

Risk-based evaluation for underground mine planning

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ABSTRACT

As underground mine planning tools become more sophisticated, mine planners have the capacity to investigate numerous mine sequencing options to identify the best strategy for a given project, creating higher value for shareholders. The information required for mine planning decisions goes beyond the external sources of uncertainty recognised by typical evaluation techniques used in the mining industry, to include technical factors (*e.g.* mine development layout) and the ability of a mineral extraction project to achieve planned production levels. Due to the individual characteristics that define underground mining projects, each will exhibit its individual risk profile, and thus advanced evaluation techniques must capture this information.

This paper describes a Risk-based Evaluation Methodology that accounts for financial and technical scheduling risk in the evaluation of underground mining projects. It provides decision-makers with more information early in the mine planning cycle by combining planning and design methodologies with evaluation techniques to identify, optimise and evaluate strategies for mining extraction sequences. Standard evaluation practices used in the mining industry (Discounted Cash Flow, Real Options and Monte Carlo Simulation) are combined with the concepts of Modern Portfolio Theory to establish an evaluation methodology that recognises financial uncertainty in the context of technical scheduling factors.

This paper will show that the Risk-based Evaluation Methodology can be used at the tactical level, as it is applied in combination with the Schedule Optimisation Tool (SOT), for the purpose of recommending a materials handling system to be implemented in a mining project. For the case study, the inclusion of more information in the decision-making process not only provides a more accurate valuation and allows for the recognition of risk, but it also alters the ultimate decision.

INTRODUCTION

As design and scheduling tools become more sophisticated, mine planners gain the capacity to investigate and review different mine sequencing options to determine better planning strategies. The availability of automated mine planning tools is also important as this reduces the time needed to create design and scheduling alternatives and provides more time for review and value adding functions by the planning team.

Improving the underground mine planning process has the ability to significantly increase the value of a project. The goal of mine planning is to maximise the value of a mineral resource; this requires the creation of a feasible long-term schedule of activities for its extraction. With suitable software tools, a mine planner has the ability to investigate numerous mine schedules to identify those that create the most value and achieve the strategic objectives of the firm. Mine planning decisions require information on external sources of uncertainty (*e.g.* mineral prices, exchange rates, etc.) that are recognised by typical evaluation techniques (*i.e.* Discounted Cash Flows (DCF)), as well as technical factors (*e.g.* mine development layout) and the ability of a mineral extraction project to achieve target production levels. Considering the uncertainty of mine schedules together with the external factors can provide mine planners with more information and better evaluation methodologies that can foster more sound decision-making practices.

OPTIMISATION, VALUATION AND RISK IN UNDERGROUND MINING

Risk mitigation in underground mine planning is a broad topic. A high level of uncertainty exists within the mining process, from the delineation of the orebody (grade and tonnage) to the market price that will be realised for the mineral produced. There are also numerous sources of uncertainty in implementing underground mine schedules. The ability to meet production levels is a crucial goal for mine planning. Meeting production targets can be as influential on the value created by a project as the external sources of uncertainty recognised through the discounting of cash flows.

There are numerous reasons why a mine may fail to meet its production plan (*e.g.* poor ground conditions, a changing labour force) [1], with the result that the value expected will not be realised. The flexibility of a plan throughout the life of the mining project will contribute value that is not taken into account by the standard practices of project evaluation used in the mining industry. The ability to change production levels, average grades produced, mining methods employed, for example, can have significant influences on the value realised from a project. Thus, just as external sources of uncertainty (*e.g.*, market prices) are accounted for in the evaluation of a project through the use of a discount rate, the uncertainty associated with a specific schedule, and the flexibility of the schedule should also be included in the evaluation.

The choice of what mining strategy to implement is usually made very early in the planning cycle. In many cases, this decision is made before sufficient data has been accumulated to make such a decision with confidence. While some uncertainties are recognised, a proper risk-based evaluation is not produced due to time constraints. Many companies limit their strategic investigation to identifying the highest value mining scenario, focusing on mining methods and production rates, with little time, if any, devoted to scheduling [2]. Unfortunately, it takes a substantial amount of time to create these alternative schedules through conventional processes, and as a result, little or no effort is placed on evaluating the risk profiles of the multiple alternatives that exist.

