Reliability Center Mine Planning Model for Caving Operations

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Abstract

Strategic mine planning defines: life of mine, mining reserves and production capacity of a mining project delineating the business value promise. In Block and Panel Caving, mine planning is supported by several geotechnical models that account for the underlying mechanics such as cave propagation, ore fragmentation, stress distribution on the production infrastructure, subsidence and gravity flow. Block and Panel Caving are mining methods that are integrated by components such as draw points, production drifts, ore passes and haulage drifts. The number of active components at a given time and the rate at which these components are incorporated into production define the production capacity of a mine. These components are subjected to be interrupted due to geotechnical upsets such as oversize, hang ups, large deformations, road repair. These interruptions influence the reliability of a given mining component to perform a specific production commitment. Thus, the true production capacity of caving methods should incorporate the expected rate of geotechnical events that could affect a given set of mining components since it would define their availability to produce a given production target. This paper, summarizes a methodology that has been devised that couples the rate of occurrence of geotechnical events and the production characteristic of a mining component through a mine wide reliability model that enables computing the true production capacity of a Block and Panel Cave mine. Then, different development strategies and production rates can be ranked together using the traditional financial project indicators together with the mine infrastructure reliability indicator. A mine wide reliability model has been implemented at DOZ PT Freeport Indonesia to support the mine expansion to 80,000 tpd. Until now the model has been calibrated and validated using historical production performance of DOZ. The model has also been used to study the effect of potential delays on the development of critical infrastructure and the coarse fragmentation expected for the Diorite rock mass. As a result of this implementation, several exercises have been performed in order to test the effect of different production scheduling components into the reliability of the long term underground mine production schedule.

1. Introduction

Production planning is the mining engineering activity that engages the natural resource inventory together with the market to offer a business promise to shareholders. Several decisions such as life of mine, mining reserve volumes, production capacity and investment profiles among others. Traditionally the components used in the production planning exercise to make such decisions have been cut off grades to delineate what resources are economic to extract, mining methods to define the way how the resources are going to be extracted over time, mining sequence to identify geometrically and space wise how the economic resources are going to depleted and development rates to define when a given piece of resource would be extracted. All these elements are decided dynamically over time, since a production plan should provide an answer to what portion of the ore body should be mined?, which mining and processing methods should be applied, when the different sections of the ore body should be mined and how much of the economic resources should be mined. In recent years much attention has been concentrated in defining and also integrating the uncertainty related to the components of the mine planning model. The uncertainty could by internal or external to the mining project itself (Kazakidis, 2002). For instance the grade and resource inventory uncertainty is considered to be internal to the project commonly, which has been modeled using stochastic simulation, has presented by Deutsch and Journel, (1997). The economic parameters used in the mine planning process such as metal prices, discount rates, and raw material costs have been considered to be external to the mining project. In this context, three sources of uncertainty are often defined for mining projects: grades and rock
characteristics, market and the mining system. Research has been done in order to integrate analysis of the first two sources of uncertainties, however, not much investigations have been taken in order to integrated the variability of the mining system to produce a certain amount of production. In particular, The Block/Panel cave mining system often lacks of a comprehensive geotechnical model due to the limited access to the rock mass given the reduced amount of drifting that is performed as part of the mining method. Another aspect of the system that induces uncertainty is the underlying mechanics that define the system functionality such as caving, fragmentation, stress and gravity flow (Brown, 2003) which are not fully understood by the mining community yet. This source of uncertainty induces geotechnical events in the mining system that tends to define the production capacity of an operation. As an example Figure 1 shows the relationship between the number of oversize and hang ups draw point events in a block cave operation and the tonnage throughput measured per month. It is clear that the frequency of geotechnical events conditioned the production capacity of a mining component, (a draw point in this case).

![Figure 1](image-url)  
**Figure 1**  Run of mine tonnage throughput as a function of draw point oversize and hang up events in a panel cave operation (Rubio, 2006)

The same effect shown in has been observed at individual components such as draw points, ore passes, equipments and other components. Thus, it is clear that when mine planners are delineating a production strategy for an ore body they should integrate this constitutive behaviour to commit production goals that are achievable and reliable. The curve shown above would be called the production characteristic curve and this would define the production constitutive behaviour of a mining component.

