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Framework for Optimizing Data Acquisition in Surface Mining Operations

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Over the lifetime of a mine project, infill drilling campaigns are implemented to improve the performance of a mine plan. Different infill drilling strategies result in many scenarios of the economics of the project. A framework to optimize the data acquisition via the implementation of infill drilling campaigns is proposed. To calculate the uncertainty in the NPV of the project, the simulated learning model (SLM) paradigm is implemented to assess the impact on the net revenue, which is matched against the cost of the infill drilling campaign. The evaluation of several infill drilling strategies is carried out by comparing their respective histograms of NPV. An automatic algorithm to implement infill drilling strategies is presented.

1. Introduction

Mine plans rely on the accuracy of the block model to characterize the geology of the deposit to maximize the net revenue. In the ideal case, the geologic characteristics of the deposit are accessible from the beginning, the optimal mine plan could be designed because all the ore and waste units in the deposit would be accurately identified. In practice, only limited information is available. Due to the limited knowledge about the ore bodies present in the deposit, the maximum profit cannot be reached. The net revenue that results from a mine plan is related to the volume of information accessible.

Drilling campaigns are the main source of information about the deposit. The volume of information they capture depends on two factors, 1) the total length drilled and 2) the strategy adopted to cover blank spots in the deposit. The performance of drilling campaigns can be evaluated in economic terms by considering the net revenue of the mine plan versus the cost of implementing the drilling campaign. Drilling campaigns can be split in two parts: 1) exploratory drilling campaign and 2) infill drilling campaign. The goal of the former is to evaluate the viability of the project and the goal of the latter is to help in the mine planning process. Different strategies adopted in the implementation of infill drilling campaigns result in different scenarios of profit of the deposit. An infill drilling strategy consists of parameters such as number of drill-holes, total length to be drilled on each period, position and geometric configuration of the drill-holes.

The gap in terms of the net revenue between the optimal mine plan (achieved with perfect knowledge) and the mine plan designed based on the available information is referred in this paper to as the cost due to uncertainty (CDU). This gap is the window where the performance of the mine plan, as the volume of information available grows, can improve. The increment in the net revenue is linked to an increment in the cost of drilling. The new profit after implementing the new infill drilling campaign can become smaller if the cost of drilling is larger than the increment in the net revenue. This variation of the profit is taken as a measure of performance of the strategy of the infill drilling campaign. Given an exploratory drilling campaign, the impact in the net revenue due to the implementation of an infill drilling strategy can be estimated by implementing the simulated learning model (SLM) paradigm. Since infill drilling campaigns are implemented through the lifetime of the project, the impact in the profit is calculated by subtracting the cost of drilling from the improvement in the net revenue in discounted terms.

In the next section, the aspects of calculating the impact in the profit of an infill drilling campaign in terms of net-present-value (NPV) are discussed. After that, a methodology for evaluating different infill drilling strategies as well as an algorithm for automating infill drilling campaigns based on current mining conditions are presented. An example section that shows the implementation details of the proposed methodology is discussed. Finally, a conclusions section is presented.

2. Background

Infill drilling campaigns are implemented according to certain strategies to update the block model of the deposit. Accordingly, the respective reduction of uncertainty in the block model allows designing more efficient mine plans in terms of net revenue. The improvement in the performance of a mine plan has a cost associated to the implementation of an infill drilling strategy. Herein, the infill drilling cost considers the process since the infill drilling plan is designed until the sampled geologic information is ready to be used to update the block model of the deposit. The contribution of an infill drilling strategy to the profit of the project (ΔP) is calculated as the difference between the increment in the net revenue of the project (ΔNR) and the cost of implementing the infill drilling campaign ($DCIF$),

$$\Delta P = \Delta NR - DCIF \,,$$

Even when an exhaustive infill drilling campaign maximizes the net revenue of the project (ΔNR), the cost of the infill drilling campaign ($DCIF$) may be so expensive that the contribution to the profit becomes negative. The performance of an infill drilling strategy is measured in terms of the contribution to the profit of the project, which in mining industry is usually calculated in terms of the net-present-value NPV. The NPV is the sum of the discounted cash flows that correspond to each of the planned periods of the project minus the initial capital cost (Hustrulid & Kuchta, 1995), it is expressed as:

$$NPV = \sum_{i=1}^{n} \frac{CF_i}{(1+r)^i} - C_0 \,, \tag{1}$$

where, n is the index number of the periods, r is the discount rate of the project, C_0 represents the initial capital cost, and CF_i stands for the cash flow of the i-th period.

