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Optimising shut-off value methodology for enhanced economic viability in sublevel caving: a case study of the Alemão Project

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Abstract

Large-scale underground mining projects typically require substantial upfront capital investments for mine development and supporting infrastructure. However, these capital expenditures are often excluded from shut-off grade calculations used in mine design and mineral resource evaluation. As a result, the application of conventional fixed shut-off grade methodologies may lead to negative cash flows during the early stages of operation, potentially compromising project feasibility.

The impact of capital costs becomes even more significant in projects with demanding minimum return requirements, where economic performance is highly sensitive to the timing of cash flow generation, even when operating and sustaining costs remain moderate. This was the case for the Alemão Project.

This paper aims to discuss the shut-off grade methodology used to achieve the required rate of return. The methodology considers a variable shut-off grade for the different mine levels that prioritises extracting high grades in the first years of operation and recovering low grades later in the mine life. Along with this strategy, the production footprint size and extraction rate were optimised, aiming to maximise the project's net present value.

Keywords: *sublevel caving, economic evaluation, optimisation*

1 Introduction

1.1 Project location and geological setting

The Alemão copper-gold deposit is located beneath the former Igarapé Bahia gold mine, in the municipality of Parauapebas, approximately 45 km west of the N4E iron mine and 125 km southwest of the city of Parauapebas in Northern Brazil (Figure 1).

The deposit is situated in the northern sector of the Carajás Mineral Province and comprises an Archaean volcano-sedimentary sequence metamorphosed under lower greenschist facies conditions. This sequence hosts polymetallic Cu-Au-Ag-Mo mineralisation and outcrops within an area dominated by the Águas Claras Formation. Structurally, the deposit exhibits a northeast orientation, parallel to the Acampamento Norte body. The lithological units are grouped into two main domains:

- Upper (sedimentary) domain: dominated by volcaniclastic and clastic metasedimentary rocks (metarhythmites, metasiltstones and metagreywackes), along with chemical rocks such as cherts and banded iron formations.

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- Lower (volcanic) domain: composed mainly of mafic to intermediate metavolcanic rocks, interbedded with volcaniclastic units and subordinate iron formations.

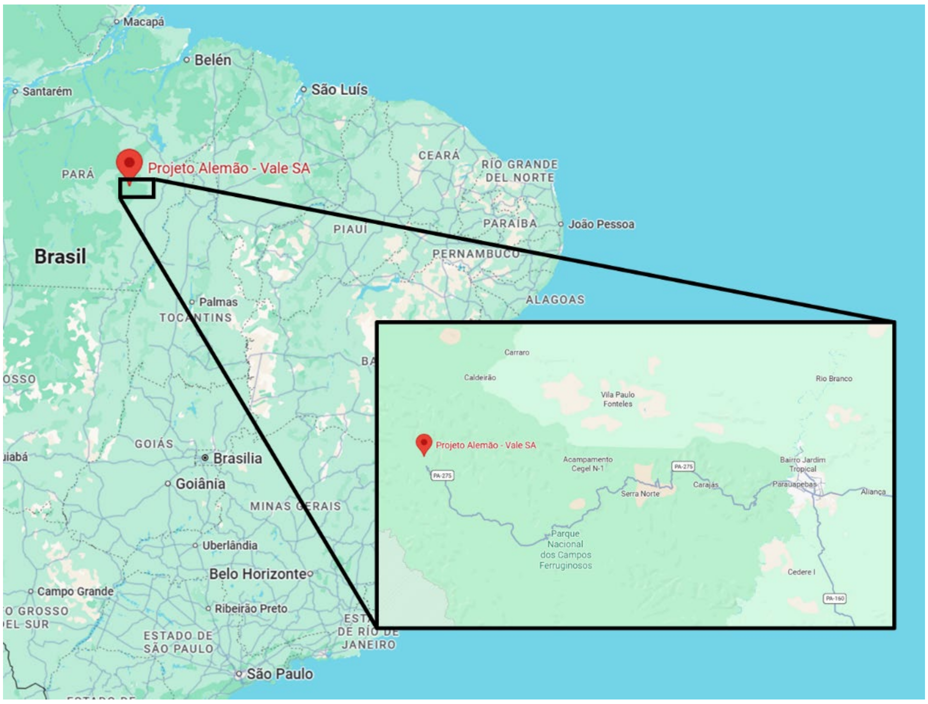


Figure 1 Location of Alemão Project

1.2 Operational background

The Igarapé Bahia gold mine was exploited by open pit methods for approximately 12 years, with a processing capacity of 5,500 tpd using relatively small-scale equipment. The pit is 255 m wide and almost 90 m deep.

Currently, Vale S.A. is advancing studies for the underground development of the Alemão Project. In previous stages, a mixed mining approach was defined considering sublevel caving for the main Alemão sector and sublevel stoping for the Acampamento Sul and Encantado sectors, as well as remaining areas of the previous sector (Figure 2).

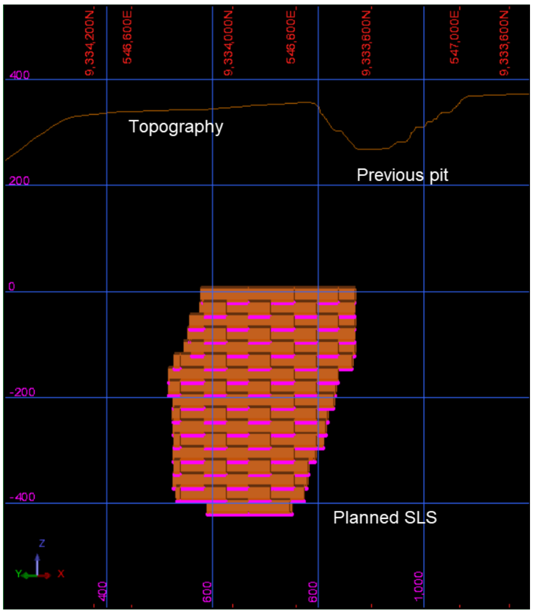


Figure 2 Vertical section of open pit and planned sublevel cave

1.3 Sublevel caving parameters

The mine design is based on a large-scale sublevel cave system, involving the extraction of vertical columns of material through induced caving. The extraction geometry is designed to ensure sufficient hydraulic radius (50 m) to promote caving propagation.