## 2 Background

Kazakidis and Scoble (2002) have introduced the concept of using mechanical reliability modeling to integrate geotechnical hazards into traditional mining systems in order to estimate the reliability of a given mine design. Also Rubio et al (2005) defined an application of reliability theory to production planning in Block Caving using redundancy allocation with identical sub components. Kazakidis and Scoble (2002) showed how a mining system could be analyzed and divided into components, in order, to compute the reliability of the system as a whole. Figure 2 shows a schematic representation of a traditional underground mining system.
The mining system in this figure is integrated out of the following components:

- 1 shaft
- 1 crusher
- 1 haulage drift
- 1 ore pass
- 1 ramp
- 3 stopes
- 1 ventilation raise

Depending on the relationship between the mining components one could use reliability block diagrams as presented by Hoyland and Rausand, 1994 to represent a simple mechanical system to construct a mine wide reliability model. Let us assume that a subsystem is composed out of three components: 1, 2 and 3. If the components are fully dependant on each other this would be modeled as the three components were connected in series as shown in Figure 3a. If three components in a system are working in redundancy this would be modeled as the components were connected in parallel as shown in Figure 3b. Figure 3c represents a system with redundancy at the subsystem level and Figure 3d shows redundancy at the component level. It can be shown that a system with redundancy at the component level Figure 3d is more reliable than a system with redundancy at the subsystem level Figure 3c.
In order to transform a mine design as shown in Figure 2 into a reliability block diagram model the methodology proposed by Hebers (1981) is used in which the author applies reliability modeling to assess the robustness of different strategies followed by ant colonies foraging for food. The concept applies in underground mining in which mine planners should look for the most robust design and production schedule that will deliver ore to plant. Then making an analogy between ants foraging for food and an underground mining system, the reliability block diagram of a mining system as shown in Figure 2 is presented in Figure 4.

Figure 4 shows that a complex underground production system can be simplified to three stopes connected in parallel and all the rest of components connected in series with the stopes. The rationale for this model is that if any of the main infrastructure components fail such as ore passes, shaft, crusher, ventilation raise or haulage the system would fail. The first comment to be made upon the model proposed above is that the traditional mining system have been designed and configured with very little or no flexibility, since the current financial valuation tools used to valuate mine design do not incorporate flexibility on the evaluation framework. Nevertheless by integrating a reliability model into the mine valuation a different optimum could be shown as it will be presented in the next section.

To compute the reliability of a mining component Vagenas et al. 2003, showed a methodology that can be used to compute the mean time between failure and the mean time to repair based on the frequency of
excavation failures by applying statistical methods used in mechanical engineering. The research discusses the difficulties of collecting geomechanical events and appropriate monitoring systems that could facilitate the analysis. Nevertheless, currently in block and panel caving mining there is often found plenty of data related to geotechnical events that tend to interrupt the ore flow through the mining system such as draw point oversize and hang ups, ore pass failures, drift convergence and collapses among others. These records have facilitated the implementation of a reliability modeling to support production planning decisions.

3 Block cave production schedule reliability

To introduce the concept of reliability in block and panel cave production planning there are some definitions that have to be outlined in order to formulate the mathematical models that would support reliability calculations.

- Event: an interruption to tonnage flow through a mining component (drawpoint, ore pass, mining equipment, etc.), it does not necessarily makes the system fail.
- Reliability (Schedule): It is the probability of a component to reach, at least, the planned tonnage in a certain time period
- Failure: when the system did not reach the planned tonnage in a certain time period.

The application of reliability theory in mine design and production scheduling would be illustrated in an application developed for the Block Cave mining method. A plan view of a typical Block Cave mine is shown in Figure 5.

The mining components of the system shown in Figure 5 are listed as follows:
- Draw points: 150-600
- Production crosscuts (Xcuts) : 15-50
- Crushers: 2-6

The block diagram reliability model associated with the traditional block cave mine design as shown in Figure 5 is presented in Figure 6.
Figure 6  Reliability block diagram of a block cave mine

The block cave reliability diagram is composed out of a subsystem of draw points connected in a structure that contains redundancy (k-out-of-n). This structure is connected in series with the production drift to define a production crosscut. The production crosscut become a sub system that contains redundancy to produce a given production target. One aspect that makes the reliability model of a block cave and panel cave mine different are subsystems that contain redundancy at the component level. For example it is observed that the draw points in a production crosscut and the crosscuts in the mine contain redundancy. This means that there are stand by components at the subsystem level, for example, in a crosscut there could be n draw points available and to meet production just k draw points are needed. The interesting part of the model is that the amount n-k would depend upon the production target assigned by the production schedule to the mine design. For example, if there are 20 draw points in a production crosscut with nominal individual productivity of 3,000 tons per month and the tonnage target for the month for the crosscut is 30,000 tons the draw points subsystem would be defined by a 10-out-of-20 model. However if the production target goes to 45,000 tons a month then the draw point subsystem is defined by a 15-out-of-20 model. This is relevant since the overall design reliability will be affected by the production target. This simple model shows that in block cave mining the mine design and the production schedule are coupled to define the reliability of the mining system.

