Sequence Analysis Using Whittle Software
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1. Introduction

The present paper describes the methodology used by NCL Ingeniería y Construcción S.A. de Chile, to sequence open pit mines using different planning criteria.

The sequence definition for an open pit mine is basically the generation of a series of nested pits (mining phases) organised according to criteria defined by the mine planning department. These criteria may change according to the main objectives of the company that owns the deposit and may cover a wide spread of options that may define totally different ways to mine the same orebody. Most common objectives for a mining company, in a private mining scenario, are:

- Minimise Costs.
- Maximise Benefit.
- Minimise Risk.
- Minimise Payback Period.
- Maximise Recovery of the Deposit.
- Etc.

Or, as most of the time, a balanced option between some of the above mentioned in a balancing proportion defined by the company.

Without doubt, the two more used approaches to define a mine sequence are:

- Sequencing based on Minimum Costs.
- Sequencing based on Maximum Benefit.

Both approaches have their advantages and disadvantages and it is not the purpose of this paper to discuss them. In recent times, a number of companies have shown great interest in knowing the "maximum benefit sequence" for their deposits, in order to compare it with other options and get a more quantitative idea of the implications of choosing one criteria or another.

In order to satisfy this requirement, NCL Ingeniería y Construcción S.A. from Santiago, Chile, has developed a methodology to produce mining sequences according to decreasing benefit, as described in this paper.

As with the well known "minimum cost sequence", the proposed methodology uses Whittle Programming software as working tools.

2. Objective

The main objective is the creation and testing of a methodology to produce a mining sequence based on the maximum benefit criteria. This sequence can then be analysed, evaluated and compared with other sequencing options to decide the final approach to be used.

3. Methodology

3.1 Problem Description

To sequence according to maximum benefit requires the generation of a "Benefit" block model, calculated for the technical-economic scenario to be analysed.

The block benefit is a direct function of the metal price. Therefore, the maximum benefit sequence is also a function of price, as opposed to the minimum costs sequence that is unique, regardless of the price.

This effect makes the maximum benefit sequence unstable against price variations and may vary from price to price.

The diagram in Table 1 shows, in two dimensions, the variations in the maximum benefit mining sequence for an imaginary deposit. The diagram shows, for each block, the mining cost. Shaded blocks show the recoverable metal units contained.

If the mining cost for each block is 5 monetary units (MU) and the processing cost for each metal block is also 5 MU, the unitary costs for mining blocks A, B and C are 0.77, 0.46 and 1.13 MU respectively.

The minimum cost sequence is then: B, A, C. This sequence is unique for a defined technical-economic scenario and doesn't depend on metal price.

Table 1 shows the benefits calculated for the mining and treatment of each block, A, B and C, calculated for different selling prices.

Table 2 shows the minimum costs and maximum benefit sequences for each metal price. Additionally, NPV has been calculated assuming that each block is mined in one year and a discount rate of 10%.

It can be seen from Table 2 that, for prices lower or equal to 2 MU, minimum cost and maximum benefit sequences are equal. For values greater than 2 MU, the maximum benefit sequence changes several times and it gives NPVs greater than the minimum cost sequence.

This NPV difference between the two methods of sequencing increases with metal price.

This simple exercise shows that the maximum benefit sequence and the minimum cost sequence may be different and that the maximum sequence depends on price.

3.2 Methodology

The Minimum Cost Sequence is defined using Four-D software and is based in the adequate selection of some of the nested pits generated by the FDOP program within the package. These pits are, by construction, organised according to increasing cost per unit and the main problem is their correct selection, based on their tonnage, dimensions, and other characteristics, consistent with the defined planning horizon desired.

The situation for Maximum Benefit Sequence is more complex, mainly due to the fact that Four-D's methods of calculating the value of a block can't produce the parametric effect required for benefits, in order to produce the set of nested pits in one single run. To cope with this problem, the use of Three-D is needed, performing several runs, and manipulating the block model in a general mining package between runs.

In this particular example, NCL has used PC-Mine, from Gemcom Services, to manipulate block models.

The definition of a Maximum Benefit mining sequence, for a given price, has been achieved by performing several Three-D runs, modifying the benefit's block model in the following way:

- For the base case, (or final pit) a direct benefit model was calculated using the standard expression Benefit = Income - Costs. To obtain the following nested pits, a new "benefit model" for each pit was produced.
- Each model is built by subtracting from the initial value a constant Kn to all the blocks. (The value of Kn changes for each new pit to be produced and their values must be calculated based on the order of magnitude of the initial benefits). This effect is different from multiplying each block value for a factor between 0 and 1 because it changes the relative importance of blocks inside the model, a process that is not achieved by the use of a multiplying factor.

A single Three-D run is done for each model, obtaining one pit for each run, optimal for that particular model. Obviously, the greater the value of Kn, the smaller the pit obtained. The family of pits produced shows the mining sequence to mine a deposit mining the shells of greater benefit first.

This exercise gives us the maximum benefit sequence for one single price. If the analysis is required for more than one price, as in the majority of the situations, the whole process, starting with a new original benefit model, must be repeated.

