 0.4) + \frac{1}{1.05} \times (0.833 \times 0.5 \times 6.16 + 0.833 \times 0.5 \times 5.96 + 0.167 \times 0.5 \times 4.34 + 0.167 \times 0.5 \times 4.14) = 11.13
\]

At the end of the calculation at time 0, the three values corresponding to minimum, average and maximum ground problem impact costs are found. Using the weighting factors for each

---

**Table 5.10: Arrays for calculation of passive NPV**

<table>
<thead>
<tr>
<th>Prob.</th>
<th>Time 0</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Gr. Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPV=</td>
<td>0.1</td>
<td>13.146</td>
<td>10.5</td>
<td>5.428</td>
<td>11.13</td>
</tr>
<tr>
<td>$12.32</td>
<td>0.8</td>
<td>12.282</td>
<td>14.11</td>
<td>4.852</td>
<td>10.56</td>
</tr>
<tr>
<td>0.1</td>
<td>11.844</td>
<td>13.19</td>
<td>3.971</td>
<td>6.371</td>
<td>9.675</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Calculation of</th>
<th>Min</th>
<th>Aver.</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPV</td>
<td>0.3</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>NPV</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>NPV</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
of them, the NPV of the project, with ground-related problems, is determined to be $12.32 million.

In this calculation, an approach that can be followed to calculate NPV by taking into account the internal risk associated with the project and risk associated with ground-related problems is introduced. However, the real options concept has not yet been examined.

In the particular mine, the operating team considers that the bulk of the ground problems are related to falls of ground in the hangingwall of some stopes that cause dilution. The alternative that is currently under evaluation is to lease a cablebolting machine at a cost of $0.5 million per year (a three-year lease), that will enable the cablebolting of the stope hangingwall, if unfavourable ground conditions are observed. The mine engineer has the flexibility to place cablebolts only in the case that this is justified by unfavourable ground conditions at a cost of $0.3 million per year. This will minimize stope dilution problems due to hangingwall ground fall, reducing the overall cost of ground-related problems in the mine by half. This means that the mine engineer will install cablebolts in the hangingwall only if the savings are greater than the cost. This is an American put option, described as follows:

\[ \text{[Option to control dilution]} : E = \text{MAX} \{ (\text{cash flow} - \text{ground cost}), (\text{cash flow} - \text{ground cost}/2 - \text{cablebolting cost}) \} = \text{cash flow} - \text{MIN} \{\text{ground cost, ground/cost}/2 - 0.3\} \]

The option will be exercised only if \(\text{ground cost}/2 > 0.3\). Is this a worthwhile option? The previous flowchart will be used to evaluate this option. The annual cash flows will now be $0.5 million less every year due to the lease cost of the cablebolting machine. The condition of the real option described above is incorporated in the spreadsheet shown in Table 5.11.
Table 5.11: Arrays for calculation of expanded NPV

<table>
<thead>
<tr>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prob.</td>
<td>Time 0</td>
<td>3.5</td>
</tr>
<tr>
<td>NPV=</td>
<td>0.1</td>
<td>12.63</td>
</tr>
<tr>
<td>$12.84</td>
<td>0.8</td>
<td>12.829</td>
</tr>
<tr>
<td>0.1</td>
<td>13.116</td>
<td>10.02</td>
</tr>
</tbody>
</table>

Gr. Risk

<table>
<thead>
<tr>
<th>Min</th>
<th>Aver.</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.56</td>
<td>2.52</td>
<td>3.84</td>
</tr>
<tr>
<td>2.01</td>
<td>2.97</td>
<td>4.29</td>
</tr>
<tr>
<td>1.61</td>
<td>2.57</td>
<td>3.89</td>
</tr>
</tbody>
</table>

NPV= $12.84 - 12.32 = $ 0.52 million.

Since this value is positive, it is worthwhile to proceed and introduce the flexibility to have the option to cablebolt the hangingwall available to the operating team.

In this example, the need for flexibility was related to the purchase of equipment. It can also be linked to a different mining layout in terms of access drifts, sequence, mining method or use of backfill. However, all these factors are examined independently of the fluctuations in metal markets, since the focus has been internal project risk and ground problem related risk.

5.7 MONTE CARLO SIMULATION ANALYSIS OF REAL OPTION AND OPERATING RISK

The introduction of uncertainty in a cash flow and the determination of the NPV of a project through Monte Carlo simulation were discussed in section 4.3.5. The application of analyses to simulate cash flows with operating risk for valuing real options through Monte Carlo simulation will be examined next. Here, the conditional statement for the valuation of the real
option is built within the cash flow calculation and the active NPV, which includes flexibility, is determined through Monte Carlo simulation. The principles of option valuation through Monte Carlo simulation are discussed by Boyle (1977), Hull (1997) and Winston, et al (1997).

5.7.1 Evaluation through simulation of a real option with operating risk

The operating risk associated with a mining project is handled herein as private (i.e., internal project) risk using Monte-Carlo simulation analysis, while the market uncertainty due to metal prices is not considered. The operating risk is included in the cash flow estimates, which are then discounted back to time zero using the risk-free rate. The following example examines the flexibility option to maintain or increase production in an underground mine.

Production of five million tonnes of ore is scheduled for the next five years in an underground gold mine. The maximum capacity of the hoisting system is one million tonnes per year. Production has been scheduled to be one million tonnes per year. However, production simulation indicated that, due to ground-related and equipment problems, there is some volatility associated with the production each year. The grade of the ore as well as operating costs have been determined. The impact of ground-related problems have been determined through the methodology shown in Chapter 3. The price of gold was set to be $300/oz ($9.6/gr) and the risk-free discount rate at 5%. The input parameters are indicated in Table 5.12. Monte Carlo simulation analysis was used to determine the annual cash flows and the NPV of the project. After discounting for time and subtracting the initial development cost, it was found that the (passive) NPV of this project was approximately $36.7 million.
Table 5.12 Input parameters and Monte Carlo simulation for the evaluation of a real option with operating risk

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production - mean tonnes</td>
<td>1,000,000</td>
<td>70,000</td>
</tr>
<tr>
<td>standard deviation (years 1-5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grade (oz/ton)</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>standard deviation (years 3-5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating cost ($)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>($/year)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-3</td>
<td>60,000,000</td>
<td>8,000,000</td>
</tr>
<tr>
<td>4-5</td>
<td>25,000,000</td>
<td></td>
</tr>
<tr>
<td>Price of gold ($/oz)</td>
<td>$300</td>
<td></td>
</tr>
<tr>
<td>Ground related problems ($/year)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-3</td>
<td>50,000</td>
<td>100,000</td>
</tr>
<tr>
<td>4-5</td>
<td>200,000</td>
<td>500,000</td>
</tr>
<tr>
<td>Risk-free rate</td>
<td>0.05</td>
<td></td>
</tr>
</tbody>
</table>

**SIMULATION (no production flexibility)**

<table>
<thead>
<tr>
<th>YEAR</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production (tonnes/yr)</td>
<td>882,343</td>
<td>1,000,000</td>
<td>1,000,000</td>
<td>1,000,000</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Grade (oz/year)</td>
<td>0.293664167</td>
<td>0.197363822</td>
<td>0.254902629</td>
<td>0.304860458</td>
<td>0.215206612</td>
</tr>
<tr>
<td>Oper. Cost ($/year)</td>
<td>$ 69,793,673</td>
<td>$ 77,646,026</td>
<td>$ 54,144,324</td>
<td>$ 52,598,956</td>
<td>$ 57,105,658</td>
</tr>
<tr>
<td>Ground problem related cost ($/year)</td>
<td>$ 129,220</td>
<td>$ 103,006</td>
<td>$ 186,472</td>
<td>$ 264,509</td>
<td>$ 135,532</td>
</tr>
<tr>
<td>CASH FLOW</td>
<td>$ 7,996,645</td>
<td>$ 18,539,884</td>
<td>$ 22,139,992</td>
<td>$ 38,594,673</td>
<td>$ 7,320,647</td>
</tr>
</tbody>
</table>