Each orebody is unique, with respect to characteristics such as shape of the deposit, mineralisation, and ground conditions. These characteristics influence the method(s) of extraction

that should be used within the mining project. Likewise, each project will have its own set of uncertainties surrounding the financial information used in its evaluation (e.g. market prices, operating costs, capital costs), and each mining project will have different constraints on the availability of resources to perform the extraction (e.g. hoisting capacity, milling capacity, manpower availability), which will constrain the scheduling process. As a result, the evaluation of each orebody should be undertaken individually on its specific merits, and not using information based on historical mining projects that may not be relevant. Unfortunately, the time requirement for data creation is immense.

The Schedule Optimisation Tool (SOT) [3] provides mine planners with the ability to investigate thousands of possible schedules. While optimality cannot be guaranteed, the case study reported in Maybee *et al.* [3] found that SOT schedules were of 20% higher value than those identified through manual scheduling processes. Hall and Stewart found that using genetic algorithms can typically find schedules with 10-15% improvement in the Net Present Value (NPV) of a project depending on the initial condition of the dataset [4].

Through the rapid creation of scheduling alternatives with SOT, the additional information can be used to characterise the risk profiles for different strategic options. These profiles can be very different, as shown conceptually in Figure 1. This figure depicts two hypothetical mining strategies by plotting the values of their scheduling alternatives based on two scheduling properties. The strategy with the low risk profile has numerous high value neighbouring schedules, giving a higher probability of achieving the mine value. On the other hand, if an extraction strategy yields a high expected value under one scheduling alternative, but all neighbouring schedules return much lower expected values, then the probability of achieving the value of this exceptional plan will be low, as a small change in the sequence will dramatically decrease the value.

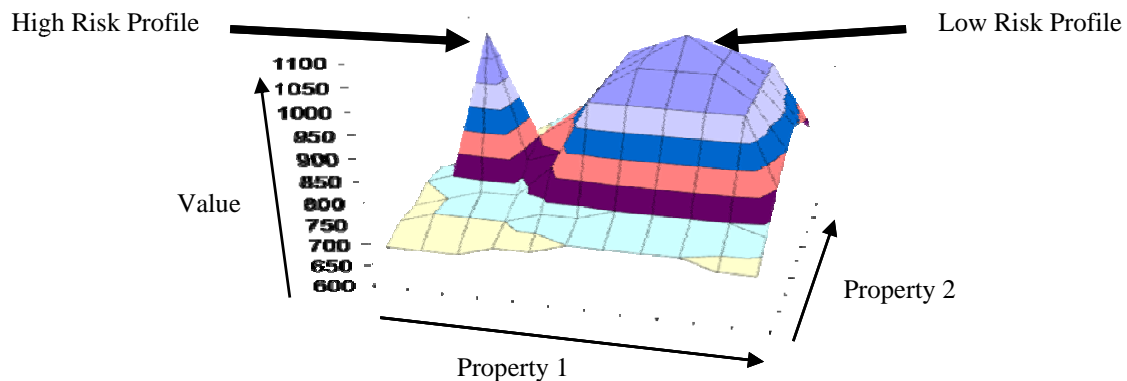


Figure 1 Hills of value after Maybee *et al.* [5]

Leveraging SOT's ability to automate the underground mine scheduling process, a Risk-based Evaluation Methodology (RbEM) has been devised by Maybee *et al* [5]. This methodology addresses the complexities associated with underground mine scheduling by combining techniques used to optimise a mining project with financial evaluation tools. The RbEM addresses the frequent necessity, in underground mining, of revising a schedule. It identifies a mining *strategy*, defined as a group of schedules that share a common set and timing of activities within a given planning horizon. These schedules then diverge after the planning horizon to provide flexibility. Having this

information gives management the ability, as uncertainty is resolved, to take advantage of opportunities and mitigate risks.

