Caving 2026 – A van As, D Cumming-Potvin & J Wesseloo (eds)
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doi:10.36487/ACG_repo/2645_50

Pre-mix model for strategic block and sublevel caving production planning

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Abstract

Block and sublevel caving (BC and SLC) are highly productive mass underground mining methods, but performance is strongly influenced by material flow, mixing and draw. Pre-mixing of ore and waste prior to extraction is critical for controlling dilution, recovery and draw efficiency. This paper presents a practical, deterministic pre-mix model for BC and SLC operations that integrates gravity-based vertical flow and spatial awareness of drawpoint locations to estimate extraction ratios and mixed grades.

Amplify Mine Planning has implemented cave flow pre-mix formulas within Deswik Planning, streamlining the determination of step-outs and mixed grades. This simple approach enables rapid evaluation and strategic comparison of footprints and production plans for mass mining methods (e.g. BC and SLC), resulting in significant time and cost savings in the early study phase. By leveraging standard production and custom fields, the pre-mix model is transparent and auditable, providing clear strategic value at the conceptual study level.

A case study of Pan American Silver's La Colorada Skarn project demonstrates the model's application and validation. Results highlight the revealed opportunities to optimise footprint location and draw strategy, and to improve ore recovery while minimising waste inflow. The model has been peer-validated against an advanced cellular automata flow modelling tool, in which the estimated pre-mix grades agree within 1% of the counterpart flow model results. The strategic pre-mix model provides a fast, cost-effective and transparent approach for early-stage mine planning. Though the method will not replace the advanced cave flow and geotechnical assessment modelling, it enables rapid generation of production plan scenarios per mining method and footprint, and parametric and sensitivity analyses, supporting informed forecasts and decisions early in the study phase. By streamlining evaluation of the method, footprint and draw strategy, the model delivers actionable insights and economic benefits. This empowers planners to optimise BC and SLC planning and forecasting with greater confidence.

Keywords: *block caving, sublevel caving, pre-mixing model, rule-based mixing, mine planning, mass mining, production forecast*

1 Introduction

As near-surface ore deposits become increasingly scarce and depleted, underground mining methods are becoming more prevalent, driven not only by increasing mining depth but also by environmental concerns and the socio-economic challenges associated with surface mining operations. For large underground deposits containing multiple orebodies, strategic planning must evaluate numerous potential mining scenarios to determine the most economically viable development pathway. Strategic footprint evaluation plays a key role in this process as it defines the spatial extent and elevation of the mining layout, which in turn influences recoverable tonnage, grade, production sequencing and overall project economics.

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In projects where multiple orebodies varying in geometry and size exist, alternative scenarios may include different mining methods applied to individual orebodies or hybrid transitions between methods as mining progresses deeper into the deposit. The ability to rapidly generate and assess these scenarios is essential during early-stage studies, where engineers must balance production capacity, capital development requirements and long-term economic value across multiple potential configurations.

Among the most widely used underground mining methods are sublevel open stoping (SLOS), sublevel caving (SLC) and block caving (BC). SLOS is a relatively selective method selected for a stable rock condition and is often used with backfill to maintain ground stability. In contrast, SLC and BC induce controlled caving of the rock mass, allowing gravity to assist the extraction of ore. Provided that the geometry, size, continuity and rock mass conditions are suitable for gravity-assisted rock breakage, and the subsidence zone created by caving does not preclude or otherwise impact the evaluations of its use, which was the case at La Colorada with existing mine infrastructure and the discovery of new veins, caving methods remain the preferred underground mining options because they offer high productivity and the lowest mining cost per tonnage, due to relatively minimal development requirements compared to SLOS or other methods.

It is understood that one of the challenges associated with caving mining methods is the inherent mixing and dilution of material. As ore is drawn from drawpoints, broken material from surrounding waste zones and overlying portions of the cave column gradually enters the draw column, resulting in complex mixing behaviour that evolves over time. Understanding material flow and mixing during the caving and production draw is critical to estimate the caving inventory or reserve for planning purposes. Production planning of SLC and particularly BC is often seen to inherently possess higher risk of uncertainty and inaccuracy than other underground mining methods due to the less selective nature of the method and sizable 'mineable unit' to mine, as opposed to an individual stope in SLOS. This represents a larger 'black box' of not-fully-understood material breakage, mixing and flow mechanisms to deal with.

Specialised cave flow modelling and simulation are widely considered the most viable methods to simulate the caving movement, mixing behaviour and dilution entry within the cave column in the absence of continuous data measurement inside the cave. Several tools such as PCBC (Diering 2007), Itasca MassFlow which is based on REBOP logic (Pierce 2010), Power Geotechnical Cellular Automata (PGCA) (Power 2012), and Flowsim (Castro et al. 2018) are widely used by the industry. While these tools provide detailed insight into flow behaviour, they often require significant computational effort, specialised expertise and additional data preparation, making them less practical for evaluating the large number of scenarios typically required during early strategic studies. Hocking & Smith (2024) indicated that the time component of caving adds more complexity in the modelling, even with this available software. It is difficult to fully understand how the contributing factors of caving such as cave shape, material fragmentation distribution and dilution change over time, and without direct investigation inside the cave zone (i.e. using smart markers), the modelling can be computationally expensive.

This study explores the implementation of simplified pre-mix algorithms within Deswik mine planning software to approximate the effects of mixing and dilution during strategic evaluations. By incorporating mixing assumptions directly into the mine planning workflow, it becomes possible to generate diluted grades prior to scheduling and optimisation, enabling the use of advanced planning tools such as Pseudoflow for footprint determination and scheduling for production plan scenario generation. This integrated approach allows engineers to evaluate numerous mining configurations rapidly while maintaining a realistic representation of dilution effects, thereby reducing reliance on costly external simulation tools during the early stages of project evaluation. Results of this study were validated against data from Pan American Silver's La Colorada Skarn project. Pan American Silver ultimately selected the SLOS method to gain added value generated from the neighbouring vein mine expansion (Pan American Silver 2026), however, the pre-mix model evaluation supported the company's strategic decision on caving options.

2 Project context

Due to the complexity and variability of contributing factors in the mixing process it is difficult to understand the caving behaviour, particularly with limited data inside the cave itself. Thus, it is extremely important to validate the model against real data. The developed pre-mix model presented in this paper was implemented and validated using the flow-modelled production schedule and grades from the existing La Colorada Skarn project property. The property consists of three main orebodies, each with mining optionality for SLOS, SLC, BC and hybrid/transitional methods. The study streamlined scenario generation and improved mixing and dilution modelling that enabled advanced production plan optimisation.

2.1 Project background

The North American Cordillera hosts the La Colorada Skarn project property, which lies within the Sierra Madre Occidental mountains. The area's landscape consists of broad flat valleys and narrow, relatively low mountain ranges and hills with altitudes between 2,100 and 2,550 m above sea level. Located in the Zacatecas mining district (see Figure 1), approximately 100 km southeast of Durango and 155 km northwest of the city of Zacatecas, Mexico, the area has a dry to semi-dry climate. Pan American Silver has been involved with this property since 1997 and began small-scale production in early 2001, mining silver, zinc and lead from three vein mines. From 2001 to 2025, Pan American produced more than 109 million ounces (Moz) of silver, 172 kilotonnes (kt) of zinc and 92 kt of lead from the Candelaria, Estrella, and Recompensa vein mines using SLOS and cut-and-fill mining methods.

