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Evaluation of Infill Drilling in the SLM Framework

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In the SLM paradigm, the performance of the mine plan depends both on the mining and data acquisition strategies. The mining strategy makes the decision about how to mine the deposit while the data acquisition strategy provides scenarios of uncertainty of the deposit in which the mining decisions are made. In this paper it is considered that the data acquisition strategy consists of two sources of information: blast-hole and infill drilling. Since the collection of extra data from the blast-hole source depends on the previously mined regions, only the collection of extra data from the infill source can be controlled and customized. This paper focuses on aspects involved in the design of the infill drilling program of the mining project. An example is presented to illustrate the implementation of the proposed evaluation.

Introduction

The evolution of the DOKD throughout the lifetime of the mining project depends on the data collection strategy implemented. The evolution of the DOKD leads to a periodic reduction of the mine sequence variability. For practicality, the production gap is chosen as a metric of performance because of its relevance to the mining of the deposit, and is calculated in terms of the mean absolute error (MAE) of the mine sequence variability. The effect of a particular data collection strategy can be measured by comparing the profiles of the production gap throughout the lifetime of the mining project, with and without implementing the data collection strategy. The data collection strategy affects the profile of production gap from the second period onwards. The case when no data collection strategy is implemented corresponds to Paradigm 2, which is the base case of the SLM paradigm. In Figure 1, a sketch of the impact of implementing an data collection strategy is presented.

The reduction of the variability of the production gap results from the combined effect of the blasthole and infill sources of information. Since the collection of extra data from the blasthole source cannot be controlled, the difference between two data collection strategies is due to the implementation of different infill drilling programs. The contribution of the blasthole source to reduce the production gap will be considered implicit of the data collection strategy. For convenience, when referring to the effect of an infill drilling program on the reduction of the production gap, the contribution of the blasthole source will be considered along with it, unless otherwise specified. Although the blasthole data is useful to inventory short term materials ready to be mined, the effect of the blasthole source alone on the reduction of the production gap is relatively small compared to the exploratory drilling because of the lower quality of the data samples. Journel & Kyriakidis (2004) commented on the impact of blasthole data on the updating of mineable reserves models.

Due to the three aspects involved in the implementation of an infill drilling program, timing, objective and quantity, it is difficult to evaluate analytically its impact on the reduction of the production gap. Similar to the case presented in Figure 1, where the impact of a data collection strategy is evaluated with respect to a base case, the performance of various infill drilling programs, in terms of reducing the production gap, can be evaluated by comparing their respective production gap profiles. In Figure 2 a sketch of three production gap profiles is presented. Infill Program 1 starts with a moderate effect in the reduction of the production gap and by period 6 this effect starts to accelerate. Infill Program 2 presents a nearly constant reduction of the production gap. Infill Program 3 presents an aggressive reduction of the production gap, with respect to Infill Programs 1 and 2. The different forms of the production gap profiles result from the different combinations of the three aspects involved in the design of the infill drilling program. In each period, except the first one, the production gap could be reduced significantly either by implementing a massive infill drilling campaign or an efficient infill drilling campaign with less number of drillholes. The profile of the production gap, from the second period onwards, is customized by implementing specific infill drilling campaigns as a function of time.

The SLM paradigm allows carrying out a realistic evaluation of infill drilling programs, as the strategies to collect the extra information account for the evolution of the DOKD. The design of this type infill drilling program can be viewed as a specific case of dynamic decision problems (Bickel & Smith, 2006). In dynamic strategies, the collection of new data is carried out progressively accounting for the outcomes of previous data sampling events, while, in static strategies, the collection of new data involves the sampling at different locations at the same time. For simplicity in the implementation of the SLM paradigm, a static strategy is used to set each infill drilling campaign that is implemented periodically.

