OreCraft: a serious game for teaching geometallurgical decision-making under priced, uncertain information

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Abstract

Geometallurgy links the properties of the ore to plant performance. However, students rarely practise the decisions on which geometallurgy depends: which test to order, when the available data justify committing capital, and how mineralogical uncertainty propagates into recovery, cash flow and environmental outcomes. This paper presents OreCraft, a web-based serious game that is built on a strict separation between a hidden, fully specified ground truth (the deposit and its block-level process response) and the partial, priced, delayed and noisy knowledge that student companies build through drilling, sampling and laboratory testing. Instructors compose reusable assets into scenarios, and students run companies through calendar-paced turns of exploration, modelling, planning, operation and settlement. Every measurement carries an instrument error and a sampling error, and the sampling error decreases with increasing sample mass and core diameter. Separation tests are computed from the scenario's own plant model; therefore, a bench test gives a slightly higher recovery than the plant, as in practice. At the end of each turn, the outcome is settled against the hidden truth and posted to a single reconciled ledger, from which the net present value and a rubric score are derived. The paper describes the architecture of the game, follows one turn from measurement to settlement, and presents the design principles that the engine enforces.

Keywords: geometallurgy; serious games; process mineralogy education; value of information; block model; measurement uncertainty

Nomenclature

Symbols are listed with the equation that introduces them. Subscripts in upright type are labels, and subscripts in italics are indices. Money is in USD and rates are per year unless stated.

Symbol	Meaning	Unit
Abbreviations		
BQ, NQ, HQ, PQ	wireline drill-core sizes, in increasing diameter	
DTR	Davis tube recovery (bench magnetic separation test)	
ESG	environmental, social and governance	
IRR	internal rate of return	
LIMS	low-intensity magnetic separation	
LOD	limit of detection	
NPV	net present value (in the game: Worth today)	
ROM	run-of-mine	
RQD	rock quality designation	
RSD	relative standard deviation	
SG	specific gravity	
USD	United States dollar	
WHIMS	wet high-intensity magnetic separation	
XRD	X-ray diffraction	
XRF	X-ray fluorescence	

Symbol	Meaning	Unit
Latin symbols		
A	scored after-tax margin: undiscounted sum of net cash (Eq. 4)	USD
A_b	mineral association of block b	0–100
C_b	texture complexity of block b	0–100
$C_{\mathrm{op},\tau}$, $C_{\mathrm{roy},\tau}$, $C_{\mathrm{tax},\tau}$, $C_{\mathrm{CO_2},\tau}$, $C_{\mathrm{oh},\tau}$, $C_{\mathrm{expl},\tau}$, $C_{\mathrm{rem},\tau}$	cost components of turn τ: operating, royalty, tax, carbon, overhead, exploration and laboratory, remediation (Eq. 3)	USD
f	head grade of the target mineral (Eq. A7)	mass fraction
$f_\varnothing$	sampling-error factor of the core diameter	–
F_τ	net cash of turn τ (Eq. 3)	USD
g, $\hat{g}$	true value and reading of a measured property (Eq. 2)	as measured
$g_{e,b}$	grade of element e in block b (Eq. 1)	mass %
K_τ	capital charged in turn τ (Eq. 3)	USD
n_y	turns per year	$\mathrm{yr^{-1}}$
$p_{e,m}$	content of element e in mineral m (Eq. 1)	mass %
r, r_{tax}, r_{roy}	annual discount rate; corporate tax rate; royalty rate	$\mathrm{yr^{-1}}$; –; –
R_T^{plant}	recovery of the target mineral at plant scale (Eq. A7)	fraction or %
S_τ	revenue of turn τ (Eq. 3)	USD
$W_{i,b}$, $W_{i,z}$	Bond ball-mill work index of block b and median of zone z	$\mathrm{kWh\ t^{-1}}$
$w_{m,b}$	mass fraction of mineral m in block b (Eq. 1)	–
Greek symbols		
β_{staff}	staff throughput bonus	–
$\varepsilon_{\mathrm{instr}}$, $\varepsilon_{\mathrm{samp}}$	instrument and sampling error of a reading (Eq. 2)	as measured
η_{plant}	plant efficiency on the target recovery (Eq. A7)	–
σ_{instr}, σ_{samp}	standard deviation of the instrument error and the sampling error (Eq. 2)	as measured
τ	turn index, counted from 0 (the game shows τ + 1)	–
Indices		
b, z, l	block; zone; processing line	
e, m, i, j, T	element; mineral; particle class (Appendix A); non-target mineral; target mineral	
Appendix A only (liberation–texture model)		
a, s_0, a_{sep}	slope and midpoint of the liberation logistic; slope of the separation kernel (Eqs. A2, A5)	–
d_{g}, d_{p}	mineral grain size; grind size P_{80} (Eq. A1)	µm
s, s_{eff}	grain-to-grind size ratio in decades; the same after erosion by texture complexity (Eq. A1)	–
L_{geom}, L_{val}	geometric liberation; liberated fraction of the valuable mineral (Eq. A2)	fraction
g, g_{c}, g_{c}^*	particle grade; cut-point of the separation; operating cut-point (Eqs. A3, A5–A7)	mass fraction
w_0, w_1	mass fractions of liberated gangue and liberated target mineral (Eq. A3)	–
$\varphi(g)$, φ_i	particle-grade distribution of the feed; mass fraction of particle class i (Eqs. A3, A6)	–
α, β, μ, ν, ν_0	Beta-distribution parameters, mean and precision; precision at C = 0 (Eq. A4)	–
κ, ξ	erosion of liberation by texture complexity; entrainment coefficient (Eqs. A1, A6)	–
R_{sep}, R_{tot}, E	separation kernel; recovery of a particle class with entrainment; entrained fraction (Eqs. A5–A6)	fraction

1. Introduction

Geometallurgy combines geology, mineralogy, comminution, mineral processing and economics into a spatially resolved prediction of how an orebody will perform (Lund and Lamberg, 2014; Dominy et al., 2018). The premise is that ore variability propagates through the plant and determines recovery, throughput, energy and water use, tailings and, ultimately, project value. Therefore, the unit of analysis is the process response of each block, not the average head

grade. Consequently, the professional skill that geometallurgy demands is judgement about information: which test to order, at what stage and at what cost and precision, and when the available knowledge is sufficient to commit capital.

University curricula rarely train this skill. Geology, mining, mineral processing, finance and sustainability are commonly taught as separate courses and with finished datasets, in which samples are given to the students rather than paid for. In industrial practice, however, decisions span the whole value chain and rest on information that is incomplete, costly, delayed and noisy, and early choices constrain later ones.

