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Systemic risks and cascading dynamics in the global cobalt supply chain



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ABSTRACT

The global transition to low-carbon technologies hinges on secure supplies of critical minerals like cobalt, yet interconnected supply chains are increasingly vulnerable to geopolitical tensions and frequent external disruptions. Existing risk assessments often treat commodities in isolation, overlooking the upstream–downstream dependencies that amplify cascading failures. Here we show systemic risks in global cobalt flows from 1998 to 2019 across 230 countries and regions by integrating trade-linked material flow analysis with a multilayer shock propagation model. Our results reveal that disruptions propagate through alternating horizontal–vertical and direct–indirect pathways, with risk concentrating at the mining stage but accumulating predominantly in refining–manufacturing bridges. These cascades yield abrupt nonlinear failures and an avalanche network four times denser than the underlying physical supply chain. Nations with low systemic fragility but high exposure rate—such as Indonesia, South Africa, and Mexico—are particularly susceptible to common random disruptions and lack resilience or effective response. Over the past two decades, global systemic risks have followed a volatile but upward trend. These findings highlight that national mitigation strategies are necessary but insufficient; achieving resilience requires stage-aware, system-level coordination and multilateral cooperation.

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1. Introduction

Low-carbon technologies, especially lithium-ion batteries (LIBs) and electric vehicles (EVs), have gained worldwide attention as pivotal tools to combat climate change [1] and strategic sectors to underpin economic competitiveness [2,3]. However, the widespread adoption of EVs brings potential resource bottlenecks and supply chain challenges [4] due to their reliance on critical minerals, such as lithium, cobalt, nickel, and graphite—of which cobalt

is among the most discussed in major economies, including the United States [5], the European Union [6], China [7], Japan [8], and Australia [9]. The common concern about cobalt relates to its inevitable supply shortages [10,11] and various potential supply chain risks [12,13], such as cobalt mining and refining concentrated in the Democratic Republic of the Congo and China [14], respectively; geographical misalignment between supply and demand [14]; dependence on copper and nickel mining as a by-product [15]; and mining- and production-related environmental, social, and governance (ESG) issues [16,17]. These potential risks may slow or suspend the deployment of EVs and further threaten the global low-carbon transition. Therefore, characterizing the global cobalt supply chain, monitoring associated risks, and exploring mitigation strategies have become crucial for

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achieving global e-mobility and climate ambitions.

With burgeoning globalization and increasing product complexity, modern global supply chains operate as highly interconnected, interdependent multilayer networks linking various raw materials, semis and final products, and economies. Recent cobalt market dynamics and increasingly frequent external disruptions have reignited concerns about the systemic instability of strongly interconnected supply chains [18,19]. On the supply side, Congo, the world's largest cobalt ore producer, suspended exports in early 2025 in a move toward export quotas [20], thereby tightening near-term cobalt availability and potentially transmitting shortages broadly through trade and processing stages. On the demand side, shifts in battery chemistry, reflected in the rising adoption of lithium iron phosphate, have reduced reliance on cobalt [21] and reconfigured upstream–downstream dependencies. Increasingly frequent external disruptions, such as pandemic-related logistics shocks [22], episodic price volatility (e.g., the Tsingshan nickel event [23]), and evolving policy and trade measures regarding critical minerals and batteries (e.g., the United States tariff investigations [24]), have led to the reallocation of flows and risks across countries and life-cycle stages [25]. Consequently, the global cobalt supply chain is increasingly susceptible to cascading supply shocks [19], meaning that even minor region- or industry-specific shocks or disruptions can propagate throughout the supply chain and create systemic risks that culminate in catastrophic failures [19]. Facing multiple global crises ahead, it is essential to carefully evaluate the risks of cobalt supply within an interconnected, interdependent multilayer network of resource production, consumption, and trade [19,26], rather than treating disruptions as isolated events.

Cobalt and LIB-related supply [27,28] and ESG [12,13] risks have mostly been evaluated under the framework of criticality assessment and are often combined with material flow analyses (MFAs) to extend from upstream (minerals) to the entire supply chain [2,29] and to include broader risk sources, such as the COVID-19 pandemic [30]. However, these periodic assessments have often been conducted for individual countries or commodities, thereby ignoring hidden interconnections across countries and interdependencies between upstream and downstream stages. Complex networks, both static and dynamic, can, in principle, assess the systemic risks arising from such interconnections and interdependencies, but data limitations at regional and industry resolutions lead most applications to focus on upstream minerals in isolation, making it difficult to capture upstream–downstream dependencies. For example, Gulley et al. first introduced the PageRank Index to assess systemic trade risks for critical minerals [31], while Sun et al. developed the Competition Index to quantify region- and commodity-based competition intensities within the LIB supply chain [32]. In addition, dynamic shock propagation models have been employed to simulate the shock propagation processes within trade networks for graphite [33], copper [34], lithium [35], cobalt [36,37], nickel [38], and LIB-related materials [39]. However, almost all assessments treat commodities in isolation, modelling them as single-layer or trade-only multiplex networks [40]—that is, individual or aggregated cobalt-containing commodities—and omit upstream–downstream dependencies. Only two recent studies on lithium [25] and LIB [41] supply chain networks have illustrated the impact of upstream critical minerals on downstream battery chemistry and supply chain disruption and have demonstrated that the systemic risks arising from these upstream–downstream dependencies are substantially larger than the risks considered from individual steps alone. To the best of our knowledge, reliable and systemic estimates of the risks in cobalt supply chain networks are hitherto unavailable, hindering the design of resilient cobalt and LIB supply chains.

