Footprint and Economic Envelope Calculation for Block/Panel Caving Mines under Geological Uncertainty

E. Vargas University of Chile, Chile

N. Morales University of Chile, Chile

X. Emery University of Chile, Chile

Abstract

Traditional long-term mine planning is based on deterministic ore body models, which ignore the uncertainty in the geological resources. Therefore, the mineable resources and mine plans are not robust and the actually obtained values may not meet the promised values at the beginning of the project. Geological uncertainty can result in important differences in the economic value of the plan and in the outline shape of the mine.

This paper deals with developing a tool that incorporates geological uncertainty in early stages of the planning process: defining the economic envelope in a massive underground mine. The rationale is to compute an economic outline of the mine that aims to maximise the contained value while limiting the difference of the height of adjacent columns, all this for each level. As a result, this tool gives an approximation of the shape and value of the economic envelope of a block cave mine, which can be used as an input to a post scheduling process.

The algorithm is tested on a real case study and validated against existing software alternatives. Afterwards, it is extended to work with geological uncertainty, which is modelled using a set of conditional simulations of the mineral grades. The results for this case study indicate that geological uncertainty can generate a gap greater than 100% in the economic value of the footprint and the total tonnage of the envelope, between the best and the worst grade scenarios. On the other hand, the shape of the envelope varies in each grade scenario, making it difficult to make an optimal decision on the placement of the developments for a posterior extraction sequence.

1 Introduction

Traditional long-term mine planning is based on deterministic information, therefore plans and decisions may not be robust against uncertainty and estimated value and production promises may not be achieved. One example of this is the uncertainty on the resource model: while techniques like conditional simulations are well developed to model the spatial variability of grades, existing mine planning tools do not allow incorporating them into the planning process. They only allow integrating uncertainty a posteriori, by means of sensitivity analyses, so that variability is estimated but not controlled.

Many authors analyse the impact of geological uncertainty in open pit mines in terms of differences between promises and actual values (e.g., Dimitrakopoulos, 2011), but there is a lack of references about uncertainty in underground mines. On the other hand, approaches are used to calculate mine reserves in block/panel caving mines. The draw point oriented methodology (Diering, 2000) has been validated and improved along the years and seems to be the mainstream methodology; meanwhile another recent methodology based on the upside down pit algorithm (Elkington et al., 2012) generate mine outlines and footprints using different cut-offs, but none of these methodologies consider geological uncertainty in their algorithm.

This work aims at developing a tool such can incorporate geological uncertainty in early stages of the planning process: defining the economic envelope in a massive underground mine. The results of the case study will be specific to the ore body and block/panel caving mining method.

2 Methodology

The main objective is to calculate the economic envelope of an ore body to be mined using the block/panel caving method. To this end, two methodologies are used to calculate the economic footprint and envelope, respectively.

2.1 Footprint Calculation

Similar to the footprint finder methodology (Diering et al. 2008), we calculate the economic level where the undercut level should be placed, it means the economic boundary and layout of the underground mine. It is based on the profit of the blocks discounted by when they will be extracted given the position of the block in the block column (equation 1).

$$v_i^{'}(x,y,z) = \frac{v(x,y,z)}{(1+\alpha)^{\frac{dz}{\text{vmining}}}} \qquad (1)$$

Where:

v and vi’ = block economic value and discounted value of the block assuming i as the undercut level [$/t].

dz = block height [m].

v mining = Vertical Mining Rate [m/yr].

α = discount rate.

To simplify the decision where to put the undercut level, the value of the footprint will be the only decision variable. This implies finding the maximum footprint economic value.

2.2 Economic Envelope Calculation

Given the results of the economic level, the next step is to calculate the economic envelope. This will represent an approximation to the mining reserves in the ore body. The methodology behind this section is based on the ultimate pit algorithm, and is applied with some modifications in order to resemble the caving geometry, as follows:

- Cut the block model:
  - Remove the block model data below the economic Z level.
  - Set the maximum height of column.
- Invert the Z coordinate in the block model.
- Create a set of slope precedence constraints in order to control the maximum adjacent height of draw (HOD).
- Calculate the economic envelope using the constraints and modified block model, given equation 2:

$$\max \sum_{i=1}^{B} v_i \cdot x_i \tag{2}$$

Where:

B = total number of blocks

v_i = economic value of block i

x_i = binary decision variable to extract block i or not

- Post processing of the envelope:
    - Set minimum column height
    - Set minimum mining footprint dimensions.

