USING REAL OPTIONS TO INTRODUCE FLEXIBILITY IN MINE PLANNING UNDER UNCERTANINTY

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ABSTRACT

Today, mine plans are optimized for a fixed set of parameters (prices, costs, resource model, etc.), knowing that they will not realize and the plan will have to be changed in the future. Uncertainty (in grades, market, etc.) is included only as a post-analysis through variability of said parameters. We postulate that more robust decisions, higher and more reliable project values are possible by considering uncertainty from the beginning of the mine planning process.

We illustrate these ideas by using real options to study the introduction of flexibilities in the planning process. This allows us to study how robust the decisions made in the standard planning procedure are, and also to see how the flexibility impacts the final value of the project. We present this technique in two case studies.

The first case study considers the uncertainty due to the delay between the moment when equipment purchase orders are placed, and the start of the operation in a long-term mine planning in an open-pit. The option consists of determining the optimum fleet size so that the expected NPV of the project is maximized over a number of scenarios.

The second case study refers to the life of an underground mine that consists of several sectors and uncertainty in prices. In this case, the options refer to the optimum timing of the mine sectors (when to start their production) so that the value of the project is maximized.

INTRODUCTION

Recently, mine planning has progressed to integrate more and more variables to the planning process and has developed tools to achieve more robust plans in terms of expected value and fulfilment of promises productive, maximize profit and/or the expected return for shareholders. Unfortunately, a significant gap still exists between what is planned (and offered as value) and the result of the implementation of the mine plans in the operation. One of the more important reasons for this is that the whole process is affected by various sources of uncertainty that are not properly accounted for in the mine planning process. These differences are reflected mainly in: (a) income, (b) costs, (c) mineral reserves and (d) investments.

The sources of uncertainty in mining, although numerous, can have varying degree of impact on the business and can be of different nature. For example, uncertainty sources can be classified as external or internal. External uncertainty is defined as one such that its source lies outside the company, the main example here is the market (commodity price, price of key inputs, investment amount, etc.). Internal uncertainty is dictated by the assets of the company and its organization. For example, geological and operational uncertainties fall in this category. On this basis, the three types of uncertainty that govern the mining business are mainly: geological, operational and market. (Mayer Z. and Kazakidis V., 2007)

The problems created by uncertainties in a mining project, occur precisely because there is no methodology or tool that integrates uncertainty properly into the mine planning process: the standard software tools are oriented towards the optimization of a fixed plan under a predefined set of parameters, therefore the robustness of the plan can only be tested after the plan has been computed and there is no way (using standard methodology) to integrate flexibility into the construction of the plans. Flexibility is understood in this article as (Mayer Z. and Kazakidis V., 2007) as the ability of a system to sustain performance, preserve a certain cost structure, adapt to changes in internal and external operating conditions, or take advantage of new development opportunities during the life cycle of the mine operational modifications.

This article aims to illustrate how the introduction of flexibility in decision-making for planning permits to address sources of uncertainty. This approach, being general, is shown in this case by applying real options for upgrading and constructing of mine plans under uncertainty, contemplating both market and geological flexibility. Specifically, we consider two case studies.

There are several ways to address uncertainty through flexibility in the planning procedure. In this paper, we work using the framework provided by real options, because they provide not only a theoretical framework, but also valuation mechanisms that allow to compute flexible solutions in reasonable time (as opposed to, for example, stochastic programming, that relies on dynamic programming approach requiring an exponential number of decisions to be computed).

Real Options in Mining

An option is the right (but not obligation) to perform a certain action in a given time (in the future). This right is established by paying a “price” (for example, an increase in the investments), and produces a net difference in the expected value of a project or asset: the “value” of the option.

Several researchers have tried to apply real options to evaluate different types of flexibilities under different sources of uncertainty. Independently of the characteristics used in the investigations, all these studies conclude that this methodology (real options) produces a profit increase over the use of discounted cash flows when applied to real options.

In the case of mining projects, there are 3 factors that affect or determine the optimal investment decisions. (Drieza, J.A. *et al*., 2002; Topal E., 2008).