Figure 2 depicts conceptually three schedules that are considered part of the same mine extraction strategy. In this figure, the strategy is a group of schedules that include activities 1 to 5 within the mine planning horizon (as represented by the solid grey line). Many strategies exist for a scheduling environment; with one of them eventually being selected for implementation as the mine plan, and due to the individual nature of an orebody, these strategies must be investigated individually to identify the one that adds the most shareholder value.

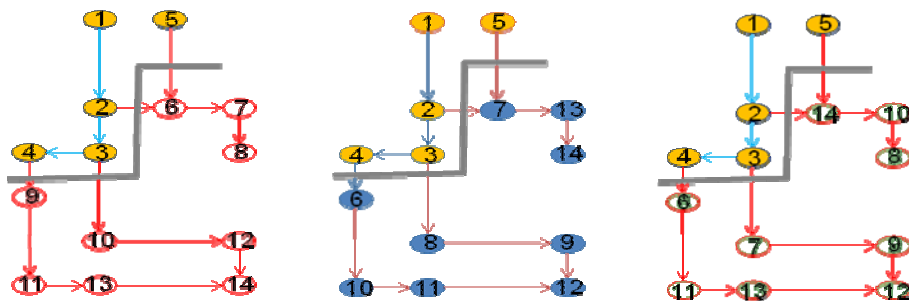


Figure 2 Representation of a mining strategy

To use the RbEM, a set of scheduling alternatives is required for each identified strategy. This is accomplished using a feature of SOT that fixes the scheduled times of a specific set of activities. By fixing the start times for activities that are within the planning horizon, and then allowing SOT to generate schedules that alter the order and timing of the activities that occur after the horizon, a group of scheduling alternatives can be automatically generated for each strategy.

The RbEM creates information for decision-making purposes as it evaluates the variation in value of each strategy with scheduling changes. While statistical measures can be used to describe the strategies (*e.g.*, mean and standard deviation); it is also possible to use techniques from Modern Portfolio Theory (MPT) to offer additional insight. Comparing strategies in mean-variance space provides decision-makers with the opportunity to recognise the risk-reward tradeoffs of competing strategies.

This analysis requires a measure of the expected return and risk. Since the RbEM uses Monte Carlo simulation to identify potential values, it is proposed that the mean of the resulting distribution is an indicator of the expected return (value). However, the typical measures used to describe risk (standard deviation and variance) fail to capture the true risk that a mining company must manage. In mining, when choosing between mutually exclusive investment opportunities (strategies) where the returns are uncertain, the greatest exposure to risk comes from the erosion of value from that which was planned. Thus, the use of a descriptor (risk measure) that focuses on the potential downside in the strategy more completely captures the risk being faced. For this reason, a semi-variant measure of risk based on the α - t mean-risk dominance model proposed by Fishburn [6] can be used to describe the risk of a strategy, where risk is measured through the probability-weighted function of the deviations below a target value.

Management in the mining industry is concerned with long-term performance, while avoiding failures in short-term performance [7], both of which are captured in the calculation of NPV,

making the α - t mean-risk dominance model an appealing measure. The general form of the downside risk function is denoted in Equation (1):

$$Risk = \frac{1}{L} \sum_{j=1}^L (t - NPV_j)^\alpha, \text{ if } NPV_j < t, \quad (1)$$

where L is the number of trials falling below the target, t is a target value and α is a corporate specific measure of risk aversion.

In this general form, the function requires the estimation of two constant values. First, a target value for the strategy (t) must be identified as the value that the company wishes to attain through the implementation of the specific strategy. For the purposes of the RbEM in the following case study, the target value for each strategy is the highest NPV found from the set of scheduling alternatives given the expected value for each of the uncertain inputs. Second, α reflects the investor's assessment of the relative consequences of failing to obtain the target value. If $\alpha < 1$, the investor is willing to gamble on the outcomes, and if $\alpha > 1$, the investor is risk-averse and requires confidence in obtaining a certain level of return. Many practitioners have discussed the value of α that is applicable for mean-risk dominance functions of this nature showing that there are many attractive features to using $\alpha = 2$ for a risk-averse investor [6, 7].

