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Strategic governance of quantum supply chains: a criticality-based framework for risk, resilience, and data-driven foresight

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Abstract

Quantum technologies are moving from laboratory research to real-world deployment, but progress rests on narrow, fragile, globally dispersed supply chains. We introduce the Quantum Criticality Index (QCI)—a tri-axial assessment of supply risk, substitutability, and strategic significance—augmented with an artificial neural network (ANN)-based trend-detection module and a forward-looking stress-testing component. A case study of molybdenum (Mo), essential for superconducting circuits, single-photon detectors, cryogenic hardware, and other dual-use, security-sensitive systems, demonstrates how the QCI pinpoints chokepoints that could hinder hardware trajectories. Building on these diagnostics, we translate risk awareness into action through a governance framework that links the stages of diagnosis, decision, and delivery. By coupling structured indicators with predictive analytics, the QCI provides policymakers and industry with an evidence-based tool that translates diagnostics directly into an operational policy roadmap for allied procurement, intellectual property governance, targeted licensing, and verifiable, sustainable supply-chain assurance. Crucially, QCI-enabled supply chain resilience can function as a hardware-oriented complement to Post-Quantum Cryptography (PQC) migration, together forming a twin-pillar security framework in which physical supply-chain assurance underpins the quantum ecosystem, while PQC protects data integrity and critical infrastructure against "harvest-now, decrypt-later" campaigns and systemic risks.

Keywords: Quantum technologies; Supply-chain governance; Critical materials; Resilience; Artificial neural networks (ANN); Quantum Criticality Index (QCI); Export controls; ESG; Allied technology strategy

1 Introduction: quantum technologies at a strategic crossroads

Quantum technologies—encompassing computing, communication, and sensing—are transitioning from laboratory prototypes to pre-commercial deployment. Major governments and corporations now regard quantum capabilities as key determinants of technological competitiveness and national security [1, 2]. Quantum communication offers the potential for globally secure networks; quantum computing may revolutionise optimisation processes, materials discovery, and cryptography; and quantum sensors are poised to transform navigation, subsurface exploration, and specific defence applications.

Unlike semiconductors or conventional information and communication technologies (ICT), quantum innovation relies on narrow, specialised supply chains that remain poorly characterised and fragile [3]. Numerous critical inputs—such as raw materials, components, and specialised equipment—are concentrated within a limited number of jurisdictions or vendors. Early-warning indicators include helium scarcity, which has restricted laboratory operations [4]; export restrictions affecting rare-earth elements and semiconductor-related inputs (e.g., gallium and germanium) that reveal systemic dependencies [5, 6]; and reliance on a small group of dilution-refrigerator suppliers [7, 8].

The dual-use characteristics of quantum technologies further amplify these vulnerabilities. Cryptographic modules, precision sensors, and superconducting qubits serve civilian markets while simultaneously providing advantages for military and intelligence applications [9, 10]. Consequently, materials and components essential to these systems attract regulatory scrutiny and may become subject to export controls, sanctions, or the weaponisation of interdependence. Several inputs—such as helium-3 (a scarce byproduct of tritium decay) [11, 12], isotopically enriched silicon-28 (required to suppress spin noise) [13, 14], thin-film lithium niobate (TFLN, $LiNbO_3$) for photonics [15], electronic-grade diamond for quantum memory [16], and superconducting metals such as niobium [17] or indium—lack readily available substitutes. These constraints extend to enabling hardware, particularly dilution refrigerators, which face multi-month lead times from a narrow supplier base (notably Bluefors and Oxford Instruments) [7, 8, 18, 19], thereby elevating tail-risk concerns where a single disruption could halt national initiatives or international deployments.

Existing assessments fall short. Government lists of critical raw materials—such as the European Union Critical Raw Materials Act (EU CRMA, 2023) [20] or the United States (U.S.) Critical Minerals Strategy [21]—are essential but often too broad, failing to capture quantum-specific challenges such as isotopic enrichment, sub-Kelvin refrigeration, or single-photon detection [22, 23]. Moreover, these lists are updated at a slower pace than advances in quantum technologies, leading to mis-prioritisation as particular architectures begin to scale.

This paper introduces the Quantum Criticality Index (QCI), a framework for evaluating vulnerabilities in the supply chains of quantum technologies, with a focus on essential raw materials, components, and equipment required for quantum-computing research, development, and manufacturing. The QCI combines supply risk, substitutability, and strategic importance to identify emerging quantum bottlenecks. Static diagnostics are enhanced through an artificial neural network (ANN)–based foresight layer that detects trend shifts and stress-test scenarios such as demand surges, regulatory changes, and regional shocks.

This framework is explicitly designed for a dual audience of policymakers and industrial strategists. For national security councils and export-control authorities, the QCI offers a dynamic alternative to static control lists, enabling the anticipation of bottlenecks before they crystallise into systemic vulnerabilities. This urgency is underscored by the "harvest-now, decrypt-later" strategy, which accelerates the timeline for strategic risk and renders immediate supply-chain resilience and allied Post-Quantum Cryptography (PQC) migration—the *twin pillars* of quantum security—prerequisites for long-term information security [10, 24]. For industrial planners and alliance managers—such as those within the NATO Defence Innovation Accelerator (DIANA) or national quantum strategy offices—the QCI provides an empirical evidentiary basis to justify strategic stockpiling, procurement diversification, and coordinated allied industrial policy.

Accordingly, this inquiry addresses three core questions: (i) how a quantum-specific criticality framework can facilitate anticipatory governance of supply chains; (ii) which indicators and methodologies most effectively capture evolving, non-linear risk trajectories; and (iii) how such diagnostics can be operationalised as tools for alliances and regulatory bodies. The paper contributes a tri-axial QCI tailored to quantum-technology inputs, an integrated ANN module for early warning and scenario analysis, and a policy roadmap that links QCI outputs to diversification, substitution, circularity, calibrated stockpiling, and standards or control alignment.