- The investments are partially or completely irreversible, this means that capital investment is required to establish the operation, with this initial investment cannot be recovered.
- Uncertainty exists about the future rewards of the investment. Some of these variables can have significant effects on future mines, such as commodity prices, deposit characteristics (geology) and operating costs.
- Finally, the investor has a margin of action in the timing of investment. Indeed, investment in a mine does not happen immediately, there is a delay between the decision of the mine and the investment in the project occurred.

Samis y Poulin (Samis and Poulin, 1996) showed that:

"Project value is influenced by economic uncertainties and physical environment, a dynamic structure of project risks and the ability to use, multiple and mutually exclusive projects."

The NPV is extensively used in mining projects although it is incapable of accounting for these influences on the value of the project. Samis and Poulin (1996) evaluate two different articles in copper and gold mines and project value calculated by the discounted cash flow (DCF) and real options valuation (ROV) techniques, concluding that ROV was more flexible and suitable for mining projects compared to DCF.

Most papers that apply ROV use very simple or hypothetical examples of projects in the mining or oil industries, and compared the traditional analysis of cash flows with ROV (McKnight, 2000).

METHODOLOGY

The methodology used in this paper, for the construction of flexible plans over time, is a feedback and iterative methodology which has the following stages:

1. Build a long-term plan, under the standard methodology mine planning (base case, for comparison).

2. Model and / or simulate the sources of uncertainty though simulation of scenarios.

3. Identify potential flexibilities and model them with an optimization model (for example linear programming), considering the restrictions and design options.

4. Valuate the options of the simulated scenarios.

5. Analyse results and compare with base case.

As mentioned before, we illustrate this methodology in two case studies. The first case study considers fleet size decisions under geological uncertainty due to the delay between the moment when equipment purchase orders are placed. The second case study studies the how the optimal timing and mining rates change according to uncertainty in prices for a big mining complex consisting of several sectors. We detail these cases next.

Case 1: Optimal Fleet Size to Address Geological Uncertainty Through Flexibility in the Sequencing of an Open Pit Mine

In this case study we are interested in evaluating the reliability of the selection of the size of the transportation fleet with regards to geological uncertainty. The aim is to model the change (learning) about the geology between the instant in which the equipment purchase orders are placed and the moment in which operations begin.

The inputs for the case study are: the economic and operational parameters and a fixed mine design. Geological uncertainty is modelled through different block models constructed by the Kriging method (the base case) and conditional simulations. We use then an optimization model that schedules the extraction in the long-term at the phase-bench level, so optimal schedules are constructed for each scenario and transportation equipment investment (option price). We compare then the different plans in terms of NPV, Variance and other indicators like reliability.

Notice that the design of the pit phases is the same for all the conditional simulations and the Kriging model. Indeed, a more detailed study may consider different designs, but this is difficult to do as there is no automatic design tool or algorithm.

Being more precise, the methodology in this use study is:

1- We construct *N+1* block models: 1 with the Kriging method and *N* conditional simulations.
2- For each of these *N+1* block models, we construct an optimal long-term schedule using a mixed linear program that works at the bench-phase level, therefore obtaining *N+1* sequences and *N+1* NPVs.
3- In order to simplify the analysis and reduce computational times, we use these NPVs to rank the conditional simulations and group them into *n* classes. The first class corresponds to the *N/n* with lowest NPV, and the last to the *N/n* scenarios with higher NPV. Within each class, the scenario with the lower NPV is chosen as a representative.
4- For each of these *n* representatives, and based on the updated reserves, the optimal sequence is constructed depending on transportation investment, so the production plan is evaluated in detail including the actual CAPEX and OPEX that apply in each case.
5- Finally, we evaluate the robustness achieved by each plan in terms of the investment level on transportation.

Using the procedure above, we obtain a pool of options to choose from depending on geological deposit conditions, the reliability they want to achieve, the option price to pay and the expected value

Case 2: Optimal Mining Project Under Market Price Uncertainty

This case study deals with a copper mine with several sectors (7) that include 6 underground operations and 1 open-pit, all coexisting and affected by external resources, like a shared plant and transportation system, as well as constraints associated to precedence and subsidence limitations between the projects.