Finally, in the general form of the α - t mean-risk dominance model, L is the number of trials that fall below the target value. This means that the downside risk is calculated based on the average deviation below the target, scaled using α , without regard for the proportion of total trials that these represent. When comparing mine scheduling strategies on a risk-return basis, it is important to recognise the proportion of the total trials that turned out positive as well. A strategy that has more potential of yielding a value below the target should be assigned a higher risk than a strategy with relatively fewer results below the target. For this reason, L is the total number of trials (both above and below the target) when calculating the risk of a strategy using the RbEM.

It should be noted that even though specific values for α and t have been chosen to demonstrate the use of the RbEM, the α - t mean-risk dominance function can adapt to corporate requirements. By using this function the mining company can choose to alter the target value and the value of α to meet their corporate requirements and risk tolerance, making it an adaptable measure of risk.

CASE STUDY APPLICATION FOR TACTICAL DECISION-MAKING

The remainder of this paper is devoted to describing how the RbEM can provide decision support at the tactical level. A more complete description of the application of the methodology is provided in Maybee *et al* [5]. SOT is embedded in the process to rapidly create and evaluate strategies for competing scenarios. This case study evaluates a mining project to decide what size of material handling system (expressed in total tonnes hoisted per year) should be implemented.

The study focuses on a narrow-vein gold producing property that is divided into eight mining areas that employ a combination of Cut and Fill (C&F) and LongHole (LH) stoping methods. The property is polymetallic, containing copper and silver mineralisation along with the primary gold mineralisation. The project is a modified greenfield operation that has an existing mill, and must move all of the extracted material (both ore and waste) to surface. The existing processing capacity is 1 million tonnes of ore per year, and a prescribed equipment fleet constrains annual access development (Table 1).

Table 1 Mining project capacities

| Resource | Yearly Capacity |
|------------------------------|-----------------|
| Jumbo Development (metres) | 6,000 |
| Jackleg Development (metres) | 8,500 |
| Mill Capacity (tonnes) | 1,000,000 |

This evaluation addresses the size of hoisting system needed to move ore and waste material to surface, for efficient use of the development resources and mill, as measured by NPV. It is anticipated that the mine will extract 24,725,509 tonnes from a combination of C&F and LH stoping methods containing 343.4 tonnes of gold, 264.9 tonnes of silver and 168,870.5 tonnes of copper. As well, 7,895,675 total tonnes of waste material must be hoisted to surface. The mine is represented as a set of activities to be scheduled from the eight mine areas, which are categorised as stoping, ore development, and waste development. Each activity has a length (in metres) and/or a mass (in tonnes) that determines a mining duration based on its extraction rate. The dependency (predecessor/successor) relationships between the activities have also been identified.

The methodology can incorporate many types of price models, but for the purposes of this case study, simple market price models have been used, as price modelling is beyond the scope of this paper. The simple price models used for industrial minerals consumed in production processes, such as nickel and copper, reflect a reverting price process based on a reversion half-life [8]. For investment minerals, such as gold and silver, a non-reverting price processes is assumed, as they behave more like financial derivatives [9].

For this case study, the spot price of copper is assumed to be \$6,116 per tonne, and following a reverting price model, the long-term copper price is expected to be \$5,940 per tonne with a 3.75 year reversion period, giving a reversion half-life of 1.875 years. The spot price of gold is assumed to be \$30,061 per kg and follows a non-reverting price model. Similarly, it is assumed that silver will follow a non-reverting price model with a spot price of \$527 per kg. For this level of project evaluation, the company uses an annual discount rate of 7.5% to represent its cost of capital, which is used to evaluate all current and potential mining projects.

RISK-BASED EVALUATION METHODOLOGY (RBEM)

The application of the RbEM is depicted in Figure 3, with a more in depth discussion of its application in Maybee *et al* [5]. The flowchart shows the steps used to apply the methodology for this case study, highlighting how SOT was integrated into the process.

