ENVIRONMENTAL RISK MANAGEMENT IN MINE DEVELOPMENT

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ABSTRACT

Techniques originally developed for hazardous waste containment design and site remediation have been adapted to the evaluation of waste disposal in open-pit mining. The method is formal and explicit yet cost effective, and ensures that development decisions are optimized and defensible. This approach to risk management is based on probabilistic risk assessment and decision analysis techniques. The method facilitates evaluation of the inter-relationships between mine development decisions, the trade-offs amongst possible consequences, the uncertainty in predicting consequences, and the flexibility to respond to changing conditions. The method has been applied, among other applications, to the evaluation of overall waste disposal systems for a major mine, the rational determination of reclamation bond values, and the design of close-out measures for a uranium mine. The approach provides a framework which links technical design criteria and relationships with costs and issues of environmental impact and public and regulatory acceptance.

INTRODUCTION

Decisions regarding mine development include alternative investigation programs, mine layouts, waste disposal systems, and reclamation schemes. Some decisions may result in significant impacts on the environment, safety, revenues and costs. Poor decisions can result in undesirable or disastrous consequences which might have been foreseen and avoided. The goal is to make decisions which result in the most desirable combination of consequences. One such combination would be minimum environmental impact, minimum hazard, maximum revenue and minimum cost.

Optimization is typically difficult to achieve for a variety of reasons:

• The various aspects of mine development are related to each other, so that decisions made regarding one aspect of mine development will affect decisions regarding other aspects.

• The various consequences which will ultimately result from any set of mine development decisions will generally not all be ideal.

• The consequences which will ultimately result from any set of mine development decisions will be uncertain beforehand.

In spite of these problems, decisions with potentially significant consequences must be made regarding mine development. Often, such decisions are reached primarily on the basis of the judgement of senior personnel, aided by analytical studies and other available information. Although such a subjective, implicit process has often been adequate in the past, it will not guarantee optimum decisions. More desirable consequences may be possible.
Such intuitive decisions cannot be defended easily to interested parties (e.g., stockholders, investors, regulators).

The objective of this paper is to explain and illustrate some practical applications of the decision analysis approach. A formal and explicit decision analysis approach, based on probabilistic risk assessment and established decision analysis techniques, is proposed to assist in making optimum and defensible decisions. This approach effectively mitigates the problems identified above, and costs much less to develop and implement than potential saving in mine development costs. The proposed approach provides the greatest confidence that the best possible consequences will result.

DECISION ANALYSIS APPROACH

The general approach proposed for making decisions regarding mine development is essentially similar to that for many other decision making applications, and has been developed and successfully applied in many cases, as described by Roberds (1990). The approach consists of the following steps, as illustrated in Figure 1:

1) System Description. An integrated, summary description of the entire system must be developed, including the main system functions, the primary components which ultimately comprise the system, the sequence of developing these components and the fundamental interactions among these components. This system description forms the framework for an optimized integrated mine development plan.

2) Criteria/Objectives. A comprehensive set of criteria and objectives of the system must be established, including constraints and preferences on the ultimate consequences. These criteria/objectives will be expressed in terms of measurable consequence. All criteria must be satisfied in order for the system to be acceptable and are non-negotiable.

3) Consequence Models. Models which adequately represent the system must be developed in order to predict the relevant consequences for any system alternative, for evaluation with respect to the established criteria and objectives. Such models are typically mathematical expressions for the consequence measures as a function of specific system parameters.

4) Assessment/Evaluation. The relevant consequences of each alternative must first be assessed and then evaluated with respect to the established criteria and objectives in order to determine the optimum mine development plan. The values of the various system parameters (as defined by the consequence models), and the uncertainties in those values, must first be assessed for each alternative based on available information. Those alternatives which are likely to fail any of the criteria will be screened out, with the remaining alternatives ranked in terms of the level to which they are likely to satisfy the set of objectives. The highest ranking alternative would be the optimum, and should be selected.
Hence, a defensible evaluation and ranking of the available alternatives can be developed on the basis of technical assessments of their consequences by experts, and criteria and objectives established by the stakeholders. One of the primary variables in this decision analysis approach is the level of detail chosen for the technical assessments. For example, the system could be described and optimized at the level of several major components, using simple consequence models with a few parameters each which are subjectively assessed. Such scoping analyses could form the basis for more detailed subsystem optimization with relatively little effort. The appropriate level of detail is obviously a function of the application, in terms of the potential benefits of optimized decisions and the level of uncertainty in predicting system consequences.