2 Background and motivation

2.1 Quantum technologies as strategic assets

Quantum innovation has become a national priority across the U.S., the EU, China, and other regions [1, 2, 10]. Reflecting its transformative and dual-use potential, the United Nations General Assembly proclaimed 2025 as the International Year of Quantum Science and Technology (IYQ), highlighting the field's global significance for sustainable development, innovation, and international security governance [25].

Some applications challenge fundamental infrastructures: future quantum computers threaten current public-key cryptography, while advanced sensors could, under certain circumstances, narrow stealth margins relevant to deterrence in undersea or aerial operations. Quantum devices are fragile—often requiring millikelvin environments and highly reliable cryogenic operations [26], with practical dependencies on specialised dilution-refrigerator systems [7, 8]. Consequently, hardware relies on complex, multi-regional supply chains for exotic materials and precision equipment. Governance frameworks remain nascent and struggle to keep pace with technological advancements as deployments approach critical sectors such as secure communications, finance, and defence, increasing bottlenecks and systemic risks [27].

This strategic landscape is defined by an asymmetry in timelines. As commentators observe, the "harvest-now, decrypt-later" operational concept means the threat window is not in the future but is open today; adversaries are actively intercepting encrypted traffic for future decryption [10, 24]. This creates a dual imperative for allied governance: while Post-Quantum Cryptography (PQC) migration—potentially flanked by Quantum Key Distribution (QKD)—acts as the necessary software shield for data integrity and critical infrastructure, the governance of quantum supply chains serves as the essential hardware shield, ensuring that the physical capabilities required to achieve (or counter) quantum advantage remain secure and accessible.

States are also strengthening their policy toolkits. In the U.S., the Department of the Treasury has finalised and implemented the outbound-investment programme established under Executive Order 14105, "Addressing United States Investments in Certain National Security Technologies and Products in Countries of Concern," effective 2 January 2025 [28, 29]. The order encompasses sectors such as quantum information technologies. Simultaneously, the National Quantum Initiative continues to finance and coordinate domestic Quantum Information Science (QIS) capabilities through its fiscal-year 2025 supplement to the President's Budget.

In Europe, initiatives such as the Quantum Flagship and the 2023 CRMA reinforce strategic autonomy and resilience in critical resources [20], while the European Commission's 2025 update to the EU Dual-Use Control List adds further quantum-related items to the export-licensing regime [30]. The 2025 update also reflects the EU's alignment with multilateral export-control regimes—namely the Wassenaar Arrangement (WA), the Missile Technology Control Regime (MTCR), the Australia Group (AG), and the Nuclear Suppliers Group (NSG)—as consolidated in 2024. Under the WA, Member States agreed to uniformly control additional dual-use and emerging-technology items, including quantum-related components and equipment, thereby ensuring consistency across national control lists and reinforcing transatlantic policy coherence [31].

In Asia, China and Japan provide instructive counterpoints. China has consolidated authorities under its Export Control Law (2020) and has progressively tightened controls on strategic inputs and technologies—most recently via Announcement No. 10 (2025), which imposes export controls on items related to tungsten, tellurium, bismuth, molybdenum, and indium [32–34]. These legal authorities coincide with structural market power, including dominant shares in rare-earth processing [35, 36]. Together with expanding catalogues governing restricted technology transfer and security reviews for outbound data and know-how, these measures signal a shift toward domestically anchored supply assurance and greater leverage over dual-use chokepoints.

Japan, operating through the Ministry of Economy, Trade and Industry (METI) under the Foreign Exchange and Foreign Trade Act (FEFTA) and aligned with WA commitments, already treats quantum cryptography and related items as licensable exports and is incrementally extending coverage to upstream enablers (e.g., advanced processors, specialised cryogenic equipment, and lithography tooling). These trade and technology-security instruments sit alongside national research and development (R&D) programmes (e.g., the Quantum Strategy and Q-LEAP) and Japan's economic-security legislation, collectively aiming to balance openness in research with tighter control of high-consequence applications.

Despite these advances, fragmented mandates and cross-border supply chains remain barriers to coherent implementation, prompting calls for stronger central coordination and shared risk-indicator frameworks across allied economies.

2.2 Criticality and supply risk frameworks

Criticality evaluates resources based on (i) the likelihood of disruption and (ii) the impact on technologies and economies [37–39]. Building on the methodology established by the U.S. National Research Council (NRC), materials are categorised in a matrix that considers supply risk and technological vulnerability/importance in use (see Fig. 1). This framework emphasises the quadrant characterised by both high risk and high impact. The indicators used typically include geographic concentration, governance quality, substitutability, and economic or technological significance [39–41].

The QCI tailors established indicators for quantum-relevant materials and components, combining both quantitative and qualitative measures (see Table 1). Many indicators align with recognised best practices, such as governance (as measured by the World Bank's World Governance Indicators, WGI), and substitutability as a key driver of impact [37–41].

