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L. Montiel
R. Dimitrakopoulos

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GERAD HEC Montréal
3000, chemin de la Côte-Sainte-Catherine
Montréal (Québec) Canada H3T 2A7

Tél. : 514 340-6053
Téléc. : 514 340-5665
info@gerad.ca
www.gerad.ca

Simultaneous stochastic optimization of production scheduling at Twin Creeks mining complex, Nevada

Luis Montiel [a]
Roussos Dimitrakopoulos [a,b]

[a] *COSMO – Stochastic Mine Planning Laboratory, Montréal (Québec) Canada, H3A 0E8*

[b] *GERAD & Department of Mining and Materials Engineering, McGill University, FDA Building, Montréal (Québec) Canada, H3A 0E8*

`luis.montiel@mail.mcgill.ca`
`roussos.dimitrakopoulos@mcgill.ca`

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Abstract: Twin Creeks is a gold mining complex part of Newmont's Nevada Operations. The mining complex is comprised of two open pits, Mega and Vista, external ore sources and a set of existing stockpiles, all providing ore for an autoclave, an oxide mill and a heap leach. Mega pit provides sulphide ore for the autoclave whereas Vista pit provides oxide ore for the oxide mill and the heap leach. Both pits operate the same mining equipment and therefore their extraction sequence must be optimized simultaneously. Stringent blending requirements are associated with the operation of the autoclave for the sulfide ore. Strategic blending optimization at large scale has brought significant value to the operation by increasing synergies. This paper presents the implementation of a stochastic optimization framework for the long-term production planning at Twin Creeks that simultaneously optimizes mining, stockpiling, blending and processing decision variables. The uncertainty and variability associated with the different sources of material is incorporated in the optimization model by means of stochastic simulations. The stochastic solution generated shows substantial potential benefits by increasing expected recoverable gold, leading to increased expected cash flows, while reducing the risk of not achieving the forecasts by increasing the probabilities of meeting production and blending targets.

Keywords: Mining complex, stochastic simultaneous optimization, stochastic simulations

1 Introduction

Mine operations are comprised of multiple components such as mineral deposits, stockpiles, external sources, mills, autoclaves. These components represent a mineral value chain, which is also known in the literature as a mining complex (Montiel and Dimitrakopoulos, 2015; Goodfellow and Dimitrakopoulos, 2016). The material extracted from the mines flows through the different components and is transformed into sellable products. This flow of material in a mineral value chain involves complex non-linear transformations which difficult the use of industry-standard optimizers. Furthermore, the optimization of a mining complex can be formulated as mixed-integer non-linear optimization program with millions of integer variables representing mining, blending, stockpiling and processing decisions prohibiting the use of conventional non-linear optimization approaches. Several methods that consider the joint consideration of multiple components of a mineral value chain are available (Hoerger et al. 1999, Chanda 2005, Stone et al. 2005, Wooller 2005, Whittle 2005, Whittle 2010). Although these methods add value by increasing the synergy between the different components of the mining complex, are not simultaneous in terms of being integrated in a single optimization formulation and, in addition, rely on simplifying assumptions that constrain their efficacy. Simplifying assumptions may represent aggregation of variables, definition of mining production schedules and policies prior to optimization such as cut-off-grade definition or destination of mining blocks, linearization of non-linear transformation functions and/or discard of uncertainty of critical parameters (Whittle 2007). The joint optimization of different components of a mining complex was introduced in Hoerger et al. (1999) who implement a mixed integer programming formulation to simultaneously optimize aspects Newmont's Nevada operations. The model is based on the work by Urbaez and Dagdelen (1999) and simultaneously optimizes the extraction of materials from multiple deposits and the delivery of ore to multiple plants, assuming fixed schedules and aggregates mining blocks to enable solutions.

Twin Creeks is a gold mining complex part of Newmont's Nevada operations. The complex is comprised of two pits, Mega and Vista, external ore sources, a set of existing stockpiles, one autoclave, one oxide mill and heap-leaching. Mega pit provides sulfide ore for the autoclave, which also receives material from external sources and a set of existing stockpiles. To help blending, the sulfide ore has been classified in more than forty sulfide material types based on grades for gold (Au), sulfide sulfur (SS), carbonate (CO_3) and organic carbon (Corg). Kawahata et al. (2016) formulate the strategic mine planning process at Twin Creeks as a multi-period mixed integer linear program. The life-of-mine production schedule is carefully optimized under tight blending process constraints with stockpiling option. This approach allows Twin Creeks to gain significant value from cost reductions and higher cash-flows. However, incorporating uncertainty and risk in the mine planning process is a key aspect for the organization to add value to their operations.

