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Planning for flexibility in underground mine production systems

V.N. KAZAKIDIS AND M. SCOBLE

V.N. Kazakidis, member SME, is associate professor with the School of Engineering, Laurentian University, Sudbury, Ontario, Canada; **M. Scoble** is professor and head with the Department of Mining and Mineral Process Engineering, University of British Columbia, Vancouver, B.C., Canada. Nonmeeting paper number 02-310. Original manuscript submitted for review March 2002 and accepted for publication November 2002. Discussion of this peer-reviewed and approved paper is invited and must be submitted to SME Publications Dept. prior to Nov. 30, 2003.

Abstract

Underground mines often face uncertainty in production planning associated with diverse sources such as grade distribution, ground conditions, equipment reliability, infrastructure needs and extraction method performance. Despite the best planning efforts, such operating uncertainty needs to be counterbalanced by the integration of some contingency to enhance the flexibility in mine plans. This paper considers how flexibility can be evaluated and integrated into proactive mine planning using the concept of a flexibility index.

Introduction

In a world of widening competition and uncertainty, operating flexibility and strategic adaptability are being increasingly recognized as critical to long-term corporate success. It has been realized in operating underground mines that the greatest scope for savings is available during the early planning stage, within and somewhat beyond the feasibility study. Here, the planning team has greater freedom to explore alternatives and assess risk using various technical and economic criteria. Once ground has been broken, the alternatives available to the operator diminish exponentially as the mine matures. Although optimization, focusing on production level and cost, are the consistent objectives of the mine operator, many key design and planning commitments have been made at the initial planning stage.

The planning stage considered here is that period between the initiation of the feasibility study and the start of mine production. Subsequent planning tends to follow the developed production plans. Modifications are made only as made necessary by changes in financial, technical or social factors. Flexibility in any plan is the ability to cope with such change. The overall objective of underground mine planning is to develop an extraction (depletion) strategy that maximizes the economic benefits from the ore reserve.

In addition to traditional engineering, other constraints need to be taken into account, such as safety, environmental and social impact. The traditional engineering effort required to produce the optimum plan is governed by technical constraints such as ground stability or ventilation. The ability to plan with confidence is often limited by a lack of geological, economic and geotechnical information on the deposit at depth (Pelley, 1994). A plans effectiveness depends on the ability to foresee and provide solutions to possible production-related problems that can occur once the mine is operational.

Production-related problems can arise from peculiarities of the underground mine as well as the complexity of the production process. To optimize the mine plan, the following individual objectives need to be met (Pelley, 1994):

- maximize the overall percent age extraction of the mineral resource,
- develop an optimum sustain able rate of extraction,
- minimize the cost per unit extracted,
- minimize the initial development time and cost,
- provide a grade-control strategy and
- 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. 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.

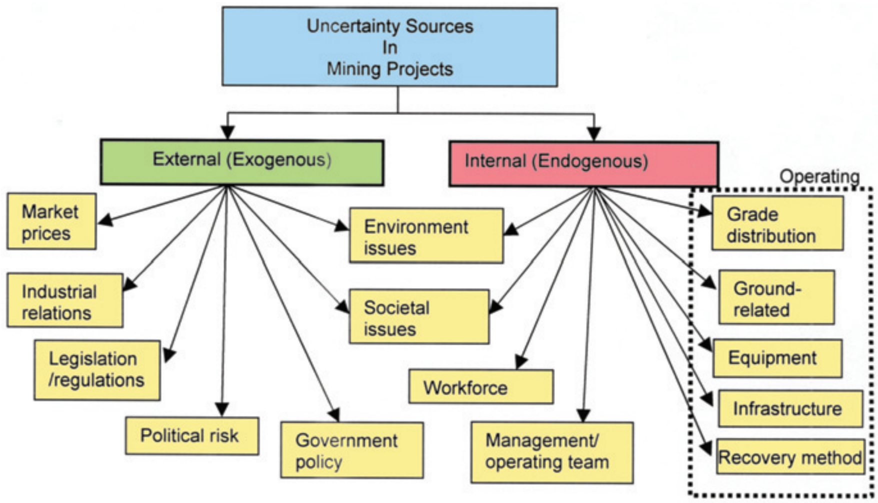
Strategic and tactical mine planning are complex and involved processes (Kazakidis et al., 1999). They also depend on the mine location, management's experience, economic conditions and local regulations. Also, mine planning has become further diversified in recent years as environmental and social factors have emerged that need to be considered in planning for sustainability (Anderson et al., 2001).

