Mine Planning – Its relationship to Risk Management

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Abstract

Mine planning is a typical engineering design function which integrate the disciplines of geology, metallurgy, geotechnics, mining and economics. The numerous uncertainties associated with geological understanding, the exposure of people to potential hazards in the work place and the need to provide a specific dollar outcome, requires a proper assessment of the risk. This paper identifies the sources of risk and suggests a rigorous methodology that can be followed to include risk management into the mine planning discipline. Techniques used in other engineering disciplines have been incorporated in this application to open pit mining. The responsibility of risk tolerance needs to be clearly defined by the directors of the mining company to allow the planning engineers to deliver an acceptable design.

1 Introduction

1.1 History:

Since risk inherently is a subjective instinct of man, it is not surprising that the first attempts at classifying risks were based on qualitative assessments by groups of persons. This still forms the most common approach to risk assessments in the mining industry. The common thesis within the financial community is that greater rewards are possible when a higher risk is tolerated, which therefore establishes the risk/reward relationship. A formal definition of risk followed as the following: Risk = {P(event)x(Consequences of the event)}. In the case of mining enterprises, the consequences could be safety of personnel, financial or company image. This definition forms the corner stone on which mining related risks are evaluated quantitatively.

Risk quantification became entrenched in the engineering discipline following some major failures of large dams and the advent of nuclear power stations in the mid 20th century, and has become standard practice in the design of chemical engineering plants. Since mining engineering is generally recognized as a high risk industry, it is only logical that these methods are now also being adopted within the mining industry.

1.2 Qualitative vs quantitative

Reliability of a risk assessment process is a function of harnessing all available information in a structured manner. Experience and knowledge is an important information source and is compiled from group workshops and is probably the most reliable data to be fed into the risk analysis process. The “Delphi Method” is one such process and relies on a “Panel of Experts”. “Review Boards” is another active process of risk identification and if need be, risk mitigation. These risk assessment procedures are commonly used in mining companies as a standard for risk management.

Results of qualitative processes are normally presented in a risk matrix format, either as block diagrams of likelihood vs severity, or in the form of bubble charts as shown in Fig 1 below.
1.3 Recent experience

There seems to be a trend developing in the last 5 years of mining projects not meeting their targets in terms of cost escalations as well as time over runs. This can probably be attributed to the economic upturn in the minerals industry worldwide and the pressure of delivery schedules with a shortage of skills to satisfy the demand. The greater incidence of major slope failures in open pit mines in recent years also testify to an increased appetite for risk to maximize economic value in the operation.

2 Risk Definition

The term risk is used in many different contexts, e.g. risk analysis, risk assessment, risk control, risk management etc. At the ‘risk’ of adding more confusion, this paper addresses the use of a risk criterion into the design of a mine to ensure a pre-defined level of risk to the mine. This process is therefore not a ‘risk analysis’ or a ‘risk assessment’, rather should be referred to as risk based design.

2.1 Technical definition

The technical definition of risk used in this paper is as given above:

Risk = \{P(event)x(Consequences of the event)\}

Where P(event) = Probability of an event occurring, expressed as a fraction of 1,

And Consequence = the cost in $ terms of the consequence assuming that the event has occurred, or the likelihood of personnel safety be impacted, expressed in ‘annual lifetime probability’.

2.2 Methodologies

The fault/event tree methodology has proved to be the simplest and most decisive process in quantifying the risk within the engineering discipline. Following the trends in other engineering disciplines, it has therefore
been adopted in this paper as the means to quantify the risks associated with mine planning. The fault/event tree methodology is a specific case of the more general application of decision tree procedures. This methodology is also referred to as the “bow tie” method, as illustrated in Fig 2 below.

![Fault/Event Tree Analytical Process: “Bow Tie”](image)

The fault tree comprises the left hand side of the bow tie, the incident at the centre of the bow tie represents the “TOP FAULT” in the fault tree analysis, and the right hand side represents the event tree with the consequences listed as the outcomes.

