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Capital without Capacity? Claimant congestion, capitalization ceilings, and the public-value boundary in state-owned mining: a calibrated application to Codelco

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Capital without Capacity?

Claimant congestion, capitalization ceilings, and the public-value boundary in state-owned mining: a calibrated application to Codelco

Abstract

State-owned mining companies must finance long-lived replacement and expansion projects while governments, creditors, employees, contractors, communities, and prospective investors make claims on the same mineral surplus. Minority capitalization can reduce leverage and strengthen governance, but it also creates durable cash-flow and control rights. This paper develops claimant congestion as a distinct mechanism linking financing structure to productive performance. The model combines effective mining capital, debt, organized claimant pressure, bridging organizational cohesion, and execution capability. An exact public-value multiplier identifies when an issuance raises enterprise value but lowers public value, separates parent from project equity, and defines a capitalization boundary at which the marginal public return becomes negative. A reconstruction of Codelco for 2009-2025 shows that US$58.1 billion of investment during 2010-2025 accompanied a 19.8% decline in production, a 25.9% decline in average ore grade, an 8.2% increase in a grade-adjusted throughput proxy, and a US$19.6 billion increase in net debt. Nested mechanism ablation shows that organizational absorption and portfolio overload create finite boundaries, direct claimant entry compresses them, and governance-mediated claimant feedback changes both their location and the ranking of instruments. Continuation of the actual post-issuance equilibria finds residuals below 3.3e-7, negative spectral abscissae, and Jacobians bounded away from singularity over architectures up to approximately US$20 billion; the benchmark transition is therefore a smooth public-value inversion rather than a fold or Hopf bifurcation. An 800-draw uncertainty analysis yields median public-value-maximizing scales of US$7.92 billion for parent common equity, US$4.17 billion for preferred equity, and US$6.25 billion for both project and layered packages. The results support staged capitalization, project ring-fencing where assets are separable, a structural distribution rule, and secure but bounded state control.

Keywords: state-owned mining; Codelco; mixed ownership; mineral rents; public value; claimant congestion; project finance; corporate governance

1 Introduction

State-owned enterprises remain central to extractive industries, energy, infrastructure, and finance. Their persistence has displaced the earlier expectation that corporatization would lead mechanically to full privatization. Contemporary state capitalism instead includes wholly owned commercial corporations, listed firms with controlling public shareholders, public-private project companies, and sovereign holding structures. These forms differ less by the presence of the State than by the allocation of cash-flow, control, information, and adaptation rights (Musacchio and Lazzarini 2014; Bruton et al. 2015; Peng et al. 2016; Poyago-Theotoky 2024).

Mining makes the ownership problem intertemporal. Current production depletes an ore body, while exploration, replacement mines, underground transitions, processing facilities, water systems, and closure obligations require expenditure years or decades before their benefits are realized. The public owner can therefore demand distributions at the same time that the corporation must preserve cash and technical capability for the next generation of assets. A commodity-price boom may enlarge current cash flow while concealing declining grades, accumulating replacement needs, or an investment portfolio beyond the organization's capacity to execute.

Partial listing is often presented as a solution. A primary issuance can supply equity without an immediate increase in debt. Minority investors can demand disclosure, comparable accounting, protection against related-party transactions, and a board able to resist ad hoc intervention. The privatization literature documents frequent performance improvements, but also substantial heterogeneity by institutional environment, sale method, investor identity, and retained state control (Boardman and Vining 1989; Megginson and Netter 2001; Gupta 2005; Bortolotti and Faccio 2009; Estrin et al. 2009). More recent studies of mixed ownership show that the power attached to minority shares and board representation can redirect strategy rather than merely improve monitoring (Wang and Tan 2021; Yuan et al. 2023).

The usual argument nevertheless omits a basic accounting of institutions. Private shareholders do not replace the Treasury, creditors, employees, contractors, regulators, regions, or communities. They join them. Every financing instrument supplies capital and simultaneously creates a bundle of claims. Ordinary shares in a parent company reach across the existing portfolio and future opportunities. Preferred shares create a senior or quasi-senior distributional claim. Project equity can confine private rights to one asset, but only when the project is genuinely separable from common infrastructure, operating knowledge, and the parent balance sheet.

This paper develops claimant congestion as the link between those rights and mining performance. Claimant congestion is not a synonym for stakeholder diversity or a normative judgment about the legitimacy of claims. It is the ratio between the effective stock of enforceable or politically persistent claims and the structural residual rent available after operations, maintenance, and financing. When that ratio rises, the corporation loses flexibility to sequence projects, retain windfalls, absorb shocks, and transmit adverse information. The resulting coordination burden can reduce the efficiency with which capital expenditure becomes functioning productive capacity.

The mechanism extends, but does not reproduce literally, structural-demographic theory. Turchin's models connect fiscal pressure, the expansion of organized claimants, competition over a constrained surplus, and declining collective capacity (Turchin 2003; Turchin and Nefedov 2009). Here the unit is a corporation, not a polity. The transferable result is that organized claims are endogenous: expected rents attract claimants, established claims persist after rents fall, and the resulting congestion feeds back into the productive base. Organizational asabiya is correspondingly interpreted as bridging cohesion across the units, professions, contractors, and principals required to deliver a mine, rather than solidarity within any one claimant group.

The contribution is analytical and empirical. First, the paper derives an exact public-value multiplier from the complete institutional-capital system. The multiplier separates the direct financial effect of an issuance from the shadow value of its effects on capital, debt, claimant pressure, cohesion, and execution. It generates a public-value inversion condition, an instrument-selection boundary, and an endogenous capitalization ceiling. Second, the Codelco application reconstructs the joint movement of production, grade, investment, debt, fiscal contributions, and operating cash generation from official data for 2009-2025. Third, four nested models separate financial rights, organizational absorption, claimant entry, and the feedback from claimant congestion to production. The ablation shows what each mechanism adds and prevents the capitalization ceiling from being attributed mechanically to a single nonlinear term. Fourth, post-issuance equilibria are continued directly and their residuals, spectra, and singular values are calculated, rather than evaluating Jacobians along transient terminal states. Fifth, an 800-draw uncertainty analysis replaces point ceilings with distributions and reports the probability that the marginal public-value multiplier remains positive at each transaction scale.

Codelco is particularly informative because it is already subject to financial-market supervision and open-company-like disclosure under Law 20.392. Listing would therefore not create transparency from zero. It would add a traded residual claim, minority rights, and a market valuation to an already corporatized public enterprise (Biblioteca del Congreso Nacional de Chile 2009). The economic question is not whether transparency is desirable, but which additional rights must be issued to obtain capital and whether those rights improve the conversion of Chile's mineral patrimony into long-run public value.

2 Public corporations as layered systems of ownership and control

2.1 A public corporation is not an incomplete private firm

A conventional agency approach compares a public enterprise with a profit-maximizing private corporation and interprets deviations from profit maximization as political or managerial costs. Such costs are important, but the comparison is incomplete when the public owner values outcomes that are not captured by distributable profit. A state-owned mining corporation may preserve geological knowledge, strategic processing capacity, countercyclical investment, regional infrastructure, bargaining power, or intergenerational options. These activities can create public value even when they reduce current dividends.

A useful starting point is a weighted public objective,

$$\Omega = \pi + \omega_f B_f + \omega_s B_s + \omega_r B_r + \omega_t B_t + \omega_i B_i,$$

where π is corporate profit and the B terms denote fiscal, strategic, regional, technological, and intergenerational benefits. The difficulty is not merely that several objectives coexist. Their weights are not fixed. Ministries, boards, governments, creditors, managers, employees, and minority investors can influence them, often on different time horizons. The effective objective function is therefore negotiated through institutions rather than given exogenously.

Aharoni (1986) emphasized that state-owned enterprises operate through complex relations among governments, boards, managers, employees, and other constituencies. Peng et al. (2016) later argued that property-rights, transaction-cost, agency, and resource-based theories all require modification when the State is an owner. Public corporations should therefore be treated as a mainstream organizational form with a distinctive allocation of rights, not as a temporary deviation from the private-firm benchmark.

2.2 Residual income, residual control, and intervention

Ownership is a bundle of rights. For financing instrument j, let

$$\mathcal{R}_j = \left(r_j^c, r_j^v, r_j^i, r_j^x, r_j^\ell, r_j^a\right),$$

where the components represent cash-flow, voting, information, exit, litigation, and asset-scope rights. Two instruments supplying the same amount of capital can create different organizations because their rights differ in breadth, seniority, duration, and enforceability.

Sappington and Stiglitz (1987) show that public and private provision both involve delegation. The relevant distinction is the institutional cost of intervention. Public ownership permits direct intervention through shareholder authority, budget decisions, appointments, and statutory mandates. Private provision requires contracts, regulation, taxation, subsidy, or renegotiation. Easier intervention gives the State valuable adaptive capacity, but it also weakens commitment when corporate priorities can be revised after investment decisions have been made.

Incomplete-contract theory sharpens the distinction. When future contingencies cannot be specified fully, ownership assigns residual control over decisions left outside the contract. Private control can strengthen incentives for cost reduction and innovation, but may also encourage excessive reductions in non-contractible quality (Hart et al. 1997). In mining, imperfectly contractible quality includes geological learning, operational redundancy, closure quality, safety culture, long-horizon mine development, and the preservation of technical capability. These assets may deteriorate long before the loss is fully visible in financial statements.

Political agency introduces another layer. Shleifer and Vishny (1994) distinguish ownership of cash flows from political control over employment and other benefits. Commercialization or partial privatization can change one dimension without eliminating bargaining among politicians and managers. A government may retain ownership but lose practical discretion through creditor covenants. It may sell a minority interest while continuing to determine appointments and extraordinary distributions. It may also preserve strategic vetoes while transferring a substantial share of future cash-flow rights.

Partial privatization therefore creates a second agency relation. Management remains accountable to the State, but the controlling State becomes accountable to minority investors. Minority shareholders require protection against uncompensated public mandates, discriminatory transactions, and opportunistic distributions. The State, conversely, must protect strategic objectives against pressures for short-horizon dividends or project selection based solely on market valuation. Mixed ownership is a system of overlapping principals rather than a linear movement from political governance to market governance.