The various steps in the proposed decision analysis approach are illustrated using the following example of a mine waste disposal system.

**EXAMPLE OF MINE WASTE CONTROL**

**System Description**

The waste control system (WCS) of a large operating open pit mine is to be evaluated and optimized. The WCS must satisfy the waste stream on demand (i.e., by storage or disposal) so that it does not back-up and limit mine production. Currently the tailings are discharged into a nearby tributary river and the waste rock is end dumped into a nearby valley. Some of the silt and sand fractions of both of these waste streams are transported down stream to a main river and ultimately the ocean, which could possibly cause environmental damage in either as well as bed aggradation in the main river. Such bed aggradation in the main river, in turn, could result in closure of the main river to shipping during periods of low flow and floods during periods of high flow. River shipping is the main mode of transport in the region, both for ore concentrate going to market and for supplies going to the mine and to the local populations. Disruptions in shipping would directly impact mine production, depending on upstream buffer storage for ore concentrate and supplies.

The overall mine system is shown on Figure 2, in terms of the major subsystems, their components and interactions.

A set of alternative WCS's, consisting of different combinations of waste rock and tailings control subsystems, are proposed to mitigate potentially adverse consequences of waste disposal to various degrees. Some combinations of these subsystem alternatives are determined by inspection to be infeasible, whereas other combinations include supplementary subsystems (for backup) or complementary subsystems (such as dredging downstream). In the example, a total of 44 feasible combinations are identified for evaluation.
Criteria/Objectives

The criteria and objectives for the evaluation of WCS alternatives must first be defined based on discussions with mine staff. The criteria include the following, as summarized by the heavy boxes in the top of Figure 3:

- Provide sufficient mine disposal capacity over the mine life.
- Obtain governmental approval for the WCS, by achieving:
  - acceptable (preferably minimum) total hazards;
  - acceptable (preferably minimum) adverse environmental consequences;
  - acceptable (preferably minimum) adverse socioeconomic consequences.
- Maintain (preferably maximize) a positive cash flow over the mine life, by achieving:
  - low (preferably minimum) total costs associated with WCS;
  - low (preferably minimum) adverse impacts on mine production;

The degree to which the set of such objectives will likely be satisfied determines the preferability among the acceptable alternatives. Thus, a process of both screening acceptable proposals, and their optimal selection is conducted.

Consequence Models

A "system influence diagram", as illustrated in Figure 3, shows how system parameters affect the performance parameters of interest, based on discussions with mine staff and expert opinion.

As an example, the adverse environmental consequences might be expressed in terms of the suspended sediment downstream in the Main River. The suspended sediment downstream is a function of the amount of silt discharged from the WCS, the silt retention efficiency of the upstream tributary river, and the flow in the Main River. In turn, the amount of silt discharged from the WCS is a function of silt produced in the waste rock and tailings, and the WCS silt retention efficiency (for both base case and all potential failure modes).

Relatively simple algorithms, which adequately "quantify" the system influence diagram are developed based on discussions with the technical experts. Simple algorithms are considered to be sufficiently representative, because the uncertainties in the system parameters are typically large. This simplification allows much more efficient analyses than more theoretically correct and complex algorithms. The algorithms are chained together to determine each relevant performance parameter as a function of the various system parameters (i.e., the end points in the system influence diagram).
"Design consists of specific combination of waste system components which satisfy mine production.

FIGURE 3  SYSTEM INFLUENCE DIAGRAM
These mathematical models are subsequently formulated in a computer spreadsheet (LOTUS 1-2-3).

Assessment

The costs and other relevant consequences of each alternative WCS are predicted by assessing the various system parameters for each alternative, and then inputting these assessments to the consequence models.