These indicators establish the foundational criteria for evaluating each material's supply risk and technological vulnerability. Many are derived from recognised best practices in

Figure 1 Criticality assessment matrix: supply risk (horizontal) vs. vulnerability/impact (vertical). Adapted from NRC (2008) [37]

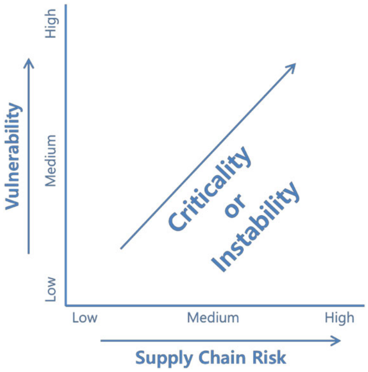

Table 1 Selected indicators for quantum-relevant inputs

Category	Indicator	Description
Supply-chain risk	Political instability / weak governance	Fragile institutions or conflict in producer states undermine reliability [41].
	Environmental & social regulation constraints	Stringent environmental and social (E&S) rules, licensing delays, community opposition constrain capacity [40].
	High production concentration	Output concentrated in few countries/entities reduces resilience [39, 40].
	Import reliance / limited reserves	Net-import dependence and small, concentrated reserves amplify exposure [42].
	By-product or intrinsic limits	Recovery as a by-product (e.g., He-3 from tritium decay) caps scalable supply [11, 40, 42].
Technological vulnerability	Indispensability to performance	Input is function-critical to device efficiency / yield [11, 37, 43].
	Absence of viable substitutes	No alternative with comparable performance / readiness [40, 43].
	Sensitivity to controls / sanctions	Items likely subject to export controls, sanctions, or list-based restrictions [31, 44–46].
	Domestic capacity & R&D pipeline	Local production / readiness and funded programmes to qualify alternatives [1, 2, 47].

the critical-materials literature. For instance, political stability and governance quality in supplier countries are widely recognised risk factors, frequently quantified through indices such as WGI to gauge supply risk [41]. Likewise, the absence of viable substitutes and the functional indispensability of a material directly elevate the severity of impact in the event of disruption; within the criticality framework, substitutability is a core determinant of a material's "importance in use" [37–40]. By systematically assessing each quantum-relevant material against these criteria, the proposed QCI identifies the most vulnerable points within quantum-technology supply chains.

Notwithstanding their value, traditional criticality frameworks are insufficient when applied to the quantum domain. We identify three primary deficiencies:

1. *Quantum blind spots.* Several resources crucial for quantum technologies—such as isotopically pure silicon-28, helium-3 gas, and specialised photonic components—are often under-weighted in standard CRM lists because conventional assessments prioritise broad macroeconomic impact over niche, high-leverage inputs for frontier technologies [11, 13, 43].
2. *Static cadence.* CRM lists and criticality assessments are updated infrequently and often rely on expert scoring and consensus, which can limit their responsiveness to

rapid demand shifts or breakthroughs (e.g., a sudden surge in demand for a particular hardware platform) [27, 37, 38, 40].

3. *Dual-use sensitivity.* The strategic importance of quantum-relevant materials extends beyond economic value to encompass geopolitical and military considerations. Contemporary criticality frameworks rarely explicitly incorporate export-control regimes, outbound-investment rules, or security-driven list controls, thereby risking the systematic under-prioritisation of defence-relevant inputs [30, 31, 45, 46].

Addressing these issues necessitates adapting criticality analysis to the unique characteristics of quantum supply chains. This includes expanding the scope to encompass quantum-specific materials, components, and equipment; enhancing the temporal dynamism of assessments; and incorporating explicit geopolitical and military criteria. Such improvements are essential to anticipate and mitigate supply risks in the quantum sector, thereby fostering a more resilient development pathway for dual-use quantum technologies.

While foundational instruments such as the European Union's Critical Raw Materials Act (CRMA) and the U.S. Critical Minerals Strategy provide essential macroeconomic baselines, they are inherently limited in the context of rapid technological disruption. These legacy frameworks typically operate on multi-year review cycles—often too slow to capture the velocity of quantum innovation—and prioritise materials based on broad economic impact (e.g., tonnage for electric vehicles (EVs) or wind turbines) rather than the niche, high-leverage dependencies characteristic of quantum systems. Consequently, vital inputs like helium-3 or isotopically enriched silicon-28 often escape high-priority classification despite their potential to induce total system paralysis. Policymakers, increasingly aware of these blind spots, have expressed a clear demand for "living" instruments. The QCI addresses this gap by offering a high-resolution, sector-specific foresight layer that complements broad mineral strategies with dynamic, granular, and updateable risk assessments.

2.3 Emerging concerns in quantum supply chains

Recent developments have revealed significant vulnerabilities within the quantum-technology supply chain, underscoring the urgent need for anticipatory governance. Primary concerns include: materials bottlenecks (e.g., concentrated refining of gallium and germanium; rare-earth processing; geographically narrow niobium supply; the intrinsic scarcity of helium-3) [5, 6, 11, 17]; equipment dependencies (ultra-low-temperature dilution refrigerators supplied by a short vendor list, notably Bluefors (Finland) and Oxford Instruments (United Kingdom)) [7, 8]; geopolitical leverage (e.g., the 2010 rare-earth episode and recent gallium/germanium controls) [5, 6]; and talent scarcity (persistent gaps between quantum-skilled roles and available specialists) [48, 49].

These concerns argue for systematic prioritisation and early intervention: some risks can be mitigated through recycling, substitution, or redesign, while non-substitutable, dual-use, and geographically concentrated chokepoints in sensitive jurisdictions demand coordinated preventive measures.

Recent alliance-level assessments corroborate these vulnerabilities. A recent report for the NATO Transatlantic Quantum Community identifies that over 90% of high-purity material processing for critical quantum components currently occurs outside the Alliance [50]. This extreme concentration in non-allied jurisdictions creates a "single point of failure" risk structure that legacy criticality frameworks—which often focus on raw extraction rather than high-purity processing—fail to capture.

2.4 Motivation for a new framework

The convergence of technical fragility, geopolitical contestation, and dual-use regulation renders the quantum ecosystem particularly susceptible to compounding risks. Policymakers increasingly recognise these threats: the EU and the U.S. have highlighted quantum as a strategically important domain—through secure-communication initiatives, alliance strategies, defence science-and-technology priorities, and tightening export-control and outbound-investment regimes [1, 2, 10, 26, 27, 30, 44–46]. However, existing analytical methods remain insufficient. Conventional critical-mineral or criticality assessments capture elements of the problem but lack a holistic and dynamic perspective tailored to quantum-specific inputs and architectures [25–27, 37, 38, 42]. No integrated framework continuously evaluates which quantum components are "too critical to fail," nor how their risk profiles evolve under plausible disruption scenarios.