Here, we adopt a networked and dynamic perspective that integrates trade-linked MFA with a multilayer shock propagation model to trace cobalt flows from 1998 to 2019 across 230 countries and regions, simulate shock propagation pathways vertically along life-cycle stages and horizontally across economies, and evaluate supply chain risks systemically. Our approach begins by quantifying, calibrating, and balancing cobalt production, consumption, and trade flows based on a trade-linked MFA framework. Then we construct a multilayer, network-based cobalt supply chain comprising six layers corresponding to cobalt life-cycle stages and employ a shock propagation model to investigate the processes, pathways, and patterns of shock propagation. Finally, we develop two interactive and systemic measures—systemic fragility and exposure rate—to assess the distribution and evolution of systemic risks, identify risk sources, and aid in constructing resilient supply chains for cobalt and LIBs. This advances beyond criticality assessments and single-layer or trade-only multiplex analyses and complements our prior publication [40] on static multiplex trade structures and interlayer correlations by moving from static descriptions to dynamic system behavior that explicitly captures hidden interconnections and upstream–downstream dependencies.

2. Materials and methods

2.1. Trade-linked material flow analysis

The trade-linked MFA framework is used to define the anthropogenic cobalt cycle, highlighting major life-cycle stages and end-uses (Fig. 1a). The spatial boundary covers all countries and regions globally—230 in total—that participate in the anthropogenic cobalt cycle (Supplementary Table S1). The temporal boundary is set to the period from 1998, when the earliest data became available, and cobalt started to penetrate the economy, to 2019, when most of the latest data were available, and to avoid the impact of the COVID-19 pandemic. National cobalt cycles comprise six transformative processes: mining, refining, manufacturing, use, waste management, and recycling. These processes are interconnected with the international market through four distributive processes: the international trade of cobalt ore, refined materials, final products, and wastes. Cobalt-containing products are categorized into nine end-uses: LIBs for EVs, energy storage systems (ESS), and consumer electronics (CE); as well as cemented carbides (C&C), superalloys (S&A), magnets (MAG), catalysts (CAT), pigments (PI), and other products (OTH).

According to the trade-linked MFA framework, all flows and stocks in the global cobalt supply chain are quantified and mass-balanced as cobalt metal equivalents. Direct and indirect cobalt flows embodied in cobalt-containing products are estimated primarily based on commodity weight and cobalt intensity (Supplementary Table S2), while cobalt embodied in waste or scraps is roughly estimated relative to the global cobalt market price. However, certain harmonized system (HS) six-digit commodities encompass multiple commodities, including those without a metal of interest [42]. For instance, HS-283329 (sulfates) contains cobalt sulfates, along with other sulfates such as iron, vanadium, chromium, and zinc. Cobalt is contained in copper ores and concentrates (HS-260300) when shipped from Congo to China, but this is not the case when it is shipped from Australia to the United States. Therefore, cobalt embodied in ore and refined material trade flows must be calibrated to satisfy the mass-balance principle within each country. We dynamically redistribute countries' net export volumes with reported mining and refining production figures to adjust questionable trade flows and minimize the absolute difference, following the method described in Supplementary Methods Section 1.3.2 and Fig. S1. This method and