In this case study, we are interesting in the flexibility of advancing and delaying the start of production sectors depending on price uncertainty to study the variability of optimal periods to start each project, and to analyse how this impacts the production plans (particularly the rates) and the value of the overall mine, and potentially to determine, if possible, simple rules (for example, price ranges) indicating that a project must start before planned, or that the project may be discarded.

Table 1 - Productive Sectors.

Sector	Start of Operations
A	In Operation
B	In Operation
C	2027
D	2039
E	2048
F	2064
G	2068

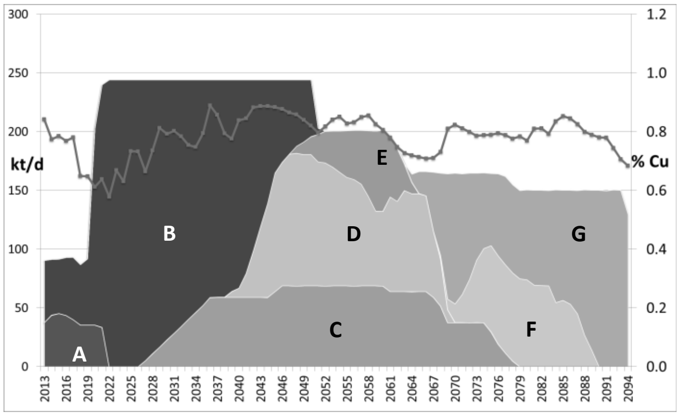

Figure 1 - Production Plan.

We start with a given reference plan indicating, constructed using the traditional parameters and methodology. For each sector (A, B, C, D, E, F, and G), the plan states: the starting period, production plan (ore tonnages and grade), and costs per ton in a yearly basis (depending on ore price). We are also given overall capacity constraints and precedence relations between the projects (for example, subsidence constraints between the open-pit and underground sectors).

We then model uncertainty using price paths that are constructed using a General Mean Reverting Process (see Figure 2). Therefore, using the reference plan (tonnages, grades and costs), and the different price paths, we can evaluate the NPV of each sector.

Furthermore, we implemented a mixed integer program that allowed us to compute the optimal schedule of the projects, which means to change the starting periods and potentially rates. Using this, we studied the robustness of planned decisions in terms of price uncertainty by looking at the changes in these decisions over the price paths.

As in the first case study, we do not change the reserves in the plans depending on the price paths, because that would require manual optimization that is not possible over a significant number of price paths.

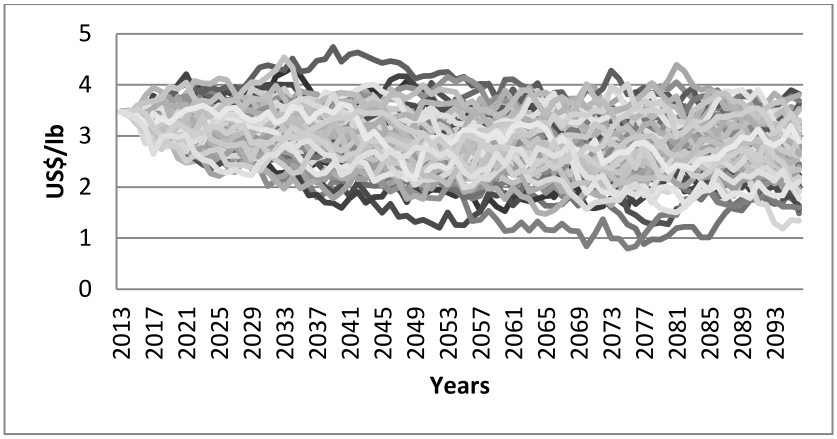

Figure 2 - Simulated Price with General Mean Reverting Process.

RESULTS AND DISCUSSION

In this section, we present the results and discussion of the case studied introduced in the previous section.

Case 1: Sequence Flexibility in Open Pit Mine Under Geological Uncertainty

In the actual case study, we used *N=100* scenarios and selected *n=10* classes. We have 11 sequences: “Krig”, for the base case; and sequences 1 to 10, each one optimal for its corresponding representative of the class.

