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Gravity-flow modelling to evaluate caving alternatives for Leveäniemi iron ore mine

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Abstract

The Leveäniemi open pit operation at Svappavaara, Sweden, is a part of LKAB's iron ore mining portfolio. The main alternatives for continued mining are expanding the open pit operation followed by later a transition to underground mining using caving methods, or transitioning directly from the current state to underground mining using sublevel caving (SLC) or block caving without further pit expansion. The trade-off between these alternatives is driven by expected tonnage-grade profiles and the capital expenditures required for the associated production infrastructure, both surface and underground. The tonnage-grade profiles are also strongly influenced by the chosen draw strategies. To support comparison of these alternatives, a PGCA gravity-flow model (Power Geotechnical Cellular Automata) was developed that can be adapted to the various draw strategies and trade-off scenarios considered in this study.

The initial SLC flow model was generated from a large number of rings, and a preliminary tonnage-grade profile was produced using basic scheduling dependencies. Alternative draw strategies were then evaluated by adjusting shut-off and draw-call criteria and refining the ring-selection process within an iterative modelling workflow.

The primary objective of this paper is to identify and recommend a preferred caving alternative for the continued mining at Leveäniemi. The recommendation is based on the resulting tonnage-grade profiles, technical feasibility, strategic considerations of each mining option, and long-term social and economic considerations. Based on the gravity-flow modelling results and the associated trade-off analysis, the authors recommend a direct transition from the present state to underground mining. Among the evaluated options, the life of mine (LOM) 30 and LOM 30 crown pillar (CP) scenarios offer the most favourable outcomes, delivering strong caving performance metrics, substantial underground tonnage, and dilution levels comparable to LKAB's existing SLC operations. These scenarios also provide the potential to extend the life of the Leveäniemi operation significantly, while reducing waste-rock stripping requirements and minimising surface-disturbance impacts.

Keywords: *LKAB, Leveäniemi mine, underground transition, gravity-flow modelling, PGCA*

1 Introduction

LKAB is a Swedish mining company operating 2 underground iron mines, Kiruna and Malmberget, and one open pit mine, Leveäniemi, located in Svappavaara. The company is internationally recognised for its large-scale underground operations using sublevel caving (SLC) mining methods. In recent years, ongoing exploration activities in these mining areas have significantly increased the mineral resource base. As a result, there has been a corresponding increase in conceptual and pre-feasibility-level studies aimed at transforming mineral resources into mineral reserves.

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1.1 Background

Recent mineral resource assessments for LKAB's ongoing operation at Leveäniemi open pit indicate potential for continued mining subject to mining methods evaluations. The current mineral resource is defined as an open pit resource (LKAB 2025). Below the existing pit shell, additional magnetite-bearing material has been identified; however, this material remains unclassified because it lacks the level of technical and economic evaluation required for reporting under the Pan European Reserves and Resources Reporting Committee mineral reserves and resources reporting code (www.percstandard.org). Further studies are therefore needed to either elevate the unclassified material into formal resource categories, or reclassify part of the existing open pit resource to an underground mineral resource.

Conceptual studies for an underground operation at Leveäniemi already exist, which indicate that underground mining, particularly SLC, is potentially feasible (Nensén et al. 2021; Sormunen & Saiang 2022; Beck Engineering 2021; Keraghel et al. 2023). These studies recommend further investigation to establish definitive mine plans and schedules. Strategically, Leveäniemi is central to realising the long-term mining potential of the broader Svappavaara area due to its connection to the area's future waste-management strategy (Sormunen 2025; Sormunen et al. 2025). Under this strategy, the depleted Leveäniemi pit – and potentially an associated underground operation – could serve as a storage facility for wet tailings and dry waste from mining the nearby Gruvberget and Mertainen deposits.

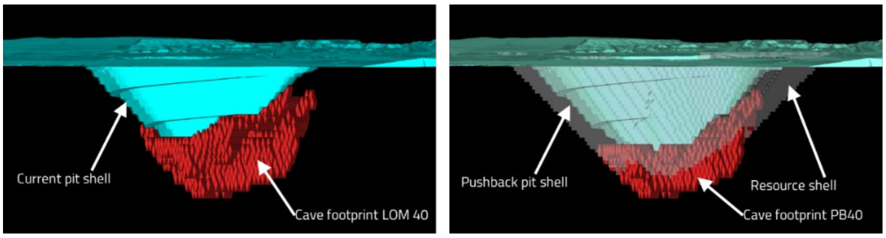
A critical challenge arises from the required sequencing of mining and waste placement. Before the depleted pit can be repurposed as a tailings storage facility, the presently unclassified material below the current pit shell must be extracted. Placing a wet-tailings facility directly above any future underground workings would pose obvious geotechnical risk, including mud-rush hazards and flooding (Jakubec 2018; Hudson-Edwards & Kemp 2024; Chileshe 2012). Such scenario would make caving-based extraction infeasible and effectively sterilise the underlying mineralisation. Additionally, the transition from open pit to underground mining is expected to influence slope stability, and depending on the scale and geometry of the cave, ground deformations and subsidence may occur beyond the current pit limit.

1.2 Problem statement

Given these interdependencies, further analysis is required to evaluate the trade-offs and constraints between different mining alternatives, the implications for waste management, and long-term area development. In this paper, 2 main alternatives for further mining at Leveäniemi are evaluated:

1. direct transition from the present state to underground mining using SLC without open pit expansion
2. expansion of the open pit by pushback, followed by a transition to underground mining using SLC.

The pushback design evaluated in this study is conceptual and differs explicitly from the resource shell that constrains the current mineral resource (Figures 1a and 1b.). Cave mining methods are preferred as underground mining methods, as they enable large-scale production required for economic viability. The SLC method allows for a top-down mining sequence, which shortens the lead time to underground production. For this reason, SLC is preferred over block caving (BC) in this study.