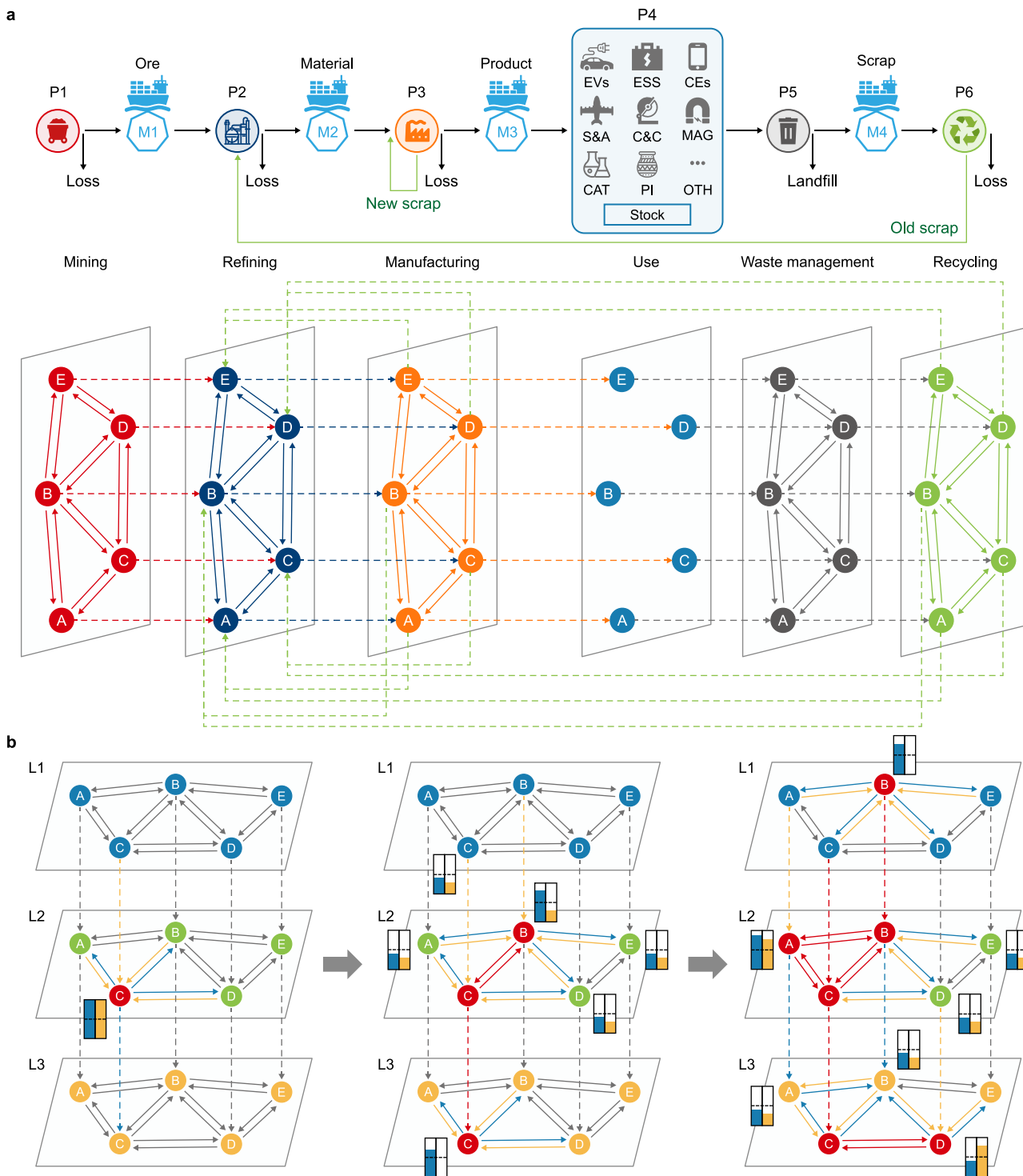


Fig. 1. Global cobalt supply chain and schematic shock propagation in a multilayer network. a, Anthropogenic cobalt cycle from mining (P1) through refining (P2), manufacturing (P3), use (P4), waste management (P5), and recycling (P6), and the associated multilayer global cobalt supply chain linking five illustrative economies (A–E) across the six stages. Cobalt-containing products are used in lithium-ion batteries (LIBs) for electric vehicles (EVs), energy storage systems (ESS), and consumer electronics (CE); as well as in cemented carbides (C&C), superalloys (S&A), magnets (MAG), catalysts (CAT), pigments (PI), and other products (OTH). **b**, Schematic example of round-by-round shock propagation in the multilayer network. Node colors denote upstream (blue), midstream (green), and downstream (yellow) layers. Each node is annotated with a blue bar and a yellow bar, indicating accumulating decrements on the supply and demand sides, respectively. When the cumulative decrements in supply (blue bar) or demand (yellow bar) exceed the buffer capacity (horizontal dashed line), the node is deemed to collapse (red node). All inflows and outflows between collapsed nodes are fully disrupted (red arrows), whereas those between a collapsed node and its non-collapsed neighbors are proportionally reduced, indicating potential supply shortages (blue arrows) and demand reduction (yellow arrows), respectively. In the schematic example, a predefined shock is imposed on country C at layer L2, where both supply and demand are fully removed (100% reduction) under a worst-case scenario. In the first round, neighbors of the shocked node (country B at layer L2 and country C at layer L3) collapse via one-step direct pathways. In the second round, neighbors of these collapsed nodes (country B at layer L1, country A at layer L2, and country D at layer L3) collapse via multistep direct pathways. Subsequent rounds may trigger additional failures through combinations of direct and indirect pathways until no further nodes fail.

the data used to track cobalt flows were reviewed in our prior publication [40].

Apparent consumption (APC) is used to balance domestic productions, international trades, and stock changes through a top-down approach with trade-linked MFA [43–45]. However, current data on global and regional total and sector-specific cobalt APC amounts are available only for the United States, the European Union, China, Japan, and the world [10,11]. Due to the lack of APC, the upstream segments capture global cobalt flows from the mining to refining stage, while the downstream segments capture only domestic flows for countries with reported APC and a portion of domestic flows derived from the mass-balance principle—such as production for export and consumption from import—and from bottom-up estimations—such as for EVs and ESS—from the refining to the use stage, as elucidated in Supplementary Methods Section 1.3.3 and Fig. S2. In this way, approximately 80% of global cobalt APC has been traced vertically through life-cycle stages, as well as horizontally across economies, while the remaining 20% represents domestic activities throughout the life-cycle stages and has only a limited impact on our subsequent supply chain network analysis. In the use stage, cobalt final products serve for several years as in-use stocks, and the cobalt outflows (old scraps) are calculated using a top-down, lifetime-delayed method. More details and assumptions about the anthropogenic cobalt cycle are described in Supplementary Methods Section 1.