2.3 Soft budgets and the extraction-rescue cycle

The soft-budget constraint arises when expected future support changes present behavior. If a firm anticipates rescue after losses or liquidity pressure, it may undertake investments, preserve cost structures, or accumulate liabilities that would not survive a credible hard-budget regime (Kornai et al. 2003). For a strategically indispensable mining corporation, liquidation is neither credible nor necessarily desirable. The relevant problem is not to create a fictitious exit threat, but to distinguish productive recapitalization from support that validates previous overcommitment.

A state owner can simultaneously harden the corporation's internal investment constraint and soften its external survival constraint. It can extract cash, weaken retained earnings, permit debt accumulation, and later recapitalize the

company because strategic continuity cannot be abandoned. This extraction-rescue cycle can persist under mixed ownership. Creditors and minority shareholders may treat strategic status as an implicit state guarantee, while the Treasury continues to demand distributions.

Market participation does not harden the budget constraint automatically. It does so only when recapitalization, fiscal extraction, and project authorization are governed by rules known before distress appears. The OECD's current governance principles accordingly emphasize an explicit ownership policy, professionalized exercise of ownership rights, separation between ownership and regulation, board autonomy, disclosure, and transparent financing of public-policy obligations (OECD 2024).

2.4 Hybrid organizations and public value

State-owned enterprises vary along several dimensions: the proportion of state ownership, the allocation of voting rights, the autonomy of the board, exposure to capital markets, and the presence of public-policy assignments. Bruton et al. (2015) describe them as hybrid organizations in which public and private logics coexist. Musacchio and Lazzarini (2014) similarly distinguish forms of state capitalism ranging from direct bureaucratic control to the State as a majority or minority investor in professionally managed corporations.

A market valuation captures expected private cash flows attached to tradable rights. It does not automatically include geological information, strategic deposits, technical learning, system redundancy, national negotiating capacity, or intergenerational options. Following public-value theory (Moore 1995), the value of a state-owned mining corporation can be represented as

$$W = sV_f + V_g + V_c + V_o + PV(B) - V_h,$$

where sV_f is the State's share of financial value, V_g is geological and informational value, V_c is organizational capability, V_o is the value of strategic options, $PV(B)$ is the present value of fiscal and other public benefits, and V_h is the expected cost of institutional fragility. A capitalization operation can raise financial value while reducing one or more of the remaining terms.

Table 1 summarizes the theoretical mechanisms incorporated in the model.

Table 1. Established theories of public corporations and the additional claimant-congestion mechanism.

Literature	Established mechanism	Role in the present model
Public-enterprise and mixed-oligopoly theory	Public firms combine welfare and commercial objectives.	Public value is broader than the State's share of enterprise cash flow.
Property rights and incomplete contracts	Residual control determines incentives for non-contractible decisions.	Financing instruments are differentiated by cash-flow, voting, information, and asset-scope rights.
Political agency and multiple principals	Politicians, boards, managers, and investors can impose conflicting objectives.	Claims are weighted by enforceability and persistence rather than counted as stakeholder categories.
Soft-budget constraints	Expected rescue changes investment and borrowing before distress.	Fiscal extraction and later recapitalization can form an extraction-rescue cycle.
Resource-based and public-value theory	Technical capabilities and strategic options are productive public assets.	Capability, cohesion, and geological options enter public value directly.
Structural-demographic theory	Organized claims can outgrow the surplus that sustains them.	Claimant pressure is endogenous and reduces capital-conversion efficiency when congested.

3 Claimant congestion and institutional capacity

3.1 From organized rents to claimant pressure

A public mining corporation is surrounded by actors whose demands differ in form but draw on the same productive base. The Treasury seeks transfers. Creditors require interest and covenant compliance. Employees and contractors seek secure income. Communities and regions expect compensation and local benefits. Managers seek budget and

organizational scope. Prospective private investors seek distributions, information, and influence over decisions. Each demand may be legitimate in isolation while the aggregate remains inconsistent with the reproduction of the mining system.

The relevant quantity is the effective stock of organized claims,

$$E = \sum_{i=1}^{n} \omega_i \, c_i,$$

where c_i is the scale of claimant i's demand and ω_i is its enforcement, bargaining, political, or control weight. A small creditor group with binding covenants may exert more pressure than thousands of dispersed shareholders. A statutory transfer rule may be more persistent than episodic political requests. The variable E is therefore not a stakeholder count and not a moral ranking of claims. It measures how strongly claims constrain adaptation of the surplus.

Structural-demographic theory provides a mechanism for making claimant pressure endogenous. In agrarian states, Turchin and Nefedov (2009) link demographic expansion, elite proliferation, fiscal stress, and political instability. The corporate adaptation focuses on the relative growth of organized claims and structural residual rent. When anticipated rents are high, claimants enter or become stronger. When rents later decline, claims do not necessarily contract at the same speed. The organization carries an overhang.

Let R denote residual rent after operating costs, maintenance, and financing. Claimant congestion is

$$\zeta = \frac{E}{R + \varepsilon},$$

where $\varepsilon > 0$ prevents a singularity when residual rent is small. Congestion rises when claims increase, when rent falls, or when both occur together. A high absolute distribution is not destabilizing when the productive surplus can sustain it. The destabilizing condition is persistence of claims relative to the reproducible surplus.

The cumulative mechanism is

anticipated rent → stronger organized claims → greater congestion

→ weaker coordination → lower execution → lower future rent

3.2 Cohesion and execution capability

Organizational cohesion A is the capacity to coordinate across operating divisions, project teams, professions, contractors, and public principals while preserving the transmission of adverse information. It is closer to bridging than bonding social capital. Strong cohesion within a ministry, union, contractor network, management group, or shareholder bloc may increase that group's ability to appropriate resources or block adaptation. The productive form of cohesion connects the actors required to transform an ore body into sustained output.

Execution capability X is analytically distinct. It includes project design, portfolio control, mine planning, commissioning, ramp-up, maintenance integration, and the preservation of specialized technical knowledge. Cohesion makes coordinated execution possible, while successful execution regenerates cohesion by demonstrating that commitments are credible. The two variables can therefore reinforce one another.

Capital is productive only when the organization can absorb it. A large project portfolio can initially create learning, technical renewal, and economies of repetition. Beyond an absorption threshold, additional simultaneous projects compete for the same engineering, operating, and decision-making resources. Portfolio load then creates interface failures, managerial dilution, schedule instability, and turnover in critical roles.

3.3 Feedback structure

Figure 1 summarizes the central feedbacks. External capital raises investment and can reduce liabilities, but the rights attached to it add claimant pressure. Fiscal extraction increases liabilities when it exceeds available cash and can strengthen the Treasury's effective claim. Cohesion and capability raise capital-conversion efficiency and output.

Claimant congestion, leverage pressure, and portfolio overload weaken them. Lower output reduces residual rent, which further increases congestion.

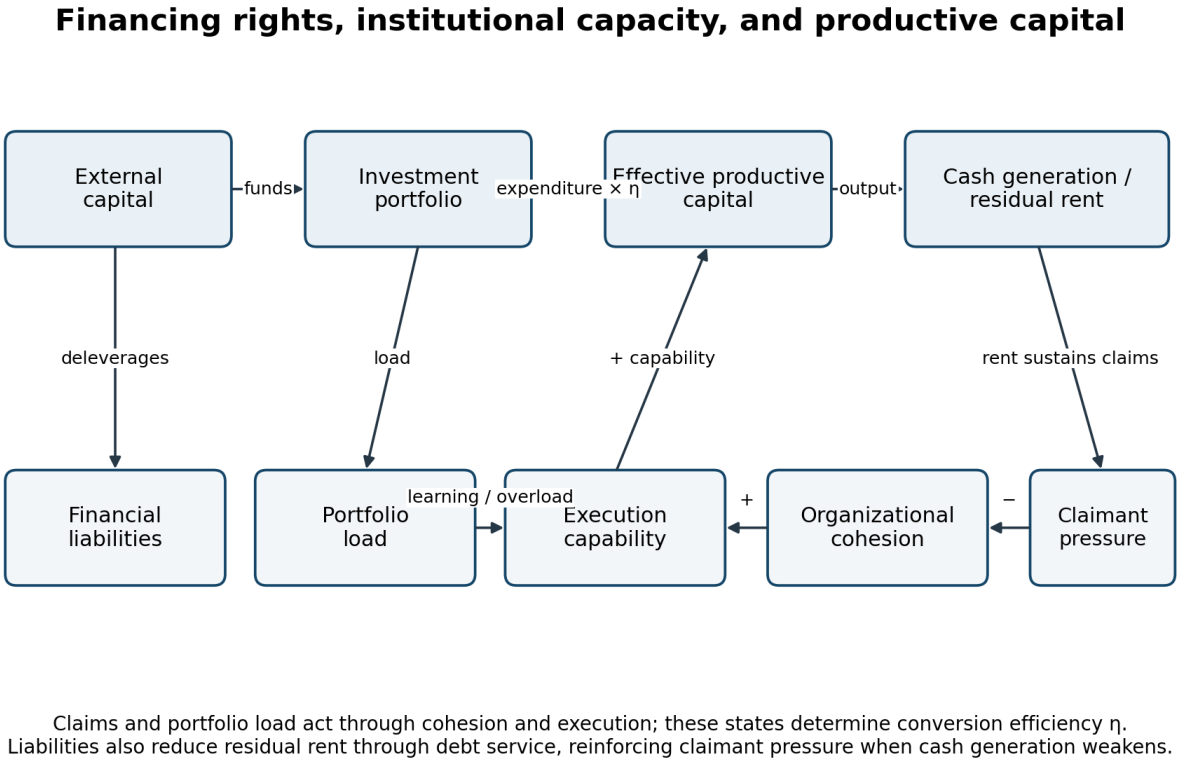


Figure 1. Institutional-capital feedback structure. Capitalization affects both the resource constraint and the stock of claims. Investment creates learning at moderate portfolio load and overload at high load.