1.1 Related work

Simulation is an established teaching tool in the individual disciplines: geostatistics is taught with SGeMS (Remy et al., 2009), mine planning is taught around Lane's cut-off framework (Lane, 1988), and flowsheet simulators such as HSC Sim (Metso, 2023) and USIM PAC (Brochot et al., 1995) are used didactically. Synthetic orebodies for geometallurgical teaching exist for iron ore (Lishchuk et al., 2018) and porphyry copper (Garrido et al., 2020); games in engineering education are reviewed by Deshpande and Huang (2011) and Udeozor et al. (2023), and value-of-information analysis is established in the geosciences (Eidsvik et al., 2015). Mining games cover the value chain unevenly: underground safety in virtual reality (Gürer et al., 2023), self-escape from coal mines (Harry's Hard Choices; Brown, 2015), outreach (Science North and CIM, 2023; BetterGeo; SGU, 2015), a virtual-reality copper concentrator (Gibson et al., 2022) and a desktop open-pit simulator (Akkoyun and Careddu, 2015). The closest analogue is the game of Valakas et al. (2025), which couples priced exploration to a hidden truth. However, none of these games combines priced information with a mineralogy-driven process response and a reconciled financial settlement, and none lets instructors compose deposits, cost sheets and rubrics without programming.

An earlier teaching precursor developed at Luleå University of Technology was Challenge: Geometallurgy!, a mining project emulator in which students mine an orebody and use process simulation to examine how geological variability and planning decisions propagate through mineral processing and project economics. The game was developed for master's level teaching and made the value of geometallurgical information visible by comparing project outcomes obtained with and without a geometallurgical programme; reported simulations showed that using such information could reduce the project payback time by up to 25% (Lishchuk et al., 2018). OreCraft retains this whole value chain, decision-based learning concept but extends it by making observations priced, delayed and noisy, separating the hidden Truth from the students' evolving Knowledge, and reconciling the physical, financial and environmental consequences of their decisions after each turn.

1.2 Contribution

The contributions of OreCraft are: (i) a Truth-and-Knowledge architecture that separates the hidden deposit and its process response (Truth) from the noisy, delayed information that student companies buy (Knowledge); (ii) a measurement model that prices every analysis in cost, delay and precision, ties sampling error to sample mass and core diameter, and derives separation tests from the scenario's own plant model; (iii) one engine that runs imported block models, synthetic deposits and hand-authored models of published deposits under identical mechanics; (iv) a single settlement that reconciles each turn into a bank ledger, a net present value and an undiscounted after-tax margin used for scoring, and states which cash flows each figure includes; and (v) a small set of design principles that the code enforces. The capitalised terms Truth and Knowledge are used in this technical sense throughout the paper.

2. The game at a glance

2.1 Architecture

OreCraft is a web application (browser front end, server-side simulation engine) with two roles. Instructors author scenarios by composing reusable, versioned assets (Table 1, Section 7). Students form companies, each with a bank account, loans, staff and one or more projects; a project is one run of a scenario. The game is driven by three engines (Figure 1): the Truth engine holds the hidden deposit and its process response (Section 3); the Knowledge engine converts priced drilling, sampling and testing into a student-visible estimate (Section 4); and the Decision-and-Economy engine turns the student's committed decisions into physical, financial and environmental outcomes (Section 5).

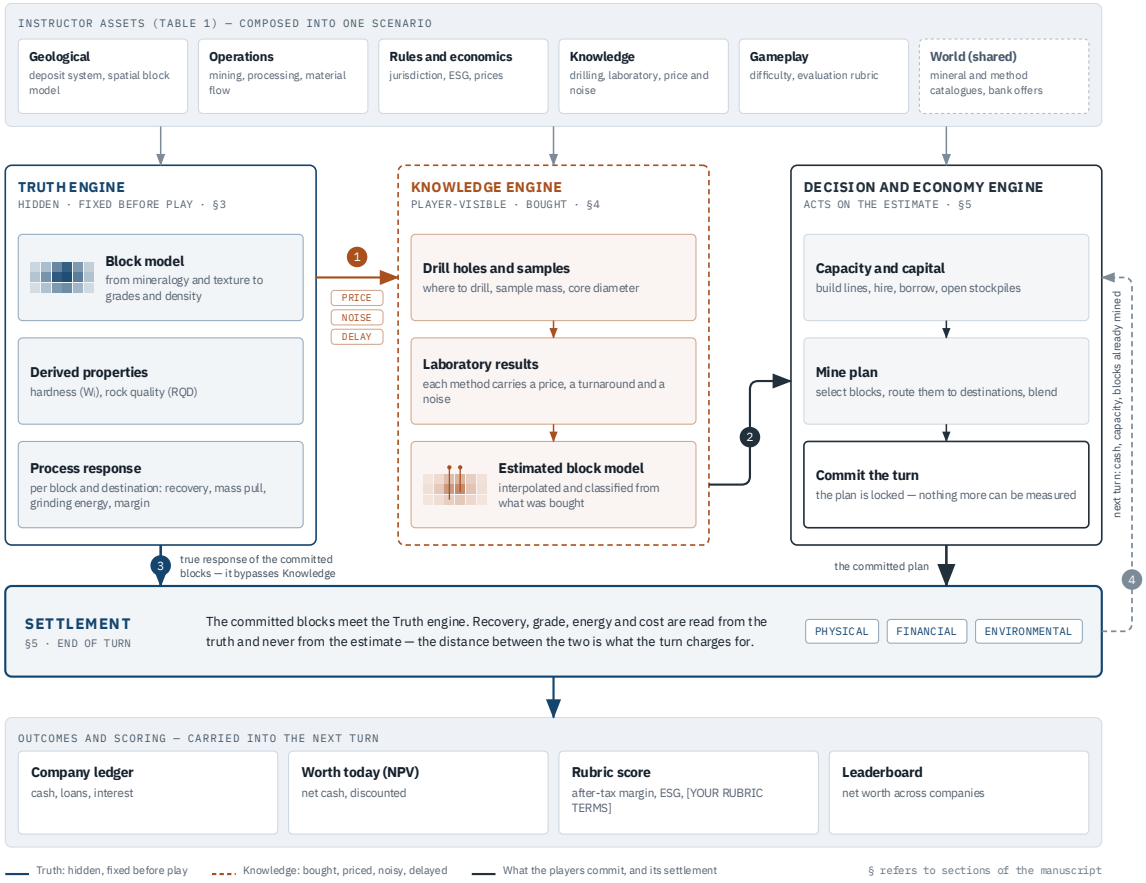


Figure 1. OreCraft architecture: instructor assets, the three engines and the information flows between them.

Table 1. Instructor asset catalogue (what the instructor sets). World catalogues (133 minerals, 137 analysis methods, 45 process-test derivations, 8 commodities with price history) are shared by all scenarios.