2.2. Global supply chain multilayer network

To investigate shock propagation along the cobalt supply chain, we use trade flows, domestic production, consumption, and recycling flows to construct a weighted and directed multilayer network with six layers corresponding to life-cycle stages: mining, refining, manufacturing, use, waste, and recycling (Fig. 1a). Stockpiles (for lack of data) and losses (for irrelevance to network resilience) are not included in this network. Following complex network terminology [46], the multilayer network characterizing the global cobalt supply chain in year t could be expressed as $\mathbf{G}(t)$:

$$\mathbf{G}(t) = (\mathbf{A}(t), \mathbf{O}(t)) = \begin{pmatrix} \mathbf{A}(t)^{[1]} & \mathbf{O}(t)^{[1,2]} & \dots & \mathbf{O}(t)^{[1,6]} \\ \mathbf{O}(t)^{[2,1]} & \mathbf{A}(t)^{[2]} & \dots & \mathbf{O}(t)^{[2,6]} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{O}(t)^{[6,1]} & \mathbf{O}(t)^{[6,1]} & \dots & \mathbf{A}(t)^{[6]} \end{pmatrix} \quad (1)$$

Intralayer matrices $\mathbf{A}(t) = \{\mathbf{A}(t)^{[1]}, \mathbf{A}(t)^{[2]}, \dots, \mathbf{A}(t)^{[6]}\}$ capture cobalt metal equivalent trade flows within each life-cycle stage, mirroring the approach used in single-layer [36] and multiplex networks [37]. For each stage/layer α , $\mathbf{A}(t)^{[\alpha]} = (\mathbf{V}^{[\alpha]}, \mathbf{E}(t)^{[\alpha]}, \mathbf{W}(t)^{[\alpha]})$ is defined as a node set $\mathbf{V}^{[\alpha]}$ (230 countries), a link matrix $\mathbf{E}(t)^{[\alpha]} \subseteq \mathbf{V}^{[\alpha]} \times \mathbf{V}^{[\alpha]}$ (trade relationships), and a weight matrix $\mathbf{W}(t)^{[\alpha]} = \{w(t)_{ij}^{\alpha}, i \neq j\}$ (trade volumes), where $w(t)_{ij}^{\alpha}$ represents the trade volume from node i to node j at layer α . Interlayer matrices $\mathbf{O}(t) = \{\mathbf{O}(t)^{[\alpha,\beta]}, \alpha \neq \beta\}$ capture cobalt metal equivalent production, consumption, waste, and recycling flows from layer α to layer β within the same country, derived from the trade-linked MFA. For each transformative process $[\alpha, \beta]$, $\mathbf{O}(t)^{[\alpha,\beta]} = (\mathbf{V}^{[\alpha]}, \mathbf{V}^{[\beta]}, \mathbf{E}(t)^{[\alpha,\beta]}, \mathbf{W}(t)^{[\alpha,\beta]})$ is defined as a start node set $\mathbf{V}^{[\alpha]}$ (230 production countries), an end node set $\mathbf{V}^{[\beta]}$ (230 consumption countries), a diagonal link matrix $\mathbf{E}(t)^{[\alpha,\beta]} \subseteq \mathbf{V}^{[\alpha]} \times \mathbf{V}^{[\beta]}$ (transformative relationships), and a diagonal weight matrix $\mathbf{W}(t)^{[\alpha,\beta]} = \{w(t)_{ii}^{[\alpha,\beta]}, \alpha \neq \beta\}$ (transformative volumes), where $w(t)_{ii}^{[\alpha,\beta]}$

represents the transformative volume from node i at layer α to node i at layer β . It is worth noting that recycling flows are linked to the refining layer to study the role of secondary production.

2.3. The shock propagation model

Based on the multilayer network of the global cobalt supply chain, we extend the linear threshold model (LTM) [47–50] to a weighted and directed multilayer network [51] to explore how shocks propagate across economies horizontally and along life-cycle stages vertically, akin to the cascading failure (Fig. 1b). The initiation of shock propagation begins with a predefined risk source (e.g., country C at layer $L2$, denoted as $n_C^{[L2]}$) at any country or life-cycle stage. As the cascade unfolds, shocks propagate both downstream, causing supply shortages, and upstream, leading to demand reduction. On the supply side, all the outflows (supply/export) from the risk source $n_C^{[L]}$ decrease by a fraction denoted as α_{supply} ; and on the demand side, all the inflows (demand/consumption/import) from $n_C^{[L]}$ also decrease by a fraction denoted as α_{demand} . These α_{supply} and α_{demand} represent the magnitude or severity of supply shortages and demand reductions [51]. Then, shock diffuses to node $n_C^{[L]}$'s neighbors to result in supply and demand decrements. For the nodes it supplies or exports to ($n_B^{[L]}$), the total decrement resulting from supply shortages is evaluated as follows:

$$\Delta W_B^{[L]}(\text{supply}) = \sum_{\alpha} \sum_i^n \alpha_{\text{supply}} \cdot w(t)_{i,B}^{[\alpha,L]}, n \in \text{affected neighbors} \quad (2)$$

