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Flexible stochastic planning: the ultimate frontier

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ABSTRACT

In recent years there have been unexpected fluctuations in the economy that have directly impacted the mining industry. For the nature of its business, the industry cannot react quickly enough to changes in variables that affect it, such as commodity prices. Although there have been some efforts in this line, such as the inclusion of scenario analysis in the PEI (Non-flexible stochastic planning) presented in MinePlanning 2011, in practice most strategic mine planning today does not consider variations in these variables when generating mine plans, thus it does not provide robust plans nor does it capture the operations' real value.

Applied mine planning has been limited to software available in the market, which have not been designed to address this issue. This paper describes how Deep Mine, a strategic mine planning software under uncertainty, tackles these problems and generates both robust and flexible mine plans that support decision making processes. Robustness deals with taking into account possible fluctuations in market and technical variables when defining a mine plan, and based on these variables, making decisions that respond best towards them without changing the plan. Flexibility deals with dynamically changing a mine plan in response to resolved uncertainties and seizing potential opportunities.

Deep Mine is proving that including flexibility when building mine plans is very promising. For a fictitious expansion project in Codelco's Radomiro Tomic designed for this paper, by considering it as an option and not an obligation, the expansion project's NPV increased in 68% under the company's expected market and technical scenarios. Furthermore, Deep Mine's deterministic NPV results for Radomiro Tomic are approximately 22% higher than those obtained using this mine's preferred strategic planning software.

INTRODUCTION

The world economy has become ever more turbulent since the financial crisis in 2008. This has led Ernst and Young's ranking (2012) to recognize the role of cost inflation (4^{th}), capital project execution (5^{th}) and price and currency volatility (7^{th}) as significant risks for the mining industry. Among the actions these companies can take to manage these risks, Ernst and Young recommends using enhanced cash flow modelling techniques, such as dynamic Discounted Cash Flow (DCF) and Real Options (RO) analysis, in order to "recognize and exploit value from volatility".

On the other hand, many industry actors and analysts, such as Ernst and Young (2012) and Guzmán (2011), recognize that the industry standard for evaluating mining projects is the static DCF calculation. This technique requires mining companies to make long-term forecasts on the main economic and technical variables affecting the project, which in practice have a zero probability of occurring.[1]

Researchers and practitioners are becoming increasingly aware that the traditional NPV technique generates results that do not necessarily represent a deposit's maximum potential. Alvarado *et al.* (2011) propose in Figure 1 the changes in the mine planning process that must be implemented in order to effectively maximize a mine's NPV. Their paper focuses on moving from Non-flexible deterministic mine planning (today's standard) to Non-flexible stochastic mine planning, which incorporates relevant uncertainties into the planning process. Nevertheless, in this case the mining sequence remains inflexible, meaning that the chosen sequence cannot react towards the realization of these uncertainties – which is precisely what mine planners do in practice.

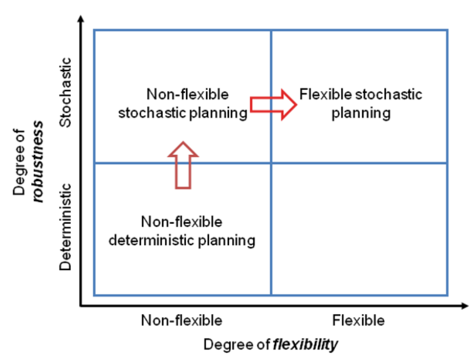

Figure 1 Mine plan classification according to degree of robustness and flexibility

This paper focuses on the design of flexible mine plans, which is the next step shown in Figure 1. To this end previous efforts in crossing this frontier are analyzed. Based on this analysis, the authors' propose a new methodology for building flexible mine plans for a wider range of options, together

[1] In general, most estimates and forecasts in mining can be considered as continuous random variables. For a detailed explanation on why variables of this type have a zero probability of attaining a specific value, see Rice (1995).

with its practical implementation. This has led to the commercial software prototype known as Deep Mine, which focuses on long term strategic planning for open pit mines. Finally, this software is used on a large-scale mine in order to illustrate its potential.

METHODOLOGY

Theoretical framework

As mentioned in the previous section, there have been past efforts to reach the ultimate frontier of Flexible stochastic mine planning. Nevertheless, up to the authors' knowledge these attempts have gone along the path of evaluating a mining sequence considering the value of flexibility, rather than incorporating this value into the process of generating the mining sequence *per se*.

