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Holistic optimization of open pit to underground joint production plan

N. Soto and D. Villa
Dassault Systèmes

ABSTRACT

It is common for Open Pit operations to face challenges throughout their life-of-mine such as decreasing grades and increasing processing and mining costs. Usually once a certain production period has been reached, planner question whether to continue the surface operation or transition to underground operations that would allow them to maintain the production in a sustainable operational framework, particularly caving operations due to their low operationing costs and high productivity. Since the decision regarding the underground operation, like the optimal elevation for production level, is largely influenced by decisions made for the surface operation, as the definition of the final pit, if planners do not visualize the joint operation an optimal plan in these cases usually leads to sub-optimal scenarios.

This paper proposes a new workflow that generates a holistic optimization for the production plan, in terms of maximizing the NPV (or any other financial KPI), for a mine deposit that begins as an Open Pit operation and then transitions to a Caving operation. Simulating multiple scenarios according to several parameters as production targets, variable mining cost expressed as "premium" in caving operations and the investment required for each scenario; planners have the possibility to explore many strategies and identify areas of optimum solutions in a reasonable time using the Hill of Value technique.

1 INTRODUCTION

The current large Open Pit mines have reached a point of growth where they must face a series of environmental and economic sustainability challenges, raising questions about operational continuity. This poses the need to evaluate alternatives such as expanding the Pit or switching to an underground operation, particularly ~~Panel~~ Caving operations, which allow reaching ore production levels similar to those in surface mining scenarios. Ensuring operational continuity in mining operations using caving methods better address scenarios of decreasing ore grades and increasing costs that currently afflict Open Pit operations.

Regarding the latter, the selection of the boundary between open-pit and cave mining is usually a biased exercise, where decisions made during the development of surface operations affect underground planning, creating sub-optimal scenarios for the overall operation transition.

Given the above, it is important to emphasize the need to generate and implement workflows that identify optimal joint production plans, considering all variables present in the mine planning of both exploitation alternatives. This work aims to provide an alternative workflow, a new methodology to maximize the potential value of a deposit by optimizing the transition between operations from the beginning.

Open Pit optimization

The process begins with the selection of the optimal pit, for which Whittle is used as the open pit optimization tool. The steps for this selection follow the traditional methodology in mine planning, that is, the creation of nested pits, definition of phases or pushbacks, and the establishment of the production schedule plan.

The first step in defining the final pit requires economic parameters and geometric constraints. Economic parameters, such as mining cost, recovery, commodity prices, processing cost, etc., allow the calculation of the economic benefit associated with the extraction of each block. Based on this value, the blocks are categorized as ore or waste, and then are sent to processing or dumps, respectively. Additionally, geometric constraints such as the slope angle and the areas where these constraints will be applied enable the establishment of precedences among blocks for extraction as Figure 1 shows.

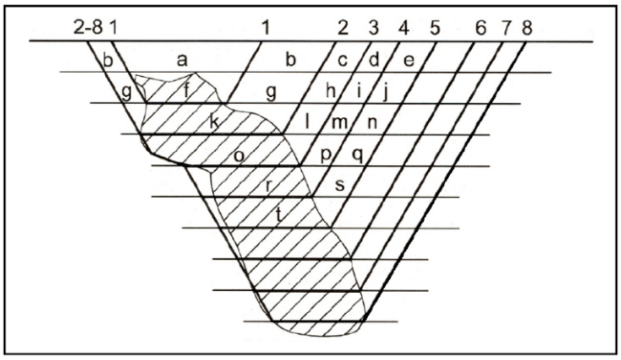

Figure 1 Whittle definition of nested pits and sequencing of the parcels (similar to blocks concept).

Whittle performs a pit search through the sequential execution of algorithms such as Lerchs-Grossman or Pseudoflow, respecting the previously mentioned precedences. It varies the benefit associated with the extraction of each block using a price-weighting factor named Revenue Factor.

Ultimately, nested pits are generated based on a range of Revenue Factor specify by the mine planner, providing an output summary with the generated pits, reporting their corresponding tonnages and the value associated to each.

The definition of the final pit involves a selection that arises from the valuation of nested pits considering a specific economic scenario. This means the combination of commodity prices, production costs, and mine planning parameters such as mining and processing limits or discount rates, for example. The choice of the final pit will depend on the criteria used by the mine planner; some alternatives may include selecting the pit with the highest value or choosing a pit that ensures sufficient tonnage to operate the mine for a certain period. Figure 2 is an example of the output of this step.

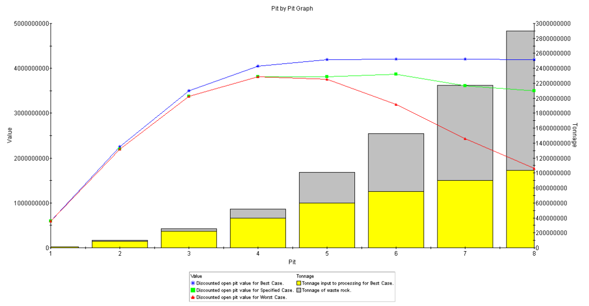

Figure 2 Pit by Pit graph.

In Whittle, phases are defined as a set of nested pits that are within the previously identified final pit. This is where a strong correlation is established between the selected phases and the resulting mine plan, as the results of the latter are conditioned by the set of selected phases.

Milawa is an alternative algorithm that allows the establishment of this sequence between phases. Particularly, one of its methods, used in the execution of this work, is responsible for the precise fulfillment of one of the following constraints: treatment capacity limit, mine movement capacity limit, and/or sales capacity (Milawa Balanced) creating feasible production plan for the open pit.

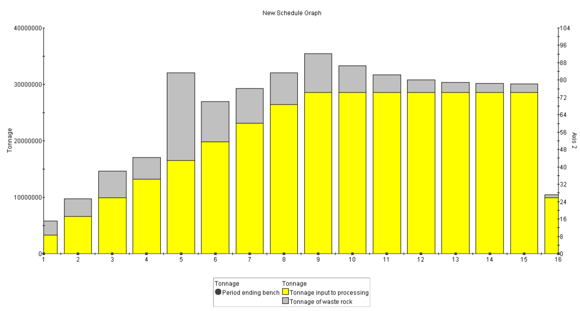

Figure 3 Schedule graph as example of production plan.

1.1 Footprint Finder

The most significant and relevant decision starting an underground mining assessment involves determining the optimal elevation of the production level. Footprint Finder (FF) swiftly addresses this query through a quick (but no less simple) analysis, using the block model as the basis for calculations. Each block within a closed polygon on one specific elevation, defined by a clipping boundary, will represent an extraction point, therefore the blocks above represent an extraction column where vertical mixing algorithms are applied. Within this mixed and diluted column, the optimal extraction height is determined by maximizing economic benefit through a specified vertical extraction rate. The steps of evaluation in Footprint Finder are outlined in **Error! Reference source not found.**.

FF simulates a production plan with several input parameters like mining sequence (**Error! Reference source not found.**a), required target tonnage and the number of new drawpoints, getting by result the tonnage, grades, and the captured value over each period (**Error! Reference source not found.**b). This analysis is reiterated for each level within a previously defined range of elevation.