For the nodes it consumes or imports from ($n_B^{[L]}$), the total decrement resulting from demand reduction is evaluated as follows:

$$\Delta W_B^{[L]}(\text{demand}) = \sum_{\alpha} \sum_j^m \alpha_{\text{demand}} \cdot w(t)_{B,j}^{[\alpha,L]}, \quad (3)$$

$m \in \text{affected neighbors}$

Next, we identify the origin of a new round of shock propagation when:

$$\Delta W_B^{[L]}(\text{supply}) > \sum_{\alpha} \sum_i^N \beta_{\text{supply}} \cdot w(t)_{i,B}^{[\alpha,L]}, N \in \text{all neighbors} \quad (4)$$

$$\Delta W_B^{[L]}(\text{demand}) > \sum_{\alpha} \sum_j^M \beta_{\text{demand}} \cdot w(t)_{B,j}^{[\alpha,L]}, M \in \text{all neighbors} \quad (5)$$

In simpler terms, for any node $n_B^{[L]}$ connected with risk source $n_C^{[L]}$, if the total decrement resulting from supply shortages $\Delta W_B^{[L]}(\text{supply})$ exceeds a fraction (β_{supply}) of its total inflows, or if the total decrement resulting from demand reduction $\Delta W_B^{[L]}(\text{demand})$ exceeds a fraction (β_{demand}) of its total outflows, neighboring node $n_B^{[L]}$ fails into collapse. Another propagation caused by node $n_B^{[L]}$ continues to spread to other neighbors until there are no more newly failed nodes, which means the shock has been fully absorbed. These β_{supply} and β_{demand} represent the capacity of a neighboring node to resist or absorb the shock caused by supply shortages or demand reductions—referred to as buffer capacity [51].

2.4. Indicators of systemic risks

Based on the modified LTM, the severity of shock propagation is quantified by the number or fraction of subsequently collapsed nodes starting from a given risk source (avalanche size or avalanche fraction) [49]. In practice, the propagation dynamics solely depend on the ratio of buffer capacity (β_{supply} or β_{demand}) to shock severity (α_{supply} or α_{demand}), also known as failure threshold Ω (equation (6)) [51].

$$\Omega = \frac{\beta_{\text{supply}}}{\alpha_{\text{supply}}} = \frac{\beta_{\text{demand}}}{\alpha_{\text{demand}}} \quad (6)$$

Substituting this into equations (4) and (5), the condition for the failure of a node is now expressed as follows:

$$\frac{\sum_{\alpha} \sum_i^n w(t)_{i,B}^{[\alpha,l]}}{\sum_{\alpha} \sum_i^N w(t)_{i,B}^{[\alpha,l]}} > \Omega, n \in \text{affected neighbors}, N \in \text{all neighbors} \quad (7)$$

$$\frac{\sum_{\alpha} \sum_i^m w(t)_{B,j}^{[l,\alpha]}}{\sum_{\alpha} \sum_i^M w(t)_{B,j}^{[l,\alpha]}} > \Omega, m \in \text{affected neighbors}, M \in \text{all neighbors} \quad (8)$$

When the relative loss caused by supply shortage (equation (7)) or demand reduction (equation (8)) exceeds the failure threshold Ω , node $n_B^{[l]}$ will fall into collapse.

Building on the conventional view that the robustness of complex networks is characterized by phase transitions [52], we develop two systemic risk indicators via a two-step failure-threshold design to ensure comparability across nodes and to account for heterogeneity. First, for comparison, we sweep a uniform failure threshold $\Omega \in [0.02, 0.80]$ and simulate shock propagation for all nodes to identify the phase transition of avalanche fractions against failure thresholds. The node-specific critical threshold for the phase transition is defined as the node's systemic fragility, indicating the potential impact of that node on the entire supply chain network. Second, considering node heterogeneity, we also assign this critical threshold as the node-specific failure threshold Ω and simulate shock propagation on the resulting heterogeneous- Ω network, where the exposure rate is defined as the probability of being shocked. This two-step design provides a built-in sensitivity analysis and relaxes the uniformity assumption while accounting for node heterogeneity by endogenizing Ω from data-driven phase behavior.