Cost of Data Acquisition Strategy

Ideally, an infill drilling program that consists of a set of massive infill drilling campaigns could be implemented to obtain a significant reduction in the production gap profile. From the perspective of improving the accuracy of the mine plan, this infill drilling program would be considered as a valid alternative. However, from the perspective the economic performance of the mine plan, this scenario is impractical as it does not consider economic aspects, including the cost of implementation of the infill drilling program and the impact on the profit of the mining project, that are important in the evaluation of mineable reserves of the deposit. The collection of infill drilling may lead to an increment or a reduction of the profit margin depending on the economic benefits, e.g., reduction of misclassification, and the cost of implementation, that could be in the order of millions of dollars (Boucher, Dimitrakopoulos, & Vargas-Guzman, 2005). Alford, Brazil, & Lee (2007) commented that in a case study of the Vera South project within the Pajingo field in Queensland, Australia, the cost of the infill drilling program was 30% of the cost of the project.

To account for the impact of an infill drilling program on the economic performance of the mine plan, the cost of the infill drilling program is broke down in the cost of the individual infill campaigns. In this paper, the cash-flow definition presented by Suriel (1984) is considered. In the case of the production stage, the cost of the infill drilling campaigns is usually assigned to the capital expenditure item. The adjustment cost is considered to be part of the mining cost item. Thus the effect of reducing the production gap is translated in the reduction of the mining cost item in the following periods. The reduction of the mining cost results in an increment in the cash-flow margin because the revenue item remains invariant. In Figure 3, it is illustrated the impact of an infill drilling program on the economic performance of the mine plan. The sum of the costs of the infill campaigns or cost of the infill drilling program is the investment made to obtain the increment in the sum of cash-flows of the order of the total reduction of the adjustment costs.

The sum of net cash flows is the metric used to measure the economic potential of the mining project. The contribution of the infill drilling program to the sum of net cash-flows, which is ultimately used as a measure of performance, is calculated as the difference between the sum of the reduction of the adjustment costs and sum of the costs of the infill drilling program. In this context, the limiting factor that prevents from implementing a massive infill drilling program is its cost of implementation. Implementing massive infill drilling programs may result in a negative contribution to the sum of net cash-flows. An optimal infill drilling program aims to maximize the contribution to the sum of net cash-flows.

For convenience, the cash-flow definition presented by Suriel (1984) is simplified. The items involved in the evaluation of the infill drilling program as illustrated by Hustrulid & Kuchta (1995) are used. The sum of net cash flows *SNCF* can be simply expressed in terms of sum of cash flows *SCF* and sum of capital expenditures *SCE* as:

$$SNCF = SCF - SCE. \tag{1}$$

The working capital item is considered as part of the *SCE*. In the SLM paradigm two *SNCF* are considered: 1) planned and 2) executed. The planned sum of net cash flows $SNCF_{PL}$ is an estimate based on the mine plan that does not consider the adjustment costs. The executed sum of cash flows $SNCF_{EX}$ is the value that is actually obtained after executing the mine plan. The discrepancy between the $SNCF_{PL}$ and $SNCF_{EX}$ is the sum of adjustment costs *AC*. The *SCE* component is similar both in $SNCF_{PL}$ and $SNCF_{EX}$, thus the *AC* can be expressed in terms of the planned and executed cash flows, SCF_{PL} and SCF_{EX}.

$$SAC = SCF_{pl} - SCF_{ex}. \tag{2}$$

The *SAC* is reduced as the infill drilling program implemented is efficient to provide a proper evolution of the DOKD that helps to improve the accuracy of the mine plan, that is, a significant reduction of the profile of the production gap. In terms of the SCF_{EX} this means an improvement, as it approaches to

SCF_{PL}. At the same time, the cost associated to reduce the *SAC* is proportional to the amount of infill drillholes collected in the infill drilling program. This cost component, cost of infill drilling program *CIP*, is charged as part of the *SCE*. The impact of an infill drilling program on the economic performance of the mining project can be measured in terms of the contributions to the $SNCF_{EX}$. For illustration purposes, the sum of net cash flows of Paradigm 2, $SNCF_{EX(0)}$, is used as the base case. Both the sum of net cash flows of the base case $SNCF_{EX(0)}$ and of the case influenced by an infill drilling program $SNCF_{EX}$ are expressed as:

$$SNCF_{ex(0)} = SCF_{ex(0)} - SCE' \tag{3}$$

$$SNCF_{ex}\left(D_t\right) = SCF_{ex}\left(D_t\right) - \left(SCE' + CIP\left(D_t\right)\right) \tag{4}$$