The QCI is proposed to fill this gap. The QCI combines recognised critical-materials methodologies with an ANN-based forward-looking stress-testing module to create a forward-looking instrument explicitly designed for quantum-supply security [43, 51–53]. Its principal features include:

- *Diagnostics* – a data-driven ranking of materials and components based on supply risk and strategic significance, including geopolitical concentration, import dependency, lack of substitutes, and dual-use security relevance [37, 38, 40, 41];
- *Foresight* – artificial neural networks trained on indicators spanning market demand, technological shifts, and policy changes to simulate demand surges, new export regulations, or geopolitical shocks, providing early warnings when previously benign inputs trend toward high criticality [43, 51–55]; and
- *Policy relevance* – translating quantitative diagnostics and foresight outputs into actionable measures such as supply diversification, strategic stockpiling, recycling programmes, substitution R&D, and international coordination mechanisms [26, 27, 30, 31, 44–46].

This paper illustrates the utility of the QCI through a case study on molybdenum (Mo) high-purity metals, which are essential to multiple quantum-hardware and military-relevant applications [40, 51]. We then derive policy recommendations from the QCI's findings. By establishing a quantum-specific criticality framework, we aim to enable anticipatory, resilient, and inclusive governance, rather than allowing avoidable supply disruptions to hinder the quantum transition.

3 Methodology

3.1 Quantum Criticality Index (QCI): tri-axial framework

The Quantum Criticality Index (QCI) assesses risks associated with procuring raw materials and key components for quantum-technology supply chains. It uses three axes—supply risk, substitutability, and strategic significance—to capture both the probability of disruption and the magnitude of consequences for quantum applications. This framework extends conventional criticality methods by incorporating quantum-specific considerations and a combination of static indicators and prospective diagnostic tools [37–40, 52, 56–58].

Supply risk Vulnerability arising from production concentration, import dependence, supplier-country governance stability, reserve sufficiency, by-product dependency, and policy or trade constraints. In markets where one country or a small group controls over half of global output—for example, molybdenum (Mo), where the top producers account for roughly 93% of world supply—even moderate supply constraints or policy changes can trigger acute price spikes or shortages. In the first half of 2025, tighter Mo-concentrate supply—amid production cuts and low inventories—drove up oxide prices despite neutral demand conditions [32, 51, 59].

Substitutability Substitutability refers to the level of difficulty associated with replacing a material without severe performance or cost penalties. Materials with unique quantum-optical, magnetic, or cryogenic properties, few viable substitutes, and/or low recycling rates exhibit higher criticality [22, 23, 40, 43].

Strategic significance Importance to critical sectors and dual-use quantum technologies, including computing, communications, and sensing. Indicators include presence on national or regional critical-materials lists [20, 42], economic footprint and price behaviour [60], and irreplaceability in vital applications [37, 40]. Even with moderate supply risks, a material may be considered critical if its strategic indispensability is high.

3.2 Data collection and indicator design

We assembled a comprehensive indicator dataset as the first step of a four-stage workflow (data → modelling → optimisation → validation). Twelve indicators span supply risk, demand dynamics, geopolitical considerations, and technology significance [37–40]. Each indicator is defined by its primary axis, data source, rationale, and direction of effect. Table 2 summarises the selected indicators used to operationalise the QCI for quantum-relevant inputs.

Utilising these indicators, we collected data for two exemplar material groups—Mo (high-purity metals) and a representative set of rare earth elements (REEs)—across 216 countries (2023). This yields $12 \times 2 \times 216 = 5184$ data points, which were subjected to careful cleaning and consistency checks [41, 51, 61].

While the QCI is structured along three conceptual axes—Supply Risk, Substitutability, and Strategic Significance—operationalisation occurs at the indicator level. Supply Risk is primarily captured through DS, MS, DI, PS, ES, RC, and PG, which reflect structural exposure to concentration, governance fragility, regulatory constraints, and production dynamics. Substitutability is operationalised through the SUB composite indicator, which captures the feasibility and cost of functional replacement. Strategic Significance is reflected in DG, ID, GSCI, and WA, which collectively measure demand momentum, domestic reliance, price sensitivity, and regulatory salience. This explicit axis-to-indicator mapping ensures conceptual consistency between the tri-axial framework and its empirical implementation.

3.3 Data preprocessing and normalisation

Given heterogeneous units and scales across indicators, we apply min–max normalisation to rescale all variables to a 0–100 range:

$$X_{\mathrm{norm}} = 100 \times \frac{X - X_{\min}}{X_{\max} - X_{\min}}.$$

Table 2 Selected indicators for quantum-relevant inputs

Indicator	Definition	Primary axis	Source (examples)	Direction
Diversity of Supply (DS)	Number and dispersion of source countries	Supply Risk	ITC trade statistics	Lower DS → higher risk
Supplier Monopoly (MS)	Dominance by a single or few suppliers	Supply Risk	ITC	Higher MS → higher risk
Import Dependency (DI)	Share of consumption met by imports	Supply Risk	UN Comtrade	Higher DI → higher risk
Political Stability (PS)	Governance stability of supplier countries	Supply Risk	WGI (World Bank)	Lower stability → higher risk
Environmental / Social Regulations (ES)	EPI/HDI proxies for regulatory stringency	Supply Risk	EPI / HDI	Stricter rules → higher risk
Resource Competition (RC)	Market concentration index (e.g., HHI)	Supply Risk	Industry data	Higher RC → higher risk
Production Growth (PG)	Production trend relative to demand	Supply Risk	USGS	Lower PG → higher risk
Feasibility or Redesign Penalty for Substitution (SUB)	Composite proxy capturing the level of difficulty associated with replacing a material, including the availability of functional substitutes at comparable performance and Technology Readiness Level (TRL), required redesign efforts, switching costs, and qualification timelines	Substitutability	Technical literature, industry reports	Higher SUB → higher criticality
Demand Growth (DG)	Recent demand growth rate	Strategic Significance	Market reports	Higher DG → higher criticality
Internal Demand (ID)	Domestic demand level	Strategic Significance	ITC / national statistics	Higher ID → higher criticality
Commodity Price Trend (GSCI)	Price-volatility proxy	Strategic Significance	S&P GSCI	More volatile → higher criticality
Wassenaar Arrangement (WA)	Export-control classification	Strategic Significance	WA control list	Listed → higher criticality