Before deciding to use one sequence or another, the whole process must be finished and mine plans should be developed and evaluated for each sequence, in order to have more information for decision making.

At the end of the process, we have a number of different plans, one per sequence, including the Minimum Cost Four-D plan, each one with its characteristics.

Main aspects to be analysed then are related with the consequences of selecting one plan or another. Typically the most important issues are:

- Price ranges for stable sequences.
- Increase in profits for using the Maximum Benefit Sequence.
- Risk level assumed for a specific scenario against the potential increase in profits.

There are no hard and fast rules. The relative priorities change from one company to another and, even inside a company, from one scenario to another. The key is that all the options must be submitted to the executives so they can make their decisions based on the widest spread of options.

4. Example

To illustrate the problem, an example was developed using a real deposit. The Four-D minimum costs sequence (MCS) was calculated plus two maximum benefit sequences, for prices P1 and P2 (MB1 & MB2).

A number of pits were developed for each MB1 & MB2 sequences. These were imported to PC-Mine where they were smoothed and mining reserves calculated.

Figure 4.1 shows, as an example, the evolution of a certain bench in the MCS sequence based on Four-D pits. Figures 4.2 and 4.3 shows the same bench evolution for sequences MB1 and MB2 respectively.

It can be noticed that the sequences are different, maintaining similar global orientation. The main differences happen around half of the life of the mine, the beginning and the end of the mine life are very similar.

Comparing sequences MCS and MB1, it can be clearly noticed that the "east side" of the deposit is mined in a different order for stages 3 and 4. MCS sequence mines first the east side and then moves north, MB1 mines the north area first and then moves east. MB2 looks very similar to MCS but postpones the opening of the small pits observed at the east side.

Simple mining plans have been developed for each sequence using OptiCut and NPV's calculated for both prices, P1 and P2.

Results are summarised in Table 4.1 in relative terms, using MCS as the 100% reference point.

Case	MCS	MB1	MB2
NPV P1	100	104.0	102.6
NPV P2	100	96.2	102.8

Table 4-1

Figures from Table 4.1 shows that for both prices, the maximum benefit sequence for the evaluation price does in fact gives the best NPV, even considering that the net increase is not very relevant.

The most important conclusion from the analysis of the table is that, if price changes from P1 to P2, the NPV for MB1 sequence drops around 8%, showing that this sequence is quite sensitive to price, meaning a more risky scenario.

With these data available, project managers have more solid information to decide which way to go, analysing pros and cons in a more quantitative way.

5. Conclusions

The selection between different methods of sequencing, and their associated mine plans, is a crucial decision in a mining project and must be done based in as much information as possible.

Mining sequence does change based on the criteria and scenario used to define it.

If a mine sequence is selected based on the maximum benefit for a forecast price, we must analyse how sensitive is this sequence to price variations and try to quantify the associated impact of price changes and the level of risk assumed.

Unfortunately, the only way to estimate the effect of such changes is the development and evaluation of the different options, from sequencing to mine planning and valuation.

It is important to have proper computational tools and procedures, to obtain the required information with reasonable accuracy and in a short time. The procedure proposed in this paper provides an easy way to obtain maximum benefit sequences for different prices.

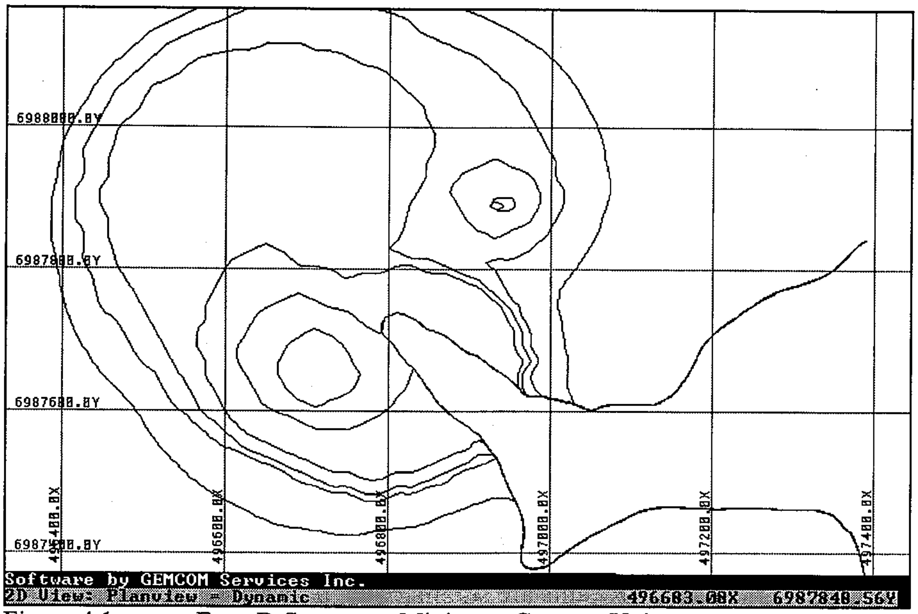

Figure 4.1 Four-D Sequence, Minimum Cost per Unit.