(a) (b)

Figure 1 (a) Topography of the Leveäniemi life of mine (LOM) design and the resulting cave footprint for scenario LOM 40; (b) Topography of the conceptual pushback (PB) design, showing the transparent resource shell and the resulting cave footprint for scenario PB 40

Multiple production scenarios, defined by variations in draw control strategy and shut-off criteria, are examined for each main alternative, including configurations with and without a crown pillar, to identify the preferred mining alternative for the Leveäniemi deposit.

The methods, assumptions, and terminology used in the scenario analysis are described in the following sections.

2 Method description

SLC is a top-down, underground mass-mining method in which the orebody is drilled and blasted in thin slices, or rings, typically with a burden of 2–4 m. The key unit operations of drilling, blasting, and mucking are carried out from crosscuts excavated through the orebody. In longitudinal SLC, crosscuts are oriented parallel to the strike of the orebody, whereas in transverse SLC, they are positioned perpendicular to the strike. In both layouts, the crosscuts are offset between subsequent production levels, and extraction proceeds in retreat from the end of each crosscut.

The combination of the retreating production sequence and the offset crosscut layouts cause overlying material, caved waste rock or previously blasted ore, to migrate downward and mix with the active rings during draw. This interaction results in dilution of the ore being mucked. To support production planning, gravity-flow models are used to quantify ore recovery, extraction ratios, and dilution under varying draw strategies and cave conditions.

2.1 Gravity-flow modelling

In mining operations, gravity flow occurs during the extraction of blasted material from stopes and drawpoints, as well as within material-handling systems such as ore passes, bins and other silos. In caving methods, gravity flow additionally includes the downward migration of caved material, such as waste or hanging wall rock, into the drawzone as ore is extracted from below. This interaction governs dilution, recovery, and flow behaviour within the cave column.

The cellular automata-based gravity-flow modelling approach used in this study is described in the following section.

2.1.1 Cellular automata

The modelling algorithm applied in this work is based on cellular automata (CA). CA methods are commonly described as stochastic, relying on controlled randomness to simulate complex physical behaviour. For example, a block within a cave column may move downward once a certain number of neighbouring blocks have been extracted; however, the exact number required can vary between iterations. As a result, 2 simulations conducted under identical conditions may yield different outcomes.

Deterministic CA models also exist, in which a block moves only after a fixed number of neighbouring blocks are removed. However, for gravity-flow modelling in cave mining, where real-world flow systems exhibit inherent variability and uncertainty, a stochastic CA approach is generally more appropriate.

The gravity-flow modelling tool employed in this paper is the Power Geotechnical Cellular Automata (PGCA) engine, available as a dedicated module within the Deswik mine-planning software. PGCA provides a stochastic simulation of granular-flow behaviour and is well-suited for evaluating material movement, dilution, and recovery in SLC operations.

2.1.2 Power Geotechnical Cellular Automata within Deswik software

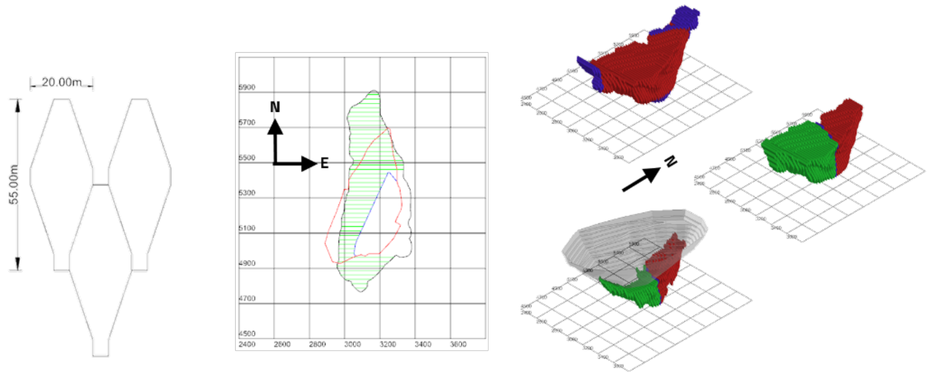
PGCA was originally a stand-alone cellular automaton modelling tool. The software has since been expanded to include additional functionality and can be configured to simulate flow behaviour for most types of caving operations (Power Geotechnical 2024). The primary mining applications for PGCA are SLC and BC; however, other variations, such as panel caving or incline caving, can be modelled depending on whether the mining method involves a single production level (as in BC) or multiple advancing production levels (as in SLC).

2.1.3 Model size and physical limitations

The Deswik PGCA engine is presently limited to a maximum of 240 million PGCA cells, with the smallest allowable block size (model resolution) being 1.25 m. PGCA automatically determines the spatial extent of the model based on the drawpoint layout and the dimensions of the input block model.

The PGCA block model typically extends beyond the initial drawpoint geometry to ensure that the flow behaviour of the outermost drawpoints is accurately captured in the simulation. In this study, the initial footprint (described in following section) spanned approximately 480 m in the X direction, 1,310 m the Y direction, and 715 m in the Z-direction.

The initial PGCA model exceeded the 240-million-cell limit and could not be executed in Deswik. Therefore, the model was reduced by excluding the drawpoints located south of Y 4815, north of Y 5915, above level 230 m, and below level -292.5 m, as shown in Figure 2c. After these reductions, the final PGCA model dimensions were 570 m (X), 1,160 m (Y), and 720 m (Z), bringing the total cell count down to within the allowable limit. The excluded areas correspond to the northern and southern domains at Leveäniemi, which are unsuitable for SLC due to their narrow geometry (Sormunen & Saiang 2022). Their removal enabled simulations at the highest resolution.



(a) (b) (c)

Figure 2 (a) Ring geometry showing sublevel spacing and crosscut offset; (b) Slice (Z 92.5) of the grade shell, including the life of mine, and pushback solids. Green lines denote crosscut centrelines; (c) Initial cave footprints. Blue areas were excluded from the gravity-flow modelling. Red and green colours indicate the mining direction from north to south and from south to north respectively, and the pushback surface is shown as a transparent solid

2.2 Workflow and process

A range of tools is available for gravity-flow modelling, and several workflows can be adopted depending on the objectives of the study. These tools may be used to generate caving footprints and production schedules or, alternatively, to evaluate existing mine designs, such as predefined ring layouts or drawpoint coordinates, in combination with associated extraction schedules.