Dimitrakopoulos, Martinez and Ramazan (2007) explain how to build mine sequences taking into account geological uncertainty. Nevertheless, this is done by designing an optimal mining sequence for different possible block models (created using conditional simulation), which are then evaluated under each block model to determine how the plan responds under uncertainty. Hence, this technique lies in the category of Non-flexible stochastic planning. Dimitrakopoulos and Abdel Sabour (2007) and Abdel Sabour and Dimitrakopoulos (2008) then expand this technique to calculate the flexibility value of terminating the mining sequence due to a potentially high downside risk in realized metal content or prices. This concept is shown in Figure 2.

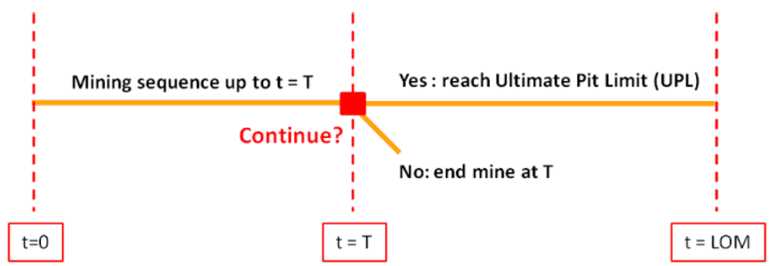

Figure 2 Option for terminating mine plan at time *T*

This type of flexibility can be easily introduced using any commercial software available in the market, since it is included by cutting the mining sequence prematurely.

Nevertheless, there are several other relevant options that introduce flexibility by **changing the mining sequence**, such as expanding plant capacity. In this case, a different mine plan must be generated for each possible path that could be taken after the decision point at time *T*. However, in order for the decision to be truly taken at time *T*, all these mine plans **must share a common mining sequence up to this point in time**. This situation is shown in Figure 3.

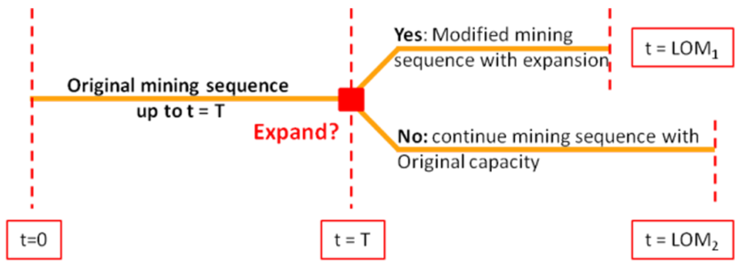

Figure 3 Option for expanding mine plan capacity at time *T*

This type of flexibility cannot be incorporated into the mine sequencing algorithms of current commercial software, since they use the entire forecast of economic and technical variables in order to determine the optimal mining sequence for the Life of Mine (LOM). Hence, introducing changes in any relevant variable at any specific point in time *T* can (and usually does) alter the mining sequence for periods prior to *T*.

Besides this, all options that alter a project's mining sequence should at least update the plan's market forecasts according to the conditions seen at the exercise date *T*, since no mine planner would question the key role of using the most recent price, cost and CAPEX forecasts in calculating a project's NPV. This will in turn affect the Ultimate Pit Limit (UPL) of the deposit, which is the starting point used to calculate an optimal mining sequence in the first place. This vicious cycle is part of the complexities of open pit mining and must be overcome in order to build flexible mine plans.

Practical implementation: Deep Mine software

Considering the impossibility in implementing flexible mine plans using current commercial software, GEM has been working since 2009 in establishing the theoretical foundations for implementing this methodology. The results of these efforts, which were presented at a prototype level over a fictitious deposit of 12.000 blocks, are shown in Valle *et al.* (2012).

Recognizing the potential of Flexible stochastic planning, BOAMine has continued GEM's efforts in order to develop Deep Mine, a commercial software prototype that generates open pit mine plans with flexibility at a strategic level – which does not consider mine design issues, such as roads and ramps. Nevertheless, additional operational restraints are indirectly considered in Deep Mine that ease the transition to short and mid-term mine planning. Figure 4 provides three different snapshots of the software's user interface, which also incorporates the latest advances in software engineering.