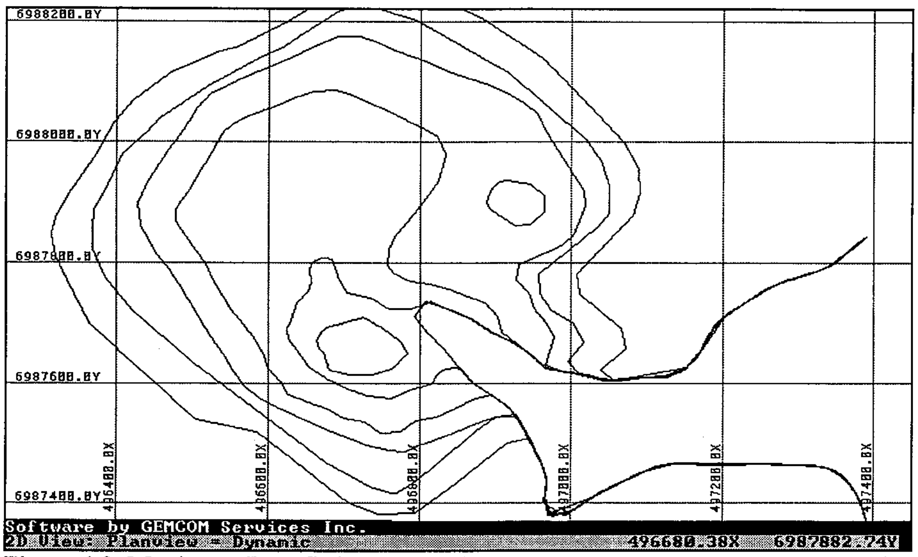

Figure 4.2. Maximum Benefit Sequence P1.

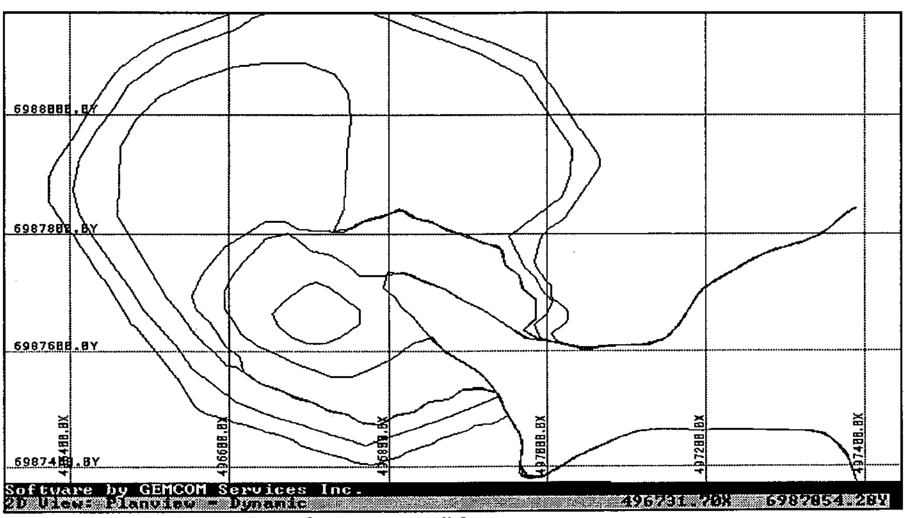

Figure 4.3. Maximum Benefit Sequence P2.

TABLE 1.

5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	5	5	5			54			5	5	5	5	5	
		55								5	5	5		
											75			

BLOCK	A	B	C
U.COST	0.77	0.46	1.13

PRICE	BENEFIT		
0.2	-37	-14.2	-70
0.4	-24	-3.4	-55
0.8	2	18.2	-25
1	15	29	-10
2	80	83	65
3	145	137	140
4	210	191	215
5	275	245	290
6	340	299	365
5	275	245	290
6	340	299	365

TABLE 2

PRICE	COST SEQUENCE 1	2	3	NPV
0.2	-14.2	-37	-70	-92
	B	A	C	
0.4	-3.4	-24	-55	-61.3
	B	A	C	
0.8	18.2	2	-25	0.05
	B	A	C	
1	29	15	-10	30.7
	B	A	C	
2	83	80	65	184
	B	A	C	
3	137	145	140	338
	B	A	C	
4	191	210	215	491
	B	A	C	
5	245	245	290	644
	B	A	C	
6	299	340	365	798
	B	A	C	

BENEFIT SEQUENCE 1	2	3	NPV
-14.2	-37	-70	-92
B	A	C	
-3.4	-24	-55	-61.3
B	A	C	
18.2	2	-25	0.05
B	A	C	
29	15	-10	30.7
B	A	C	
83	80	65	184
B	A	C	
145	140	137	339
A	C	B	
215	210	191	495
C	A	B	
290	275	245	653
C	A	B	
365	340	299	810
C	A	B	

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