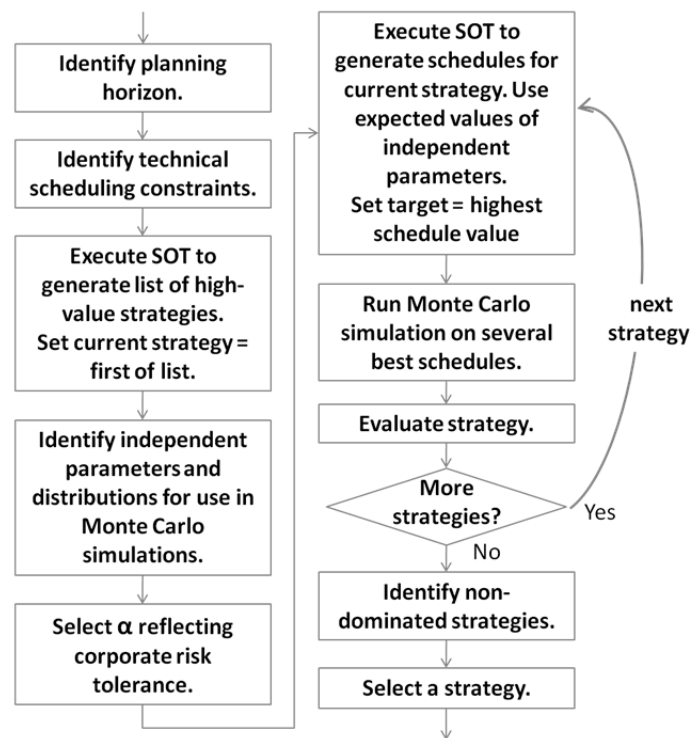


Figure 3 Overview of the Risk-based Evaluation Methodology (RbEM)

The evaluation process begins with the identification of a mine planning horizon. This horizon reflects the length of time that the mining company requires for a given decision to take effect. Since it is a common set and timing of activities in this horizon that make different schedules part of the same strategy, the horizon is an integral part of a mine extraction strategy. With the use of an automated scheduling tool, it is possible for the duration of the planning horizon in the RbEM to be much shorter than historically considered.

For this tactical level case study, strategies were selected based on parameters commonly used to guide the underground mine scheduling process. These strategies are described in Table 2.

Table 2 Mining strategies

| Strategy Name | Description |
|--------------------------------|---|
| 1 Highest Grade | Schedules the activities with the highest grade as early as practical |
| 2 Highest Mineral Mass | Schedules the activities with the highest mineral mass as early as practical |
| 3 Lowest Cost | Schedules the activities with the lowest mining cost as early as practical |
| 4 Highest Grade by Area | Schedules activities in the mine area with the highest grade as early as practical |
| 5 Highest Mineral Mass by Area | Schedules activities in the mine area with the highest mineral mass as early as practical |

Using SOT with a planning horizon of six months, 1400 schedules were generated for each of these strategies. The ten best schedules for each strategy were exported to a financial model in Microsoft Excel™; this financial model was used for the risk-based analysis. The financial model contains the tonnages and amount of mineral extracted (tonnage multiplied by grade) for each activity, and the cost of extraction for each type of activity.

Through the use of the spreadsheet model and the RiskAMP Monte Carlo simulation add-in, the strategies were investigated for their sensitivity to random changes in independent parameters. Financial uncertainties that impact the value of the mining operations were identified and modelled as probability distributions in the spreadsheet model. For this study, market price volatility and average grade for the three minerals being extracted was investigated. As described previously, it is assumed that market prices will follow either a reverting or non-reverting process, depending upon their attractiveness as an investment asset. Market prices will also be influenced by unforeseen price shocks that arise from the volatility of the mineral. It is through these price shocks that the mineral price uncertainty will be incorporated in the evaluation model.

Figure 4 shows a distribution of potential price shocks that will influence the market price of gold. In this distribution there is the possibility that annual price shocks will range from a decrease of 16% to an increase of 20%, with the most likely outcome being an increase of 11%. Likewise, it is expected that the market price of silver will follow a non-reverting process as an investment commodity, and will incur price shocks ranging from a 25% loss to a gain of 34%, with the expectation that this shock will be an increase of 8%. Copper prices will follow a reverting price process, where the annual shock is expected to be an increase of 7%, and will range from a loss of 24% to a gain of 32%.