Risk based design is a probabilistic approach applied to what is perceived to be the best and worst case scenarios during the life of the mine. Time is also a component of the risk decision and it is conceivable that higher risks could be tolerated for a shorter period of time, such as at the end of the life of mine. The worst case scenario would therefore represent the highest risk scenario during the life of the mine.

2.3 **Time considerations**

Typical time dependent risks in an open pit mine are: minimum in pit ore exposure, rom stockpile capacity, number of haul ramps, haul ramp width, slope stability at the end of mine life, equipment life, etc. All these parameters can be handled within the risk design process using established probability theory of ageing probability calculation, e.g for a slope failure condition to develop: 

\[
P(F) = 1 - (1-p_1)(1-p_2)\ldots(1-p_n),
\]

where each bracket represents the probability of the slope not failing in preceding years or pushback geometry’s etc.

2.4 **Insurances vs production**

Quantifying the economic value of risk according to the above definition of risk, is a common practice in financial institutions and the insurance industry amongst others. The approach is so common that there are software suppliers dedicated to this market.
In the case of the insurance industry, risks are assessed on the statistical data available from many years. This data provides measured probability of occurrences as well as the cost of the incidents. Risk is then determined from trends applicable within the particular sector. The determination of the ‘cost of risk’ is then used to determine the premiums required to cover the cost of failure incidents.

In the wider financial sector, risk is valued using a knowledge basis and relies on experience and expertise to arrive at the cost of risk. For things like hedge funds of the futures market, it is simply impossible to develop actuarial risks for single future events (e.g. the price of a stock in one year’s time or the spot price of copper for delivery at a future date). Rather, risk assessment for such situations uses such statistical data as is relevant, financial models, and expert (reasoned) opinion to develop judgments about both the likelihood and the scope of the future financial event. But, even though derived differently from the insurance industry, the risk cost is used in the same way to devalue the asset and to determine an equitable lending rate in the event of loan financing or share value in the case of takeover transactions. This latter approach is more akin to the risk based design in a mining operation.

3 Sources of Risk

Each of the blocks contains uncertainties that contribute toward the probability of not achieving the output target, defined as the top fault: NOT ENOUGH COPPER. Using the range analysis technique, the likelihood is determined of not achieving or over achieving the target production. Risk is the measure of under achieving while opportunity is the measure of over achieving.

This paper is specifically focused on risk associated with the mine planning aspects only, but Fig 3 illustrates the context within the overall mining business.

Figure 3 Fault tree for a typical large Cu mine, identifying the sources of risk
3.1 Fault tree for the mine plan

The design criterion for a mine business plan would typically be NPV or NPC. A typical business plan would range from 5 to 10 years, depending upon the business risk period (BRP) adopted by management. For a life of mine that spans over a number of business periods the criterion for a plan would be more risk orientated than NPV driven, i.e., the criterion would be based on cost of metal production together with option creation.

3.2 Technical Risks

Technical risks are largely associated with the uncertainty in data and assumptions in design parameters. These risks arise when:

- The geological model does not predict the mineral resource within acceptable accuracy
- The geotechnical model does not perform as required.
- The mine plan turns out to be over optimistic

All of these technical risks can be evaluated quantitatively, mitigated pro-actively and the mine plan adjusted to satisfy management’s risk criteria.

3.3 Management Risks

Management risks are mostly associated with the personnel skills, training programs, investor interests and macro economic scenarios. These risks arise when:

- Operational standards are not up to required expectation
- QA/QC of operations and reconciliations to actual performance are not carried out diligently
- Sensitivity to HR issues are not handled correctly and communication is poor
- Investor needs are put on the backburner (arrogance) and reporting standards are lacking. Again a lack of communication.
Macro economic parameters such as price forecasting, exchange rates, royalty and taxes etc., are not usually the responsibility of the planning engineer, but belong to the board room. Information on which these decisions are based, should be provided to the board by the planning engineer, e.g. a minerals balance sheet\(^{(3)}\) (MBS) which would include the marketability curve for the mineral resource. A typical example is shown in Fig 5 below.