The decision to incorporate flexibility in the sequences of the plan is based on the increased productivity which allows switching between sequences that may be carried out under these conditions. For this, the methodology considers the sequence 8 as the starting sequence as it is one that provides the highest expected value. Additional sequences are considered as the investment (price of the option) in transportation increases. Thus 10 options were obtained, each with options and option prices values generated (change in the respective CAPEX). Table 2 presents every option in order of increasing price, and the sequences that are feasible at each investment level. As expected, as the price of the option increases this allows for a greater productivity based on more equipment haulage, transport and perforation, which can be decided among a larger number of extraction sequences. Thus all options were evaluated and the obtained results are shown in Table 2.

Finally, Table 3 summarizes the information regarding each option. We observe that, while this set of data reliability (measured as the probability of having a positive NPV) does not have substantial changes, the expected NPV values and the standard deviation observed in each case are interesting to note.

Table 2 - Available Sequence to run for each of the available options.

	Option									
	1	2	3	4	5	6	7	8	9	10
Op. Price [MUS$]	0.0	0.3	4.2	5.0	9.4	12.6	42.2	47.8	66.5	69.3
Feasible Sequences	Krig.	Krig.	Krig.	Krig.	Krig.	Krig.	Krig.	Krig.	Krig.	Krig.
	8	8	3	3	3	3	1	1	1	1
		9	8	6	6	4	3	3	2	2
			9	8	8	6	4	4	3	3
				9	9	8	6	5	4	4
					10	9	8	6	5	5
						10	9	8	6	6
							10	9	8	7
								10	9	8
									10	9

Table 3 - Detailed results per opton: Expected VAN, Price, Standard Deviation, Reliability.

	Option 1	**Option 2**	**Option 3**	**Option 4**	**Option 5**	**Option 6**	**Option 7**	**Option 8**	**Option 9**	**Option 10**
Option Price [MUS$]	0.0	0.3	4.2	5.0	9.4	12.6	42.2	47.8	66.5	69.3
E(NPV) [MUS$]	338.4	342.5	345.5	348.8	345.2	342.5	317.5	324.2	306.6	307.2
Option Value [MUS$]	0.8	4.9	7.9	11.2	7.6	4.9	-20.2	-13.4	-31.0	-30.5
Reliability	0.977	0.975	0.979	0.979	0.978	0.977	0.973	0.981	0.976	0.975
Stan. Dev [MUS$]	169	174	170	171	172					
Discount Investment [MUS$]	3015.4	3015.8	3020.2	3021.1	3026.5					

Stan. Dev [MUS$]	172	164	156	155	157
Discount Investment [MUS$]	3030.1	3064.1	3070.3	3092.2	3095.5

Case 2: Optimal Underground Project Under Market Price Uncertainty

In this case we compare the base case plan given by the traditional methodology (i.e. no option to change timing and rates) and the optimal plans that use the option to change 8roject starting periods and rates. After running the optimization 8roject8 N=200 price paths, all equally probable. Table 4 shows a summary of these results. It should be mentioned that for the evaluation we used a yearly discount rate time that is constant and equal to 8%, and that the integrality gap in the mixed integer program was set to 0.1%.

Table 4 – Statistical summary evaluations for different simulations of the copper 8roje.

	With Option	Without Option	Difference
Max NPV MUS$	36,919	36,734	185
Min NPV MUS$	18,877	18,860	17
Expected NPV MUS$	26,435	26,329	106
Std.Dev. NPV MUS$	3,421	3,394	27

Table 4 shows how the addition of flexibility in the plans increases the NPV of the 8roject. This can also be seen in Figure 3, where the histogram value of each of the case studies and the curve of % of accumulated value are presented. While NPV differences may look relatively small, we observe that they hide very relevant changes in the 8roject, as it is shown in Figure 4. Indeed, the overall plan is very robust up to year 2040, which is due to the precedence and subsidence constraints proper of the case study, but there is a lot of variability starting at this point, in terms of 8roject timing and production.