The steps described above are solved using the MineLink library which is part of the BOS2M open-pit scheduler and sequencer (Rubio et al 2011). In addition, the results of the economic level (footprint) are validated against PCBC (GEMS) software commonly used in caving mines.

2.3 Extension to consider geological uncertainty

Once we have developed a tool to optimise the economical envelope, the geological uncertainty is introduced by using conditional simulations to generate different resource models. The simulations are constructed with the TBSIM program (Emery and Lantuéjoul, 2006). For each simulation (block model scenario), the optimal footprint and economic outline of the mine can be computed. Subsequently, a quantification of the uncertainty is done, applying the Value at Risk (VaR) evaluation which has been used in previous publications to assess the impact of geological uncertainty in open pit projects (Vielma et al. 2009).

3 Data

The data consist of 100 simulations of a real ore body. Each one of these simulations has a total of 2.34 million blocks of 10x10x10 m^3 and 149 levels (10 meters per level). The copper grade was the only simulated variable, and the tonnage and density for each block are assumed constant. It is also supposed that all the calculations are done over the same mineralised zone (same rock type). The economic data used in the block evaluation is shown in Table 1.

Table 1 Economic parameters

Parameter	Value
Price [US$/t]	2.5
Selling Cost [US$/t]	0.35
Mine Cost [US$/t]	10
Plant Cost [US$/t]	16.1
Recovery	87%
Density [ton/m3]	2.7
Maximum Column Height [m]	500

Minimum Column Height [m]	100
Productivity [tpd]	200
Utilisation [days/year]	200
Slope Angle	45°- 60°- 90°

Also, validation was done over block model obtained by kriging and 10 different simulations, using the same economic parameters in the two methodologies. No development costs where used in the economic evaluation.

4 Results

4.1 Validation

Between the methodology used in this paper and PCBC there are some differences in terms of accumulated value, tonnage and area of the footprint, thus there are differences in the economic level where the undercut level will be placed. Table 2 summarises these differences for the 11 block models evaluated (negative values mean PCBC values are greater than MineLink values).

Table2 Differences between PCBC and MineLink methodologies

	Differences			
Block Model	**Level**	**Economic Value**	**Tonnage**	**Area**
Kriging	-2	-5%	10%	-33%
1	-5	9%	17%	-14%
2	-1	4%	14%	-6%
3	-1	8%	15%	-13%
4	-1	3%	13%	-7%
5	-1	-2%	11%	-18%
6	-1	-4%	11%	-17%
7	1	2%	11%	-14%
8	-1	1%	13%	-12%
9	-4	0%	11%	-8%
10	0	6%	15%	-1%

To illustrate the previous table, the results for the accumulated economic value and tonnage for one simulated block model are shown in Figure 1.

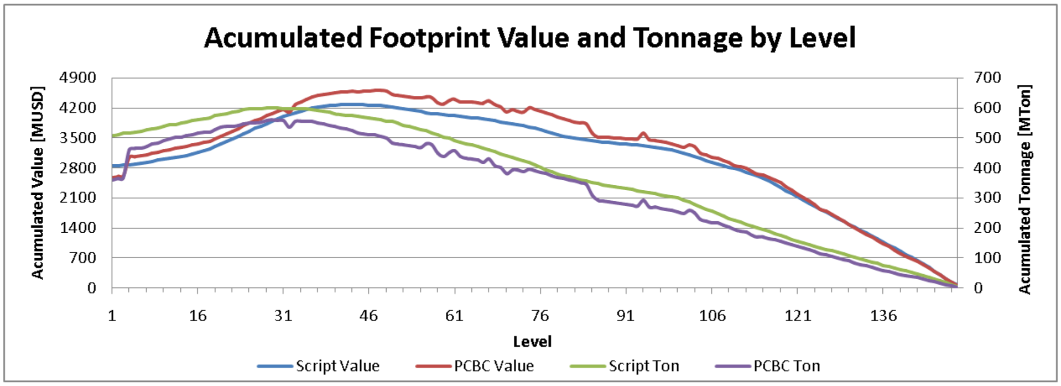


Figure 1 Footprint validation results over one simulation

The difference in value between these two methodologies is up to 10% near the optimum economic level, and greater differences can be observed in the last and less deep levels.

4.2 Footprints Results

Appling the methodology described in this paper, different curves of accumulated value and tonnage can be generated for each scenario. Given that all these curves were generated over 100 simulations of the ore body, the differences between the curves depict the geological variability or uncertainty (Figures 2 and 3).