![Marketability curve for a typical Copper Porphyry](image)

**Figure 5  Marketability curve for a typical Copper Porphyry**

This curve represents the competitiveness of the resource within the supply market, when compared to the world producer cost curve. Fig 5 also presents the sensitivity of the resource to key uncertainties such as grades, slope angles and costs.

### 4 Mine Planning

Mine planning is like any other engineering design process and consists of the following steps as proposed by Bieniawski: (and previously also presented by Prof Stacey)\(^{(2)}\)

1. Clearly define the design objectives, criteria for design etc. Example, maximize value ito NPV, IRR, Risk etc
2. define the required information to reduce uncertainty
3. optimize the simplicity of the design components, e.g. pushback sequences
4. apply state of practice procedures
5. optimize the total design concept
6. ensure constructability

One of the most difficult decisions for a mine manager to make is to define how much information is enough to proceed with the mine plan. Mineral resource geologists have overcome that problem by adopting a code (JORC or SAMREC) for defining the different levels of confidence into Measured, Indicated and Inferred. These classifications are presented in Fig 6
CLASSIFICATION OF CONFIDENCE LEVELS

GEOTECHNICAL, MINING, ECONOMIC, METALURGICAL, MARKETING, ENVIRONMENTAL, SOCIAL AND GOVERNMENTAL FACTORS MAY CAUSE MATERIAL TO MOVE BETWEEN RESOURCES AND RESERVES

Figure 6  Mineral resource and ore reserve classification according to JORC

To convert mineral resources to ore reserves all the modifying factors as listed at the bottom of the figure, needs to be known at the same level of confidence as the resources to obtain a balanced design. This provides the standard by which all information should be judged and therefore also defines the data requirement for each of the modifying factors.

4.1 Optimization: inventory definition

The first step in the design process is the definition of ore inventory, erroneously referred to as pit optimization. Having determined the level of confidence required for the particular stage of design as discussed above, the inventory of economic ore is determined by using the Lerch-Grossman algorithm or the floating cone method. An important output from this design process is the marketability curve shown in Fig 5.

Since the optimization process is based on incremental prices, only profitable ore within the particular price limit is defined as ore. This process is therefore effectively a marginal cost analysis of the orebody, from which Fig 5 can be derived.

4.2 Business Risk Period (BRP)

Concept of the business risk period has been discussed by Steffen. In mining, as in any other business, time is an important ingredient in the risk exposure. The period of time over which a mining company is prepared to risk operating capital in developing the mineral resource has to be a conscious decision for that capital can only be retrieved from the ore to be mined from that development. In the case of open pit mines, pushbacks in deep open pits can take up to 10 years to complete. There has to be a level of confidence and risk that the development is adding value. The BRP effectively becomes the period of the business plan, because investments have to be made for that period. Business plans are therefore not arbitrary time intervals that appear convenient to accountants, but based on real business principles of risk and return.
4.3 **Vol Variance = ore exposure**

The volume variance characteristic of the orebody is the most important parameter from which the mine plan can be optimized. This characteristic determines the volume of ore to be exposed and the No of ore operating faces required to maintain a constant feed to the plant. Plant sensitivity to short term changes in feed needs to be addressed with a suitable stockpiling strategy. Effectively, this defines the logistics of the mining operation.

![Volume Variance Diagram](image)

**Figure 7** Diagrammatic volume vs grade variance curve

4.4 **Expansion optimization**

Expansion optimization is key to the efficient operation of the mine. A trade off between narrow pushback to minimize waste stripping and increased productivity in wider pushbacks, has to be evaluated. There is little reliable data on productivity of equipment in relation to bench height, pushback width and length and access geometry. These decisions are mostly taken on personal experience and preferences. Some useful tools have been developed to assist the planning engineer in this regard, e.g. COMET software. This part of the design process is best assessed by carrying out a quantitative risk assessment on alternative layouts, since the input parameters are not certain.