Key design parameters include:

- level spacing: 25 m
- drift spacing: 15 m
- drift dimensions: 5.0 × 4.5 m
- use of large-capacity load–haul–dump equipment
- radial hydraulic drilling.

In specific areas, sublevel stoping is applied as a complementary method, particularly where geotechnical or geometrical constraints require it. Figure 3 shows the proposed design.

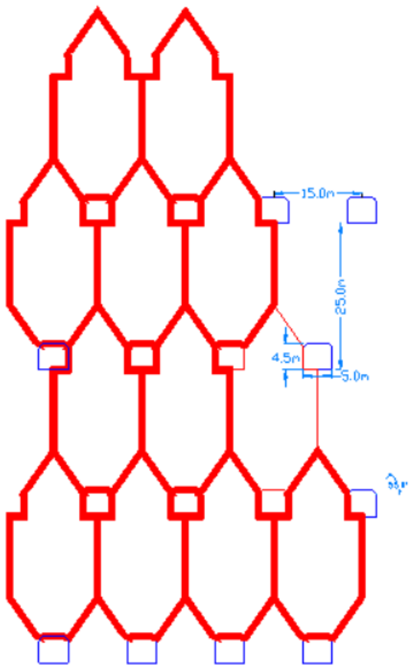


Figure 3 Alemão rings and development design

1.4 Dilution model

The dilution model is based on the volumetric mixing approach implemented in the PCSLC software, derived from Laubscher's concepts. This methodology accounts for the interaction between ore and waste during gravitational flow. Evaluation units are rings defined as 15 × 25 m blocks with 5 m vertical increments. The recoverable material depends on the mixing intensity, which determines the balance between ore recovery and dilution.

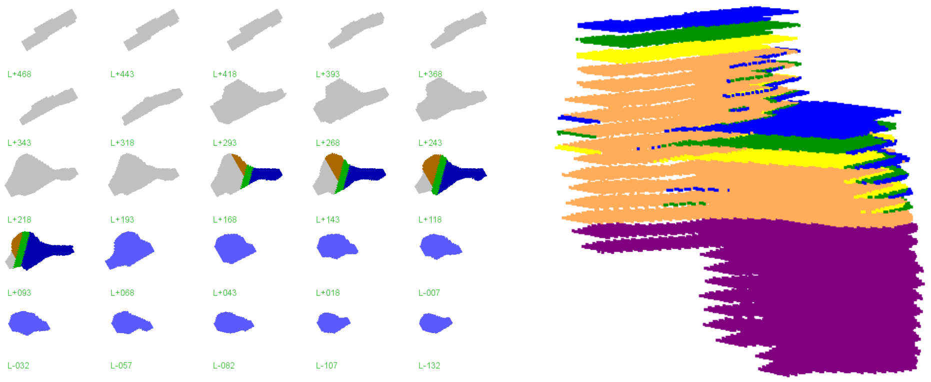
Key operational considerations include:

- limiting extraction in upper levels to control early dilution and to minimise airgap formation prior to the cave propagating to surface
- restricting extraction in low-grade zones (~30%)
- allowing extraction greater than 100% in high-grade zones or in cases of positive dilution.

1.5 Previous model and limitations on the regular sublevel cave evaluation

1.5.1 Step-out model – base case

The base case model consisted of 25 sublevels, starting from elevation 468 m down to −132 m. The sequence begins from the left sector of the footwall, and the mining front advances using a flat shape. Figure 4 shows the geometry of each level and the mining direction.



(a) (b)

Figure 4 (a) Shapes and mining direction of 'step' model for Alemão sublevel cave; (b) Isometric view of Alemão sublevel cave (right), with each point representing a ring

Figure 5 shows the ore blocks with positive economic value and the corresponding rings for each of the first 9 levels in detail. The first 3 levels comply with geomechanical constraints, particularly the minimum span (50 m) and the requirement to maintain the same shape. Beyond the third level, this restriction is relaxed, allowing the shape and size of subsequent levels to be adjusted according to the deposit's mineralisation, thereby minimising the inclusion of waste (beneficial tonnes in USD/t is less than zero).