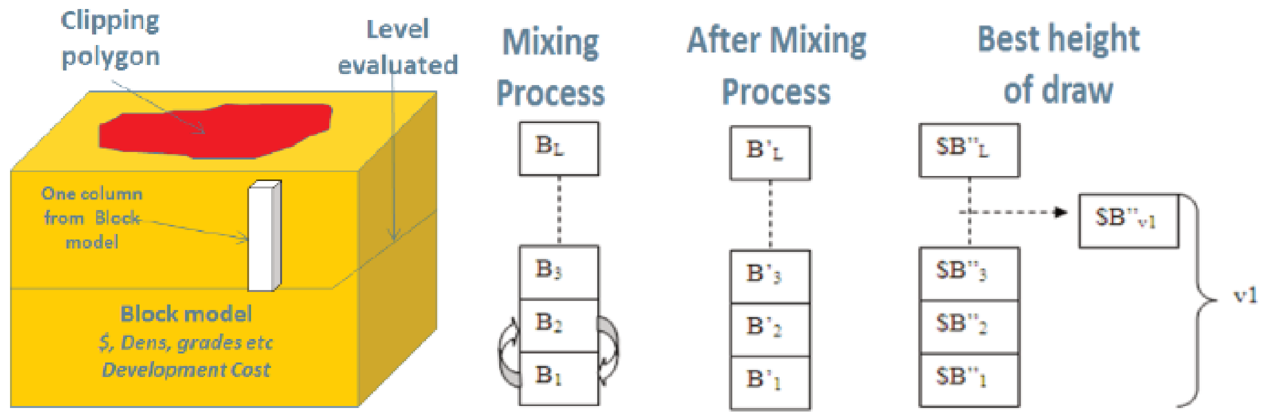

Figure 4 Footprint Finder's evaluation step.

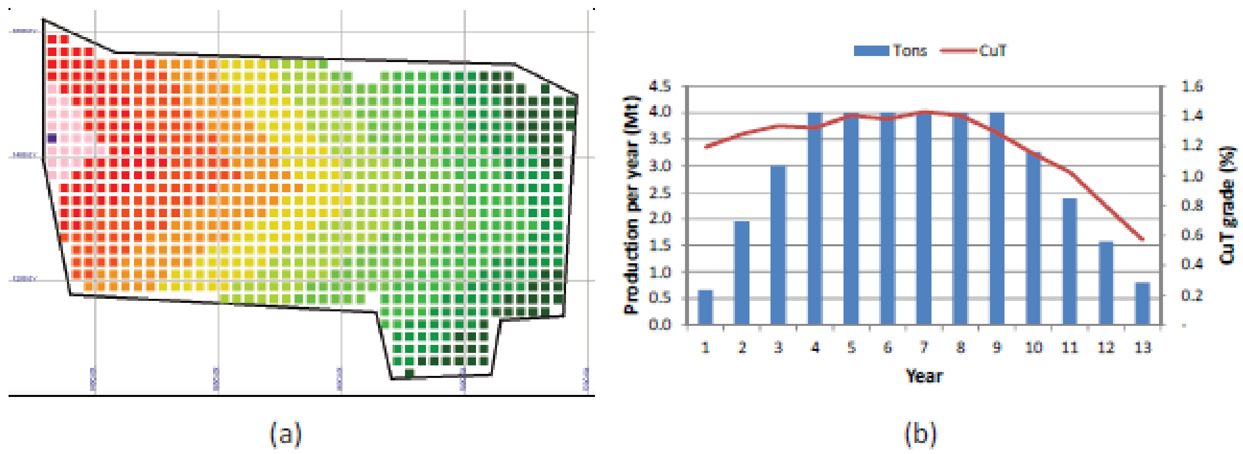

Figure 5 Production Schedule in Footprint Finder. (a) Mine Sequence, (b) Tonnage and Grade.

After all evaluations have been carried out, parameters such as tonnage and the economic value of the envelopes for each potential elevation can be compared with the aim of selecting the optimal extraction level position as the one that maximizes the Net Present Value (NPV) as show in **Error! Reference source not found.**b.

1.2 Current approach of optimal transition scenario

The implementation of underground mining as an alternative to continue operations after reaching the limit of an open-pit operation is a biased search, meaning it is applied only to the remaining portion of the deposit once the goal of the surface operation has been achieved, whatever that goal may be. An example of this is reaching the final pit, previously defined as the one that maximizes the economic value of the surface operation.

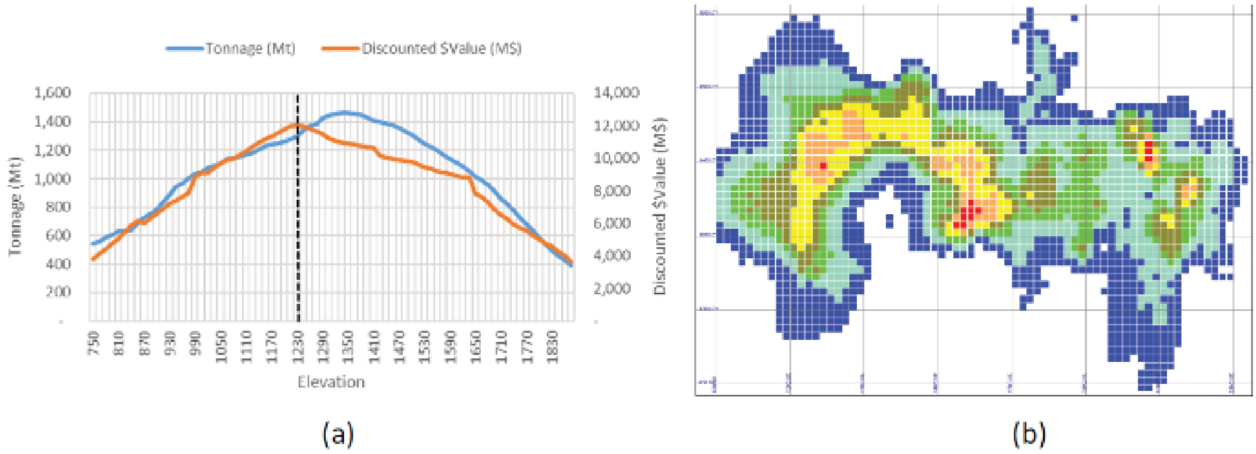

Figure 6 Results from Footprint Finder. (a) Value and tonnage distribution, (b) Footprint Size.

In this case, all material above the pit is updated to "air" category, i.e. density and grades equal to zero. After this update, Footprint Finder is executed over the remaining portion of the orebody with the objective to identify the optimal elevation of the production level.

The final selection of scenarios for both open-pit and cave mining corresponds to an isolated search for each operation. The decision becomes even more complex when considering additional options such as building a smaller mine with a lower production rate, implying lower capital costs for example.

2 FINANCIAL KEY PERFORMANCE INDICATORS

Decision-making in the strategic planning of mines is intricate due to the multitude of inputs and the numerous options and criteria available for selecting optimal and, more importantly, feasible scenarios. Utilizing key performance indicators (KPIs) provides a straightforward method to monitor, measure, and compare each of the evaluated scenarios within the feasible solution space. In this study, two KPIs, net present value (NPV) and internal rate of return (IRR), are used. Furthermore, capital cost is a crucial factor in the ultimate selection process during the exercise.

2.1 Capital expenditures

Capital expenditures (CAPEX) are the investment required to bring a new mineral project into production. Particularly for Open Pit and caving projects this is one of the main challenges since both are highly capital-intensive; most of them typically report a total upfront CAPEX of USD 500M to over USD 10B. One of the main drivers for CAPEX assumptions, for Open Pit and caving projects, are based on the size of the footprint associated with the production target since these are directly affected by development, ventilation, material handling infrastructure, etc.

2.2 Net Present Value

NPV is the value of all future cash flows (positive and negative) over the entire life of an investment discounted to the present. NPV analysis is a form of intrinsic valuation and is used extensively across finance and accounting for determining the value of a business, investment security, capital project, new venture, cost reduction program, and anything that involves cash flow (CFI Education Inc. 2022). It is calculated according to equation 1.

$$NPV = \sum_{n=1}^{N} (Z_n \cdot (1 + r)^{-n}) - X_0 \qquad (1)$$

Where Z_n is the cash flow in time n, r is the discount rate in terms of the period length of n and X_0 is the cash outflow in time 0 (i.e. the purchase price or initial investment).