**INITIAL INVESTMENT**: $30,000,000

**NPV** = $ 17,412,839

**NPV = 17,412,839**

**SIMULATION (with flexibility to add 100,000 tonne production for the next year)**

<table>
<thead>
<tr>
<th>YEAR</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production (tonnes/yr)</td>
<td>882,343</td>
<td>1,100,000</td>
<td>1,000,000</td>
<td>1,000,000</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Grade (oz/year)</td>
<td>$ 0.29</td>
<td>$ 0.20</td>
<td>$ 0.25</td>
<td>$ 0.30</td>
<td>$ 0.22</td>
</tr>
<tr>
<td>Oper. Cost ($/year)</td>
<td>$ 69,793,673</td>
<td>$ 77,646,026</td>
<td>$ 54,144,324</td>
<td>$ 52,598,956</td>
<td>$ 57,105,658</td>
</tr>
<tr>
<td>Ground problem related cost ($/year)</td>
<td>$ 129,220</td>
<td>$ 103,006</td>
<td>$ 186,472</td>
<td>$ 264,509</td>
<td>$ 135,532</td>
</tr>
<tr>
<td>CASH FLOW</td>
<td>$ 7,996,645</td>
<td>$ 12,618,970</td>
<td>$ 22,139,992</td>
<td>$ 38,594,673</td>
<td>$ 7,320,647</td>
</tr>
</tbody>
</table>

**INITIAL INVESTMENT**: $30,000,000

**NPV** = $ 22,783,284

**NPV = 22,783,284**

160
Assume that the mine engineer realizes inadequate utilization of the shaft capacity, resulting in a mine production shortfall at the end of the five years against the five million tonne target. The mine engineer considers the possibility of increasing the capacity of the hoist by 10% and altering the mine plan to include the option to produce up to 100,000 tonnes in addition to the annual production, if the production of the previous year is under 900,000 tonnes. The predetermined level of production at which the option will be exercised at the end of each year constitutes a multiple European put barrier option. The cost to the mining project to incorporate this option is $4 million (discounted at time 0). Is this option worthwhile?

The IF statement is incorporated in the production row of the project and the annual cash flows are recalculated. The calculated cash flows are displayed in Figure 5.4. The difference between the two annual cash flows indicates the option value. The new NPV is found to be approximately $41.7 million. The difference between this new NPV and the passive NPV is in excess of the $4 million that is the cost of the option. The net value of this option is $41.7 - $4 - $36.7 = $1 million. Therefore, the modification of the mine plan to increase the hoist capacity and give the option to produce 100,000 additional tonnes per year is desirable.

It should be pointed out that this analysis only considered the private (operating) risk of the project. The market risk has not been considered (i.e., the price of gold has been assumed constant). A sensitivity analysis of the value of the option for a range of gold prices is shown in Figure 5.5. It can be seen that the value of the option increases with the price of gold.
Figure 5.4: Distribution of annual cash flows

Figure 5.5: Sensitivity analysis of the option value with respect to the price of gold
5.7.2 Example with simulation of an option to expand

The example provide here is based on the methodology provided by Winston (1998), Winston and Albright (1997) and Hull (1997) to value the option to expand. The methodology is based on the lognormal model and is particularly useful to evaluate options once a cash-flow simulation has already determined the value of a project.

The revenue from a five-year mining project was determined using simulation. The expected value (risk adjusted) of the revenues was found to be $100 million and the volatility 20% (volatility is reflected in the measure of the standard deviation - for a methodology to calculate volatility, see Winston, 1998). The initial investment cost is $90 million. The mine engineer has built into the mine plan, (through appropriate design for sequence, backfill and ground support), the ability to extend the project’s life through mining of the remnant mine pillars by paying at the end of the five years an extra cost of $25 million. This will provide an additional cash flow that will improve the value of the project at the end of the five years by 20%. However, the mine engineer will exercise this option only if it will improve the value of the project. What is the value of the option to expand in this project?

Initially, the current value of the project is $100 - $90 = $10 million. To calculate the value of the option to expand, the risk neutral valuation process, described by Winston (1998), is followed. The random value of the project five years from now is generated using the lognormal model. If the option to expand is chosen, the cash flows in five years will be:

\[ 1.2 \times \text{(value in five years)} - 20 \]
If there is no expansion, the cash flows in five years will simply be equal to the value of the project. Therefore, the cash flows in five years will be given by the formula:

\[ = \text{MAX} \{ (1.2 \times \text{value in five years}) - \text{expansion cost} , \text{value in five years} \} \]

Then, the discounted value of the cash flows with the formula is computed:

\[ \text{EXP}(- \text{time} \times \text{risk-free rate}) \times \text{cash flow} - \text{investment cost} \]

The above process is illustrated in Table 5.13.

**Table 5.13: Calculation of the value of the option to expand**

<table>
<thead>
<tr>
<th>time = 5 years</th>
<th>MAX statement</th>
<th>risk-free rate, ( r )</th>
<th>Current value</th>
<th>Investment cost</th>
<th>Value with no option</th>
<th>Volatility (e.g. Normal (0, 1))</th>
<th>Value 5 years from now</th>
<th>Cash Flows in 5 Years</th>
<th>Discounted value of cash flows</th>
<th>Expansion cost, $</th>
<th>Expansion factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.07</td>
<td>100</td>
<td>90</td>
<td>10</td>
<td>0.2</td>
<td>0.463</td>
<td>157.94</td>
<td>164.53</td>
<td>25.94</td>
<td>163</td>
<td>25</td>
<td>0.2</td>
</tr>
</tbody>
</table>

| option to expand = NPV with flexib - passive NPV = \$2.8 |
| option to expand = 12.8 |

With expansion worth 12.8 million, so option is worth 12.8 - (10) = 2.8 million.

After running 5000 iterations, it is found that the option to expand is worth an average of $2.8 million. It is of interest to conduct a parametric simulation analysis with respect to the effect of volatility on the project revenues. Increase of volatility in this case does not alter average project value, as shown in Figure 5.6. However, it increases the upper and lower limits of the project value.
5.8 REVIEW

In this chapter, a number of approaches that allow the evaluation of flexibility in a mining system in terms of the potential impact of various ground-related problems were examined.

In Chapters 4 and 5 it has been demonstrated that ground-related problems can impact on more than one operating parameter. It is the opinion of the author that examining individual ground-related problems in isolation can lead to significantly underestimating the cumulative impact of these problems on a mining system. In many cases, the same ground-related problem can result in dilution, loss of ore reserve, production delays, and additional cost to repair the problem. These, as a result, can impact on the cash flows by reducing revenues, increasing costs, increasing project risk and prolonging the time that is required to mine an
orebody. Any type of flexibility in the mining system can be assessed by including the appropriate options factor within the calculation of operating parameters and costs.

As was discussed in section 4.2.3, evaluation of alternatives based on production simulation alone (i.e., that excludes economic analysis), may prove to be biased. However, in some cases, based on past experience, the order of magnitude of the potential impact of ground-related problems is known. Production simulation can then be used as the sole means to conduct decision making. Economic analysis, such as the DCF and options pricing, normally require as their input the results of a production simulation. Prior to carrying out flexibility assessment using real options, a model needs to be established that includes the key operating cost-revenue factors and the internal risk associated with a particular project.

Binomial lattices can be used in cases in which one risk factor is evaluated in the calculation of the total internal project risk. The binomial lattice approach will require structuring the project uncertainty in a lattice format. Although this may not be feasible in more complex cases, it certainly appeals in cases in which the volatility of cash flows is already available. The binomial lattice approach considers a uniform risk through time, with a limitation for more complex problems.