A large polymetallic skarn deposit was discovered in 2018 from a brownfield exploration drilling program. The skarn mineralisation zone is located between 700 to 1,900 m below surface, extending some 1,800 m in a northeast–southwest direction and 650 m in a northwest–southeast direction. Skarn mineralisation differs from the vein mine, being more complex and disseminated in nature, and lends itself to bulk mass mining, which includes SLC and BC methodologies.

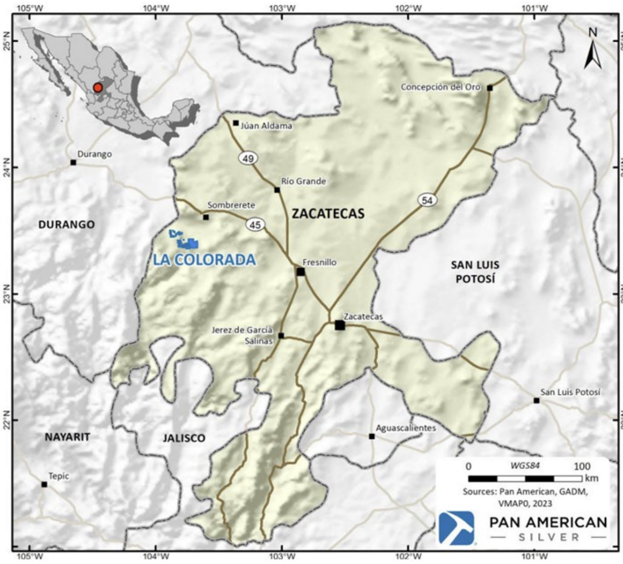


Figure 1 Location of the La Colorada Skarn project (Pan American Silver 2023)

2.2 Geology and structure

Mineralisation is primarily hosted by the Lower Cretaceous Cuesta del Cura Formation; a thick limestone–shale sequence deposited in a reef environment and representing the oldest unit exposed on the site. This unit is overlain by the Upper Cretaceous Indidura Formation and unconformably by the Late Cretaceous–Early Paleocene Ahuichilla conglomerate. Dacite flows and tuffs of the Lower Volcanic Complex overlie the sedimentary sequence of multiple intrusive phases, and brecciation events have driven widespread skarn alteration and Ag-Pb-Zn mineralisation overprinted by a later lower-temperature multiphase epithermal event.

Regional faults formed acted as pathways for porphyry intrusions and associated hydrothermal fluids. Intrusions emplacement fractured the sedimentary sequence, increasing porosity and permeability in the limestone host rocks and causing contact metamorphism and mineralogical changes, driven by hot fluids and later groundwater infiltration.

Contact metamorphism produced marble, hornfels and recrystallised limestone, followed by a prograde metasomatic stage forming garnet, pyroxene and wollastonite, and a retrograde stage characterised first by epidote- and amphibole-rich assemblages and later by chlorite, quartz, calcite and sulphides containing Zn, Pb, Ag, Cu and Mo. The final stage comprises distal carbonate replacement deposits (CRD) and sulphides-bearing veinlets, where carbonate rocks were replaced by massive sulphides.

2.3 Mining method assessment

The La Colorada Skarn deposit is divided into three zones: 901, 902 and 903, as shown in Figure 2. The size and footprint of each zone allow for a significant degree of optionality for bulk mining methods, including cave mining. In the scenario assessed in this paper: the 901 will use SLC due to its inclined geometry; 902 will be mined using BC because of its massive form and extensive footprint; and 903 will employ SLOS with paste backfill, as it lies beneath active and planned mining operations in the vein mine.

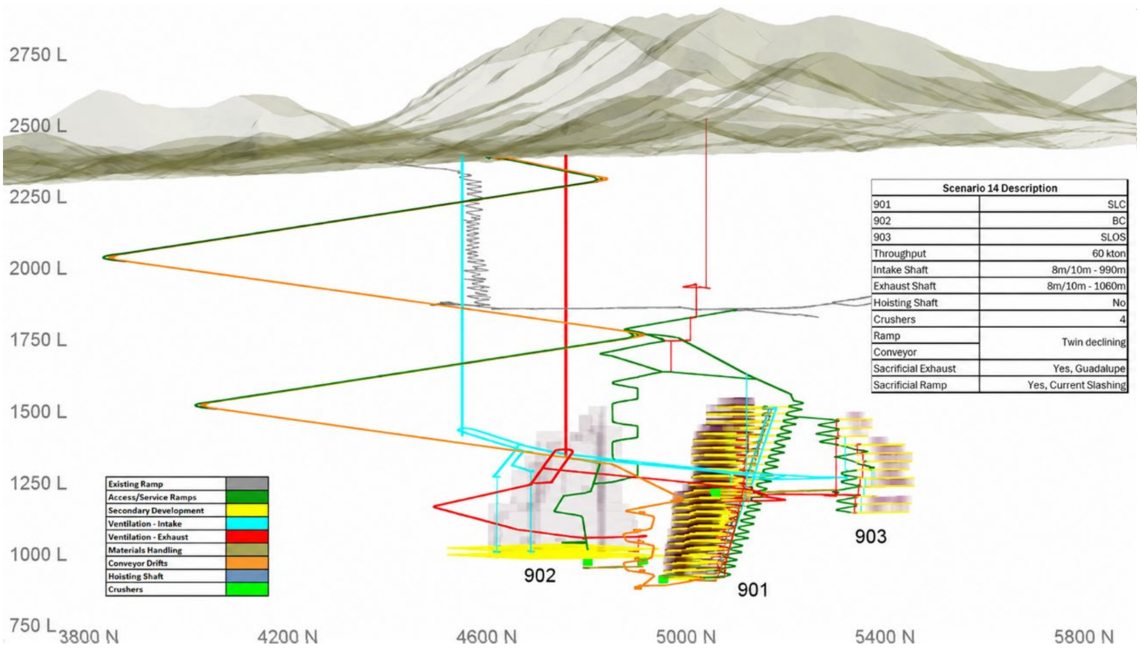


Figure 2 Longitudinal profile of La Colorada Skarn with the tested mining methods

Under this evaluated scenario, the existing site infrastructure would see an increase in capacity from a nominal of 2,000 tonnes per day (tpd) from the vein mine to an estimated 45,000 tpd from the three mining zones of the La Colorada Skarn. Many of the existing buildings and surface infrastructure would need to be relocated as they are located within the projected subsidence area. Material handling includes the use of ramps and conveyors to the surface. The principal geological units relevant to caveability include a competent unweathered limestone crown that overlies the 901 and 902 deposits with a thickness of approximately 350 to 450 m and 600 to 650 m, respectively. The limestone is overlain by a highly to extremely weathered dacite rock mass which extends to surface.