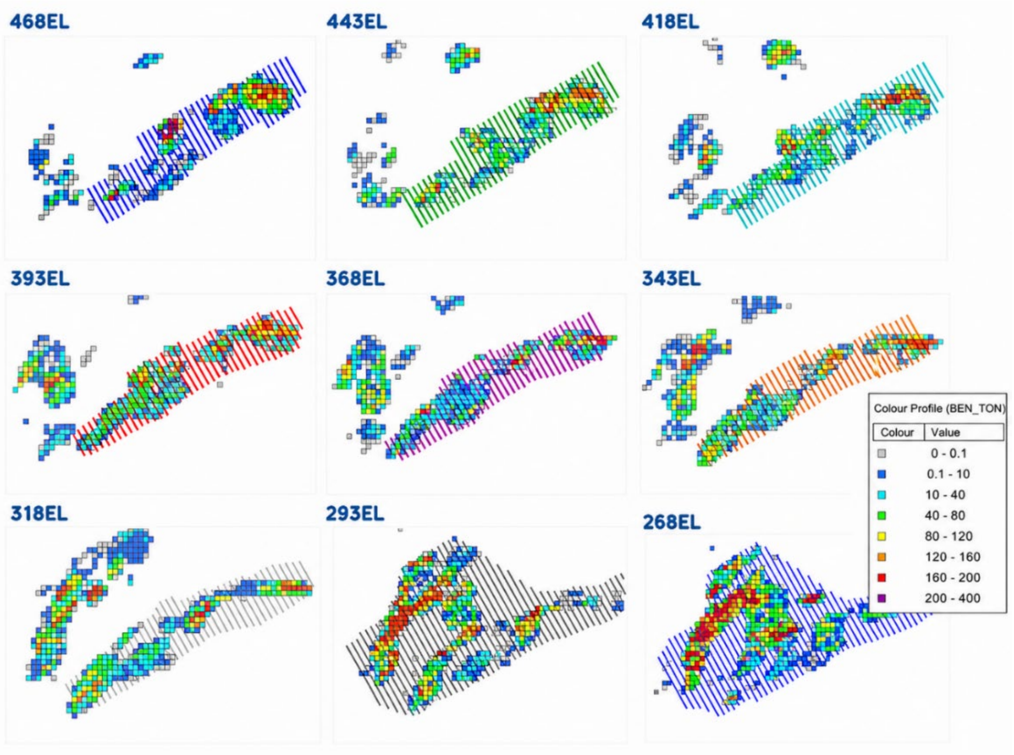


Figure 5 Alemão sublevel cave footprint for levels 468–268, blocks display beneficial tonnes (USD/t) greater than zero

The life of mine is 21 years, with estimated resources of 103 Mt grading at 1.39% Cu and 1 ppm Au. The nameplate production rate is 6 Mtpa following a 5-year ramp-up period. Variability in the production rate in years 5–9 is due to the difficulty of maintaining the production rate while respecting the mining sequence and shape, given the change in geometry between the first 7 levels and the subsequent ones.

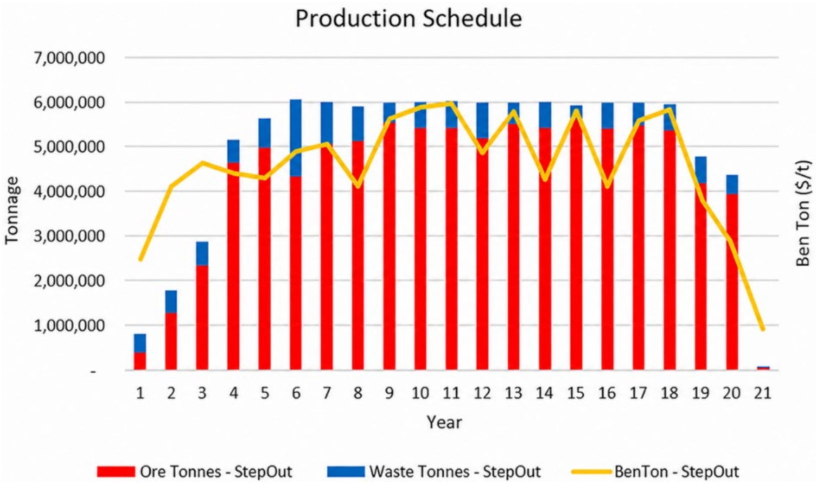


Figure 6 Production plan for Alemão sublevel cave model using 'step-out' layout

In addition to the difficulty of maintaining production during years 5–9, subsequent geomechanical feasibility analyses showed that the transition between levels 318 and 293 hindered caving propagation. Based on this, a second model was developed, starting from level 268. The selection of this level is supported by the grade distribution observed in the rings with depth (Figure 7), where a high-grade core of copper and gold is located.

The resources excluded from this new model will be recovered using sublevel stoping.

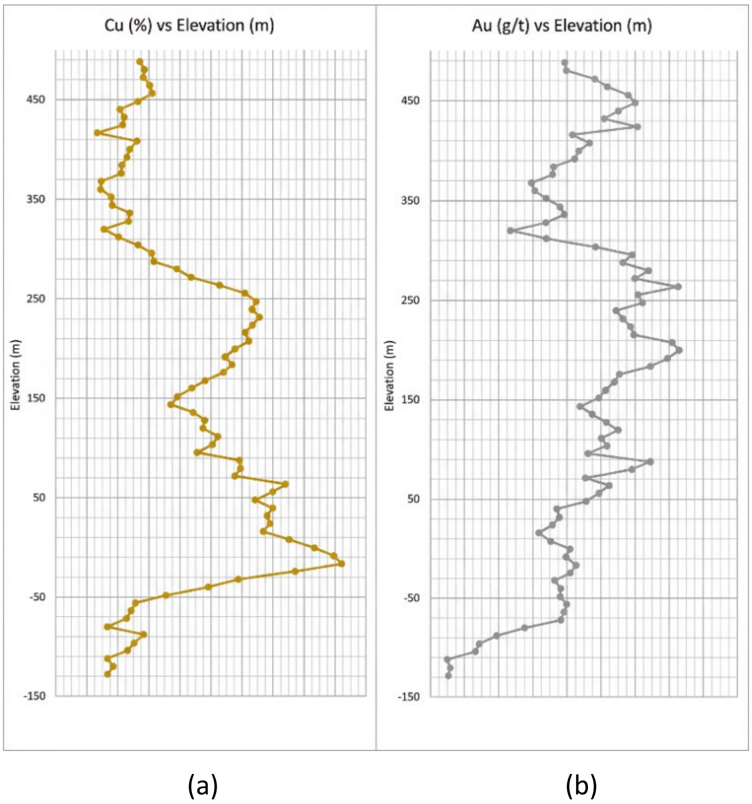


Figure 7 Rings showing copper (a) and gold (b) in situ grades profile by elevation, with grades increasing from left to right