Group	Asset	Instructor sets
Geological	Deposit system	Payable, associated and gangue minerals; penalty elements; zones; textures; rock types
	Spatial deposit	Grid and block size; seed, continuity, boundary blending; zone geometry; median texture and work index per zone
Operations	Mining system	Open pit and/or underground; slope, bench height, advance limits; unit costs; throughput
	Mineral processing	Recovery model and parameters (Section 3); target mineral; grind size; plant efficiency; optional tails scavenger

Group	Asset	Instructor sets
	Material flow	Flowsheet graph (Crushing → Grinding → Concentration per line; stockpiles, waste dump, tailings dam, direct shipping); capital, build time, extra operating cost and power per line
Rules and economics	Jurisdiction	Tax, royalty, carbon price; energy and water prices; permit thresholds
	ESG	CO_2, water and energy intensities; recycling; tailings method; community spend
	Economy	Prices, payables, treatment charges; capital; closure bond; freight; quality terms; overhead; discount rate; staff roles
Knowledge	Knowledge profile	Drill diameters; laboratory subset with prices, noise, mass rules and turnaround; rigs
Gameplay	Difficulty	Starting reveals; pre-drilled holes; starting capital
	Evaluation	Rubric dimensions, weights, targets
World	Bank offers	Principal cap, rate, term, amortisation

2.2 Game loop

Play follows a six-phase loop (Figure 2): Explore (drill, sample), Plan (laboratory, plants, inventory), Model (interpret, estimate), Operate (select and route blocks), Commit (review and settle the turn) and Result (net present value and per-turn outcomes). Time is calendar-paced: a turn is a month, a quarter or a year, as set in the scenario, and every quantity that the instructor enters per year is scaled by the number of turns per year, n_y. Drill rigs and laboratory batches run on the game clock; therefore, each task takes approximately as long as it would in practice. All randomness is seeded (the deposit generator by the spatial model's seed, each measurement by keys derived from sample and method). Therefore, a run can be reproduced from its scenario and action log, provided that the scenario's assets have not been changed; a run references the editable scenario, not a frozen copy of it.

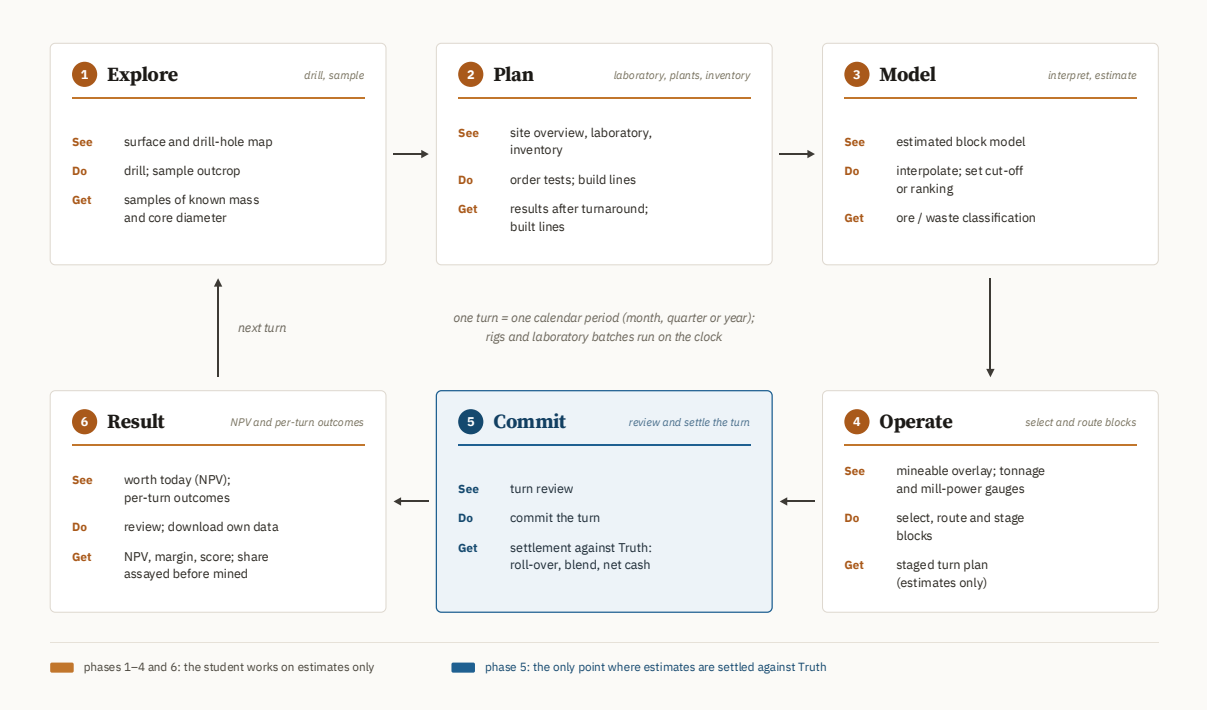


Figure 2. The six-phase loop to run the in-game company.

2.3 One turn, end to end

Figure 3 traces one turn and serves as a map for the rest of the paper. Truth is fixed before play: every block has its properties and, for every destination, a stored process response (Section 3). None of this information is visible to the student. (1) Drilling or outcrop sampling yields samples of known mass and core diameter, at a cost and after a delay. (2) Each laboratory analysis returns the true value plus instrument and sampling error (Eq. 2) and consumes sample mass. (3) The student interpolates the results into an estimated block model and classifies blocks. (4) Using that estimate, the student selects and routes blocks, builds processing lines, hires staff and borrows money; while the turn is staged, the game shows the expected tonnage and grinding energy, which are estimated from the student's own density and hardness readings or from published typical and design values, never from Truth. (5) When the student commits the turn, the engine settles it, i.e. it calculates the outcome from Truth instead of from the estimate. The engine (6) fits the committed blocks, in staging order, to the turn's tonnage budget and to each line's mill power at the ore's true hardness, rolling whatever does not fit into the next turn; (7) applies the quality terms to each line's blend; and (8) nets one cash figure for the turn from the true response of the committed blocks (Eq. 3). (9) Every component is posted to the company's bank ledger with loans and interest, and (10) the settled cash flow gives the net present value, the graded margin and the rubric score (Eq. 4). Because Truth is fully specified, the game can also compute, at the same point, what a student with better information would have earned.