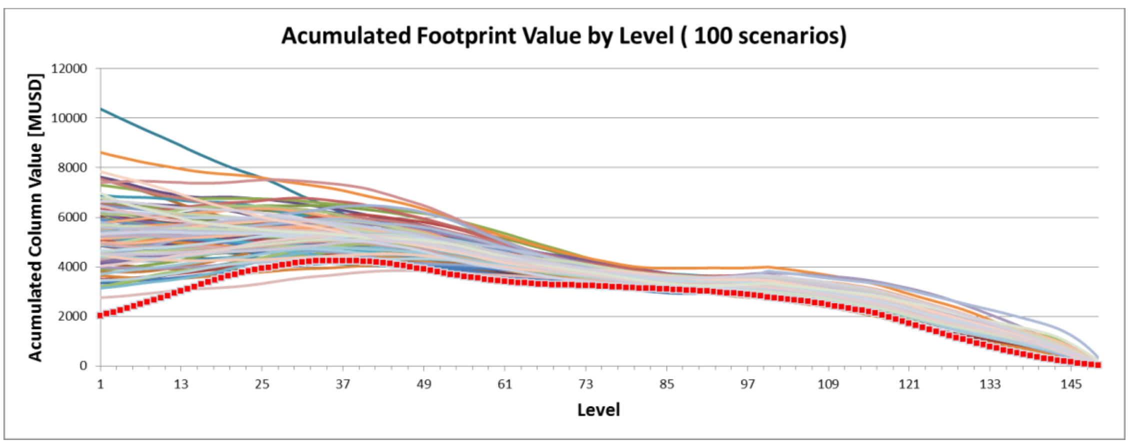


Figure 2 Footprint Results: value over 100 simulations (dashed curve is the kriging scenario)

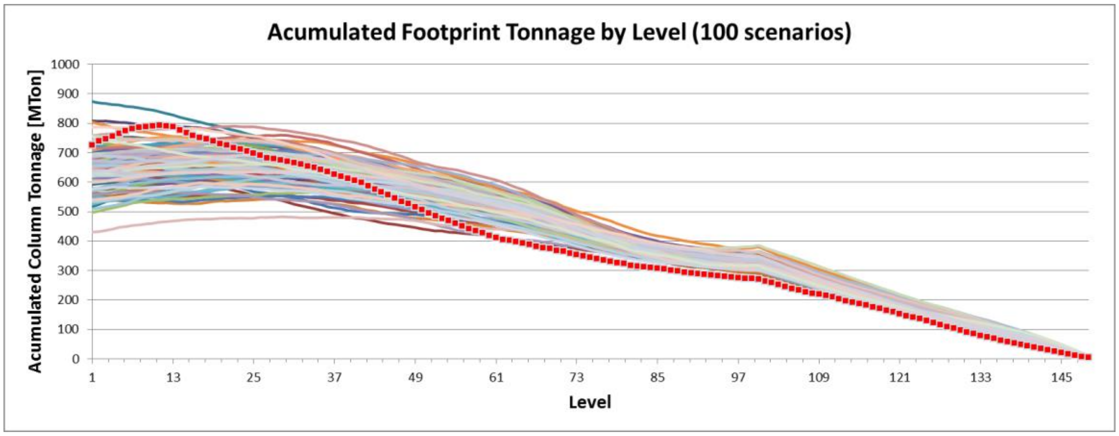
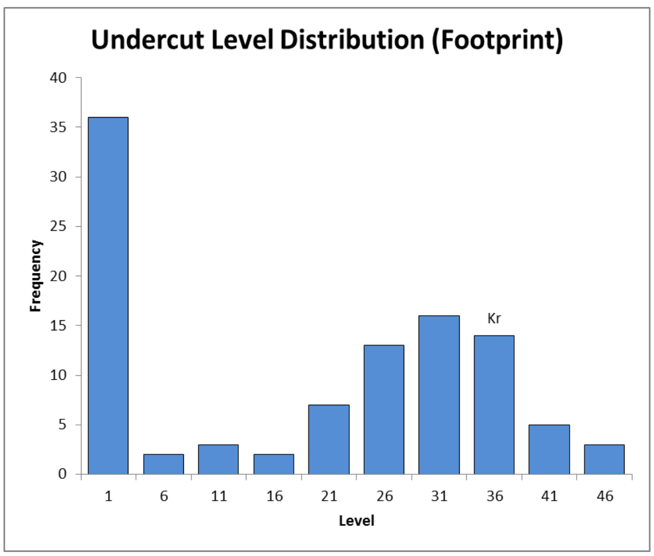


Figure 3 Footprint Results, tonnage over 100 simulations (dashed curve is the kriging scenario)

The accumulated value of the footprint varies for every simulation, thus the placement of the undercut level will have the same behaviour, resulting in a distribution of elevations (Figure 4).