Sources of uncertainty for mining projects

Internal sources of uncertainty are those that are dictated by the deposit itself. External sources are determined by outside considerations, such as business or market requirements (Krantz and Scott, 1992). The internal sources in a min-

FIGURE 1

Sources of uncertainty in mining projects.



ing project relate, for example, to grade distribution, ground conditions, workforce, management/operating team, equipment and infrastructure. The external sources include market prices, environmental conditions, political/country risk, community relations, industrial relations, stakeholder issues, legislation and government policy (Smith, 1995; Dunbar et al., 1998). Depending on the type of analysis conducted and on the particular characteristics of a mining project, certain conditions may be perceived as internal rather than external, or vice versa.

Common sources of risk in mining projects are summarized in Fig. 1. According to Worth and Haystead (1990), the risk factors evaluated in a feasibility study by a financial institution include operational risk, technical risk, completion and cost overrun risk, market and price risk, country risk, legal risk and environmental risk. Environmental and safety-related aspects of mining project risk assessment have been evaluated by Summers (2000).

The efficacy of the production schedule and cost estimates in a mine plan will depend on its ability to account for 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. Obtaining additional information about a particular parameter (such as further drilling to improve the confidence in the grade estimation) can possibly reduce this risk, or building contingency into the plan through greater flexibility can mitigate this risk.

The flexibility needs of mineral resource investments as related to market risk have been examined by several authors (Singh and Skibniewski, 1991; Kajner and Sparks, 1992; Sagi et al., 1995; Samis and Poulin, 1997; Dunbar et al., 1998; Trigeorgis, 1998). Several types of flexibility have been identified for natural-resource investments by Trigeorgis (1990, 1998) that relate to the ability to defer investment, expand, contract, temporarily shut down, abandon and switch use. In that sense, flexibility needs to be built into a project to not only 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. The risk imposed by internal project factors that are nonmarket related, such as associated with operational uncertainty, is often not examined in such analyses.

Types of flexibility in underground mining systems

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. Examples of specific factors governing flexibility identified in planning and design of underground hard rock mines (Kazakidis, 2001) include:

- maintaining development openings well ahead of stope production,
- prediction of dilution and oversize and the measures to contain the problem,
- stope sequencing that includes "back pocket" stopes,
- bin capacity to accommodate production delays and the stockpiling of ore,
- scheduling mine production to accommodate quality and throughput requirements,
- extra support of openings in anticipation of rehabilitation needs,
- retaining the ability to blast out of sequence,
- ensuring the availability of spare equipment to maintain production levels,
- creation and use of alternative mine openings (ore passes, drifts),
- access to external resources (contractors, consultants),
- adequacy of inventory available in a warehouse,
- budgetary contingencies,
- ability of personnel to recognize a problem and
- breadth of training of mine personnel.

An evaluation of mine-planning practices in underground mines indicates that there is no systematic method for introducing flexibility in mine planning and design. This procedure is not documented or formalized. Instead, it is subjective and depends on the experience of the senior planner. Currently, there appears to be no formalized process to quantify the value of flexible alternatives in a mine plan. The process of decision making in mine planning, including the links to operating risk and flexibility assessment, is shown in Fig. 2.

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 alternative mining approaches should be sufficiently flexible to deal with difficult and unanticipated ground conditions. Despite such recognition of its importance, there are few means available to evaluate the level of flexibility inherent within a mine production plan.