2.3 Internal Rate of Return

IRR is the discount rate at which the NPV of an investment is equal to zero. Put in another way, it's the compound annual return an investor expects to earn (or actually earned) over the life of an investment. Typically, investors and managers of businesses look at both NPV and IRR in conjunction with other figures when making a decision (CFI Education Inc. 2022).

$$NPV = \sum_{n=1}^{N} (Z_n \cdot (1 + IRR)^{-n}) - X_0 = 0 \tag{2}$$

2.4 Hill of Value

The Hill of Value (HoV) is a methodology proposed by Brian Hall in "Cut-off Grades and Optimizing the Strategic Mine Plan" (Hall 2017) and used by many authors to work with Open Pit and ~~block~~ caving optimization (Ovalle 2014, Villa 2022, Hocking et al. 2020). Hall's approach emphasizes the need to have an integrated point of view when choosing the cut-off grade (CoG), and the production rate in a mining project. The author achieves this through a 3D representation of the influence of each factor to the NPV, as is shown in Figure 7.

The main contribution of HoV is that it increases the visibility, to the mine planner, of a new perspective in the Mine Project Evaluation. As Brian Hall indicates, the CoG and the production rate are commonly two independent decisions in most cases. These values must be optimized in conjunction with obtaining the maximum NPV (Hocking et al. 2020).

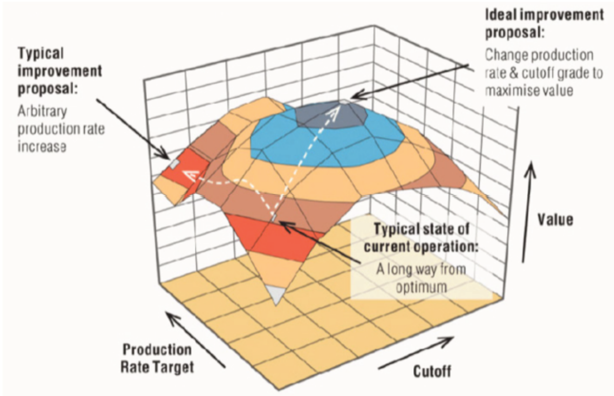

Figure 7 Hill of value optimisation technique. (Hall 2017).

3 SIMULATION MODEL

The simulation model created for this work aims to determine the best joint production plan from the combination of open pit and caving operations with the goal of maximizing financial KPIs, NPV or IRR. By addressing the sub-optimality of the traditional approach through the execution of multiple scenarios using an automated flow of processes, tasks, and components.

3.1 Isight description

Isight is a program that allows concatenating activities or tasks, from multiple applications or software. Generating an automated workflow where the output variables of a component are handled as input variables for the next one within the chain of activities. In this way, the risks associated with layer errors are reduced (Dassault Systèmes 2020).

The capacity to integrate and automate various applications or tasks speeds up the assessment of alternatives in mine planning. Furthermore, it offers post-processing tools enabling users to compare outcomes and establish connections between the inputs and outputs of the process.

Also, Isight has multiple components that connect directly to software such as Excel, text files, databases, etc. It can also connect with any application that is executed via command line such as Surpac or Whittle, that are the principal planning tools used on this work.

Since this is an automated model, it allows the execution of the workflow multiple times. Each time a new value for a parameter is modified, Isight quantifies the sensitivity of the results from this variation. Also, using constraints in the evaluation and establishing a configuration of design variables that allow defining optimal results (optimization), simulating uncontrolled variables, and finding the combination of design variables that would minimize the expected uncertainty in the results (robustness and reliability). Allowing the user better visibility of the feasible solutions and identifying the design parameters that deliver optimal results (Dassault Systèmes 2022, Villa 2022).

3.2 *Isight Transition Model*

Error! Reference source not found. describes the workflow used in this work. The model has been simplified, just for presentation purposes, but essentially summaries the main tasks within this flow, which are:

- Nested Pits generation and Pit by Pit Evaluation.
- Transition Parameters
  - Open Pit Schedule parameters
  - Caving Schedule parameters
- Combined results of multiple execution runs.
- Identify scenarios that maximize NPV and IRR (max NPV, max IRR)

Each of these components is describe in the following sections.

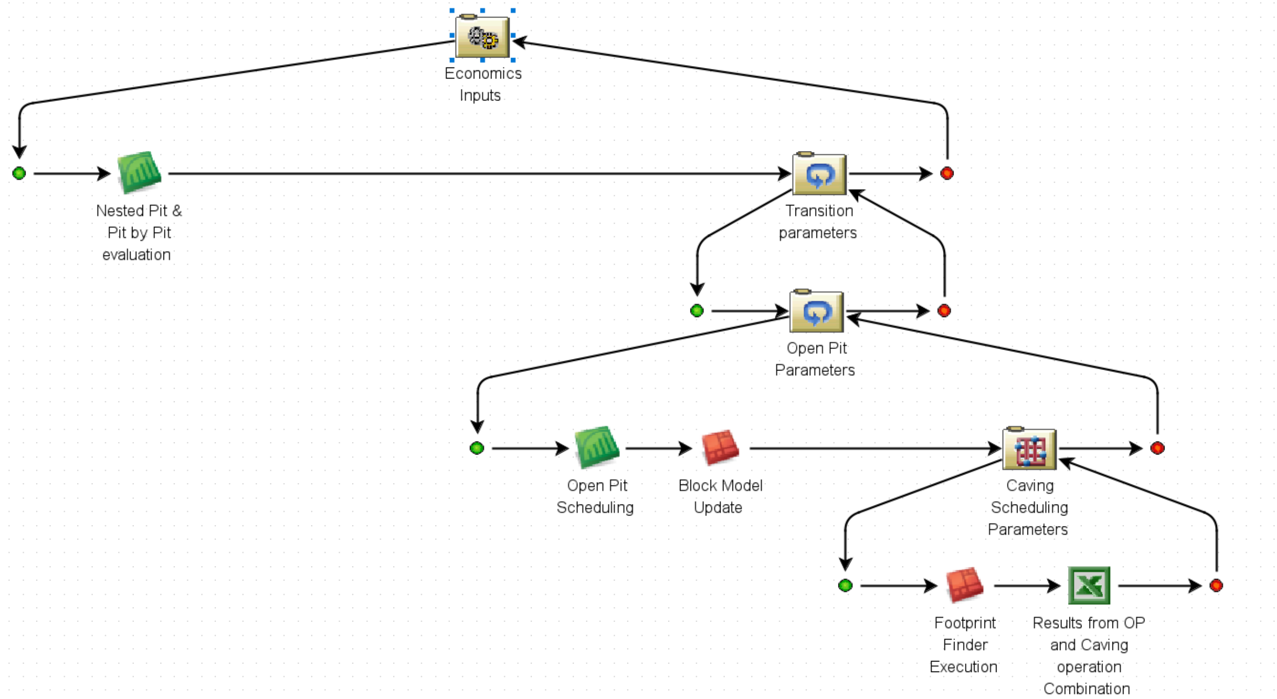

Figure 8 Whittle and Surpac (Footprint Finder) Isight workflow for transition analysis.

3.2.1 Pitshells generation and Pit by Pit Evaluation.

The first item "Nested Pit & Pit by Pit evaluation" considers four tasks, two of them are Whittle executions, the first one of them runs the nested Pits definition, based on economic inputs and geometric constraints, and the second one is the evaluation of each pit shell according to a specific economic scenario that creates the pit by pit graph showing the economic envelop of value and tonnage.