Notes (abbreviations & dimensions). ITC = International Trade Centre [61]; WGI = Worldwide Governance Indicators (World Bank) [41]; EPI / HDI = Environmental Performance Index / Human Development Index [62, 63]; HHI = Herfindahl-Hirschman Index; USGS = U.S. Geological Survey [51]; S&P GSCI = S&P Goldman Sachs Commodity Index [60]; WA = Wassenaar Arrangement [31].

Typical dimensions: DS, MS, DI, PS, ES, RC, PG are country-level; GSCI and WA are material-level; SUB, ID, and DG may be programme- or market-level depending on implementation.

Here, X denotes the raw indicator value, while X_{min} and X_{max} represent its minimum and maximum values, respectively. This transformation expresses all indicators on a common scale, preventing features with larger numeric ranges from unduly dominating downstream modelling and optimisation procedures [64, 65].

3.4 Foresight module: ANN-based predictive modelling

Following the construction of a clean, normalised dataset, we develop a predictive model to estimate a material's criticality based on the input indicators. An artificial neural network (ANN) is employed to capture complex, non-linear relationships among multiple features [52]. The model optimises weights and biases to maximise predictive performance between the indicator set and the target criticality score.

Key hyperparameters—including the number of layers, activation functions, optimisation algorithm, and dataset partitioning—are selected following standard machine-learning practice [64, 65]. Let

$$x \in \mathbb{R}^{12}$$

denote the 12-indicator input vector. Hidden-layer activations use ReLU, while the output is linear. Model performance is evaluated using the coefficient of determination:

$$R^2 = 1 - \frac{\sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \hat{y})^2},$$

where y_i and $\hat{y}_i$ denote the observed and predicted criticality values for observation i, respectively, and $\hat{y}$ is their sample mean. All model development was conducted in Python, using TensorFlow ($\geq$2.0) and scikit-learn ($\geq$0.23) [64, 65]. To enhance policy interpretability, we compute post-hoc feature attributions (e.g., SHAP) on the trained ANN.

3.5 Weight optimisation via particle swarm optimisation (PSO)

While the ANN produces a criticality score for any specified set of indicator values, we additionally examine the inverse problem: identifying combinations of indicator levels that generate worst-case (high-criticality) configurations. For this purpose, we employ particle swarm optimisation (PSO), a metaheuristic search method that complements machine-learning models by exploring risk-amplifying parameter spaces [54, 56–58].

For particle i at iteration k, the position and velocity updates are defined as:

$$\begin{aligned}
\mathbf{x}_i^{(k+1)} &= \mathbf{x}_i^{(k)} + \mathbf{v}_i^{(k+1)}, \\
\mathbf{v}_i^{(k+1)} &= \omega \mathbf{v}_i^{(k)} + c_1 r_1 (\mathbf{p}_i - \mathbf{x}_i^{(k)}) + c_2 r_2 (\mathbf{p}_g - \mathbf{x}_i^{(k)}),
\end{aligned}$$

where $\mathbf{x}_i^{(k)}$ and $\mathbf{v}_i^{(k)}$ denote the position and velocity of particle i at iteration k, respectively; ω is the inertia weight (typically 0.4–1.4); c_1 and c_2 are acceleration coefficients; $r_1, r_2 \sim U[0,1]$; $\mathbf{p}_i$ is the particle's best-known position; and $\mathbf{p}_g$ is the global best position. PSO is implemented in Python using open-source libraries, without reliance on proprietary solvers.

3.6 Summary and validation

Integrating the components above yields a rigorous, data-driven, and forward-looking QCI. A tri-axial structure—supply risk, substitutability, and strategic significance—is instantiated through twelve measurable indicators normalised to a 0–100 scale, combined with an ANN-based predictive module for early warning and a PSO layer enabling forward-looking stress testing [37–40, 52, 56–58, 64, 65]. The framework is inherently adaptive: indicators and weights can be updated as new data or policy shocks emerge, and models are retrainable.

In subsequent sections, we validate the methodology through case studies. High-purity molybdenum (Mo) is examined to illustrate QCI scoring in practice. We compute Mo's axis scores, apply the ANN to project criticality under demand growth scenarios, and show how PSO-optimised configurations yield a final assessment. The results identify known supply vulnerabilities and limited substitutability, flagging Mo as a high-concern material—consistent with recent production trends and China's 2025 export-licensing measures [32, 51].

For applied use cases, we additionally report:

(a) a control-elasticity sub-index, capturing how marginal changes in licensing or outbound-investment rules shift QCI score;
(b) a component-level supplier-concentration metric (HHI and within-allies share); and
(c) an early-warning flag triggered when ANN-predicted trajectories cross predefined thresholds (e.g., helium-3 stockout horizons or dilution-refrigerator lead times).