During a preliminary assessment completed in 2023 the mining rock mass rating (MRMR) was estimated to range between 42 and 86. Laubscher's Stability Chart correlates these results to a hydraulic radius ranging between 28 and 35 (Laubscher 1994; Laubscher & Jakubec 2000).

3 Methodology

3.1 Pre-mix model implementation in Deswik

A significant challenge associated with the planning and evaluation of caving methods is the prediction of mineable inventory and ore grades, primarily due to uncertainty in mixing and dilution from waste material during extraction. A rule-based approach, using standard fields and formulas in Deswik.Scheduler, provides a straightforward and transparent framework that is easy to understand and validate without relying on external flow simulation software early on. This approach allowed a simplified mixing logic to be fully integrated into the existing mine planning workflow, enabling rapid and cost-effective strategic evaluations with greater flexibility in production planning scenarios while maintaining consistency between resource modelling, footprint optimisation and scheduling. Moreover, the estimation of extraction ratios, tonnage, mixed grades, and recoverable inventory throughout the production life of mine can be automated in schedule.

Figure 3 shows the generic process flow of the methodology in applying a pre-mixing model from the tool perspective to generate a caving production plan. The process requires a discretisation of the mineable shape or resource model into practical geometry, i.e. rings for the SLC mining method or cubes for the BC method. Each ring or cube/block carries resource information such as density, grades, material type, etc. derived from the block model.

The discretised shapes are subsequently converted to ‘tasks’ in Deswik.Scheduler where relationships or sequences between tasks can be defined. The pre-mix template and assumptions are then applied in the scheduler before scheduling. The initial output of production plan can be optimised on discounted margins to refine the footprint and the extent of high-value material which is used for schedule iteration and final output.

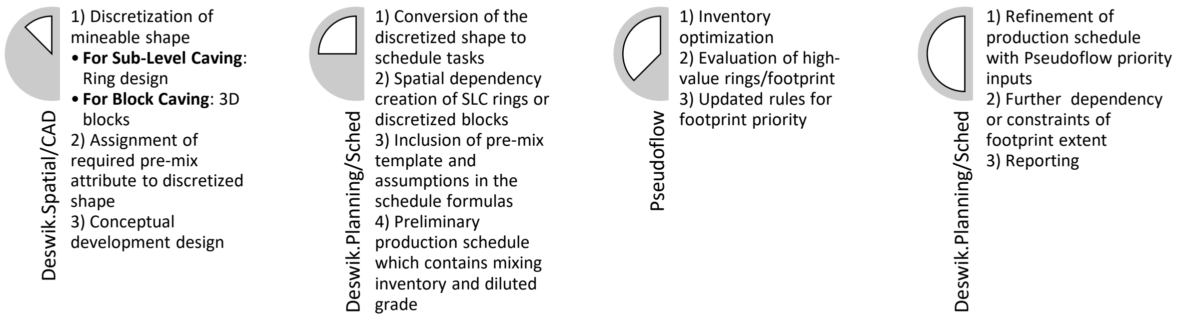


Figure 3 Main framework for implementing material mixing rules (detailed process of mixing rules in the following sections)

The additional advantage of implementing the mixing framework within Deswik is the ability to integrate directly with advanced optimisation tools available within the software. In this study, the pre-mixed models were used in conjunction with the Pseudoflow optimisation algorithm (Hochbaum 2008) to generate economically optimal mining footprints for both SLC and BC scenarios. Because Pseudoflow operates directly on the grade and tonnage information contained within the scheduler, the incorporation of pre-mixed grades ensures that dilution effects are implicitly considered during the optimisation process. This integration allows footprint optimisation to reflect a more realistic mixing occurrence for material at drawpoint than models that rely solely on in situ resource grades. Furthermore, the speed at which Pseudoflow operates within Deswik allows many footprint elevations and configurations to be evaluated quickly, assuming favourable rock mass conditions for all configurations and elevations, and supporting strategic decision-making across multiple orebodies and mining method alternatives.

3.1.1 Sublevel caving pre-mix template for 901 zone

Despite having a similarity to the caving process, SLC and BC differ in their design, scale, selectivity and operational controls. BC involves undercutting a large ore block and allowing it to fracture and cave under gravity, while SLC typically involves progressive retreating along sublevels where blasted rings are drawn from drawpoints as the overlying material caves (Laubscher 1994, 2000; Bull & Page 2000). A pre-mix model in this study differs slightly for SLC and BC.

In the SLC implementation, the process begins with discretising the resource model or mineable zone into 3D 'arrow-like' or 'funnel' shaped rings representing the planned drilling and blasting geometry. Generation of all possible rings must capture the mineable zone completely to ensure accurate grades and tonnage. For 901 zone, the rings are 25 m-high by 15 m-wide by 3-m thick burden, following the planned mining practice and equipment availability (Figure 4). The height represents the level spacing of the planned SLC mine. In this study there were 31,700 rings generated within the 901 zone, representing approximately 109 Mt of material inventory.

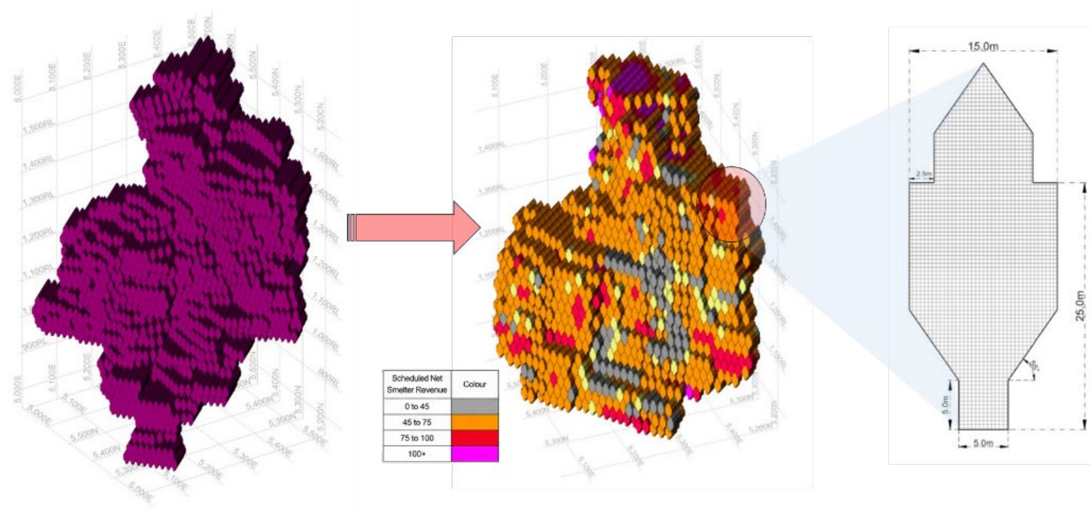


Figure 4 Discretisation of the 901 mineable area with 25 m high by 15 m wide sublevel caving rings

The pre-mix template is then applied to neighbouring or spatially connected rings as depicted in Figure 5. Grades from surrounding and overlying rings within the elliptical pattern are cascaded down to the primary ring according to predefined mixing ratios and spatial dependencies, producing a diluted grade at drawpoint (bottom ring) that reflects expected material mixing during draw. Each ring is assigned to a pre-mix grade calculated using weighted recovery contributions representing primary, secondary, tertiary and quaternary material sources, along with an allowance from external dilution. This approach follows the Hocking recovery pre-mix assumption (Hocking & Smith 2024), though the mixing is applied at the rings, not in the block model cell. The draw grades were automatically calculated in Deswik.Scheduler for each ring. Subsequently, with this pre-mix assumption, the Pseudoflow optimisation is used to generate seed economic footprints which are later refined to create a smooth, continuous footprint.

