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Simulated Learning Model Framework for Evaluation of Long Term Reserves in Surface Mining

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In the evaluation of the economic potential of a mining project, two paradigms are usually implemented. They are: 1) estimation, and 2) simulation paradigm. However, in terms of uncertainty management, these two paradigms are limited. The basic problem is that they do not account for the periodic updating of information, which is an inherent feature of mine processes. The collection of extra information in each period reduces the state of uncertainty in the model periodically. The estimation paradigm assumes that the periodic updating of information does not take place in the mining process; hence the state of uncertainty remains static throughout the lifetime of the project. For this reason, the estimation paradigm is considered as pessimistic. The simulation paradigm assumes in each realization that reality is accessible beforehand; hence there is no uncertainty in each scenario and there is no need to account for the periodic updating. For this reason, the simulation paradigm is considered as optimistic. In this paper, a new paradigm for evaluating mining projects is presented. This paradigm simulates scenarios of the periodic updating of information. In each scenario, the mine plan is calculated based on the periodic updating of information by implementing a computational learning method. Because of this characteristic, this paradigm is named simulated learning model (SLM). The background, methodology, and an example are presented in this paper.

Introduction

During the economic evaluation of surface mining projects, life-of-mine (LOM) plans are designed to estimate the economic potential of mineral deposits. LOM plans define the extraction sequence of the deposit, one goal is to maximize the profit of the project. The design of a mine plan can be divided in three stages: 1) numerical modeling of the deposit, 2) long-term planning, and 3) short-term planning (Whittle & Whittle, 1999). The design of the LOM mine plan corresponds to the first two stages. For simplicity, the LOM plan will be referred to as mine plan.

In the first stage of the design of a mine plan, the numerical model of the deposit is built at a selective mining unit (SMU) resolution by implementing geostatistical methods. In the long-term planning stage, the ultimate pit and its corresponding mining sequence are calculated based on the numerical model by implementing optimization techniques that aim to maximize the revenue of the project. There are two paradigms that can be used to in the evaluation of the mining project: 1) estimation and 2) simulation paradigm. Dominy, Noppé, and Annels (2002) discussed the implementation of these two paradigms in the design of surface mining projects. In the estimation paradigm, the model of the deposit is built using kriging techniques. The mine plan is based on the estimated model of the deposit. This paradigm is widely implemented in industry. In the simulation paradigm, the model of the deposit is a simulated model that comprises a set of realizations of the deposit. A set of mine plans, one for each realization of the deposit, is calculated. This paradigm is quite computationally expensive and is seldom implemented in real cases for reporting reserves.

In practice, throughout the lifetime of a mine project, mine plans are updated periodically due to new information (see Figure 1). The new information that updates the existing data is collected from many sources like infill drilling campaigns, blast-hole data, etc. At the beginning of each period, the model of the deposit is built with the latest information and a new mine plan is designed accordingly. When comparing the previous mining sequence versus the new mining sequence, the difference of the region planned for the current period is due to the new information collected. The region planned in the previous mining sequence was designed based on less information than the latest. In economic terms, the gap between planned revenue and the real revenue is smaller when the last mine plan is executed, compared to the previous mine plan. In each period, only the first region planned is executed. The rest of the regions planned will be updated in the following periods.

The two mine planning paradigms do not account for the periodic updating of information of the mining process. The estimation paradigm assumes that the first mine plan can be used throughout the lifetime of the project without updating it. The simulation paradigm generates the mine plans under the assumption that in each realization reality is accessible; hence there is no need to update information. In practice, the state of uncertainty of the deposit evolves throughout the lifetime of the project due to the periodic additional collection of information. In uncertainty management terms, the estimation paradigm is considered as pessimistic and the simulation paradigm as optimistic. These two paradigms represent the two extremes in the evaluation of a mine project in presence of uncertainty.

In this document, a third paradigm is proposed that accounts for the periodic updating of information due to the acquisition of new samples. In this paradigm, a set of information-updating scenarios are simulated, and for each scenario a mine plan is generated. Since in each period the updating of the mine plan is implemented in a computing learning fashion, this paradigm is called simulated learning model (SLM). The result of this paradigm is a set of realistic mine plans that will be used to evaluate the uncertainty of the economic potential of the project.