This set of pitshells will be used as potential final pits in the following components. For each one of them, nine different alternatives of production target, and therefore CAPEX requirement, is going to be applied. Transition analysis will be executed merging the results of the Open Pit scheduling with the addition of the underground operation. This process is described in the following sections.

3.2.2 Open Pit Schedule Parameters.

After each potential final pit has been identified the workflow moves to the component call "transition parameter", where a loop is established with the intention of repeating the sub-flow under it with as many pits as have been identified in the pit by pit graph.

For each one of these pits, nine potential production targets are applied. This step is the reason for the loop named "Open Pit Parameters"; here the sub-flow below this loop will be executed as many times as production targets were defined (9).

About the Open Pit schedule task, the pushbacks are selected "manually", this is the name of the configuration of MILAWA Balanced (in the automated workflow execution, a text editor component modifies log files, so no manual changes are required from the user). The phases (or pushbacks) are selected as the nested pits contained inside the evaluated final pit. For example if the pitshell evaluated as the final pit (for one of the "Transition parameters" Loop runs) is number 6, the pushbacks will be nested pits 1, 2, 3, 4, 5 and finally pit number 6 as the final pit.

The result of the open pit schedule is saved in a csv file and each column in it is saved in parameters that will be used when the workflows merge it with the caving results in the Excel component.

3.2.3 Caving Schedule parameters

For this particular loop, a Design of Experiment was used. This simulation technique allows executing a workflow running Footprint Finder by simulating a wide range of alternatives with specific inputs and constraints.

The purpose of this step is to select the best elevation for a Caving operation based on the schedule and financial results. Using Footprint Finder managed by the Design of Experiment, it will be able to simulate multiple scenarios changing inputs such as production target, premium and capital cost, etc.

Premium is a differential of the mine cost that allows evaluate the economic performances of small mines with focus on the high grades.The results of this execution is saved in the standard excel output file of FF. One more time, the columns of the periods are saved and will be used in the next task in order to merge with, the previously executed, open pit schedule results.

3.2.4 Combined results of multiple execution runs.

The results from both optimizations will be summarized here, reporting tonnage, grade, and financial results (NPV and IRR) of every combination of final pit and caving production plan, based on the parameters used, such as final pit selection, production target for open pit and caving, premium and CAPEX.

CAPEX for each operation is calculated using a linear regression from benchmarking operational data, equations 3 and 4 shows the detail. It can be seen that both depend on the target production.

$$CAPEX\_OP = ROUND((68.96 * Production\ [Mtpa] + 104.75) * 1000000{,}0) \tag{3}$$

$$CAPEX_{UG} = -(0.043 * Production\ (tpd) + 8.9633) * 1000000 * Investment\ Ponderator \tag{4}$$

Investment Ponderator is a factor that is used to adjust the CAPEX required for Caving operations since part of the investment, such as the construction of the mill plant or the reduction of the caving operation access distances, that most of the time connect the last bench of the open pit with the production level, has been addressed and/or resolved by the superficial operation. 60% is a usual value in multi-lift projects and is going to be used in this evaluation.

The results of each operation are programmed with a unique simultaneous operation period.

Also, the CAPEX for each operation is applied entirely to period 0 and n-1, where period n is the first period of the caving operation according to the rule presented above.

This analysis will generate multiple scenarios making it difficult to analyze and select the best alternative, consequently, it is necessary to group them into pairs combining the production target for each operation and choosing from this group the pair with the highest NPV and IRR. This value will be used in the HoV map to select zones with the best results.

4 CASE STUDY

The case study was done using a fictitious orebody. It is modelled as a superficial massive porphyry copper and molybdenum deposit similar to many large open pit and block cave mines currently in operation. The block size is 15 X 15 X 15 meters. The overall view of the grade distribution in 3D using 0.3 and 0.9% cut-off grade are shown in Figure 9 Copper distribution. Resources at cut-off grade 0.3% Cu (Above), Resources at cut-off grade 0.6% Cu (Below).

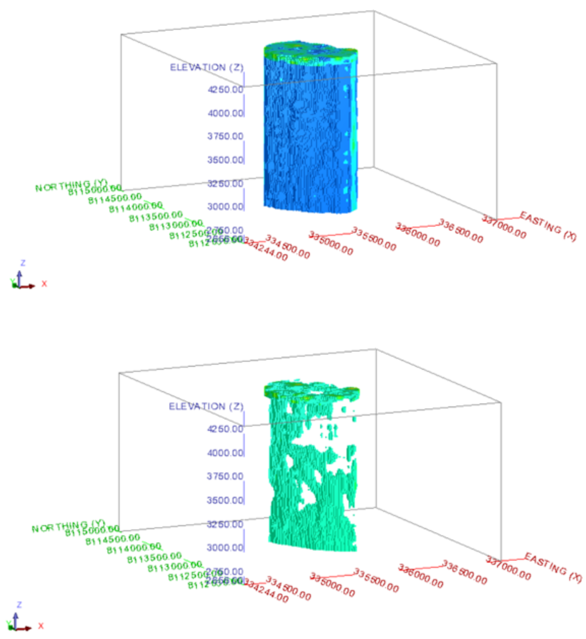

Figure 9 Copper distribution. Resources at cut-off grade 0.3% Cu (Above), Resources at cut-off grade 0.6% Cu (Below).

4.1 Whittle setup

The economic model is one of the most important inputs for this type of analysis; in this case, the open pit economic scenario was created based on copper and molybdenum revenue using the values listed in Table 1.

Table 1 Revenue Model

Input	Value
Copper price	3.85 USD/pound
Molybdenum price	16.01 USD/pound
Copper recovery	0.85%
Molybdenum recovery	0.6%
Copper Sell Cost	0.50 USD/pound
Moly Sell Cost	1.61
Reference Mining Cost	2.43 USD/t
Mining Recovery Fraction	95%
MCAF	1.00+0.0073*SQ(DIS(X, Y, Z, 97*BX, 101*BY, 111*BZ))
Processing Cost	11.38 USD/t

Whittle Optimization parameters are shown in Table 2.

Table 2 Whittle Optimization parameters

Input	Value
Optimization Method	Pseudoflow
Nested	16.01 USD/pound
Start RF	0.1
End RF	1
Step size RF	0.1
Moly Sell Cost	1.61
Mining Limit	60 Mt
Processing Limit	varies according to the evaluated scenario
Ramp up	5 years

4.2 Footprint Finder setup

Table 3 shows the financial parameters used for the revenue model and the FF parameters.

Table 3 Revenue Model for FF.

Input	Value
Copper price	3.85 USD/pound
Molybdenum price	16.01 USD/pound
Copper recovery	0.85%
Molybdenum recovery	0.6%
Copper Sell Cost	0.50 USD/pound
Moly Sell Cost	1.61
Mining Cost	8.62 USD/t
Processing Cost	11.38 USD/t

Footprint Finder inputs are shown in Table 4.

Table 4 Footprint Finder inputs.

Input	Value
Maximum allowable height of draw	600 m
Vertical mining rate	80 m/year
Height of interaction zone	100 m
First Dilution Entry	0.6
Discount Rate	10%
Development cost	3,000 USD/m^2
Target tons	varies according to the evaluated scenario
Ramp up	6 years
Opening rates	120 blocks/year

4.3 Base case definition

A base case is created using the traditional approach; particularly for this scenario, the intention is maintaining the production target for Open Pit and Caving operations. 28Mt is the selected target. The combined scenario follows three steps.

- Run Whittle Optimization, identify the pit with the greater value of NPV and run the schedule for that specific final pit.
- Update the block model using the pit surface from the previous step, selecting the optimal elevation for the caving scenario based on maximizing the value of this operation running Footprint Finder.
- Calculate the CAPEX for each scenario based on the production target, merge the cashflows and report the joint production plan and the financial KPI.