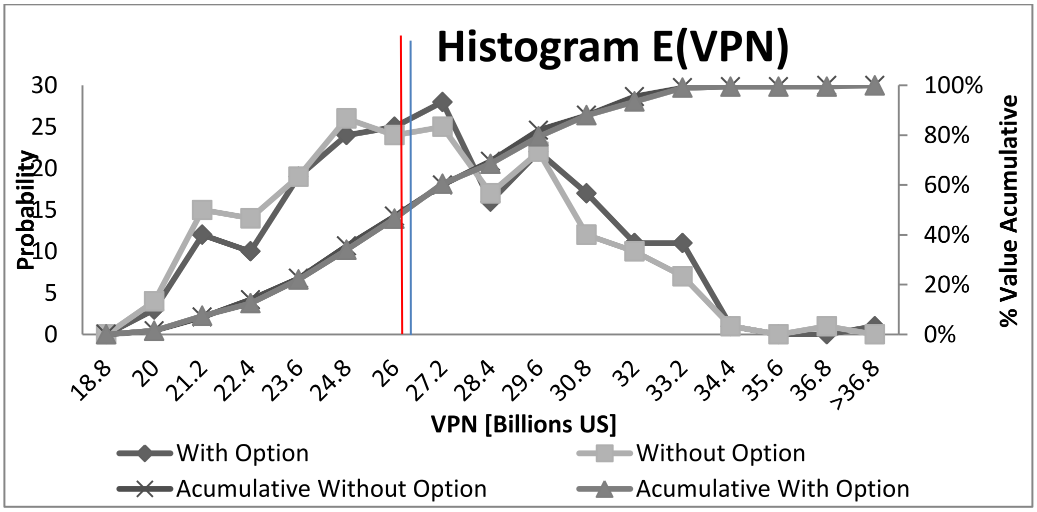

Figure 3 – Histogram and % accumulative value according to case study.

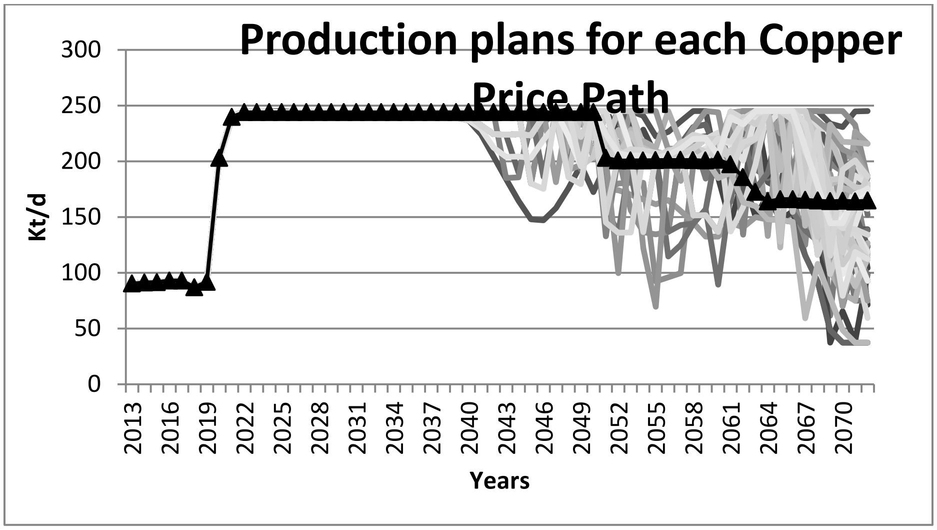

Figure 4 – Production Plan for each Copper Price Paths (base case in line marked).

Another element to explain the relatively small difference in expected NPVs is presented in Figure 5 and corresponds to the effect of the discount rate. Indeed, Figure 5 shows the discounted and non-discounted cash flows as well as the cumulative discounted value of the whole project (as percentage). We can see that by year 2040, when the changes in the plans are observed, the cumulative value of the project is close to 85% of the total, i.e. the possible variations in the beginning of the projects can affect at most the 15% of the total project value. Conversely, these relatively small changes correspond to very large variations on the non-discounted cash flows.