4.5 **Slope angles**

Slope angles are a key economic and risk parameter in open pits with high stripping ratios. Small changes in angles can provide large economic benefits, but can also determine the limit between stable and unstable slopes. Since the objective of mining is to maximize the value, steepening the slope angles to their limits are always under scrutiny. This is a clear case of evaluating risk against reward, where risk is not the failure of the slope, but the consequences of a failure. The author is of the opinion that slope failures are acceptable in open pit mines, provided that the consequences have been properly managed. Slope designs in open pit mines are therefore different from Civil Engineering slope designs, whence most of the design philosophy originates. The risk approach to slope design where design criteria are formulated for risk instead of a factor of safety, allows for the business case to be made for executive decision. This is illustrated in Fig 8 below.
SLOPE FAILURE (Normal Operating conditions) Include uncertainties for deviations in:
- Rock Mass Strength
- Structures
- Geology
- Groundwater

Analytical Model Uncertainty
Seismic Events

\[ \Delta P_{\text{unc}} \]
\[ \Delta P_{\text{seis}} \]

Figure 8  Risk approach to slope design

4.6 Ramp layout

Common perception is that single ramps save overburden stripping. This is probably true in small open pits, mined in very competent rock. It is also a truism that single ramps constitute the highest risk to the operation due to the potential of failure. Mitigation would be to design the slopes flatter, increase the width of the road or providing a second access road. When evaluated on a risk basis, a dual ramp system could be preferred as the slope angles could be increased to that of the single ramp design without changing the risk, or could even improve the risk exposure and improve truck productivity. Dual access is also preferred when haul routes traverse the slope below an operating pushback due to the rill (overspill) problem.

Ramp location within the pit walls can also be optimized when considering the relationship between the P(F) vs Slope angle for the different geotechnical domains and slope orientation.

4.7 Operating foot print

Production rate from a mining area is determined by the footprint and the bench height. These parameters constrain the rate of vertical advance that can be achieved for the particular orebody. In wet climate zones, it is further restrained by the capacity of the sump for the duration of the wet season. Again there is little reliable data that can be used to guide planners to schedule production rates for these situations. Mostly they are estimated from experience and mining simulation models.

5 Risk Evaluation

Review of mining plans are complex for it inter relates many activities into a single outcome. The reviewer is expected to pronounce if the plan is achievable in practice and what the risks are associated with the plan. More often than not, different reviewers will express opinions in terms of high, medium or low risk. While subjective opinion can never be totally eliminated from the process, a methodology is required that would address all the same variables and provide a suitable ranking to each.

5.1 Methodology

The methodology used is based on the decision tree process. The structure of the decision tree simulates the mining process and dependent and independent variables identified. Using the fault tree model, and applying ‘AND’(dependent variable) as well as ‘OR’(independent variables) gates, the likelihood of achieving the criteria can be determined by applying a range of values to each input parameter, and doing a Monte Carlo
simulation. A typical result is shown in Fig 9 diagrammatically. Sophisticated simulation models can achieve the same outcomes.

In this modeling process, subjective assessments are made of the range of values for each input variable, with credible lower and upper values. The modeling process also identifies the most sensitive parameters affecting the distribution of outcomes, allowing these to be investigated further.