Monte Carlo simulation, in contrast, has the advantage of including all key internal project risks associated with revenue (independent of the price of metal), grade, operating costs and additional costs due to ground-related problems. The example shown in section 5.7.1 is representative of the examination of several sources of uncertainty in a project over time. The result of Monte Carlo simulation is the calculation of annual cash flows that include internal risk factors. The Monte Carlo simulation approach allows the inclusion of the conditional
statements exactly where there is impact due to ground-related problems. Risk can vary through time, and can be applied to several parameters that enter into the calculation of cash flows. This provides significant flexibility in setting up a problem that is not available elsewhere.

Whether binomial lattices or Monte Carlo simulation is used, it is critically important to recognize the form of flexibility under evaluation. The selection of the appropriate conditional statement (i.e., \textit{IF, MIN, MAX}) within the annual cash flows is critical in assessing a particular option. Since the option under evaluation can have an impact on several operating parameters, it is important that appropriate conditional statements are included within all factors that are related to the calculation of cash flows. In all cases, the value of flexibility (i.e., option value) is calculated by subtracting the passive NPV from the active one. In principal, if the resulting number is positive, then the flexibility is desirable.

Selecting the appropriate discount rate is important in any calculation of NPV. If market risk is not present, then the discount rate of cash flows that already contain in their calculation internal project risk should be discounted using the risk-free rate, as shown in section 5.7.1. The risk-free rate can be obtained from T-bills, bonds etc. When evaluating an operating option, it may not be required to include the market risk. Instead, it is recommended to conduct a sensitivity analysis in terms of the price of the metal to see if this can have an impact on the decision making process.
CHAPTER 6:
METHODOLOGY FOR FLEXIBLE MINING SYSTEMS

6.1 GENERAL ASPECTS

Following the introduction of analyses to engineer flexible mining systems confronted with ground-related problems in underground hard rock mines, a procedure that links the objectives of a flexibility analysis with the available approaches can now be explored. The proposed methodology will be based on knowledge that has been built in previous chapters. Its applicability will be explored through application to demonstrative examples that are based on real case studies from Ontario mines.

During the long-term mine planning and design stage, and as part of a feasibility study, the mine engineer conducts a careful evaluation of the available alternatives and optimizes and refines mine plans that were constructed at previous stages. The objective of this study is to introduce a methodology to evaluate the operating risk that is associated with ground-related problems and the need to introduce flexibility that includes:

- The classification of excavation components in a mining layout (e.g., drifts, stopes) in subsystems;
- The evaluation of the potential ground-related problems that can develop in these operating mining subsystems over their life cycle;
- The evaluation of the frequency and duration of subsystem production delays; and,
- The evaluation of the cost impact of ground-related problems in terms of delays, rework, dilution and loss of ore.
The frequency of ground-related problems in a particular subsystem may vary through time. In general, there are two distinct stages in a mining subsystem life cycle, the development stage and the operating stage. Depending on the characteristics of the particular subsystem, it may be sensible to adopt different performance parameters for each period.

In assessing the above parameters, the mine engineer will base any decisions on:

- Records of past performance of a particular mining subsystem or method in that mine;
- Historical corporate records of performance of subsystems under similar conditions;
- Historical records available in mining literature;
- Personal professional experience and expertise;
- Specialized geomechanical analyses that are carried out as part of a feasibility or a subsequent mine planning project; and,
- Benchmarking data from other mining operations.

A methodology was discussed in detail in Chapter 3 and is summarized in Figure 6.1. Once the mine engineer is able to quantify the potential impact of ground-related problems, this can be included in production simulation and in project valuation analysis. As was discussed in section 4.2, limited optimization and decision making can be performed based exclusively on production simulation during the mine planning process, particularly when only the order of magnitude of impact on production is needed to be known. However, it is the project valuation analysis that provides the opportunity to make the critical decisions in a mining project. The optimization of a mine plan consists of evaluation of alternatives, operating risk, and opportunities.
Figure 6.1: Methodology to incorporate internal project risk due to ground-related problems for project valuation and optimization
The optimization process can include reversing a previous decision that has a negative impact on a mine plan, refining the plan by modifying a particular design parameter, or adding components, where this is justified economically. Mine design parameters and their links to ground-related problems were analyzed in Chapter 2. In order to optimize a particular mine design parameter, once its impact on a mine production system is known, the mine engineer usually has to choose among the following processes:

- Minimize risk through planning to avoid causative situations; or,
- Build in flexibility; or,
- A combination of the above.

Where it is not feasible to minimize risk through a plan to avoid a potential ground-related problem, flexibility needs to be built into the overall mining system to reduce the operating risk. The ability to maintain the production level of a mine, or to avoid certain problems through up front design improvisations, can be considered as a flexibility option to maintain the prescheduled production schedule. The alternatives are evaluated by running project valuation and flexibility analyses once the appropriate changes have been introduced (Figure 6.1). The end product provides a key input for decision making by the mine planning and design team.

Decision making in mine planning and design is critical for the establishment of a profitable and safe mining operation over time. Decisions that are made at this stage will impact on the efficiency of the operation through time. Once a mine enters the operating stage, the ability to modify the production plan significantly decreases with time (i.e., flexibility diminishes with progression through the mine life cycle). The process of decision making in mine
planning and the link to operating risk assessment, as well as the need to introduce flexibility in the production system, are shown in Figure 6.2.

In order for risk assessment and flexibility analyses to become effective, they should be incorporated at the appropriate stages of a well-structured process. Prior to decision making, the mine engineer will need to identify:

- The decision criteria;
- The problems and the alternatives;
- The objectives of the design or schedule; and,
- The means to assess performance.

Once the operating risk has been assessed as part of the decision making process, the mine engineer will need to ensure that the selected alternatives meet corporate criteria prior to implementing the mine plan.

6.2 METHODOLOGY FOR INTERNAL RISK MODEL

The ground-related problems that place at risk the targeted performance of a mine production system need to be determined. A classification of the impact of this source of problems was introduced in Chapter 3. Once these have been identified, their frequency, repair time, and production impact have to be determined with utmost diligence. A procedure to assess these has been proposed in sections 3.3 and 3.4. The procedure can be adjusted to fit the needs of a particular mine planning exercise.
Figure 6.2: Decision-making process for mine planning and design for assessment of alternatives and risk
In addition to selecting the appropriate reliability and cost impact parameters for a particular subsystem, the mine engineer will need to foresee fluctuation of these parameters over time. The reliability model is time dependent, and gives the ability to include increase of risk (i.e., decrease in reliability) at different rates through time, based on the anticipated characteristics of a mine subsystem. Although the focus of this study has been the impact of ground-related problems, the proposed methodology can also be used for assessing the impact of operating problems in an internal risk model.

As pointed out by Pelley (1994) and Bawden (1993), unless the characteristics of the rock mass have been seriously misjudged, or the wrong mining method has been selected, the frequency of ground-related problems is relatively low during the first few years of a mine. On the basis of these findings, and the case studies presented in this thesis, the risk and the impact of ground-related problems in an underground mine can be described as shown in Figure 6.3.

![Ground-related problems: Risk & impact](image)

**Figure 6.3:** Typical risk/impact distribution, due to ground-related problems versus mine life
Initially, the lack of knowledge of the rock mass response to mining can result in a relatively high risk of not avoiding ground-related problems. Once knowledge has been gained and incorporated into future planning, refinement and adjustment of mine plans will result in a decrease of the risk and impact of ground-related problems in the production cycle. However, with the creation of remnant recovery situations in mines (e.g., sill pillars), the risk-impact will gradually increase near the end of a mine’s life.

The chances of avoiding ground-related problems in mines may be higher where the following apply:

- Experience has been gained about the rock mass performance by mining adjacent orebodies under the same geologic conditions;
- The operating team has extensive experience in planning and operating underground mines;
- There is contingency built into the plan to counterbalance uncertainties; and,
- There is a plan to minimize the creation of challenging mining conditions near the end of a mine’s life, such as posed by highly stressed sill pillars;
- Appropriate stoping methods with low operating risk have been predetermined as part of long-term planning to extract remnants with a high potential for ground-related problems.