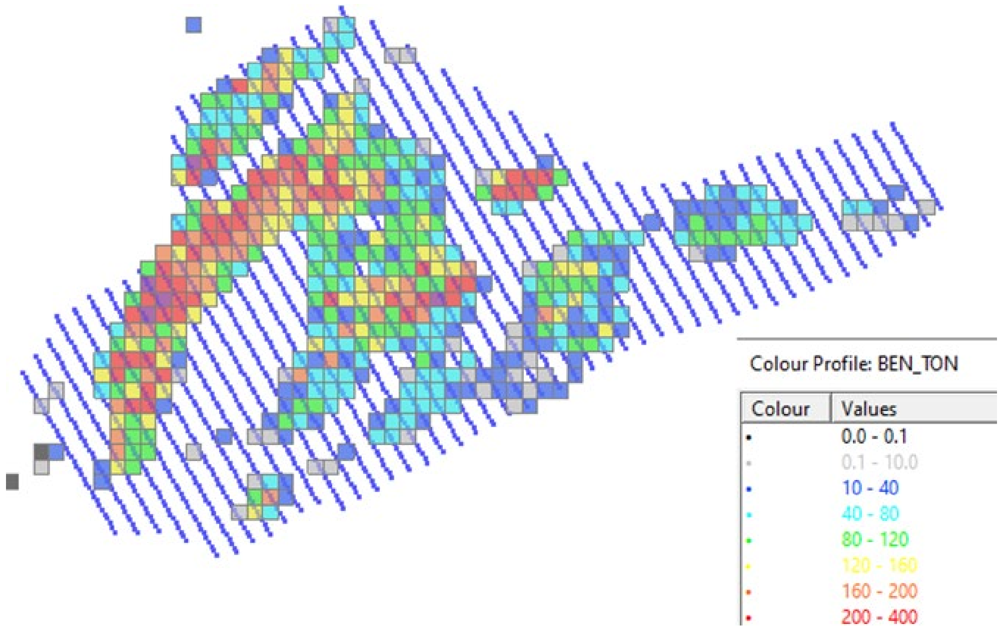


Figure 8 Alemão sublevel cave model using 'step' footprint at level 268, blocks display beneficial tonnes (USD/t) greater than zero

One of the key challenges in planning and optimising the production schedule for the Alemão operation is dealing with the irregularity of the mineralisation, particularly waste inside the footprint layout. Sublevel caving operations are generally designed for more massive and continuous orebodies; however, this is not the case at Alemão. Figure 8 shows an example for level 268: there are rings located in areas where the block benefit per tonne is negative. These correspond to pure dilution rings, which must still be extracted at a minimum of 30% to comply with geomechanical constraints required for caving propagation.

When production schedules are generated based on a unique shut-off value for ring closure – typically defined using operational costs (mining and processing) – cash flow may become negative, as capital expenditures are not explicitly considered in the optimisation process.

Therefore, it is necessary to adopt a methodology that improves cash flow generation and enhances economic key performance indicators (KPIs) such as net present value (NPV) and internal rate of return (IRR).

2 Variable shut-off grade as an improvement in the economic key performance indicator

2.1 Footprint Finder to define the layout and optimise the extraction percentage

As previously stated, the Alemão deposit exhibits irregular mineralisation, generating waste zones within the proposed sublevel cave layout. One approach to minimise the impact of waste on early project cash flows is to implement a variable shut-off grade profile for each level during the optimisation process in PCSLC Footprint Finder (PCSLC-FF).

PCSLC-FF builds an economic model using inputs such as metal prices (increased in this evaluation by 13% for gold and 15% for copper relative to the base case, based on the new economic model), operating costs, production targets, mining direction and evaluated levels. It then defines the economic footprint and performs an optimisation of extraction percentages through multiple iterations, determining for each block (and subsequently rings) the optimal combination that maximises ore recovery while minimising dilution.

The previous model was developed using the standard methodology, with a single shut-off value equal to the sum of mining and processing costs. Although this evaluation yields a positive NPV, it does not achieve the required IRR, and therefore an alternative optimisation approach is required.

Based on this, and with the objective of improving early cash flows, a variable shut-off decreasing by levels (Table 1), higher than the actual operating cost for the first 14 levels, is introduced. This cost is used by Footprint Finder to construct the economic model, define the economic interest of each zone, and generate iterations that optimise extraction percentages within specified ranges.

Table 1 Variable shut-off grades used for each elevation in Alemão sublevel cave

Level	Average extraction	Unique shut-off (USD/t)	Variable shut-off (USD/t)
L+268	40%	40.29	80
L+243	49%	40.29	75
L+218	56%	40.29	70
L+193	67%	40.29	70
L+168	70%	40.29	70
L+143	79%	40.29	70
L+118	108%	40.29	65
L+093	168%	40.29	65
L+068	184%	40.29	65
L+043	189%	40.29	60
L+018	191%	40.29	60
L-007	192%	40.29	55
L-032	188%	40.29	55
L-057	193%	40.29	55
L-082	190%	40.29	40.29
L-107	184%	40.29	40.29
L-132	190%	40.29	40.29

Using Isight, an automated and iterative PCSLC-FF workflow was developed, following a methodology similar to that presented by Villa (2022) and Soto (2024). A total of 200 simulations were performed to identify the optimal set of shut-off values.