To ensure auditability and avoid performative compliance, these indicators are tied to externally verifiable disclosure checklists, while regulatory signals are mapped to the control-elasticity sub-index through updates to multilateral control lists (Wassenaar Arrangement) and the U.S. outbound-investment program (Executive Order 14105), allowing QCI scores to endogenise evolving dual-use frictions [24, 28, 66].

4 Case study: Molybdenum (Mo) criticality in quantum technologies

4.1 Molybdenum supply-chain risk

Molybdenum's supply chain exhibits substantial concentration and inherent vulnerability. According to the U.S. Geological Survey, global mine output in 2023 was approximately 260,000 metric tons, with China, Chile, Peru, the United States, and Mexico collectively accounting for about 93% of total production. China remained the largest producer (around 110,000 tons) and continued to face environmental-permitting constraints that limited domestic expansion [51]. This highly concentrated structure underscores the potential for supply shocks, particularly when coupled with policy or regulatory disruptions.

Preliminary results of the QCI analysis on molybdenum were publicly presented at the 2nd Annual Stanford Responsible Quantum Technology Conference in May 2024, highlighting emerging supply-chain concentration and policy sensitivity prior to the introduction of formal export-licensing measures [67]. On 4 February 2025, China imposed export-licensing requirements on molybdenum—alongside tungsten and other strategic metals—under Announcement No. 10 (2025) [32]. Even without an outright ban, these measures pushed global prices higher and raised near-term concerns about shortages, echoing earlier episodes of leverage involving rare earth elements [59]. Import-dependent economies therefore face pronounced exposure to such shocks: abrupt controls can disrupt manufacturing timelines, inflate costs, and force complex material substitutions.

Substitutability remains limited across high-performance applications. As a refractory metal, Mo imparts exceptional high-temperature strength and corrosion resistance to alloys; alternative elements (e.g., vanadium or chromium) only partially replicate these properties. Mo-based alloys are also used in high-temperature structural components—for example, as container materials in molten-salt reactor designs or as foundry substrates for sapphire crystal growth—owing to their strength and corrosion resistance. This limited substitutability amplifies supply risk [51].

4.2 Vulnerability in quantum applications

Mo plays quiet but enabling roles across multiple quantum-hardware architectures:

- *Single-photon detectors (SNSPDs):* ultrathin molybdenum-silicide (MoSi) nanowires achieve high system detection efficiency at 1550 nm with low timing jitter at cryogenic temperatures [22].
- *Superconducting circuits and resonators:* Mo–Re alloys combine mechanical robustness with favourable superconducting properties under strain and magnetic field [23].
- *Cryogenic infrastructure:* high-purity Mo fasteners and thermal links provide low thermal expansion and minimal magnetic impurities in dilution refrigerators and ultra-high-vacuum systems [7, 8].

Although present demand remains modest, scalability constitutes the primary vulnerability. As SNSPD arrays, wiring density, and cryogenic fleets expand, specialised Mo forms (e.g., high-purity powders, thin films, and alloy feedstock) may become rate-limiting. Substitutes (e.g., WSi, NbN, or NbTiN) often require system redesign and entail performance penalties—such as reduced efficiency, higher loss, or lower critical current—thereby translating supply risk directly into technical vulnerability. This dynamic mirrors the way helium-3 scarcity constrains low-temperature operations more broadly [11].

4.3 Comparative quantum criticality (vs. REEs)

We benchmark Mo using the QCI matrix with (x) supply risk and (y) quantum impact/irreplaceability. Heavy rare earth elements (REEs) such as ytterbium (Yb) and erbium (Er) occupy the high-risk/high-impact quadrant: they are technologically indispensable for applications including trapped-ion qubits, optical clocks, C-band amplification, and quantum repeaters, and they exhibit highly concentrated supply chains.

Historically, Mo ranked lower in supply risk owing to more diversified mining operations. However, refining capacity and policy leverage remain concentrated in a small number of jurisdictions. When combined with Mo's enabling role and limited substitutability in quantum components, its position on the QCI plot shifts upward and rightward, approaching heavy REEs in priority—albeit with a narrower application scope.

4.4 Molybdenum in the ecosystem of chokepoints

Mo's positioning toward the upper-right quadrant of the QCI matrix reflects a compound risk structure characterised by concentrated supply, regulatory exposure, and constrained substitutability. This configuration generates a chokepoint pattern in which even modest policy shocks—such as export licensing requirements—can cascade into qualification delays, cost escalation, and design inflexibility across quantum-hardware ecosystems. The derivation is sequential: elevated supply concentration increases exposure to geopolitical leverage; limited substitution pathways amplify technical rigidity; and strategic significance magnifies systemic impact. Together, these factors translate the QCI score into identifiable chokepoints—namely, export-sensitive processing nodes, specialised high-purity inputs, and certification-bound hardware components—thereby informing the selection of targeted policy levers. These linkages are summarised in Table 3, which maps QCI signals and structural drivers to illustrative policy levers and time horizons. As illustrated in Fig. 2, the QCI framework positions molybdenum increasingly closer to high-criticality rare-earth elements as supply risk, regulatory sensitivity, and limited substitutability interact within the quantum technology ecosystem.