The development and the production stages of the life cycle of a particular mining subsystem can also be related to the frequencies of different ground-related problems. As a result, when selecting the appropriate parameters for a subsystem, the time effects can be incorporated in three ways:
• The time-dependent reliability model with a combination of chance and wearing-out failure periods;
• The separation of development and production stages; and
• The introduction of different risk conditions through different stages during the extraction of the orebody (e.g., early in life cycle versus late in life cycle).

The selection of the most appropriate approach, or a combination of them, will be a function of the subsystem type, its anticipated performance, and the particular characteristics of the mining operation (e.g., depth, mining method, extraction rate, etc).

6.3 METHODOLOGY FOR FLEXIBILITY ASSESSMENT

During the optimization stage of mine planning, the mine engineer needs to evaluate design alternatives that will minimize the overall risk to the production system through time, minimize the potential production disruptions, and take advantage of opportunities that may develop. The analyses that can be used to assess flexibility in mines, in terms of the risk associated with ground-related problems, were discussed in Chapter 5. Operating flexibility with respect to ground-related problems can include:

• The ability to introduce in the future an optional change in a mine design parameter (alternative plan) that will provide to the operator the ability to counterbalance the impact of a ground-related problem on the mine production system.

• The ability to expand mine production if favourable ground conditions (i.e., better than anticipated) are found in a mine sector.
• The up front modification of a design parameter (e.g., sequence, stoping method, support system) to enable the operator to maintain the prescheduled production levels under low operating risk conditions.

These three types of operating flexibility have been discussed in detail in section 5.5, and mathematical formulations have been provided. The case has been made in Chapter 5 that, at present, Monte Carlo simulation provides the most adequate approach to determine the value of flexibility using real options. Decisions that will be made using the results of a flexibility analysis can be based on:

• Production, costs, or cash flows over time;
• NPV of a project;
• Cash flow distribution;
• Value of an option;
• Initial investment required;
• Comparison of cost and benefits to introduce flexibility alternatives.

The design or operating parameters that a mine engineer may consider modifying as a result of anticipated adverse ground-related conditions, can include:

• The spatial layout of a mine (e.g., number of accesses to an orebody or mining zone)
• The geometrical characteristics of components of mining subsystems (e.g., shape-size);
• The mining/stoping sequence or schedule;
• Routing and access (in terms of the ability to route a mining process along different paths in 3-D space);
• Capacity (e.g., throughput, hoisting, storage);
- Equipment characteristics (e.g., ability to drill various diameter holes, size of equipment);
- Mining and stoping method;
- Ground support-reinforcement;
- Resource availability to handle problems (personnel, equipment);
- Training available in the labour force (e.g., to use a different stoping method or support system, multiskilling);
- Design, planning and operating expertise.

For each of these design parameters, the mine engineer will have to evaluate the requirements and the benefits of introducing a particular type of flexibility by altering a mine design parameter. A checklist to examine operating flexibility needs for various design parameters is given in Figure 6.4. Here, the mine engineer can evaluate the alternatives that should be considered, and define the type of operating flexibility and evaluation analyses.

It should be noted that the last type of operating flexibility can include significant subcategories of design issues where the performance of the production system is directly linked to the risk of ground-related problems in a particular subsystem of a mine. The mine engineer may often choose to decrease operating risk to production delays, by installing a more reliable ground-support system or by drilling larger diameter holes to avoid potential hole squeezing problems in stope areas where high stress concentrations are anticipated. In the case that anticipated adverse ground conditions are verified, then the design modification can prove worthwhile. In the opposite case, the added flexibility would prove not to be required. The impact that lack of flexibility in a particular subsystem has on other ones by creating a "bottleneck" in a mine’s production system also needs to be considered. A
Figure 6.4: Checklist for operating flexibility needs with respect to ground-related problems for various parameters

relatively small operating problem in a mine subsystem often results in additional ones in other sectors of a mine, with significant implications for production and costs. This is often due to the interaction of a design parameter with other engineering aspects (e.g., drainage, ventilation).
6.4 OPTIMIZING PRODUCTION SYSTEMS WITH GROUND-RELATED PROBLEMS

The case studies presented in Chapter 2 indicated that selecting an appropriate extraction sequence in an underground mine could have several repercussions for the overall productivity of the operation. Optimum mining sequences from an operating point that ignore ground-related problems can result in a significant deviation from pre-set production targets. The mine engineer needs to evaluate the alternative sequences that are available, and choose the one that provides both efficiency and flexibility to the production system by taking into account the production constraints imposed by ground-related problems.

In an example presented here, two mining alternative sequences are considered during the planning of the mining extension of a nickel orebody: with pillars and pillarless, as shown in Figure 6.5. The example is based on the evaluation of alternative sequences in a sector of a nickel mine in the Sudbury basin. The input parameters are based on average values used for the valuation of similar mining projects (J.S. Redpath, 1986, Baiden, 1993) and on field-survey data collected at mines. A scheduled production for each of the two sequences indicates that the pillarless sequence has a slower start up than that with pillars, as shown in Table 6.1. During the first year, development work needs to take place in the area at a cost of $20 million. Based on past cost records, the mining and milling costs\(^1\) in the particular mine are $45 per tonne. A value of ore of $200 (2.6% Ni at 3.50 $/lb) is taken as constant throughout the mining of the orebody.

\(^1\) Mining and milling costs are part of the cash costs, which are part of the break-even costs in a mining project. Cash costs include production costs, marketing and refining charges and project administration expenses. Break-even costs are defined as consisting of cash costs plus royalties, production taxes (total cash costs) plus depreciation, depletion and amortization and reclamation costs (total production costs) and general and administration expenses, exploration expenses, and income and mining taxes.
Figure 6.5: Consideration of two mining sequences (longitudinal views)
Table 6.1: Production based on two alternative sequences

| Year | Pillarless sequence | | | Sequence with pillars | | |
|------|---------------------|------|------|-----------------------|------|
|      | Stopes mined | Tonnes |               | Stopes mined | Tonnes |
| 1    | -            | -      |               | -            | -      |
| 2    | 4            | 64,000 |               | 9            | 144,000 |
| 3    | 8            | 128,000|               | 10           | 160,000 |
| 4    | 10           | 160,000|               | 10           | 160,000 |
| 5    | 10           | 160,000|               | 10           | 160,000 |
| 6    | 10           | 160,000|               | 10           | 160,000 |
| 7    | 10           | 160,000|               | 10           | 160,000 |
| 8    | 7            | 112,000|               | -            | -      |
| 9    | -            | -      |               | -            | -      |
| TOTAL| 59           | 944,000|               | 59           | 944,000 |

Assuming a discount rate of 6%, and using a conventional discounted cash flow analysis, the net present value of the two alternative sequences is determined. It is found that the sequence with pillars indicated a higher NPV than the pillarless sequence. The cumulative cash flow throughout the mining period is also higher for the case of the sequence with pillars, as shown in Figure 6.6. The same cumulative cash flow is achieved by the sequence with pillars almost a year earlier, resulting in an improved NPV for the project. Based on the analysis conducted here, if any delays related to ground-related problems are not taken into account, the sequence with pillars is the preferable one, based on its higher NPV.

The mine planning team examines historical data on delays and production losses in mines under the same conditions and observes that the sequence with pillars is associated with more ground-related problems due to the need for rehabilitation, pillar stress conditions, hole squeezing and rework. These problems were concentrated in the stope areas of an actual mine sector in the same mine.
The planning team decides to quantify these problems in terms of impact on production and costs. It is determined that the impact of ground-related problems in this case is in terms of production loss/delays, additional costs, and prolongation of the mine's life.