where, $SCF_{EX(0)}$is the sum of cash flows of Paradigm 2, SCF_{EX} is the sum of cash flows influenced by the infill drilling program, *SCE'* is the sum of capital expenditure without considering the cost of implementing the cost of the infill drilling program *CIP*, and D_t denotes the influence of the infill drilling program. In practice, the *SCE* of Paradigm 2 does consider a specific cost of implementing the infill drilling program, but its influence in the sum of net cash flows is not accounted for. In Equation (3), it is considered that *SCE'* equals *SCE*, as no infill drilling program is implemented.

The contribution to the sum of net cash flows $\Delta SNCF_{EX}$ due to the implementation of an infill drilling program D_t is expressed as:

$$\Delta SNCF_{ex}\left(D_t\right) = SNCF_{ex}\left(D_t\right) - SNCF_{ex(0)} \tag{5}$$

By substituting Equations (3) and (4) in (5), the contribution to the sum of net cash flows is expressed as:

$$\Delta SNCF_{ex}\left(D_t\right) = \Delta SCF\left(D_t\right) - CIP\left(D_t\right) \tag{6}$$

where, ΔSCF.is the improvement in the sum of cash flows due to influence of an infill drilling program.

The infill drilling program affects the two components of $\Delta SNCF_{EX}(D_t)$ in different ways. In the case of $\Delta SCF_{EX}(D_t)$, it depends on the reduction of the production gap. The effect is based on either the efficiency of the collection strategy and/or on the amount of extra data sampled. In the case of $CIP(D_t)$, it depends on the amount of extra data collected. In Figure 4, a sketch of a case where the fixed collection strategy is considered. In this scenario, the effect on the two components is represented as a function of the amount of extra data collected by the infill drilling program. In the case where the infill drilling program is not implemented, there is still influence of the collected blasthole data. The contribution of the blasthole data to the improvement of the $\Delta SNCF_{EX}$ comes at no cost, since the cost of the infill drilling program is not present. As soon as infill drillholes are collected, a cost of implementation of the drilling program $CIP(D_t)$ is associated to the improvement of the $\Delta SNCF_{EX}$. Because of the different behaviours of the two components, the intersection of the corresponding curves defines the limit at which the infill drilling program becomes unfeasible, as it results in negative contributions to the $SNCF_{EX}$.

In Figure 5, a sketch of the $\Delta SNCF_{EX}$. curve of the case shown in Figure 4 is presented. In this specific case, the curve of the contribution to the $SNCF_{EX}$ has a convex shape, where the segment above zero represents the feasible region. Beyond the positive segment, any configuration of the infill drilling program, despite increasing the SCF_{EX}, contributes negatively to the $SNCF_{EX}$. The size of the infill drilling campaign that results in the maximum contribution can be easily estimated from the curve.

The case presented in Figure 4 and Figure 5 illustrates the impact of an infill drilling program on the contribution to the $SNCF_{EX}$ for a specific case, where the collection strategy is fixed. In practice, the three aspects involved in the design of an infill drilling program makes the maximization of the contribution to the $SNCF_{EX}$ a highly-dimensional problem. The design of the optimal infill drilling program would involve calculating different parameters, including what infill drilling strategy is to be used in each period, how much extra data and of what type to collect in the infill drilling program, and how to configure specified infill drilling campaigns throughout the lifetime of the mining project. The selection of an inappropriate infill drilling strategy has a negative economic impact on the profit of the mining project, as in retrospect, a denser or a sparse that necessary configurations result in a reduction of the profit margin of the mining project (Metz, 1992).

In computational learning, active learning methodologies focus on finding optimal data acquisition strategies that require less extra data (Settles, 2009). The motivation of active learning is that extra information is expensive or difficult to acquire. The problem that it is addressed by active learning is similar to designing efficient infill drilling programs. Some of the metrics and techniques of active learning are used to design and evaluate infill drilling programs.