Two common problems are present during the evaluation of mining reserves, these are: support and information effect (Journel & Huijbregts, 1978), (Chilés & Delfiner, 1999), (Journel & Kyriakidis, 2004). Support effect is related to the resolution of at which the model of the deposit is built. The geologic characteristics of the deposit have to be represented in the model at a SMU resolution for evaluation of reserves purpose. Information effect considers the effect of the estimation error in the accuracy of the mine plan. In practice, this error is calculated as the difference between the estimated block values in long term model versus the block values in the short term model. Short-term models are built based on blast-hole information, and are used to schedule material to their respective destinations on a daily or weekly basis. The support effect in mining has been widely studied by many authors (Journel & Huijbregts, 1978), (Parker, 1980), (Isaaks & Srivastaba, 1989). However, the information effect in the evaluation of reserves has been discussed only by few authors like Isaaks (2005). Froyland, Menabde, Stone, and Hodson (2004) proposed a methodology to value extra infill drilling information. In the SLM paradigm, both support and information effect is accounted for. Since the periodic updating of information is simulated, the cost due to uncertainty can be calculated is expected value terms.

In the next two sections, a brief description of the conventional paradigms is presented. In the following two sections, the SLM paradigm is introduced and the methodology to implement it is presented. The following section discusses the implementation of the SLM paradigm in a synthetic example. In the last section, conclusions and final remarks are presented.

Paradigm 1: Estimation

The estimation paradigm consists of a mine plan that is designed based on an estimated model of the deposit. This paradigm uses an estimated model as the input that represents the geology of the deposit. In industry, the implementation of kriging techniques to build estimated models has become standard practice. Since only one model is available, the evaluation of the economic potential of the project relies on the design of one mine plan (see Figure 2 - A). The use of estimated models in mine planning has been extensively discussed by many authors such as David (1977), Journel and Huijbregts (1978), and Hustrulid and Kuchta (1998) among others.

According to international reporting guidelines, e.g., JORC code (Australasian Joint Ore Reserves Committee, 2008), blocks in estimated resource models are categorized as inferred, indicated, and measured based on local uncertainty parameters. These guidelines suggest that during the design of the mine plan all inferred blocks have to be considered and reported as waste blocks, regardless of their economic value. Following these guidelines is a requisite to report the economic potential of a project.

In terms of uncertainty management, the estimation paradigm is considered as pessimistic because it does not account for the periodical updating of information of the mining process. In the estimation paradigm it is assumed that throughout the life of the project the state of uncertainty in the model remains static.

Paradigm 2: Simulation

The simulation paradigm uses a simulated model of the deposit, where one mine plan is designed for each realization of the simulated model, thus resulting in a set mine plans. In this paradigm, the input that represents the geology of the deposit is a simulated model. Like kriging estimated models, simulated models are also built by implementing geostatistical techniques (David, 1977), (Journel & Huijbregts, 1978). Simulated models comprise a set of realizations, which are equally probable representations of the deposit modelled. In this paradigm, a mine plan is designed for each realization of the simulated model, thus resulting in a set of scenarios of the economic potential of the mining project (see Figure 2 - B). The implementation of this paradigm in small case studies or using partially simulated models has been presented by many authors, Dimitrakopoulos (1997) and Van Brunt &

Rossi (1999) among others. Some authors proposed the use of simulated models to analyze the risk associated to mine plans, e.g. Rossi and Van Brunt (1997).

The implementation of the simulation paradigm in industry is not yet standard practice. In industry, due to the many relevant geologic variables to design a mine plan, e.g., multiple metal elements, contaminants, mineralogy content, etc., building an estimated model is computationally expensive. This, besides the fact that mine planning design is also another computationally demanding process, the implementation of the simulation paradigm is intractable for industrial use. Dominy, Noppé, and Annels (2002) mentioned that due to the difficulty of automating the operational optimization during the design of the final pit, dealing with a large number of realizations is impractical when evaluating reserves. The simulation paradigm is considered as optimistic, since each of the mine plans is designed under the assumption that the complete geologic knowledge of the deposit is accessible in advance.