3. Results and discussion

3.1. Global cobalt supply chain network

Increased globalization and specialization over the past two decades have led to a globally interconnected and integrated cobalt supply chain, but most products remain heavily reliant on a few key actors, especially Congo and China in the mining and refining stages, respectively (Fig. 2 and Supplementary Fig. S3). In 2019, approximately 70% (100 kt) of global cobalt was extracted in the form of crude cobalt salts (i.e., hydroxide and carbonate) from Congo as a by-product of the copper hydrometallurgical process [53]. Then, almost all of these cobalt intermediates (97 kt) were shipped to China for

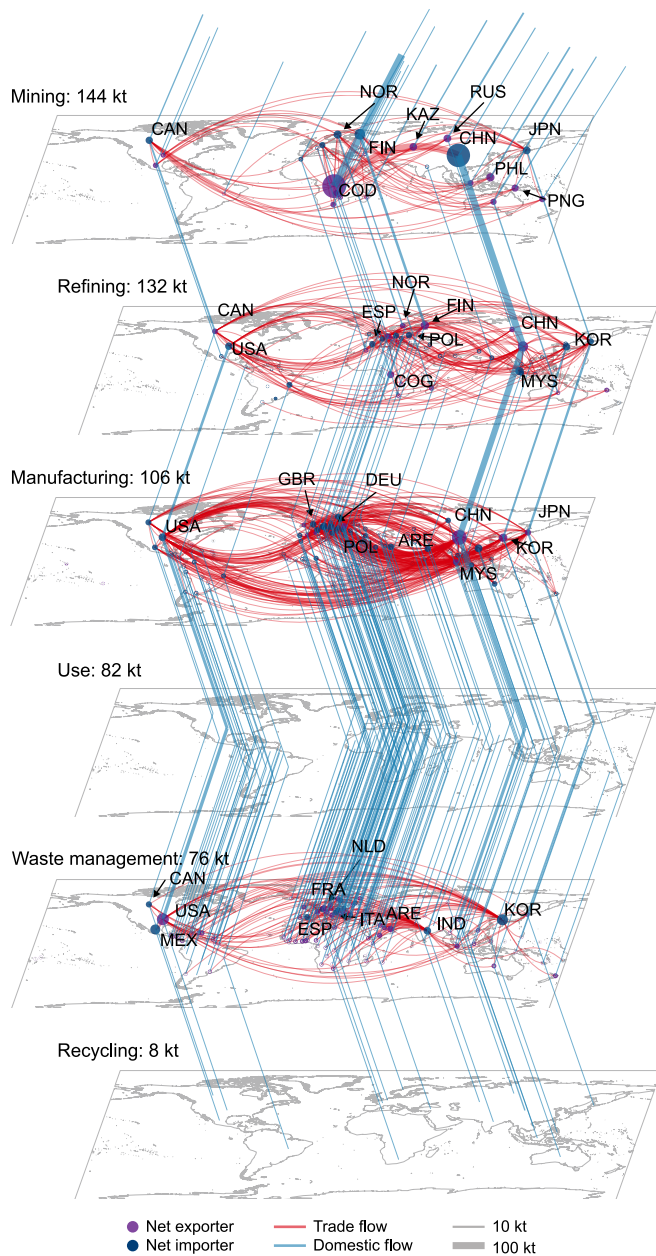


Fig. 2. Multilayer network of the global cobalt supply chain in 2019. Economies are shown as geographically positioned nodes, with size proportional to net import volume, and colored by whether the economy is a net exporter (purple) or net importer (dark blue). Red links denote international trade flows within each layer, whereas light-blue links denote transformative flows within the same economy. Flow width is proportional to the cobalt volume, and flows are drawn clockwise. For visual clarity, only flows exceeding 10 t of cobalt are shown. ARE: the United Arab Emirates, CAN: Canada, CHN: China, COD: the Democratic Republic of the Congo, COG: Republic of the Congo, DEU: Germany, ESP: Spain, FIN: Finland, FRA: France, GBR: the United Kingdom, IND: India, ITA: Italy, JPN: Japan, KAZ: Kazakhstan, KOR: Korea, NLD: the Netherlands, NOR: Norway, PHL: Philippines, PNG: Papua New Guinea, POL: Poland, RUS: Russia, USA: the United States of America, MEX: Mexico, MYS: Malaysia.

further chemical refining. Other significant producers—including Russia (6.3 kt), Australia (5.7 kt), and the Philippines (5.1 kt)—mainly produced cobalt intermediates—namely, nickel- and cobalt-bearing mattes, hydroxide, and sulfide—as by-products of the smelting of nickel sulfides or laterite ores [53]. In the refining stage, China produced approximately 68% (90 kt) of global refined cobalt, followed by Finland (12.5 kt), Canada (6.1 kt), and Norway (4.4 kt), from either

cobalt ore or intermediate chemicals to refined chemicals, powders, and metals [12]. In the manufacturing stage, China (69 kt), the European Union (14 kt), the United States (12 kt), Japan (10 kt), and Korea (8 kt) manufactured approximately 90% of cobalt-containing final products. In the use stage, China (33 kt), the United States (16 kt), the European Union (11 kt), and Japan (8 kt) were the largest consumers. Regarding waste management and recycling, the United States was the largest exporter of cobalt waste, while Korea, Mexico, India, and Canada were the primary importers. The highly mismatched conditions of upstream supply and downstream demand expose the fragility of the current global cobalt supply chain.