4 A dynamic model of hybrid ownership

4.1 State variables and production

Let

$$y = (K, D, E, A, X)^{\top}$$

describe the corporation. Effective productive capital K consists of assets capable of generating reliable output. Financial liabilities are represented by D. The stock E measures organized claimant pressure, A bridging organizational cohesion, and X execution and operating capability. Cohesion and capability are normalized to $[0,1]$.

Mineral output is

$$Q = \Gamma K^{\alpha} A^{\gamma} X^{\beta}, \qquad 0 < \alpha \leq 1, \quad \beta, \gamma > 0,$$

where Γ collects ore grade, recoverability, mine geometry, and other geological conditions. The specification does not imply that cohesion substitutes mechanically for ore or equipment. It states that installed assets generate less effective output when technical interfaces fail, adverse information is suppressed, or project and operating units cannot coordinate.

Operating cash generation before financing and owner distributions is

$$C = (p - c_q)Q - c_K K,$$

where p is the realized mineral price, c_q the variable unit-cost component, and $c_K K$ fixed operating costs. Capital maintenance is represented separately by $I_m(K)$.

To preserve differentiability, define the smooth positive-part function

$$\psi_\epsilon(v) = \frac{v + \sqrt{v^2 + \epsilon^2}}{2}.$$

Structural residual rent is

$$R = \psi_\epsilon[C - r_D D - I_m(K)].$$

This residual is not reported accounting profit. It is the flow that can be distributed or committed without immediately reducing the reproduction of productive capacity.

4.2 Investment, leverage, and capital conversion

Authorized investment is

$$I = I_0 + i_R R + i_u u + i_K \psi_\epsilon\left(K^\dagger - K\right),$$

where u is external capitalization, $K^\dagger$ the desired productive-capital stock, i_R the share of residual rent retained for investment, and i_u the share of new external capital allocated to investment rather than deleveraging or liquidity.

Portfolio load and leverage pressure are

$$L = \frac{I}{K + \kappa}, \qquad d = \frac{D}{K + \kappa}.$$

Capital expenditure does not become productive capital one-for-one. Conversion efficiency is

$$\eta = \eta_0 \frac{A^{m_A} X^{m_X}}{1 + \chi\zeta}.$$

Cohesion and capability increase the share of expenditure converted into functioning assets. Claimant congestion lowers it through fragmentation, reprioritization, duplicated interfaces, premature distribution, and competition for critical personnel. Productive capital therefore evolves as

$$\dot{K} = \eta I - \delta_K K.$$

The financing identity is

$$\dot{D} = I + T + r_D D - C - u,$$

where T combines fiscal extraction and uncompensated public mandates. A simple rule is

$$T = \tau C + T_0.$$

External capitalization reduces liabilities on impact only to the extent that it is not absorbed by additional investment. Since $\partial I / \partial u = i_u$,

$$\frac{\partial \dot{D}}{\partial u} = i_u - 1.$$

Capitalization deleverages the corporation when $i_u < 1$, leaves debt unchanged on impact when $i_u = 1$, and can be followed by further debt accumulation when the availability of equity induces an investment programme larger than the funds raised.

4.3 Claimant pressure

Claimant pressure grows when residual rent per effective claimant exceeds the level needed to maintain a claim and contracts when rents fall or governance removes unsupported and overlapping claims:

$$\dot{E} = r_E E \left[\frac{R}{\bar{r}(E + \varepsilon_E)} - 1\right] + \sigma_J u + \sigma_T T - \mu_G G E.$$

The coefficient σ_j is the claimant loading of financing instrument j. It depends on the rights attached to the capital, the scope of assets covered, ownership concentration, and the duration of the claim. Parent-company ordinary equity is expected to have a higher σ_j than project-level equity because its rights extend across the whole corporate opportunity set. Preferred equity can occupy an intermediate position. The governance term does not eliminate legitimate stakeholders; it represents the capacity to clarify mandates, rank claims, expose their costs, and prevent several actors from exercising overlapping authority over the same decision.

4.4 Cohesion and capability

Cohesion evolves as

$$\dot{A} = P_A(1 - A) - H_A A,$$

with

$$P_A = a_0 + a_G G + a_X X$$

and

$$H_A = a_E \zeta + a_D d + a_L L^2 + a_M M.$$

Governance quality G and successful execution regenerate cohesion. Congestion, leverage, portfolio overload, and mission conflict M weaken it. The quadratic load term reflects the disproportionate coordination burden created when several large projects compete for the same specialized resources.

Execution capability evolves as

$$\dot{X} = P_X(1 - X) - H_X X,$$

where

$$P_X = x_0 + x_A A + x_L L\exp(-L/L_c)$$

and

$$H_X = x_E \zeta + x_D d + x_O L^2.$$

The term $L\exp(-L/L_c)$ represents learning from investment activity. It rises at low and moderate load but declines when the organization exceeds its effective learning scale. The L^2 term captures direct overload. Capital and capability are therefore complementary only over a bounded range.

5 Public-value multipliers and endogenous capitalization ceilings

The dynamic system determines the effect of a financing operation through all five state variables. Let y* be a locally stable equilibrium satisfying F(y*,u,j)=0, where u is the scale of capitalization and j denotes the financing architecture. Let W(y,u,j) be public value, including the State's residual financial interest, fiscal flows, capability, strategic options, and expected fragility costs. If the equilibrium Jacobian J=F_y is nonsingular, the implicit-function theorem gives

$$dy^*/du = -J^{-1}F_u.$$

The total public-value effect is therefore

$$M_j \equiv dW_j/du = W_u - W_\gamma J^{-1}F_u.$$

Define the shadow-value vector q by $q = -J^{-T}W_\gamma^T$. The same expression becomes

$$M_j = W_u + q^T F_{uj}.$$

This multiplier is exact locally. W_u contains the direct cash, dilution, distribution, and option effects of the instrument. F_u contains its effects on productive investment, deleveraging, claimant loading, governance, mission conflict, and partner-supplied capability. The vector q prices those state changes through the entire feedback system. Productive capital, cohesion, and capability ordinarily have positive shadow values; debt and claimant pressure ordinarily have negative values. Their magnitudes are endogenous and need not be constant across financing scales.

Proposition 1 — Public-value inversion

An issuance can raise enterprise value while lowering public value. Let V denote enterprise value and W public value. A public-value inversion occurs exactly when $V_u + q_v^T F_u > 0$ but $W_u + q w^T F_u < 0$. The first inequality can hold because the corporation receives cash and lowers financing risk. The second can fail because the State surrenders residual rights, the instrument adds claimant pressure, or strategic and institutional losses exceed the enterprise-value gain.

The distinction resolves an ambiguity in privatization analysis. A successful placement, lower leverage, or higher quoted enterprise value does not establish a gain for the public owner. Public value can fall even when the company becomes more valuable because the State owns a smaller share, minority rights constrain non-contractible public options, or additional distributions reduce future capital formation.

Proposition 2 — Instrument-selection boundary

For two instruments j and k introduced from the same initial state, j has the larger marginal public return if and only if $(W_u^j - W_u^k) + q^T(F_u^j - F_u^k) > 0$. Project equity therefore dominates parent common equity only when its lower parent-level claimant loading and any partner-supplied capability exceed interface costs, the value of cash-flow sharing, and the loss of portfolio flexibility. The boundary is an economic result, not an assumed ranking of instruments.

When direct cash proceeds are equal, the comparison can be displayed schematically as

$$-q^E \Delta\sigma + q^x \Delta x + q^D \Delta d \;>\; \text{interface costs + dilution and cash-flow sharing.}$$

Here $\Delta\sigma$ is the reduction in claimant loading, Δx is partner-supplied capability, and Δd is the difference in deleveraging. A project with extensive shared infrastructure may lie on the parent-equity side of the boundary even if it is legally ring-fenced. Conversely, a technically separable project with a capable partner can create more public value than parent equity despite sharing project cash flows.

Proposition 3 — Endogenous capitalization ceiling

Let $M_j(u)$ be continuous, positive at small u, and negative beyond some finite scale. Then $u^*_j = \inf\{u \geq 0 : M_j(u)=0\}$ is the public-value-maximizing capitalization ceiling whenever $M'_j(u^*_j)<0$. Below u^*_j, an additional unit of capital adds public value; above it, dilution, claimant congestion, rigid distributions, or portfolio overload exceed the productive gain.

The ceiling is not a statutory recommendation and is not the maximum finance the market would provide. It is a state-dependent marginal boundary. Better project separability, lower claimant loading, stronger execution capability, or more valuable deleveraging can move it outward. A high existing capability can also reduce the optimal tranche because the organization has less unused productive headroom. The relationship is therefore nonlinear and need not be monotone in a single governance index.

For a transition over a finite horizon rather than a stationary equilibrium, the same decomposition is obtained from the costate of the dynamic public-value functional. Appendix A gives the corresponding adjoint expression. The numerical application below evaluates that finite-horizon multiplier directly and checks the equilibrium spectrum separately.

6 Codelco data, institutional observations, and calibration

6.1 Data and definitions

The empirical reconstruction combines Codelco's restated key financial and operational series with annual reports, financial statements, and the COCHILCO investment series. The common window is 2009-2025. Production refers to total copper production reported in the restated 2025 series. Investment is reported in current US dollars; the model uses ratios to EBITDA and a 2025 scale rather than treating the nominal series as a homogeneous capital stock. Treasury contributions and net interest are retained separately because one is an owner claim and the other a

contractual financial claim. Their sum divided by EBITDA is used as a transparent first proxy for claimant load, not as a complete estimate of E.