For the purposes of this paper, predefined SLC footprints and extraction sequences were assumed. The overall modelling workflow and the iterative approach applied by the authors are described below.

2.2.1 The Leveäniemi deposit

The magnetite mineralisation at Leveäniemi strikes approximately north–south, dips steeply to the east, and measures roughly 450 m in thickness and 1,200 m in length. The high-grade core of the deposit is surrounded by several lenses containing both waste material and lower grade magnetite, the latter exhibiting substantial grade variability.

2.2.1.1 Initial footprint

The initial SLC footprint was generated from a grade shell constructed using the geological resource block model. The grade shell consisted of blocks classified as magnetite with Fe grades exceeding 10% and was subsequently expanded by 25 m to encompass the full extent of the magnetite mineralisation.

Crosscuts were then derived from this grade shell by slicing the deposit at 27.5 m sublevel intervals and placing crosscuts at 25 m centre-to-centre spacing, with a 12.5 m offset applied across all slices. These sublevel intervals and offset are consistent with LKAB’s current operations. Any portions of the crosscuts that extend beyond the open pit pushback limits were removed.

The resulting crosscuts were converted into SLC-style stopes, which were then sliced at 3.0 m intervals to generate the ring geometry. These steps, along with the resulting initial cave footprints, are illustrated in Figures 2a–2c.

2.2.1.2 Initial schedule

For scheduling purposes, each ring is assigned a set of attributes, including the production level, X–Y coordinates, blasting sequence, and mining direction, which together form a unique ring ID. These attributes define the dependencies between the rings and can be aggregated to establish higher-level inter-group dependencies.

The basic mining sequence is governed by the following general scheduling rules and dependencies:

- Crosscut depletion progressing from the hanging wall towards footwall.
- Formation of a V-shaped mining front expanding outwards from the central axis, as illustrated in Figure 3.
- A maximum lead-lag distance of 9 m between active rings, consistent with LKAB’s current underground operations.
- Prescribed lag of approximately 50 m between successive levels to prevent undermining the overlying production level.

This rule set is intentionally generic to facilitate adaptation if required, and scheduling priority is assigned to descending levels. All scenarios evaluated in this study were generated using identical set of scheduling rules and dependency structures.

The resulting schedules were subsequently used as input for Deswik Cave flow-modelling simulations.

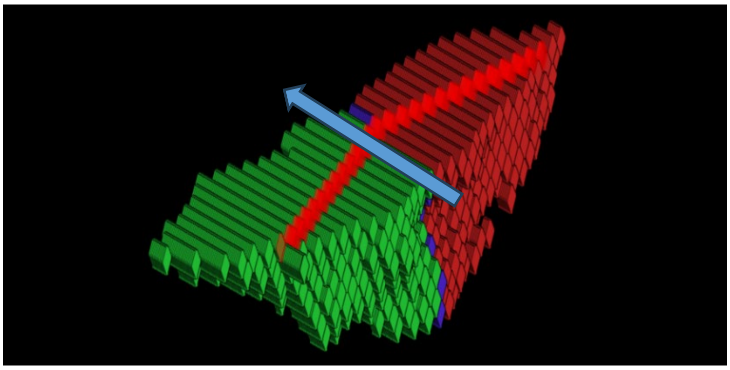


Figure 3 Basic mining sequence illustrating the general scheduling rules and dependencies used in this study. The blue colour denotes the axis, while green and red indicate mining directions progressing from north to south and south to north, respectively. The resulting V-shaped mining front is highlighted

2.2.2 Flow modelling of sublevel caving using Deswik Cave

The inputs required for the flow-modelling simulations include:

- a drawpoint file containing the spatial coordinates of all drawpoints
- a schedule file defining the extraction order and timing
- a block model file containing density, rock-type, and grade information.

In addition to these core inputs, several model parameters can be specified to control how the simulation is executed. These parameters and their functions within the simulation logic are briefly outlined in the following subsections.

2.2.2.1 Ring/drawpoint geometry

In the flow model, the ring burden, the distance between successive rings, was set to 3.0 m. The shoulder angles were defined at 70°, and the ring inclination (dump angle) was fixed at 0° (vertical). Alternative ring geometries can be created by modifying these parameters, enabling the modelling of longitudinal or transverse SLC layouts, as well as slot-drive configurations.

However, given the conceptual nature of this study, a single ring geometry and a transverse SLC layout were assumed throughout, as illustrated earlier in Figure 2.

2.2.2.2 Draw call and shut-off criteria

Two key criteria govern material extraction in the flow-modelling simulations: the draw-call criterion and shut-off criterion. Under a draw-call criterion, the model extracts a specified tonnage from a drawpoint regardless of the resulting grade.

When a grade-based shut-off criterion is used, the model determines the total extracted tonnes dynamically. Extraction continues until the defined shut-off conditions are met. The shut-off logic consists of initial and final shut-off grades, each with corresponding tonnage thresholds that must be specified before the simulation is run. These parameters include the initial shut-off tonnage, the final shut-off tonnage, and the maximum draw limit. A simplified process flow for the shut-off logic is shown in Figure 4.

Under a shut-off criterion, the initial shut-off tonnage is always extracted. If the modelled grade after this initial extraction falls below the initial shut-off-grade, the drawpoint is closed. Otherwise, extraction continues until the final shut-off tonnage threshold is reached. At this stage, the modelled grade is compared against the final shut-off-grade:

- If the grade falls below the final shut-off-grade, extraction stops.
- If the grade remains above the criterion, extraction continues until the maximum draw tonnage is reached.

For this study, the initial and final shut-off tonnage parameters were set to 2,000 and 12,000 t, respectively, with a maximum draw limit of 40,000 t. The initial threshold approximates the swell tonnage of a single fired ring, while the final threshold represents roughly 100% extraction of the fired tonnage. The maximum draw limit was applied to constrain the influence that individual rings could have on overall production.