Evaluation of Infill Drilling Programs

In mining, the design of the proper infill drilling program is a very difficult process that involves several aspects, including geologic and operating. During the mining operations, the position of the infill drillholes is restricted to available regions in the operations. For example, it is not practical to position drillholes in the final walls or main road accesses. The drilling and quality of the infill samples are affected by geologic characteristics, including rock quality, openness, and water content, which have to be considered in the different infill drilling alternatives that are evaluated (Shaddrick, 1987). The size of the samples plays an important role in the collection of infill data. The selection of the sample size depends on the type of mineralization present. The type of the deposit affects the spacing of the infill drillholes. The configuration of the ore body affects the decision of the orientation of the infill drillholes. These aspects are discussed by (Metz, 1992).

The design of efficient infill drilling programs, in the SLM framework, is a high dimensional problem due to the parameters of the three aspects involved. Bickel and Smith (2006) and Martinelli, Eidsvik, Hauge, & Forland (2011) commented about the complexity of designing drilling strategies. It is not the goal of this paper to propose a methodology to find a fully optimal infill drilling program, but to propose guidelines to design efficient infill drilling programs as part of the evaluation of data acquisition scenarios. The most appropriate infill drilling program to be implemented is selected among a set of feasible alternatives based on its performance of improving the profit margin of the mining project.

To relieve the complexity of the problem, the different infill drilling programs are evaluated based on their respective objective aspect. However, it may results in a wide range of possible alternatives, as the objective aspect of an infill drilling program consists of the individual objectives of each infill drilling campaign throughout the lifetime of the mining project. In Figure 6, a sketch of the objectives of two infill drilling programs is presented. The objective of infill drilling program A considers to focus on reducing uncertainty in the long, medium and short term plan in the first two periods. After that, the infill drilling program focuses only in the medium and short term plan in the following two periods. Finally, for the rest of the periods, only the reduction of uncertainty in short term plan is considered in the objective of the infill drilling program. In the case of infill drilling program B, these individual objectives of the infill drilling campaigns are different in terms of the timing when they are implemented. Two similar objectives of infill drilling campaigns, such as focusing on the short term plan, may even consider different criteria to position infill drillholes. This aspect adds more complexity to the problem and makes it very difficult to express the design of an infill drilling program as an optimization problem.

Even after reducing the dimensionality of the problem by considering a set of infill drilling program objectives, instead of the whole spectrum of possibilities, the selection of the most efficient infill drilling program is still a high dimensional problem. The next aspect two deal with is the amount of infill drilling data to collect. Similar to the case of the definition of the objectives of the individual infill drilling campaigns, the amount of infill drilling data to collect is also affected by the timing aspect. Thus the problem is focused on finding the configuration of the number of infill drillholes to collect in each period that improves the efficiency of the infill drilling objectives considered. In computational learning, learning curves are used to compare the performance of learning algorithms as a function of the size of the training dataset (Perlich, Provost, & Simonoff, 2003). Learning curves allow identifying patterns that depend on the characteristics of the training dataset of the learning algorithms (Perlich, Provost, & Simonoff, 2003). The performance of the selected infill drilling program objectives is compared based on their respective learning curves, as the model of the mining process behaves as a computational learning process. In Figure 4, the incremental SCF line is a case of a learning curve that measures the performance of a infill drilling program objective for a set of configurations of infill drillholes collected. The combination of the number of infill drillholes in each period is enormous, which would require to generate a hyper-learning curve of number-of-periods dimensions. For simplicity, the combinations of number of infill drillholes to collect can be represented parameterized by an initial and a final number of infill drillholes to collect, within a specified range of periods. In Figure 7, an example of a case of the configuration of number of infill drillholes is presented. The combination of number of infill drillholes to collect is restricted to the evaluation of transitions, increasing, decreasing, or constant, in the number of infill drillholes to collect. In the example presented, the transitions behave linearly. Additional flexibility can be added by considering quadratic or cubic transition curves to evaluate more complex behaviors, e.g., convex and concave transitions.