Paradigm 3: Simulated learning model (SLM)

This paradigm accounts for the periodic updating of information of mining processes. The updating information is simulated using geostatistical methods. Unlike the simulation paradigm, where realizations of the deposit are generated, in this paradigm, the simulation consists of generating scenarios of the periodic updating of information (see Figure 2 - C). A set of mine plans, one for each information-updating scenario, is generated. To differentiate between the mine plans of the conventional paradigms and the output mine plans of this paradigm, the latter will be referred to as SLM mine plans.

For each realization of the information-updating scenario, a SLM mine plan is calculated. Each SLM mine plan provides a probable scenario of the economic potential of the project. Unlike the estimation paradigm, where only one economic scenario is calculated, in the SLM paradigm, the uncertainty in the economic scenarios can be approached. Like the simulation paradigm, the SLM paradigm can be used to evaluate the risk associated to mining projects. The SLM paradigm accounts for the mining process in a more realistic manner.

In the context of the SLM paradigm, the estimation paradigm represents the initial state where no source of information-updating is considered in the mining process. The periodic updating of information reduces the economic loss due to the use less informed mine plans, thus incrementing the revenue of the project. However, if the cost of extra data collection is larger than the increment in the revenue of the project, it is preferred to design the mine plan based on the available information (Froyland, Menabde, Stone, & Hodson, 2004). Froyland, Menabde, Stone, and Hodson (2004) proposed a methodology to calculate the maximum value that can be paid for additional infill drilling. The authors highlighted the importance of the use of additional information if it is economically feasible.

Information-updating scenarios

Each of the scenarios of the periodic updating of information consists of two sources of information: 1) infill drilling campaign, and 2) blast-hole drilling. The collection of the updating information interacts with the mining process on a period basis. The infill drilling information is sampled from the deposit based on the configuration of planned infill drill-holes. The number, position and geometric configuration of infill drill-holes in each period are set up in the infill drilling plan of the project. Infill drilling plans are subject to an exploration strategy and more importantly to an infill drilling budget. The cost of the infill drilling plan is assigned to the capital cost, thus it affects directly to the profit of the project. In the SLM paradigm, the design of an infill drilling plan becomes an additional parameter of the mine plan. The blast-hole information is sampled from operative blast-hole drilling patterns. The cost of the blast-hole information is assigned to the operative cost, and has no direct effect in the profit of the project.

The simulation of both sources of information, blast hole and infill drilling, is conditioned to the existing data. In the case of the infill drilling campaign, the simulation is done at point scale, at the location of the samples of the planned infill drill-holes. In practice, there are different types of infill drill-holes, where the quality of the samples is proportional to the cost of the drilling type. For example, air-reverse drilling produces more sampling error than diamond drilling; however, air reverse drilling is cheaper. Geostatistical methods can be implemented to account for sampling errors in estimation and simulation, Cuba, Ortiz, and Leuangthong (2008), Deraisme (2009). In the case of blast-hole information, the simulation of the samples is done at a larger scale to reproduce the configuration of blast-hole data in the deposit.

In this paradigm, both the implementation of the infill drilling plan and the blast-hole sampling are parameterized for automation purpose. Based on the infill drilling plan parameters an algorithm positions and samples the specified infill drilling campaign in each period. The sampling of blast-hole data is implemented in the same manner.

SLM mine planning

In the implementation of this paradigm, the SLM mine plan is calculated sequentially in periods throughout the lifetime of the project. In each period, a set of events is set:

- Implementation and sampling of the infill campaign in the current period, except for the first period where only the existing data is used to estimate the model of the deposit. The infill drill-holes planned for the current period are positioned in the deposit and the sample values are simulated conditioned to the existing data. The simulated values of the infill drill-holes are added to the current state of information.
- Estimation of the model of the deposit using the current state of information. Since the current state of information consists of two sources of information of different scales, co-kriging techniques are preferred to be implemented.
- Calculation of the ultimate-pit and corresponding mine sequencing.
- The region to be mined in the current period is added to the SLM mine plan.
- Sampling of the blast-hole information from the region to be mined in the current period. Like in the case of the infill drilling data, the blast-hole data is simulated conditioned to the current existing information. Since the blast-hole data is of different scale than drill-holes, the simulated values should account for this difference in scale. e.g., discretize blast-holes. The simulated values of the blast-hole data are added to the current state of information.