The results (Figure 10 Pit by pit graph results for Base Case show that the optimal final pit, based on maximizing the NPV, is pit number 5, i.e. revenue factor equals to 0.7, that envelops represent 437Mt of ore, 174Mt of waste and an open pit cashflow of USD3,456M. The schedule graph is generated for the selected pit, Figure 11 Schedule Graph for max NPV pit. The details of metric tonnes, grades and cashflow for each period are saved and will be combined with the results of FF.

The Block Model is updated using the final pit as a constraint as Figure 12 shows. After the update, the block model is ready to be evaluated using FF, the reference elevation is calculated as 15 meters (one block size on z coordinate) below the minimum bench of the final pit in this case bench 81, that refers to 3,856 meters (Base of the block model is 2,656 meters). Figure 13 Shows that the optimal elevation for this base case is elevation 3,256 meters, for this specific scenario the schedule is shown in Figure 14 Caving operation, best elevation schedule. The caving economic envelop reports a LOM of 29 years, with 537Mt and a discounted value of USD1,628M.

Finally, the CAPEX for the Open Pit is USD2,077M and USD2,055M for the caving operation. The reported NPV and IRR for the base case are USD1,292M and 18.17% respectively.

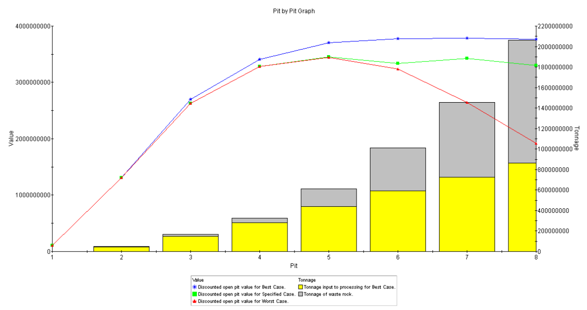

Figure 10 Pit by pit graph results for Base Case.

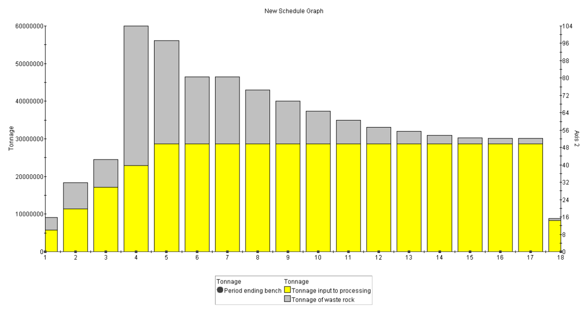

Figure 11 Schedule Graph for max NPV pit.

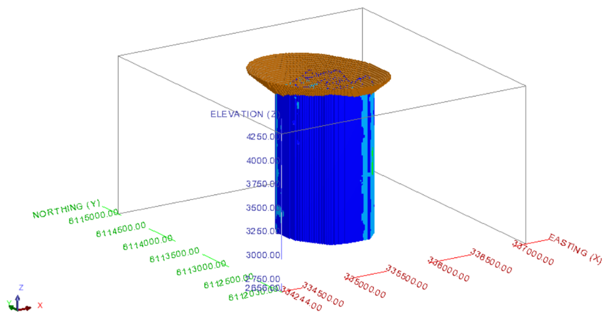

Figure 12 Update block Model for Base case.

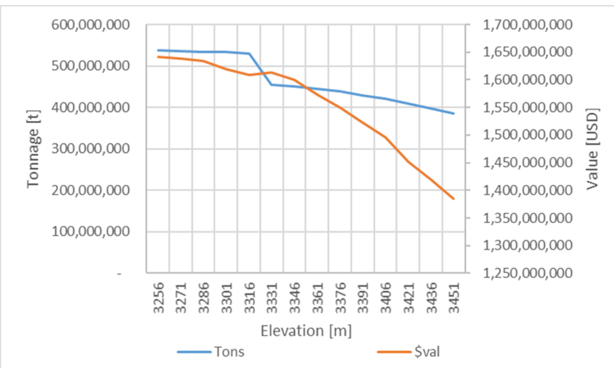

Figure 13 FF Results.

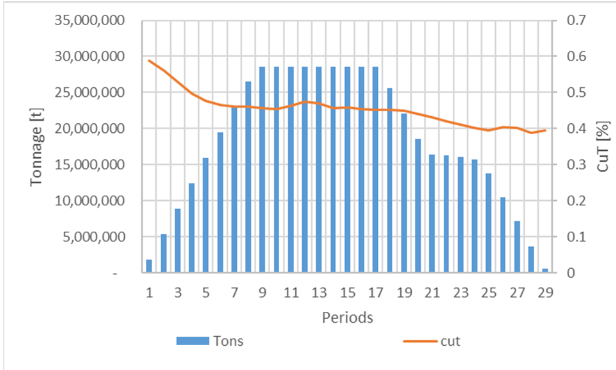

Figure 14 Caving operation, best elevation schedule.

4.4 Transition simulation model

The model presented in SIMULATION MODEL is used with the aims to define the best combination of an open pit and caving production plan.

4.4.1 Pitshells generation and Pit by Pit Evaluation.

In this example, the objective was to define the set of nested pits based on the economic scenario presented in the

$$CAPEX\_OP = ROUND((68.96 * Production\ [Mtpa] + 104.75) * 1000000{,}0) \quad (3)$$

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Investment Ponderator is a factor that is used to adjust the CAPEX required for Caving operations since part of the investment, such as the construction of the mill plant or the reduction of the caving operation access distances, that most of the time connect the last bench of the open pit with the production level, has been addressed and/or resolved by the superficial operation. 60% is a usual value in multi-lift projects and is going to be used in this evaluation.

The results of each operation are programmed with a unique simultaneous operation period.

Also, the CAPEX for each operation is applied entirely to period 0 and n-1, where period n is the first period of the caving operation according to the rule presented above.

This analysis will generate multiple scenarios making it difficult to analyze and select the best alternative, consequently, it is necessary to group them into pairs combining the production target for each operation and choosing from this group the pair with the highest NPV and IRR. This value will be used in the HoV map to select zones with the best results.

CASE STUDY. Each pit on the pit list will be used as a final pit, and the resultant schedule will be compared with the results of FF. The model created has 8 pits where the Revenue Factor moves between 0.3 and 1.

4.4.2 Open pit Schedule Parameters

Each nested pit is evaluated as a final pit. For that purpose the schedule graphs are created using different production targets trying to understand the value of the various sizes of open pits in this deposit. Not only aiming for a large pit associated with a large capital investment but also assessing a small one with focus on high grades working with a lower CAPEX. Table 5 describes the inputs used for the Open Pit Schedule Loop component.

Table 5 Values used on Open Pit Scheduling

Processing Limit	Value
1	1.0E7
2	1.135E7
3	1.298E7
4	1.462E7
5	2.279E7
6	2.86E7
7	3.09E7
8	4.732E7
9	5.549E7

In terms of evaluation, every pit on the nested pit list will be modelled as final pit, for this example the pit list contains 8 pits and 9 potential processing limits (associated with a specific CAPEX) so 72 scenarios for the Open Pit are created. In each case, a production schedule will be created providing detailed information per year (ore and waste tonnage and grade).

4.4.3 Caving Schedule parameters

For this particular loop, a Design of the Experiment (DOE) was used, with two parameters included on it, Premium and Production target. Five values for Production Target and three for Premium has been included in this analysis. Table 6 shows the design matrix minimum, maximum and increments for each parameter.