The two dimensional parameterization of the amount of infill drillholes collected results in the characterization of the effect of the infill drilling program objective by a ΔSCF_{EX} surface. The ΔSCF_{EX} values are mapped from their corresponding configurations of number of drillholes collected. Similarly, the costs of implementing each configuration of number of infill drillholes collected results in the corresponding *CIP* surface. The performance of the infill drilling program objective is ultimately measured by the $\Delta SNCF_{EX}$ surface, which is estimated based on the ΔSCF_{EX} and *CIP* surfaces, as presented in equation (6). In the $\Delta SNCF_{EX}$ surface, the evaluation of the performance of the infill drilling program objective is limited to the number of infill drillholes cases evaluated.

Comparison to Conventional Paradigms

In the SLM paradigm, the economic performance of the mine plan is measured in terms of the $SNCF_{EX}$. The conventional paradigms consider either the $SNCF_{PL}$ and $SNCF_{EX}$ as economic performance metrics. Although the $SNCF_{EX}$ is more complex to calculate than $SNCF_{PL}$, it is a more robust and realistic metric, as it considers more aspects of the mining process. In this section, it is discussed the differences of the SLM paradigm with respect to its conventional counterparts in terms of how they account for the economic aspects of the mine plan. The $SNCF_{EX}$ is used as the metric for comparison.

The benefits of the implementation of an infill drilling program are quantified in terms of ΔSCF_{EX} component. In Paradigm 1, the SCF_{PL} is used as the metric of performance of the mining strategy. The SCF_{PL} is independent of the infill drilling program proposed. Thus the impact of the sampling strategy is not directly accounted for in economic terms. In Paradigm 2, the assessment of uncertainty in the mining strategy designed in Paradigm 1 allows the estimation of the SCF_{EX}. The negative economic impact of the production gap associated to the mining strategy can be quantified. However, the SCF_{EX} is based only on the initial dataset and does not consider the extra data that is collected throughout the lifetime of the mining project. In Paradigm 3, an assumption that reality is accessible in advance is made. In this context, the SCF_{PL} equals the SCF_{EX}. There is no negative impact of the production gap. Paradigm 1 is not included in the comparison with the other paradigms, as the SCF_{EX} cannot be calculated. Among Paradigms 2, 3, and SLM, the largest impact of the production gap is present in Paradigm 2, and in Paradigm 3 this impact is null. Since Paradigm 2 is considered the base case of the SLM paradigm, the relationship between their respective SCF_{EXE} is:

$$SCF_{ex}^{(P2)} > SCF_{ex}^{(SLM)} > SCF_{ex}^{(P3)},$$

where, $SCF_{ex}^{(P2)}$, $SCF_{ex}^{(SLM)}$, and $SCF_{ex}^{(P3)}$ are the SCF_{EX} values of Paradigm 2, SLM Paradigm, and Paradigm 3, respectively.

The gap between $SCF_{ex}^{(P2)}$ and $SCF_{ex}^{(SLM)}$ is the effect of the blasthole data. Even if no infill drilling campaign is implemented, blasthole data is collected from the regions mined. The gap between $SCF_{ex}^{(SLM)}$ and $SCF_{ex}^{(P3)}$ is due two reasons: 1) it is unrealistic to be able to sample whole deposit, and 2) even if the whole deposit is sampled as extra data, the production gap of the first period is subject to the initial dataset and cannot be avoided.

The cost of the implementation of an infill drilling program is quantified in terms of the *CIP* component. In Paradigm 2, since the sampling strategy does not influence the SCF_{EX} component, the *CIP* component would be expected to be zero. In Paradigm 3, the *CIP* component would be enormous as it would require to sample the whole deposit. In practice, an appropriate value is assigned to the infill drilling program cost. The subjective nature of the *CIP* component makes that the SLM paradigm and the conventional paradigms are not comparable in $SNCF_{EX}$ terms.

Example

The initial dataset consists of twenty eight vertical drillholes placed over a regular grid of 50 x 50 m. Based on the initial dataset, the SLM paradigm is implemented to generate a set of one hundred mining scenarios. The infill drilling program implemented consists of eight infill drillholes in each period. The objective of the mining strategy is to preserve a production of 2500MT per period.