The draw strategies and scenarios evaluated in this paper are differentiated primarily by the shut-off grades applied. The draw-call criterion was used only in later iterations to constrain extraction in ramp-up and step-out rings, and rings containing waste.

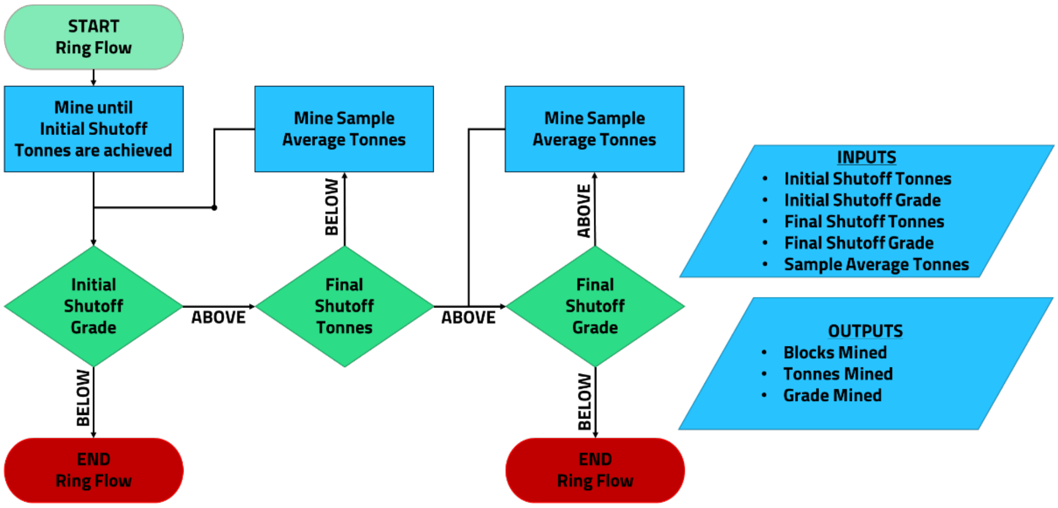


Figure 4 Process map illustrating the logic applied to initial and final shut-off-tonnage thresholds and the corresponding grade-based shut-off criteria

2.2.2.3 Shut-off type, draw input width, fines migration, cave shape

Two shut-off algorithms can be applied in combination with the shut-off-grade criterion. The first is the instantaneous shut-off, which evaluates a grade sample each time material is extracted from the drawpoint. If the sampled grade falls below the specified shut-off grade, the drawpoint is closed immediately. In this case, each 'sample' corresponds to the grade of PGCA cells extracted during that flow-modelling step.

The second algorithm is the sample-average shut-off. Instead of evaluating a single instantaneous sample, this method back-calculates the average grade of the previously drawn material over a defined sampling period. For example, with a sampling period of 200 t, the algorithm may use the last 3 extraction samples (e.g. 3 × 80 t = 240 t) to determine whether the shut-off condition has been met. This approach generally yields higher total draw and lower average grades for a given shut-off grade threshold.

The draw input width is measured at half the height of the draw ellipsoid. A commonly used reference value for calibration corresponds to a 5 m wide drawpoint at 1,100 m^3 material drawn (Power Geotechnical 2024).

Fines migration allows the modeller to assign distinct flow properties to different rock types. This capability can be used, for example, to simulate waste introduced at the base of the pit or to represent backfill used in sublevel shrinkage mining.

The cave-shape file is a DXF geometry that can be used to constrain the flow model so that only known caved regions are permitted to flow toward the drawpoints. Other potential uses could include delaying hanging wall failure by restricting material movement to predefined zones.

In this study, the sample-average shut-off was applied throughout, using a sampling period of 200 t. All simulations were performed without fines migration and without bounding cave shapes. The draw-input width was kept constant at 15 m across all scenarios.

2.2.2.4 Model simplifications

The authors acknowledge that the layouts, production schedules and model parameters applied in this study represent significant simplifications and fail to reproduce all intricacies of large-scale underground caving operations. Accordingly, the method should be regarded as conceptual, suitable for comparative analyses at early project stages. The following sections document the modelling workflow and provide guidance for further investigations and high-level recommendations.

2.3 Scenario development

The initial cave footprints inherently include both internal and external dilution. The Leveäniemi orebody exhibits substantial internal grade variability and is surrounded by low-grade magnetite mineralisation, both of which further influence dilution within the initial footprints.

These initial footprints served as a starting point for the iterative ring-selection process described in the following section. Shut-off grade thresholds of 30, 40, and 50% Fe were applied to both primary mining options. The naming convention for the scenarios is descriptive. LOM and PB (pushback) refer to the development strategy – either a direct transition to underground mining or a pushback followed by underground mining. CP denotes scenarios that include a crown pillar, and the numeric identifier (e.g. 30, 40, 50) represents the shut-off-grade threshold applied in that scenario (Table 1). In all scenarios, the initial and final shut-off grades were identical. For example, in option PB 50, both the initial and final shut-off grades were set to 50% Fe.

Table 1 Model scenarios

Option	Scenario name	Initial–final shut-off (% Fe)
Direct transition to underground from current state (LOM)	LOM 30	30–30
	LOM 40	40–40
	LOM 50	50–50
	LOM 30 (CP)	30–30
	LOM 40 (CP)	40–40
	LOM 50 (CP)	50–50
Pushback followed by transition to underground (PB)	PB 30	30–30
	PB 40	40–40
	PB 50	50–50
	PB 30 (CP)	30–30
	PB 40 (CP)	40–40
	PB 50 (CP)	50–50

2.3.1 Ring-selection process, iterations, and cave-shape definition

The first set of iterations was carried out using the initial cave footprints, which were modelled in Deswik Cave with the shut-off-grade thresholds defined in the previous section. The gravity-flow simulations generated estimates of caving grade and caved tonnes for each drawpoint, along with a completion status. These outputs, caving Fe grade, extracted tonnes, and drawpoint completion status were then imported back into Deswik CAD and analysed using the ring-selection criteria described below.