To account for the periodic updating of information in the mine planning process, the mining sequence of a SLM mine plan consists of all the first regions planned in the updated mining sequences of each period. The updating of the mine plan in each period is calculated by implementing the estimation paradigm based on the current state of information in each period. In practice, the periodic updating of the estimation paradigm throughout the lifetime of the project is standard practice.

In the different information updating scenarios, the spatial configuration of the ore bodies in the deposit vary due to the simulation of the updating sources of information. Information updating-scenarios in which the ore bodies in the model are closer to the surface will result in large ore inventories than information-updating scenarios where the ore bodies are deeper. This variability in the ore inventories will lead to the variability in the variables of the mining scenario, e.g., capital cost, lifetime of the project, etc. This uncertainty in the variables of the mining scenarios can be also assessed in the simulation paradigm. However, the interaction between them cannot be accounted for, for example the variability in the infill drilling cost cannot be linked to the lifetime of the project. In the simulation paradigm, the infill drilling cost cannot be calculated because perfect knowledge of the deposit is assumed in each scenario, thus there is no need to update the model of the deposit. In the SLM paradigm, by mimicking the periodic development of the mining process, the interaction between the mine planning variables that interact during the lifetime of the project can be accounted for, thus giving a more realistic set of results to evaluate mining project.

Methodology

The input data consists of the database of the available exploratory drilling campaign. Like in the conventional paradigms, the set of mining parameters to evaluate are specified. These parameters contain information about how the deposit is going to be mined, e.g., configuration of pit slopes, processing plant specifications, etc.

The infill drilling strategy, blast-hole drilling pattern, and sampling specifications are extra parameters that are not present in the conventional paradigms.

- **Infill drilling strategy**: Consists of the infill drilling plan to be implemented throughout the lifetime of the project. This plan defines the strategy for positioning the infill drill-holes as the mining process takes place. The infill drilling strategy should be parameterized so that an algorithm can automate the implementation of the infill drilling in the deposit. The type of infill drill-holes is also specified as part of the drilling strategy, e.g., diamond or air-reverse drill-holes.

- **Blast-hole drilling pattern**: The blast-hole drilling grid is specified. In practice, different grids can be defined according to the type of material mined in the deposit, e.g., ore material requires a denser grid than waste material. Due to the differences in scale with respect to the exploratory drilling information, during the estimation of the model of the deposit, the technique implemented should consider the integration of data of different scales like co-kriging.
- **Sampling specifications**: Depending on the infill drilling type, a sampling error parameter should be specified. Air-reverse drill holes are less expensive than diamond drill-holes, at the cost of getting a larger sampling error. A sampling error parameter should be also specified for the blast-hole sampling.

Simulation of periods

In each period, three stages are defined. These stages have their own set of events:

1. At the beginning of the period:

- Except for the first period, execute the infill drilling plan for the current period, and simulate the sampled values of the drilling campaign. The corresponding sampling error is added based on the type of infill drilling chosen.
- Add the simulated infill drilling samples to the current database.
- Estimate the geologic model of the deposit using all the available information.
- Calculate the economic model, the ultimate pit, and its corresponding mining sequence.

2. During the period:

- Extract the first region of the mining sequence by updating the current topography.

3. At the end of each period:

- Design a blast-hole drilling pattern over the mined region and simulate the sampled values. The simulation is done at the blast-hole scale and the proper sampling error is added.
- Add the simulated blast-hole samples to the current database.

In each period, after calculating the mine plan, if the ore tonnage in the ultimate pit is smaller than a minimum ore tonnage threshold to be treated, the mining process is stopped.

Simulation of information-updating scenarios

Each scenario is simulated independently. In each scenario, the mine plan is calculated sequentially by simulating one period after another until the ore inventory in the current scenario has been mined. The mine plan of the current scenario comprises the regions mined in each period throughout the lifetime of the project. The information stored in each scenario consists of:

- SLM mining sequence. The SLM ultimate pit is calculated as the combination of the SLM mining sequences.
- Final dataset updated until the end of the mining process. This comprises real data, simulated infill data, and simulated blast-hole data.
- Estimated geologic and economic models of each period.
- Mining sequences and ultimate pits of each period.