A set of different configurations, over a range of twelve periods, of initial a final number of infill drillholes are considered. The number of initial and final infill drillholes evaluated is: 0, 2, 4, 6, 8, 10, 15, 20, and 40. The total number of cases evaluated is 81 cases, where 100 realizations are generated in each case. The surfaces of the incremental profit and its corresponding components, incremental revenue, and infill drilling program implementation cost are presented in Figure 8. The incremental revenue is calculated based on the revenue of Paradigm 2, where no infill drillholes neither blastholes are implemented.

Based on the incremental profit, the most appropriate infill program is between 10 to 20 infill drillholes in the first period and 0 drillholes in the 12th period. In this example, the major impact of the infill drilling program is seen in the earlier periods, and in the latter periods tend not to contribute negatively to profit of the mining project. This exercise presents the implementation of a tool for decision making.

Concluding remarks

The three aspects involved in the design of infill drilling programs makes the optimization of the design a highly dimensional problem. In this paper, an approach to evaluate designs of infill drilling programs is discussed. However, even if an optimal infill drilling program is designed, the mine plan is still sub-optimal, since the mining strategy is considered fixed. An optimization of the mine plan requires that both the mining and sampling strategies are considered together.

The infill drilling program to be implemented has to be carefully analyzed, since an inefficient infill drilling program, in an attempt of reducing the profile of the production gap and improve the SCF_{EX} may contribute negatively to the $SNCF_{EX}$ of the mining project.

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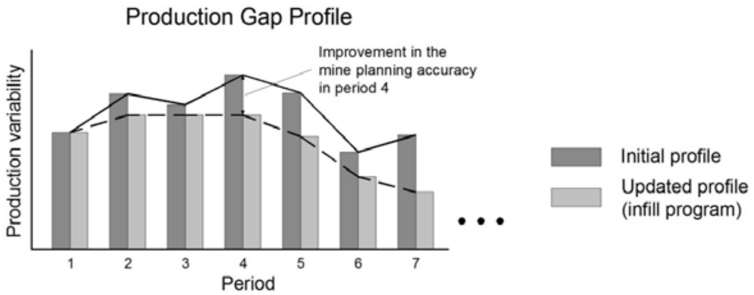

Figure 1: Sketch of production gap profile with and without implementing a data acquisition strategy; notice the production variability in the first period is not affected by the data acquisition strategy

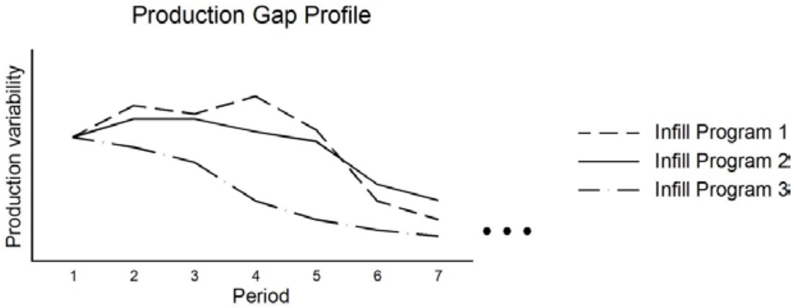

Figure 2: Sketch of production gap profiles of three infill drilling programs

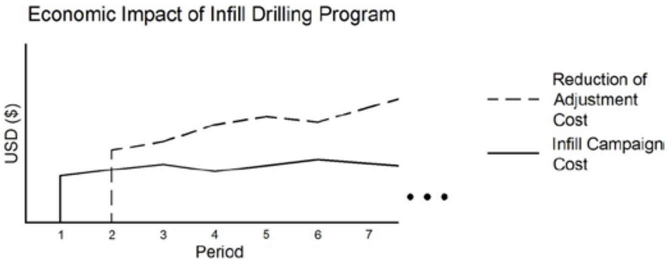

Figure 3: Sketch of impact of infill drilling program on the economic performance of the mine plan

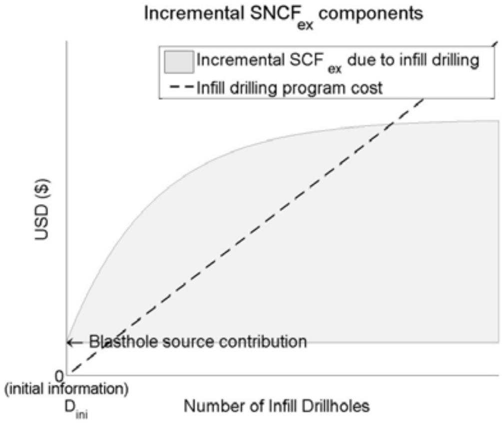

Figure 4: Sketch of effect of infill drilling program size on $\Delta SNCF_{ex}$ components for a fixed infill drilling strategy