Twin Creeks has facilities to process different ore types coming from multiple sources. The quality of the source material is of crucial importance as it determines the amount of gold that can be recovered from the complex and therefore the expected cash flows. The uncertainty of the material quality and variability has been modelled using stochastic simulations (Goovaerts 1997). This paper presents an approach that incorporates this uncertainty in the simultaneous optimization of all components of the Twin Creeks gold complex. The approach focuses on generating mining, stockpiling and blending schedules that maximize expected NPV while controlling production rates and satisfying blending requirements. The stochastic solution is benchmarked against the actual mine's long-term plan in 2013. This helps in checking the ability of the stochastic framework to anticipate the performance obtained in previous mined-out areas.

In the following sections, the method utilized for optimizing the mining complex in the presence of material type uncertainty is first presented. The implementation of the method at Twin Creeks and comparisons to the mine's conventional solution are detailed next. Conclusions are presented in the last section.

2 Stochastic scheduling optimization method

The stochastic scheduling optimization approach is composed of two steps. Firstly, an initial solution is generated, then additional constraints are imposed to adapt the initial solution to pre-existing mine infrastructure and mineability requirements, as it may be needed.

The stochastic scheduling optimization of Twin Creeks is formulated as a stochastic mixed-integer, non-linear programming (SMINLP) formulation aiming to generate a single mining, stockpiling, blending, and processing plan that maximizes the expected NPV while generating feasible production rates that satisfy blending requirements. The optimization model used herein is based on the following objective function:

$$\max O = \sum_{t=1}^{T} \frac{1}{S} \sum_{s=1}^{S} \Big(DiscProfit\,(s,t) - PenDeviations(s,t) \Big) - \sum_{i=1}^{N} PenDisconnection(i) \tag{1}$$

where T is the number of years of the life-of-mine, S is the set of scenarios that model the global supply uncertainty, N is the number of mining blocks considering all deposits, $DiscProfit(s,t)$ is the discounted profit in period t and scenario s, $PenDeviations(s,t)$ are the penalized deviations from production and operational targets in period t and scenario s based on geological risk discounting and deferment, and $PenDisconnection(i)$ is the penalty associated with having the block i disconnected from some of its neighbours in the mining sequence. The discounted profits are evaluated considering revenues and costs associated to the different components of the mineral vale chain. The penalized deviations, $PenDeviations(s,t)$, are calculated by considering mining capacities, processing capacities, and operational ranges for blending properties. The term $PenDisconnection(i)$ looks for smoothed mining sequences by penalizing the disconnection of blocks within the sequences.

Given the large number of variables in the SMINLP formulation, standard industry available optimizers cannot be used to solve this problem. A metaheuristic based on simulated annealing with multiple neighborhoods is implemented to generate the stochastic solutions. The perturbation mechanism iteratively modifies the sequence of extraction of the mining blocks, the destination of the blocks and the reclaiming schedule from the blending stockpiles. The detailed description of the formulation and solution method can be found in Montiel and Dimitrakopoulos (2015).

The production sequences at the mines of the mining complex considered are adapted to consider pre-existing infrastructure and mineability requirements. The adaptation of the mining sequences of individual pits is performed bench by bench in descending order. This guarantees the minimum mining width along with the connectivity of the blocks on a bench within the same period; only one extraction face for each bench in each period is allowed. Every adapted bench satisfies slope constraints and mining rates. Once a bench has been adapted, the blending, stockpiling and processing decisions are re-optimized accordingly to satisfy blending and processing requirements. The process is repeated until all the benches from all pits involved have been adapted (Figure 1).