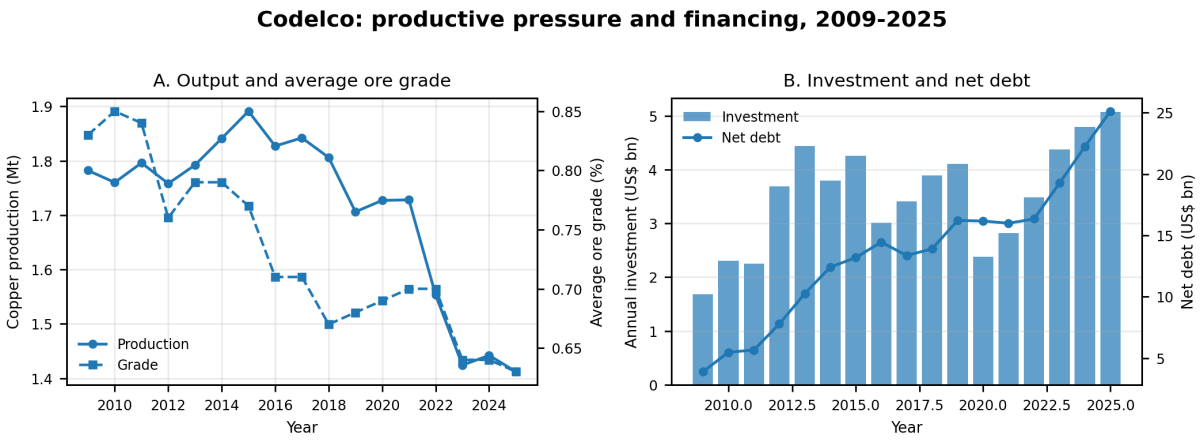


Figure 2. Codelco production, average ore grade, annual investment, and net debt, 2009-2025. Sources: Codelco (2026a) and COCHILCO (2025). The 2025 production series is restated.

Between 2010 and 2025, cumulative reported investment reached US$58.086 billion. Over the same interval, total copper production declined by 19.8%, average ore grade declined by 25.9%, and net debt increased by US$19.645 billion. These figures can support two opposite but incomplete narratives: that investment failed, or that Codelco merely needs still more capital. A grade-adjusted throughput proxy—production divided by average grade—increased by 8.2%. The proxy is not a metallurgical mass balance, but it shows that the system processed more effective ore per unit of contained grade even as headline copper output fell. Much of the investment burden was therefore reproductive: it compensated for geological deterioration, aging facilities, and structural transitions rather than producing a proportional increase in saleable copper.

Table 2. Codelco operating and financial indicators by period. Monetary values are annual averages in US$ billion unless otherwise stated.

Period	Production (Mt)	Grade (%)	C1 (¢/lb)	Investment	EBITDA	Net debt / EBITDA	Claimant load
2009-2013	1.778	0.814	128.1	2.87	7.48	0.92	0.63
2014-2019	1.819	0.722	138.6	3.75	4.38	3.38	0.44
2020-2025	1.548	0.667	173.6	3.82	6.25	3.33	0.47

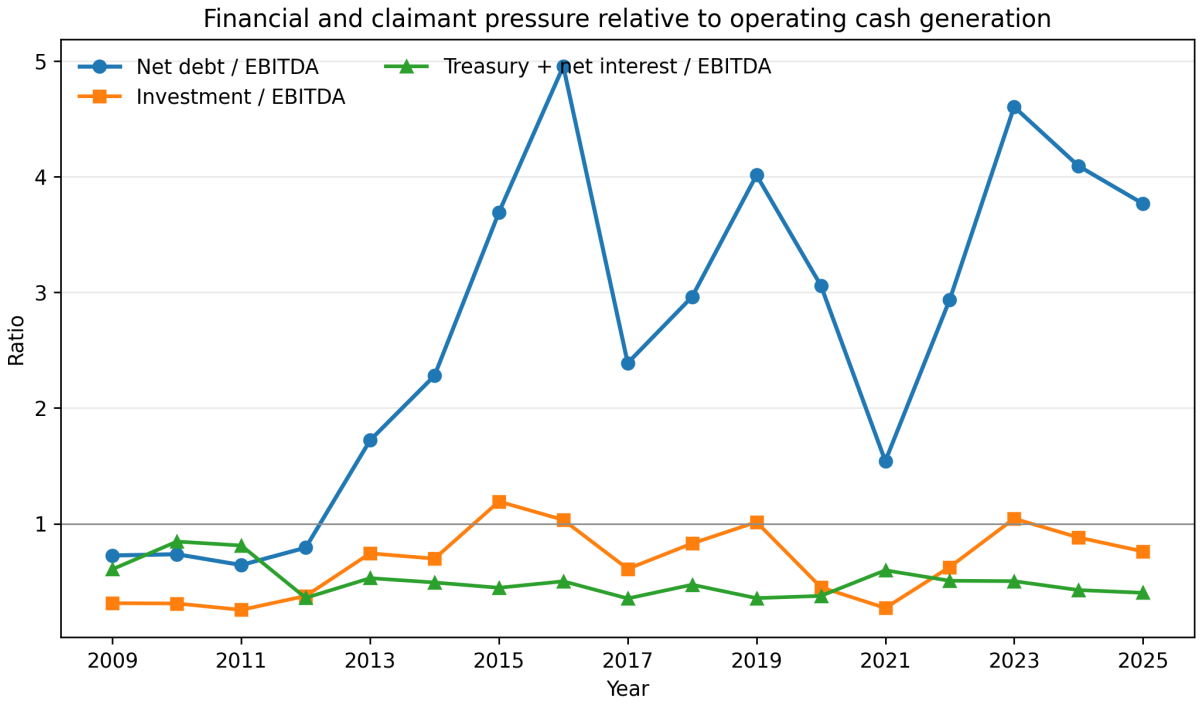


Figure 3. Net debt, investment, and the observable claimant-load proxy relative to EBITDA. The proxy equals Treasury contributions plus net interest divided by EBITDA; it excludes labor, contractor, regional, and prospective shareholder claims.

The period averages reveal a structural shift. Mean net debt/EBITDA increased from 0.92 in 2009-2013 to 3.38 in 2014-2019 and remained at 3.33 in 2020-2025. Investment/EBITDA more than doubled from 0.40 to 0.90 during 2014-2019 before falling to 0.67. The observable claimant-load proxy averaged 0.63 in the high-distribution years 2009-2013, declined to 0.44, and rose to 0.47 in 2020-2025. Claimant pressure therefore did not disappear when Treasury transfers fell: financial claims expanded as debt accumulated.

6.2 Information integrity as productive capacity

The 2025 production-reporting correction provides a direct institutional observation. Codelco's internal audit found that 26,875 tonnes reported as finished production in December 2025 did not satisfy the internal recognition conditions. The company corrected production reports, recalculated variable incentives, applied disciplinary measures, and commissioned an external KPMG review of the 2024 and 2025 production reports. Codelco stated that the finding did not require a restatement of its audited 2025 financial statements (Codelco 2026b, 2026c).

The importance of the event for the model is not the size of the correction alone. The audit identified deviations from internal rules, improper use of exception criteria, deficiencies in approval mechanisms, and effects on performance indicators and incentives. Information integrity is therefore not a cosmetic governance variable. It enters execution capability and cohesion because project selection, operating decisions, incentives, and board oversight depend on whether adverse operational information reaches the decision level without being converted into an apparently favorable indicator.

6.3 Calibration

The model is calibrated rather than statistically estimated. The purpose is to evaluate whether the analytical boundaries can occur at economically relevant scales under parameters anchored to Codelco's observed flows. All monetary variables are normalized by 2025 EBITDA, US$6.6697 billion. The initial debt state is 25.117/6.6697=3.766. The observable claimant state is initialized at (1.778+0.909)/6.6697=0.403 using Treasury contributions and net interest. The effective capital index is normalized to one. Cohesion and capability are initialized at 0.55 and varied in robustness tests. The 2025 interest-to-debt ratio anchors the financial cost, and the

investment and distribution equations reproduce the order of magnitude of 2025 investment and Treasury contributions.

External capital is introduced over four years and evaluated over a 25-year horizon at a 5% real discount rate. Parent common equity receives a permanent market-governance effect and dilutes the State's terminal financial share. Preferred equity creates a smaller control claim but a recurring distribution. Project equity directs a larger share of proceeds to productive investment and can add partner capability; it also shares project cash flow and incurs interface costs that rise as separability falls. The layered package combines limited parent equity, preferred capital, and project equity. These assumptions are reported explicitly so that the numerical results remain auditable and alterable rather than appearing as estimated facts.

Table 3. Principal benchmark calibration.

Quantity	Benchmark	Empirical or conceptual anchor	Sensitivity treatment
2025 EBITDA scale	US$6.6697 bn	Codelco restated key data	Fixed
Initial net debt D	3.766 EBITDA	US$25.117 bn / EBITDA	Fixed
Initial observable claimant stock E	0.403	Treasury + net interest / EBITDA	Claimant loading ±25%
Initial cohesion A and capability X	0.55, 0.55	Mid-range latent-state benchmark	0.45-0.65
Real discount rate	5%	Long-horizon public-value benchmark	4-7% in code
Issuance interval	4 years	Staged capitalization	Alternative paths available
Project separability	0.80	Moderately ring-fenceable project	0.50-0.95
Evaluation horizon	25 years	Mine-project and financing horizon	20-30 years in code

7 Results

7.1 The capitalization ceiling is a public-value boundary

Figure 4 reports the finite-horizon public-value multiplier for four instruments. All four are value-creating at sufficiently small scale in the benchmark calibration, but their marginal returns decline as the issuance expands. The decline is generated by the full system: additional capital reduces debt and raises investment, while larger portfolios, broader claims, distributions, dilution, and interface costs progressively offset those gains. The multiplier crosses zero without a discontinuity. The public-value ceiling is therefore an interior optimum rather than a claim that the corporation is unable to raise more finance.