Estimation of SLC Ring Recovery	Hocking and Smith (2024)
Primary	55%
Secondary	18%
Tertiary	11%
Quaternary	6%
External Dilution	10%

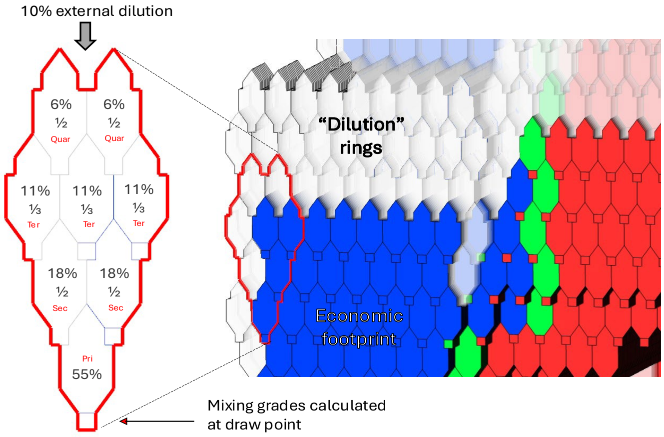


Figure 5 Sublevel (SLC) caving pre-mix rule of spatial inclusion and ring recovery (following Hocking & Smith 2024)

An additional deterministic rule set in Deswik.Scheduler is to automatically govern mining recoveries for each ring depending on extraction draw level. The first level of draw for any step-out was at a relatively low recovery of 60% to mitigate opening of a potentially unsafe void and early dilution entry. The second level of draw had a higher ring recovery of 80%, while the third rings were set to 100% recovery. Moreover, the third and second from bottom levels were set to 115% and 120% recovery, respectively. The bottom level of rings counted for 140% recovery. The ring location logic and automatic assignment of ring recovery codes are significant time-savers, given the scale of the deposits and scenarios that ran. With several scenarios and SLC footprint sizes being considered early in the project, this automatic assignment of recoveries significantly accelerated the iteration. The production scheduling work assumed 400 tpd per drawpoint ring.

3.1.2 Block caving pre-mix template for 902 zone

For the BC implementation, a similar concept is applied by discretising the resource/mineable zone with a 3D grid of blocks which also corresponds to drawpoints or drawbells. In this study, each block was set to 30 × 30 × 30 m, as illustrated in Figure 6. The entire grid covered the resource zone between 90 to 510 m high, which was later extended up by 210 m more to model the overlying waste material for dilution mixing.

For 902 resource model coverage, a total of about 1,900 blocks were generated, reflecting a resource inventory of 221 Mt. Given the geo block model of the project was 15 × 15 × 15 m, each of the discretised blocks may carry a weighted average value of at least eight block model cells, which was considered sufficiently granular for the project while remaining computationally simple enough to support rapid scenario iterations.

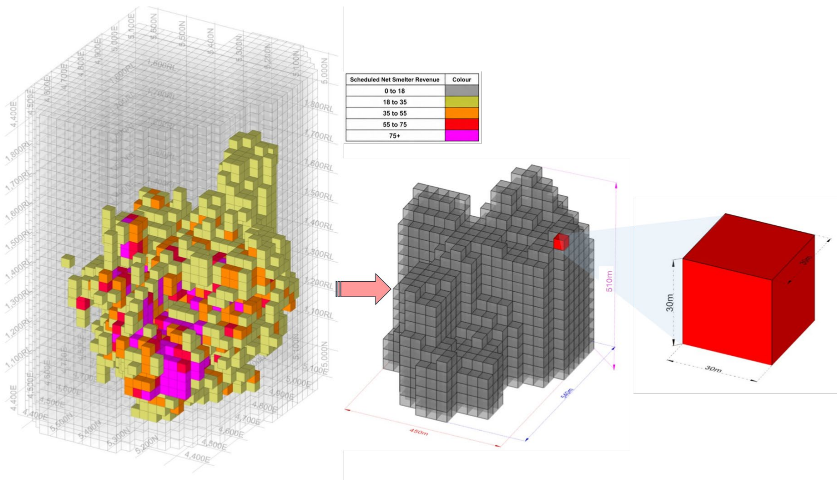


Figure 6 Discretisation of the 902 mineable resource zone using 30 × 30 × 30 m grid blocks

After the discretisation, each individual block was linked to another block above it, corresponding to the bottom-up mining sequence of the BC. For the first 30 m-high blocks, an assumed 50% recovery was assigned, accounting for the major and minor apex pillars.

Mixing is calculated vertically within the draw column based on empirical dilution entry relationships derived from Laubscher's height of interaction zone (HIZ) and composition curves (Laubscher 1994, 2000). These curves provide a practical representation of how material from different heights within the cave column interact and contribute to the material drawn at the drawpoint. Based on this relationship, the model calculates dilution percentages and corresponding dilution heights while also identifying specific blocks that contribute to dilution, allowing dilution blocks above the primary extraction block to contribute to the final mixed grade.

As noted in Figure 6, the maximum draw height of 902 zone is 510 m. The total volume of all the discretisation blocks is roughly 64,450,000 m^3, sitting on the 225,000 m^2 footprint area. Average column height is then estimated to be within the range of 286.4 m (i.e. volume divided by the footprint area).

Studies completed in 2024 on the La Colorada Skarn project suggested an MRMR estimation between 42 and 86. Thus Laubscher's HIZ was estimated to be around 80 m for 30 m panel by 18 m drawpoint spacing, El Teniente layout (Figure 7).