Some of the system parameter values for an alternative WCS depend strongly on whether one or more of the WCS components fail and, if so, in what mode. Hence, a comprehensive set of possible failure modes (scenarios) must be identified for each WCS component, based on discussions with the technical experts.

The following major failure modes could be identified for a tailings dam:

- "Embankment instability" entailing costs to repair the damage and impacting mine production.
- "Overtopping" due to spillway malfunction.

The various system parameters, both for expected conditions and for specific failure modes, are estimated. The relative likelihood of any value of a parameter, given a specific failure mode, and the relative likelihood of each failure mode occurring, are defined by a simple triangular distribution, as shown on Figure 4.

For continuous variables, such as costs, the upper and lower bounds, as well as the most likely values, are estimated. A triangular probability distribution is fitted to these points and is an approximation of the assessor's actual beliefs.

An example of the use of expert judgement to define continuous variables is the assessment of the probability of seismic failure of a tailings dyke or retention dam. A dyke comprising loose tailings materials would be expected to exhibit distress when subjected to relatively low ground accelerations, in contrast with a dam comprising compacted fill. This assessment is illustrated in Figure 5(a) conceptually, and is assigned triangular distributions of probability of failure in Figure 5(b).

For bivariate parameters such as the occurrence of a specific failure mode, a single probability is defined.

Whitman (1984) described the evaluation of the factors affecting cracking of the core of an earth dam, as illustrated in Figure 6(a). A decision analysis of the probability of the back up systems working to prevent failure can be constructed, as shown in Figure 6(b).

All such assessments reflect the technical experts' opinions, based on available information, experience and judgement. Such assessments are not precise nor are they unique, possibly varying among experts, Roberds (1990).

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(a) Conditional pdf for system parameter

(b) Independent probability of failure

Fig. 4 INPUT ASSESSMENTS

Fig. 5 EXPERT OPINION OF SEISMIC RISK
The impact of such limitations can be evaluated subsequently by sensitivity studies.

The uncertainties in the parameter values and in the failure modes for each alternative WCS necessarily lead to uncertainties in the predictions of costs and other relevant consequences for that alternative.

The uncertainties in the predictions of costs and other relevant consequences are determined by "Monte Carlo simulation" using the computer spreadsheet model (LOTUS 1-2-3) with a probabilistic add-on, "@RISK", (Palisade, 1988).

Figure 7a shows the uncertainty in the "total predicted cost" for each of the acceptable WCS alternatives by Monte Carlo simulation. This prediction is based on the assessed probability distributions for the capital and normal operating costs, the costs associated with each occurrence of specific failure types (i.e., for cleanup, repair, remediation), and the number and type of failures which might occur over the mine lifetime, for each alternative. As illustrated in Figure 7b, for one alternative WCS, the uncertainty in each prediction can be expressed in terms of a "cumulative distribution function" (cdf), which expresses the probability that the actual total cost will be less than some value.

Evaluation

The various WCS alternatives are evaluated and ranked with respect to their "total value" in meeting the collective set of criteria/objectives. This total value is determined by:

1. Quantifying the objectives, in terms of a value scale (e.g., 0 for worst to 10 for best) for each objective and that objective's relative importance (e.g., 0.0 for unimportant to 1.0 for solely important). The owner's judgement, as opposed to the technical expert's, is used to develop these value scales and relative importance for each of the objectives.

2. Translating the predicted performance parameters to values (using the value scale), weighting the values (using relative importance), and summing the translated/weighted values.

The uncertainty in the "total value" is determined for each WCS alternative, based on the correlated probability distributions for the total costs and other relevant consequences. The "best" WCS alternative is identified with respect to satisfying the collective set of criteria/objectives, as quantified by the specified value judgements. As illustrated in Figure 8, the uncertainty in the difference in total value (relative to the "best" alternative) is also determined for each of the WCS alternatives.