The production delays were determined based on performance records of the pillarless sequence and that with pillars from similar layouts and rock mass characteristics. It has been assumed that the life span of the mine can be prolonged to complete the mining of ore reserves in the particular sector. The analysis is shown in Figure 6.7 and in Appendix I. Historical records indicated that a pillarless sequence in the particular environment was associated with a reduced frequency of ground-related problems, compared to the sequence with pillars. Costs associated with redrilling and rehabilitation were incorporated into the cash flow calculations. Using the approach introduced in Chapters 4 and 5, Monte Carlo simulation was employed to determine annual cash flows and NPV corresponding to the two alternative sequences, as shown in Figure 6.7. Cumulative cash flow values are compared in Figure 6.8.
Figure 6.7: Calculation of cash flows and NPV for two alternative sequences with ground-related problems.

Figure 6.8: Cumulative cash flows for the two alternative sequences with ground-related problems using Monte Carlo simulation.
It can be seen that, when ground-related problems are taken into account, the pillarless sequence results in significantly improved cash flows and NPV for the project. Although during the first three years the cash flows from the sequence with pillars are better than those provided by a pillarless sequence, over the mine cycle of Block 1, the pillarless sequence is found to be preferable, due to the reduced impact of anticipated ground-related problems.

In the analysis examined above, the value of ore was constant through the time period considered in this analysis. In order to examine the impact of the metal market on the decision to proceed with a certain sequence, however, a sensitivity analysis was conducted in terms of the value of ore. The results are shown in Figure 6.9. It can be seen that, for the range considered in this analysis, the decision to proceed with a pillarless sequence is not affected by the value of ore. It can also be seen that the difference in NPV between the two

![Figure 6.9: Sensitivity analysis of the difference in NPV (value of the pillarless sequence versus value of the sequence with pillars) with respect to the value of ore.](image-url)
sequences is highest when the value of ore is low. Similar results were obtained when a sensitivity analysis was conducted with respect to the discount rate.

Selecting and optimizing a production schedule in a mine should not exclude the potential impact of ground-related problems, as shown in the example presented here. Quantification and proper analysis of these problems should be required prior to conducting decision making in mine planning and design.

6.5 CORPORATE CONSTRAINTS THAT REQUIRE FLEXIBLE MINING SYSTEMS

In addition to cost minimization and maintenance of production levels, decision making in mine planning and design of underground hard rock mines is often constrained by benchmarks and requirements preset at a corporate level of a mineral resource company. Flexibility can become a means to accommodate such strategic constraints, while tactical constraints, such as operating costs and production levels, are also optimized. To demonstrate this concept, an analysis will be carried out, based on the example introduced in section 6.4.

Consider that, although the pillarless sequence was found as optimum from the project value point of view, there are corporate constraints which required the evaluation of the alternatives that will allow completion of mining of this sector over a seven year period. The pillarless sequence has a very attractive NPV, but it will require almost nine years for mining to be completed. The mine planning and design team has to reconsider its initial recommendation and explore other options. The sequence with pillars again becomes a “candidate”; however, the concern for this sequence is the high impact of ground-related problems on mine
production. The team considers the option of adding contingency into the mine plan in order to reduce the potential impact on production.

The option under consideration is one where extra crews will be maintained throughout mining of the zone to accommodate repairs and rehabilitation. In addition, supplementary equipment that can fast track the repair time for ground-related problems will be acquired, and the mine personnel will be trained in mucking and drilling remotely. This contingency plan will result in additional initial capital costs of $2 million dollars and additional annual operating costs of $300,000. If ground-related problems are encountered, then the rehabilitation will also have a cost in terms of material and consumables. This cost will only occur if rehabilitation work is required in a stope. This real option is a form of insurance that the operation will maintain the prescheduled production rates by managing risk due to ground-related problems and introducing contingency throughout mining this sector. As discussed in section 5.7.1, this is a form of multiple European put barrier option.

After the appropriate substitutions are made, and a conditional statement is built into the spreadsheet to accommodate the option under evaluation, cumulative cash flows and NPV are determined. The option with the “rehabilitation crews” is found to have an NPV of $86.7. The cumulative cash flows are shown in Figure 6.10.

The new option improved the NPV of the project mining the sequence with pillars by $86.7 - $79 = $7.7 million. Therefore, it is desirable from the economic point of view. The results of this analysis are dependent on the presumed frequency of ground-related problems, and the costs to accommodate the needs for rehabilitation and rework. Should the intensity of
Figure 6.10: Cumulative cash flows for the two alternative sequences with ground-related problems using Monte Carlo simulation.

these problems, or the cost to adopt measures to minimize their impact on production increase, then the analysis may result in a different conclusion. Safety considerations in adopting the sequence with pillars were addressed, and the solution for remote drilling and mucking was determined as adequate to minimize the exposure of mine personnel to potentially unsafe conditions.

The idealized cash flows presented in Figure 6.6 provided a start up point, but were inadequate since they ignored the probability, and impact of ground-related problems. Once these problems are expressed in terms of their economic impact, then they can prove to be decisive in motivating analysis and adopting appropriate to optimize the production schedule. Quantifying the probability of ground-related problems for an economic analysis is needed in order to include them in the optimization of a mine plan.
6.6 SENSITIVITY ANALYSES IN DECISION MAKING

Uncertainty with respect to certain parameters that is addressed in flexibility assessment can be examined through sensitivity analyses. These were carried out in a number of examples examined in Chapters 4 and 5, with respect to the price of metal, discount rate, and volatility. The uncertainty that often exists in determining the potential impact of ground-related problems in a production system can also be examined using sensitivity analyses. In the example considered in sections 6.4 and 6.5, the impact of the various levels of intensity of ground-related problems on production was examined, as shown in Figure 6.11. Here, the NPV for the sequence with pillars with ground-related problems was calculated for the basic case as well as for that with the additional crews option, analyzed in section 6.5. Monte Carlo simulation was used to determine the NPV of the project for various levels of average impact of ground-related problems, as shown in Figure 6.11.

![Figure 6.11: Sensitivity analysis for the sequence with pillars with respect to the intensity of ground-related problems](image)

Figure 6.11: Sensitivity analysis for the sequence with pillars with respect to the intensity of ground-related problems
The NPV for the basic example (examined in section 6.4) decreases linearly as the intensity of the ground-related problems increases. The NPV for the case with the extra crew that was examined in section 6.5 has a more complex behaviour due to the introduced non-linearity of the flexibility option through the conditional statement. If there are no ground-related problems, the NPV of the project will be less than for the basic study. It is reduced by the amount of the additional capital and operating expenses that are invested to acquire this particular flexibility option. In such a case, it is assumed that the extra crew and the equipment stay idle. Once ground-related problems start occurring, the benefits of the flexibility option are realized. However, the option starts “paying off” when the intensity of ground-related problems exceeds a 17,000 tonnes production loss annually. For a level of ground-related problems that does not exceed that value, the flexibility option does not provide any added value to the project. Once the intensity of ground-related problems exceeds 17,000 tonnes of lost production, then the option obtains a positive value, and it becomes worthwhile to include it in the project. The higher the intensity of the ground-related problems, then the higher the value of the option will be, as long as there is the ability to keep up with the problems and maintain the prescheduled production levels. For the frequency of problems examined in section 6.5, the value of the option with the extra crews has been found to be $7.7 million. The fact that the NPV for the case with the flexibility option remains relatively constant at $87 million, once the production impact exceeds 15,000 tonnes, is due to the assumption made that the extra crews will be able to perform adequately, and handle a certain range of ground-related problems. It should be evident that once ground-related problems escalate beyond the anticipated range of impact, then the flexibility option may be found to be inadequate, and production delays will then be inevitable. In such a case, redesign of the whole sequence may prove to be a better choice. Being able to make a good
estimate of the anticipated frequency of ground-related problems is critical in order to introduce the appropriate type of flexibility into the project, as well as the means to counterbalance their impact on production.

Sensitivity analyses such as those presented here are valuable to a decision maker, since they provide a means to include the uncertainty related to a particular parameter in the valuation of a project or an alternative. Since the intensity of ground-related problems cannot be predicted with certainty, conducting a sensitivity analysis can be used to examine the efficiency of an adopted flexibility option to a particular design, for a certain range of impacts or frequency of operating problem types. In that way, the possibility of creating production "bottlenecks", due to ground-related problems, can be minimized.