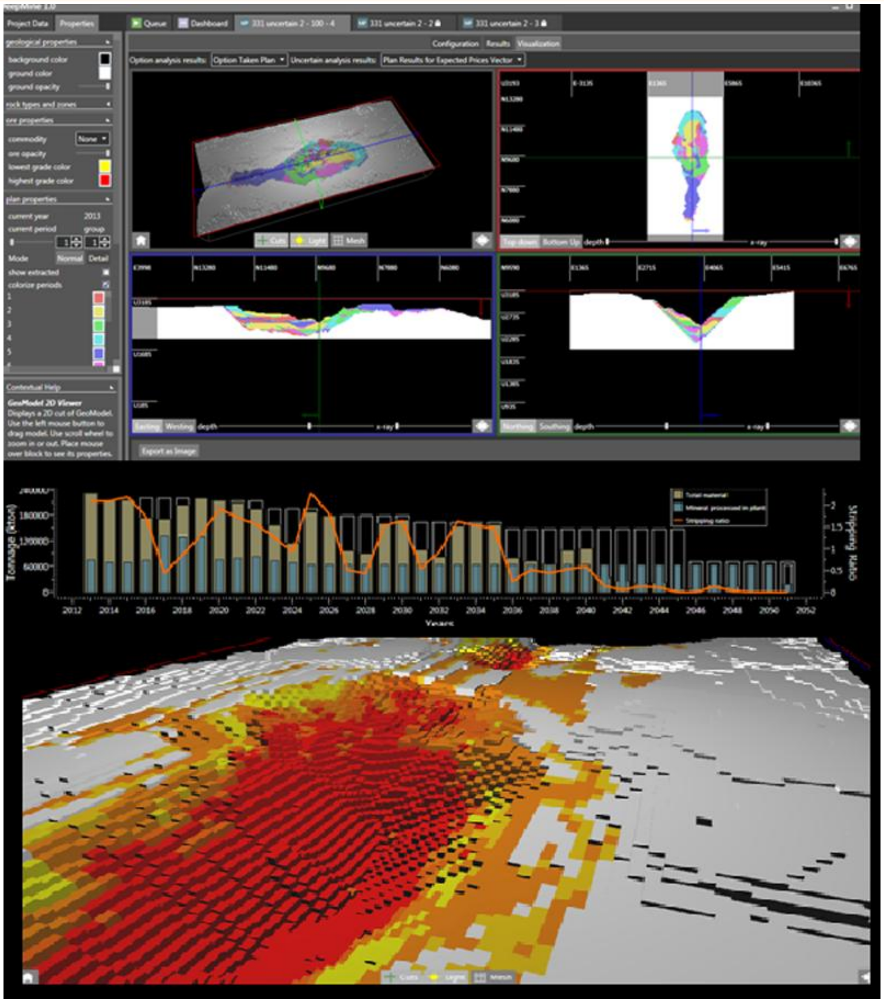

Figure 4 Different views of Deep Mine's user interface

At present, Deep Mine is capable of incorporating uncertainty into one or more commodity prices as stochastic processes, where each process receives as inputs: (1) the mean reversion rate, (2) the price's volatility, and (3) the long run price of each commodity. With price uncertainty, Deep Mine can calculate different types of mine sequences:

- Deterministic, which assumes a fixed price scenario in the same fashion as other commercial software do.
- Best Robust Plan, which calculates the mine sequence that reacts best towards the price uncertainty defined by the user. This is done in the same fashion as Alvarado *et al.* (2011).
- Flexible plans, which allow the user to introduce one option at a certain point of time T, which updates both technical and economic variables according to user inputs.

For the flexible plan case, additional parameters must be given by the user in order for the option to be exercised: (1) a trigger price, which is the condition used by the program to determine which path to take, (2) a cost (typically an investment) for exercising the option, and (3) a lead time for the changes in technical variables to take effect.

Finally, on a different note, it is important to mention that an additional source of flexibility regarding plant processing is included in Deep Mine for all mining sequences that consider price uncertainty. This is due to the fact that a mining sequence must be committed for the LOM, but each block's processing destination can be decided according to the commodity price at the time of extraction. Therefore, Deep Mine allows the user to evaluate a mining sequence at different price realizations to see which blocks go to each destination. This can be seen graphically in Figure 5, where the block destinations (marked by different colours) change between the best and worst case price scenarios (left and right, respectively). In the worst case scenario, a greater tonnage is considered waste (in red), which would have been considered as ore in the best case scenario.

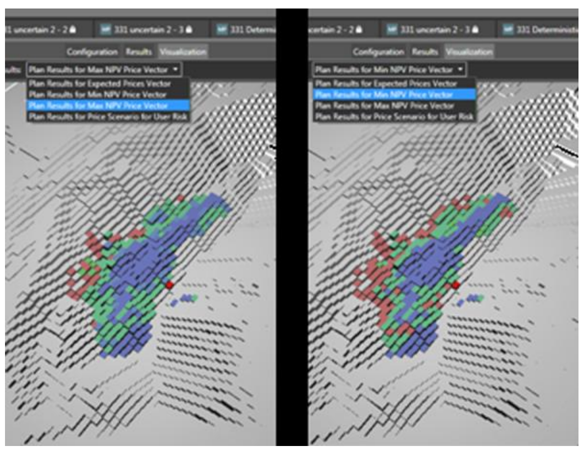

Figure 5 Example of plant processing flexibility in Deep Mine

RESULTS AND DISCUSSION

In order to show the potential value that flexible stochastic planning can add to mine planning, a expansion project is evaluated for Codelco's Radomiro Tomic mine using flexible plans generated by Deep Mine. It is important to disclose at this point that this project was conceived solely for this study.