The effect of uncertainties on the ranking can be determined by sensitivity studies. If found to be significant, the uncertainties can be reduced by further work until the alternatives are more clearly differentiated.
RECLAMATION PLANNING

Reclamation planning requires the engineer to take a very long term view of possible abandonment alternatives. Again a panel of experts is called upon to assign probabilities to possible modes of failure over the long term. For a facility such as a uranium mine tailings impoundment the concept of "walking away" is invalid. Rather, there is a choice between conducting routine periodic inspection and maintenance or doing nothing and reacting to problems as they occur. The adverse eventualities considered could include undetected defects, earthquakes, floods, droughts, and overall degradation. The expert panel must agree upon the decision analysis system which links these events with their effects, and their remediation, and the probability distributions for each linkage. The owners and regulators must review each possible branch of the system which should terminate with an acceptable solution. The owner establishes cost criteria, and can decide upon the optimum strategy using the approved decision analysis system.

A mine development plan includes plans for mine reclamation at mine closure resulting in a specific financial liability when implemented. The exact amount of this financial liability cannot be accurately known far in advance of when it is incurred, due to a variety of reasons, such as the conditions of the mine at closure, as well as changing regulations and construction costs/practices with time.

A bond fund is used to guarantee that sufficient funds are available to pay for adequate mine reclamation, whenever it becomes necessary. A variety of options are potentially available for determining the appropriate value of such a fund:

(1) Each mine can provide assurance up front that sufficient funds are available to cover the maximum reasonably possible reclamation cost which could occur at any time, which would be expected to be far in the future at planned mine closure. Hence, the mine would have to provide assurance that a very large amount of funds are available from the beginning, even though it is not expected to be used for a long time unless the mine is prematurely closed.

or   (2) Each mine could provide assurance at any time that sufficient funds are available to cover the maximum reasonably possible reclamation cost which could occur at that time. Hence, the mine could build up the bond fund with time at a rate sufficient to cover the potential liabilities, including reclamation as planned at closure. Such an approach would require periodic audits and assessments to determine the value of the bond fund and the amount of financial liability with time. At the time of planned mine closure, if not prematurely closed, the fund would equal that provided up front in Option 1.

Regardless of the option chosen, the fund should consider the uncertainties in future reclamation costs, if they occur, as well as when such reclamation occurs.
The approach in determining the appropriate rates that a mine should pay to cover reclamation at planned mine closure can be summarized as follows:

1. Develop mine reclamation plans for different stages of mine development (i.e., in case the mine closes prematurely), as well as at planned mine closure.

2. Estimate the costs associated with implementing such mine reclamation plans at each of the various stages of mine development.

3. Select an acceptable level of risk associated with the potential mine reclamation costs.

4. Determine the appropriate premium on the potential reclamation costs, to cover risks associated of underestimating costs, and the cost of tying up a large sum of funds for an extended period of time in an escrow fund.

5. Periodically audit and assess the potential liabilities associated with reclamation.

These steps are amenable to the use of decision analysis methods, as described for management and optimization of a Waste Control System.

CONCLUSIONS

An overall mine development plan, with a comprehensive set of contingencies, can be developed cost effectively using a decision analysis approach. The possible consequences, and the uncertainty are assessed for each alternative, consistent with available information based primarily on technical judgement. Tradeoffs among consequences are evaluated based primarily on value judgements of the various interested parties to identify those decision alternatives which will most likely result in the most preferred set of consequences. Constraints as well as preferences can be explicitly considered and the aspects of mine development which significantly affect the most important consequences can be identified and assessed in more detail. The explicit nature of this approach provides:

• clear justification and defense of the results to interested parties (e.g., regulatory agencies); and

• ready evaluation of the effect of possible changes in assessments (e.g., changes in technical assessments due to proposed additional work or changes in value judgements due to negotiations among the interested parties) beforehand.

Risk management in mine development can be achieved primarily by evaluating the hazards and impacts associated with alternative mine development plans, and then selecting the plan which has least risk. Once the experts have agreed upon the system, its analysis using spreadsheet software is relatively straightforward. Although the quality of the input may vary, the process of establishing the project-specific decision analysis system is very valuable because it is explicit and includes sensitivity analyses.
Further, this process serves to dispel misperceptions that projects can be judged against fixed, often arbitrary, numerical criteria. The decision analysis system provides a rational framework for negotiation.

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References