2.3.1.1 Exclusion of low-grade areas in the footwall and hanging wall

The first ring-selection criterion is based on both the caving Fe grade and the drawpoint's position within the crosscut. For each crosscut, the outermost rings with a caving Fe grade below the shut-off-grade threshold for the given strategy were excluded from subsequent iterations. This criterion removes low-grade edge material in both the footwall and the hanging wall. An illustration of this step is provided in Figure 5a.

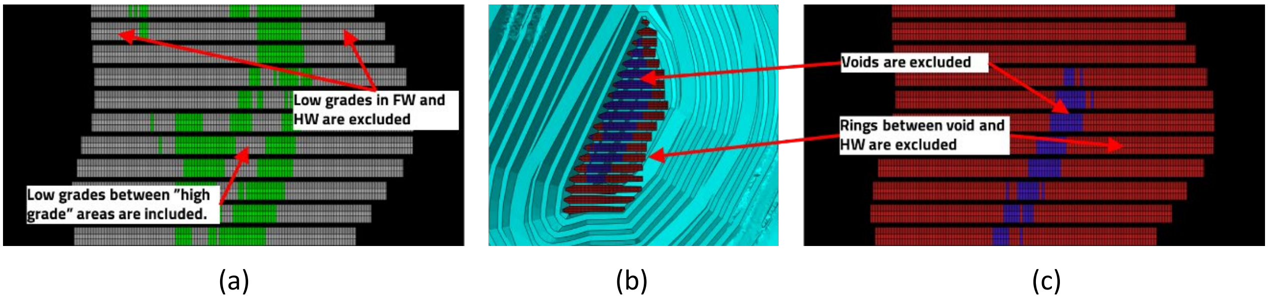


Figure 5 (a) Illustration of the ring-selection criteria. Grey colour indicates rings with modelled Fe grades below the scenario-specific threshold grade; (b–c) Illustration of void or air-proximity conditions where the ring and cave geometry intersect the depleted pit topography

2.3.1.2 Completion status

The modelled completion status records the reason extraction ceased at each ring or drawpoint. Possible outcomes include meeting initial or final shut-off thresholds, reaching the maximum-tonnage limit, or encountering a void or air-proximity condition.

For ring-selection purposes, all rings that opened into a void were removed from subsequent iterations. In addition, any rings located between voids and the last intact ring toward the hanging wall were also excluded. This criterion reflects the actual ring geometry where the cave surface intersects the depleted pit topography. The application of this rule is illustrated in Figure 5b–c.

2.3.1.3 Identifying outliers, minimum mining width

The exclusion of the sub-threshold rings for each draw strategy resulted in some crosscuts and drawpoints becoming disconnected from the main cave geometry. These isolated outliers, as illustrated in Figure 6, are intuitively understood to negatively affect gravity-flow performance and were therefore removed from subsequent iterations.

A minimum mining-width criterion was also applied. This width represents the narrowest practical excavation that can be mined using the selected method. In this study, the minimum width was set to 12 m, corresponding to 4 rings with a 3 m burden each. Accordingly, each crosscut was required to contain a minimum of 4 drawpoints. Any crosscuts with fewer than 4 drawpoints were removed from subsequent iterations.

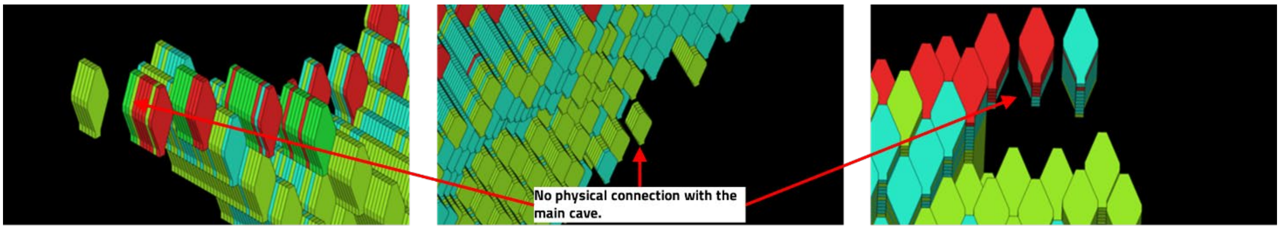


Figure 6 Outlier drawpoints that are disconnected from the main cave geometry, with examples pointed out using red arrows

2.3.1.4 Identification of step-out rings, application of ramp-up criterion and internal waste

As described earlier, the draw-call criterion is applied to ramp-up rings, step-out rings, and rings containing internal waste.

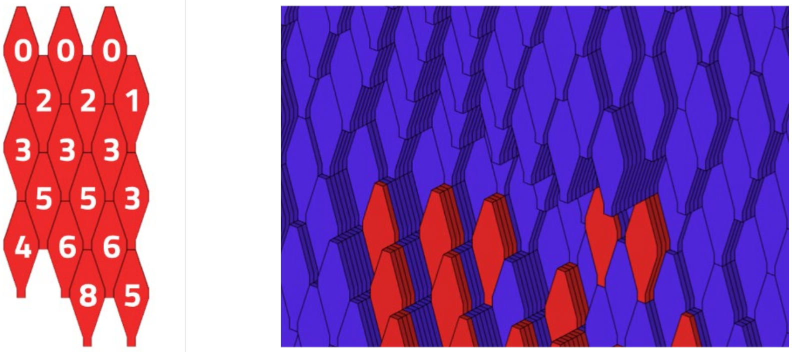
The vertical extraction sequence, illustrated in Figure 7a, is defined by the number of drawpoints located above the drawpoint being evaluated. In this study, the following definitions were used:

- First extraction sequence: no drawpoints above the evaluated drawpoint; a draw-call criterion of 40% of the fired tonnes is applied
- Second extraction sequence: 1-2 drawpoints above; draw-call criterion of 60% of the fired tonnes.

- Third extraction sequence: 3-4 drawpoints above; draw-call criterion of 80% of the fired tonnes.
- Subsequent extraction sequences: the shut-off criterion is applied instead of the draw-call criterion.