6.7 FLEXIBILITY INDEX

In the previous sections, it was demonstrated that options-based analysis was able not only to reverse the traditional DCF-based decision, but also to underscore the importance of active management of the project over time, while providing guidelines for its optimal operation. The value of the option has been determined by subtracting the NPV of the base case from the NPV (i.e., passive NPV) from the alternative with flexibility. However, reduction of risk expressed as the standard deviation of the mean of the NPV is often desired in a mining project. Mean-standard deviation diagrams, as used in conventional financial analyses (Luenberger, 1998), can be used to demonstrate the benefits of introducing flexibility into a project. Flexibility can result in improvement of the NPV, reduction of risk, or both, as shown in Figure 6.12. The mine planning team can then assess the impact of various
parameters that must be considered in the calculation of the value of a project, or of a particular alternative.

The decision making in a mining project often has budgetary constraints that can influence a decision to introduce a flexibility option. In order for the mine planning team to assess which of the flexible alternatives are most valuable in an operation, a flexibility index is proposed here. Such an index is defined as follows:

$$\text{Flexibility Index, } F(\%) = \frac{\text{Option Value, } OV}{\text{NPV passive}} \times 100 \quad , \quad OV > 0$$

A flexibility index of 10% would indicate that the introduced flexibility alternative would improve the NPV of the base case of a project (passive NPV) by 10%.
A flexibility alternative is often associated with capital and/or operating costs that have to occur in order for the particular alternative to be active throughout the project. These costs are additional capital outlays, and will occur whether or not the operator exercises the flexibility option. This “premium” includes the up front capital outlays, as well as the additional outlays that may have to occur during the operating stage of a mine to maintain (i.e., not to exercise) the option, discounted at time zero using the risk-free rate of return.

A comparison of the size of this capital cost outlay with the flexibility index can provide a means to examine which of the alternatives are most attractive and would be valuable to introduce as part of the mine plan optimization. Four flexibility alternatives are examined in Figure 6.13.

Figure 6.13: Examination of flexibility options in a mining project
Alternative A1 is characterized by a relatively low flexibility index and a relatively high cost to implement. Implementation of alternative A2 will have a high impact on the value of the project, but will also have a high implementation cost. Alternative A3 has both a low cost and a low impact on the value of the project. Finally, alternative A4 has the higher impact of the four, while its implementation cost is the lowest, and should be the most preferable one.

In the example presented in section 5.6, the flexibility index can be calculated to be:

\[
\text{Flexibility Index, } F(\%) = \frac{\text{Option Value, OV}}{\text{NPV passive}} \times 100 = \frac{\$7.7}{\$79} \times 100 = 9.7\%
\]

The "premium" that needs to be paid in order to maintain the flexibility alternative during the mining project is determined to be $3.28 million, by discounting the related annual costs to time zero.

The impact that a particular flexible alternative will have on the overall NPV of a project will be a function of the particular characteristics of the mining system and the anticipated operating risk due to ground-related problems. Costly alternatives such as the lining of an orepass or the increase of the capacity of a hoisting system, may prove to be valuable (have a high impact) when significant production delays are anticipated related to the performance of particular mining subsystems. In cases of low operating risk, the same alternatives may be found to have only a significantly smaller impact.

The placement of a second unlined orepass is a typical example of a low cost flexible alternative that can have a high impact on the maintenance of the production schedule of a mine, since the impact of hang-ups can be minimized. Design alternatives such as the placement of grizzlies or the minimization of finger raises in the same orepass, are also low
cost design solutions that can be found to control hang-ups and damage to pass walls, therefore significantly improving the overall performance of the particular subsystem.

Overall, the impact of each design alternative in a flexible mining system would need to be evaluated separately in order to determine its overall impact throughout the life cycle of the production system. This will enable the classification of the various alternatives similarly to Figure 6.13, which will provide a key input to the decision maker for budget allocation purposes and prioritization of flexible alternatives. Generalizations can only be made in cases where two mining systems are similar in terms of the operating risk present, the production rate, and the overall mine layout.

The evaluation of a number of independent flexibility alternatives is often constrained by budgetary restrictions. Once the cost and the impact of these alternatives has been determined, the combination that meets budgetary constraints while optimizing project value needs to be determined. Linear programming, using the simplex method (Anderson, et al, 1997), can be used to select the alternatives in an optimization analysis and provide a problem-solving approach to help with decision making. The objective is maximization of the NPV of the project while budgetary or other constraints are met.

In cases where the flexibility alternatives are not independent but interact, the problem of optimization becomes more complex. In such cases, it is suggested that the value of a combined option be determined through a flexibility analysis prior to conducting the optimization analysis.
6.8 REVIEW

The methodology for flexibility assessment in an underground mine operation accounting for ground-related problems should be considered as having four key phases:

- the determination of the potential types of ground-related problems that can occur in a mining subsystem over time;
- the evaluation of their frequency and cost impact;
- the simulation of the performance of the mine production system, including ground-related problems; and,
- an appropriate financial analysis to consider the types of flexibility that are required as part of mine planning and design.

It is critical to properly identify the types of flexibility that need to be introduced in a mining project to counterbalance operating risk. Identifying the types of flexibility will require the assessment of several design parameters and alternatives that can be influenced by ground-related problems throughout the life of the mining operation. The cost of mine planning and design that is incurred early in the project is small relative to the total cost of a mining operation. However, it is during that early stage that the commitment to future expenditures and production rates is inherently made. Knowing the types of risks that are to be faced critically affects the selection of the appropriate alternative and the economic analysis to be carried out, as well as the confidence in decision making.

Sensitivity analyses can prove to be valuable in assessing the impact of uncertainty with respect to ground-related problems. Although forecasting ground-related problems can never be a trivial exercise, due to the common lack of geomechanical and historical production
data, sensitivity analyses can place risk and consequences in perspective, and enable appropriate decisions to be made as part of mine planning and design. This process can also provide the evidence necessary to justify expenditure on further data collection and analysis at an early stage.
CHAPTER 7:
CONCLUSIONS AND RECOMMENDATIONS

This research has aimed to contribute to understanding the interaction between ground-related problems and mining systems as a basis for the development of more flexible mining systems. This should be further facilitated with the emergence of new enabling technologies and their application to underground mining. It is suggested that operating flexibility is an integral part of effective mine planning and design in underground hard rock mines. Minimization of costs as a single objective of underground operations is not adequate to optimize a mine plan. The quality of the design plan and the time at which this can be successfully implemented are critical components of an optimization process. The ability to recognize the forms of flexibility that need to be introduced in a mine plan is an essential part of such a process. An innovative approach to quantify operating flexibility and a methodology to integrate it with decision making in mine planning and design were introduced in this thesis.

A time-dependent internal risk model was established to quantify the impact of ground-related problems in mine production systems. Subjective probabilities provide the input for reliability analysis that can derive the parameters that are required as input for a production simulation. Flexibility needs in mine planning and design, with respect to ground-related problems, can be assessed through real options analyses. In order to design effective and efficient mines the potential for production disruptions and additional cost outlays should be evaluated as part of mine planning. When conventional design cannot provide feasible
solutions that can manage the operating risk in a mining environment, then flexibility needs to be introduced into the mine plans and the production schedule.

7.1 CONCLUSIONS

The financial objective of a mineral resource corporation is to maximize the wealth of the investors in the corporation. Investment projects should be accepted only if their value adequately exceeds their cost, so that their acceptance increases the wealth of shareholders (Brennan and Trigeorgis, 2000). It was demonstrated that ground-related problems can impose significant risks that can make a mining project unprofitable. Ignoring the potential for such problems during the mine life cycle can result in a gross overestimation of the scheduled production rate, or underestimation of production costs. Once unanticipated ground-related problems develop in a mining operation, it is generally very difficult and costly to alter the particular design or the method that is followed for the extraction of the orebody. The adverse impact of inappropriate planning and design decisions that are made years in advance can be realized during their implementation in the operating phase of the mine life cycle.

