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A New Approach to Forecast Long Term Recoverable Reserves: The Simulation Learning Model

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The conventional paradigms used to estimate the economic potential of mineral deposits may deliver unrealistic results. They consider unrealistic assumptions about the mining process when long term plans are analyzed. The impact of infill drilling campaigns and blast-hole/grade control data is not accounted for during the analysis. A new paradigm to evaluate mining projects is proposed, where the impact of information updating during the mining process is accounted for by implementing a simulation learning model (SLM) approach. Several realistic mining scenarios are simulated, and their corresponding profits are summarized to infer a more appropriate distribution of uncertainty of the economic potential of the mining project. The proposed paradigm allows the analysis of the mining process variability on a global and period basis, as well as the economic evaluation of infill drilling campaigns in the performance of the long term mine plan.

1 Introduction

The calculation of recoverable reserves plays a critical role during the evaluation of a project, since profitable business opportunities may be lost or bad investments on projects can be made if the reserve numbers are not properly estimated. Calculating reserves consists of building a numerical model of the deposit and designing the best mining strategy or mine plan that maximizes the profit. The model of the deposit is built at a block resolution and often calculated using geostatistics. The mine plan consists of the mineable limits combined with a sequence of extraction by periods. The region of the block model contained within the mineable limits is considered to report recoverable reserves.

There are three traditional paradigms to calculate reserves: 1) estimation, 2) estimation-with-uncertainty, and 3) simulation. In each of these paradigms, the best model is built with all the current information for the scheduling of future periods; however, in practice, during the lifetime of the mining project, the reserves are updated periodically based on new information. Therefore, the reserves calculated in future periods will change. The updating of information is not accounted for in the traditional paradigms. Not considering the effect of information during the calculation of reserves may result in an unrealistic analysis of the economic potential of the deposit.

The performance of a long term mine plan in terms of maximizing profit is proportional to the volume of information available. Ideally, in presence of complete information of the deposit, the mine plan that maximizes the profit of the deposit could be designed. As the volume of information available increases, the mine plans designed converges into the optimal plan. The simulation paradigm considers that in each realization reality is accessible. The estimation paradigm considers the information available during the lifetime of the project is limited and does not change. In practice, the volume of information grows periodically, thus improving the performance of the mine plan accordingly. By comparing the scenarios of information of the two traditional paradigms against the practical case, the estimation paradigm appears to be pessimistic and the simulation paradigm optimistic.

A new paradigm that accounts for the updating of information during the mining process is proposed. It is considered that the volume of information collected from the deposit grows periodically. Accordingly, the efficiency of the long term mine plan improves over time. The reserve numbers from the proposed paradigm are more realistic than either assuming no additional information or perfect knowledge of the deposit. In the proposed paradigm, several scenarios of the mining process are simulated. On each of them, the information is updated periodically by simulating the sampling of the deposit by infill campaigns and blast-holes. The proposed paradigm is named simulation-learning-model (SLM) because the periodical updating of information can be considered as a learning process of three steps: 1) update information from the deposit, 2) adjust the long term mine plan, and 3) use the updated recoverable reserves to evaluate the project.

In the next section, aspects of the traditional paradigms, the SLM paradigm and the effect of information updating during the mining process are discussed. After that, a methodology to implement the SLM paradigm is presented and discussed. The aspects and implementation details of the SLM are presented in the example section, where two cases are discussed. Finally, a section of conclusions are presented.

2 Background

A surface mine plan to evaluate reserves can be split in two parts, delineation of the final pit and mine sequencing. The final pit is used to calculate global numbers of tonnage and metal content of the deposit. Two popular algorithms to calculate final pits are floating-cone (developed by Kennecott Copper in 1961) and the algorithm proposed by Lerchs and Grossmann (1965). The mine sequencing consists of scheduling the reserves in periods subject to operational conditions. It describes how the final pit is going to be mined. The sequence of mining is designed to maximize the profit of the project among other goals.

The performance of a mine plan is measured in economic terms. The use of discounted cash flow analysis is widely implemented to evaluate reserves. This analysis is based on the calculation of representative present values of future cash flows. The use of the net-present-value NPV to summarize the cash flows of the mining project is commonly implemented in practice (Whittle & Whittle, 1999).

Due to the limited number of drill-holes, mine plans could be designed based on a block model that accounts for uncertainty. The volume of the blocks considers the selectivity of the deposit based on geologic and mining conditions (Journel & Kyriakidis, 2004). The block model of the deposit could be estimated or simulated. Based on these two forms of the block model, three paradigms can be implemented to evaluate reserves: 1) estimation, 2) estimation-with-uncertainty, and 3) simulation.

2.1 Paradigm 1: Estimation

This paradigm considers the use of a single estimated model, often based on ordinary kriging. The NPV of the deposit is calculated using one mine plan (see Figure 1-left). The uncertainty in the estimated block model is accounted for by categorizing blocks as measured, indicated, and inferred (Australasian Joint Ore Reserves Committee, 2008).

The kriging plan is often tuned to achieve reliable recoverable reserve predictions or to mitigate conditional bias. The former objective is common in long term planning (Isaaks, 2005).

2.2 Paradigm 2: Estimation with uncertainty

This paradigm can be seen as an extension of paradigm 1. The final pit and the mine sequencing calculated in paradigm 1 are used to evaluate different realizations of the block model (see Figure 1-right). The mine plan could be also designed based on the e-type block model. A distribution of uncertainty in NPVs can be evaluated from the realizations.

2.3 Paradigm 3: Simulation

This paradigm consists of simulating several realizations of the block model and designing for each of them a mine plan. The distribution of the NPVs of the project can be inferred from evaluating each realization with its respective mine plan (see Figure 2).