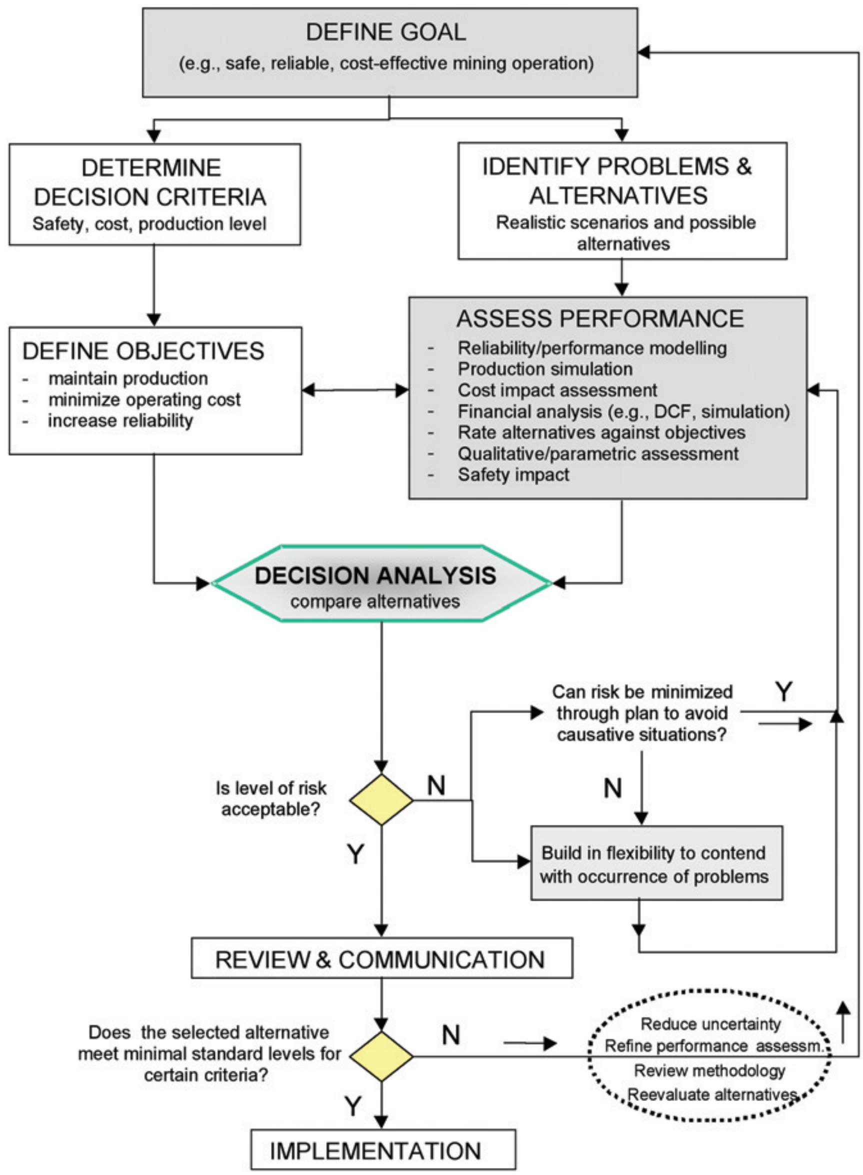
Valuation of production plan flexibility

Valuation of operational flexibility in mines can be conducted by comparing alternative scenarios. Here, the impact can be valued of a particular scenario on the mine production and the operating cost. Although traditional discounted cash flow (DCF) analysis and production simulation can be used to evaluate alternatives, the true value of flexibility cannot be determined.

Operating flexibility often considers the risk associated with nonmarket-related factors such as those operating problems that result in deviation from prespecified production and cost performance. Such flexibility is often constrained by geological complexity and excavation geometry, layout, access, sequence and mining method. Real options, in the form of multiple European put or call barrier options have been shown (Kazakidis, 2001) to provide an effective means to value flexible operating alternatives associated with ground-related problems in a mining system.