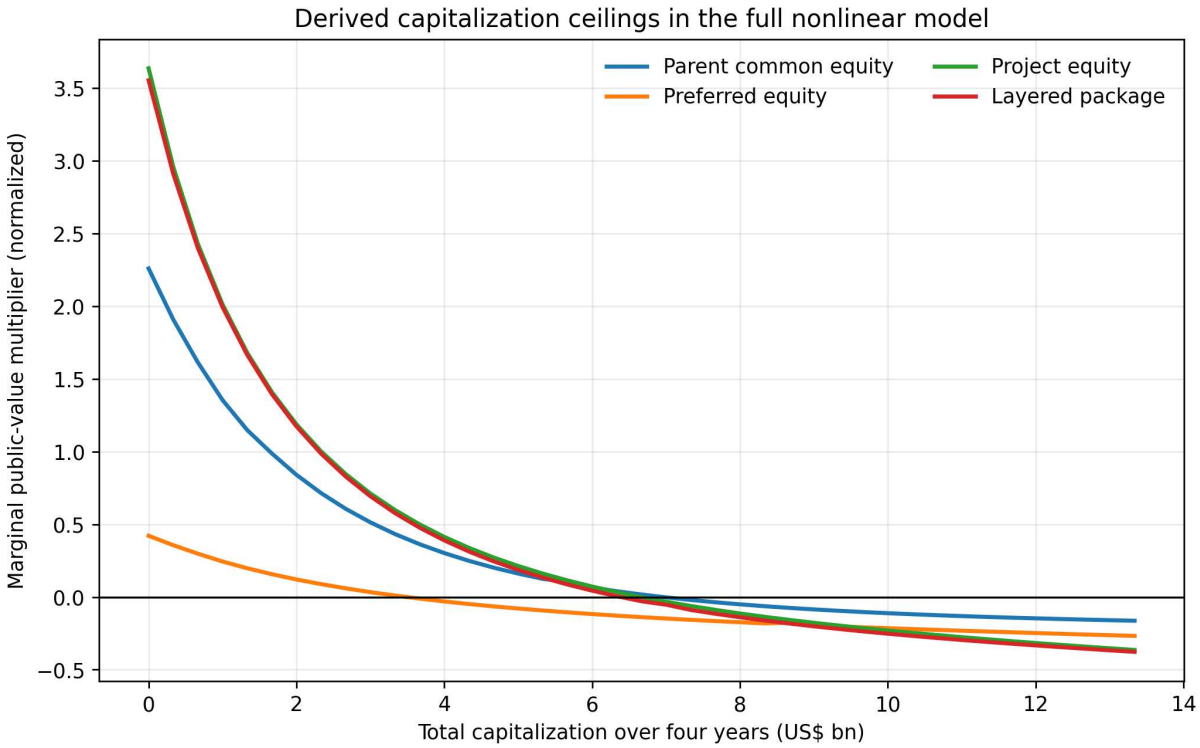


Figure 4. Marginal public-value multiplier as capitalization increases. The zero crossing is the endogenous capitalization ceiling. Capitalization is expressed in US$ billion using 2025 EBITDA as the normalization scale.

Table 4. Benchmark capitalization ceilings and public-value gains.

Instrument	Ceiling (EBITDA)	Ceiling (US$ bn)	Maximum Δ public value	State financial share at ceiling
Parent common equity	1.156	7.71	0.821	91.0%
Preferred equity	0.674	4.50	0.161	100%
Project equity (s=0.80)	0.999	6.66	1.084	100% at parent
Layered package (s=0.80)	0.970	6.47	1.068	98.0%

The numerical magnitudes are scenario results, not recommended transaction sizes. Their analytical content is the ordering and the existence of an interior boundary. Preferred equity has the lowest ceiling because its recurring distribution remains rigid after the deleveraging benefit has been obtained. Parent common equity has a larger safe scale because market governance raises capability in the calibration, but its maximum public-value gain is below the project and layered cases because it transfers a permanent share of the entire corporate portfolio. Project and layered financing produce the largest gains when project separability is high enough to prevent interface costs from overwhelming their lower parent-level claimant loading.

7.2 Project separability determines the instrument boundary

Figure 5 calculates the difference between project equity and parent common equity for a capitalization equal to 0.75 times 2025 EBITDA, approximately US$5.0 billion. The vertical axis varies project separability; the horizontal axis varies the claimant loading of parent equity. Project equity dominates above the zero contour. At the benchmark claimant loading, the boundary lies near a separability index of 0.58. Below that level, dependence on common infrastructure, operating knowledge, and parent guarantees makes legal ring-fencing economically incomplete.

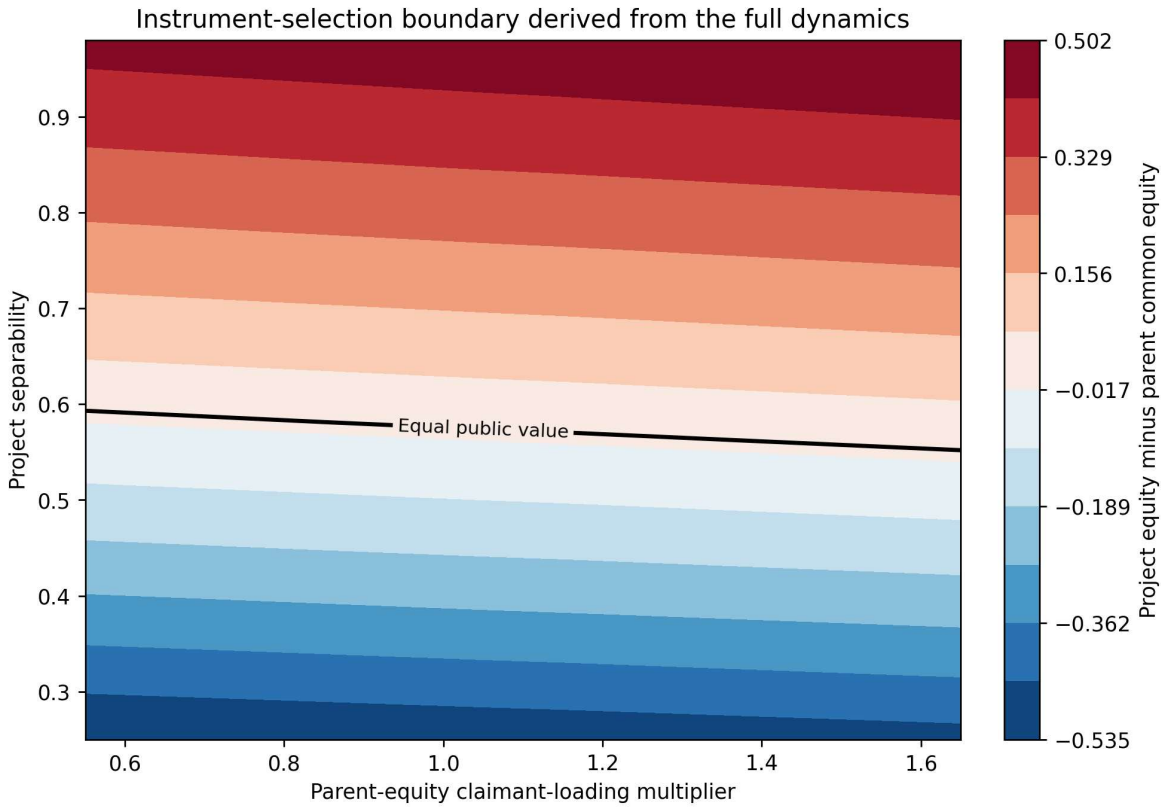


Figure 5. Instrument-selection boundary. Positive values indicate that project equity creates more public value than parent common equity; negative values favor parent equity. The contour is derived from the complete dynamics, not imposed as an instrument ranking.

This result provides a practical screening rule. Project finance is not preferable merely because it preserves parent ownership. The project must have identifiable cash flows, bounded interfaces, credible construction and operating responsibility, and a partner contribution beyond cash. Deeply integrated underground transitions or common processing systems can remain better financed at the parent level. Stand-alone water, energy, logistics, or technically separable mine-development packages are stronger candidates for ring-fenced participation.

7.3 Governance changes value, but does not remove diminishing returns

Governance improvements raise the level of public value by strengthening cohesion, information quality, and conversion efficiency. They do not make capitalization indefinitely productive. Figure 6 maps the marginal public-value multiplier for the layered package over capitalization and governance changes. The zero contour remains near US$6-7 billion in the benchmark region. Governance shifts the contour and raises the value generated below it, but dilution, distributions, and portfolio load still produce diminishing marginal returns.

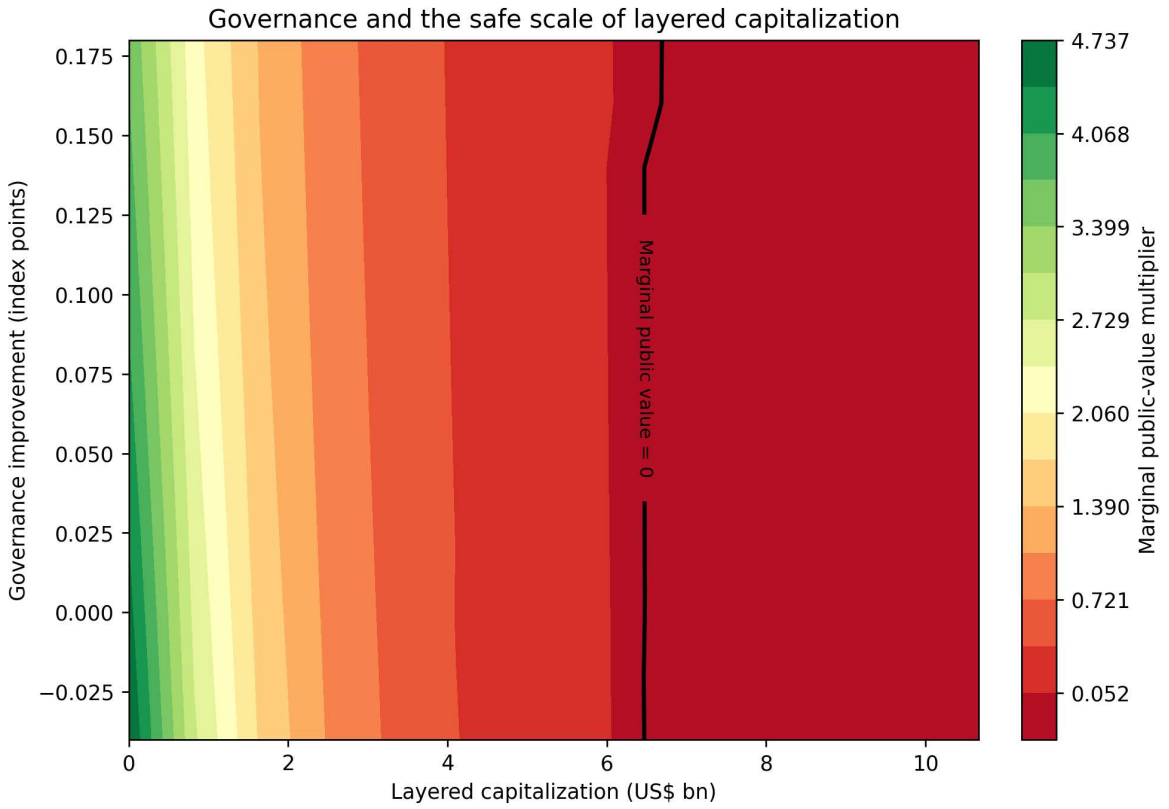


Figure 6. Marginal public-value multiplier for layered capitalization over financing scale and governance improvement. The black contour marks the public-value ceiling.