Unlike in paradigm 1, there is no problem of tuning a kriging plan, since the variability of the deposit is reproduced in each of the realizations. This paradigm is not widely implemented in practice because the realizations of the deposit are computationally expensive to generate. Moreover, because of the difficulty of automating the estimation of the final pit, dealing with a large number of realizations is not practical (Dominy, Noppé, & Annels, 2002). Finally, planning on each realization independently amounts to assuming perfect knowledge of the ore body in the future.

2.4 Effect of information updating in mine planning

From the moment a mining project begins to operate, new information from the deposit is continuously being collected. At the end of each time period, the volume of information from the deposit is upgraded. Accordingly, the block model of the deposit tends to be more accurate and approaches to reality. The sources of the new information are infill campaigns and blast-hole data. When designing a long term plan, this periodical updating of information should be considered as part of the mining process.

Paradigms 1 and 2 are not considered realistic, because they do not model the periodical updating of information and mine plan. They are often pessimistic. On the other hand, paradigm 3 is optimistic, because on each of the realizations assumes the deposit is exhaustively sampled before the initial plan is designed, so no updating of information is necessary. In this context, the conventional paradigms are the extreme cases of the analysis. A realistic NPV of the project is likely in between of the values calculated by these conventional paradigms.

2.5 Proposed paradigm: Simulated learning model

In this paradigm, the periodical updating of information is accounted. The block model, the mine plan, and the NPV of the project change as the information from the deposit is updated. At the end of each period, extra data is added to the existing information from two sources, 1) from the mined region in the current period in the form of blast-holes and 2) from infill drilling campaigns, which aim to reduce the uncertainty of future regions to be mined (see Figure 3).

In practice, from the long term plan designed at the beginning of the first period, only the sequence that corresponds to the first period is mined in the deposit. At the beginning of the second period a new long term plan is designed based on the updated information from the first period and the sequence that corresponds to the second period is executed. The mined region in the second period is different to the region proposed in the initial plan because the updated information modifies the block model. This cycle is repeated through the lifetime of the project. The true geologic characteristics of the deposit are not available to update the information during the periods of the project. Hence, a set of realizations are generated. They all are similar in the first period, because there is only the existing information. Updating the information from the mined regions in the form of blast holes information is relatively simple to implement compared to infill drilling. Infill drilling campaigns on each periods are designed considering a variety of strategies and targets dictated by company policies. The implementation of an infill drilling strategy becomes a new parameter of the mine plan.

The planning process in the proposed paradigm has aspects of the three essential steps of learning. 1) Remembering: assemble previous information and collect new information for upgrading the model, 2) adapting: the planning process is adjusted according to the changes in the block model, and 3) generalizing: the updated mine plan is the best decision that can be made in the current state of the information to mine the following periods (Marsland, 2009). The proposed paradigm simulates the learning process that occurs on each period while mining the deposit. Therefore, the proposed paradigm is named simulating-learning-model (SLM).

The proposed paradigm evaluates recoverable reserves and provides a measure of uncertainty in the NPV of the project. The proposed paradigm provides a more realistic approach to evaluate alternative long term plans.

3 Methodology

For the proposed approach the events that occur at each period (see Figure 4) are as follows:

At the beginning of each period:

- Build a block model using all available information.
- Design a long term mine plan based on the block model.

During each period:

- Execute the mine plan for the current period.

At the end of each period:

- Assemble the information from the mined region in the form of blast-hole data.
- Gather the infill drilling information.

Since the true geologic characteristics of the deposit are not accessible to update the initial data, the two sources are simulated conditioned to the available information at the beginning of the period. The differences in scale and sample quality could be considered.

The mining process continues until there are no more profitable regions to mine (see Figure 5). Thus, the final pit is the last surface after mining these periods. Each realization is considered as one scenario of the mining process.

The analysis of the NPV of the mining project is done considering several mining scenarios. All these are equally probable to occur based on the initial information available. The first period is supported by the initial available dataset, thus it is the same for all realizations mining scenarios (see Figure 6).

The proposed workflow is:

1) Build a model, plan and mine the first period.

A block model is built and a long term mine plan is designed based on it. After sequencing the final pit, the region that corresponds to the first period is executed by updating the current topography.

2) Generate scenarios of the updating information.

The blast-hole data from the mined region and the infill drilling campaign for mining the next period are simulated on each realization.

3) Analyze the mining scenarios.

Each realization of the updated information leads to a different scenario. The final pit and corresponding sequencing of each scenario is calculated:

a) Generate one scenario of the current period.

i. Update the block model.

Using the same modeling parameters as in the first period, the block model is updated as the information increases. Unlike what happens in practice, parameters such as variograms are not changed since the updating information was simulated using the variogram of the initial data.

ii. Design a plan to mine the current period.

The mine plan is updated with the new block model. The topographic surface is updated by the latest mine plan of the current period. If there is no region to mine in the current period, go to step c).

iii. Simulate a realization of the updating information after mining the current period.

The current information of the deposit is updated from two sources, blast-hole data sampled from the mined region and infill drilling campaign for planning the next period. The infill drilling campaign is designed considering the updated topographic surface.

b) Proceed to the next period.

Return to previous step 3a) if there is a profitable stage to mine.

c) Analyze the final pit.

Calculate the NPV from the resulting mining sequence. The surface of the deposit is the final pit for the current mining scenario.

Go to step 3) if there are still more scenarios to analyze.

4) Summarize the results of each mining scenario.

Summarize the realizations of NPV for the project. Furthermore, additional information such as the probability of each block to be mined on a certain period, variability of the spatial configuration of mined regions for particular regions can also be obtained from analyzing the simulated mining scenarios.

The methodology used for building the block model is not restricted only to kriging estimation. Other methodologies such as using the e-type of realizations can be also implemented. Similarly, any pit optimization and scheduling algorithms can be used. The SLM paradigm is sensitive to the sources of information updating considered. In the case of the blast-hole data, because of the differences in support, data integration techniques should be implemented to update the block model. In the case of the infill campaigns, because of the several mining scenarios analyzed, an automated algorithm to place the drill-holes based on the current mining conditions is recommended to be implemented.