In the NPV expression (1), the total capital cost consists of two parts: 1) the initial capital cost that is incurred to put the project into operation C_0 and 2) the capital costs in each of the periods C_i. The total capital costs of the project can be expressed as:

$$C = \sum_{i=1}^{n} \frac{C_i}{(1+r)^i} + C_0 \,, \tag{2}$$

Based on (1) and (2) the NPV can be expressed in terms of net revenue and capital cost:

$$NPV = \sum_{i=1}^{n} \frac{NR_i}{(1+r)^i} - C \,, \tag{3}$$

where, NR_i stands for the net revenues of each period.

Conventionally, the cost of the exploratory campaign is charged to C_0 and the cost of the infill campaign to the capital costs of each period C_i. From expression (3) the NPV can be expressed in terms of the infill drilling cost as:

$$\begin{aligned} NPV &= \sum_{i=1}^{n} \frac{NR_i}{(1+r)^i} - \left[CID + OC\right] \\ NPV &= NR - \left[CID + OC\right] \qquad , \end{aligned} \tag{4}$$

where, NR is the total net revenue, CID is the infill drilling cost, and OC stands for the remaining of the capital cost other than the infill drilling cost.

In case the true geologic characteristics of the deposit are accessible, the mine plan that maximizes the net revenue NR_R can be designed. The net revenues obtained in presence of uncertainty NR_U (4) are smaller than NR_R. The gap between NR_R and NR_U is referred to as the cost due to uncertainty CDU. This cost considers the profit lost for not having access to the true geologic characteristics of the deposit. The optimal net revenue can be expressed as:

$$\begin{aligned} NR_R &= CDU + NR_U \\ NR_R &= CDU + NPV + \left[CID + OC\right]. \end{aligned} \tag{5}$$

For a specific amount of money to be spent in the infill drilling campaign, the NPV of the project is able to grow within the margin of the CDU (see Figure 1), thus the NPV is not necessarily proportional to the infill drilling cost. Two drilling strategies with similar infill drilling costs may have a different impact in the NPV of the project. One parameter that influences the performance of a drilling strategy, besides the amount of information sampled, is the methodology implemented to cover blank regions in the deposit. Efficient infill drilling strategies capture the as much information possible from the deposit. Research has been focused on ways to find efficient configurations of drilling campaigns such as Drew (1979), Miller (1991).

Assuming the infill drilling strategy considers an efficient methodology to capture information from the deposit, the analysis of performance can be focused on the amount of information sampled. From expression (5), the NPV of the project is sensitive to the improvement in the performance of the mine plan (*NR*) and the cost of the infill drilling campaign (*CID*) as presented in Figure 2.

From (5) the combination of the CDU and the capital cost *C* results in a combined cost, which by subtracting it from the maximum net revenue NR_R results in the NPV of the project (see Figure 2). As the volume of information sampled from the deposit increases, the CDU decreases and at the same time the capital cost increases. The increment in the capital cost is due to the increment in the infill drilling cost. The NPV as a function of the total length drilled has a convex behaviour, thus a maximum (see Figure 2). The more important parameter for optimizing the NPV is not available, which is the net maximum revenue of the deposit NR_R. Considering expression (4), the NPV can be calculated by implementing the SLM paradigm and the optimization approached heuristically by evaluating several infill drilling strategies.

3. Methodology

The input of the proposed framework consists of a set of infill drilling strategies, which are automated by an algorithm that is presented in the next section. The infill drilling strategies are implemented in each realization of the simulated mining scenarios. The input parameters of the algorithm consider the configuration of the existing drilling campaign, mined regions, and final pit. The evaluation of the infill drilling campaigns is discussed after in the following section. The SLM paradigm is implemented to assess the net revenue for each of them. The increment in the capital cost due to the infill drilling campaign is obtained from the infill drilling algorithm. The histograms of the NPVs of each of the infill drilling strategies are evaluated together.