The information stored captures the evolution of uncertainty as the mining process in each scenario takes place. The analysis of the SLM mine plans is done based on more information than the conventional paradigms.

Example

In this example, the SLM paradigm is implemented on a synthetic 3D deposit. The model resolution of the deposit is 100 x 60 x 40. An initial topographic surface is assigned to define the initial state of the deposit (see Figure 3 - left). The available data consists of an exploratory campaign of 40 vertical drill-holes, drilled over a regular grid of 50 x 50. The drill-hole data was sampled from an unconditional realization of the deposit (see Figure 3 - right). For illustration purpose, the cut-off grade is set to mean of the metal element of the deposit, and the plant requirement is set to 2000 blocks of ore in each period.

The infill drilling plan consists of three drill-holes per period. An algorithm to position the infill drill-holes with respect to the current state of the ultimate pit and the existing drilling information is designed to automate the infill drilling process. Additionally, blast-hole information is sampled from the mined regions. In Figure 4, the topography at the end of the mining process and its respective collected data for one SLM realization are presented. The state of this topography (Figure 4 - left) has been shaped throughout the lifetime of the project by the simulated updating information, both infill drilling and blast-hole data (Figure 4 - right). This is a probable scenario of how the mining process could take place in the SLM framework.

The deposit is evaluated using 25 SLM realizations. In Figure 5 - left, the histogram of the lifetime of the simulated mine plans is presented. The variability in the lifetime is due to the variability in the spatial configuration of ore bodies in the models of the deposit. Models with an ore body configuration closer to the surface result in larger ore inventories than models with deeper ore bodies. Due to the constraint of the processing plan, larger ore inventories require more periods to be mined. The variability in the number of periods leads to the variability in the total length of infill drill-holes sampled (see Figure 5 - right). The cost of an infill drilling campaign is calculated as a function of the total length of the infill campaign.

The variability in the configuration of the mining sequences lead to the variability in the revenues of the project (see Figure 6 - left). Unlike the conventional paradigms, where the profit of the project can be calculated directly, because the capital cost is assumed constant, in the SLM paradigm, the variability of the infill drilling cost expenses makes the capital cost variable. In Figure 6 - right, the correspondence between the mine plan revenue versus the total infill drilling is presented. In the SLM paradigm, the calculation of the capital cost is more detailed than assuming an approximated infill drilling cost per period. The dependence between the mine plan revenue and cost is calculated from the simulation of the mining process.

Conclusions

The SLM paradigm proposes a new framework for the evaluation of the surface mining projects. Unlike the conventional paradigms, the SLM paradigm delivers more realistic realizations of mine plans, thus a better approach of the uncertainty in the economic potential of the deposit. In the SLM paradigm, a set of mine plans that account for the periodic updating of information are simulated. The economic parameters of the economic potential of the deposit are analyzed in uncertainty terms.

The simulation of the scenarios of information-updating allows the evaluation of different infill drilling strategies. This particular characteristic of the SLM paradigm permits to value infill drilling campaigns in economic terms. The variability of mine plans for different infill drilling strategies can be evaluated. By identifying sensitive regions, these can be targeted by real infill drilling to validate them. By reducing the variability in the mine plans, major mining patterns can be identified, which will help in the evaluation of the project.

In the SLM paradigm, the information-updating process accounts for the uncertainty in the continuous variables of the deposit. However, the main geologic structure of the deposit remains static. In practice, the periodic information-updating process, with real data, updates the global geologic structure of the deposit. Based on new information, geologists re-draw the geologic interpretation of the deposit. Geostatistical methodologies that account for the variability of the geologic structure of the deposit, such as object based techniques or multiple point statistics, can be implemented. However, its use in mining is not standard even in the publications where the simulation paradigm is discussed.