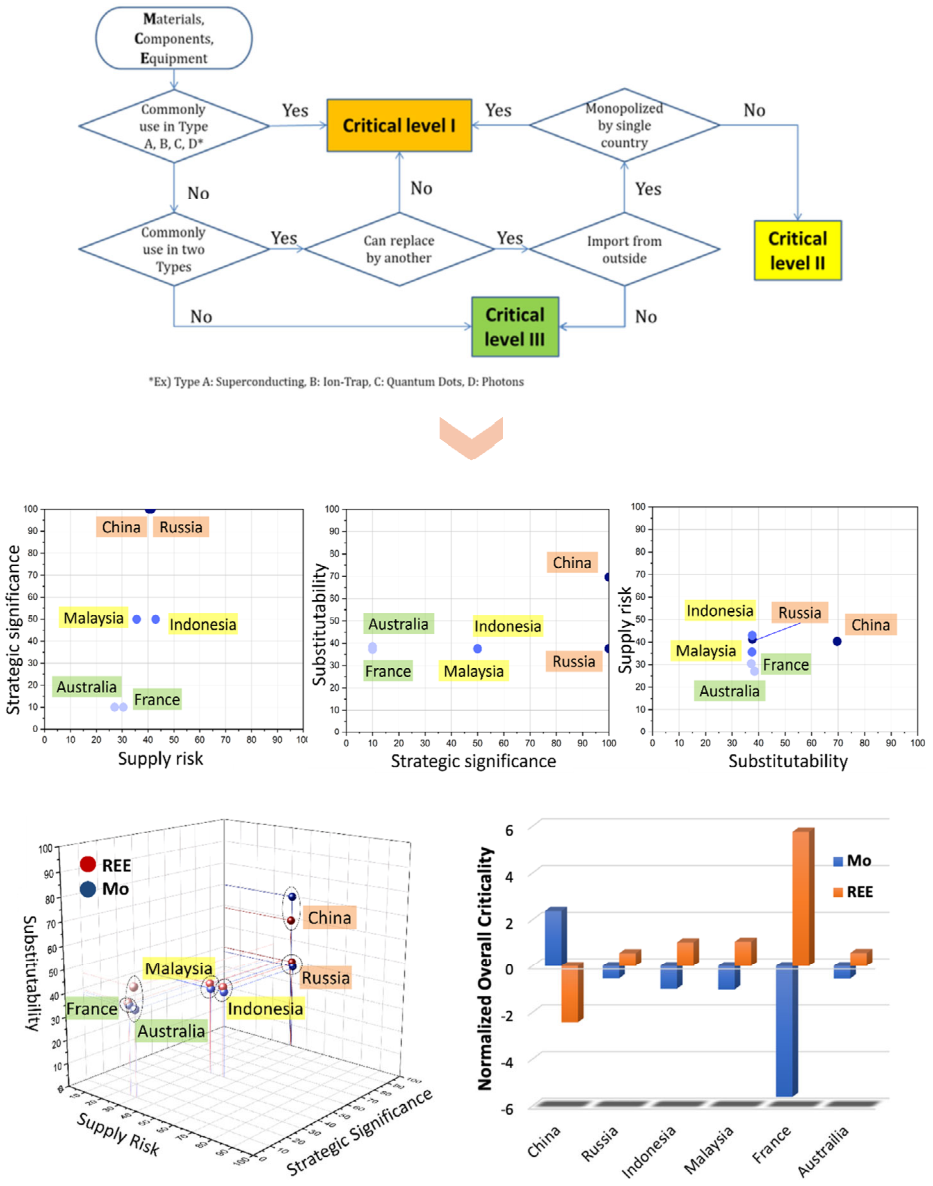

Figure 2 Application of the Quantum Criticality Index (QCI): Relative positioning of molybdenum (Mo) and selected rare earth elements (REEs) in the U.S. case study. The horizontal axis represents Supply Risk, incorporating production concentration, import dependence, governance stability, and regulatory exposure. The vertical axis captures Strategic Significance and quantum-specific impact, including indispensability in high-performance architectures and dual-use sensitivity. Materials located in the upper-right quadrant exhibit simultaneous high supply vulnerability and high strategic impact, indicating elevated policy urgency. Mo's upward-rightward shift reflects increasing regulatory sensitivity and constrained substitutability, bringing its risk profile closer to heavy REEs despite narrower application scope. Quadrant positioning provides a direct signal for prioritisation in allied procurement, substitution R&D, and supply-chain assurance strategies

Mo's pattern—concentrated supply coupled with limited substitutability under policy shock—recurs across multiple quantum enablers. Cryogenics face multi-month lead times for dilution refrigerators (DRs) despite Bluefors' expansion of U.S. production capacity; helium-3 stocks are intrinsically rate-limited by tritium decay and Department of Energy processing; thin-film lithium niobate (TFLN/LNOI) relies on a small number of high-

Table 3 From QCI signal to policy action

QCI signal	Structural driver	Policy lever	Time horizon
High supply concentration	Limited refining jurisdictions	Allied procurement coordination	Short-term
Low substitutability	Design-embedded material dependency	Substitution R&D funding	Medium-term
Regulatory sensitivity	Export-control exposure	Targeted licensing & trusted trade corridors	Immediate
Strategic indispensability	Dual-use quantum architecture reliance	Strategic stockpiling & FRAND licensing	Medium–Long-term

Note. This template demonstrates how QCI outputs can be directly translated into policy-brief inputs suitable for interagency coordination.

quality wafer suppliers; and a single producer dominates the Western supply of electronic-grade diamond.

Accordingly, we pair the QCI's diagnostic signal with (i) an allied implementation blueprint for near-term action and (ii) a legislative design for durable, risk-tiered governance, together closing the loop from detection to delivery [12, 14–16, 18, 24, 68].

5 Policy and conclusion: translating foresight into governance

To operationalise the QCI's diagnostic and foresight capabilities, policymakers will need to translate risk alerts into concrete actions. We posit that this governance framework should function as one of two *twin pillars* for comprehensive quantum security: while Post-Quantum Cryptography (PQC) protects the digital domain against "harvest-now, decrypt-later" threats—potentially complemented by Quantum Key Distribution (QKD) [10, 24]—the QCI safeguards the physical supply chain that underpins the entire quantum ecosystem. We therefore propose a governance architecture organised around three phases: Diagnosis, Decision, and Delivery. Related discussions in recent policy and strategic analyses further highlight the growing importance of securing critical quantum supply chains and allied governance frameworks [71–81].