The result qualifies the statement that governance should precede capitalization. Better governance is valuable even without a transaction, and it generally raises the value produced by a given issuance. Yet an organization already operating at high capability can have less unused absorption capacity, so its optimal incremental tranche need not rise monotonically. Governance-first sequencing remains desirable because it improves conversion and reduces the risk of irreversible loss, not because it abolishes the ceiling.

7.4 Mechanism ablation identifies what creates the boundary

The capitalization boundary is not attributed to claimant congestion merely because claimant pressure appears in the full model. Four nested specifications separate the mechanisms. M0 allows finance, deleveraging, dilution, preferred distributions, and project cash-flow sharing while holding institutional states fixed. M1 endogenizes cohesion and execution capability and activates learning and portfolio overload, but excludes claimant entry and claimant effects on production. M2 adds instrument-specific claimant entry and its direct public and enterprise-value costs, while still preventing claimant pressure from altering capital conversion, cohesion, or capability. M3 restores the complete feedback from claimant congestion to those productive states.

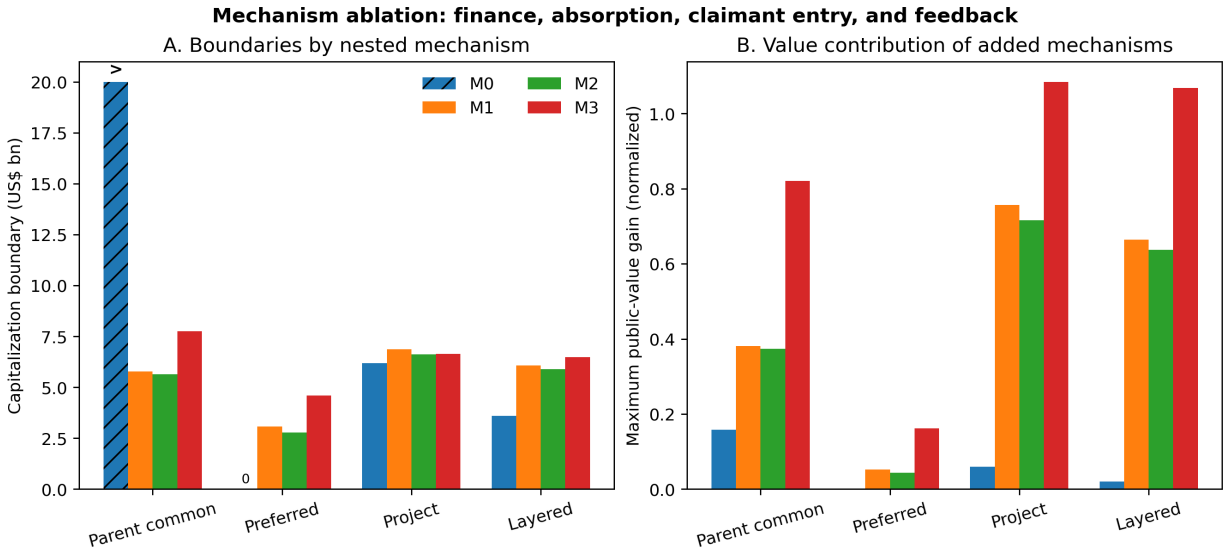


Figure 7. Mechanism ablation. M0 contains financial rights with fixed institutions; M1 adds endogenous absorption and overload; M2 adds claimant entry and direct claims; M3 adds the full feedback from claimant congestion to capital conversion, cohesion, and execution. The hatched M0 parent-common bar is right-censored above the US$20.0 billion grid; M0 preferred equity is not value-creating at the margin.

Table 5. Capitalization boundaries under nested mechanisms (US$ billion).

Model	Parent common	Preferred	Project	Layered	Project separability boundary
M0 Finance only	>20.0	Not positive	6.19	3.59	0.824
M1 + absorption/overload	5.78	3.08	6.87	6.06	0.467
M2 + claimant entry	5.63	2.78	6.63	5.90	0.481
M3 Full feedback	7.76	4.61	6.64	6.48	0.576

The ablation rejects two simple interpretations. Claimant congestion is not necessary for every finite boundary: once organizational absorption and portfolio overload are admitted in M1, parent common equity acquires a finite boundary near US$5.78 billion and the project and layered packages generate much larger gains than in the fixed-institution model. Yet claimant pressure is not redundant. Direct claimant entry in M2 lowers every interior boundary and reduces the maximum public-value gain. Restoring the full feedback in M3 changes the result again. Governance associated with the transaction can discipline incumbent claims and improve the conversion of capital, so the parent-common boundary moves outward to US$7.76 billion even though claimant entry remains costly. The claimant mechanism is therefore bidirectional: new rights add pressure, while credible governance can reduce the pre-existing stock and its productive drag.

The project-equity boundary also moves materially. At a US$5.0 billion transaction, project equity requires separability above 0.467 under absorption and overload alone, 0.481 after direct claimant entry, and 0.576 under the complete feedback. The final increase occurs because low-separability projects transmit partner claims and interface failures into the parent organization, where they affect cohesion and execution. This shift is the independent contribution of claimant congestion to the instrument-selection result; it is not reproduced by dilution or portfolio overload alone.

7.5 Equilibrium continuation excludes a local bifurcation in the calibrated region

The stability test is performed on equilibria rather than transient terminal states. For each instrument, the post-issuance autonomous system was solved for $F(y^*;U,j)=0$ and continued from zero to three times 2025 EBITDA, approximately US$20.0 billion. The continuation retained permanent governance and capability effects associated with the architecture while setting the temporary issuance flow to zero. Every solution satisfied the equilibrium equations with a residual norm below 3.3e-7.

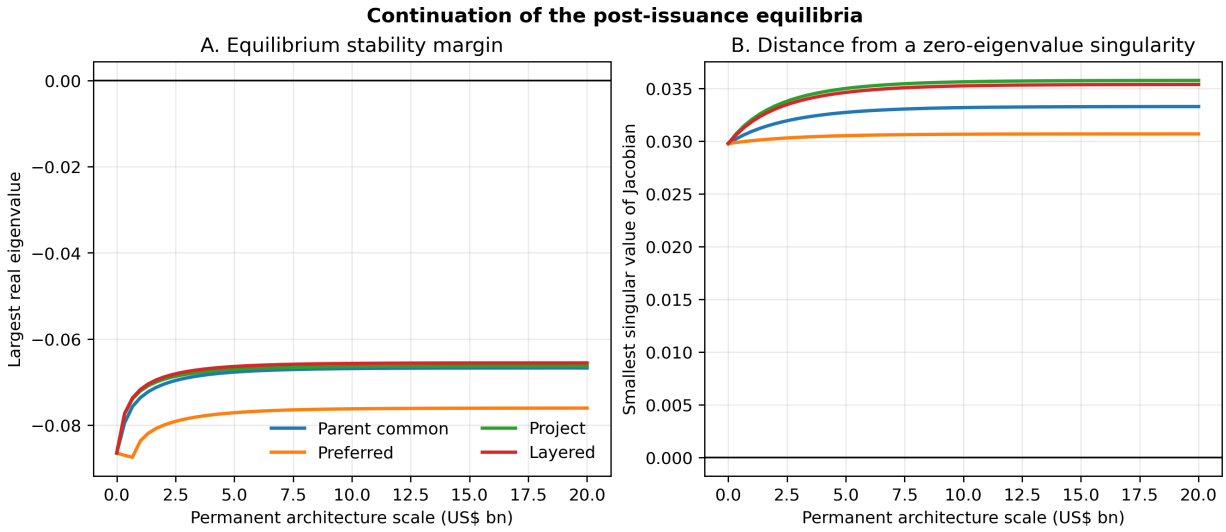


Figure 8. Continuation of the post-issuance equilibria. The spectral abscissa remains negative and the smallest singular value of the Jacobian remains positive throughout the examined architecture scale.

Table 6. Equilibrium and stability diagnostics over US$0-20.0 billion.

Instrument	Maximum residual norm	Largest spectral abscissa	Minimum Jacobian singular value	Largest imaginary part
Parent common	3.29e-07	-0.0667	0.0298	0.0143
Preferred	3.29e-07	-0.0760	0.0298	0.0081
Project	3.29e-07	-0.0663	0.0298	0.0173
Layered	3.29e-07	-0.0656	0.0298	0.0210

A fold would require a singular Jacobian with a simple zero eigenvalue. The smallest singular value remains at least 0.0298. A Hopf bifurcation would require a complex pair whose real part reaches zero. The largest spectral abscissa remains no greater than -0.0656, while the largest imaginary component remains small. No fold, cusp, Hopf, or higher-codimension point is therefore present on the continued equilibrium branches in the calibrated range. This result is stronger than the earlier inspection of simulated end states and establishes that the public-value ceiling is not a hidden stability loss.

The distinction is substantive. The equilibrium state can remain dynamically stable while the ownership architecture ceases to create public value at the margin. Dilution, distributions, claimant loading, and interface costs alter the objective before they destabilize production. A government can therefore cross the public-value boundary without observing a corporate crisis, which makes ex ante staging more important rather than less.