3 The Twin Creeks gold mining complex

Twin Creeks processes both sulfide and oxide ore in its processing facilities. The sulfide ore is processed in a sage autoclave, which recovers gold based on Au and Corg grades. The autoclave has stringent blending requirements for SS, CO_3, Corg and SS/CO_3 ratio. The sulfide ore extracted from Mega pit can be sent directly to the sage autoclave or can be stockpiled per its material type. In the mine's long term plan of 2013 (TC-2013 plan) there are 22 existing sulfide stockpiles that can be blended with the material extracted from Mega pit. The sulfide material types can be grouped in 11 different blend types based on SS, CO_3 and Corg (Table 1). Concentrate from external plants (Mill 5 and Mag concentrates) and ore coming from an underground mine (TRJV) are also added to the autoclave. The Mill 5 concentrate comes from the Mill 5 facility located in the Carlin operation in Nevada, whereas the Mag concentrate comes from a physical magnetic separation added to the Mill 6 roaster in Carlin. To satisfy blending requirements, acid is added to the autoclave to reduce the concentration of CO_3, and therefore, put the SS/CO_3 ratio within the operational ranges. Although, the acid allows for more flexibility in blending the material for the autoclave, the amount of acid consumption should not exceed the maximum amount of acid in the long-term plan (approximately 40Kton per year). The mining, stockpiling and blending schedules seek to maximize the expected net present value (NPV) while satisfying the blending requirements in the autoclave.

The oxide ore extracted from Vista pit can be sent to an oxide Juniper mill, oxide leaching, or oxide stockpiles. There are no blending requirements for oxide ore. Thus, the scheduling of the Vista pit is purely

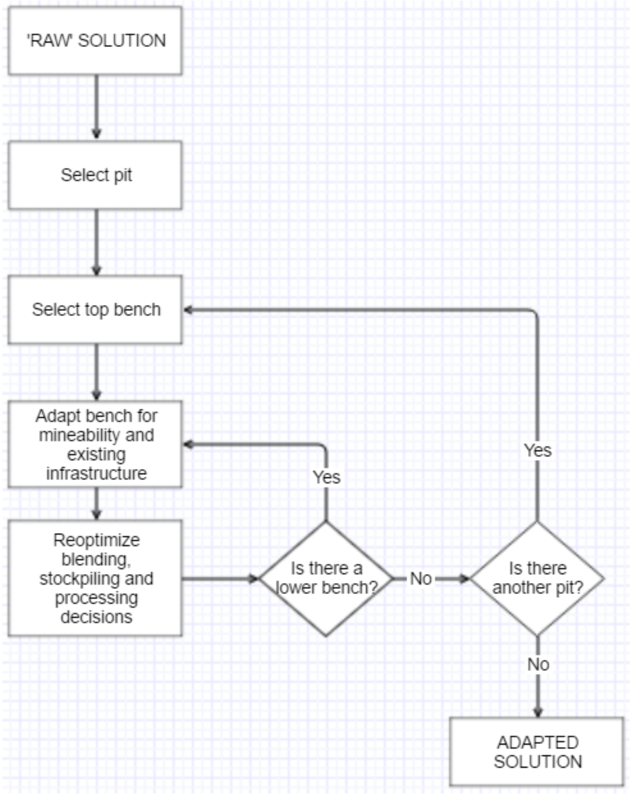


Figure 1: Adaptation of 'raw' stochastic solution

Table 1: Blend types of sulfide ore

Sulfide Blend Types	Description
A	Low SS and medium-low CO_3
B	High SS and medium CO_3
C	Medium-high SS and low CO_3
D	Low SS and low CO_3
E	High Corg and medium-low CO_3
F	High CO_3
G	Low SS and medium-high CO_3
H	High SS and low CO_3
I	Very high CO_3
K	High Corg and High CO_3
O	Very high Corg

based on gold grades and the mining rates depend on the global extraction capacity of the complex as both pits operate the same mining equipment. This highlights the importance of a concurrent optimization of both pits and as part of the Tween Creeks mining complex. A schematic representation of the complex can be observed in Figure 2.

The different components of the mining complex are strongly interrelated, and therefore they must be simultaneously optimized during the mine planning and production scheduling process. The mining, stockpiling, blending, and processing strategies and the quality of the source material determine the expected recoverable gold and associated cash flows. Sources of material are Mega and Vista pits, existing stockpiles and external ore sources. There is a large uncertainty and variability associated with the different sources of material in terms of grades and material types. Smooth orebodies mislead the blending strategy, the planning decisions and the project expectations (Dimitrakopoulos et al, 2002; Goodfellow and Dimitrakopoulos, 2017; other) and it is, thus, critical to characterize grade and material type variability and uncertainty in all sources of material. To minimize risk and increase value it is necessary to simultaneously optimize the different components of the mining complex in the presence of uncertainty.