	Footprint value statistics		
Level	**Minimum**	**Maximum**	**Average**
1	4,846	6,325	5,613
6	5,404	5,691	5,548
11	5,096	5,704	5,325
16	5,529	6,461	5,995
21	4,389	6,347	5,349
26	4,802	7,516	5,745
31	4,322	5,938	5,183
36	4,187	6,478	5,091
41	4,534	5,038	4,799
46	3,853	4,628	4,190

Figure 4 Undercut Level Placement Distribution (Kr indicates the place of the kriging scenario)

From Figure 4, class level 1 has the greatest average value and frequency while class level 36 (where the kriging scenario is placed) has one of the lowest average values.

4.3 Economic Envelope Results

Given the undercut elevation for each block model (economic footprint result), the envelope or outline of the mine is calculated over the 100 simulations in order to give an idea of the reserves on each block model. The distributions of the value and mean grade are shown in Figure 5.

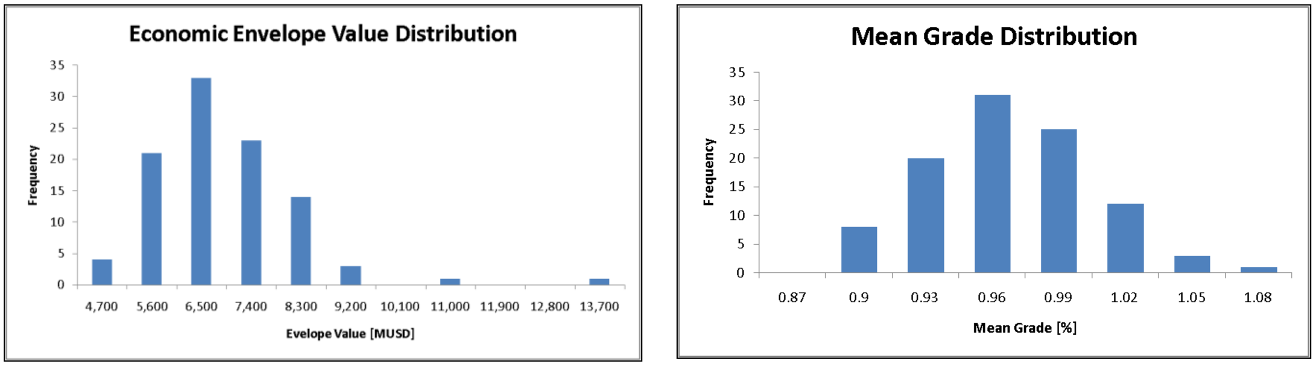


Figure 5 Economic Envelope Value and Mean Grade Distribution

The shape of the envelope changes because of the geological uncertainty and the variability in the placement of the economic footprint. To illustrate this point, the kriging, best and worst economic values are displayed in Figure 6.