### 5.2 Criteria

Invariably the NPV is the most common criterion for adjudication, but since the mine planning function is largely aiming to minimize the cost, the Net Present Cost is often used as a closer estimate of the efficiency of the mine plan, or the profile of operating cost per ton RoM. The question that still remains is: what is an acceptable confidence level of achieving the criterion, say NPV. In normal operating practice, it would generally be accepted that a plan should deliver within the 5% to 10% accuracy of cost, corresponding to a confidence level of 90% to 95%. The author is of the opinion that no single criteria can define the true value of any mining plan. For that purpose a comprehensive criteria has been suggested as follows:

**Comprehensive economic criterion for mining operations in order of importance:**

1. A reasonable return to shareholders, i.e. a dividend in line with shareholder expectation for the sector of the market in which the mine competes
2. Risk: A competitive cost profile wrt the world producer cost curve
3. Optionality: provide sufficient flexibility within the mine plan to utilize opportunity and mitigate against low prices in the future.
4. Maximize economic value in terms of NPV, IRR etc only after the previous three components have been satisfied. These values should be accompanied by a statement of confidence, expressed as a percentage. This is illustrated in Fig 10 below.
In Fig 10, three different mine plans are compared and the likely NPV determined for each, with the critical variables ranked wrt the influence on the NPV calculated.

### 6 Risk Mitigation

The major risk mitigation factors available to the mine planning engineer are:

#### 6.1 Flexibility

Flexibility translates to availability of ore. Most mining plans incorporate a policy of minimum ore exposed at all times to cover the short term requirement of ore delivery to the processing facility. There is clearly a cost associated with the provision of buffer stocks within the pit and the optimum tonnage provided can be
evaluated in economic terms. Normally these are based on the ore circuit only, and ignore the risk associated with a shortfall in waste stripping.

6.2 Option creation

Option creation is a larger version of the above flexibility. It is again developed by providing greater ore availability but not necessarily in the immediate short term. It encompasses advanced stripping to the extent that within a one year period, equipment can be redeployed and additional ore made available for increased metal production by changing the cog policy. The reverse scenario is when costs need to be lowered, stripping can be reduced without affecting the ore output to the plant. This degree of flexibility comes at a cost greater than that for normal operational flexibility, but adds additional value that can be quantified in terms of option valuation theory and therefore adds to shareholder value. It is also clear from this brief discussion that there is an optimum option value when the cost exceeds the additional option value created, as illustrated diagrammatically in Fig 11.

![Fig 11. Including option value into the NPV presentation.](image)

6.3 Business Risk Period

Adoption of a BRP limits the investment exposure of the mine to a defined period, which can be repeated regularly through out the period of the mine life. Refer Steffen (3).

6.4 Minerals Balance Sheet

The minerals balance sheet has been discussed in 1997 by Steffen(3) in detail. It is a communication form that allows decision makers from different backgrounds to synthesize the value and risks associated with different ore deposits. It is a form of data presentation that facilitates strategic process on a common information sheet that is illustrated in Fig 12.
7 Risk:Reward

Within the mining operation there are a number of different areas in which the acceptance of additional risk result in increased rewards to the mine and visa versa. These are areas that should be actively evaluated and presented to decision makers, for it represents the corporate view on tolerability of risk.

7.1 Ore exposure

Short term ore supply to cover normal operational interruptions

7.2 Stockpiling strategy

This is tied closely with the cut off grade strategy and addresses the utilization of the mineral resource. It therefore also impacts on the total value harnessed from the resource and is linked to the future commodity price scenarios. Stock piling is the main risk mitigation strategy available to planning engineers to manage uncertainties to the ore flow. Cost of the stockpiling strategy can be determined from the volume variance
characteristics of the orebody as previously described, and the benefit is determined from the improved recoveries obtained in the process plant due to a constant quality ore supply. Many examples exist of mines gaining big benefits from improved stockpiling strategies.

### 7.3 Slope design

- Categorization of slope design confidences as per the classification of ore reserves will provide a basis of information requirements to meet the required confidence in the ore reserve definition. The risks to reserves are therefore compatible with that of the mineral resource. This assumes that the metallurgical information on processing costs and recoveries are at the same level of confidence, using the same classification basis. Fig 13 illustrates a typical case of slope confidence defined for the remaining life of mine. Benefits of the process result from planning the exploration campaign to obtain the correct amount of information to satisfy the classification of the resource model.