FIGURE 2

Process for mine planning and design for assessment of alternatives and risk (Kazakidis, 2001).



The applicability of options theory to make management decisions established several real options approaches for the evaluation of new technologies containing uncertainty in technical and financial performance (Armstrong and Galli, 1997; Dunbar et al., 1998; Samis and Poulin 1998; Trigeorgis, 1998). It was indicated that, using an option-based approach, an expanded net present value (NPV) can be calculated that includes the "static" NPV determined from a conventional DCF analysis plus an option premium that reflects the value of strategic options.

$$Expanded\ NPV = Static\ NPV + Option\ premium \qquad (1)$$

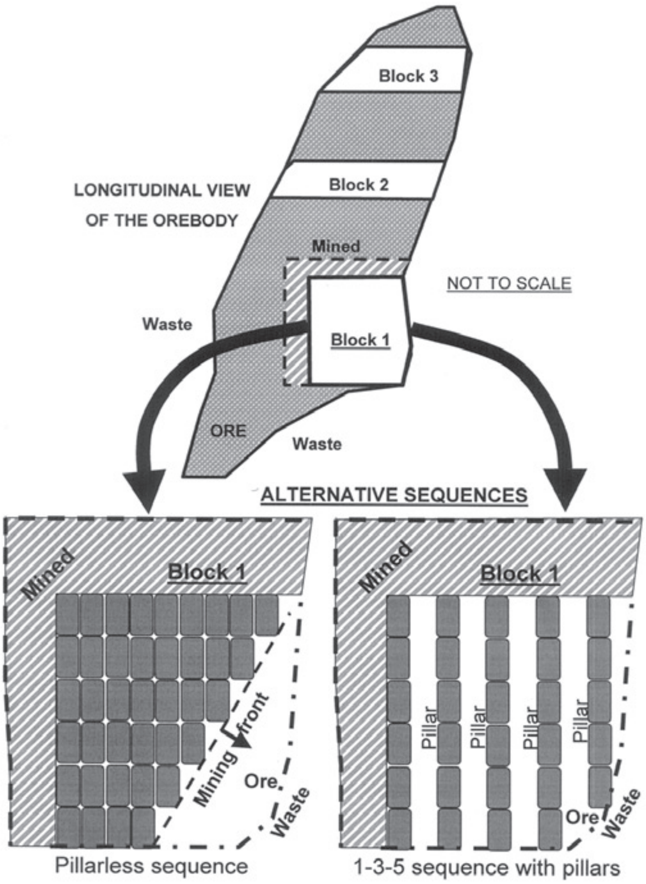
The application of real options to assess the flexibility of a mining system that contains operating risk/volatility due to production delays associated with ground-related problems was evaluated using Monte Carlo simulation (Kazakidis, 2001). Operating flexibility with respect to ground-related problems 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 favorable ground conditions (better than anticipated) is found in a mine sector.
- The up-front modification of a design parameter (sequence, stoping method and support system) to enable the operator to maintain the prescheduled production levels under low operating risk conditions.

In the example shown in Fig. 3, two alternative mining sequences were considered during the planning of

FIGURE 3

Consideration of two mining sequences.



the mining extension of a nickel orebody. A production schedule for each of the two sequences indicates that the pillarless sequence has a slower start up than that with pillars.

Once the potential production delays and additional operating cost due to ground-related problems are considered and quantified, then it becomes evident that this alone can change the decision over which sequence would be preferable. As an example of the introduction of flexibility into a mine plan, the availability of an extra rehabilitation crew is evaluated for the sequence with pillars. The cumulative cash flows are shown in Fig. 4. It is found that this option improves the overall NPV of the project and, therefore, that it is desirable to introduce this form of flexibility.