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Figures

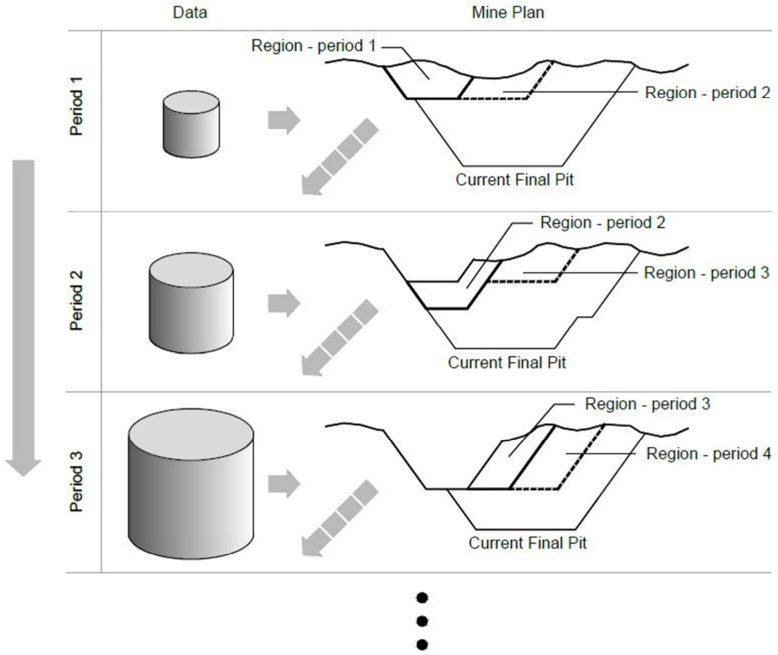

Figure 1: Sketch of periodic updating of the LOM plan due to collection of new information

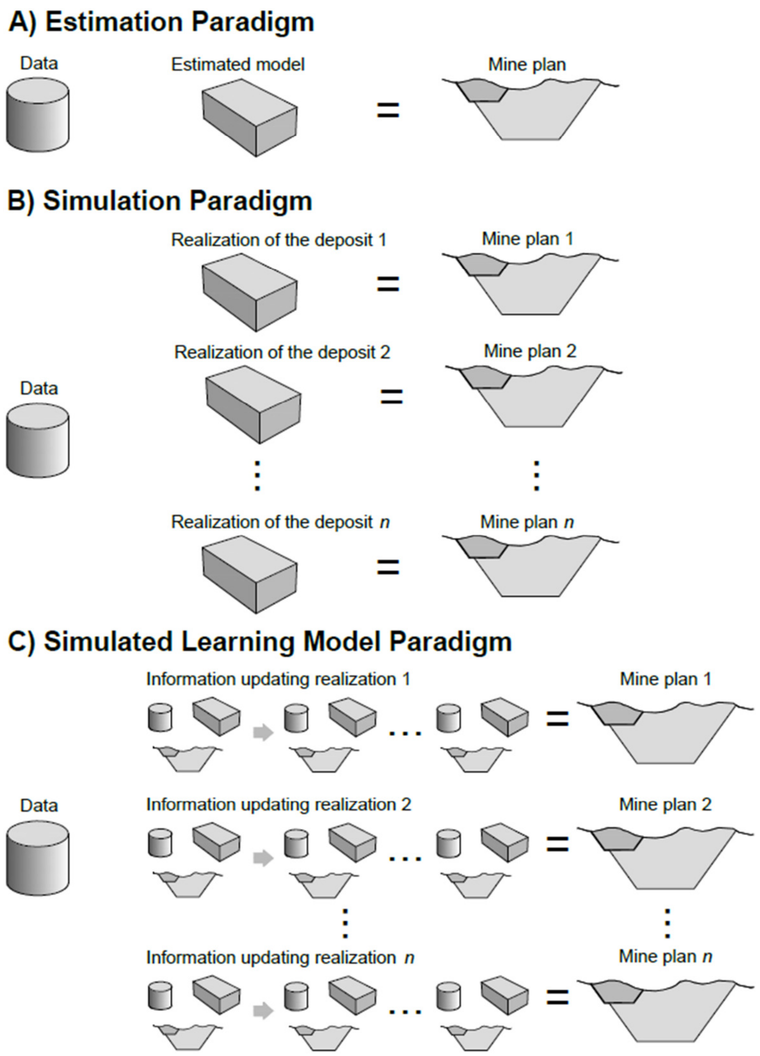

Figure 2: Diagram of the Estimation (top), Simulation (middle), and SLM paradigms (bottom)