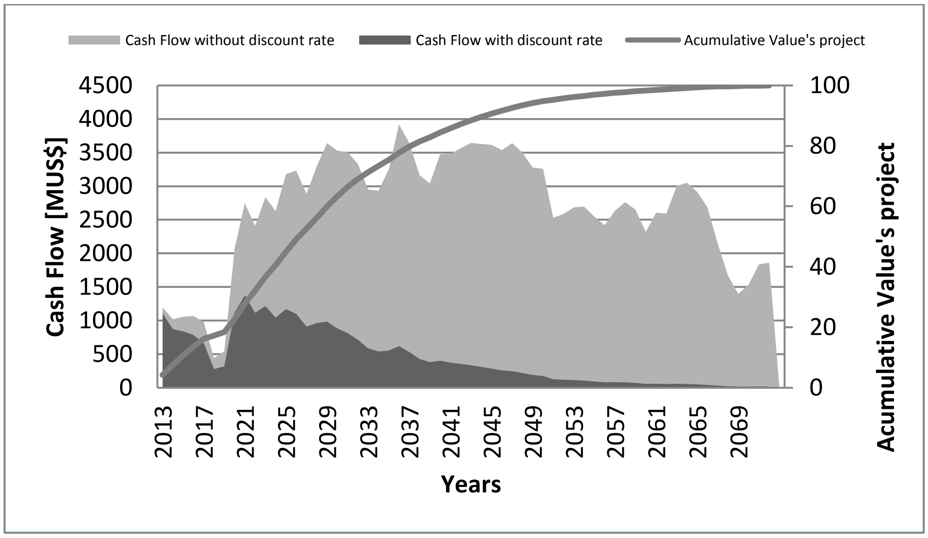

Figure 5 - Discounted and non-discounted cash flows over project life.

Another type of analysis that can be performed using the methodology is the variability of the starting periods for each sector. We present some of them in Table 5 (Sectors A, B and C are not included because they always start in the same years because the capacity and precedence constraints force that). In the table, by "Starting year" we mean the first investment period and by "%" the frequency over the scenarios (price paths).

Table 5 - Optimal sector starts depending on price paths.

Mine D		Mine E		Mine F		Mine G	
Starting years	%	Starting years	%	Starting years	%	Starting years	%
2029	81.0	never	0.5	never	23.0	never	2.5
2030	18.0	2035	81.0	2054	73.5	2049	77.5
2031	0.0	2036	17.0	2055	1.0	2050	19.0
2032	0.0	2037	0.5	2060	0.5	2051	0.5
2033	0.0	2040	0.5	2061	2.0	2054	0.5
2034	0.50	2056	0.5	>2061	0.0	>2055	0.0

For example, we observe Sector F never begins in the period in which it was planned in the base case (2056). Indeed, with we see that with probability 73.5% it is convenient to start the investments for this sector 2 years before planned. Conversely, there is a 23% of the scenarios in which the sector can be discarded. We recall that these plans take into account all required interactions between the projects in terms of total production capacity and interferences.

Table 6 -Analysis of the probability of discarding Sector F.

Copper Price	**2**		**2.1**		**2.2**		**2.3**	
Year of Decision	2053	2052	2053	2052	2053	2052	2053	2052
# discard paths	3	3	5	4	7	5	9	7
# total paths	12	9	17	12	22	17	31	27
% discard paths	25.0	33.3	29.4	33.3	31.8	29.4	29.0	25.9
Copper Price	**2.4**		**2.5**		**2.75**		**3**	
Year of Decisions	2053	2052	2053	2052	2053	2052	2053	2052
# discard paths	15	11	16	15	26	20	33	30
# total paths	47	40	58	50	96	84	131	119
% discard paths	31.9	27.5	27.6	30.0	27.1	23.8	25.2	25.2

Table 6 shows a more detailed analysis made for the sector F, assuming that the project should start in 2054, for different price scenarios going from 2 USD/lb up to 3 USD/lb, assuming that the decision (of performing the project or not) has to be made either in 2052 or 2053. For these years, we count the total number of paths so that the price is at most the given value (# total paths), the number of paths (among those) in which the project is discarded, and the corresponding percentage. We observe that, in fact, the probability of rejecting the project is at least 25%, but can go up to 33%, depending on the decision date and price scenario

Finally, we also performed a good case/bad case by selecting some limit price paths that are presented in Figure 6, with the correponding plans in Figure 7. This analysis shows how different the plans actually are, both in terms of value and reserves (Table 7).