5.1 Diagnosis and decision

The process begins with the establishment of QCI-linked stockpile triggers. Governments should publish clear thresholds—such as helium-3 reserve floors or dilution refrigerator (DR) spare-parts buffers—that automatically activate pre-funded resilience mechanisms when ANN-generated forecasts breach specified risk levels [12]. This approach shifts supply-chain management from reactive crisis response to anticipatory preparedness.

5.2 Delivery: allied procurement and IP governance

Beyond domestic stockpiling, effective delivery requires deep international coordination. To address the challenge of low-volume, high-criticality markets, allies could establish Allied Purchasing Facilities (APFs) modelled on the NATO Support and Procurement Agency (NSPA) or the COVAX. These facilities would execute multi-year "take-or-pay" advance market commitments for critical hardware (e.g., DRs and cryocoolers). By aggregating demand, APFs would de-risk supplier investment and incentivise second-site manufacturing and in-region spares hubs [18].

We further recommend targeted licensing and the creation of "reverse dependencies" through trusted trade corridors for quantum supply chains. Specifically, governance frameworks should leverage outbound and inbound screening regimes—such as E.O. 14105 and updates to multilateral export-control lists—to protect allied capacity for DRs, helium-3 handling, thin-film lithium niobate (TFLN, $LiNbO_3$) wafers, and diamond, while minimising collateral effects on adjacent photonics industries [28, 31]. Building on this secure foundation, allies can prioritise and expedite licensing for certified end-users within the alliance. As commentators argue, this approach need not be purely defensive: by securing dominance in key processing nodes, allies can generate reverse dependencies that provide geo-economic leverage, effectively turning supply-chain resilience into an instrument of statecraft [69].

Governance must also extend to intellectual property (IP) pools covering the intangible supply chain, where process know-how (e.g., TFLN wafer etching) is often the primary bottleneck. We recommend the formation of allied IP pools for non-differentiating enabling technologies. In addition, state-funded breakthroughs in critical component manufacturing should be subject to Fair, Reasonable, and Non-Discriminatory (FRAND) licensing obligations. This prevents the weaponisation of patents and ensures that essential fabrication techniques remain accessible to the allied industrial base [68].

Finally, to ensure supply-chain integrity, governance should encompass origin assurance for quantum-grade inputs. We recommend adopting verifiable credentials for origin and processing of key materials—notably helium-3, silicon-28, diamond, and lithium niobate—tethered to QCI scores, with non-compliant inputs incurring de-risking penalties in public procurement processes [12, 14–16]. This procurement-led approach also provides a practical mechanism for integrating the environmental, social, and governance (ESG) considerations. By conditioning public contracts for new extraction or processing on compliance with stringent environmental standards and "just transition" principles, allies can de-risk supply chains without compromising sustainability goals. The urgency of these measures is underscored by industry-reported DR lead times (approximately 6–9 months) and persistent supplier concentration, which together confirm a systemic bottleneck [7, 8, 18, 19].

5.3 Agility in a shifting landscape

A central challenge in governing quantum technologies is their pre-paradigmatic state [70]. It remains uncertain whether superconducting, trapped-ion, neutral-atom, or photonic architectures will ultimately dominate. Static governance tools therefore risk obsolescence if the leading technological pathway—and the associated material-demand profile—shifts.

The QCI addresses this uncertainty through algorithmic agility. The framework is model-agnostic: while core indicators (e.g., supply risk and geopolitical concentration) remain constant, the weighting of specific inputs can be rapidly recalibrated via the PSO layer as technological modalities evolve. For example, if the industry pivots from superconducting qubits (dependent on molybdenum and niobium) to photonic systems (dependent on TFLN and specialised optics), the QCI can re-optimise criticality rankings in near real time. This enables policymakers to maintain a living dashboard that adapts to the non-linear trajectory of quantum innovation, ensuring relevance regardless of which hardware architecture prevails.

5.4 Conclusion

Ultimately, operationalising the QCI transforms strategic foresight into anticipatory governance. By linking data-driven diagnostics to enforceable procurement, IP licensing, and ESG mechanisms, allies can institutionalise quantum supply-chain resilience rather than reacting to crises ex post. This reinforces a comprehensive *twin-pillar* security architecture: just as PQC protects data integrity and critical infrastructure, the QCI safeguards the availability of the physical inputs on which quantum systems depend. The QCI thus functions not only as a technical metric, but as a policy framework—one that informs and operationalises coordinated, evidence-based, and values-driven governance for dual-use quantum technologies.

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Author contributions
D.C. (Dongyoun Cho) led the manuscript preparation, integration, and submission. D.C. structured the overall argument, harmonised the technical and policy sections, ensured coherence across the manuscript, and served as the corresponding author. M.K. (Mauritz Kop) contributed to the conceptual foundation and designed the legal-policy analysis, particularly regarding technology governance, export controls, and intellectual-property frameworks. M.K. refined the discussion on allied standardisation and regulatory coherence, and linked QCI-enabled supply chain resilience to PQC-migration. M.L. (Min-Ha Lee) designed and initiated the Quantum Criticality Index (QCI) concept, and led the development and implementation of the methodological components, including the ANN-based foresight model and PSO optimisation. M.L. also collected and validated the case-study data and contributed to the technical interpretation of QCI indicators. All authors reviewed and approved the final version of the manuscript.

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Data availability
All data used in this study are derived from publicly available, open-source datasets cited in the reference list. Derived indicators and modelling outputs can be reproduced using these sources and the methods described in the paper.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Declaration on large language model use
Large Language Models (LLMs) such as ChatGPT were used only as a writing assistant for grammar and language clarity. No AI system contributed to the conceptual, analytical, or interpretative aspects of this work, and thus no authorship attribution is assigned to LLMs. This use has been properly acknowledged in the Methods section.

Competing interests
The authors declare no competing interests.

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