Table 6. Values used on DoE

Parameter	Production Target	Premium
Min.	15,000,000	0
Max.	28,600,000	10
Increment	4,650,000	5

Each Production Target is associated to one specified CAPEX, so since the dimension of the design matrix is 5 x 3, 15 alternatives for the caving schedule are going to be executed.

4.4.4 Combined results of multiple execution runs.

Based on the review information, 72 scenarios for Open Pit are combined with 15 potential scenarios of Caving, so 1,080 transition scenarios are considered. However, since pits 1 and 2 don't have enough material to be considered as final pits, therefore only 810 scenarios are executed. **Error! Reference source not found.** describes an example of the combination of Open Pit and Caving tonnage and the cash flow calculated per period whilst allocating capital costs at the beginning of each operation based on the production target used. As a rule for this simulation the caving operation starts one period before the Open Pit operation finishes.

In order to be able to review the best combination of production parameters for each operation, the results are grouped used the combined production target for each operation. Based on this grouping for each combination of production target, 18 scenarios are evaluated (the combination of Premium for caving operation, final pit and footprint allocation). **Error! Reference source not found.** shows and example of these group.

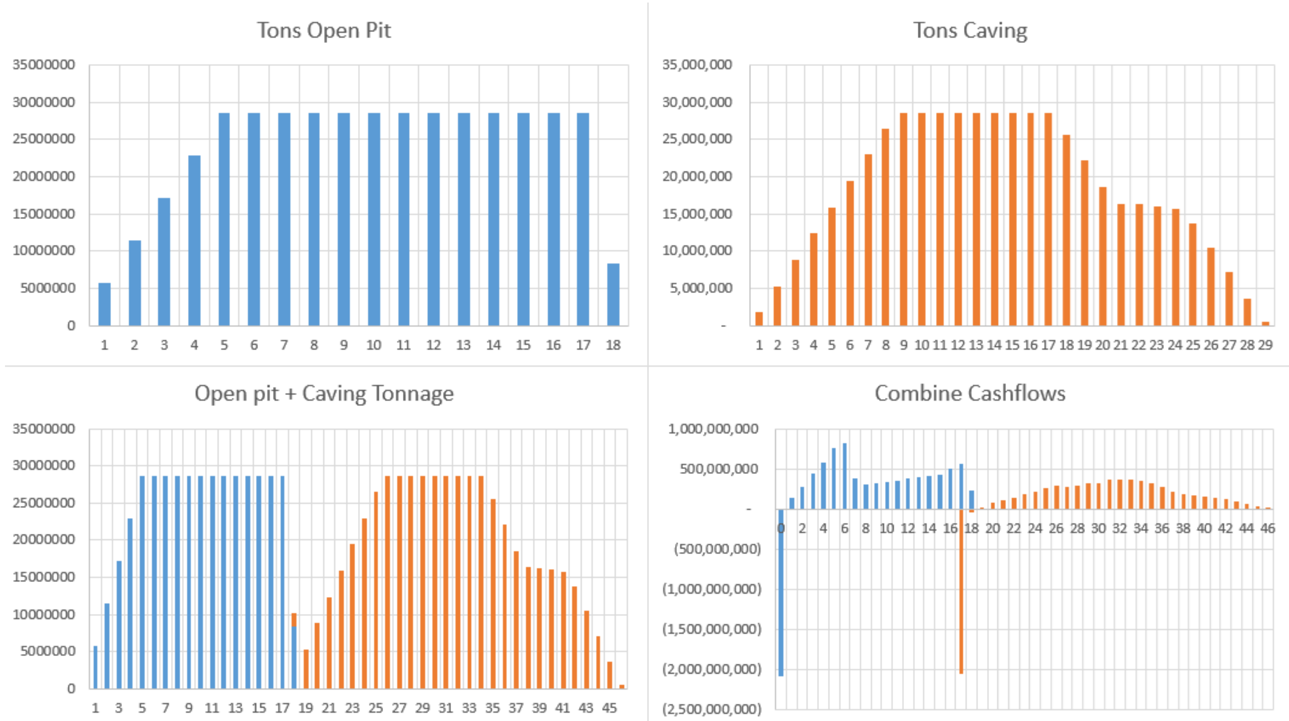

Figure 15 Transition Open pit to Caving, tonnage and cash flow combination.

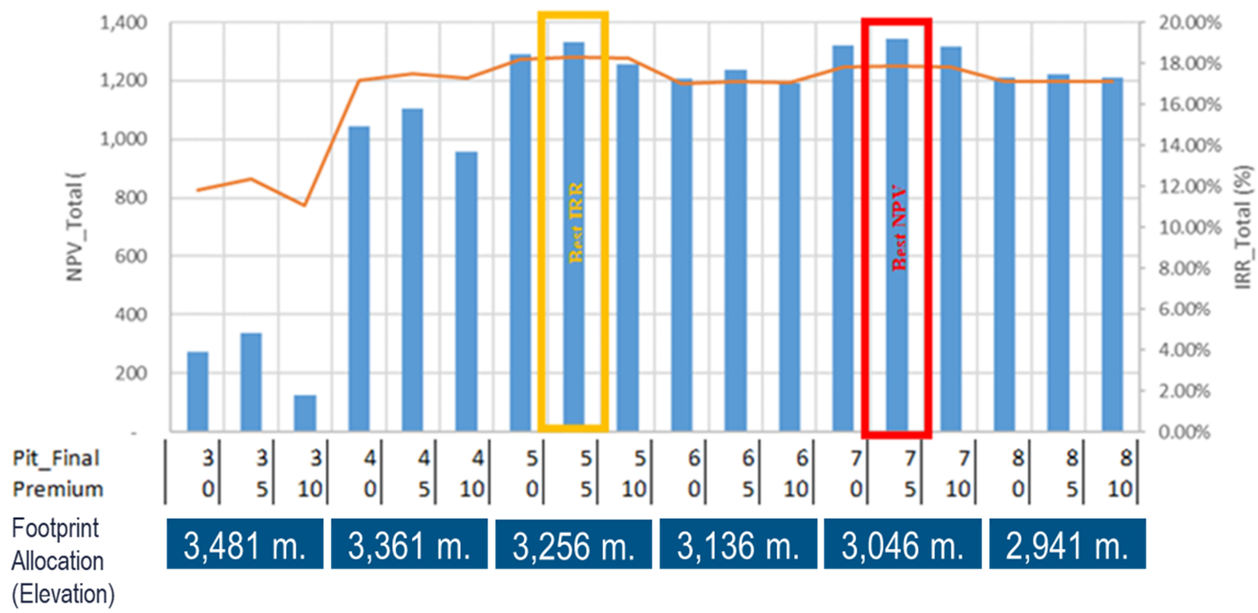

Figure 16 Example of results of scenarios grouped by production target.

From these results its possible to conclude:

The best NPV was obtained from pit 5 as the final pit, with 30.97Mt/year and 10Mt/year as the production targets for Open Pit and Caving operations respectively and a Premium 10USD/t. This NPV could be a result of the large open pit mine with a higher production target (and CAPEX for open pit operation) that accelerated the financial return of this operation meanwhile for caving operation the focus will be on the high grades portion so a lower CAPEX for underground is required.

The best IRR was achieved from pit 4 as the final pit, 11.35Mt and 10Mt as yearly production targets for the Open Pit and Caving operations respectively and a premium of 10USD/t. In this case, both operations are aiming for a smaller mine, a smaller nested final pit is required and the caving mine is reduced in size, targeting the highest grade material; therefore, the capital invested is lower, maximising the IRR.

Error! Reference source not found. shows an example of the detailed results obtained for the combination of input where it is possible to see NPV, IRR, CAPEX, tonnage, Cu & Mo grade and years of total production estimated.