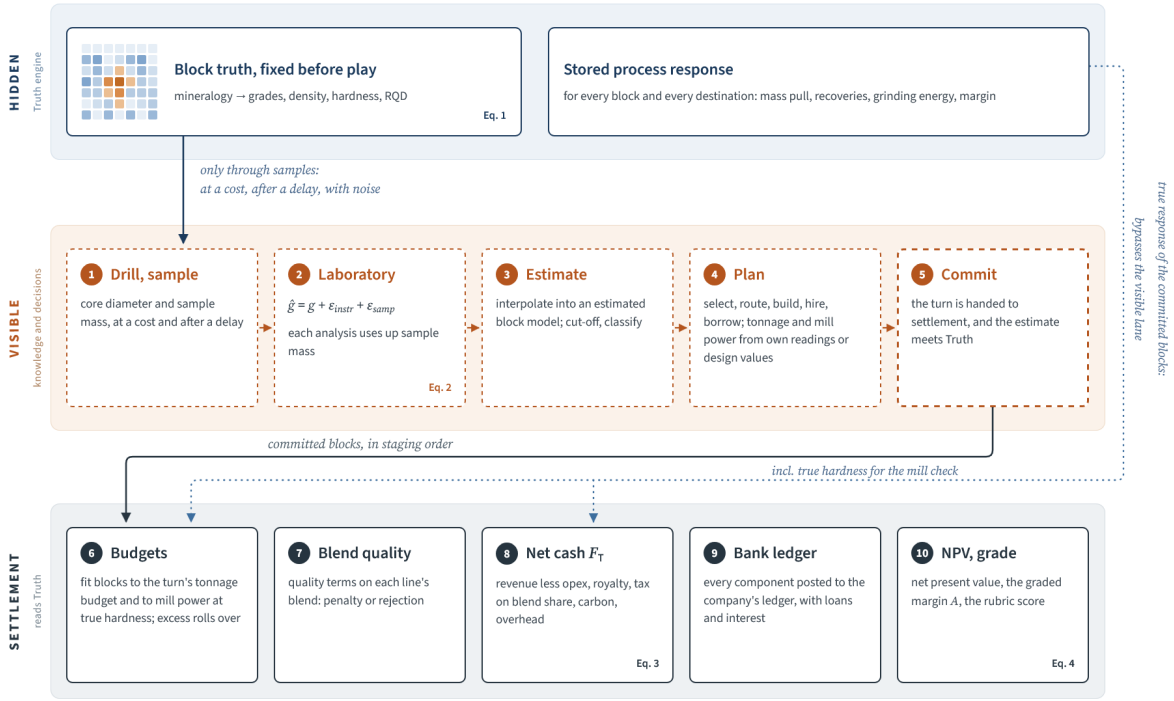
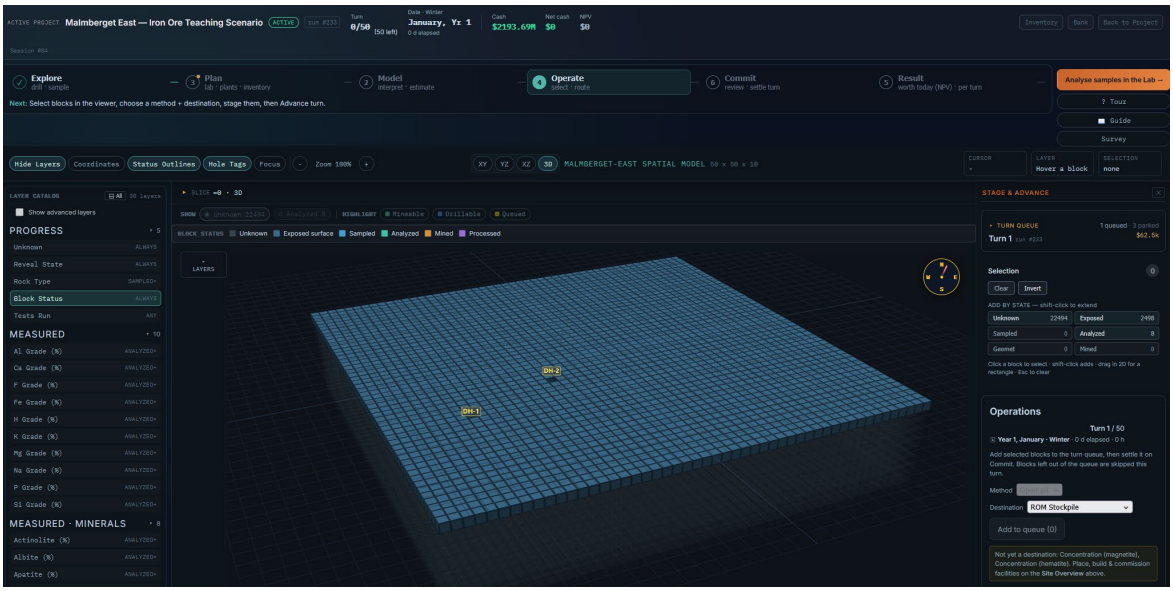
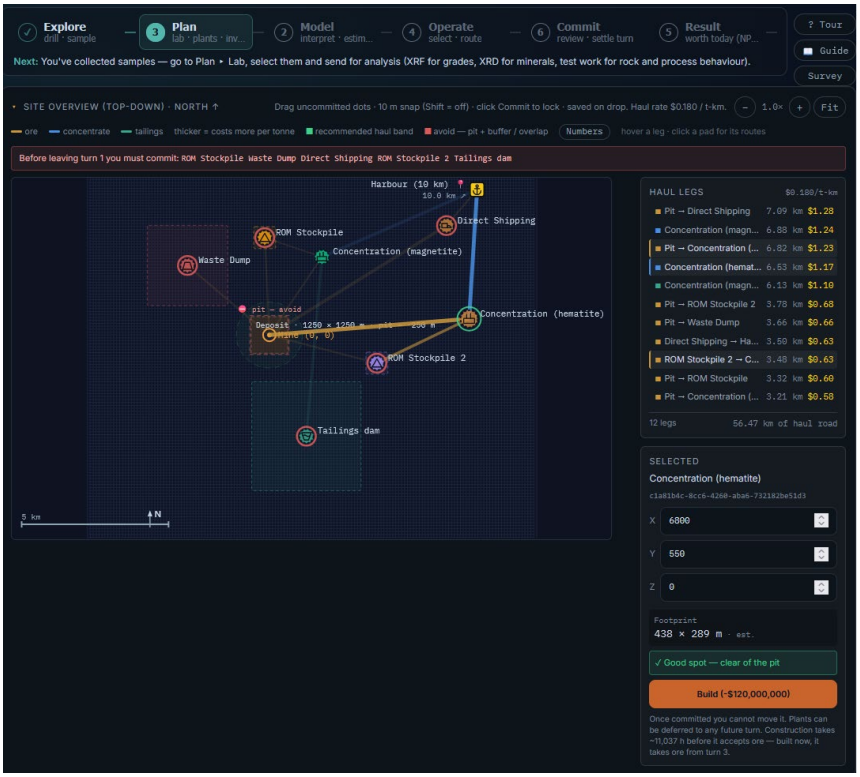


Figure 3. One turn from Truth to settlement. Numbers refer to the steps in Section 2.3.

Figure 4 shows the student workstation in the Operate phase, the site overview on which lines, stockpiles, dumps and haul legs are placed, and the Result page on which a run is reported. Students are supported by three aids: a Reference data page for each project, which is generated from the scenario's assets and states every rate, price, limit, rule and cost formula in force but never reveals the true block properties; a Student Guide with a glossary that uses the terms of the interface; and downloads of their own assays, decisions and cash flow.