4 Example

Two cases are presented. The first case discusses the implementation of the SLM paradigm and shows the impact of the information updating during the mine planning process. It is presented how the SLM paradigm approaches to the optimal plan considering the ideal case that reality is accessible. The second case discusses the evaluation of a deposit without having access to reality. Paradigm 1, paradigm 3 and the SLM paradigm are compared.

4.1 Impact of information updating during mine planning

A reference model of a deposit that consists of three rock types and one grade variable is built over on a volume of 5000 × 2500 × 1000 cubic meters at a point resolution of 500 x 250 x 50. Three rock types correspond to high grade

(HG), medium grade (MG), and low grade (LG) geologic structures in the deposit. The metal content variable was generated by simulation of three exponential distributions according to the rock type code, that is, high-grade (HG) mean is 2.5, medium-grade (MG) mean is 1.0, and low-grade (LM) mean is 0.5. An initial topographic surface was arbitrarily assigned to the model.

To calculate the recoverable reserves, a block model and mining parameters are set as follows: The SMU block size of the block model is 50m × 50m × 20m, the floating cone algorithm is considered for calculating the long term plan of the deposit and for mine sequencing. Approximately 6000 SMU blocks can be mined in each period. The interest rate is set at 10% per period. The cut-off grade is set to 2%. For simplicity, no capital cost is considered in the analysis. The available information consists of an exploratory campaign of 50 vertical drill-holes placed over a regular grid of 500 x 500 m.

In this part of the exercise, the optimal mine plan based on reality is compared to the mine plans obtained in paradigm 1 and the SLM paradigm. To avoid bias due to preferential sampling, the drilling pattern of available exploratory campaign is shifted randomly 50 times over the region of the deposit.

The first period planned in paradigm 1 is considered as the first period of the SLM paradigm mine plan. As part of the first period, this region is mined and additional information is collected in the form of blast-hole data and infill drilling campaign (see Figure 7). For simplicity, one blast-hole is sampled for each mined SMU block and an infill drilling campaign that consists of five vertical drill-holes per period is randomly placed over the updated surface. This new information provides a new scenario of the block model (see Figure 8), making the plan for mining the second period different from what was initially proposed in the mine plan of paradigm 1. Similarly, as part of the second period, the region planned is mined following the new mine plan and the new information is collected in the form of blast-hole data and a new infill drilling campaign. At the beginning of the third period, the block model is updated by the new information updated recently (see Figure 9). The updating process of the first and second period is repeated through the lifetime of the project until there are no more profitable regions to mine. The final pit is composed of the first regions planned in each period.

Because some of the ore bodies were not captured in the exploratory drilling campaign, differences between the mine plan of paradigm 1 and of reality arise (see Figure 10). In the mine plan based on reality, all of the ore bodies in the deposit are considered (see Figure 11-top). In the mine plan of paradigm 1, only the accessible portion of them is considered in the evaluation, thus resulting in a conservative scenario (Figure 11-middle). In the SLM paradigm, this missing information is completed periodically, thus the mine plan is able to approach to the real case over time (Figure 11-bottom).

The histograms of NPVs calculated using paradigm 1 and SLM paradigm for the 50 drilling scenarios are compared to the optimal NPV obtained from planning based on reality (see Figure 12). The average NPV of paradigm 1 is pessimistic compared to the reality case because the information used is limited, only a portion of the total ore bodies are reproduced in the block model. The average NPV of the SLM paradigm approaches better to the optimal NPV than paradigm 1. The SLM paradigm has the same starting point as paradigm 1, but as the deposit is mined, the periodical increment in the volume of information approaches the mine plan to the optimal plan. The speed of correction of the SLM paradigm is proportional to the volume of information that is updated.

4.2 Comparison of SLM paradigm versus conventional paradigms

For this example, the true geologic characteristics of the deposit are not accessible but only an initial exploratory drilling campaign dataset. The geology of the sampled deposit consists of two rock types, high grade (HG) and low grade (LG). The metal content variable follows an exponential distribution with means according to the rock type, 2.5 for HG and 0.5 for LG. Unlike the first example, only one scenario of the exploratory drilling campaign is considered.

Paradigm 1 is implemented conventionally based on the initial data. For implementing paradigm 3, 30 realizations of the deposit are generated and a final pit and its respective sequencing are calculated for each of the realizations. In the SLM paradigm, 30 mining scenarios are simulated, the implementation is similar to what was presented in the previous example, except the two sources of information are simulated instead of sampled from reality.

The average of the NPVs obtained in paradigm 3 is larger than both paradigm 1 and the SLM paradigm. It occurs because paradigm 3 assumes that scenarios of reality are available. The NPV of paradigm 1 is the smaller than paradigm 3 because the mine plan is based on a model that accounts for uncertainty. However, paradigm 1 does not consider the periodical updating of information that occurs during the mining process, hence results pessimistic. The NPVs of the SLM paradigm results more realistic because the periodical improvement due to the updating of information is accounted for. The average NPV of the SLM paradigm is located between paradigm 1 and paradigm 3.

The gap in the average NPVs between paradigm 3 and the SLM can be identified as the cost-due-to uncertainty. This gap occurs because of the lack of complete information of the deposit and is inversely proportional to the information available. Paradigm 3 assumes the deposit is mined assuming there is no error in the decisions made during mine planning, while the SLM paradigm assumes the mine plans are not error free and are corrected throughout the lifetime of the project as more information is collected (see Figure 13).

5 Conclusions

The design of a mine plan is supported on the current available information. Only when reality is known these decisions can be claimed as 'optimal', otherwise, any of these decisions will be associated to errors that will make the mine plan non-optimal. The degree of the potential errors associated to the mine plans designed is inversely proportional to the availability of information, that is, as more information is collected from the deposit, the degree of errors is reduced.