Step-out rings were identified using similar logic. In this study, a step-out ring is defined as a drawpoint located outside the extraction-level perimeter of the level above. The distinction between a first sequence ring and a step-out is ring illustrated in Figure 7b. A draw-call criterion of 40% of fired tonnes was applied to all step-out rings.

Rings containing internal waste were identified based on the modelled caving Fe grade from the gravity-flow simulations. If the modelled Fe grade fell below the shut-off threshold used in the scenario, then the ring was classified as containing internal waste. For such rings, a draw-call criterion of 30% of the fired tonnes was applied.



(a) (b)

Figure 7 (a) Illustration of the extraction sequence. The number of drawpoints located above the analysed drawpoint is shown in white; (b) Illustration of step-out rings. These drawpoints have no drawpoints directly above them.

2.3.2 Crown pillar

In the scenarios described above, a direct transition to underground mining, without pushback, was assumed – that is, no CP was modelled. In these cases, the uppermost drawpoints were assumed to break through the topography or pit floor, resulting in higher ore recovery because the material between the open pit and the underground workings was fully extracted.

However, such a direct transition presents several operational risks. Surface runoff may flow directly into the underground mine, potentially causing flooding or mud inflows. In arctic environments, exposure of the cave opening to cold surface conditions may also lead to freezing issues in the uppermost production levels.

As an alternative, a CP (a rock mass barrier, often consisting partly of ore) can be left in place to separate the open pit floor from the underground workings. CPs provide multiple protective functions:

- preventing water inflow and mud rushes into underground openings
- offering thermal insulation in cold regions (Sokolov et al. 2013)
- reducing the risk of cave-through or surface daylighting
- maintaining the stability of the surface infrastructure (Dintwe et al. 2021).

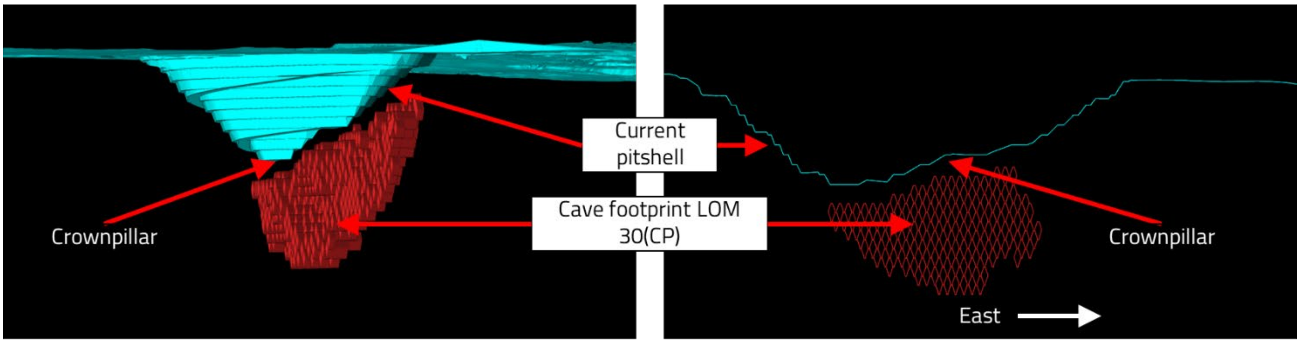
The major drawback is that the material within the CP becomes partly unrecoverable, thereby reducing overall ore recovery. This will be further studied with a comprehensive geotechnical model.

2.3.2.1 Modelling of the crown pillar

In this study, the CP was modelled solely to evaluate its effect on tonnage-grade profiles across the different scenarios. The adopted CP should be interpreted as a conceptual assumption and not as a geotechnically valid design. Although geotechnical considerations are very crucial, they are outside the scope of the present study; however, they will be addressed in the forthcoming advanced geotechnically coupled material-flow models.

A 40 m, CP threshold was assumed for the analysis. The CP was implemented by excluding all drawpoints for which the vertical distance between drawpoint and the base of the open pit surface was less than 40 m. Examples of the resulting cave geometries are shown in Figures 8a and 8b. After this exclusion, the full ring-selection process, as described previously, was applied.

The CP was assumed to cave in the gravity-flow simulations. However, because draw in the uppermost levels is constrained by the ramp-up criterion, the simulated outcomes are considered representative of ore recovery and dilution.



(a) (b)

Figure 8 Resulting cave geometries for scenario LOM 30(CP). (a) View from northeast below the topography; (b) Cross-section (X 182900), looking west

2.4 Tonnage and grade calculations

The in situ tonnage and grades were obtained directly from the geological resource block model, while the modelled caving Fe grades and extracted tonnes were retrieved from the gravity-flow output files. All resulting data was assigned to the corresponding drawpoints, after which the production schedules were used to consolidate and report the tonnage-grade profiles for each scenario.

2.4.1 Definitions and additional output information

In addition to tonnage and grade, the flow-model output includes several variables that support further interpretation of cave performance. These are briefly defined below.

2.4.1.1 Dilution

In this study, dilution is defined as the amount of non-ore material extracted in the simulation. In the geological resource block, mineralised blocks are classified as ore, whereas waste materials in the footwall, internal waste zones, and hanging wall, are assigned their respective lithology codes (e.g. dacite, greenstone, or overburden). The gravity-flow output reports the tonnage of each material type extracted, which is then imported into Deswik for dilution analysis. Importantly, ore blocks with Fe grades below the scenario-specific shut-off-grade are not counted as dilution, as they remain classified as ore with the block model.

2.4.1.2 Extraction ratio

The extraction ratio is defined as:

$$Extraction\ ratio = \frac{extracted\ tonnes}{in\ situ\ tonnes} \quad (1)$$

The extraction ratio is a key performance indicator in cave mining as it reflects both ore recovery and the degree of dilution. Values above 100% typically indicate significant inflow of caved waste material (Manzoor et al. 2022; Laubscher 1994).

2.4.1.3 Closure criterion

The closure criterion records the reason why extraction ceased at each drawpoint. Possible outcomes include:

- initial or final shut-off grade reached
- maximum-tonnage limit reached
- drawpoint intersecting a void or encountering air-proximity conditions
- other shut-off or geometric constraints.