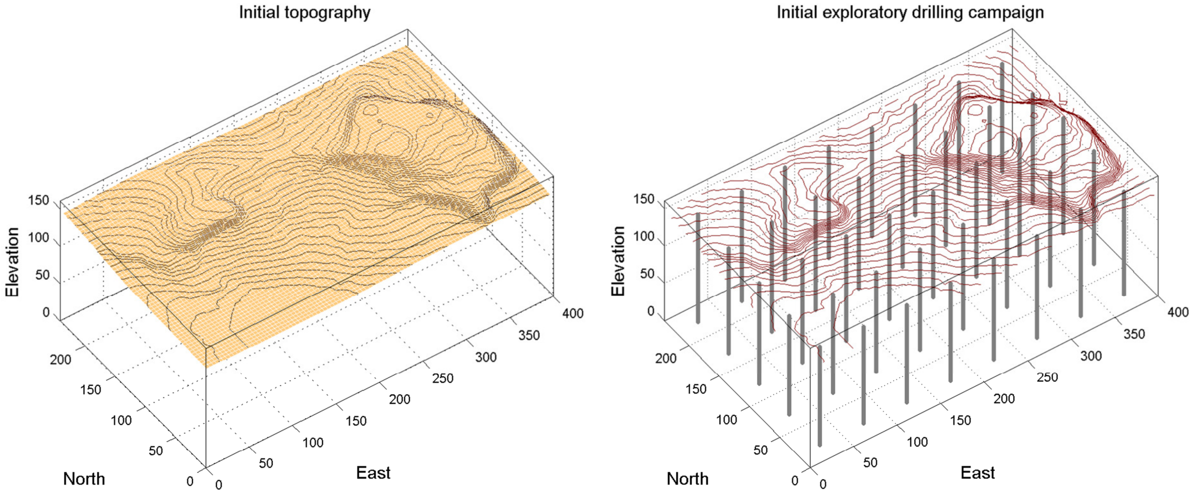

Figure 3: Initial topography (left) and initial exploratory drilling campaign (right)

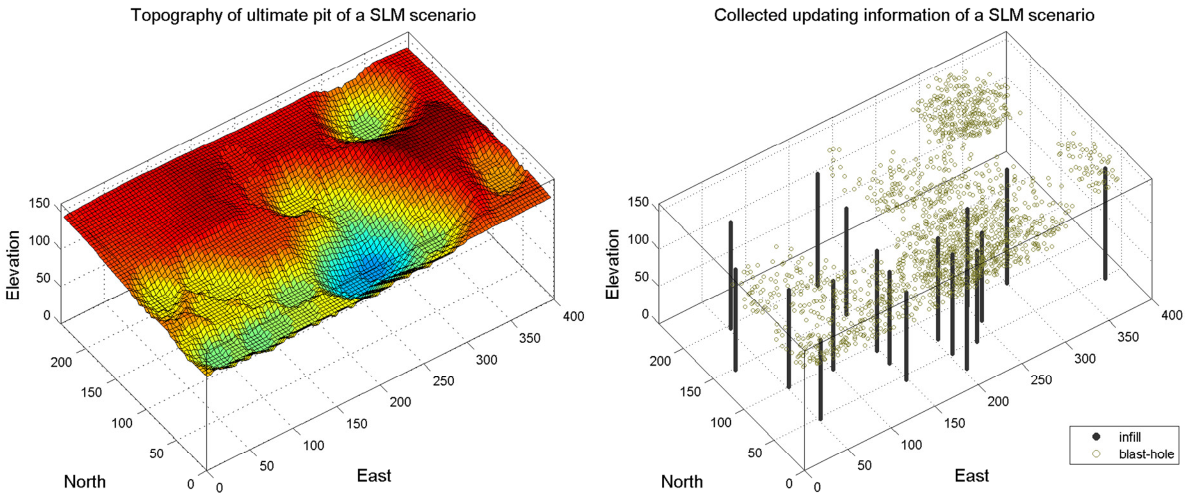

Figure 4: Ultimate pit (left) and collected updating information throughout the lifetime of the project (right) of a SLM scenario