Paradigm 1 does not consider the effect of information updating during the mining process. In practice, the collection of more information occurs periodically throughout the lifetime of the mine. After each period, the decisions proposed in the updated mine plan will be associated to less error. Thus the mine plan is corrected over time. On the other hand paradigm 3 assumes the deposit is exhaustively sampled on each realization. These two paradigms represent two extremes of the economic evaluation of the deposit, depending on the initial information available.

The SLM paradigm is a tool for evaluating reserves accounting for the availability of information during mine planning. Several mining scenarios of the deposit are simulated. By comparing the resulting NPVs of the SLM paradigm versus paradigm 3, the economic impact of the available information in the NPV of the project can be evaluated. Decisions about whether or not is convenient to add drill-holes to the initial dataset or what infill drilling strategy to adopt can be quantified in economic terms. The SLM paradigm is computationally expensive to implement compared to the conventional paradigms because the block models are periodically updated as well as the mine plans over several scenarios.

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Figures

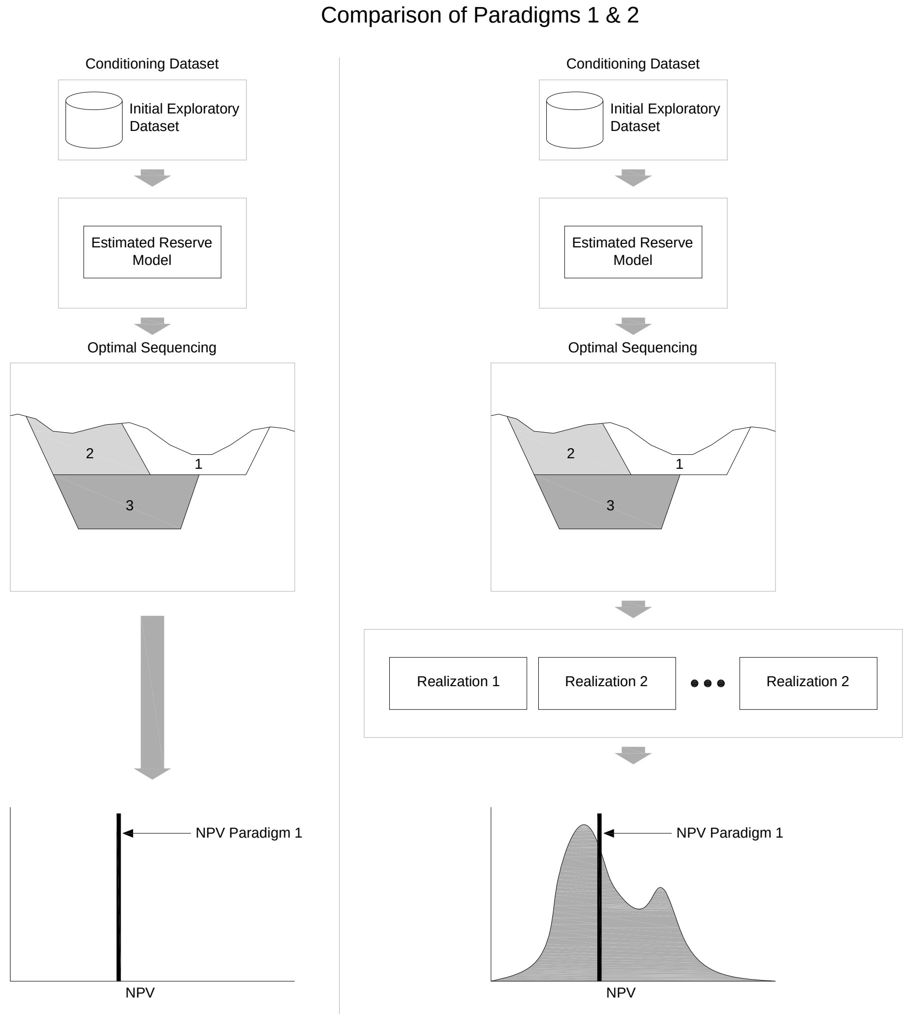

Figure 1: Comparison of paradigm 1 (left) and paradigm 2 (right) for evaluating reserves.

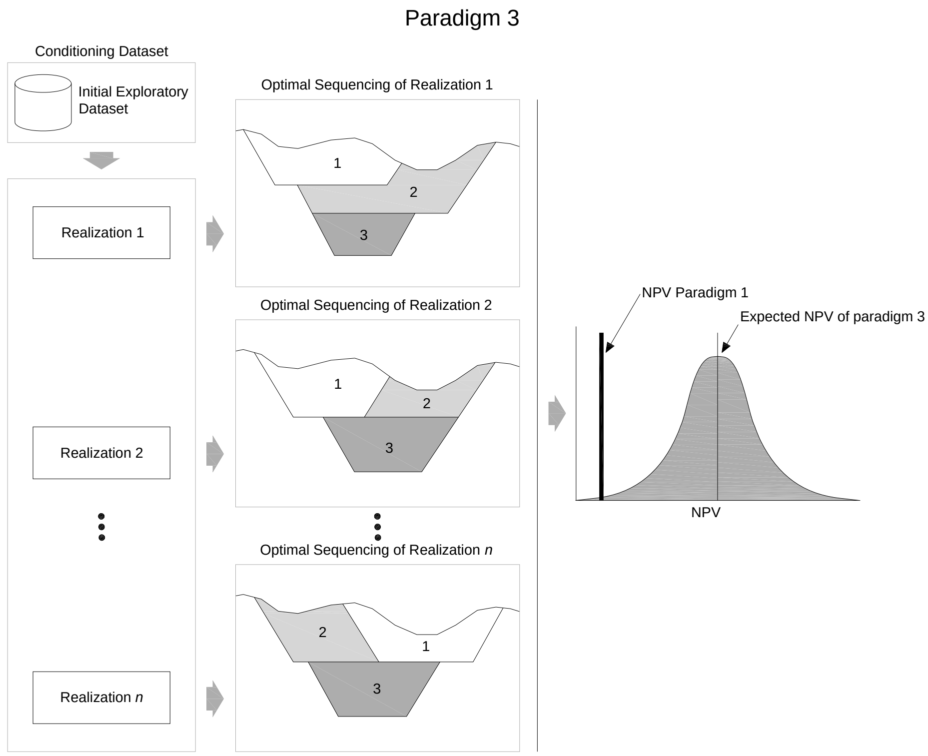

Figure 2: Sketch of paradigm 3 to evaluate reserves.