The initial mine feasibility study, traditionally conducted in a scenario of information inadequacies, tends to set the tone for the ultimate planning. Lack of adequate information is no excuse for ignoring the linkage between ground-related problems and anticipated cash flows in an underground operation. As the case studies demonstrated, ground-related problems are often seen from the point of view of tactical or short-term planning, or from the safety point of view. It would not be an understatement to say there is often confusion about the role of mining geomechanics in long term planning and production scheduling. The
economic impact of design decisions made early in the mine life cycle is often not fully realized when it comes to potential production disruptions or understanding of ground-related problems that can occur through time in the mining operation.

The cost committed during the planning stage of a mine (usually in the range of hundreds of millions of dollars), fully justifies the extra effort required to identify the types of ground-related problems that can develop in a mining subsystem through time, and their impact on the forecasts of a feasibility study. “If you can measure what you are speaking about, and express it in numbers, you know something about it” (Lord Kelvin, 1824-1907). This statement appropriately relates to knowledge of ground-related problems and minimizing operating risk in mines.

There is today an inadequate documentation of ground-related problems in mines. Legislation and health and safety concerns force a detailed documentation of ground-related problems that can be hazardous to mining personnel. On the other hand, there is often a lack of documentation of ground-related problems with respect to their impact on production over time. Lack of proper incentives, job prioritization, as well as the fear of being blamed for an improper action plan, are some of the reasons for the lack of such documentation. This thesis underlines the need for proper surveillance and recording of production delays and deviation from the initial long term plan, or the feasibility study, in a systematic way that can provide the information required to assess the future performance of mine production systems. This will intensify in its relevance as the economics of scale and the intensity of automation increase in underground mining.
Mining is associated with several uncertainty factors as discussed in Chapter 1. These are unavoidable in the decision making underlying initial feasibility studies. However, it is important to strive to “learn” from past mistakes. It is important to promote a corporate culture where knowledge is acquired to minimize uncertainty. Improving the quality of design in a mining corporation is directly related to the amount of knowledge that is readily available. Only then will the mine planning and design team be able to assume, with a high probability of success, the role of optimization, improvement, and maintenance of preset realistic production targets.

Discussions organized during this research with mine planning and design personnel in several underground mines, indicate that uncertainty in diagnosing ground conditions and predicting problems can often be a reason for not integrating their impact into production planning analysis. The inability to achieve high precision in predicting potential problems should not be a justification to avoid integrating their impact in an analysis. As was pointed out by Aristotle, many centuries ago, “...it is the mark of an educated man to look for precision in each class of things just so far as the nature of the subject admits” (Aristotle, 384-322 BCE).

The natural characteristics of a mine impose an uncertainty that can never be absent from man-made excavations in rock masses. The fact that the purpose of a mining enterprise is to extract a product for profit establishes a direct link between profitability and mine system performance. Only when ground-related problems are expressed in a “language” understandable by the analyst of a mineral investment can their potential to become players in project valuation be fully realized. Today, mining geomechanics is utilized as part of the
design of a mine. However, its focus has not been the determination of the impact of ground-related problems in a production system. This thesis intends to bridge that gap, and provide a means to "translate" ground-related problems into economic and production terms that can be used by a mine engineer in the valuation of a hard rock mining project.

It has been postulated in this thesis that the impact of ground-related problems can significantly govern cash flow generation. In effect, ground-related problem assessment is a quality parameter in annual cash flow estimation. Poor quality in planning and design can in itself lead to ground-related problems, with their impact realized and accounted for in the final cash flow calculations. This thesis has introduced a cost model that enables the mine engineer to include the impact of ground-related problems as a reduction in cash inflows due to production delays, reduced recovery, or dilution, as well as the increase in cost outlays due to the need for rework. Other costs can include the effect of throughput time as a result of prolongation of a mine's life due to ground-related problems and the lost opportunity costs, since the investment yields a lower rate of return than other investment alternatives.

The frequency and duration of ground-related problems in an internal risk model has been examined using a time-dependent reliability analysis. The proposed methodology enables the determination of reliability parameters that can describe the performance of a mining subsystem over time. This is particularly important, since the frequency and the intensity of ground-related problems in the same mining subsystem can vary through time. In lieu of available data records, the input that is required in this analysis can be based on subjective probabilities, which are determined based on the experience of an individual in a particular operation, or in operations with similar ground conditions. Although this process is
subjective, it provides a means for the analysis to include the problems that a mine planning and design expert considers likely to develop during the mine life cycle.

Once an internal risk model with respect to ground-related problems is established, then annual cash flows may be extended to include uncertainty due to other parameters. Risk can be minimized by planning to avoid causative situations, and/or by building in flexibility to contend with occurrence of problems. Flexibility is often seen as a result of lack of confidence in the forecast of a production problem or in the quality of a particular design. However, even if low uncertainty was present in predicting the behaviour of a production system, flexibility could still prove feasible in comparison to low risk alternative designs or to opportunities and needs to deviate from the original plan, which may develop during the course of mining.

Prior to conducting a financial analysis to assess flexibility requirements in a mining system, it is necessary to: comprehend the situation, access information, understand alternatives, be able to cost options and, be able to estimate benefits.

Real options have been shown to provide a valuable vehicle for assessing flexible alternatives in a mining system. However, by nature, they require that the option be constructed in such a way that there is no obligation for the operator to exercise the option when this is desirable at an extra premium. In designing flexible mine operating systems, the ability to handle difficult situations that can develop during the mine life cycle is an additional form of flexibility. Such flexibility may not necessarily be expressed as a common
real option, since the whole cost of the flexibility can be paid up front, with no extra premium required.

The conventional real option analyses that have been considered by economists often focus on strategic options with market uncertainty. Such options with respect to a mining project have been recently discussed by Moel and Tufano (2000). Operating alternatives that were examined in this thesis do not fall into these categories. Although the options may be related to long term planning, the term "strategic", as used by economists, is not applicable here. To an economist, the operating options that were examined here focus more on an operating scenario such as the corporate decision making of purchasing (or selling) mineral rights. Operating options in long term mine planning can be considered as strategic in the context of a mining operation, since they are made well ahead of the opening of a mine, or at least many years prior to their implementation. The concept of application of real options in production planning of flexible mining systems, introduced in this thesis, is a unique application of a financial approach to a different decision-making process. Ground-related problems have been the source of the operating uncertainty that was considered in this thesis. The ability to assess the impact of ground-related problems in decision making through flexibility analyses has been demonstrated through examples that are based on real case studies.

The option to maintain a prescheduled production rate and operating costs that are endangered due to risk from ground-related problems is the option that finds the most applications for a range of problem types. Here, the main advantage of real options analysis is to incorporate managerial flexibility into the project and its valuation. Even if the precise rate of ground-related problems is unknown, sensitivity analysis in terms of the potential
impact of ground-related problems can provide a key input for decision making in the valuation of alternatives. Other types of options can focus on design optimization through the selection of the alternative with the highest potential to benefit the project, or the option to expand when favourable ground conditions allow.

It is beneficial to introduce uncertainty into all parameters involved in a calculation of annual cash flows or NPV using Monte-Carlo simulation. This eliminates the difficult task of choosing an appropriate discount rate, since internal project risk is already contained in the cash flows. Once the cash flows are established through simulation, then they can be discounted for time using a risk-free rate that is easily determined. The fact that mine owners usually enter into forward contracts to sell the mine output in the future at pre-agreed prices, eliminates the price risk (market risk) and the relevant discount rate would then be the risk-free rate. This enables the analyst to focus on the internal project risk factors, as opposed to the market risk, in a flexibility analysis which uses conventional discounted cash flow or real option analyses.