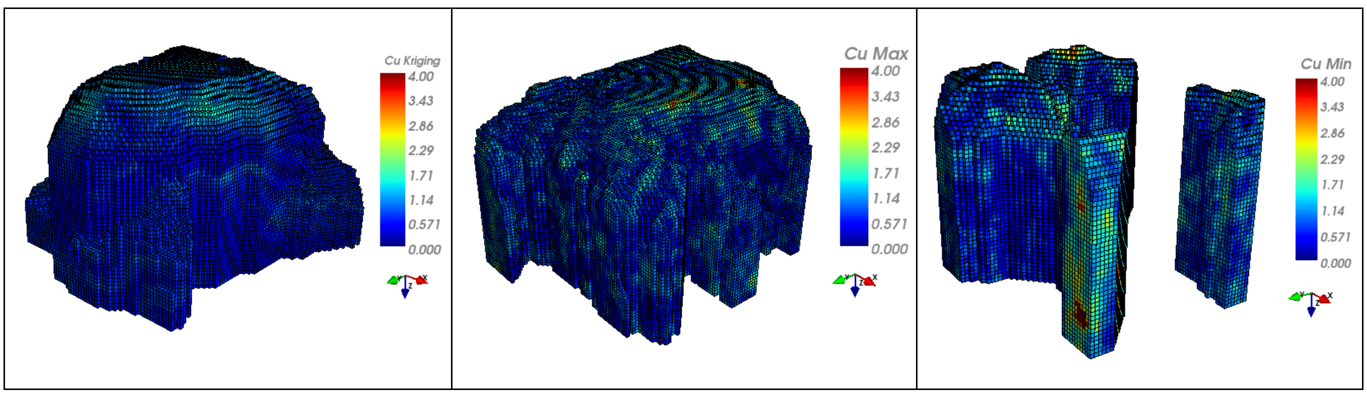


Figure6 Economic Envelope for Kriging, Best and Worst Values Scenarios

Given the previous results, a measure of the risk is really useful to summarise the variability. In this case the value at risk (VaR) evaluation is done. To calculate the VaR of the economic value, the distribution can be estimated as a lognormal distribution, which allows calculating the value associated with some risks levels (Table 3). Similar fittings are considered for the tonnage, area and mean grade distributions.

Table3 Value at Risk for Economic Envelope results compared against average and kriging values

	Value at Risk				
	1%	**3%**	**5%**	**Average**	**Kriging**
Value [MUSD]	4,030	4,400	4,605	6,477	6,207
Tonnage [Mton]	321	348	363	494	576
Area Footprint [m^2]	271,000	294,000	306,500	420,084	550,000
Mean Grade [%]	0.904	0.932	0.951	0.930	0.894

5 Conclusions

Geological uncertainty is a subject that recently has been integrated in open pit mining to know the risks and opportunities present in mining projects, but this uncertainty has been less studied in underground mine projects, specifically in block/panel caving mines which represent massive operations and, once they start the cave, great modifications to the mining method are not easy to perform. With this motivation, a methodology able to calculate the footprint and economic envelope of an underground mine under geological uncertainty is proposed, in order to have a wide vision of the possibilities besides deterministic approaches or kriging estimates.

The footprint tool was validated against commonly used PCBC software, resulting in differences around 10% near the maximum economic level, which is a good approximation considering that both tools are an approximation to reality.

In terms of economic value, the kriging scenario is one of the worst along the levels in the ore body. Using the uncertainty approach, one generates possibilities to improve the profit, and in addition the placement of the economic footprint varies because of the variability in the accumulated value per column, noting differences in footprint value up to 8,000 MUSD. Given the 100 simulations shown here, there is a probability of about 36% to find the economic footprint in the deepest elevation (level 1) and only 14% probability to find it in the level 36 (where the kriged model says it should be). A good decision must consider the values and these probabilities so the maximum profit could be gained at the minimum risk.

Once the placement of the footprint is done, the next step is to estimate the economic envelope or outline of the mine. In this aspect differences in the shape and value are noted. The envelope economic value obtained by the kriged block model is below the expected economic value obtained with the 100 simulations, which could be attributed to the grade smoothing made by the kriging method. The value at risk analysis in this case tell us that with a 5% of risk the value of the economic envelope could be 29% less than the expected value, which means approximately 1,800 MUSD.

As a general thought, geostatistical simulations give us many possible scenarios, which can be assumed alike the real ore body, thus a risk analysis for the results of a large amount of simulations could help us to take the best decision for the project given the geological uncertainty.

Acknowledgements

The authors thank the Advanced Mining Technology Centre (AMTC), Delphos Mine Planning Laboratory and the Mining Engineering Department at the University of Chile for supplying the resources needed to develop this research.

References

1. Dimitrakopoulos R., 2011, 'Stochastic Optimization For Strategic Mine Planning: A Decade of Developments', Journal of Mining Science March 2011, Volume 47, Issue 2, pp 138-150.
2. Diering T., 2000, 'PC-BC: A Block Cave Design and Draw Control System', MassMin 2000 (pp. 469-484). Brisbane, Australia.
3. Elkington T., Bates L. and Richter O., 2012, 'Block Caving Outline Optimisation', MassMin 2012, Sudbury, Ontario, Canada.
4. Diering T., Richter O. and Villa D., 2008, 'Block Cave Production Scheduling Using PCBC', MassMin 2008, Luleå, Sweden.
5. Vargas M., Morales N. and Rubio E., 2009, 'A short term mine planning model for open-pit mines with blending constraints', MinePlanning 2009, Santiago, Chile.
6. Emery X., Lantuéjoul C., 2006, 'TBSIM: A computer program for conditional simulation of three-dimensional Gaussian random fields via the turning bands method', Computers & Geosciences, Volume 32, Issue 10, December 2006, Pages 1615–1628.
7. Vielma J., Espinoza D. and Moreno E., 2009, 'Risk control in ultimate pits using conditional simulations' in Proceeding of APCOM 2009, Vancouver, Canada.