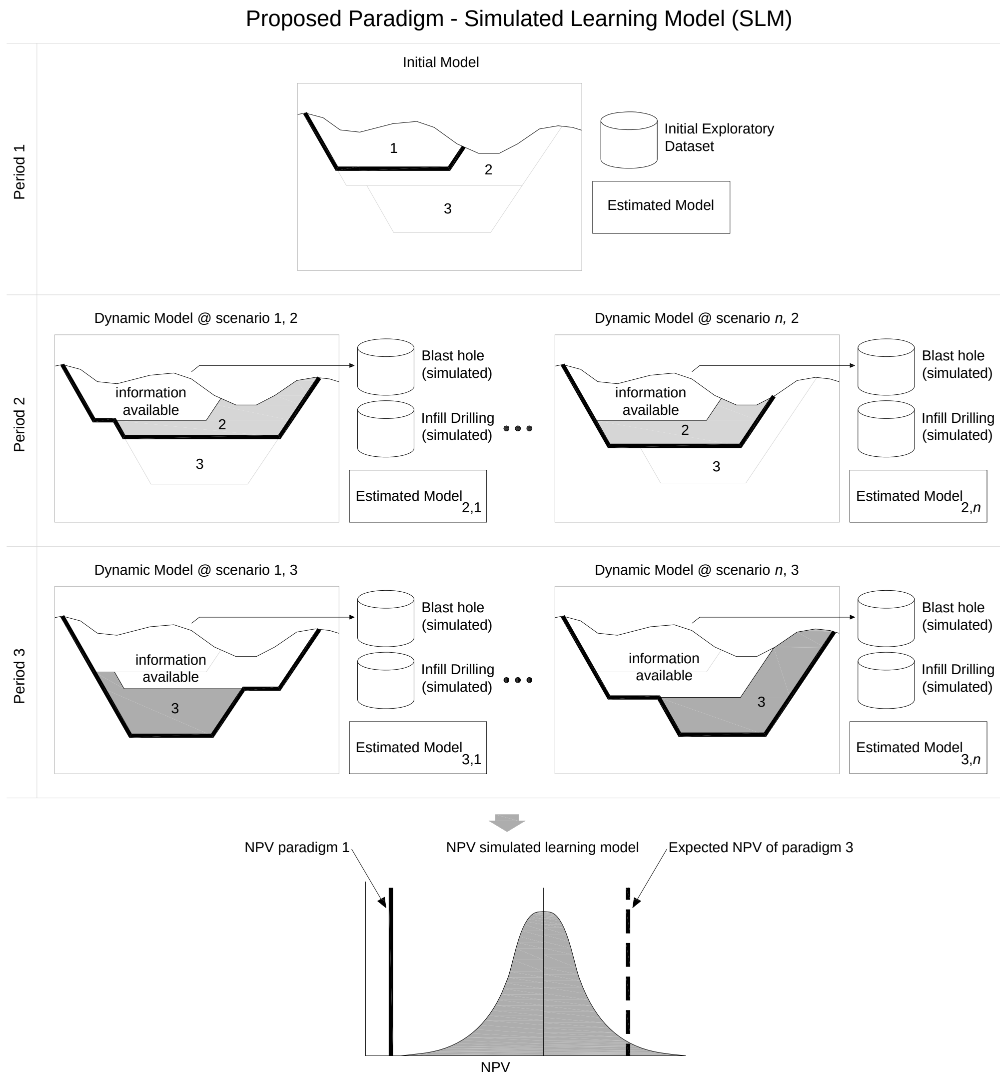

Figure 3: Sketch of the proposed paradigm: Simulated learning model SLM.

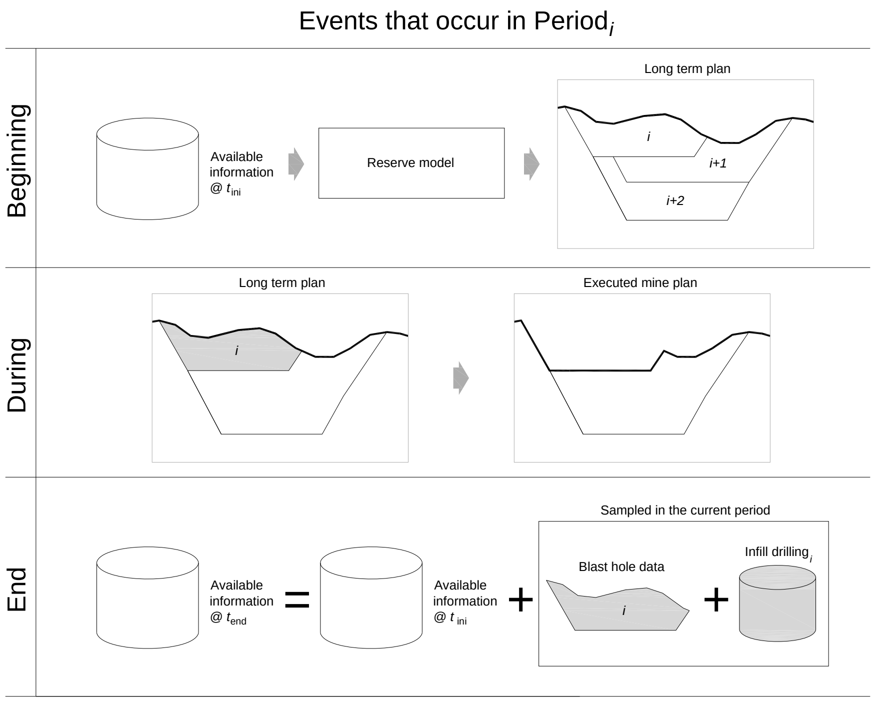

Figure 4: Sketch of the events that occur during each period.