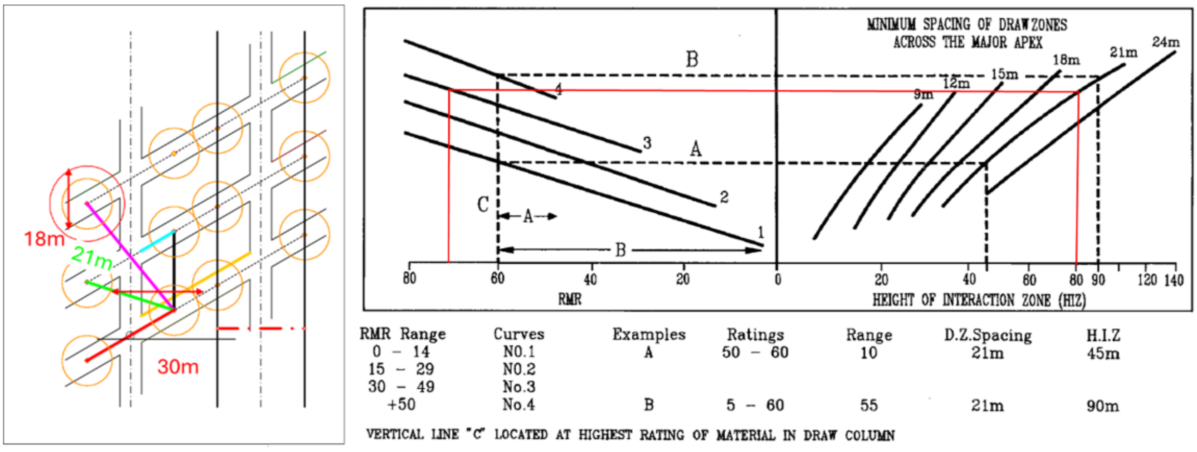
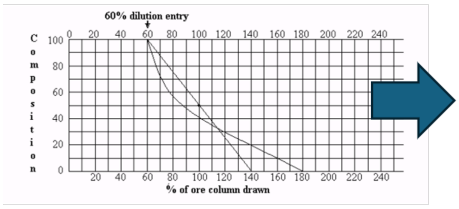


Figure 7 Planned panel layout and height of interaction zone estimation for La Colorada Skarn orebody using Laubscher's formula (Laubscher 1994, 2000)

An estimated 60% dilution entry is used for the project according to the information provided in Table 1. Subsequently, the 60% dilution entry non-linear curve derived from Laubscher's study (Figure 8) was re-produced and used as a basis to estimate dilution height and dilution percentage in Deswik.Scheduler's pre-mix template.

Table 1 Caving parameters of the 902 zone for Laubscher's dilution entry model

Parameter	Symbol	Value	Reference
Draw column height	A	286	Estimated from Laubscher (1994), mining rock mass rating, panel layout
Height of interaction zone	B	80	
Draw control factor	C	0.8	
Dilution entry		60%	Calculated: ((A-B)/A) × C



Original Laubscher's curve (1994, 2000)

Reproduced Laubscher's 60% dilution entry curve									Estimated Dilution Height for La Colorada 902 zone			
Draw %	Composition	Inst Dilution	Incr Draw	Inst Grade	Incr Grade	CumAvg Grade	Avg Dilution	Avg Ore Recovery	Draw Height	Incr Composition	Incr Dilution	Dilution Height
0	100%	0%	0	2.00%	2.00%	0.0%	0.0%	0.0%	0.0	100.0%	0.0%	0.0
10	100%	0%	10	2.00%	2.00%	2.0%	0.0%	10.0%	31.0	100.0%	0.0%	0.0
20	100%	0%	10	2.00%	2.00%	2.0%	0.0%	20.0%	62.0	100.0%	0.0%	0.0
30	100%	0%	10	2.00%	2.00%	2.0%	0.0%	30.0%	93.0	100.0%	0.0%	0.0
40	100%	0%	10	2.00%	2.00%	2.0%	0.0%	40.0%	124.0	100.0%	0.0%	0.0
50	100%	0%	10	2.00%	2.00%	2.0%	0.0%	50.0%	155.0	100.0%	0.0%	0.0
60	100%	0%	10	2.00%	2.00%	2.0%	0.0%	60.0%	186.0	100.0%	0.0%	0.0
70	72%	28%	10	1.58%	1.79%	2.0%	2.0%	68.6%	217.0	86.0%	14.0%	4.3
80	57%	43%	10	1.36%	1.47%	1.9%	6.2%	75.1%	248.0	64.5%	35.5%	15.3
90	48%	52%	10	1.22%	1.29%	1.8%	10.8%	80.3%	279.0	52.5%	47.5%	30.1
100	42%	58%	10	1.13%	1.18%	1.8%	15.2%	84.8%	310.0	45.0%	55.0%	47.1
110	36%	64%	10	1.04%	1.09%	1.7%	19.4%	88.7%	341.0	39.0%	61.0%	66.0
120	30%	70%	10	0.95%	1.00%	1.7%	23.3%	92.0%	372.0	33.0%	67.0%	86.8
130	25%	75%	10	0.88%	0.91%	1.6%	27.1%	94.8%	403.0	27.5%	72.5%	109.3
140	20%	80%	10	0.80%	0.84%	1.5%	30.7%	97.0%	434.0	22.5%	77.5%	133.3
150	15%	85%	10	0.73%	0.76%	1.5%	34.2%	98.8%	465.0	17.5%	82.5%	158.9
160	10%	90%	10	0.65%	0.69%	1.4%	37.5%	100.0%	496.0	12.5%	87.5%	186.0
170	5%	95%	10	0.58%	0.61%	1.4%	40.7%	100.8%	527.0	7.5%	92.5%	214.7
180	0%	100%	10	0.50%	0.54%	1.3%	43.9%	101.0%	558.0	2.5%	97.5%	244.9
190	0%	100%	10	0.50%	0.50%	1.3%	46.8%	101.0%	589.0	0.0%	100.0%	275.9
200	0%	100%	10	0.50%	0.50%	1.3%	49.5%	101.0%	620.0	0.0%	100.0%	306.9
210	0%	100%	10	0.50%	0.50%	1.2%	51.9%	101.0%	651.0	0.0%	100.0%	337.9
220	0%	100%	10	0.50%	0.50%	1.2%	54.1%	101.0%	682.0	0.0%	100.0%	368.9
230	0%	100%	10	0.50%	0.50%	1.2%	56.1%	101.0%	713.0	0.0%	100.0%	399.9
240	0%	100%	10	0.50%	0.50%	1.1%	57.9%	101.0%	744.0	0.0%	100.0%	430.9

Figure 8 Laubscher's 60% dilution entry curve was adapted for 902 zone dilution estimates

The estimated dilution height supplied information on the dilution blocks required to add to the model and the percentage inclusion written in the pre-mix template. For 902 zone, the added dilution in the model is depicted in Figure 9 as overlying blue blocks. An average of 30 m high dilution was applied to columns over the entire footprint.