ACTIVE PROJECT
Malmberget East — Iron Ore Teaching Scenario
ACTIVE
Explore
Plan
Model
Operate
Commit
Result
Analyse samples in the Lab →
Tour
Guide
Survey
Hide Layers
Coordinates
Status Outlines
Hole Tags
Focus
MALMBERGET-EAST SPATIAL MODEL
PROGRESS
MEASURED
MEASURED · MINERALS
DH-1
DH-2
Operations
Add to queue (0)
Build (-$120,000,000)


Explore
Plan
Model
Operate
Commit
Result
Next: You've collected samples — go to Plan • Lab, select them and send for analysis (XRF for grades, XRD for minerals, test work for rock and process behaviour).
? Tour
Guide
Survey
SITE OVERVIEW (TOP-DOWN) · NORTH ↑
Before leaving turn 1 you must commit: ROM Stockpile Waste Dump Direct Shipping ROM Stockpile 2 Tailings dam
Harbour (10 km)
Direct Shipping
ROM Stockpile
Concentration (magnetite)
Waste Dump
Concentration (hematite)
ROM Stockpile 2
Tailings dam
HAUL LEGS
SELECTED
Concentration (hematite)
Footprint
438 × 289 m · est.
✓ Good spot — clear of the pit

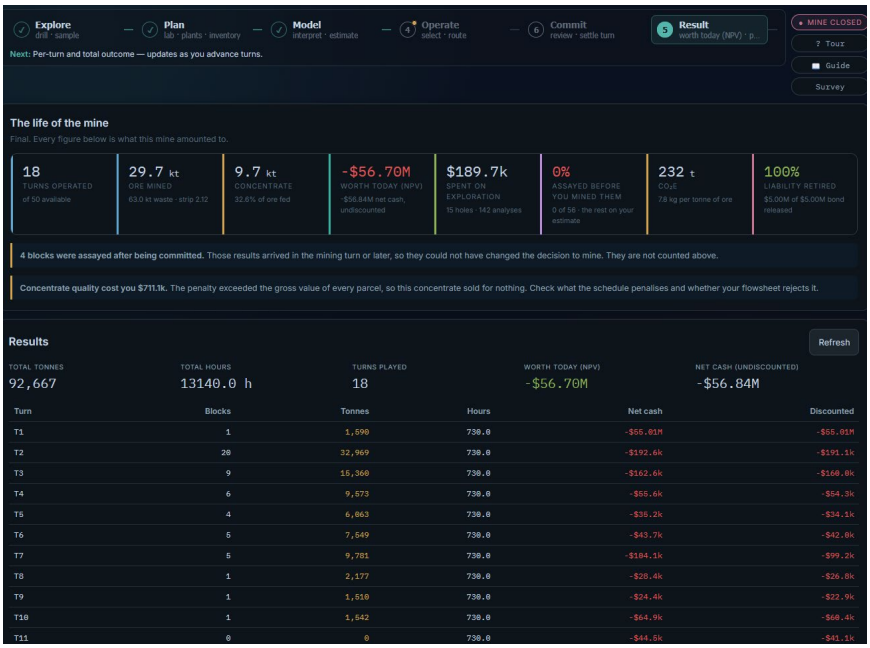


Figure 4. Student workstation in the Operate phase (a), site overview (b) and the Result page of a completed run (c).

3. Truth: what the game knows

The deposit is a three-dimensional grid of blocks whose true defined by mineralogy, following the mineralogical approach to geometallurgy (Lamberg, 2011). Each block b carries lithology and zone, modal mineralogy and textural descriptors (grain size, texture complexity C_b and mineral association A_b, both scaled 0–100); everything else is derived from them. Truth is generated from the geological assets, imported from a real block model, or hand-authored from a published deposit description (for example the simplified block model of eastern Malmberget by Schleret, 2024); all three routes give the same data structure. Chemistry follows the mineralogy through the mineral catalogue:

$$g_{e,b} = \sum_{m} w_{m,b}\ p_{e,m} \tag{1}$$

where $w_{m,b}$ is the mass fraction of mineral m and $p_{e,m}$ the mass per cent of element e in it, so elemental and mineralogical truth are consistent in the sense of element-to-mineral conversion (Parian et al., 2015). Stored grades are calculated from the stored mineralogy by Eq. 1 and recalculated after spatial smoothing; noise enters only when a sample is measured (Section 4). A truth import whose grades disagree with its minerals is rejected, and the publish checklist blocks a scenario whose stored grades drift from Eq. 1. The catalogue also records iron by oxidation state, but grades and assays report total Fe, so magnetite and hematite can be distinguished only by mineralogical and magnetic methods. Density is the mass-weighted harmonic mean of the mineral densities; hardness, the Bond ball-mill work index, is scaled from the zone median by texture complexity and association; and rock quality designation is estimated from Mohs hardness, rock type and texture complexity, and raises extraction cost through a ground-support factor.

Each block also stores its process response at every destination. Each concentration line is assigned a processing profile that selects one of four recovery models. All profiles in the current scenarios use a two-product mass balance on the target mineral: non-target minerals report to

concentrate in proportion to their mass, a plant efficiency derates the target's recovery, and an optional tails scavenger recovers a second mineral from the tailings into the same concentrate. Two empirical head-grade models and a three-stage liberation–texture model (Appendix A; implemented but uncalibrated) are the alternatives. Grinding energy follows Bond (1961) with each block's own work index. All of this is computed once, when the scenario is committed, and stored per block and destination; settlement reads the stored values and never re-runs the process models.

4. Knowledge: what the student pays to learn

Each block passes through a sequence of knowledge states that can only advance: unknown, exposed, drilled, sampled, analysed, geometallurgically characterised, mined, processed. Mining exposes the pit floor and walls and reveals rock type, but grade and process response can be obtained only by drilling or outcrop sampling followed by laboratory work. Core comes in four diameters, each with a cost and time per metre and a sampling-error factor $f_{\varnothing}$. Every sample has a mass (core length × mass per metre); each analysis consumes a fraction of the remaining mass and requires a minimum mass, so an interval that has been assayed repeatedly may no longer qualify for a mass-hungry test such as Bond grindability. Each method has a price, a turnaround, noise parameters and mass rules (Table 2), so every test is a trade-off between cost, delay, precision and the sample mass it uses up. A measurement returns the true value g corrupted by independent instrument and sampling errors:

$$\hat{g} = g + \varepsilon_{\text{instr}} + \varepsilon_{\text{samp}}, \qquad \varepsilon_{\text{instr}} \sim \mathcal{N}\left(0, \sigma^2_{\text{instr}}\right), \quad \varepsilon_{\text{samp}} \sim \mathcal{N}\left(0, \sigma^2_{\text{samp}}\right) \tag{2}$$

The standard deviation of the instrument error is proportional to the reading, with the limit of detection as its lower bound. The standard deviation of the sampling error scales with the reading, the core-diameter factor and the inverse square root of sample mass, and is bounded between 0.4 and 3 times its value at a reference mass of 5 kg. The mass dependence follows Gy's fundamental sampling error, whose variance is inversely proportional to sample mass (Gy, 1979); the remaining factors of Gy's sampling constant are lumped into the method's relative standard deviation, a deliberately phenomenological simplification. A larger sample mass or core diameter therefore reduces only the sampling error, while the instrument error sets the floor. The instrument error is seeded by the pair (sample, method) and the sampling error by the pair (sample, property), so a second method on the same sample sees a new instrument error but the same sampling error; only a new or larger sample reduces it. A method cannot be repeated on one sample.