The closure criterion provides critical insight into cave behaviour and overall cave performance.

2.4.1.4 Number of drawpoints, draw-call application and shut-off behaviour

For each scenario, the model records the number of drawpoints that:

- ran to completion under draw-call rules
- shut off due to initial or final shut-off-grade
- shut off after reaching the maximum-tonnage limits
- were closed due to voids or air-proximity conditions.

These counts provide an overview of how the investigated draw strategy controlled the extraction and how the cave interacted with the drawpoints.

In addition to the numerical outputs, the extracted blocks can also be visualised graphically. These graphical outputs can be used to support the interpretation of cave behaviour and to enhance any animations of the material-flow process or associated production schedule.

3 Results

A total of 12 scenarios shown in Table 1 were developed and analysed using the gravity-flow model. The results are presented in 2 tables: Table 2 summarises the primary caving-related performance metrics, while Table 3 provides detailed drawpoint-level information, including the completion status. The header row in each table defines the variables included.

Table 2 Primary caving-related performance metrics

Scenario name	Initial/final shut-off	In situ tonnes (Mt)	Modelled tonnes (Mt)	Extraction ratio (%)	Ore tonnes (Mt)	Waste tonnes (Mt)	Dilution (%)	Modelled Fe (%)
LOM 30	30–30	126.7	152.7	121	127.5	25.3	20	40.4
LOM 40	40–40	82.2	80.5	98	75.1	5.4	7	48.8
LOM 50	50–50	56.3	48.5	86	47.4	1.2	2	53.1
LOM 30 (CP)	30–30	88.3	135.7	154	116.2	19.6	17	41.5

Scenario name	Initial/final shut-off	In situ tonnes (Mt)	Modelled tonnes (Mt)	Extraction ratio (%)	Ore tonnes (Mt)	Waste tonnes (Mt)	Dilution (%)	Modelled Fe (%)
LOM 40 (CP)	40–40	54.6	56.4	103	53.6	2.8	5	49.2
LOM 50 (CP)	50–50	29.6	23.0	77	22.7	0.3	1	57.4
PB 30	30–30	78.3	90.9	116	79.2	11.7	15	40.7
PB 40	40–40	46.6	44.7	96	42.9	1.8	4	49.2
PB 50	50–50	31.2	22.2	71	22.0	0.2	1	54.7
PB 30 (CP)	30–30	50.4	71.8	143	65.9	6.0	9	42.1
PB 40 (CP)	40–40	25.7	21.0	82	20.5	0.5	2	49.7
PB 50 (CP)	50–50	15.4	11.3	73	11.2	0.0	0	56.5

Table 3 Detailed drawpoint metrics

Scenario name	Rings selected (total)	Draw-call criterion (total)	Shut-off criterion (total)	Draw-call of all rings (%)	Drawpoint ran to completion (%)	Initial shut-off activated (%)	Final shut-off activated (%)	Max. tonnes shut-off activated (%)
LOM 30	16,057	8,369	7,688	52	52	23	20	5
LOM 40	9,885	6,963	2,922	70	70	10	16	4
LOM 50	6,549	5,398	1,151	82	82	7	9	2
LOM 30 (CP)	11,334	6,213	5,121	55	55	20	23	2
LOM 40 (CP)	6,625	4,998	1,627	75	75	6	13	6
LOM 50 (CP)	4,173	3,624	549	87	87	5	7	2
PB 30	9,935	6,168	3,767	62	62	16	18	4
PB 40	5,573	4,380	1,193	79	79	5	13	3
PB 50	3,619	3,303	316	91	91	2	5	2
PB 30 (CP)	6,394	4,645	1,749	73	73	8	11	9
PB 40 (CP)	3,061	2,703	358	88	88	1	8	2
PB 50 (CP)	1,758	1,664	94	95	95	1	3	1

3.1 Primary Key Performance Indicators (KPI) results

The primary tonnage-grade profiles exhibit behaviour typical of SLC operations. Increasing the shut-off threshold (from 30 to 50%) has a strong positive impact on the modelled Fe grade (LOM: 40.4 to 53.1%; PB: 40.7 to 54.7%) and dilution (LOM: 20 to 2%; PB: 15 to 1%). As expected, the ore tonnes decrease substantially (LOM: 127.5 to 47.4 Mt; PB: 79.2 to 22.0 Mt) along with a corresponding reduction in extraction ratio (LOM: 121 to 86%; PB: 116 to 71%).

Scenarios incorporating a CP generally show lower ore and waste tonnes but slightly higher extraction ratios, indicating that the CP is only partially recovered through caving from the lower levels. The CP also improves the modelled Fe grade and reduces overall dilution.

Two scenarios, LOM 30 and LOM 30 (CP), contain the highest total Fe metal while maintaining moderate dilution levels. The extraction ratios (121 and 154%, respectively) exceed typical values observed at LKAB's operating underground mines in Kiruna and Malmberget, where extraction ratios are generally lower due to mature cave conditions. The modelled Fe grades in both scenarios are also lower than those observed in current operations, reflecting the more heterogeneous grade distribution at Leveäniemi.

3.2 Drawpoint metrics

The drawpoint metrics are consistent with the primary cave KPIs. The number of rings selected is directly proportional to the in situ tonnes and varies depending on whether a CP is applied. As expected, increasing the shut-off-grade threshold reduces the number of rings selected, which is consistent with the ring-selection process. Consequently, the proportion of rings governed by the draw-call criterion increases. This occurs primarily because the ramp-up and step-out criteria apply to a smaller overall ring inventory.

Applying a CP results in fewer rings selected and a higher share of draw-call completions. In some cases – most notably at the 30–40% shut-off thresholds – there are fewer grade-based shutoffs but a higher proportion of max-tonnes shutoffs. This indicates that parts of the CP are only partially recovered through caving from the lower levels, consistent with the behaviour observed in the primary KPIs.