Based on the best NPV and IRR obtained from each pair of production targets for each operation a hill of value was created for each Financial KPI (**Error! Reference source not found.**). This 3D and the projection in 2D is the best graphic method to display results where:

X-axis: Production target for the Cave mine, Y-axis: Production target for the Open Pit mine, and Z-axis: NPV and IRR, respectively.

Feasible solutions that optimize both NPV and IRR can be identified within specific ranges in both key performance indicators (KPIs). This enables a more focused analysis by narrowing down the study area. Additionally, the approach offers alternatives that allow the combination of NPV and IRR to maximize both objectives.

Additional analysis could be performed using all sets of results from this model to better understand the potential correlation between inputs and outputs obtained from 2D statistics analysis; an example is shown in **Error! Reference source not found.**.

Premium	CAPEX_OP	Pit_analisis	Produccion_cav	Produccion_OP	CAPEX_Caving	IRR	Ley_cu_total	Ley_mo_total	LOM	Periodos_Targe	Periodos_Targe	Tonelaje_Total	VAN
0	2,240,441,200	5	19,300,000	30,970,000	(1,388,544,647)	18.34%	0.461	0.019	54	12	20	974,150,846.31	1,358,531,777.16
0	2,240,441,200	5	23,950,000	30,970,000	(1,721,794,647)	18.22%	0.461	0.019	46	12	12	974,151,939.87	1,340,323,355.63
0	2,240,441,200	5	28,600,000	30,970,000	(2,055,044,647)	18.04%	0.461	0.019	45	12	9	974,152,201.41	1,292,106,898.17
5	2,240,441,200	5	10,000,000	30,970,000	(722,044,647)	18.65%	0.493	0.021	54	12	20	717,901,291.34	1,432,523,992.98
5	2,240,441,200	5	14,650,000	30,970,000	(1,055,294,647)	18.60%	0.493	0.021	44	12	10	717,901,289.94	1,448,336,181.48
5	2,240,441,200	5	19,300,000	30,970,000	(1,388,544,647)	18.52%	0.493	0.021	41	12	8	717,901,705.00	1,436,132,739.99
5	2,240,441,200	5	23,950,000	30,970,000	(1,721,794,647)	18.40%	0.493	0.021	40	12	6	717,902,546.78	1,405,328,984.47
5	2,240,441,200	5	28,600,000	30,970,000	(2,055,044,647)	18.20%	0.493	0.021	36	12	-	717,902,610.83	1,338,227,657.36
10	2,240,441,200	5	10,000,000	30,970,000	(722,044,647)	18.76%	0.500	0.021	41	12	7	574,537,001.17	1,462,409,238.41
10	2,240,441,200	5	14,650,000	30,970,000	(1,055,294,647)	18.68%	0.500	0.021	34	12	2	574,537,051.04	1,442,736,603.78
10	2,240,441,200	5	19,300,000	30,970,000	(1,388,544,647)	18.54%	0.500	0.021	33	12	-	574,537,099.84	1,391,435,510.56
10	2,240,441,200	5	23,950,000	30,970,000	(1,721,794,647)	18.35%	0.500	0.021	32	12	-	574,537,267.51	1,323,920,978.96
10	2,240,441,200	5	28,600,000	30,970,000	(2,055,044,647)	18.13%	0.500	0.021	32	12	-	574,537,267.51	1,251,396,069.46
0	3,367,937,200	5	10,000,000	47,320,000	(722,044,647)	14.68%	0.461	0.019	74	5	45	974,150,409.84	893,723,591.76
0	3,367,937,200	5	14,650,000	47,320,000	(1,055,294,647)	14.60%	0.461	0.019	59	5	30	974,150,293.69	921,188,747.62
0	3,367,937,200	5	19,300,000	47,320,000	(1,388,544,647)	14.47%	0.461	0.019	49	5	20	974,150,845.31	923,113,209.27
0	3,367,937,200	5	23,950,000	47,320,000	(1,721,794,647)	14.27%	0.461	0.019	41	5	12	974,151,938.87	893,788,364.31
0	3,367,937,200	5	28,600,000	47,320,000	(2,055,044,647)	13.91%	0.461	0.019	40	5	9	974,152,200.41	816,135,277.40
5	3,367,937,200	5	10,000,000	47,320,000	(722,044,647)	15.08%	0.493	0.021	49	5	20	717,901,290.34	1,042,278,412.77
5	3,367,937,200	5	14,650,000	47,320,000	(1,055,294,647)	15.05%	0.493	0.021	39	5	10	717,901,288.94	1,067,744,100.47
5	3,367,937,200	5	19,300,000	47,320,000	(1,388,544,647)	14.93%	0.493	0.021	36	5	8	717,901,704.00	1,048,090,335.92
5	3,367,937,200	5	23,950,000	47,320,000	(1,721,794,647)	14.70%	0.493	0.021	35	5	6	717,902,545.78	998,480,579.62
5	3,367,937,200	5	28,600,000	47,320,000	(2,055,044,647)	14.28%	0.493	0.021	31	5	-	717,902,609.83	890,413,221.28
10	3,367,937,200	5	10,000,000	47,320,000	(722,044,647)	15.33%	0.500	0.021	36	5	7	574,537,000.17	1,090,408,899.39
10	3,367,937,200	5	14,650,000	47,320,000	(1,055,294,647)	15.19%	0.500	0.021	29	5	2	574,537,050.04	1,058,725,924.58

Figure 17 Summary results of scenarios.

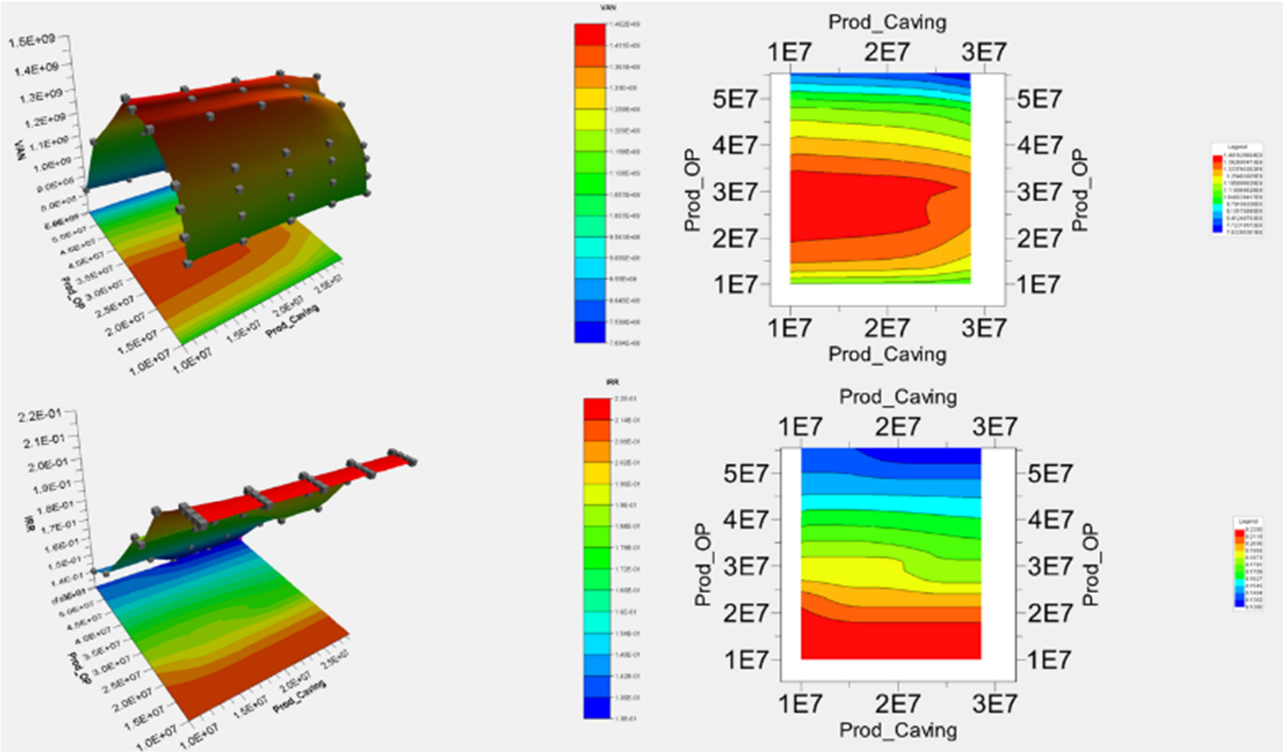

Figure 18 Hill of Value for NPV and IRR for combination of Production target for OP and Caving operation.