Radomiro Tomic (RT) is a large scale open pit copper mine located in the north of Chile, near the city of Calama. The mine began production as an oxide operation in 1999, moving on to add sulphides in 2008. From a geological perspective, currently this deposit has a block model with 12.442.500 entries, with a large amount of resources to guarantee production for the next 50 years at current extraction rates.

Given the amount of resources, RT is currently studying to expand its sulphide line in a project known as RT Phase II. This expansion was valued using Deep Mine, reaching a deterministic mining sequence that increased the mine's NPV in approximately 22% compared to the commercial software used by RT for strategic planning. The mining sequences in both cases do not consider mine design elements, such as roads and ramps.

To value the potential of further expanding RT's sulphide processing capacity beyond Phase II (assuming that it is built), a fictitious project is considered, which adds an additional expansion of 200 ktpd to RT's concentrator plant capacity in 2020. However, recognizing that RT is not forced to execute this expansion under low copper price scenarios, this project is modelled in Deep Mine as an expansion option with a copper trigger price of 3 US$/lb, an investment cost of 3,500 MUS$ and a lead time of two years between the decision and operation of the increased plant capacity. Therefore, in this case, the decision of building the expansion must be made in 2018.

When evaluating RT's mine sequences with and without the additional expansion in a deterministic setting, the mine plan with the expansion adds 170 MUS$ to the mine's NPV. This proves there is economic potential in extracting RT's sulphides faster.

On the other hand, when evaluating this project using flexibility, Deep Mine increases RT's NPV in 530 MUS$. This additional value is explained because RT has the right, but not the obligation, of expanding plant capacity. Therefore, RT exercises this option only when the copper price is above the trigger price, avoiding to invest the 3,500 MUS$ in low copper price scenarios.

Considering these results, it is possible to calculate the expansion option's value using equation (1) shown below. This value amounts to 360 MUS$, which represents approximately 68% of the expansion project's value of 530 MUS$.

$$NPV^{Option} = NPV^{\text{Flexible}} - Max\left\{NPV^{\text{Deterministic}}_{\text{With expansion}}, NPV^{\text{Deterministic}}_{\text{Without expansion}}\right\} \tag{1}$$

On a final note, it is important to recognize that this project's value may seem low compared to RT's NPV.[2] Nevertheless, this is due to the fact that the cash flows attributed to the project start from the year 2020 onwards. Hence, as time passes and the decision date (2018) comes closer, this project's value will become ever more important for RT.

CONCLUSIONS

This paper builds from Alvarado *et al.* (2011) in order to lay the theoretical foundations for implementing flexible mine plans. This requires generating mining sequences that are the same until the decision point at time T, differing afterwards according to whether the option is exercised or not. Because of these complexities, flexible plans as described here cannot be generated using existing commercial software.

Recognizing this technological gap, BOAMine has built Deep Mine, the first commercial software prototype that can generate flexible mine plans at a strategic level. It has already been tested in a fictitious expansion project for Codelco's RT mine designed solely for this study. The results obtained are promising: (1) the use of flexibility significantly increased the NPV associated with the

[2] Although this information cannot be disclosed due to confidentiality reasons, it suffices to say that currently this is the largest mine of Codelco in terms of annual copper production, which is in turn the world's largest copper producer.

expansion project, and (2) Deep Mine's deterministic plans improve RT's NPV compared to this mine's preferred strategic planning software under the same economic and technical scenarios.

Nevertheless, there is still much to be done in this line of research. Today, BOAMine is focusing on adding additional sources of uncertainty to be considered in the construction of mining sequences, such as geological, geotechnical and cost uncertainty. Related to this, considering multiple uncertainties can lead to the need for designing complex options with more than one exercise date. This type of options, known as compounded options, should further improve the flexibility results obtained in this study. Hence, the first steps in crossing the frontier of Flexible stochastic planning have been taken, but there is still much value to be attained by improving this mine planning process in the future.

ACKNOWLEDGEMENTS

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