7.6 Probabilistic boundaries under institutional uncertainty

Point ceilings give a false impression of precision because cohesion, execution capability, claimant loading, interface costs, and strategic value are imperfectly observed. The calibrated model was therefore evaluated over 800 reproducible uncertainty draws. Initial cohesion and capability were drawn from triangular distributions spanning 0.43-0.69; the claimant stock, discount rate, capital-conversion efficiency, congestion effect, claimant loading, capability transfer, interface cost, overload intensity, dilution, governance effect, project separability, and all public-flow and terminal-value weights were varied independently around the benchmark. The exercise is prior-predictive sensitivity analysis rather than posterior estimation: it measures how decision boundaries propagate from transparent parameter ranges.

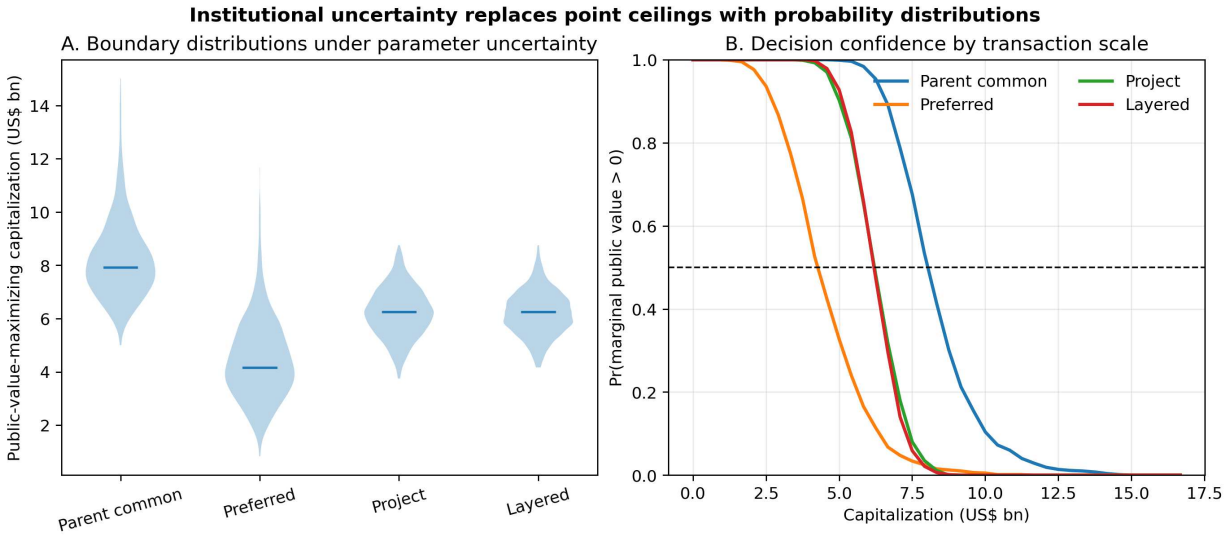


Figure 9. Capitalization boundaries under parameter and public-value uncertainty. Panel A reports the distribution of the public-value-maximizing scale. Panel B reports the share of 800 draws in which the marginal public-value multiplier remains positive.

Table 7. Probabilistic capitalization boundaries and instrument rankings.

Instrument	5th percentile	Median	95th percentile	Pr(best at own optimum)	Pr(best at US$5.0 bn)	Median max. gain
Parent common	6.25	7.92	10.84	10.8%	6.0%	0.744
Preferred	2.48	4.17	7.09	0.0%	0.0%	0.129
Project	4.59	6.25	7.92	42.9%	41.0%	0.912
Layered	5.00	6.25	7.50	46.4%	53.0%	0.914

The uncertainty analysis changes the interpretation of the benchmark values without eliminating the ordering. Median maximizing scales are US$7.92 billion for parent common equity, US$4.17 billion for preferred equity, and US$6.25 billion for both project and layered packages. The 5th-95th percentile intervals are wide: US$6.25-10.84 billion for parent common, US$2.48-7.09 billion for preferred, US$4.59-7.92 billion for project equity, and US$5.00-7.50 billion for the layered package. All 800 draws contain an interior maximum within the US$16.67 billion search interval.

The ranking is also probabilistic. At each instrument's own optimum, the layered package is best in 46.4% of draws and project equity in 42.9%; parent common equity is best in 10.8%, while preferred equity is never best. At a common transaction scale of approximately US$5.0 billion, the layered package is best in 53.0% of draws, project equity in 41.0%, and parent common equity in 6.0%. These frequencies do not identify a universally dominant instrument. They identify the institutional conditions under which each package is defensible.

Table 8. Probability that marginal public value remains positive at selected transaction scales.

Instrument	Approximately US$3 bn	Approximately US$5 bn	Approximately US$7 bn
Parent common	100.0%	99.9%	78.8%
Preferred	86.8%	32.8%	4.8%
Project	100.0%	90.2%	18.0%
Layered	100.0%	92.8%	14.0%

At approximately US$5.0 billion, the marginal multiplier remains positive in 99.9% of parent-common draws, 92.8% of layered draws, 90.3% of project-equity draws, and only 32.8% of preferred-equity draws. Near US$7.1 billion, the corresponding probabilities are 78.8%, 14.0%, 18.0%, and 4.8%. This provides a decision rule for staging: a later

tranche should be issued only while the probability of positive marginal public value remains above a publicly chosen confidence threshold and observed conversion performance is consistent with the parameter region supporting that probability.

7.7 Interpretation

The three analyses perform different tasks. Ablation identifies causal work inside the model: absorption and overload create finite productive boundaries; direct claimant entry shifts them inward; and governance-mediated claimant feedback changes both the size and the ranking of instruments. Equilibrium continuation determines that these boundaries are not local dynamical bifurcations. Probabilistic propagation determines how confidently the boundaries can be used for policy. Together they replace a hand-calibrated point result with a mechanism decomposition, a formal stability classification, and a distribution of decision-relevant thresholds.

The resulting recommendation is deliberately conditional. A first tranche near US$3 billion remains value-creating in almost every uncertainty draw for all four instruments except that preferred capital already has a lower margin. Around US$5 billion, parent common, project, and layered packages remain robust, but the preferred case becomes doubtful. Beyond US$7 billion, only parent common equity retains a high probability of positive marginal value, and that advantage is purchased through broader permanent dilution. The comparison must therefore include the scope of the rights transferred, not only the probability that the transaction remains marginally positive.

8 A layered institutional architecture for Codelco

8.1 Separate mineral patrimony from tradable claims

The national mineral patrimony and the operating corporation should not be treated as identical assets. Strategic mineral rights can remain entirely public while the operating holding receives durable development and operating rights sufficient to support long-horizon investment. Private investors would then acquire claims on operating cash flows and defined projects rather than an unrestricted share of the sovereign mineral endowment. The separation must not reduce the operator to a revocable contractor; security, duration, and adaptation rights must be credible.

8.2 Establish a professional ownership function and structural distribution rule

Chile's ownership, fiscal, regulatory, and policy functions should operate through distinct channels. A professional state ownership entity would publish the purpose of ownership, risk appetite, board-nomination criteria, dividend policy, and capitalization corridor. Mining, environmental, safety, and competition authorities would retain regulation. The Treasury would determine fiscal policy through an explicit rule rather than informal operating instructions. These arrangements implement the OECD principles of informed ownership, board responsibility, equitable treatment of minority investors, and explicit public-service obligations (OECD 2024).

Ordinary distributions should be calculated after structural maintenance, replacement investment, debt-service requirements, and an agreed debt corridor. Copper-price windfalls should be divided explicitly among debt reduction, investment, stabilization reserves, and exceptional fiscal transfers. Temporary rents should not create permanent recurrent claims without an explicit change in policy.

8.3 Use the narrowest instrument capable of carrying each risk

Parent common equity is appropriate when financing needs are portfolio-wide, project cash flows cannot be separated, and the governance value of a market float is large. Preferred capital is suitable for deleveraging only when its distribution terms absorb the copper cycle. Project equity is strongest when the asset is separable and the partner contributes technology, construction discipline, or operating capability. Shared infrastructure and parent guarantees must be priced as interfaces rather than hidden behind legal ring-fencing.

8.4 Stage capitalization and preserve secure control

Capital should enter in tranches linked to independently verified conversion into functioning assets. Later tranches would depend on capital-conversion efficiency, debt, execution capability, and claimant congestion rather than expenditure alone. A secure state voting floor—more robust than a bare 50%—would reduce recurring contests over

control. A narrowly drafted sovereign share could protect changes of control, strategic mineral rights, liquidation, and disposal of designated infrastructure. It should not allow routine intervention in mine planning, procurement, staffing, or commercial contracts.

8.5 Make public mandates visible

A public mandate should appear as a compensated service, an explicit reduction in expected owner return, or a statutory obligation incorporated into the corporate purpose. Its resource cost must be visible even when its public benefit cannot be monetized precisely. Unrecorded mandates create mission conflict and make weak commercial performance indistinguishable from deliberate public-value production.