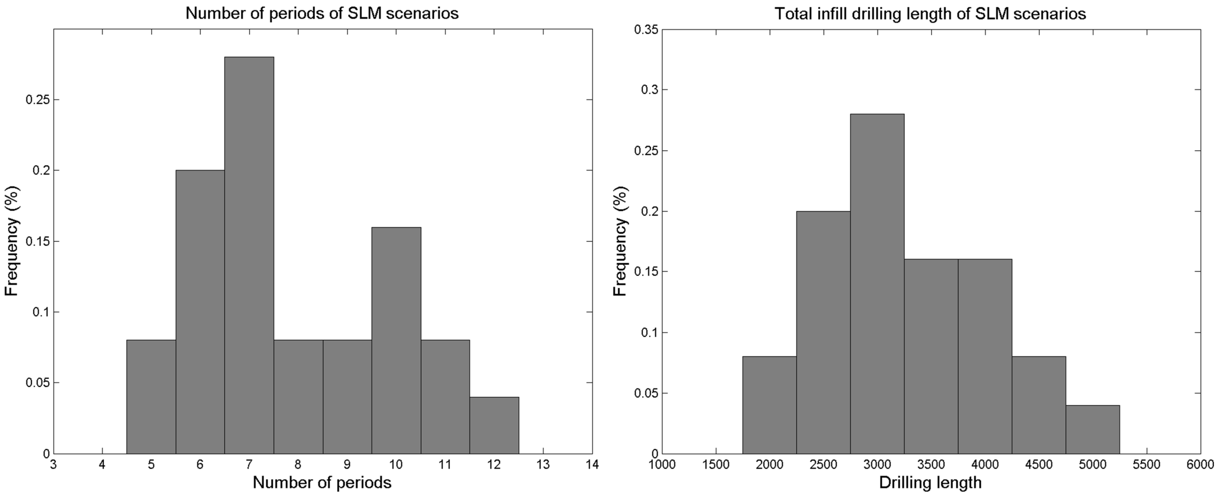

Figure 5: histogram of number of periods (left) and total infill drilling length (right) of the SLM mine plan scenarios

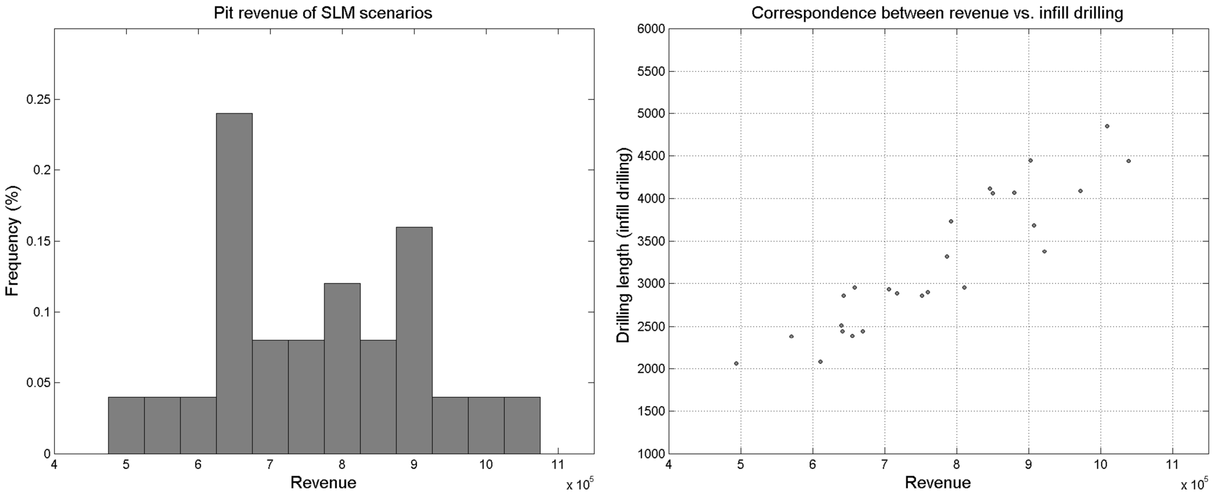

Figure 6: histogram of revenues of SLM mine plans (left) and scatter plot between revenues versus collected infill drilling information (right)