The resulting scenarios were evaluated using the discounted cash flow – the main KPI, verifying whether the shut-off values are decreasing by levels and the generated production schedule achieved the required tonnage targets. Table 2 shows the minimum and maximum values analysed.

Table 2 Variable shut-off grades used for each elevation in Alemão sublevel cave

Parameter	Maximum	Minimum	Interval
Shut-off grade	100	50	5
Reduction interval	5	1	1

As an example, if level 268 uses USD 90/t as the shut-off value, the below level's shut-off value must – as a maximum – be the same value, after running PCSLC-FF If the target tonnage for the first periods (where that level is active) is not achieved, the scenario is defined as invalid, the initial shut-off value is reduced by the reduction interval and the PCSLC-FF workflow runs again (Figure 9).

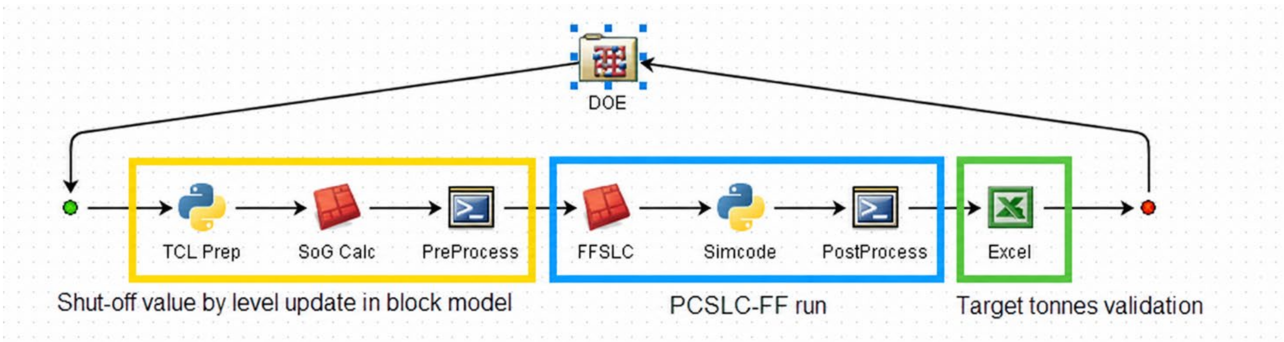


Figure 9 Isight workflow used for the variable shut-off validation

For example, in the upper level, a minimum extraction of 40% is applied to rings that are economically positive under this new definition. Therefore, during the early periods, extraction is focused on high-grade material where cash flow offsets the inclusion of waste rings, while also leaving remnant material to be recovered at lower levels through the natural dilution mechanism of the method.

As mining progresses deeper, the artificial cost gradually decreases. In addition to targeting high-grade zones at each level, the plan incorporates remnant material from the upper levels, resulting in dilution that is not necessarily negative and can contribute positively to the value of the lower rings.

The optimisation of extraction percentages is performed on a block-by-block basis (Figure 10), where the planner defines minimum and maximum extraction ranges for each potential level. Through iterative adjustments – by increasing or decreasing the initial extraction percentages – an optimal combination is achieved that maximises discounted cash flow.

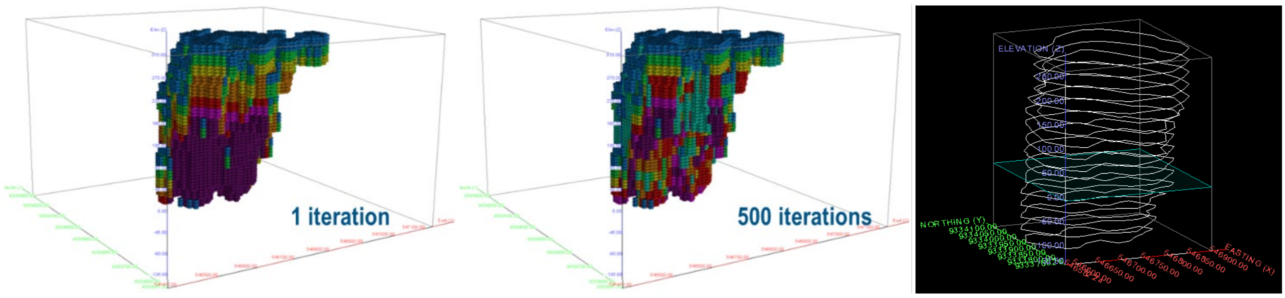


Figure 10 Differences in the allocation of extraction percentages assigned to blocks based on the number of iterations in the Alemão sublevel cave model, along with the polygons representing the boundaries of each level

2.2 Production schedule results

The resolution of Footprint Finder results corresponds to the block model level; therefore, to formalise the production plan, it must be modelled at the ring level. For this purpose, PCSLC is used with the following considerations:

- economic model defined in the Footprint Finder evaluation
- footprint boundaries for each level
- optimised extraction percentages
- minimum hydraulic radius of 70 m for the first 3 levels
- geomechanical constraints for minimum extraction percentages in the first 3 levels and waste rings
    - 40% minimum for Level 1
    - 50% minimum for Level 2

- 30% minimum for waste rings from Level 3 onwards
- 250% as maximum.

2.2.1 Production schedule results for 'reduced' model

The second model consists of a total of 16,861 rings distributed across 17 levels, from level 268 down to −132. The sequence uses the same starting point and mining direction for the production plan (Figure 11).

Due to the refined geometry, the levels are more continuous vertically, and in most cases, the shape of each lower level is contained within the footprint of the upper level, providing improved geomechanical feasibility.