To compute the reliability of a k-out-of-n system a combinatorial approach is needed in which all the possible combinations of k out of n draw points are evaluated. Every one of the combinations would be connected in series, and all the combinations would be connected in parallel. Thus, a simple binomial distribution could be used to compute the reliability of this system. Nevertheless, the components in the block panel caving case are non identical, i.e. they show different reliabilities among the set. This complicates the calculation and a recursive approach has been introduced by Rubio (2006) in order to compute the reliability of this structure. The problem formulation is presented below:
\( n \) number of components in the system
\( k \) minimum number of components that must function for the k-out-of-n system to function
\( r_i \) reliability of component \( i, i = 1, 2, \ldots, n \)
\( r \) reliability of each component when all components are identical.
\( q_i \) unreliability of component \( i, q_i = 1 - p_i, i = 1, 2, \ldots, n \)
\( q \) unreliability of each component when all components are identical \( q = 1 - p \)
\( R_e(i,n) \) intermediate reliability entry which represents the probability that exactly \( i \) out of \( n \) components are functioning
\( R(k,n) \) reliability of a k-out-of-n system or probability that at least \( k \) out of the \( n \) components are functioning, where \( 0 \leq k \leq n \) and both \( k \) and \( n \) are integers
\( Q(k,n) \) unreliability of a k-out-of-n or probability that less than \( k \) out of the \( n \) components are functioning, where \( 0 \leq k \leq n \) and both \( k \) and \( n \) are integers, \( Q(k,n) = 1 - R(k,n) \)

Suppose that in a given crosscut there are \( n \) draw points available and depending on the average draw point yield and the crosscut production target, \( k \) out of the \( n \) draw points are needed to meet the target. Define a subset of \( i \) functioning in series out of \( n \) available as \( s_i \) with \( C_{i,n} \) (where \( \tau = 1,2,\cdots C_{i,n} \) is the combinatorial of \( n \) over \( i \)) and \( k \leq i \leq n \). (\( i < k \) will not be a feasible system.) Then the reliability of a given subset \( s_i \) is

\[
R(s_i) = \text{Probability that components } t \in s_i \text{ available} \\
\quad \times \text{Probability that components } t \in s_i^{n-i} \text{ are not available}
\]

\[
= \prod r_i(t \in s_i) \prod q_i(t \in s_i^{n-i})
\]

Denote the set of all \( s_i \) subsets is by \( S_i^n \). Then the reliability of the k-out-of-n system with non-identical and independent components is given by

\[
R(k,n) = \sum_{i=k}^{n} \sum_{s_i} \left[ \prod r_i(t \in s_i) \prod q_i(t \in s_i^{n-i}) \right]
\]

To solve the above the recursive algorithm developed by Barlow and Heidtmann (1984) is available to compute the intermediate entry reliabilities \( R_e(i,j) = q_j R_e(i,j-1) + p_j R_e(i-1,j-1) \). Then the intermediate entry reliabilities are summed to compute the k-out-of-n subsystem reliability as shown below:

\[
R(k,n) = \sum_{i=k}^{n} R_e(i,n)
\]

Incorporating the tunnel or production drift reliability into the above equation the production crosscut reliability is computed as follows: \( R_{CX} = R_T R(k,n) \), where \( R_T \) is the production drift reliability and \( R_{CX} \) is the crosscut reliability. As an example Figure 7 shows how a subsystem defined by a 10 out of 15 draw points behaves reliability wise compared to a 10 draw point connected in series.
System Reliability

Component Reliability

Figure 7 Comparison between a 10-out-of-15 draw point subsystem with a 10 draw points connected in series.

One fundamental component of the block cave reliability model has to do with computing the reliability of the mining components. The following describes the methodology to compute the reliability of a mining component.