3.2. Shock propagation through the global cobalt supply chain

In the global, integrated, and interconnected cobalt supply chain, minor region- or industry-specific disruptions will propagate horizontally across economies and vertically through the cobalt life-cycle stages, giving rise to catastrophic failures (Fig. 3). Shock propagation involves two mechanisms: direct and indirect. Intuitively, shocks spread directly through successive direct channels. Take the shock originating from Congo at the mining stage (Fig. 3a) as an example. Initially, the shock diffuses directly to China at the mining stage, primarily through China's largest trade relationship (97 kt of cobalt intermediates from Congo). Then, successive rounds of shocks originating in China rapidly propagate vertically along China's domestic supply chain and horizontally across diverse trade partners. This eventually leads to a 32% collapse after 10 rounds of propagation. However, the shock spreading through supply chains in cascades is not necessarily limited to direct channels. In other words, when the weight of linkages is insufficient to transmit shocks directly, the impacts of weak nodes and linkages can accumulate, giving rise to indirect cascades [50]. Take the shock originating from the United States at the manufacturing stage (Fig. 3b) as an example. Although Spain and the United States have negligible direct manufacturing trade (1% of Spain's manufacturing exports and 6% of its manufacturing imports), accumulative impacts from upstream/downstream and other countries would disturb their trade in the seventh round of propagation. After 12 rounds of propagation, 25% of nodes would fall into collapse. Such alternating direct and indirect cascades amplify the impacts of weak nodes and links, thereby identifying direct, indirect, and invisible interdependencies and interconnections [49]. These shock propagation channels provide scientific evidence for assessing and mitigating the systemic risks inherent in the global cobalt supply chain.

According to the shock propagation mechanism, we categorize a full avalanche process into three subprocesses (Fig. 3c): (i) a one-step direct avalanche: collapse by direct impact from the risk source, (ii) a multistep direct avalanche: collapse by multiple direct cascade processes, and (iii) an indirect avalanche: collapse through indirect cascade processes. Countries with high connectivity or extensive trade partners, such as China (6–11%) and the United States (2–5%), have the highest fractions of one-step direct avalanches. In comparison, multistep direct and indirect avalanches are more common and larger for nodes with large avalanche sizes. For countries with higher multistep avalanche fractions, such as China and Congo, shock spreads directly via successive direct channels. This intuitive approach facilitates understanding and capturing early warning signals—also denoted as a relatively gradual phase transition process in Supplementary Figs. S8–S10. For countries with higher indirect avalanche fractions, such as Finland, Korea, the Netherlands, and the United States, shock spreads in a highly entangled way. Those microscopic failures may not accumulate linearly but instead occur abruptly (Supplementary Figs. S8–S10), making it challenging to capture

early-warning signals to prevent them or devise effective responses.

From the life-stage composition of the avalanche fractions (Fig. 3c), the mining layer has more avalanche sizes or fractions than any other layer for its most concentrated production landscape (Supplementary Fig. S11). However, the collapsed mass predominantly accumulates during the refining and manufacturing stages, given the strong vertical bridges and dense trade links, and recycling still has a limited impact on the robustness or resilience of the current cobalt supply (Supplementary Fig. S12). This shows why single-layer or trade-only multiplex views are incomplete; they privilege horizontal trade hubs [40], whereas our multilayer analysis reveals alternating horizontal/vertical pathways that lengthen cascades and expose multistage knock-ons. As a result, transformer economies with modest trade volumes but pivotal refining/manufacturing roles—such as Finland and the Netherlands—rise in disruption-generating and disruption-receiving potential, while pure trader hubs are de-emphasized. This pattern is consistent with lithium's multilayer findings, in which China's integrated domestic chain extends its influence from refining to multiple life-cycle stages [25], reinforcing the idea that multistage coupling, rather than trade volume alone, governs systemic risk.

To further elucidate the general patterns of shock propagation, we iterate over all nodes to construct an avalanche network (Fig. 4). In an avalanche network, nodes are connected by a direct link if a shock originating from one node could potentially cause the other node to collapse, and are grouped by the Infomap algorithm [54] to identify structures and communities. Alternating direct and indirect cascades amplify the role of teleconnections [50]—hibernated in interdependence and interconnections—to form a denser avalanche network (36,755 links, density: 0.06) than the underlying supply chain network (10,736 links, density: 0.02). In addition, a hierarchical multiple core-periphery structure is identified in the avalanche network, but not in the underlying supply chain network. For the whole network, the robustness or resilience of the global cobalt supply chain is hierarchically controlled by hub communities and hub nodes. Core communities (large grey bubbles)—especially the group comprising Belgium, China, Congo, Japan, Korea, Finland, Germany, and the United States—have dense intra-connections and high intercommunity connection strength, thus acting as "risk hubs" to limit or absorb local disruptions and rapidly amplify local disruptions to catastrophic failures. Periphery communities (small grey bubbles) have dense internal connections but fewer connections between communities; thus, they act as "risk bottlenecks" that fragment the whole network. In each community, it can be further divided into core (large nodes) and periphery (small nodes) substructures. The resilience of each community depends on the robustness of the core nodes.