1. Automatic algorithm to implement infill drilling campaign strategies

The methodology of the infill drilling campaign to cover blank spots is implemented periodically and defined by three parameters: 1) the drilling configuration with respect to mined regions, 2) the drilling configuration with respect to the current final pit, and 3) the current configuration of previous drilling campaign. The model used is:

$$d_s(\mathbf{u}) = d_n(\mathbf{u}) \cdot f_m(\mathbf{u}) \cdot f_p(\mathbf{u}), \tag{6}$$

where, **u** is the location of the collar of the infill drill-hole evaluated, $d_s(\mathbf{u})$ is the selection distance, $d_n(\mathbf{u})$ is the closest distance to the existing drilling campaign, $f_m(\mathbf{u})$ is a factor that accounts for previously mined regions, and $f_p(\mathbf{u})$ is a factor that accounts for the final pit.

The implementation of the selection distance can be seen as a 2D problem because it deals with the positioning of the collars of the new infill drill-holes over an existing surface. The selection distance (6) is calculated over a region where the infill drilling campaign can be implemented and the selection criterion consists of selecting the maximum as the optimal location. The $d_n(\mathbf{u})$ component is calculated as the closest distance between the location **u** and the collars of the existing drilling campaign. It makes the potential location of the new infill drill-hole to target the blank regions not covered by the existing drilling campaign.

The weighting factor $f_m(\mathbf{u})$ guides the decision of the optimal position with respect to the mined regions considering the projection of the boundaries in 2D (see Figure 3-left). First, the closest distance between the location **u** to the boundary of the mined region is calculated, d_m. Whether **u** is located inside or outside the mined boundary the preferential selection of the optimal location is guided by weighting factors, wm_{in} and wm_{out} respectively, that give priority to both regions, that is:

$$f_m(\mathbf{u}) = \begin{cases} 1 - \dfrac{(wm_{in} \cdot d_m)}{\max(d_m)}, & \mathbf{u} \text{ is inside the mined region} \\ 1 - \dfrac{(wm_{out} \cdot d_m)}{\max(d_m)}, & \mathbf{u} \text{ is outside the mined region} \end{cases},$$

Similarly, the weighting factor with respect to the final pit $f_p(\mathbf{u})$ is calculated by considering the weighting factors wp_{in} and wp_{out} for the regions inside and outside of the final pit respectively (see Figure 3-right).

$$f_p(\mathbf{u}) = \begin{cases} 1 - \dfrac{(wp_{in} \cdot d_p)}{\max(d_p)}, & \mathbf{u} \text{ is inside the final pit region} \\ 1 - \dfrac{(wp_{out} \cdot d_p)}{\max(d_p)}, & \mathbf{u} \text{ is outside the final pit region} \end{cases}.$$

The workflow to design a specific number of infill drill-holes in each period is as follows:

1. Set the number of infill drill-holes, weighting factors for the mined regions and the final pit.
2. Calculate the maps of the weighting factors of mined regions $f_m(\mathbf{u})$ and of final pit $f_p(\mathbf{u})$.
3. Calculate the map of the distances closest to the existing drilling campaign.
4. Calculate the map of the selection distance.
5. Select the maximum location within the selection distance map the location that results in the maximum value as the location of one infill drill-hole.
6. If there are more infill drill-holes to be placed, go to step 4, otherwise finish the workflow.

The presented algorithm only considers vertical drill-holes, although it can be complemented to account for inclined drill-holes and fixed distances.

2. Implementation of the evaluation of infill-drilling strategies

In this paper, the volume of information drilled is set by scheduling a number of infill drill-holes in each period. In Figure 4, two infill drilling strategies are sketched. Strategy 1 considers a constant number of drill-holes in each period during the lifetime of the project and strategy 2 considers a variable number of drill-holes, where the volume of information sampled is periodically reduced. Even when these two strategies may collect the same volume of information, the timing and the regions that they cover in the deposit result in different profitability scenarios. The performance of several drilling strategies can be evaluated by combining the volume and the timing of drilling during the lifetime of the project in terms of NPV.