Three rules keep results physically consistent. (i) A mineralogical result is closed to 100 % only if the minerals the method measures make up at least 95 % of the rock; a single-mineral method such as Satmagan reports its mineral as a share of the rock. (ii) Separation tests are not stored properties but are computed from the recovery model of the line concerned: bench tests (Davis tube, LIMS, WHIMS) separate at $\eta_{\text{plant}} = 1$ and pilot tests at the plant's efficiency, so bench recoveries are a few per cent higher than plant recoveries, as in practice. (iii) Noise on recoveries and rejections is bounded, so no result exceeds 100 % and a clean feed is never reported as a suspiciously exact 100 %. Laboratory batches take a turnaround plus a time per sample, and an optional exploration gate recommends a minimum spend before production; the gate is advisory and serves to make the cost of not knowing visible before the first block is committed.

Table 2. Five examples from the laboratory catalogue (137 methods). Noise is RSD_{instr} / RSD_{samp} (%) at the reference mass; mass is the fraction of the remaining sample consumed / the minimum required. Values as authored in the Malmberget East knowledge profile; prices and noise levels are instructor-editable.

Method	Reveals	Cost (USD)	Time (h)	Noise (%)	Mass used / min.
Satmagan	Magnetite (share of rock)	25	240	8 / 3	50 % / 0.1 kg
Davis tube	Mass pull; Fe recovery (bench)	47	240	4 / 6; 2 / 2	50 % / 0.1 kg
Fused-disc XRF	Fe, Si, Al, Ca, Mg, K, Na, P	67	240	4 / 2	30 % / 0.05 kg
Bond ball-mill work index	W_i; grinding energy	350	672	5 / 2	90 % / 8 kg
Quantitative XRD	Modal mineralogy	404	336	8 / 3	50 % / 0.1 kg

5. Decisions and settlement

Decisions. Measurements populate an estimated block model on the workstation (Figure 4a). Any measured variable, including work index and process recoveries, is interpolated by inverse-distance weighting with a student-chosen power, a deterministic stand-in for kriging (Chilès and Delfiner, 2012). Students classify blocks with a cut-off on the estimate (Lane, 1988) or a ranking formula over their revealed assays, and route them. Open-pit mining is top-down: a block is mineable when every block above it is gone and, where enforced, when the slope cone above it has been stripped; the overlay of mineable blocks applies the same rules as the server. A waste dump must exist before mining and a tailings dam before processing. Mined blocks go to a processing line, a run-of-mine stockpile (paying a holding cost and deferring the processing decision), direct shipping or the waste dump, with haulage priced per tonne-kilometre along the student's own site layout (Figure 4b). Each line runs crushing, grinding, concentration and is built separately, with its own capital, build time and extra operating cost per tonne; building charges the capital at once, and ore cannot be routed to a line before its build clock runs out. Staff add small, priced effects (lower unit costs, a throughput bonus β_{staff}, lower loan interest). The estimate-to-truth gap is paid only at settlement, as dilution and ore loss, and result screens report the share of mined blocks that had been assayed before the decision.

Two budgets per turn. A calendar turn has two physical budgets: tonnage (throughput × turn hours, raised by β_{staff}) and, per line, grinding energy (installed power × turn hours, raised by the same bonus). During staging, the game compares the estimated staged tonnage with its budget and estimates each line's grinding energy from the student's own work-index or grinding-energy readings, or from the line's design work index for blocks not measured; both are warnings, never refusals. Planned tonnages are also estimates: block volume multiplied by the student's own density measurement or, failing that, by the typical density of the block's visible rock type (a per-rock-type aggregate published in Reference data), the deposit's average density or the design SG of the deposit type, in that order. At settlement the engine takes the committed blocks in staging order and applies both budgets at each block's true tonnage and grinding energy. From the first block that does not fit onwards, all remaining blocks roll into the next turn (on the final turn they are left undone), and the settlement reports each line's energy used against its budget. Hard ore therefore costs throughput, and a student who has not measured hardness learns it at settlement, not before.

Quality on the turn blend. Buyers price the concentrate a line ships, not individual blocks, so penalties and premiums apply to each line's blend over the turn, weighted by concentrate tonnes. A penalty element has a threshold, a price per step above it and a rejection limit, so a blend between threshold and limit pays a graded penalty and one above the limit is rejected and earns nothing; phosphorus bands follow industry practice (S&P Global Commodity Insights, 2018). A block that would be rejected on its own can therefore be sold inside a passing blend. Royalty and

benefit sharing follow the blend's revenue change at their rates, and corporate tax is recomputed block by block on each block's share of the blend revenue, net of its own costs and depreciation, so a block rescued by the blend is taxed on what it actually earned. Each settlement reports every line's blend grades and the penalty or rejection incurred.

One ledger. Each turn nets one signed figure, the net cash

$$F_\tau = S_\tau - C_{\text{op},\tau} - C_{\text{roy},\tau} - C_{\text{tax},\tau} - C_{\text{CO}_2,\tau} - C_{\text{oh},\tau} - C_{\text{expl},\tau} - C_{\text{rem},\tau} - K_\tau \quad (3)$$

which subtracts from the revenue (after quality terms and freight) the operating cost (extraction scaled by the ground-support factor, loading, haulage, processing and energy, ESG costs and any permit surcharge), royalty, tax, carbon, overhead that partly follows utilisation, exploration and laboratory spend, remediation and capital. Every component is a signed row in the company's bank ledger, together with loan disbursements, interest and repayments, which are financing flows and therefore never enter F_τ. A loan is serviced by the run in which it was taken and is repaid from company cash when that run ends. Starting capital follows a stated rule.

Worth today and score. Two figures are derived from the same settled cash flow:

$$\text{NPV} = \sum_\tau F_\tau \, (1+r)^{-\tau/n_y}, \qquad A = \sum_\tau F_\tau \quad (4)$$

Worth today, the game's label for NPV, discounts each settled turn at the scenario's annual rate r on calendar time, counting turns from $\tau = 0$ (n_y turns per year; the game labels turn τ as turn $\tau + 1$). The rubric score uses the undiscounted after-tax margin A. Therefore, the score rewards how much the mine earned, while NPV also rewards when it earned it (Figure 4c). Internal rate of return, payback and break-even are computed from the same cash flow. Each rubric dimension is scored against a target, and the composite score is a weighted mean of the dimensions. The targets are suggested from a perfect-knowledge plan computed from the scenario's own Truth, and the publish checklist warns when an authored target falls outside 20–100 % of what that plan achieves. A class view shows anonymised medians, and a leaderboard ranks companies by net worth (cash minus debt).

6. Design principles

Five design principles emerged during the development of OreCraft. Each principle is enforced by the game rather than left to the instructor. Table 3 maps the learning outcomes to the mechanics that carry them and to the signals used in assessment; instructors can shift the emphasis between outcomes through the Knowledge, Difficulty and Evaluation assets.