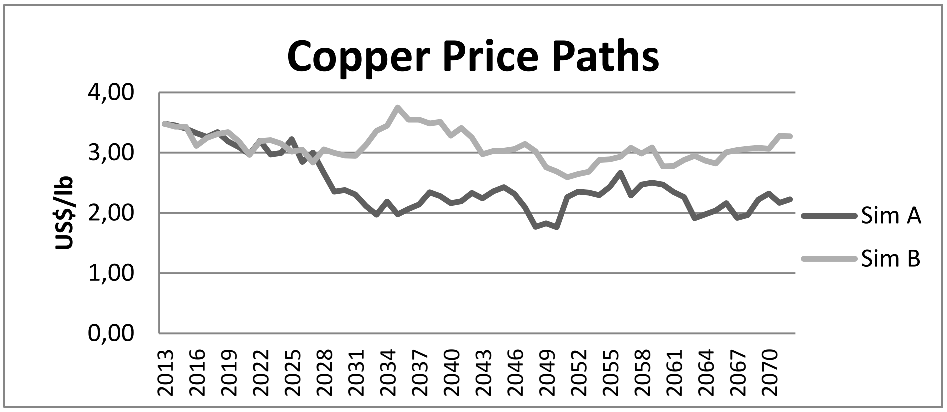

Figure 6 - Price paths (good and bad cases).

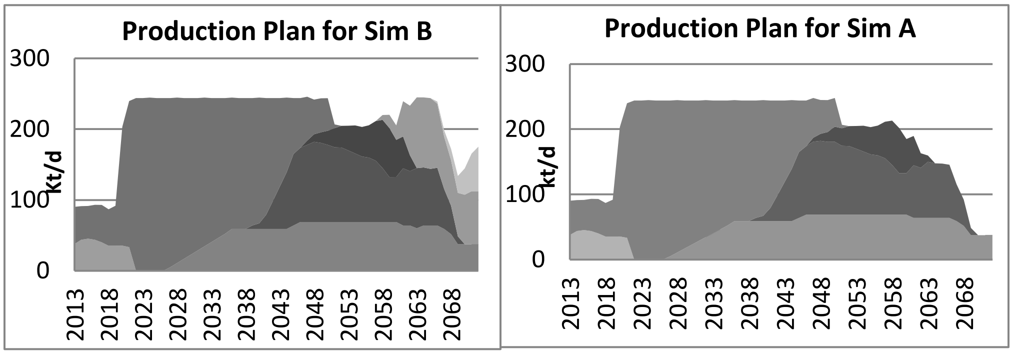

Figure 7 - Deaggregated (by sectors) production plans (good price case “B”, and bad price case “A”).

Table 7 - Analysis of differences in mineral reserves.

	Production Plan Sim A	Production Plan Sim B	Difference
Reserves Kton	4,214,719	4,653,458	438,739
NPV MUS$	21,476	26,751	5,295

CONCLUSIONS

We have presented some applications of real options to study the impact of flexibility in mine planning, either in terms of expected NPV, variability or reliability of the plans obtained. We illustrate this application in two case studies. The application performed in this case is different than in other studies in the sense that it is more adapted to the mining industry.

The results show that, indeed, it is possible to generate coverings while maintaining or even increasing the value of the project by introducing some flexibility in some of the outcomes of the planning process. In the first case study, this flexibility is gained in the scheduling of the production, by considering different options regarding the size of the mining capacity, and it is used to increase expected value while maintaining reliability. In the second case study, the flexibility is put into the timing of a mine sector, and a criteria are developed (based on price) to determine whether it is convenient to start a certain project earlier than expected; even in a very constrained scenarios.

In both case studies, the data and option scenarios were limited in terms of the impact produced. We believe this impact will increase when more powerful options are considered. For example, in the case of the second study, a lot more flexibility can be gained if the production plans of all the projects are allowed to change. This requires a deeper analysis and a higher level of detail, in terms of investments and costs for example, that we plan to do as future work.

A main result of this paper is that the methodology of real options is very versatile, extendable, and applicable to mining; but (as it is known), the actual impact of this strongly depends of other parameters like the level of variability and the value of the project. For example, for very long-term scenarios (Case 2), the actual impact is not clear or diminished considering the effect of the discount rate over a time horizon longer than 50 years.

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