3.1 Rate of occurrence of geotechnical events

For a given collection of mining infrastructure \( S \) such as draw point, production drift, ore pass, compute the cumulative number of events \( N_i(t) \) over a given tonnage maturity \( t \) of component \( i \) of set \( S \). Compute the average of \( N_i(t) \) to define \( M(t) \) which would represent the average tendency of \( S \) to experience a geotechnical event. Compute the rate of occurrence of geotechnical events for \( S \) as \( \frac{\partial M(t)}{\partial t} = w(t) \). This process has been computed for draw points of three different block and panel cave operations and the results are shown in Figure 8.

Figure 8 Rate of occurrence of draw points geotechnical events for three operating block and panel cave mines.
Figure 8 shows that there is a similar tendency (decay) for all three observed rate of occurrence of events with different intensities for the same maturity. This is highly correlated with the rock mass environment in which these operations are working. In fact, there is a direct correlation between $w(t)$ and the rock mass rating.

3.2 Mining Component reliability

To compute the reliability of a given mining component the expected number of event in a given planning period needs to be estimated. Then, the expected number of events is computed by numerical integration of $w(t)$ over the planning tonnage $t^p_i$ committed in the production schedule for a given planning period. Having the expected number of geotechnical events $\tilde{N}$ one could compute the conditional tonnage distribution over the production characteristic curve of the mining component. The production characteristic curves represent the trend of production in a given planning period as a function of the number of geotechnical events. This curve is often computed as a function of production back analysis or discrete events simulations. Then the reliability of a mining component is computed by reading on the cumulative probability distribution conditioned to the expected number of geotechnical events $R(t,t^p_i) = P(t^p_i > t^p_i \mid N(t) = \tilde{N})$. A diagrammatic representation of the process is shown in Figure 9.

![Figure 9](image.png)

**Figure 9**  Estimation of draw point reliability from a production characteristic curve

After computing the reliability of the mining components these estimates are integrated into the k-out-of-n block cave block reliability diagram to estimate the reliability of the whole production system. Thus, a mine planner could simulate different production targets passing through the mining system at different stages of the mine life as shown in Figure 10. An exercise like this one would allow financial evaluators to assess project risk assessment as a function of the inherent reliability of the mining system, rock mass behaviour and production targets.
4 DOZ ESZ Extension Case Study

DOZ mine is currently the most productive Mechanized Panel Cave operation in the world producing 53,000 tpd and is facing an expansion to accomplish 80,000 tpd by the fourth quarter of 2009. The new mineralized zones that are going to be mined in the expansion consists of mainly Diorite rock which is expected to have coarse fragmentation and eventually high stress, so maybe the relatively good behavior of the rock mass in the past is not going to be the same, therefore, the question of how much reliable is the schedule to reach the productive promises is not a question easy to answer. These facts have motivate PT Freeport Indonesia to develop a reliability model that could assist mining engineers to visualize potential production bottleneck and monitor the effect of different fragmentation on the overall mine production capacity as a result of operational geotechnical interferences.

4.1 Reliability model for PT Freeport Indonesia

One of the difficulties of the DOZ reliability model is that the mining infrastructure contains a separate haulage level that connects with the production level through ore passes. Therefore, the reliability model presented before for block caving can not directly be used to assess the DOZ production schedule reliability. A diagrammatic representation of the DOZ mine layout is presented as follows:

The main mining components considered in the model are: 1332 draw points, 37 production drifts, 53 ore passes and 3 haulage drifts. It is important to note that the model consider, for each period, only the available infrastructure for reliability calculations, according to the development schedules and status (active, closed).
of each component. The three dimensionality of the mining infrastructure was solved by adding another \( k\text{-out-of-}n \) structure that represents the ore passes connected to a given haulage drift. This structure would be connected in series with the \( k\text{-out-of-}n \) structure of production crosscuts. The following is a representation of the model.