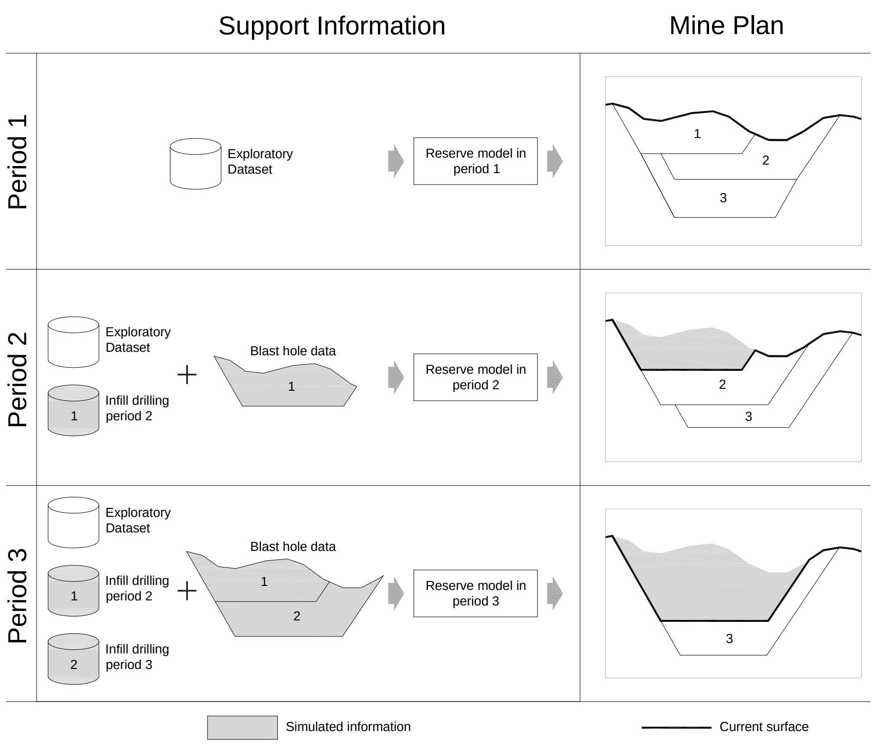

Figure 5: Sketch of mine planning updating in the proposed approach.

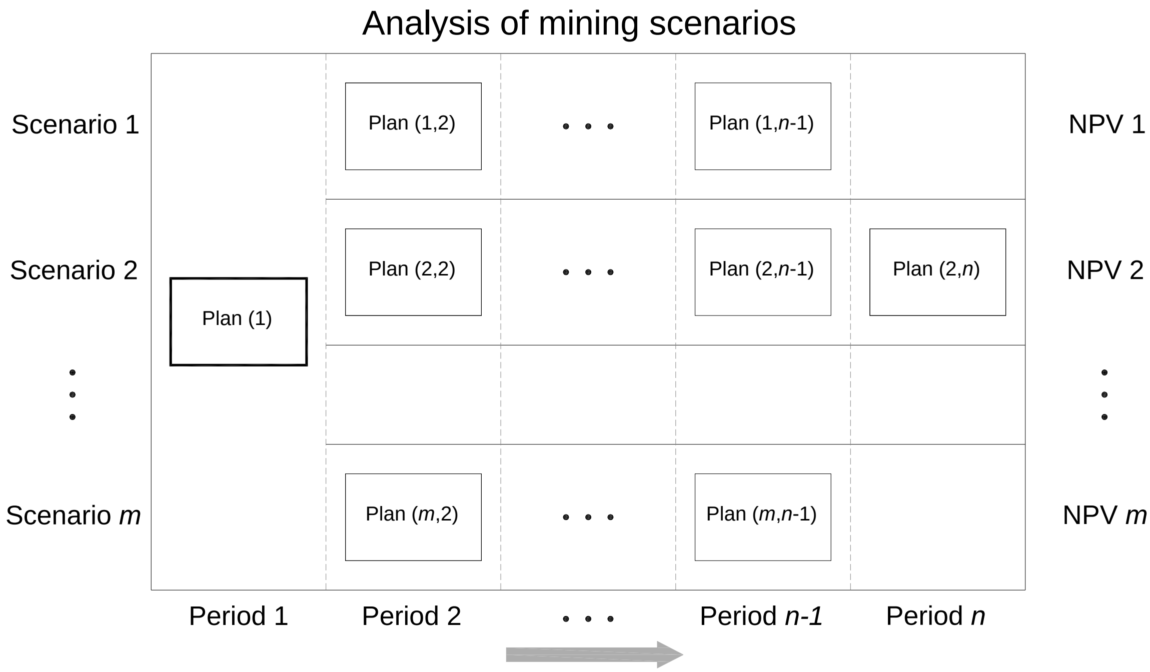

Figure 6: Sketch of the framework to analyze mining scenarios.