The proposed workflow to evaluate one infill drilling strategy is:

1. **Define an infill drilling strategy for evaluation:** Consists of proposing a candidate of an infill drilling strategy by scheduling the number of infill drill holes per period. The implementation of the infill drilling campaign is considered to occur by the end of each period.
2. **Define the parameters for implementing the SLM paradigm:** Set the mining conditions at which the mining process takes place, such as cut-off grade, pit optimization methodology, and mine scheduling constraints. A set of realizations of the mining process is simulated, where the specified infill drilling strategy is implemented in each of them.
3. **Calculate the net revenues for each simulated mining scenario:** The corresponding net revenue is calculated for each realization of the mining process by considering a discounted approach.

4. **Calculate the histogram of profits of the evaluated infill drilling strategy:** The profit of each mining scenario is calculated by subtracting the discounted cost of the infill drilling campaign and the rest of the capital cost from the net revenue.

The evaluation of a set of infill drilling strategies considers the analysis of their corresponding histograms. The analysis consists of evaluating the risk of the project in terms of profit. The infill drilling strategy that results in the maximum averaged profit may not be necessarily the optimal. According to risk management scenarios, risk averse or risk taking, the selection of the optimal infill drilling scenarios vary from case to case.

4. Example

An initial exploratory drilling campaign of 50 vertical drill-holes sampled over a regular grid of 500×500m is considered as the input data. The volume of the deposit is 5000×2500×1000 cubic meters. Two rock types that correspond to high grade (HG) and low grade (LG) are considered as the geology of the deposit. The metal content was generated by simulation of two exponential distributions according to the rock type, that is, mean of HG is 2.5 and of LG is 0.5. An initial topographic surface is arbitrarily assigned to the model. To calculate the recoverable reserves, a block model and mining parameters are set as follows: The SMU size is 50×50×20 cubic meters, the floating cone algorithm is implemented to calculate the long term plan and the mine sequencing. Approximately 6000 SMU blocks are set to be mined in each period. The interest rate is set at 10% per period. The cut-off grade is set at 2%.

The SLM paradigm is implemented to assess the impact of the infill drilling strategies on the NPV of the project. Four infill drilling strategies are evaluated considering 30 realizations of the mining process in each case. On each realization, the NPV is calculated by subtracting the corresponding values of cost of infill drilling from the net revenue. For simplicity, only the infill drilling cost is considered as the capital cost. The impact on the uncertainty in the NPVs due to the implementation a drilling strategy is evaluated by comparing the resulting histograms of NPV of each case.

Four infill drilling strategies are evaluated:

- Strategy 1: 3 drill-holes per period,
- Strategy 2: 5 drill-holes per period,
- Strategy 3: 7 drill-holes per period, and
- Strategy 4: starts at 6 drill-holes in the first period and decreases 1 per period.

The automatic algorithm for positioning drill-holes presented in the methodology section is implemented. The weighting factors to place infill drill-holes with respect to the mined regions are set to 1.0 for both locations inside and outside. In this part, the algorithm tries to make the new infill drill-holes are located near the boundary of the mined regions regardless of whether the drill-hole is located inside or outside the mined region (see Figure 5-left). In the case of the remaining final pit, the weighting factor for the locations inside is set to 0.5 and 1.5 for locations outside. This configuration gives more importance to locate infill drill-holes inside the final pit region than of outside (see Figure 5-right).

The initial map of the distances (see Figure 6-left) is adjusted by the two weighting factors to obtain the selection distance map (see Figure 6-right). The location of the next infill drill-hole is positioned at the maximum value of the selection distance map. The configuration of an infill drilling strategy of variable drill-holes per period is presented in Figure 7. For the first two periods, the algorithm for positioning the infill drill-holes adapts to the existing mined region and the remaining final pit. Because of the different configurations of topographies that result from the different realizations of the mining scenarios, there is uncertainty associated to the total length drilled and to the cost of drilling.

Each of infill drilling strategies impacts differently on the NPV of the project (see Figure 8-left) based on their respective costs of implementation (see Figure 8-right). The scenarios of uncertainty of each of them can be evaluated based on a risk analysis. The first three drilling strategies consider a constant number of infill drill-holes per period. As more infill drill-holes are added, the dispersion in the NPV decreases. In a conservative risk scenario, strategy 2 appears to be more attractive than strategy 1. The histogram of the strategy 2 is narrower than of strategy 1. Implementing strategy 1 may result in a larger NPV than strategy 2 but at a larger risk of making less profit. Strategy 3 appears to be the least attractive in the group of four because the cost of drilling made the NPV significantly smaller. The effect of strategy 4 appears very similar to strategy 1 despite their costs of implementation are very different.