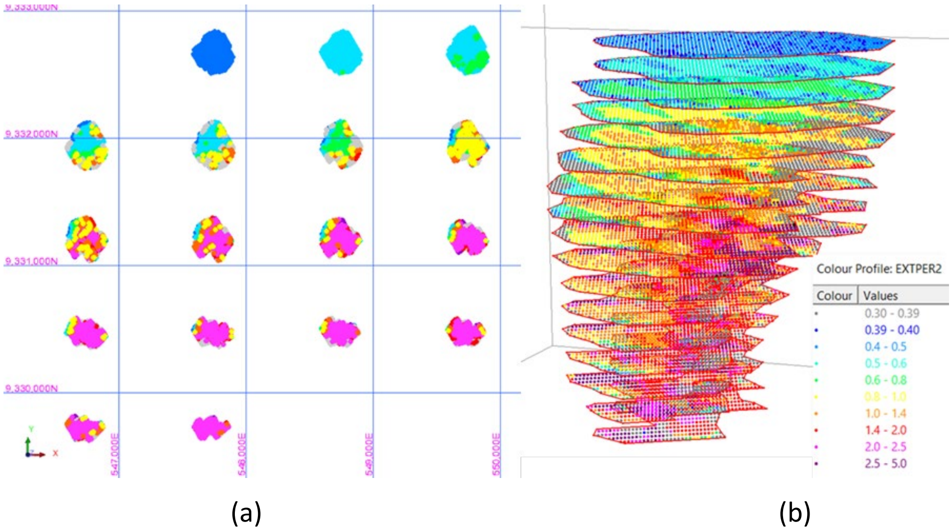


Figure 11 (a) Shapes of each level in 'reduced' model for Alemão sublevel cave; (b) Isometric view of Alemão sublevel cave, with each point representing a ring

The generated production plan considers resources of 83.4 Mt, of which 80.6 Mt correspond to ore and 2.7 Mt to waste, grading at 1.04% Cu and 0.92 ppm Au. The corresponding life of mine is 17 years, as shown in Figure 12.

Another key difference compared to the previous model is that, due to changes in geometry and level selection, the shape of the mining front remains simpler as mining progresses deeper. As a result, the production plan and sequence (Figure 13) are significantly more stable in terms of tonnage extracted per period.

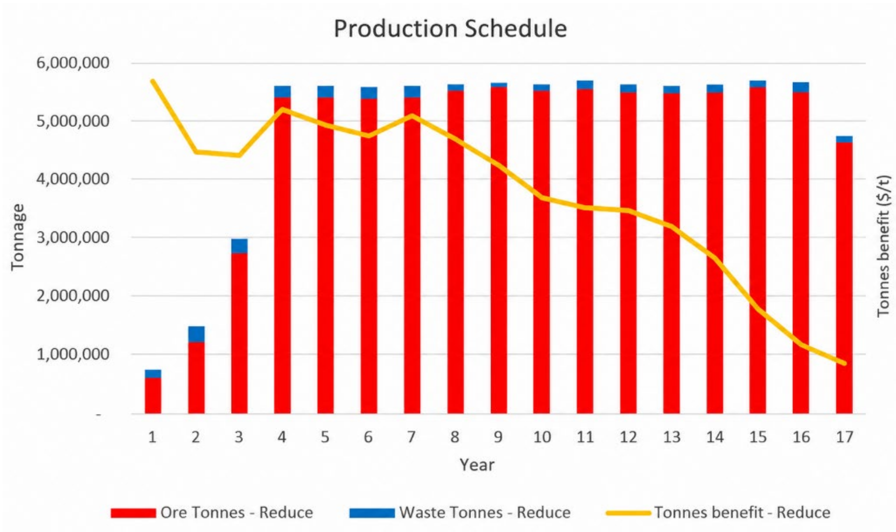


Figure 12 Production plan for 'reduced' Alemão sublevel cave model

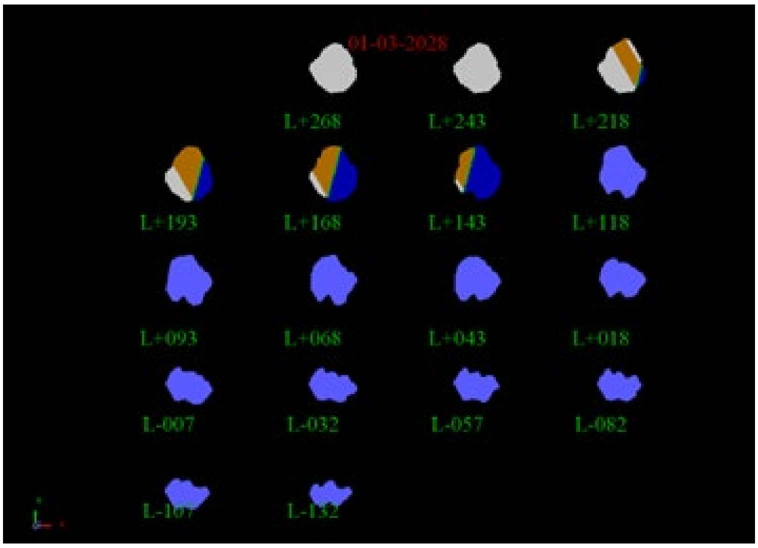


Figure 13 Mine sequence associated with the new layout for the 'reduced' Alemão sublevel cave model

The differentiation between waste and ore responds to a requirement from the client to distinguish how much of the extracted material has a positive economic value, regardless of whether the material is extracted from the active mining level or originates from upper levels as dilution.