![Diagram of slope design for different classifications during life of mine](image)

**Fig 13** Criteria for slope design for different classifications during life of mine

- Consequences of slope failures can be expressed in terms of fatalities, economic impact of minor to medium scale and major catastrophic impact requiring a force majeur declaration. Also consequences may result in worker reactions to unsafe working conditions and investor reaction to unexpected design failures.

- Criteria: the most difficult criterion to accept for miners is that of fatality. All mining companies have a mission statement of zero tolerance for fatalities. “There is no such thing as nil risk”\(^{(5)}\). This is not reasonable, but also not necessary as there are many codes in engineering that stipulates the design criteria for fatalities that are acceptable. These criteria are related to the incidence of deaths due to natural causes, expressed as annual lifetime probability of death. This is usually presented in a F-N diagram as shown in Fig 14.
Fig 14  Annual fatality frequency vs No of fatalities (F-N)

These criteria follow on long term multi-industry research statistics. Of particular note is the single fatality with an annual frequency of $10^{-4}$, corresponding to the “negligible” incidence line. This line is also known as the divide between voluntary and involuntary risk. This line is derived from the lowest incidence during a person’s life cycle of deaths due to natural causes in the north American population during the mid 90’s. This lowest incidence of death occurs at an age of 10 to 14 years. Case examples of deep open pit slopes are shown in Fig 14.

8 Value Optimization

- Option valuation

Utilizing the methodology of option valuation as applied to alternative mine planning options is a convenient application for optimizing the value of a mine plan. As mentioned previously, the options revolve around the degree of flexibility that is introduced within the mine plan at a measurable cost, for opportunities to be exercised at a later date, valued using option theory. Most commonly used methodology is the Black & Scholes model used in financial option markets. This process effectively allows the planning engineer to maximize the value by introducing a range of the degree of flexibility as illustrated in Fig 11.
• **Slope/stability optimization, monitoring**

In open pit mines where the depth is governed by limiting costs compared to an underground mine alternative, the most tangible option to increasing value is by steepening the slope angles. This increase in value is accompanied by an increase in risk of slope failures. A clear optimization process presents itself to the mine management who has to make the ultimate decision on the risk that they are prepared to tolerate. This requirement is specifically in contrast to the commonly accepted approach of management abdicating their responsibility of deciding tolerable risk levels under the banner of “we employ geotechnical engineers to advise us of these matters”. The geotechnical engineer’s competence extends to advising the manager of the quantitative correlation between slope angles and risks, but not to the business decision of “what risk is appropriate for the economic benefit gained for the shareholders”. This is the subject of some specific papers in this conference.

9 Conclusion

• **Major risks**

Technical risks: From a technical perspective, the major risks are related to geological understanding, from a mineralogical, structural and rock mass performance perspective. Prediction of slope performance has now replaced the mineral resource models as the greatest risk factor due mainly to the lack of sufficient geotechnical data. Groundwater understanding and predictive modeling has also become an increasingly important risk factor in mine design.

Business risks: Future prices will always remain the major uncertainty and also a risk factor as there is little that can be done to control these in the present volatile financial environment. Capital and operating cost estimates have become increasingly more difficult to manage in the present boom environment.

• **Major opportunities**

Optimization of cutback designs presents a major opportunity for improved returns, e.g. the COMET solutions. Similarly, introducing the volume variance statistic into the planning cycle presents a real opportunity for value adding. In valuation terms, the use of option analyses to determine the value of introducing planned flexibility options into the mine plan will not only add value to a mining project but also reduce the likelihood of destroying value.

• **Management responsibilities**

Mine owners are inherently risk takers. Unless the tolerable risk levels are clearly defined to the mine planners, the resulting risk exposure will be totally different to what the mine owners had in mind. From the mine planning and operations perspective, safety and economic risks can now be defined in specific terms to allow the planners to achieve the maximum returns for the stated risk levels.

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11 References