In this example, the calculation of the histograms for evaluating the different infill drilling strategies is parameterized by the scheduling of the number of drill-holes per period. An additional parameter is the settings of the weighting factors that guide the positioning of the infill drill-holes, which is fixed in this example. Moreover, considering additional parameters such as inclination angle, inclined direction and fixed lengths, increases the level of complexity in the implementation of the infill drilling campaign strategies. Hence, it is more tractable to evaluate specific infill drilling strategies rather than considering an optimization approach.

5. Conclusions

Different infill drilling strategies can be evaluated in terms of uncertainty scenarios of the NPV of the project. The proposed framework allows assessing the histogram of NPV for a proposed infill drilling strategy. The comparison of the performance is based on an analysis of their corresponding scenarios of uncertainty of the NPV. Due to the several parameters that participate in the implementation of infill drilling campaigns the proposed framework consists of a heuristic approach to optimize the data acquisition from the deposit. The SLM paradigm is implemented to obtain the net revenues and the automatic infill drilling algorithm is used to obtain the cost of drilling.

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Miller, W. J. (1991). Optimization of Grid-Drilling Using Computer Simulation. *Mathematical Geology* , 201-218.

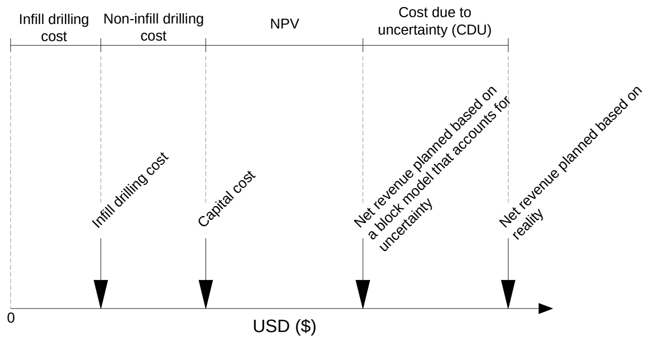

Figure 1: Presence of the cost due to uncertainty CDU in the economic evaluation of reserves.

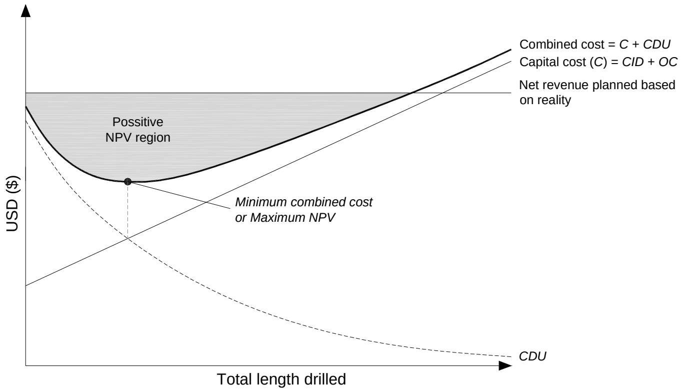

Figure 2: Sensitivity of the NPV of the project based on amount of information sampled in the infill drilling campaign.

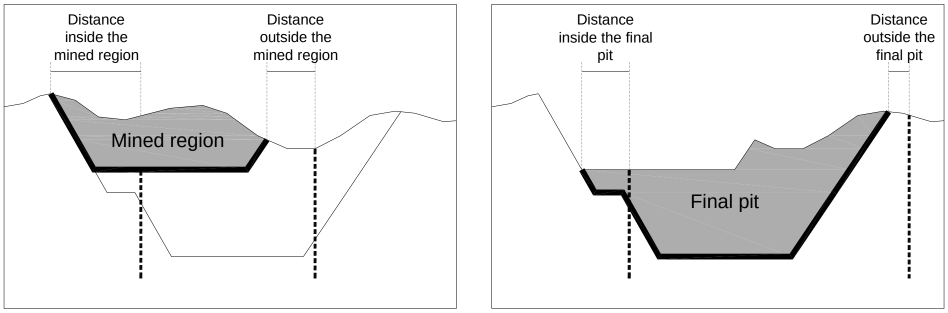

Figure 3: Scheme for calculating distance factors relative to mined regions (left) and final pit (right)