The results of such an analysis depend on the presumed frequency of ground-related problems and the costs to accommodate the needs for rehabilitation and rework. Should the intensity of these problems, or the cost to adopt measures to minimize their impact on production increase, then the analysis may result in a different conclusion. A sensitivity analysis for the sequence with pillars, with respect to the intensity of ground-related problems, is shown in Fig. 5. It can be seen that, once the annual impact of ground-related problems on lost production exceeds 17 kt (18,740 st), then the option obtains a positive value, and it becomes worthwhile to include it in the project.

Flexibility index

The decision making in a mining project often has budgetary constraints that can influence a decision to introduce a flexible option. 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

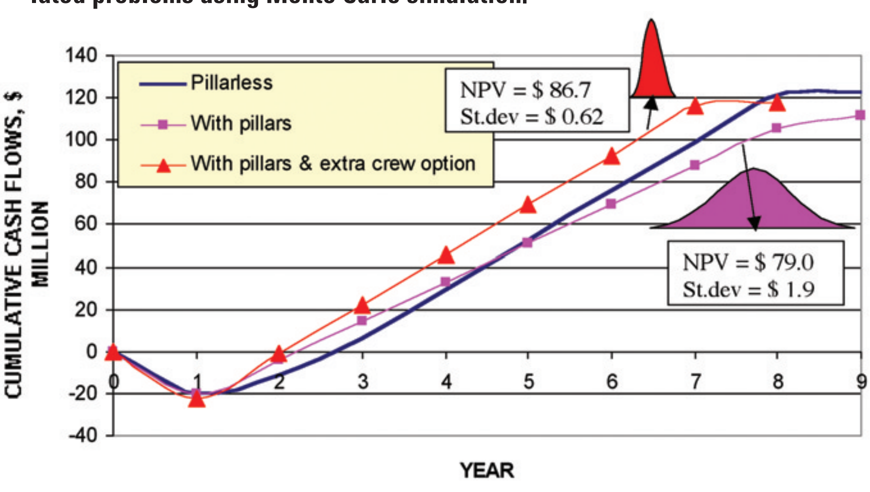
$$\text{Flexibility index, } F(\%) = \frac{\text{Option value, } OV}{NPV \ \ passive} \times 100, \quad OV > 0 \qquad (2)$$

A flexibility index value of 10 percent would indicate that the introduced flexible alternative would improve the NPV of the base case of a project (passive) NPV by 10 percent.

A flexible alternative is often associated with capital and/or operating costs that have to occur 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 flexible 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 (not necessarily to exercise) the option, discounted at time zero.

FIGURE 4

Cumulative cash flows for the two alternative sequences with ground-related problems using Monte Carlo simulation.



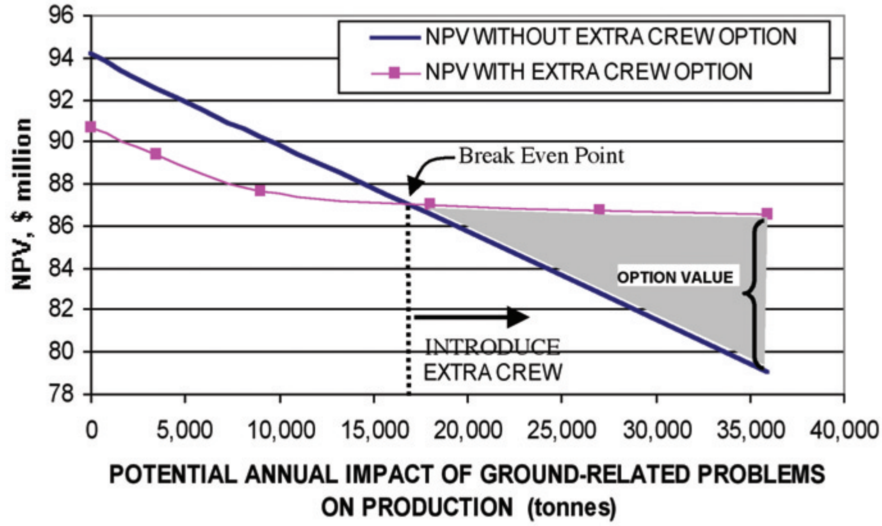
A comparison of the size of this capital cost outlay with the flexibility index can provide a means to examine which of the alternatives are most attractive and would be valuable to introduce as part of the mine plan optimization. Four flexible alternatives are examined in Fig. 6.