Consequences must be gradual and visible. A student learns from a consequence only if it changes gradually with the decision and is actually shown to the student. Therefore, quality penalties increase stepwise between a threshold and a rejection limit. Capacity works the same way: tonnage or grinding energy beyond a turn's budget rolls into the next turn instead of being refused, and the settlement report states which budget was limiting.

One figure means one thing. Three figures are kept apart: worth today (NPV, discounted), the scored after-tax margin (the same net cash, undiscounted) and the company bank ledger, which also carries starting capital, loans and interest. The Result page shows worth today beside the undiscounted net cash (Figure 4c), and the Cash flow page states which cash flows each figure includes.

Laboratory and plant agree by construction. Separation tests are computed from the line's own recovery model, so a bench test differs from the plant result only by the plant efficiency. Similarly, the work index that the laboratory reports for a block is the work index at which the mill grinds that block, plus measurement noise. Any difference between test and plant is therefore caused by the student's sampling or by the known bench-to-plant bias, never by a hidden second model.

Information is priced. Every measurement costs money, time and sample mass, and its precision depends on the mass and core the student paid for. The value of a test therefore depends on the decision it informs. For example, a phosphorus assay costing about USD 540 has an expected value of information of USD 57 k, whereas a Davis tube, Satmagan or work-index test on the same blocks has none, because none of these tests can change the decision.

Nothing reveals Truth before commit. Everything a student sees while planning is an estimate, built either from the student's own measurements or from published typical and design values. This rule applies to grinding: the staged mill-power check and the turn preview use the student's hardness readings or the line's design work index, and the true hardness is applied only at settlement, with roll-over. It also applies to tonnage: every planned tonnage is block volume times an estimated density (Section 5). One exception remains: an instructor may switch on a mining-schedule hint that is computed from Truth; this hint is off by default.

Table 3. Learning outcomes, the mechanics and design principles that carry them, and assessment signals.

Learning outcome	Mechanic (principle)	Assessment signal
Value of information	Priced, noisy, delayed measurement (Eq. 2); sample mass and core diameter; exploration gate (information is priced)	Exploration spend; share of mined blocks assayed before the decision; value of a test
Integrated value-chain thinking	One settlement from block to ledger (Eqs. 3–4) (one figure means one thing)	After-tax margin against target; NPV
Geometallurgical reasoning	Mineral-specific lines; separation tests and work index from the plant's own model (laboratory and plant agree by construction)	Routing per domain; laboratory versus plant recovery
Product quality and blending	Stepwise quality terms on the turn blend; blend report; blend-share tax (consequences gradual and visible)	Penalties and rejections
Decision under uncertainty	Estimates only before commit; true tonnage, hardness and response applied at settlement, with roll-over (nothing reveals Truth before commit)	Dilution and ore loss; tonnes rolled over
Capital and financing	Plant builds; starting-capital rule; loans serviced by their run	Payback; interest paid; defaults
Sustainability	ESG costs, permit thresholds and surcharges, tailings method, closure bond	CO_2 score; permit status

7. Authoring and keeping the model coherent

A scenario fixes one asset of each kind (Table 1) plus the calendar, the price deck and the site layout. The world catalogues of minerals, analysis methods, process-test derivations and commodities are shared by all scenarios. Scenarios can be cloned with private copies of their assets, so a course can adapt a scenario without touching the original. A publish checklist blocks release while any item fails (for example an analysis the laboratory cannot deliver, or stored element grades that disagree with Eq. 1) and gives a warning for less severe problems, such as a rubric target that an asset change has made unreachable or trivial.

Keeping a model of this size coherent is itself a design task. An administrator System Map documents the code base at three levels: 11 domains, about 100 components, and automatically generated detail at file, route and database-table level, with version markers that show what changed in each release. Its impact analysis lists the components downstream of a proposed

change and, when the change touches the truth computation, the scenarios whose stored outcomes and rubric targets must be recomputed. An asset edit history records every create, update and delete of an asset with its author and a field-level diff, and layer rules (forbidden-import contracts checked by a test) prevent, for example, the service layer from depending on the API layer.

8. Discussion and limitations

OreCraft's contribution is the combination of Truth-versus-Knowledge separation, priced information, full-chain geometallurgy and a reconciled settlement in one authorable environment, rather than any single mechanic. The simplifications of the game are deliberate and are stated below. The two-product model that the current scenarios use does not depend on texture, and the texture-sensitive model (Appendix A) is not yet calibrated. Mineral chemistry is fixed per mineral. Gangue minerals report to the concentrate in proportion to their mass. Revenue is priced once, when Truth is computed, at one price per commodity. Therefore, prices do not change during a run, and price risk is not yet part of the lesson. Royalty is ad valorem only.

Tax is calculated with a floor for each block: each block is taxed on its own margin, with a minimum of zero. Therefore, a loss-making block does not offset the taxable profit of a profitable block in the same turn, as it would in a company tax return; the blend correction re-taxes blocks on their share of the blend but keeps the floor. The perfect-knowledge plan from which rubric targets are suggested ignores mill power and relies on roll-over to stay feasible; because the scored margin is undiscounted, roll-over does not reduce the score of that plan, only its NPV. Before its density is measured, a block with a visible rock type is planned at the typical density of that rock type. This density is an average over the block model, similar to the density table of a feasibility study, rather than the block's own value (Section 5). Four accounting choices remain open: the release of the closure bond is credited to the bank account but not to the net cash or the score; IRR and payback exclude exploration and remediation, which NPV includes; starting capital is granted per run and so accumulates across a company's runs; and the rubric's revenue metric uses block revenue rather than the blend-adjusted figure.

This paper documents the design and the models of the game; it does not evaluate learning outcomes. The next step is a controlled comparison of decision quality against matched problem-set instruction, using the action log that each run preserves, followed by further deposit and process archetypes (porphyry copper, hydrometallurgy) and instructor analytics. Beyond teaching, the engine allows alternative flowsheets, cut-off strategies or exploration budgets to be compared on one imported block model without a separate cash model.

9. Conclusion

Geometallurgy is a discipline of decisions made under uncertainty across a value chain, and it can be taught as such only where information has a price and outcomes are settled against a hidden reality. OreCraft provides such an environment: Truth separated from Knowledge, a measurement model grounded in sampling error, separation tests that agree with the plant, and a settlement that makes every mineralogical decision legible in cash, grade and environmental terms.

Although developed primarily for education, OreCraft is not limited only to classroom exercise. Its modular and authorable engine can accommodate different deposits, commodities, flowsheets, cost structures, measurement programmes and assessment criteria. This enables instructors to construct project-based courses in which students follow a case from exploration and characterization through mine planning, processing, operation and closure. The same framework can support conceptual project studies by comparing alternative exploration campaigns, testwork

strategies, cut-off policies and process configurations using a common block model and economic basis.