The full picture of a flexible alternative can be assessed through a financial analysis that captures both the production fluctuation and the cost factors. However, production simulation can, in certain cases, prove adequate in making decisions related to the impact of ground problems, provided that there is a good understanding of the order of magnitude of such problems. Automated mines will face different design and safety constraints that likely will lead to a different philosophy when it comes to evaluating alternatives and introducing flexibility. The ability to record the encountered ground conditions during the mining process
and adjust the production system accordingly, offer several opportunities in terms of building flexibility that can enhance the value of a mining project.

The paradigm explored in this thesis is the integration of geomechanics, mine planning, economic theory, information technology, and decision making. The developed methodology can help the mine operator to introduce into the decision-making process new concepts and approaches that can assist in the optimization of mine planning and design through the realization of risks and opportunities that can develop during the mine life cycle. The ultimate objective is the establishment, during the course of mine planning and design, of flexible mining systems with controlled uncertainty and optimal value.

The next-generation flexible mining systems that will survive in the highly competitive world of metal markets will be those able to adapt to downturns due to problems such as ground-related problems, whilst also taking advantage of opportunities from upturns due to the overestimation of adverse ground conditions. In these mining systems, the assessment of the impact of ground-related problems will be part of the normal course of mine planning and design through a well-established process to assess potential cost and production impact.

7.2 FUTURE WORK

This thesis is the first of its kind to attempt to bridge the gap between ground-related problems, mine planning, production simulation, and financial analysis. Further work to implement operational systems will be needed to introduce activity based costing in the
assessment of costs in mining subsystems through time as well as to *establish records* in mine information systems related to the production impact of ground-related problems.

New developments in information technologies, including ground-sensing and automation in underground hard rock mines, will enable the establishment of databases with operating delays that currently are not available in a format that would allow the accurate, objective, and swift determination of the frequency and the impact of ground-related problems during the operating stages of a mine. The establishment of unbiased records that are not dependent on the existing mining culture will provide a basis for the introduction of changes to current management systems and to the decision making process. The impact of new information on mine management warrants further research.

With the introduction of activity based costing and new information technologies, production simulation could then include all factors involved in cash flow calculations and allow alternative scenarios to be fully explored. The potential for production and cash flow bottlenecks can be evaluated, and flexibility can then be introduced where this is required. In this way, flexibility assessment can then become an integral part of mine planning and design in the next generation mine planning software systems.

The methodology introduced in this thesis can be used to address *other types of operating problems* that are related to external and internal risk factors. The next step will be to integrate all sources of internal risk (e.g., equipment, infrastructure, ground-related problems) in a comprehensive methodology. The outcome will be an integrated mine planning and design system that will enable the mine engineer to explore, in a short time, alternatives and
events that can occur during the full mine life cycle. *Quality control in planning* could then be tracked and optimal solutions introduced where this is appropriate. The planned performance of a flexible mining system could then be compared with the one encountered during the operating stages of a mine. This can lead to design improvisations and fine-tuning of future planned mining systems with lower uncertainty and higher production performance. Internal project risk/uncertainty management would then become the focus of quality control in planning and design for conventional or automated mines.

Optimization of *equipment selection* (e.g., capacity, fleet size) will also be impacted by the operating risk present in a mining system, the quality control requirements, and the need to introduce and maintain flexibility in the production system. *Exogenous sources of uncertainty* and flexible alternatives that may become available will also need to be assessed as part of the overall project valuation process.

*Price shocks*, defined as short-lived booms and busts in world metal markets, can have a significant impact on the viability and the production schedule of a mining operation. A corporate decision to increase or decrease production may encounter constraints related to existing infrastructure and operating risk to implement a change in the existing production schedule and overall mine design. The presence of flexibility within the structure of a mining system to accommodate the impact of price shocks requires further research.
BIBLIOGRAPHY


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APPENDIX I: Spreadsheets for the Methodology Example
### STEP 1: CASH FLOWS WITHOUT RISK OR FLEXIBILITY

- **Stop size**: 16,000 tonnes
- **Value**: $200 per tonne
- **Oper. cost**: $45 per tonne
- **Initial investment**: 20,000,000 at the end of year 1
- **Risk-free rate**: 0.06

#### Production Loss Due to Ground/Related Problems in Stope (Tonnes)

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<thead>
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<th>Year</th>
<th>Pillarless sequence</th>
<th>Sequence with pillars</th>
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<tbody>
<tr>
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<td>Most</td>
<td>Max</td>
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<tr>
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<td>0</td>
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<td>8000</td>
</tr>
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<td>8000</td>
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<td>8000</td>
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#### Pillarless Sequence

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<th>Op costs</th>
<th>Gr. prob</th>
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<th>Cashflow</th>
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<td>$ 9,920,000</td>
</tr>
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<td>160,000</td>
<td>32,000,000</td>
<td>7,200,000</td>
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<td>$ 24,800,000</td>
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**NPV** = 93,971,718
## STEP 2: CASH FLOWS WITH RISK

<table>
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<th>stope size</th>
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<td>$200 per tonne</td>
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<tr>
<td>Oper. cost</td>
<td>$45 per tonne</td>
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### Initial investment
- 20,000,000 at the end of year 1
- 16,000 tns = 10x15x30-4,500 m³

### Risk-free
- 0.06

#### PRODUCTION LOSS DUE TO GROUND-RELATED PROBLEMS IN STOPES (TONNES)

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<tr>
<th>Year</th>
<th>Min</th>
<th>Most</th>
<th>Max</th>
<th>Min</th>
<th>Most</th>
<th>Max</th>
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</table>

### AVERAGE
- 8000
- 36000

#### A - PILLARLESS SEQUENCE - CASH FLOWS

<table>
<thead>
<tr>
<th>Year</th>
<th>Throughput</th>
<th>Revenues</th>
<th>Op. costs</th>
<th>Gr. prob.</th>
<th>Cash flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>541,733</td>
<td>23,001,549</td>
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### TOTAL
- 944,000

#### NPV=
- 65,155,056

#### PILLOWLESS SEQUENCE

<table>
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<th>YEAR</th>
<th>1</th>
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<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
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</thead>
<tbody>
<tr>
<td>CASE A</td>
<td>-20,000,000</td>
<td>8141618</td>
<td>18086732</td>
<td>23015602</td>
<td>2E+07</td>
<td>32017090</td>
<td>23054766</td>
<td>22538462</td>
<td>1,396,800</td>
</tr>
<tr>
<td>CASE B</td>
<td>-20,000,000</td>
<td>15947164</td>
<td>18304480</td>
<td>18407104</td>
<td>2E+07</td>
<td>18421970</td>
<td>18431506</td>
<td>17282382</td>
<td>6,445,900</td>
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</table>

#### CUMMULATIVE CASH FLOW ($ MILLION)

<table>
<thead>
<tr>
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<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>
</tr>
</thead>
<tbody>
<tr>
<td>CASE A</td>
<td>-20</td>
<td>-11.858182</td>
<td>6.21055</td>
<td>29.226152</td>
<td>52.271</td>
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<tr>
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<td>14.25164</td>
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<td>87.972702</td>
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### B - SEQUENCE WITH PILLARS - CASH FLOWS

<table>
<thead>
<tr>
<th>YEAR</th>
<th>Throughput</th>
<th>Revenues</th>
<th>Op. costs</th>
<th>Gr. prob.</th>
<th>Cash flow</th>
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</thead>
<tbody>
<tr>
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### TOTAL
- 944,000

#### NPV=
- 82,065,143

#### SEQUENCE WITH PILLARS

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<td>6,445,900</td>
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<table>
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<tr>
<th>YEAR</th>
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<tr>
<td>CASE B</td>
<td>-20</td>
<td>-4.052836</td>
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<td>105.255084</td>
<td>111.700984</td>
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STEP 4: SENSITIVITY ANALYSIS

AVERAGE IMPACT OF GROUND RELATED PROBLEMS

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<th>6000</th>
<th>18000</th>
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<td>92.1</td>
<td>90.25</td>
<td>88.5</td>
<td>82.8</td>
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<td>54.55</td>
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