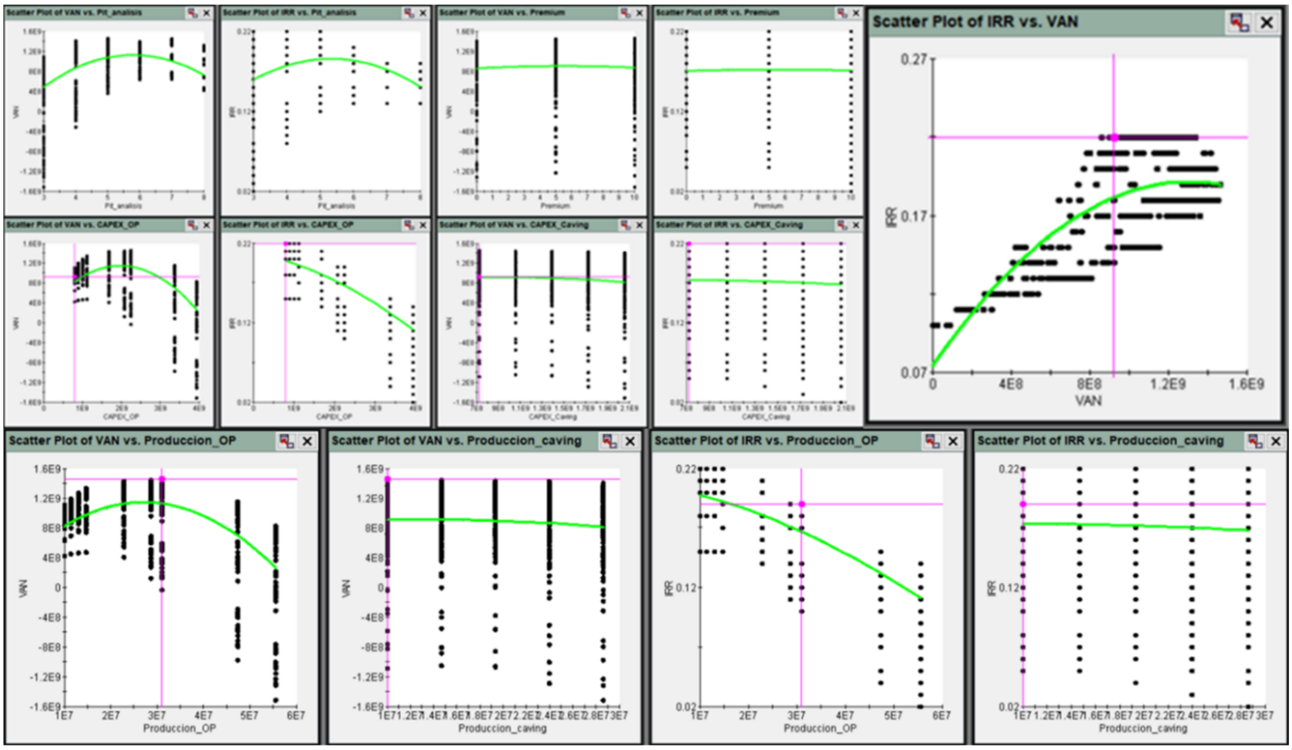

Figure 19 2D Scatter plots.

The NPV and IRR results show a non linear correlation, that allows the author to keep exploring alternatives that aim to maximize both KPIs at the same time.

The results are strongly conditioned by the performance in the open pit operations. This is mainly due to two factors: first, the influence of the time variable in the calculation of the cash flows of the joint scenarios, the caving operation is only executed at the completion of the Open Pit operation, so the CAPEX of the Open Pit operation and the subsequent cashflows returns take a greater weight on NPV calculation. In addition, the CAPEX of the caving operation is paid, in part, by the cash flow obtained by the Open Pit operation, so the effect of the financial returns of the caving operation are minimized.

The selection of pits 5 to7, as the final pits, minimizes the variance in the NPV & IRR results.

5 SUMMARY

The presented model effectively analyzed the selection of the best combination of Open Pit and Caving operation through multiple scenario simulations giving the mine planner visibility of the feasible scenario alternatives. 810 scenarios were simulated in 1.17 days, and the summarized results for the Case Study are shown in Table 7.

Table 7 Joint production plan summary results

	Base Case	Max NPV	Max IRR
Prod Caving (Mt)	28.60	10.00	10.00
Prod OP (Mt)	28.60	30.97	11.35
VAN (Mt)	1,321	1,462	1,195
Premium (USD/t)	0	10	10
CAPEX_OP (MUSD)	2,077	2,240	887
CAPEX_UG (MUSD)	2,055	722	722
Final Pit	5	5	4
Footprint Finder Elevation (m)	3,256	3,256	3,361
IRR (%)	18.165%	18.759%	22.472%
Cu (%)	0.461	0.500	0.545
Mo (%)	0.019	0.021	0.022
LOM (years)	46	41	49
years of full production OP	13	12	22
years of full production UG	9	7	7
Tonnage (Mt)	974	575	410

The NPV and IRR were calculated for the traditional approach using the same criteria as the rest of the simulated scenarios.

Therefore, targeting production of 28.6 Mtpy for both operations requires a significant capital invested upfront, which is reflected in a lower NPV and IRR reported. The scenario that maximized NPV used a marginally higher production target for the Open Pit operation, compared with the base case. In this way, even when the CAPEX increases slightly, the production of the open pit is accelerated and increased the NPV coming from this portion and ultimately from the joint operations.

Similarly, the scenario that maximized IRR is able to achieve it’s financial KPIs based on having a smaller operation that requires a lower capital investment.

6 CONCLUSION

The presented workflow is able to give an answer to the optimal joint production plan by simulating multiple scenarios, that increase the visibility for the mine planner or decision maker using financial metrics that allows comparisons between the multiple scenarios and understanding the project's financial returns.

In this instance, the model exhibited enhancement in both Net Present Value (NPV) and Internal Rate of Return (IRR) through simulations of multiple scenarios. These simulations were defined using inputs such as production targets for open pit and caving operations, shut-off grade, and capital costs. By doing so, it illustrates the efficacy of this alternative optimization method compared to conventional approaches. This is achieved by uncovering possibilities that were not initially considered, thus presenting viable and appealing alternatives in terms of final pit selection, footprint size, mine plan, and strategic design. Ultimately, this enables the identification of optimal options prior to undertaking detailed work.

This approach yields a more accurate representation of value. By utilizing 2D and 3D data analysis, such as the HoV map, it enhances comprehension of the relationships between inputs and outputs. This facilitates easy summarization and comparison of scenarios, thereby aiding in the assessment of robustness and decision-making processes.

To summarize, the automated workflow and optimization elements introduces a new methodology capable of returning optimal joint production plans for transition scenarios. It consolidates individual workflow stages (assessment and production scheduling of each operation, results integration, and economic analysis) and streamlines the visualization and analysis of numerous scenarios through embedded optimization logic.

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