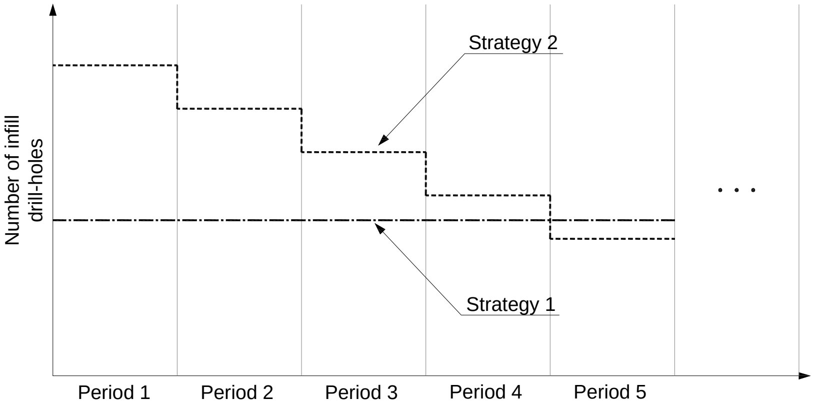

Figure 4: Definition of two infill drilling strategies depending on the number of drill-holes scheduled per period.

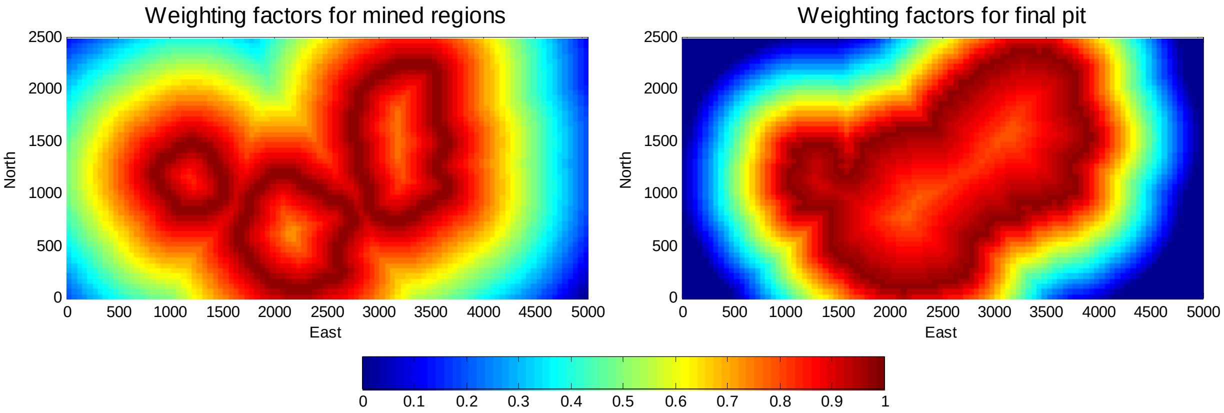

Figure 5: Weighting factors for placing infill drill-holes with respect to mined regions (left) and final pit (right).