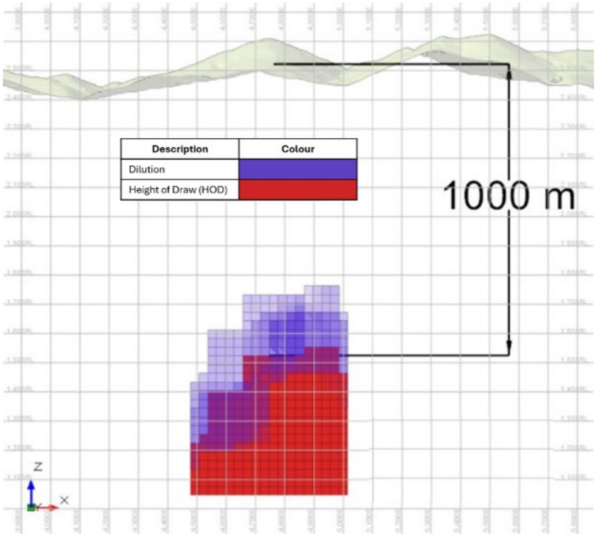


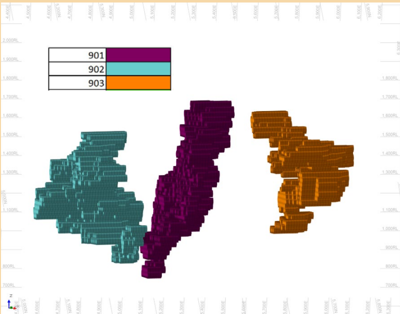
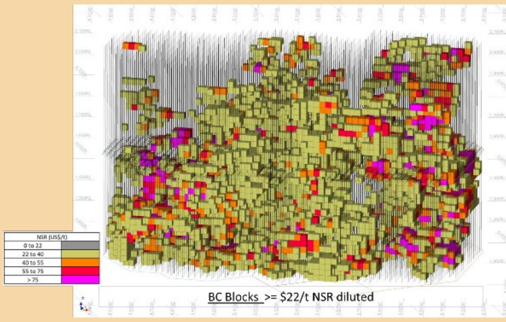
Figure 9 Modelled dilution inclusion (blue blocks) for 902 zone

Similar to the SLC case, these assumptions, mixing parameters and formulas were written in Deswik.Scheduler, providing inputs and governing algorithms in production planning and inventory scheduling.

4 Scenario generation and optimisation

Optimisation of SLC and BC mining methods using Pseudoflow was performed to maximise inventory and footprint extent. More specifically, the optimisation process evaluated different draw height scenarios and footprint configurations. Given that Pseudoflow was run directly in the scheduler, post mixing, inventory, footprint and height of draw were evaluated based on mixed grades and tonnages, as opposed to on an in situ basis. Table 2 shows the key assumptions for Pseudoflow inputs, which were derived from industry benchmarking.

Table 2 Pseudoflow optimisation assumptions

Sublevel caving	Block caving
25 m-high × 15 m-wide rings evaluated	30 × 30 × 30 m blocks evaluated
Operating and sustaining capital: $45/t	Footprint development cost: USD 2,500/m^2
Dilution 20.4% (67.5% dilution grade factor)	Operating cost: USD 22/t
Recovery 85%	Minimum draw height: 90 m
50,000 tpd throughput	Maximum column height: 510 m
360 days/yr, ~19 years mine life	Unconstrained waste height
	
Pseudoflow and schedule optimisation result:	Pseudoflow and schedule optimisation result:
Scheduled tonnage output – 350 Mt	Scheduled tonnage output – 726 Mt
Scheduled Net Smelter Revenue – USD 82.8/tonne	Scheduled net smelter revenue – USD 47.4/tonne
Scheduled annual margin – USD 680.4 M/tonne	Scheduled annual margin – USD 731.1 M/tonne

Footprint elevation for measured, indicated and inferred inventory was also optimised as part of the project evaluation. This was accomplished through a simple comparison of inventories and values generated using the intervals of 30 m starting at 860 m and going up to 1,580 m. A general cost was assigned to the cost per metre of development for both access and ventilation as well as a time lag to develop each lower elevation. The final inventories were evaluated at an equivalent present value at an 8% discount rate. Table 3 summarises the optimisation results, highlighting the variance in estimated discounted margin relative to the base case of 1,040 m footprint elevation. Lower horizon options exhibit comparable contained value, however, they require additional time and capital investment to reach footprint depth, resulting in a lower equivalent present value. In contrast, higher footprint elevations sacrifice column value, leading to a reduced overall margin.

Table 3 Block cave footprint elevation trade-off with 1,040 m elevation as a base case

Raw Pseudoflow block cave inventory						% change vs base case
Elevation envelope (m)	**Sched inventory (kt)**	**Sched Ag (g/t)**	**Sched Pb (%)**	**Sched Zn (%)**	**Sched Net Smelter Revenue (USD/t)**	**Estimated margin**
860–1,370	302,461	19.19	0.60	1.50	43.89	−13.4%
890–1,400	295,355	19.65	0.64	1.56	45.38	−7.3%
920–1,430	292,494	19.83	0.67	1.59	46.31	−2.6%
950–1,460	280,605	20.18	0.71	1.61	47.23	−1.0%
980–1,490	269,867	20.58	0.76	1.61	47.82	−1.2%
1,010–1,520	254,707	21.14	0.81	1.62	49.11	−0.5%
1,040–1,550 (base case)	231,346	21.95	0.89	1.67	51.30	0.0%
1,070–1,580	218,037	22.17	0.93	1.65	51.56	−3.7%

The values of ore column from selected elevations of all mining zones are shown in Figure 10. Optimisation on the caving initiation and mining direction was simply dictated by these column values. In a few cases the resulting footprint was manually smoothed to ensure geometric continuity and practical mine design considerations, producing a final footprint that is deemed both operationally feasible and consistent with the modelled cave behaviour, referring to reviewed geotechnical data, analyses and numerical stress modelling work by the internal and external technical review boards.

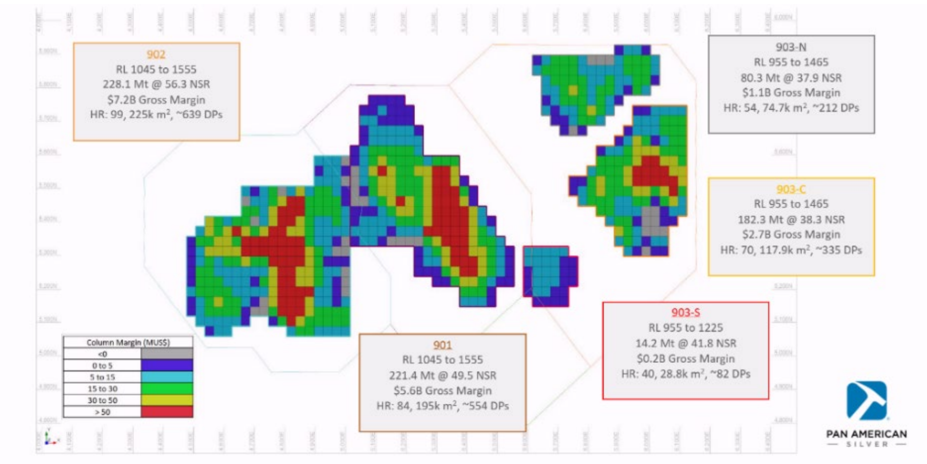


Figure 10 Cave footprint optimisation on the column values for all zones

In addition to evaluating each individual mining method, the optimisation also investigated the hybrid mining methods beyond the original SLOS method proposed in the latest NI 43-101 study (Pan American Silver 2023). In total, the team had generated and completed 15 scenarios of individual, and combinations of, SLOS, SLC and BC to support the strategic mining decision for the La Colorada Skarn (Figure 11).

Multiple hybrid mining scenarios were analysed to evaluate the financial robustness of the mine plan, including the capital commitment timeline, and the option that yields the highest economic value for the project. These included SLOS–BC and SLC–BC scenarios, both of which target a significant portion of the high-grade ore near the top of the ore column before transitioning to BC for the remainder (Figure 12). In a standalone BC mining method, this high-grade zone would be drawn near the end of mine life and exist within the interaction zone such that the mixing grade would suffer due to dilution.