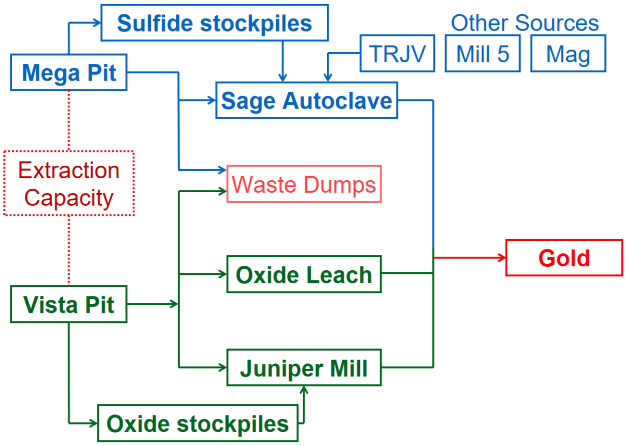


Figure 2: The Twin Creeks gold mining complex (two mineral deposits, multiple stockpiles, thre external sources, processing destinations)

4 Risk analysis of TC long-term production schedule

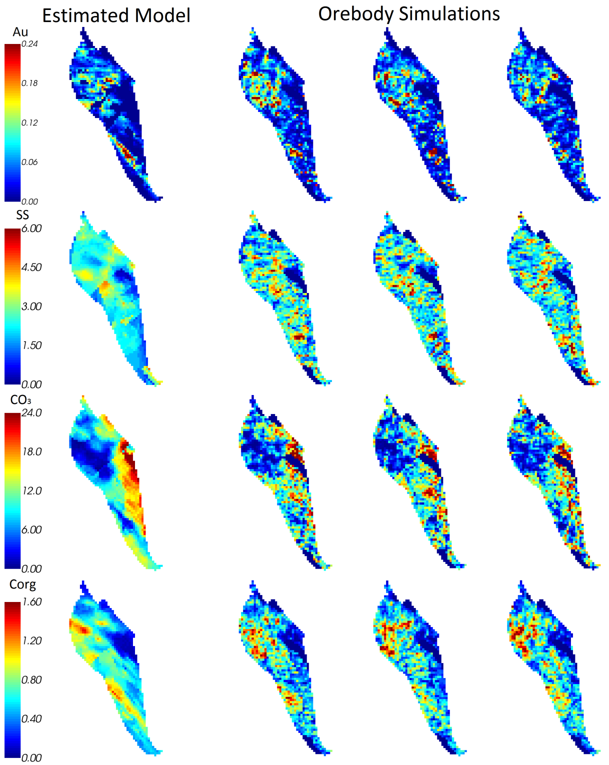
The mine's long-term plan in 2013 (TC-2013 plan) is based on estimated models of the deposits (Mega and Vista), constant average grades for the stockpiles and forecasted grades and tones from the external sources, ignoring the actual variability and uncertainty of the source materials. According to this plan, the sage autoclave is fed at full capacity during the entire LOM while satisfying the blending requirements by adding acid to the sulfide ore. The acid reduces the concentration of CO_3, which allows having the SS/CO_3 ratio within the operational ranges for the autoclave. In this deterministic framework, the acid consumption is forecasted to remain well controlled during the LOM and never exceeds the maximum amount of acid usage. It should be noted that this is not observed in the forecasts generated with the proposed approach, accounting for uncertainty and variability of the different sources of material.

The uncertainty of the material in the TC gold mining complex is modelled through stochastic simulations. The mineral deposits are simulated using geostatistical orebody simulations (Boucher and Dimitrakopoulos 2009, Mustapha et al. 2014). For Mega pit, the grades of Au, SS, CO3 and Corg are simulated, whereas, only Au is simulated for Vista pit (Figure 3). Since Vista pit only provides oxide ore that does not involve blending requirements, there is no need to consider the other elements as well. There are stockpiles that have been sampled to assess their quality and variability, which is used to generate a set of stochastic simulations for each sampled stockpile. The stockpiles that had no drilling information are simulated using production grade control data. The uncertainty of the material coming from external sources is described using a set of Monte Carlo simulations where the distributions were generated based on the quality of the external material during the previous production years (Figure 4).