From the grade profile over the life of mine (Figure 14), it can be observed that adjusting the extraction percentages through the variable shut-off value by level in PCSLC-FF enables accelerated extraction of high-grade zones during the early periods. As mining progresses deeper, part of the remnant material begins to positively dilute the lower levels, enriching the grade profile. As shown in the next section, this results in a more attractive model from an economic standpoint.

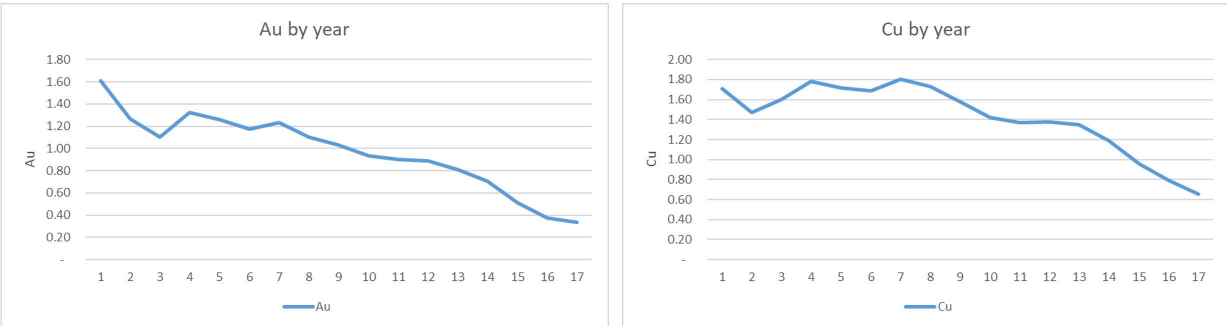


Figure 14 Gold and copper grades by year for 'reduced' Alemão sublevel cave model

3 Comparison between models

To compare the models using economic KPIs, a capex structure has been applied that is based on 2 elements derived from previous references: a fixed component and a variable component associated with ore production. These are distributed over the 3 periods prior to the start of production in the following proportions:

- Year −3: 28%
- Year −2: 39%
- Year −1: 33%.

From the recovered tonnes perspective (Figure 15), the models show a difference of 19.4%, with the base case being higher. However, when refining the comparison in terms of extracted waste and ore, 2 distinct behaviours emerge. First, ore tonnage (Figure 16) is relatively similar in both cases, with a difference of 11.2%

between scenarios. In the base case (step-out), the exclusion of upper levels is partially offset by the positive increase in metal prices in the second scenario (reduced layout).

The most significant change is observed for waste material (Figure 17). The increase in prices reduces the portion of the deposit classified as waste, while the variable shut-off strategy enables positive dilution by extracting high-grade material at each level and leaving remnant material above the real operating cost. As a result, the waste reported in the optimised scenario represents only 21.7% of that in the base case.

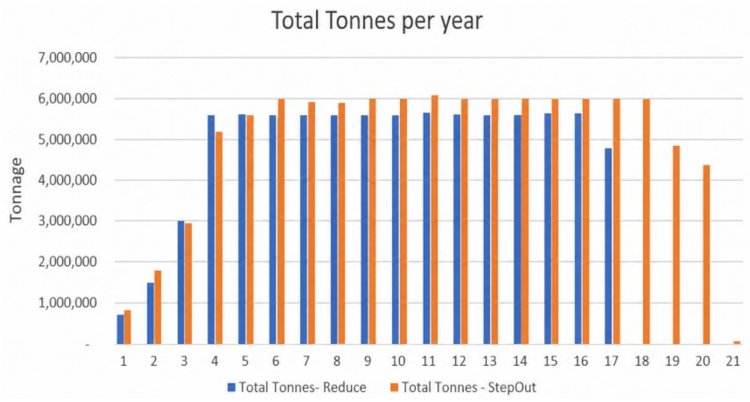


Figure 15 Total tonnes per year between model base case (step-out) and optimised model (reduced)

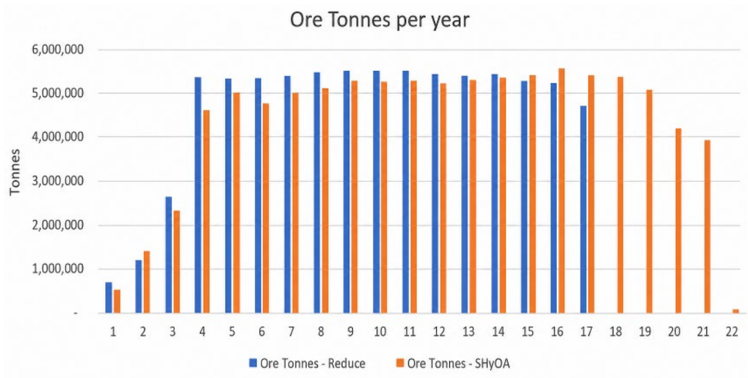


Figure 16 Ore tonnes per year between model base case (step-out) and optimised model (reduced)

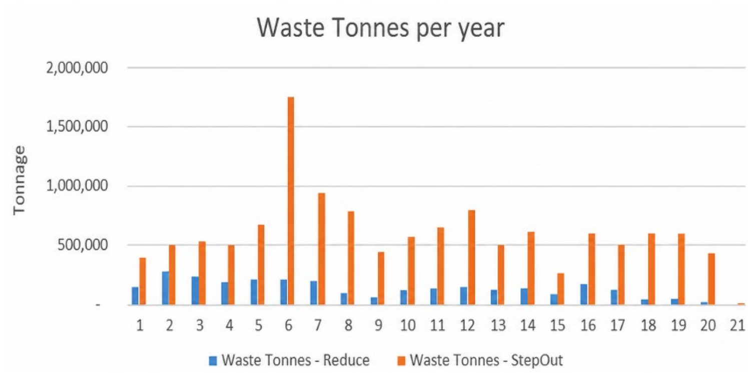


Figure 17 Waste tonnes per year between model base case (step-out) and optimised model (reduced)

The application of a variable shut-off strategy has a clear impact on the grade profiles' project value over the life of mine(Figures 18 and 19). In the optimised scenario, these profiles show significantly higher values than the base case, indicating that mining starts in high-grade zones. Additionally, dilution processes generate a mixture that enhances the value of lower levels through the contribution of positive remnant material from upper levels.