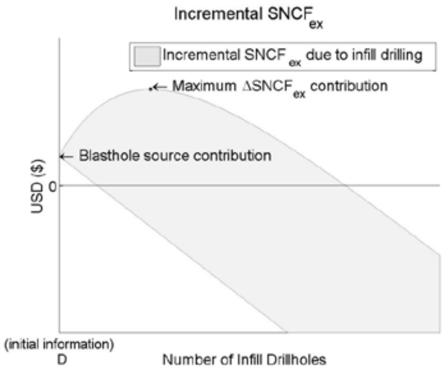

Figure 5: Sketch of effect of infill drilling program size on $\Delta SNCF_{ex}$ for a fixed infill drilling strategy

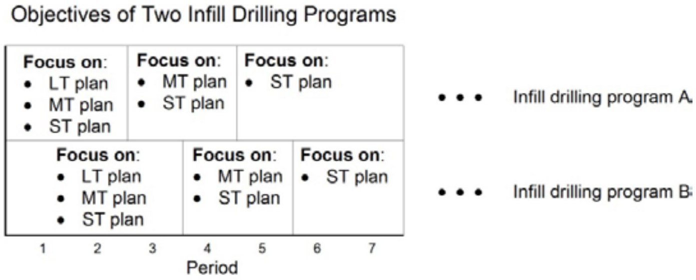

Figure 6: Sketch of objectives of two drilling programs

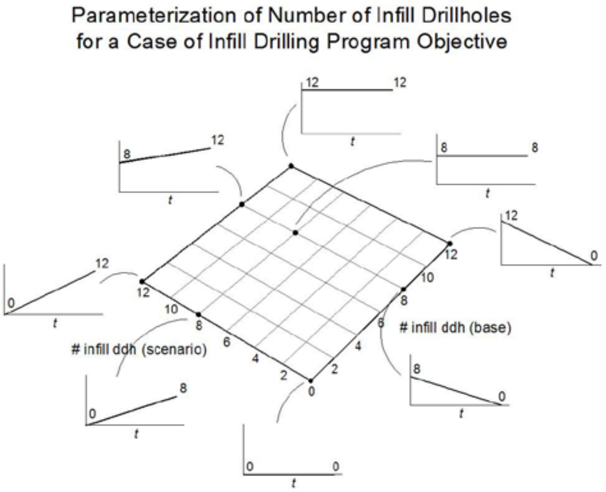

Figure 7: Sketch of the parameterization of the amount of extra infill drilling data collected for a case of an infill drilling program objective

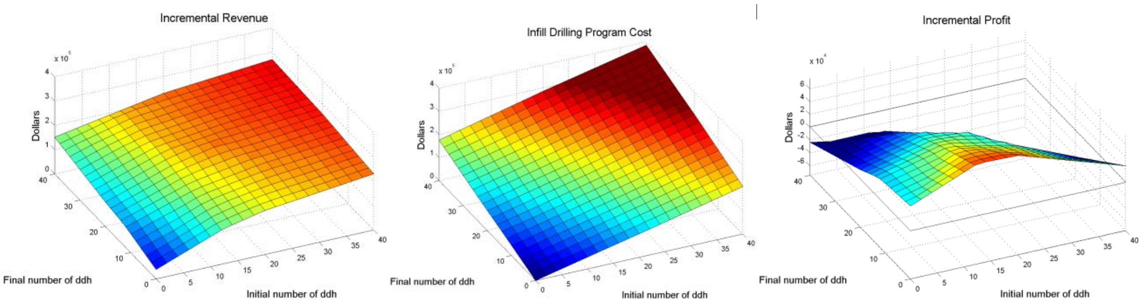

Figure 8: Surfaces of incremental revenue, infill drilling program, and incremental profit