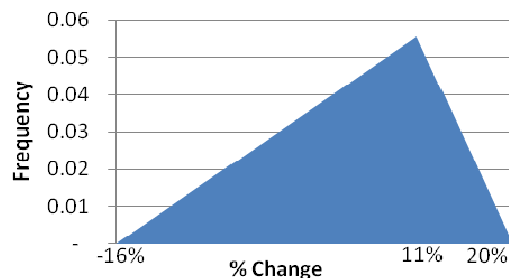


Figure 4 Distribution for gold price shock

The average grade for all three of the mined minerals has uncertainty associated with the techniques that were used in the delineation of the orebody, and will be affected by mine recovery and dilution. Since gold is the primary mineral for this operation, it is assumed that there is confidence in the prediction of its average grade resulting in a distribution that is plus or minus 5%. Copper and silver grades, on the other hand, are represented by a distribution that ranges from plus to minus 10%.

With the strategy identified and the uncertainties modelled, a Monte Carlo simulation was run to investigate how these changes affect each of the schedules that comprise the strategy. The Monte Carlo simulation was run for 5,000 iterations with each of the scheduling alternatives for the strategy being evaluated for each realisation of the uncertain factors (*e.g.*, market price and average grade). Using these values, the NPV for each of the scheduling alternatives within the strategy was re-calculated.

It is at this point that a Real Options (RO) approach to valuation was taken. Since the scheduling alternatives share a common set of activities within the planning horizon, it was assumed that

management has the ability to make decisions after that point depending upon the state of the environment. To account for this, it was assumed that the choice would be the one that yields the highest NPV. For this reason, the schedule with the highest value was recorded as the strategy result for each iteration. After 5,000 iterations, a distribution of the values obtained from that strategy was created. The evaluation process was then re-run for each of the identified strategies, and the results compared to decide on the strategy of mining that should be undertaken.

RESULTS

The analysis in this study was performed in two parts. To start, it was assumed that the project can build a hoisting system that can handle between 1.2 million and 1.5 million tonnes of material per year. As a result, the RbEM was applied to the project for each of the four mutually exclusive operating scenarios (hoisting capacities of 1.2 million, 1.3 million, 1.4 million and 1.5 million tonnes per year). For each of these scenarios, an increase in upfront capital is required as shown in Table 3, with the 1.2 million tonnes per year option being used as the base case.

Table 3 Incremental capital

| Scenario (million tonnes) | Incremental Capital Required (million \$) |
|---------------------------|---|
| 1.2 | 0 |
| 1.3 | 10 |
| 1.4 | 20 |
| 1.5 | 30 |

The RbEM was applied to evaluate which strategy of mining from Table 2 should be implemented for each of the independent scenarios in Table 3. Under the assumption that the company is risk-averse ($\alpha = 2$), the results for the 1.2 million tonnes per year hoisting scenario are presented in mean-variance space in Figure 5.

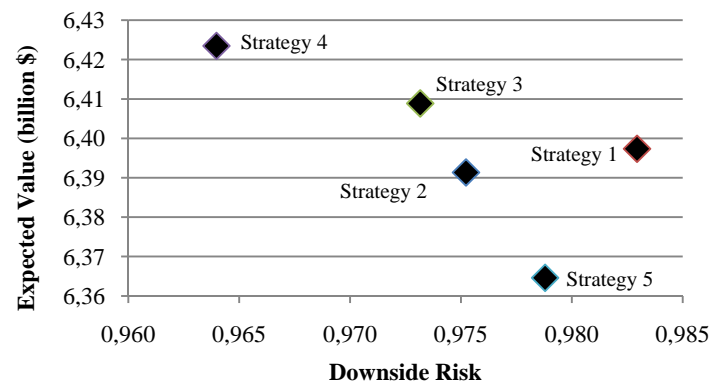


Figure 5 Mean-variant comparison of strategy results for the 1.2 million tonnes per year hoisting scenario