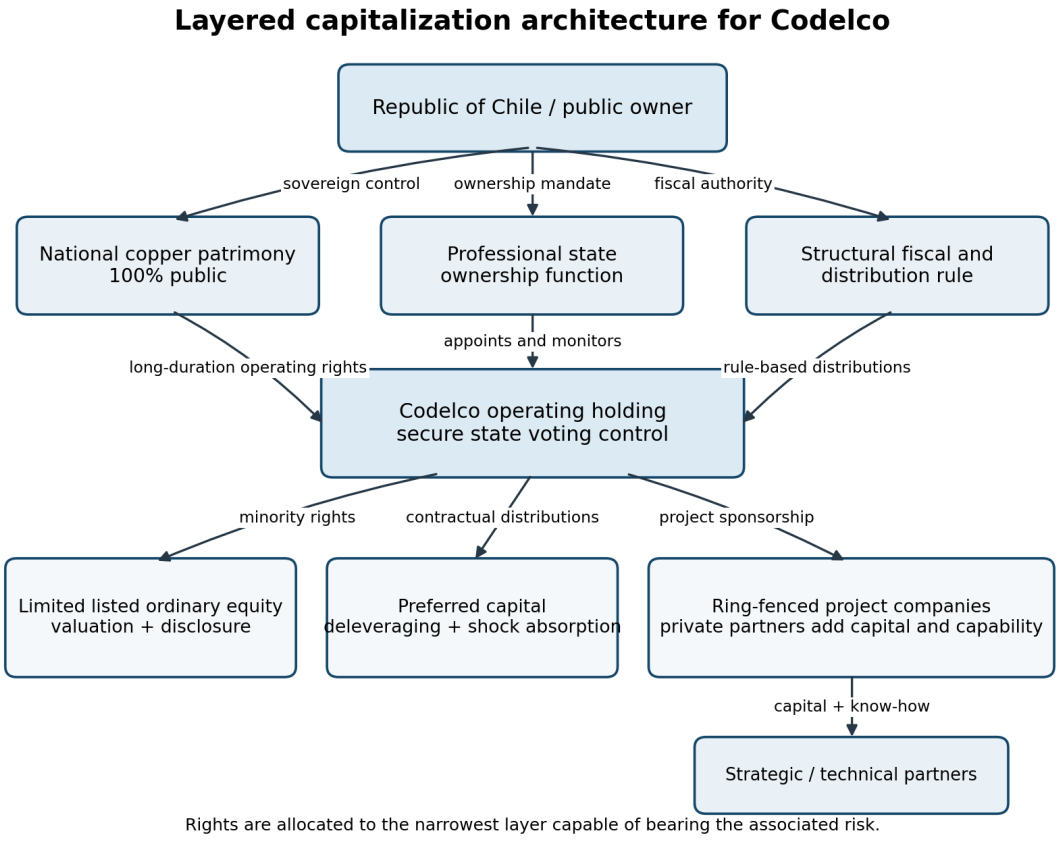


Figure 10. Layered institutional architecture. Strategic mineral patrimony remains entirely public; the operating holding retains secure state control; preferred, listed, and project capital carry distinct rights and risks.

9 Discussion

The analysis changes the unit of comparison in mixed ownership. The relevant object is not the percentage privatized but the public-value multiplier of the rights issued. This distinction explains why the same cash proceeds can produce different outcomes. Parent equity provides portfolio flexibility and market governance but reaches the whole opportunity set. Project equity limits parent dilution but can create costly interfaces. Preferred capital avoids voting dilution while adding a rigid distribution. Debt preserves ownership while transferring effective control through seniority and covenants.

Claimant congestion differs from conventional multiple-principal agency in two respects. First, claimant pressure is endogenous. Expected mineral rents, guarantees, and financing structures change the number, size, and persistence of claims. Second, the mechanism is productive rather than solely distributive. Congestion reduces capital-conversion efficiency and execution capability, so competition over rent can shrink the future rent over which actors compete. The model thereby connects public-corporation theory to the reproduction of a depleting mineral asset.

The Codelco record supports a constrained interpretation. The 2009-2025 data do not prove that claimant congestion caused the production decline. Grades fell sharply, and the grade-adjusted throughput proxy increased. The reconstruction instead rejects single-cause narratives. Codelco invested at a very high rate, expanded net debt, and improved effective throughput, yet did not offset geological deterioration in headline production. Its problem is simultaneously financial, geological, operational, and institutional. A financing reform that addresses only one dimension can shift the burden into another.

The 2025 production-reporting correction illustrates the model's information channel more directly. An indicator tied to incentives was recognized under deficient approval and exception procedures, and the board later expanded external assurance. The event shows how information quality, incentives, and control architecture enter productive capacity. It should not be generalized beyond the official findings, but it confirms that governance cannot be represented only by board independence or disclosure volume.

The calibrated ceilings are not forecasts. Cohesion, capability, interface costs, and strategic option values are not observed with the precision of debt or production. The numerical results are best understood as disciplined comparative statics anchored to Codelco's scale. Their value lies in the exact analytical decomposition, the reproducible assumptions, and the derived boundaries. A subsequent empirical paper can estimate the latent states from division- and project-level data; the present result identifies what must be measured and why.

The equilibrium continuation establishes that no local bifurcation occurs on the calibrated post-issuance branches up to approximately US$20 billion. More severe delays, political discontinuities, safety shocks, or nonlinear creditor responses could produce a different spectrum, but they are not required for the policy result. The public-value boundary is crossed while the operating equilibrium remains locally stable and can therefore be passed without a visible corporate crisis. This distinction strengthens the case for marginal evaluation: financial and operational stability do not guarantee that the next unit of capitalization still creates public value.

10 Conclusion

Codelco's capitalization problem is not a binary choice between preserving public ownership and accepting privatization. It is a design problem in which every financing instrument supplies cash and creates rights. Those rights differ in breadth, seniority, duration, and their effect on the organization's capacity to transform expenditure into functioning mines.

The paper derives an exact public-value multiplier from the joint dynamics of productive capital, debt, claimant pressure, organizational cohesion, and execution capability. Mechanism ablation shows that finite capitalization boundaries arise first from organizational absorption and portfolio overload, are compressed by direct claimant entry, and are then repositioned by the governance-mediated feedback of claims on cohesion, capability, and capital conversion. The full mechanism can therefore change both the scale and the ranking of financing instruments rather than merely adding a generic penalty. Equilibrium continuation further shows that these public-value inversions occur on locally stable branches, while the uncertainty analysis converts the apparent ceilings into probability distributions rather than point forecasts.

Official Codelco data show why this distinction matters. From 2010 to 2025, US$58.1 billion of investment and a US$19.6 billion increase in net debt accompanied falling production and sharply declining grades, while a grade-adjusted throughput proxy increased. The corporation has not simply lacked capital, nor has investment simply failed. It has used large amounts of capital to reproduce productive capacity under worsening geological and institutional conditions.

The strongest initial architecture is therefore layered and contingent. Strategic mineral patrimony remains entirely public. The State retains secure voting control of the operating holding. Separable projects admit partners able to add capability. Preferred and limited listed capital address leverage and market governance without treating all risks as parent ordinary equity. A structural distribution rule, explicit mandates, professional state ownership, and independent project assurance precede and condition later tranches.

The central mineral-economic result is that capital has an institutional marginal product. That marginal product is uncertain but measurable as a probability distribution. The objective is not to maximize the amount raised, but to

issue each tranche only while the probability that the next unit creates public value remains sufficiently high and the rights transferred remain narrower than the productive problem they are intended to solve.

Appendix A. Finite-horizon public-value derivative

Let the financing program have total scale U and time profile u(t;U). For instrument j, define the public-value functional

$$J_j(U) = \int_0^T e^{-rt} L(y(t),u(t;U),j)\, dt + e^{-rT} \Phi(y(T),U,j).$$

The state equation is $\dot{y}=F(y,u,j)$, with y(0) fixed. Define the current-value costate λ by

$$\dot{\lambda} = \rho\lambda - F_y^T\lambda - L_y^T, \quad \lambda(T)=\Phi_y^T.$$

The exact derivative with respect to the transaction scale is

$$dJ_j/dU = e^{-rT}\Phi_u + \int_0^T e^{-rt} [L_u + \lambda^T F_u]\, (\partial u/\partial U)\, dt.$$

The first term captures terminal dilution and direct instrument rights. The integral prices cash-flow effects and the induced changes in all state variables. The numerical multiplier in Section 7 is the finite-difference evaluation of this derivative. The equilibrium expression in Section 5 is recovered when the path converges to a stable stationary state and the horizon becomes long.

Appendix B. Equilibrium continuation and transition classification

For each financing architecture j and permanent architecture scale U, the post-issuance autonomous system was defined by setting the temporary issuance flow to zero while retaining the permanent governance and capability terms associated with U. Equilibria were calculated from

$$F(y^*,U,j) = 0.$$

Continuation used the preceding solution as the initial value for the next capitalization level and constrained K, D, and E to be non-negative and A and X to remain in (0,1). The maximum residual norm over 244 equilibria was 3.3e-7. At each equilibrium, the Jacobian $J=D_\gamma F$ was computed by centered differences. A fold requires det(J)=0 and a simple zero eigenvalue; a Hopf point requires a complex pair with zero real part and a transversal crossing. Across US$0-20.0 billion, the largest spectral abscissa was -0.0656 and the smallest singular value of J was 0.0298. Neither prerequisite occurred, so higher-order normal-form coefficients were not calculated.

Appendix C. Nested mechanism specifications

M0 retains the financial identity, debt reduction, productive investment, dilution, preferred distributions, and project cash-flow sharing, while holding E, A, and X fixed. M1 makes A and X endogenous and activates investment learning and portfolio overload, but excludes claimant entry and all effects of E on capital conversion, cohesion, or capability. M2 adds instrument-specific claimant entry and the direct public and enterprise-value costs of E, but maintains zero claimant coefficients in the productive equations. M3 restores the complete claimant-congestion feedback. The nesting changes no financial-right term across models, allowing differences in ceilings, gains, and the project-separability boundary to be attributed to the mechanisms added at each step.

Appendix D. Uncertainty propagation and reproducibility

The uncertainty analysis uses 800 draws generated with seed 20260729. Initial cohesion and capability follow triangular distributions on 0.43-0.69 with mode 0.55. The initial claimant stock is multiplied by a triangular factor on 0.70-1.35 with mode 1. The real discount rate is uniform on 4-7%. Capital-conversion efficiency, claimant loading, capability transfer, interface cost, overload, dilution, governance effects, and public-value weights are multiplied by independent lognormal variables centered at one. Project separability follows a triangular distribution on 0.45-0.97 with mode 0.80. The model is evaluated on a capitalization grid from zero to 2.5 times 2025 EBITDA. The public-value-maximizing scale is the grid maximum, and the marginal-positive probability is the share of draws with a positive numerical derivative at each scale.

The supplementary package contains the 2009-2025 derived dataset, period summaries, benchmark model, nested ablation results, equilibrium continuation, probabilistic draw-level results, probability curves, figures, and executable scripts. Official source values are retained separately from derived ratios. The analysis is prior-predictive sensitivity analysis, not a posterior parameter estimate from the Codelco time series.

Declarations

Conflict of interest: The author declares no competing interests.

Data availability: The underlying corporate and investment series are publicly available from Codelco and COCHILCO. The derived dataset and code accompany the manuscript as supplementary material.

Generative AI statement: AI-assisted tools were used only for limited editorial support and translation from Spanish. The author assumes full responsibility for the accuracy, integrity, and final content of the article.

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