From a value-per-tonne perspective, this is particularly attractive, as it implies higher cash flows during the early years compared to the base case.

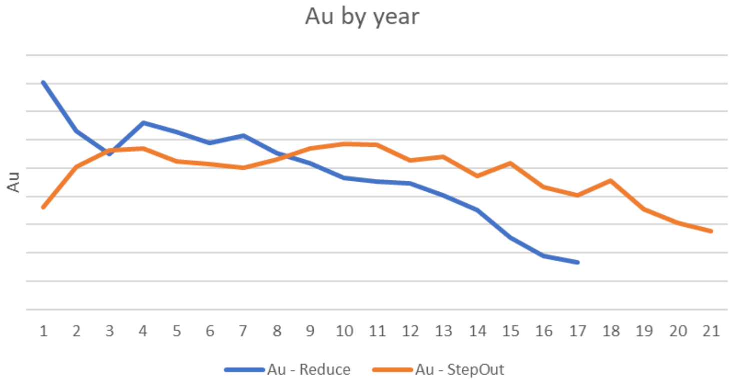


Figure 18 Gold grade per year between model base case (step-out) and optimised model (reduced)

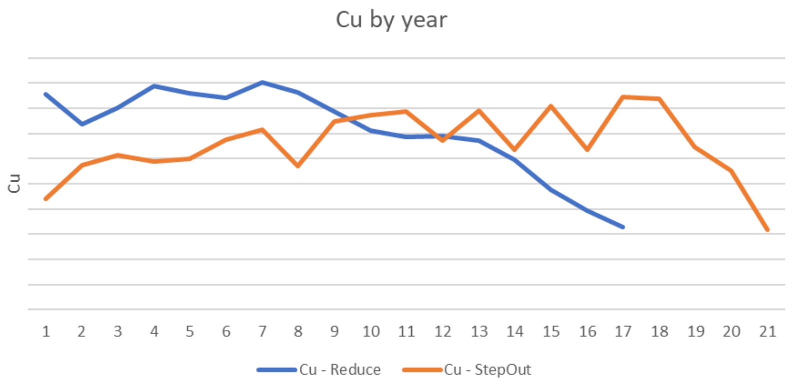


Figure 19 Copper grade per year between model base case (step-out) and optimised model (reduced)

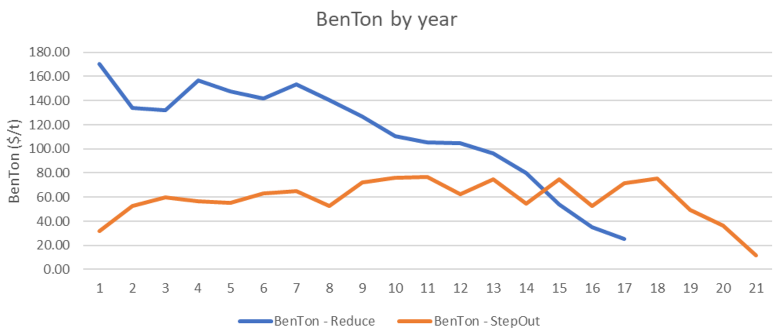


Figure 20 Beneficial tonnes (BenTon) (USD/t) per year between model base case (step-out) and optimised model (reduced)

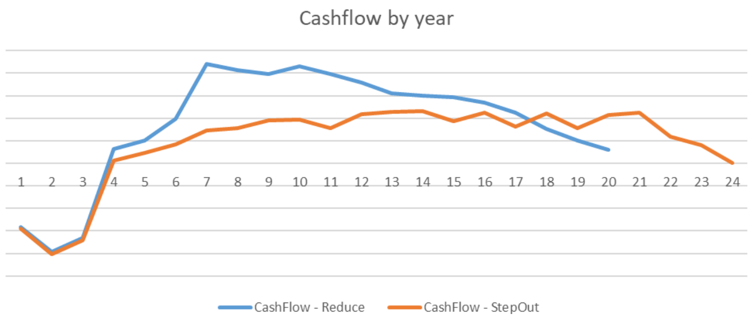


Figure 21 Cash flow per year between model base case (step-out) and optimised model (reduced)

In summary, the changes introduced to the model have generated significantly higher cash flows compared to the base case, resulting in an NPV using 9% as discount rate for the optimised model that is 15 times higher than the base case and an IRR that is twice as high. This improvement places the project above the minimum threshold, supporting its economic feasibility.

4 Conclusion

Conventional static cut-off grade approaches are inadequate for large-scale sublevel cave projects, as they do not account for capex and may lead to economically unfeasible outcomes.

The application of a dynamic shut-off grade strategy, supported by an artificial cost in the optimisation process, enables prioritisation of high-grade material in early years, significantly improving early cash flows and overall project economics.

The use of Footprint Finder to optimise layout and extraction percentages enhances dilution management and adapts the plan for grade variability, while the optimised 'reduced' model improves both geomechanical feasibility and production stability.

As a result, the proposed methodology delivers substantial increases in NPV and IRR, demonstrating its effectiveness in maximising value and enabling project feasibility in complex sublevel cave operations.

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