Other details of mine planning such as mine design, a hydraulic radius requirement of 28–38 to start caving, a lead-lag 45° angle, rings and drawbell blasting rates, mining rates, pre-production/drawpoint constructions, caving initiation and propagation direction, and other parameters or assumptions were incorporated in the scheduling rules, dependencies and priorities.

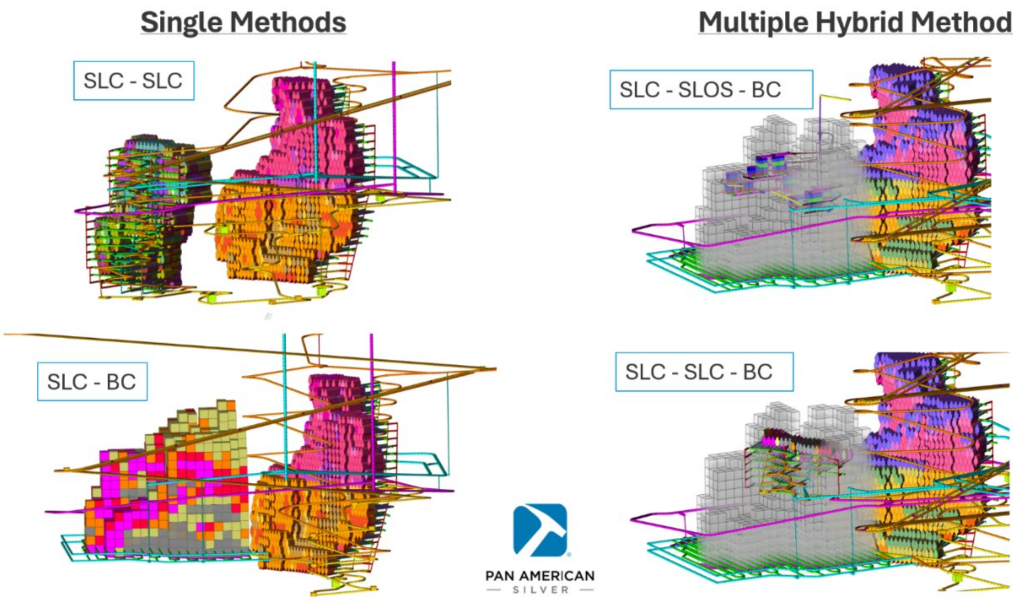


Figure 11 Mining strategy evaluation of La Colorada Skarn project, investigating combination of sublevel caving (SLC), sublevel open stoping (SLOS), and block caving (BC)

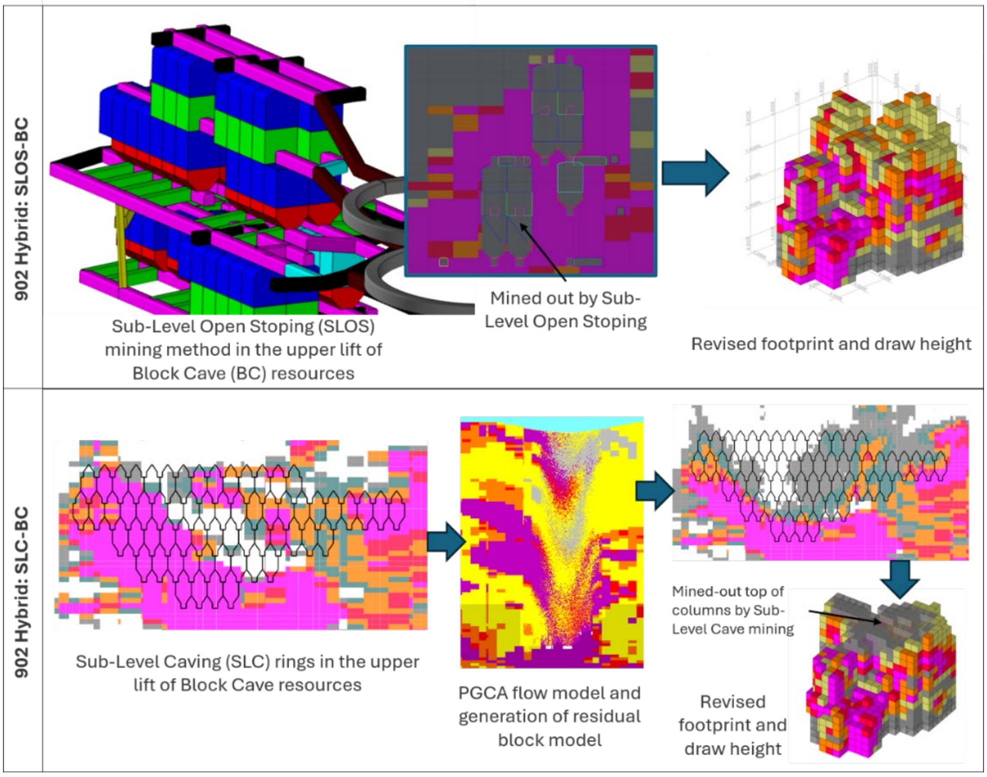


Figure 12 Optimisation of draw heights and cave footprint for hybrid methods using Power Geotechnical Cellular Automata (PGCA)

Table 4 summarises the main scenarios of mining evaluation completed for the La Colorada Skarn project throughput from each case. Additionally, multiple sub-scenarios of mine planning were completed for parametric studies and sensitivity analyses on key driving assumptions.

Table 4 Summary of mine planning evaluation and optimisation

Parent scenarios	Mining rate (tpd)	Optimisation, evaluation cases
Sublevel open stoping (SLOS)	12,000	Value-based sequence priority, incremental profitability
Sublevel caving (SLC)	15,000	Footprint, flow model, net present values
Block caving (BC)	30,000	Footprint boundary, draw height, flow model, net present values
Hybrid/combination: SLOS-SLC–BC, SLC–BC	46,000–60,000	All above, ramp-up strategies, capital commitment, SLC–BC transition and timeline, net present values

With design tools, the pre-mix template, Pseudoflow optimisation and scheduling capabilities integrated within a single platform, the scenario iterations were conducted more efficiently and seamlessly, resulting in faster scenario generation, improved consistency and a more transparent workflow in evaluating the strategic economic value of the project.

5 Discussion

5.1 Rapid scenario generation with a pre-mix model

A total of 15 scenarios were completed and evaluated for the project. At the time of writing, additional scenarios are being progressed to further refine the SLOS-SLC–BC hybrid case. The integration of the caving pre-mix template within the mine planning software enabled rapid completion of the required design update, caving inventory estimation, production schedule and optimisation within a single platform. The methodology enabled efficient evaluation of several development and production strategies within a consistent planning framework and a limited timeframe, supporting rapid comparison of technical and economic outcomes. The results provided clear visibility of the relative performance of each alternative evaluated for key project drivers, including net present value, internal rate of return, capital intensity and implementation risk.