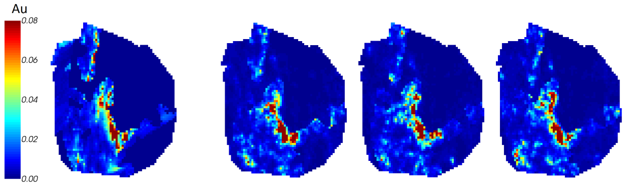
The resulting risk analysis quantifies the risk of the schedule to meet its production forecasts in the presence of uncertainty of the materials to be supplied. The output values of a given project indicator (metal produced, cash flows, blending properties, other) are represented by risk profiles which are expressed as probability values, typically the P10, P50, and P90. P10 represents a 10% chance of having at least that value, which means that for 90% of the scenarios the values are higher than P10. P50 represents the value at which 50% of scenarios fall above and 50% fall below, and P90 represents a 90% chance of having a value below that value.

Figure 5 shows that the total recoverable gold at the end of the life-of-mine is expected to be lower than the prediction in the TC's conventional long-term plan. The P50 of the total recoverable gold for the TC-2013 plan assessed here (red line in Figure 5) is 4% lower than predicted by the conventional mine schedule (blue line in Figure 5). The risk analysis follows the actual results obtained in the TC complex in years 2013-2015. The difference between the recoverable gold forecasted in the TC-2013 plan and the ones observed in the risk analysis comes from the inability of the estimated models to reproduce the actual variability of the mineral deposits. It is well known that estimation techniques such as kriging, the one used to estimate Mega and Vista pits, generate smoothed representation of the deposits which translates into misleading forecasts (Dimitrakopoulos et al. 2002, Albor and Dimitrakopoulos 2009, Ramazan and Dimitrakopoulos 2013). Mine production scheduling is highly influenced by the distribution of high-grade areas within the deposit(s) and, therefore, an inaccurate representation of the variability of the deposit(s) misguides the extraction sequence in the presence of uncertainty.

The decrease in recoverable gold observed in the risk analysis has a direct impact on the discounted cash flows forecasted. The cumulative discounted cash flow is expected to be around 6% less than that predicted by the conventional TC-2013 plan (Figure 6). The difference becomes 9% when looking at the coming 6 years of production. Significant differences in the grades of SS, CO_3 and Corg are also observed in the risk analysis. Figure 7-left shows the SS grades along the different scenarios and the prediction in the TC-2013 Plan. Larger fluctuations in the SS of the material that feeds the autoclave are observed along the different scenarios. These fluctuations are also present in the other blending properties, such as the CO_3 and SS/CO_3 ratio. When the CO_3 increases considerably, acid is added to the autoclave to decrease its concentration and balance the SS/CO_3 ratio. However, given the large fluctuations of SS and CO_3 observed in the risk analysis, the consumption of acid largely exceeds the planned maximum amount in some years, reflecting a failure in the blending strategy in the presence of uncertainty (Figure 7-right), with implications for forecasted production.



Mega Pit - Bench 4080



Vista Pit - Bench 4600

Figure 3: Orebody simulations of Mega and Vista pits

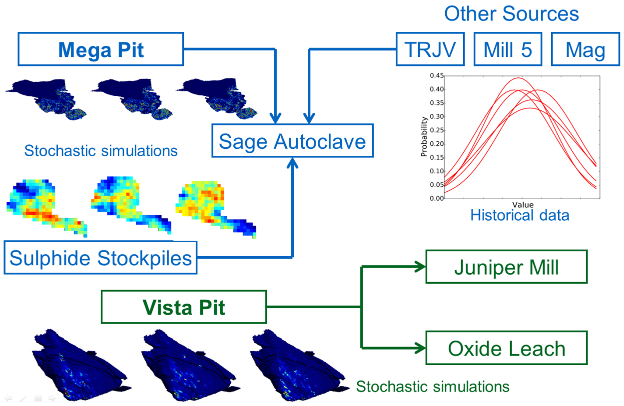


Figure 4: Uncertainty in the different sources of material (pits, stockpiles, external sources)