Alternative A1 (a second crusher in addition to an existing high-performance crusher) is characterized by a relatively low flexibility index value and a relatively high cost to implement it. The implementation of Alternative A2 (an increase in hoisting capacity at a later stage of a mine's life) will have a high impact on the value of the project, but will also have a high implementation cost. Alternative A3 (an additional vent raise) has a low cost and a low impact on the value of the project. Finally, Alternative A4 (a second unlined orepass system in a mine) has the higher impact of the four, while its implementation cost is the lowest, and it should be the most preferable one.

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, for example, 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.

FIGURE 5

Sensitivity analysis for the sequence with pillars with respect to the intensity of ground-related problems.



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, because 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, they can significantly improve 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 to determine its overall impact throughout the life cycle of the production system. This will enable the classification of the various alternatives in the manner shown in Fig. 6, which should provide a key input to the decision maker for budget allocation and prioritization of flexible alternatives.

Conclusion

Real options can provide a means for assessing flexibility in a mining system. Quantifying the probability of operating problems in terms of economic impact is needed to consider the optimization of a mine plan. Once an internal-risk model is established, then annual cash flows may be extended to include uncertainty due to various parameters.

The authors used ground-related problems and the evaluation of stoping schedule alternatives as an example of the approach. Risk can be minimized by planning to avoid causative situations and by building in flexibility to contend with the occurrence of such problems. The next-generation flexible mining systems for the competitive world of metal markets will be those able to adapt to downturns due to operating problems, while also taking advantage of opportunities from upturns. Evaluation of flexible alternatives will need to be conducted with reference to criteria such as the flexibility index demonstrated here. ■

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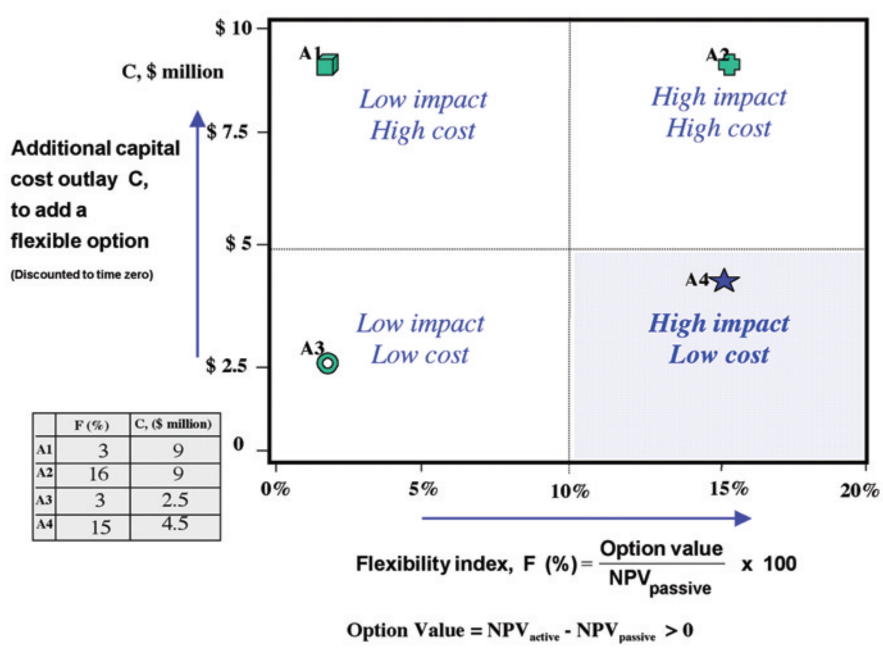
FIGURE 6

Classification of flexible options in a mining project using the flexibility index.



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