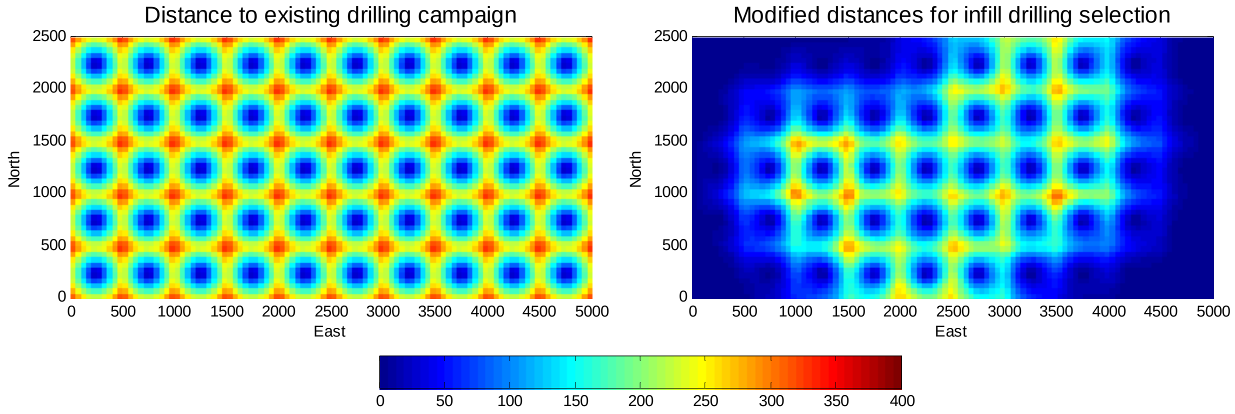

Figure 6: Map of distance to existing drilling campaign (left) and of selection distance (right).

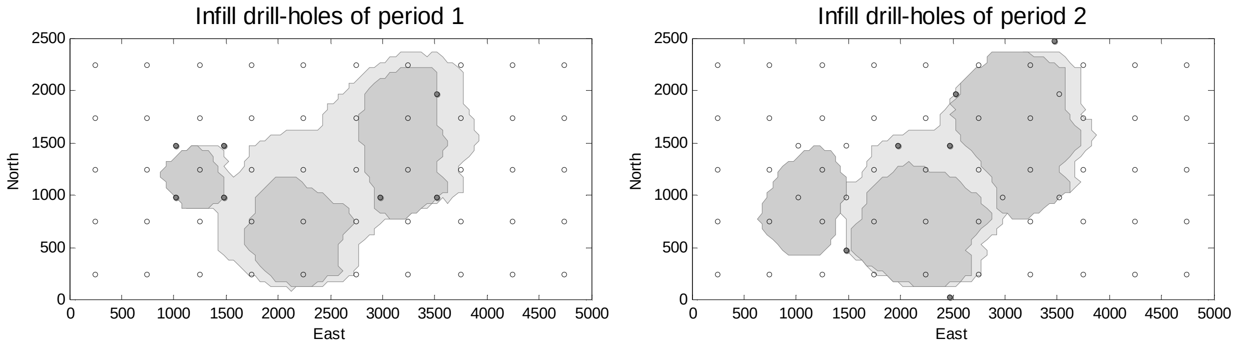

Figure 7: Implemented infill drilling campaign strategy of variable drill-holes per period. The filled dots represent the collars of the new infill drilling information added and the empty dots the collars of existing information.

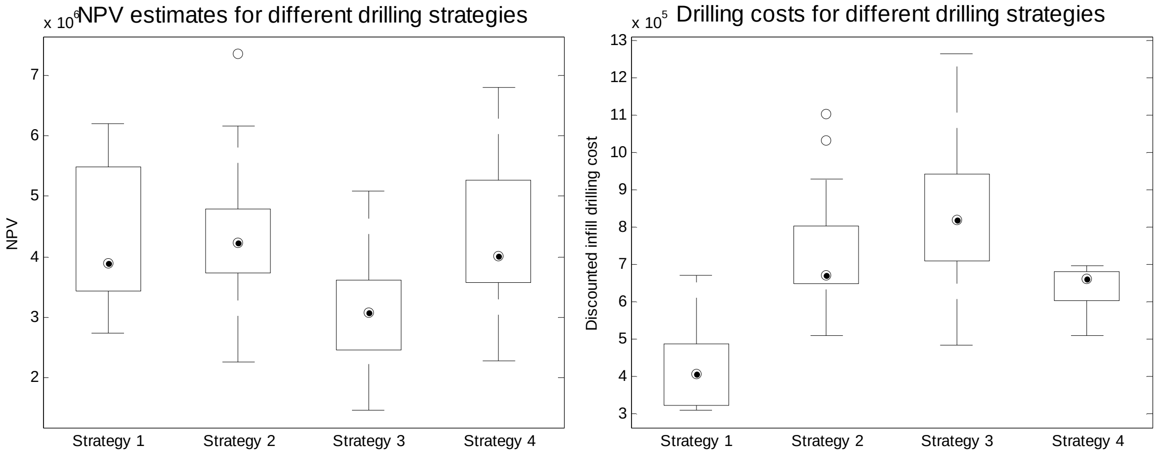

Figure 8: Comparison of NPV (left) and drilling cost (right) scenarios of the project for different infill drilling strategies.