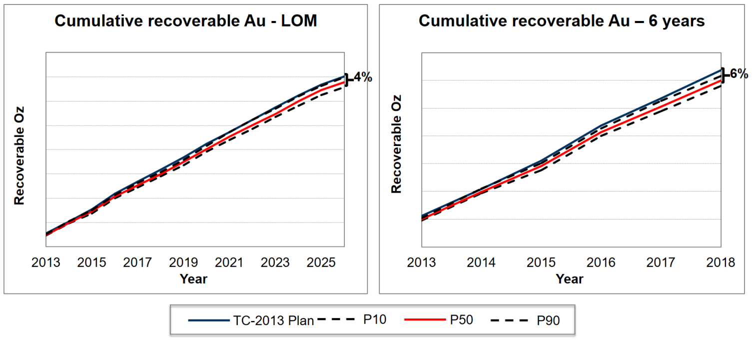


Figure 5: Risk profile of the TC-2013 Plan for cumulative recoverable gold

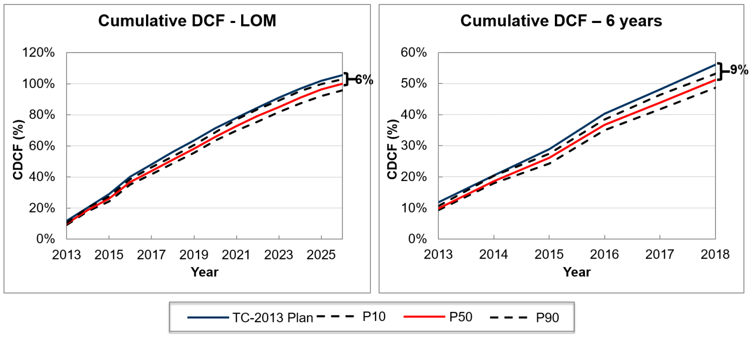


Figure 6: Risk profile of the TC-2013 Plan for cumulative DCF

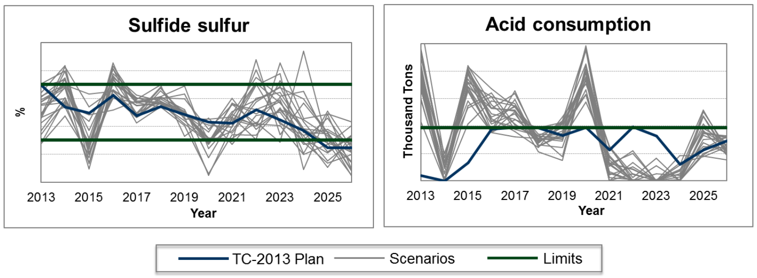


Figure 7: Sulfide sulfur and acid consumption with TC-2013 Plan

5 Stochastic scheduling optimization at Twin Creeks

The risk analysis of the previous section shows significant shortfalls of the TC-2013 Plan in the presence of uncertainty. Uncertainty is inherent to a mining operation where large portions of material are extracted with limited information obtained through drilling campaigns. Although the uncertainty cannot be eliminated, it can be incorporated during optimization by means of stochastic optimization formulations, which as a result generate more robust solutions when compared to the deterministic counterparts.

Similar to the TC-2013 Plan, the stochastic solution considers all blending types for the sulfide ore, respects mining rates and feeds the autoclave at full capacity. The stochastic solution incorporates all the operational practical aspects required, such as the utilization of existing infrastructure such as roads and ramps for both pits Mega and Vista and a minimum mining width for the safe and efficient operation of the mining equipment and the utilization of existing infrastructure like roads and ramps for both pits Mega and Vista. Therefore, the stochastic solution and the TC-2013 plan are comparable as they are both practical. The risk analysis of the recoverable gold with the stochastic solution is displayed in Figure 8. The red line represents the P50 of the TC-2013 Plan to provide a comparison between both the mine's plan and the stochastic one. The stochastic solution is expected to recover around 6% more gold by the end of the LOM (Figure 8-left). The difference between the stochastic solution and the TC-2013 Plan is more evident when looking at the first 6 years, when the stochastic solution is expected to recover around 9% more gold than the TC-2013 Plan (Figure 8-right). Although there is significant uncertainty associated with material from external sources, that uncertainty affects both the TC-2013 plan and the stochastic solution in a similar way. The difference in recoverable gold between the stochastic solution and the TC-2013 Plan originates from a different mining and blending strategy mostly associated with the sulfide ore.