5.2 Validation and comparison with flow models

Validation of the pre-mix template is a critical step in ensuring that simplified representations of material flow, recovery and dilution remain reliable for strategic decisions. While having the mixing algorithms in a single platform such as Deswik offers significant advantages in speed and flexibility, the assumptions must be benchmarked against more rigorous flow modelling applications to establish confidence in the outputs. In addition, by comparing the results, the similarity in the outcomes ensures a sufficient basis for evaluating alternative mining scenarios at the strategic level using the simplified models.

In this study, validation was conducted using PGCA, which applies cellular automata principles to simulate the complex gravity-driven flow, mixing and dilution. PGCA was embedded in the Deswik.Caving tool and used to generate distinct flow models for each SLC and BC case. Scheduled quantities and inventory, exported from Deswik.Scheduler, as well as drawpoint coordinates and tonnage per drawpoint per month, were imported to PGCA as simulation inputs. Figure 13 shows the SLC scenario output against the PGCA flow modelling of the same scenarios. The comparison on the cumulative revenue over time indicated an insignificant difference of 0.9%.

For the BC case, the same scenario modelled with a pre-mix template in Deswik mine planning was subsequently exported and modelled using PGCA, and the results indicated a close agreement with a deviation within 0.6%. This is shown in Figure 14.

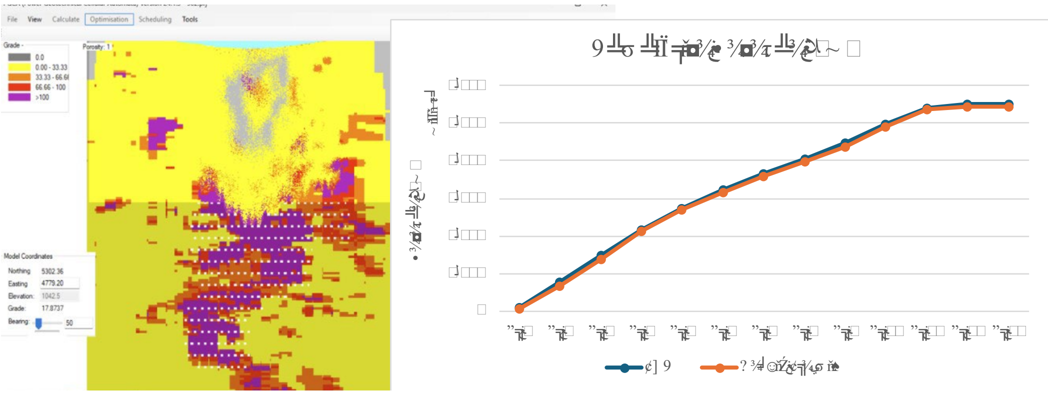


Figure 13 Power Geotechnical Cellular Automata validation versus a sublevel caving pre-mix scenario of 0.9% alignment on Revenue values

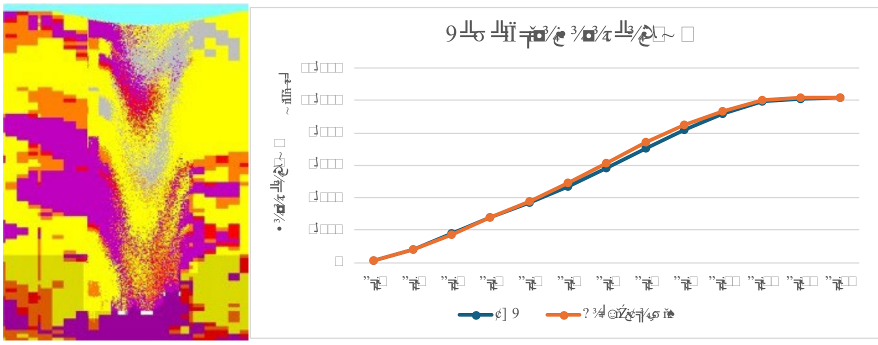


Figure 14 Power Geotechnical Cellular Automata validation versus a block caving pre-mix scenario within 0.6% alignment on Revenue values

5.3 Limitations and recommendations for the approach

The integration directly into Deswik of mixing algorithms that are deterministic and easy to understand by mine engineers represents a significant advancement in the evaluation of underground mass mining methods, particularly at the strategic planning stage, in terms of reduced cost, increased computational speed and enhanced flexibility to rapidly generate and assess multiple planning scenarios across SLOS, SLC, BC and hybrid mining strategies, as demonstrated for the La Colorada Skarn project deposit.

However, the pre-mix models developed in this study rely on several simplified assumptions that should be recognised when interpreting results. The assumptions and fixed parameters such as recovery ratios, generalised mixing relationships and representations of material flow do not fully capture the variability and complexity of caving behaviour, which is more rigorously simulated using material flow applications such as Geovia PCBC™/PCSLC™ or PGCA. Additionally, empirical approaches such as those derived from Laubscher's studies provide a strong foundation but may not reflect site-specific or localised geotechnical conditions or material flow behaviour. The validation against the PGCA flow model demonstrated strong agreement on the planned life of mine, though notable discrepancies were observed in the early years of SLC modelling. These differences are likely attributable to the conservative assumptions applied in the pre-mix recovery approach, particularly in handling cascading material, which may delay or dampen early production contributions.

Despite these limitations, the pre-mix template approach offers practical and sufficiently accurate approximation for early-stage evaluations. There are clear opportunities for further refinement, including the introduction of dynamic mixing ratios that vary with drawpoint location, extraction level or cave maturity, as well as the expanded automation of recovery assignment and footprint smoothing. Such enhancements would improve both the reproducibility and efficiency of the approach.

It is important to note that while the approach presented in this study is well suited for strategic evaluations, the specialised caving flow applications such as PCBC/PCSLC or PGCA remain recommended for detailed reserve estimation and output verification.

6 Conclusion

In summary, this study demonstrates a robust deterministic pre-mix modelling for both sublevel caving (SLC) and block caving (BC) proposals for the La Colorada Skarn project. The pre-mix templates were effectively implemented within Deswik mine planning software to support strategic footprint evaluation, rapid scenario iterations across complex multi-orebody projects, production scheduling and economic evaluation. The integration with Pseudoflow optimisation and automation further accelerated the evaluation and decision-making in selected mining methods, mine design, transition timing between SLC 901 zone and BC 902 zone orebodies, and capital decisions. Furthermore, verification against flow modelling Power Geotechnical Cellular Automata showed that the mixed tonnage and grade outputs were within 0.9% and 0.6% variance, respectively, for the SLC and BC projects. These results demonstrate strong agreement between the pre-mix template implemented in Deswik and more advanced flow simulations. Consequently, this methodology represents a practical and scalable solution for large-scale, multi-orebody caving mine evaluations.

Overall, the strategic evaluation of SLC, BC and hybrid scenarios using pre-mix templates in Deswik demonstrates the clear visibility of the relative performance of each alternative evaluated for key project drivers, including economic value and implementation risk.

Acknowledgement

The authors would like to thank Pan American Silver for permission to use site data and publish this paper.

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