![Reliability block diagram of a complex multi layer panel cave operation](image)

**Figure 12** Reliability block diagram of a complex multi layer panel cave operation

As an example the rate of occurrence of geotechnical events and the production characteristic curve for draw points are presented as follows

![Rate of occurrence of geotechnical events and Draw points PCC curve](image)

**Figure 13** Rate of occurrence of geotechnical events and production characteristic curves of DOZ draw points.

In order to validate the reliability model there was selected a single production crosscut and for two years of historical monthly production the tonnages were played back into the reliability model. The expected outcome is to have a constant reliability of 100% since these tonnages were selected from historical performance. The results of this analysis are summarized in Figure 14. It is shown that for over 1.5 Mt/month the model reliability drops significantly. This is due to the maximum productivity of the haulage truck drift which is set to be at that level. There is still undergoing analysis to backup the maximum productivity of the haulage truck system in order to update this parameter in the reliability model.
4.2 Mine Design and Production Schedule Analysis

Once the model has been reasonably validated at the panel and draw point level. The first numerical experiment set up consisted of analysing the reliability performance of a production crosscut with one or two ore passes. Figure 15 shows that there is no much difference up to 110 Kt/month. Nevertheless the analysis showed that with the same level of reliability two ore passes could facilitate the increment of production of about 25Kt/month.

Note that the free risk tonnage (maximum tonnage with 100% reliability) increases from 100Kt/month to 125Kt/month, this effect is mainly because the tonnage that comes from the panel has two exists, so each ore pass is less stressed. In the other hand, if the planner has to move, for example, 150kt/month from this panel, the reliability increases from 25% (one ore pass case) to 55% (two ore passes case). Certainly the above quantifications allow the mine planner to make better decisions.

A second level of reliability analysis desired at Freeport consisted of analysing the effect of development delays and unrecoverable geotechnical events faced in critical mining infrastructure.

Simulation 1: Construction delay at ore pass

This simulation consisted on analyzing the effect of an ore pass development delay, in particular (LP04S), from September 08 to December 08. The results are summarized in Figure 16.

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Figure 14 One panel historical reliability

Figure 15 1 vs. 2 ore passes per production drift
The decrease in reliability is due to the ore pass LP04N (located in the same panel) that has to support the whole panel production instead of just sustain half of the tonnage. This creates a LP04N very unreliable to produce the total panel target and consequently reduces the overall system reliability.

**Simulation 2: Unrecoverable geotechnical event at ore pass**

This simulation scenario consisted in to analyze the impact in the reliability of the schedule the permanent closure of the ore pass LP06S (due to a collapse or a non recoverable geotechnical event) in June 2008. The results are summarized in the following graph:

Reduction in reliability is due to the ore pass LP06S (located in the same panel) has to support all the tonnage of the panel (instead divide the panel tonnage: half for LP06 and half for LP06S), reducing its own reliability and the whole system reliability value. In this case the failure in the ore pass is non recoverable and the system can not recover to normal situation. Additionally, in comparison with simulation 1, in that months in which neither Panel 04 nor Panel 06 have two active ore passes (Sep 08, Oct 08 and Nov 08), the impact in the reliability values seems to be larger when panel 06 loses redundancy in ore passes and it is due to Panel 06 support more tonnage than Panel 04. Eventually, a deeper schedule reliability analysis would aim to detect critical components for the whole ore management system, for a given schedule.
5 Discussion and Conclusions

The understanding of Block and Panel caving as mining systems can be facilitated throughout a reliability model that integrates the inherent constitutive behavior of rock mass within the mining system. The reliability model integrates mine design, together with the underground development schedule and the production schedule to facilitate the assessment of robustness of a given mining system.

The reliability model showed a high dependency on infrastructure availability and development scheduling not much on draw points, so this tool allows quantifying several issues, listed as follows:

- The productive performance of a block and panel cave mining system does not depend just on the draw points available and their production characteristics. To reliably assess the production capacity of a complex multi layer mining system the overall infrastructure availability should be considered as in the case of block and panel caving haulage crosscut performance are critical to deliver the production targets to the crusher.

- Production and development schedules for panel caving are not independent. Naturally, if the mine is not prepared it can’t produce any ton, but the way we prepare the mine impacts in the probability of achievement of a given production schedule because the available infrastructure to move out the tonnage it’s going to be different for different development schedules.

It was shown that the reliability model was able to reproduce the historical mine performance with some initial parameters. However, it is important to improve the current model by incorporating the actual frequency of geotechnical events of ore passes and haulage crosscuts. Also a proposed improvement has to do with developing production characteristic curves for production crosscuts that could eventually operate with two LHDs and two ore passes. This would provide a whole new range of analysis that are not often considered when planning a block cave mine.

Finally, it can be seen that this tool allows detecting critical components for the ore management system and quantifying its impact on the overall mining system. Particularly for the study case analyzed in this paper, the production capacity will be highly dependant on the ore management system availability, so another issue becomes relevant: infrastructure repair strategies.

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