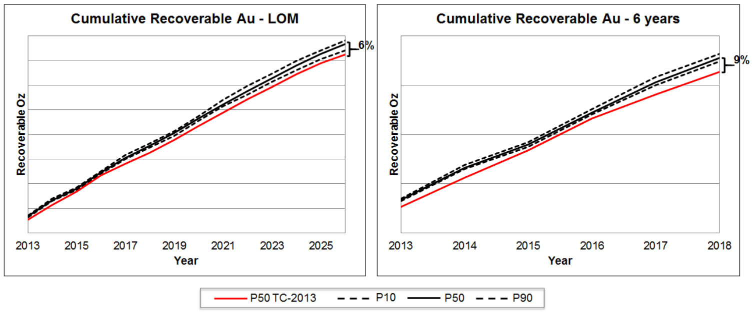


Figure 8: Risk profile of the stochastic solution for cumulative recoverable gold

The larger amount of recoverable gold in the stochastic solution leads to 7% higher cumulative discounted cash flow by the end of the LOM, when compared to the TC-2013 Plan (Figure 9). The economic benefit is even more apparent within the first 6 years, when the stochastic solution generates a cumulative discounted cash flow 9% higher than the TC-2013 Plan. As noted earlier, the stochastic approach that considers the supply uncertainty scenarios is able to blend different levels of uncertainty to reduce risk and increase value. This is also evident when looking at the blending properties in the autoclave (Figure 10). The SS is well controlled through the different scenarios and does not have fluctuations as large as in the TC-2013 Plan (Figure 10-left). Less fluctuations are also observed in the stochastic solution for the other blending properties, such as CO_3 and SS/CO_3 ratio. As a result, the acid consumption remains well controlled in the stochastic solution by not exceeding largely the maximum amount in the long-term plan as in the TC-2013 Plan (Figure 10-right).

The stochastic solution is able to recover more gold and satisfy blending requirements by changing the mining and blending strategies. The extraction sequence with the TC-2013 Plan and the stochastic solution for Mega and Vista pits can be observed in Figure 11 and Figure 12 respectively. The stochastic solution is delaying the extraction of low grade sulfide ore from Mega pit in the first years while recovering more gold from the stockpiles in the autoclave. Whereas in the TC-2013 Plan the mining complex operates at full mining capacity in years 2014-2015, the stochastic schedule utilizes the mining equipment at full capacity in

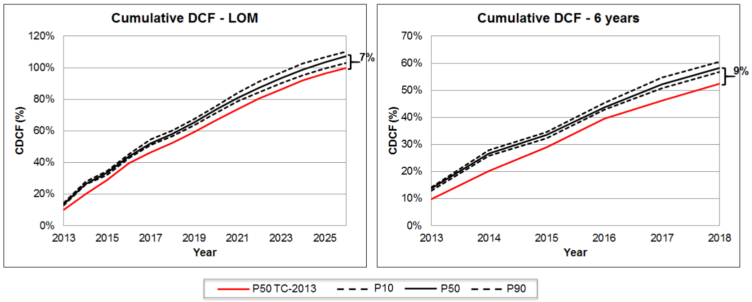


Figure 9: Risk profile of the stochastic solution for cumulative DCF

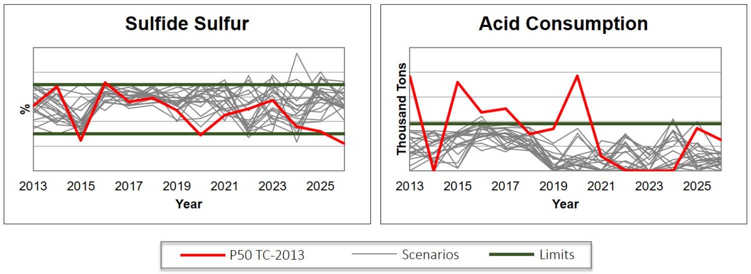


Figure 10: Stochastic solution – Sulfide sulfur and acid consumption

years 2015–2016–2017. The mining rates decrease in both solutions at a similar rate towards the end of the extraction from the pits in 2022.