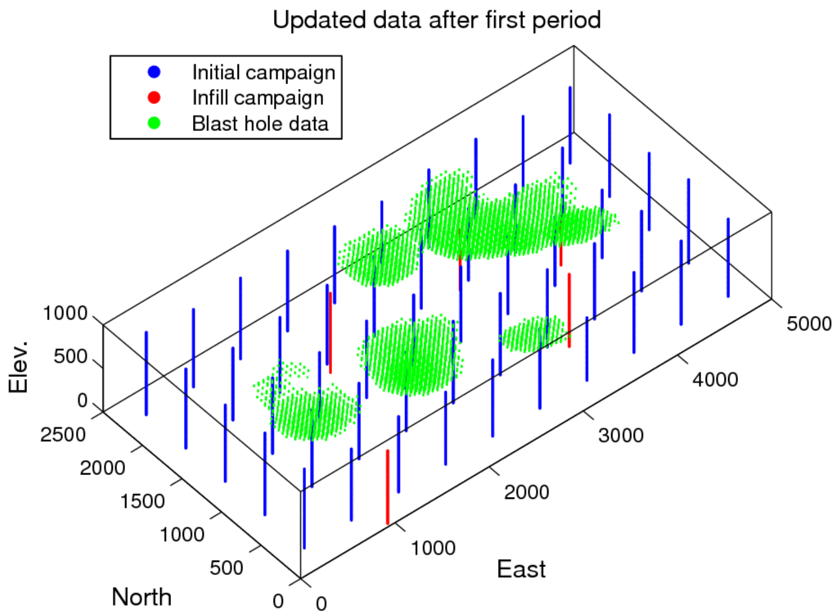

Figure 7: Updated information by blast-hole data and infill campaign after mining the first period.

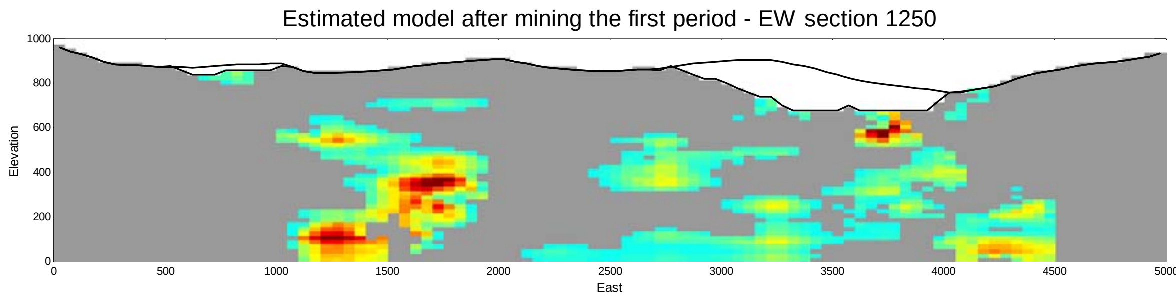

Figure 8: Section EW 1250 of updated block model after mining the first period.

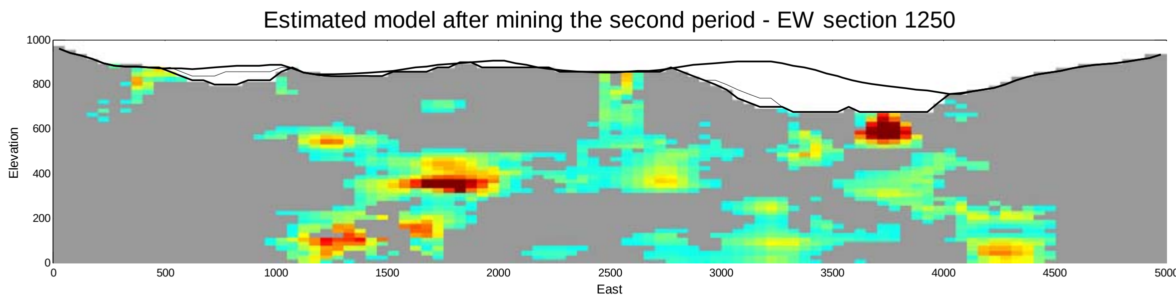

Figure 9: Section EW 1250 of updated block model after mining the second period.

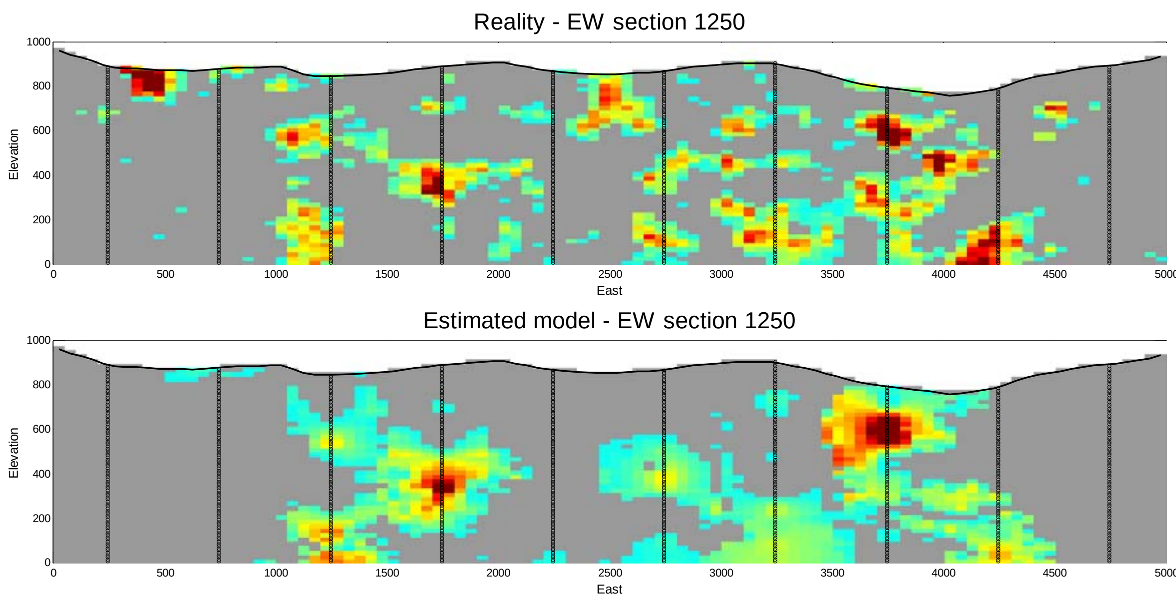

Figure 10: Exploratory drilling campaign versus ‘reality’ (top) and estimated model (bottom) in EW section 1250.