Figure 5 shows that Strategy 4 dominates all other tested strategies for the 1.2 million tonnes per year hoisting scenario, as it has the highest expected value for the lowest level of assumed risk. As a result, the other strategies are considered to be inefficient. The same process was followed for the other scenarios (1.3, 1.4 and 1.5 million tonnes per year) with the results summarised in Table 4. In this analysis, a value and measure of risk are identified for each of the independent scenarios through the implementation of the recommended strategy found using the RbEM. The results were then compared to determine if the additional value that can be obtained justifies the additional capital investment and risk.

Table 4 Risk-based results

| Scenario (million tonnes) | Strategy | Expected Value (billion\$) | Risk Measure |
|---------------------------|----------|----------------------------|--------------|
| 1.2 | 4 | 6.423 | 0.964 |
| 1.3 | 4 | 6.404 | 0.968 |
| 1.4 | 4 | 6.481 | 0.985 |
| 1.5 | 4 | 6.354 | 0.942 |

The scenario that hoists 1.4 million tonnes of material per year has the highest expected value, but also has the highest level of risk. Alternatively, the scenario that hoists 1.5 million tonnes of ore and waste per year has the lowest level of risk, but also the lowest expected value. These results are presented in mean-variance space in Figure 6.

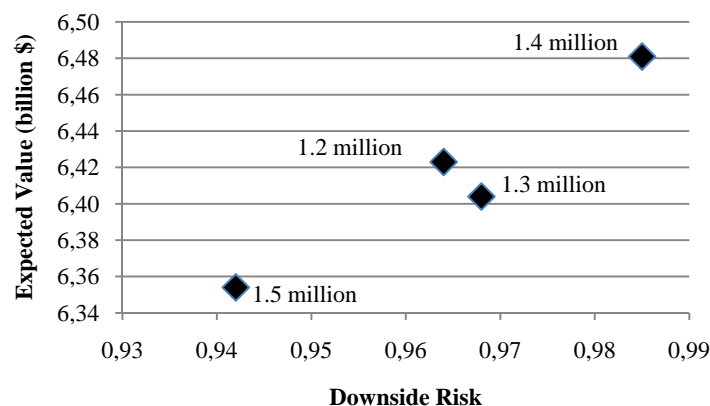


Figure 6 Mean-variant comparison of selected strategies for all scenarios

This figure shows that the 1.3 million tonnes per year scenario is inefficient, as there is another option (1.2 million tonnes per year) that has a higher expected value with a lower level of risk. The implementation decision is then between the remaining three scenarios, and what level of risk-return trade off the company is willing to bear. This is a decision that the company must make based on their appetite for risk. One method of making this decision, for example, would be to assume that the company is risk-averse, and divide the expected return for each scenario by the

measure of risk to find the proportion of additional risk that must be assumed to achieve an increased expected value.

CONCLUSION

The RbEM offers a framework that can be used to evaluate the risk characteristics of mining strategies. Its structure allows for the incorporation of financial uncertainty into the evaluation process, while realising that mining is performed as a group of dependent extraction activities that must be sequenced and scheduled. As a result, the use of this methodology requires the creation of scheduling alternatives for a mine design to model the flexibility within a mining strategy, which can be time consuming using manual scheduling processes. Fortunately, with SOT being incorporated into the process, this time requirement is dramatically reduced. Through the use of a case study, it was demonstrated that this process can be applied at the tactical decision-making level.

This methodology allows for mining information to be included earlier in the decision-making process, when there is the potential to greatly impact the value of the project. The model, with SOT embedded in the process, offers an improvement upon current RO and dynamic DCF valuations in that it can handle very large datasets with thousands of activities to be scheduled, whereas current models that evaluate the risk of a mine plan are limited to working at the level of mine areas or zones. By recognising that a strategy consisting of multiple scheduling options exists, rather than a single extraction schedule, new information on value and risk can be generated for mine planning decision support.

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