The extraction sequences of both pits are highly constrained from the shapes of previous mined-out areas and existing infrastructure. Although the stochastic solution shows a significant gain in expected recoverable gold, cash flows and blending at the autoclave, a solution generated from the start or early years of a mining operation can significantly increase the benefits of a stochastic optimization framework. This allows more flexibility in the mining sequence by allocating roads and ramps according to the stochastic mining sequence itself, rather than being forced to use existing infrastructure. Furthermore, the ultimate pit limits in a stochastic optimization framework differ from the ones obtained through conventional pit limit optimization (Dimitrakopoulos 2011), and the same was found for two pits of the Tween Creeks mining complex. A conventionally optimal pit limit is constructed from smooth representations of a mineral deposit and ignores geological variability and uncertainty, which then leads also to failures in the presence of complex blending operations. This is particularly sensitive issue for Mega pit, where the truly optimal pit limit depends on the ability to blend the material from the deposit and the existing stockpiles with the required properties in terms of SS, CO_3, SS/CO_3 ratio and Corg for the autoclave. This means that rather than optimizing the pit limit based on economic values of blocks, it should be optimized based on the ability of providing ‘blendable’ material for the autoclave. This can be done by letting the stochastic optimizer to decide when to stop mining when generating the mine production schedule rather than imposing a previously defined ultimate pit. This study has been done at Twin Creeks obtaining a larger pit limit for Mega deposit by incorporating some resources adjacent to mined-out areas. However, the accessibility to these possible resources is limited and therefore not included in this paper. This highlights the importance to apply stochastic formulations as early as possible in the life-of-mine.

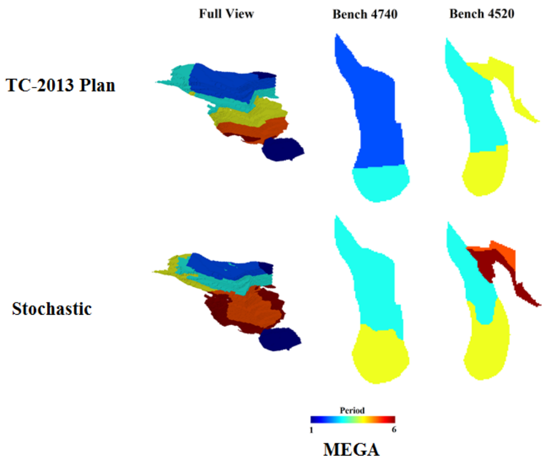


Figure 11: LOM production schedule for Mega pit: TC-2013 plan (top) and stochastic solution (bottom)

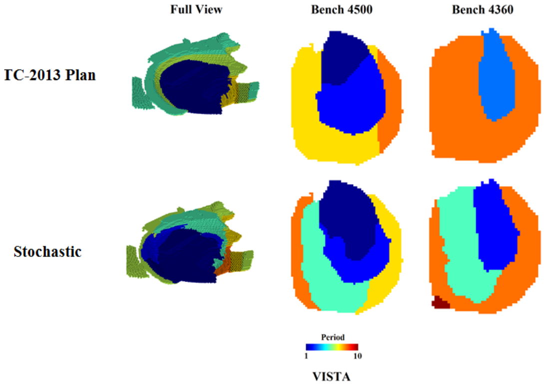


Figure 12: LOM production schedule for Vista pit: TC-2013 plan (top) and stochastic solution (bottom)

6 Conclusions

This paper presents the implementation of a stochastic optimization framework for long-term mine planning at Twin Creeks gold mining complex in Nevada, USA. Twin Creeks incorporate material from different sources to its different processing facilities. For the mineral deposits, geostatistical simulation methods are used to model the geological uncertainty and variability. Stochastic simulations are also used for modelling the uncertainty and variability of some existing sulfide stockpiles, where mine operators have performed drilling campaigns. For the rest of existing stockpiles, historical grade control data is used to model their variability and uncertainty. Similarly, the uncertainty of the material coming from external sources is modelled by generating scenarios based on production data from the previous years. The different scenarios are combined to model the global uncertainty of the input material of the mining complex as well as their variability. The uncertainty is, therefore, modelled considering all information available from geology, production and grade control departments.

The simultaneous stochastic long-term optimization of the Tween Creeks gold mining complex shows, when compared the corresponding conventional approach, (i) substantial potential gains and added value by increasing the expected recoverable gold and, consequently, discounted cash flows; (ii) managing effectively and reducing the risk of not achieving forecasts (maximizing the probabilities of meeting production and blending targets); (iii) control of blending by reducing the acid consumption at the autoclave. It is important to note that this occurs despite the fact that the extraction sequences of both Vista and Mega pits are highly constrained from previously mined-out areas and existing infrastructure.

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