Overall, only a small number of drawpoints reach the maximum-tonnage criterion. The maximum draw limit used in this study (40,000 t) corresponds to approximately 400% extraction at a single drawpoint, a behaviour that has also been observed in LKAB's operating SLC mines at Kiruna and Malmberget.

In most scenarios, final shut-off activation criteria slightly exceed the initial shut-off activation criteria, indicating that many drawpoints enter the final sampling window before the modelled grade falls below the threshold. Conversely, drawpoints that reach initial shut-off provide evidence of internal waste entering the draw column from within the cave geometry.

Across all scenarios, the draw-call completion category is the dominant outcome, which is consistent with the production ramp-up and step-out criteria described above.

3.3 Pushback option

The pushback option used in this study was interrogated against the geological resource block model. Following the same principles used to define dilution in this paper, the interrogation is based on the rock-type coding in the block model: blocks coded as ore are treated as ore regardless of Fe grade, whereas blocks coded as non-ore lithologies are treated as waste. The interrogation results are presented in Table 4.

Table 4 Interrogation results for the Leveäniemi pushback

	Ore (Mt)	Waste (Mt)	Ore Fe (%)	SR (waste/ore)	Fe metal (Mt)
LEV PB	51.1	99.6	44.1	1.9	22.5

The conceptual pushback design used in this study contains approximately 51.1 Mt of ore and 99.6 Mt of waste rock. Assuming a production rate of 7 Mtpa, the current LOM at Leveäniemi could be extended by approximately by 7.3 years.

3.4 Tonnage-grade profile trade-offs

The goal of this paper was to evaluate 2 primary alternatives for further mining at Leveäniemi. Trade-offs between direct transition to underground mining, with and without crown pillar, across the different shut-off-threshold criteria are presented in Table 5.

Table 5 Tonnage-grade profile trade-off results

Trade-off	LOM modelled tonnes (Mt)	LOM modelled Fe (%)	LOM Fe metal (Mt)	PB modelled tonnes (Mt)	PB modelled Fe (%)	PB Fe metal (Mt)	Difference in tonnes (Mt)	Difference in Fe metal (Mt)
LOM 30 vs PB 30	152.7	40.4	61.7	90.9	40.7	37.0	61.8	24.7
LOM 40 vs PB 40	75.1	48.8	36.6	42.9	49.2	21.1	32.2	15.5
LOM 50 vs PB 50	47.4	53.1	25.2	22	54.7	12.0	25.4	13.1
LOM 30 (CP) vs PB 30 (CP)	116.2	41.5	48.2	65.9	42.1	27.7	50.3	20.5
LOM 40 (CP) vs PB 40 (CP)	53.6	49.2	26.4	20.5	49.7	10.2	33.1	16.2
LOM 50 (CP) vs PB 50 (CP)	22.7	57.4	13.0	11.2	56.5	6.3	11.5	6.7

Above tonnage-grade profile results are intended primarily for comparative analyses between scenarios.

For the lowest shut-off-threshold options –LOM 30 and LOM 30 (CP) – a direct transition to underground mining results in nearly identical Fe metal production tonnes (Table 5). Based on the primary KPI indicators, both scenarios yield substantial underground tonnage with moderate dilution. The LOM 30 (CP) case achieves a particularly high extraction ratio (154%), see Table 2, which exceeds typical benchmark values observed at LKAB's operating underground mines.

For the intermediate shut-off-threshold options – LOM 40 and LOM 40 (CP) – the direct-transition case shows a notable reduction of Fe metal produced compared with the pushback option. Nevertheless, both scenarios deliver significant underground tonnage, relatively high modelled Fe grades, and low dilution, maintaining attractive tonnage-grade characteristics.

For the highest shut-off-threshold options, LOM 50 and LOM 50 (CP), the direct transition case results in the lowest Fe metal output of all tested scenarios, see Table 5. These cases also show lower extraction ratios and negligible dilution, as shown in Table 2, reflecting the increasingly selective nature of extraction at high shut-off thresholds.

4 Discussion and conclusion

The pushback route appears to maximise the Fe metal recovery across the evaluated scenarios. However, this approach has a pronounced negative impact on underground tonnage, particularly at the higher shut-off-grade thresholds by reducing the quantity and quality of the material extracted from the underground. In addition, the pushback option is expected to require substantial capital investment in waste rock stripping before ore can be accessed. This results in large volumes of dry waste (99.6 Mt), necessitating additional waste-dump capacity adjacent to current operations. Although the pushback scenario may extend the life of the existing open pit operation by approximately 7 years, further capital investments would be required for subsequent underground development.

Mining of the underground resource at Leveäniemi is essential for unlocking the long-term mining potential of the wider Svappavaara area, especially if the depleted Leveäniemi pit is to be repurposed for mine-waste storage. A key strategic question for Leveäniemi is therefore how to maximise and effectively deplete the underground resource, rather than pursuing a short-term extension of open pit operations. In this context, the results indicate that a direct transition to underground mining, particularly at the lower shut-off-grade thresholds, could be a viable and preferable option. The LOM 30 and LOM 30 (CP) scenarios provide caving KPI values broadly consistent with LKAB's existing underground operations and have the potential to extend production by approximately 16 years. Additionally, the direct-transition route generates significantly less dry waste and eliminates the need for large-scale stripping before reaching ore.

It is important to note that no formal economic (capex/opex) analysis has been conducted. The conclusions are therefore based on qualitative comparison of the KPIs derived from the gravity-flow modelling, combined with high-level operational and strategic considerations. As such, the recommendation to prioritise a direct transition to underground mining should be considered indicative rather than definitive, and subject to further investigation.

This study is conceptual in nature; nevertheless, the results provide a robust foundation and a structured framework for subsequent analyses. The outcomes should be used as inputs for further investigations, including slope-stability and subsidence modelling, refinement of preliminary mine designs, and further development of underground production systems.

Further work is required to improve the reliability and applicability of the results. This includes the use of fully coupled mechanical cave flow-models, as well as detailed investigation of key input parameters such as fragmentation, blasting performance, and material-flow characteristics. Such work is necessary to better quantify the limitations of the gravity-flow modelling approach and to support more advanced mine planning.

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