The architecture also provides a basis for more dynamic scenario analysis. Future developments can allow physical and economic outcomes to be recalculated under fluctuating commodity prices and other time-dependent conditions. Optimization algorithms can be incorporated for defined objectives, such as maximizing NPV, recovery or resource utilization, or minimizing energy use and environmental impacts. These optimized solutions can provide scenario-specific benchmarks against which student decisions or alternative project strategies can be compared. Such benchmarks would not prescribe a single correct solution but would help identify the trade-offs between competing technical, economic and environmental objectives.

Development of the platform is ongoing. Current priorities include adding further deposit and process archetypes, improving the calibration of mineralogy-based response models, introducing dynamic market conditions and optimization capabilities, and expanding instructor and researcher analytics. Planned classroom trials and controlled evaluation of learning outcomes will be used to assess its educational effectiveness and guide subsequent development. Through this iterative process, OreCraft is intended to develop from a serious game into a flexible platform for education, experimentation and collaborative mine-to-metal project studies.

Software availability

OreCraft v0.9.0-t171 runs at https://geomet.orecraft.se and is available for academic collaboration on request.

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Declaration of generative AI use

During the preparation of this work the authors used generative AI tools (Claude, Anthropic) to draft and edit text, to check references and the numerical consistency of the worked example, and to draw Figures 1–3 from the authors' specifications. After using these tools, the authors reviewed and edited the content as needed.

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APPENDIX

Appendix A. Liberation–texture recovery model

The fourth recovery model (Section 3) links grain size, grind size and texture to a grade–recovery curve in three stages. The model is implemented but not calibrated: the default constants ($a = 2.6$, $s_0 = 0.35$, $\kappa = 1.5$, $\nu_0 = 22$, $\xi = 0.06$, $a_{\text{sep}} = 13$) are illustrative and require calibration against liberation data before quantitative use. Two alternative Stage-1 kernels (a softened Gaudin form and a fracture-bias form) are also implemented.

Stage 1, liberation. Geometric liberation follows a logistic function of the grain-to-grind size ratio in decades, s, eroded by texture complexity C; the liberated fraction of the valuable mineral is further reduced by association A:

$$s = \log_{10}\left(\frac{d_{\text{g}}}{d_{\text{p}}}\right), \qquad s_{\text{eff}} = s - \kappa\,\frac{C}{100} \tag{A1}$$

$$L_{\text{geom}} = \left[1 + \exp\left(-a\,(s_{\text{eff}} - s_0)\right)\right]^{-1}, \qquad L_{\text{val}} = \left(1 - \frac{A}{100}\right) L_{\text{geom}} \tag{A2}$$

where d_{g} is the mineral grain size and d_{p} the grind size (P_{80}).

Stage 2, particle population. The feed is distributed over particle grade g (mass fraction of the target mineral in a particle) as liberated gangue ($g = 0$, mass fraction w_0), liberated target mineral ($g = 1$, w_1) and a Beta-distributed composite continuum whose mean μ follows from the mass balance on f and whose spread depends on complexity:

$$\varphi(g) = w_0\,\delta(g) + w_1\,\delta(g-1) + (1 - w_0 - w_1)\,\text{Beta}(g;\alpha,\beta) \tag{A3}$$

$$\alpha = \max(\mu\nu,\, 0.06), \qquad \beta = \max\big((1-\mu)\nu,\, 0.06\big), \qquad \nu = \nu_0\left(1 - 0.8\,\frac{C}{100}\right) \tag{A4}$$

In the engine, $w_1 = fL_{\text{val}}$, $w_0 = (1-f)L_{\text{geom}}$ and $\mu = f(1-L_{\text{val}})/[f(1-L_{\text{val}}) + (1-f)(1-L_{\text{geom}})]$, clamped to [0.001, 0.999]; the Beta density is discretised on the interior nodes of a 160-interval grid in g.

Stage 3, separation. Each particle class i passes a logistic separation kernel with cut-point g_{c}; entrainment with coefficient ξ adds a non-selective floor:

$$R_{\text{sep}}(g; g_{\text{c}}) = \left[1 + \exp\left(-a_{\text{sep}}\,(g - g_{\text{c}})\right)\right]^{-1} \tag{A5}$$

$$E(g_{\text{c}}) = \xi \sum_i \varphi_i\; R_{\text{sep}}(g_i; g_{\text{c}}), \qquad R_{\text{tot}}(g; g_{\text{c}}) = E(g_{\text{c}}) + [1 - E(g_{\text{c}})]R_{\text{sep}}(g; g_{\text{c}}) \tag{A6}$$

Sweeping g_{c} traces the grade–recovery curve (Figure A1). The plant runs at a single cut-point g_{c}^{*} solved once per profile when truth is computed (the economic optimum when the Economy asset defines prices, otherwise a grade-based optimum; a cut-point set by the instructor overrides both), and the target recovery is

$$R_T^{\text{plant}} = \frac{\eta_{\text{plant}}}{f} \sum_i \varphi_i\; g_i\, R_{\text{tot}}(g_i; g_{\text{c}}^{*}) \tag{A7}$$

In the engine, the denominator of Eq. A7 is the feed grade represented by φ, that is $\Sigma_i\, g_i\varphi_i$, which equals f to within the discretisation error of the grid, and η_{plant} multiplies the resulting target recovery. The cut-point is written g_{c} and the entrainment coefficient ξ to avoid a clash with the element index e.

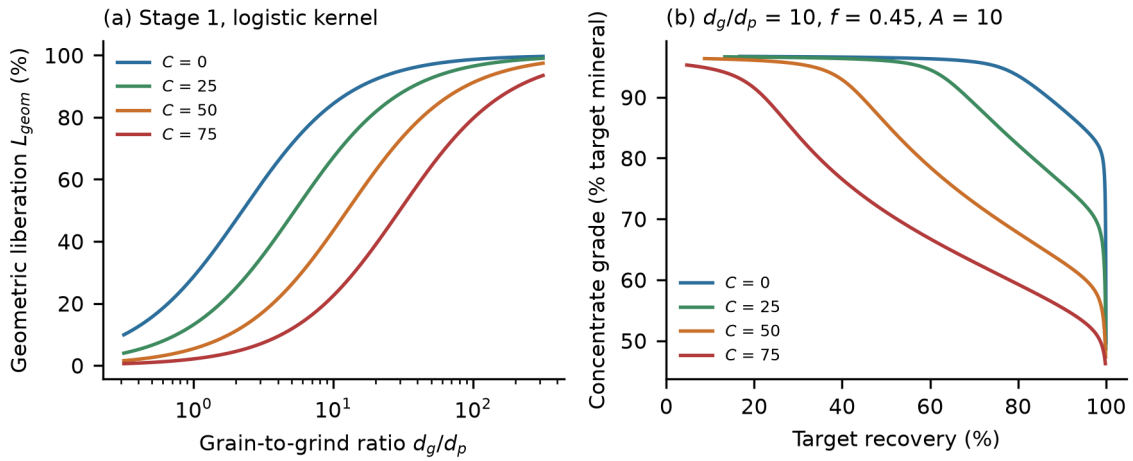

Figure A1. Liberation–texture model with default constants.