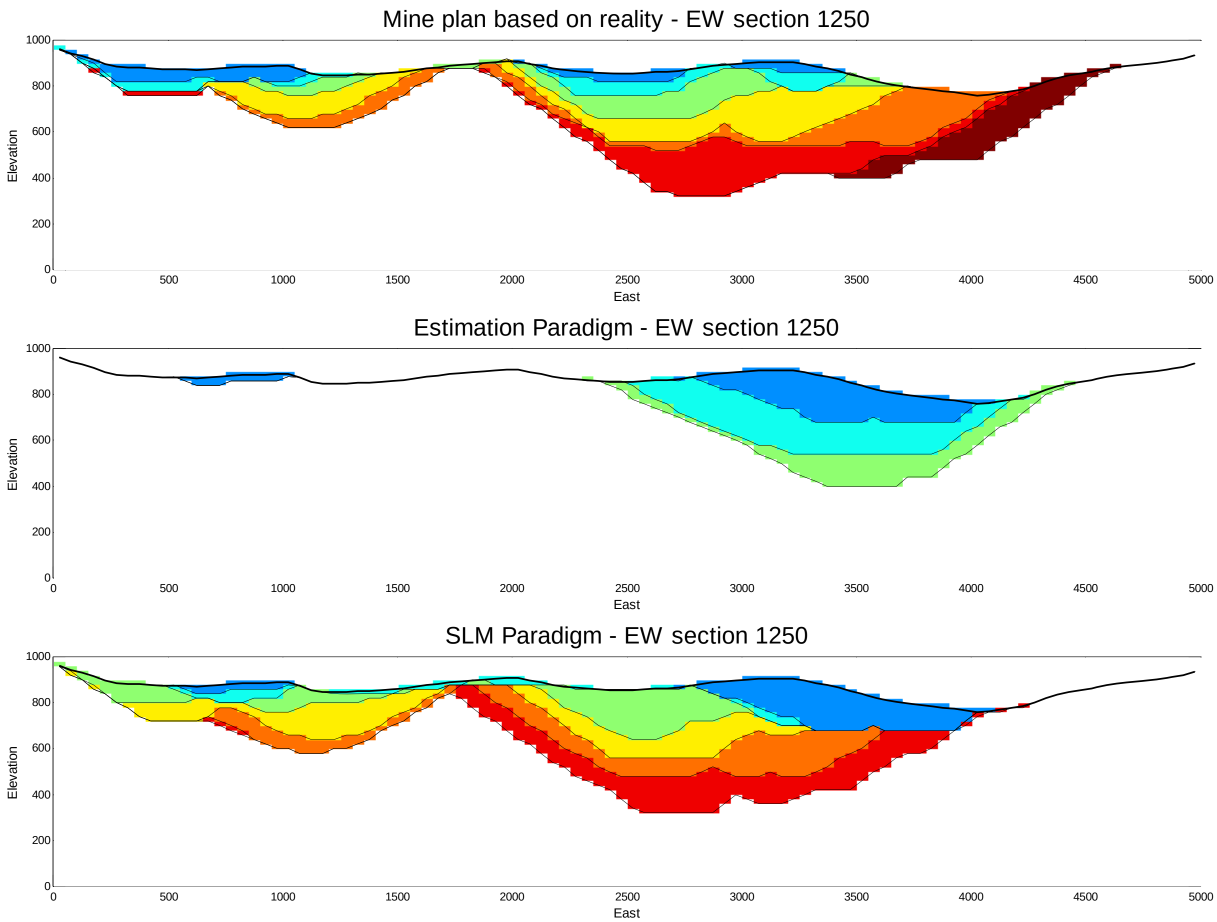

Figure 11: Sequencing of final pit obtained based on reality (top), estimation paradigm (middle) and SLM paradigm (bottom).

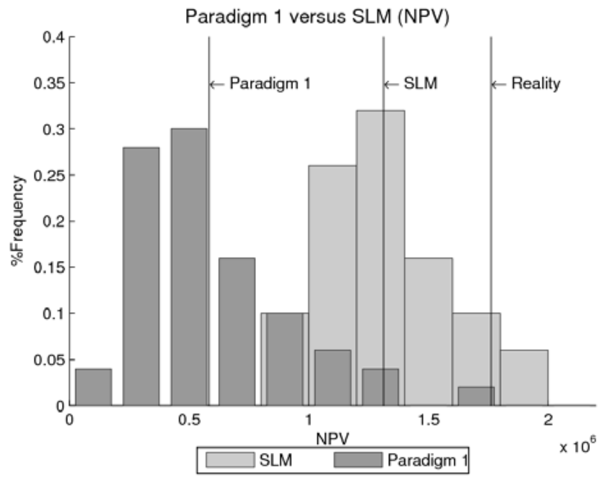

Figure 12: Histograms of NPVs of 50 drilling scenarios of paradigm 1 and information updating approach compared to the NPV calculated based on the 'true' block model of the deposit.

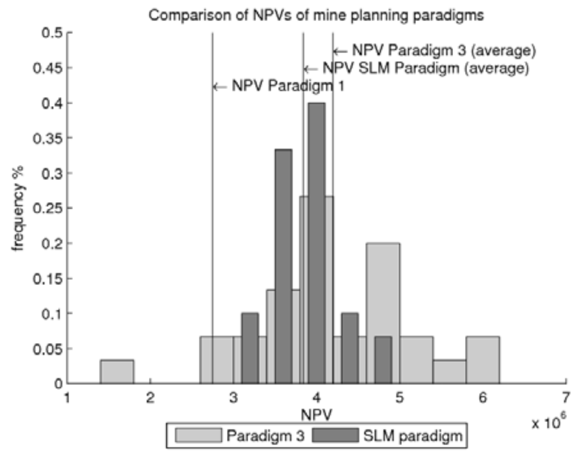

Figure 13: Comparison of paradigm 1, paradigm 3 and SLM paradigm for economic evaluation of a mineral deposit.