To alleviate systemic risks, traditional mitigation strategies—such as increasing buffer capacity and strategic stockpiling—can be effective for individual countries (Supplementary Fig. S10). However, given the higher interconnections and interdependencies within the avalanche network, these strategies may have adverse effects on other countries or even on the overall network performance. For instance, if major countries compete to build strategic stockpiles, the heightened competition for cobalt will place an additional burden on mineral extraction, undermine developing countries' access to minerals, and potentially slow or suspend progress in mitigating global supply risks. Therefore, enhancing the resilience of global cobalt supply chain networks requires system-level approaches that balance efficiency and security. In the oil industry, it has been shown that short-term risks can be almost eliminated by joint stockpiling and emergency

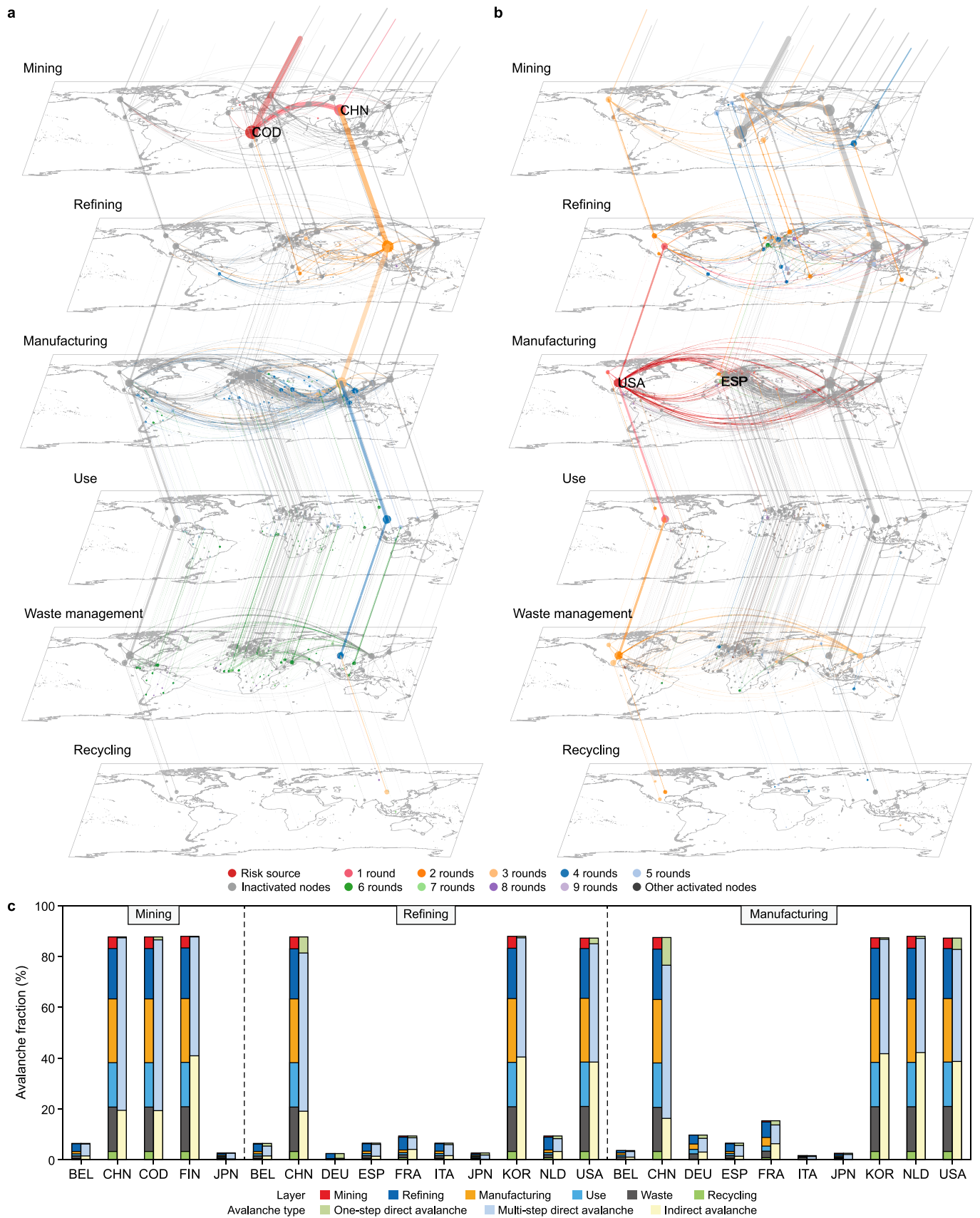


Fig. 3. Shock propagation dynamics through the global cobalt supply chain network. a, Illustrative propagation processes initiated from Congo at the mining stage, with a failure threshold $\Omega = 0.6$, highlighting direct shock propagation channels based on the static multilayer network in 2019. Diffuse round: 10; Avalanche fraction: 32%. **b**, Illustrative propagation processes initiated from the United States at the manufacturing stage with $\Omega = 0.35$, illustrating indirect shock propagation channels based on the static multilayer

sharing [55], creating a win–win situation for both exporters and importers. Establishing a shared mechanism for mineral resources in place of individual strategic stockpiling can reduce the scale of stockpiling, collectively address short-term risks, and prevent resource wastage. Cooperation between major producers and consumers—such as by establishing joint stockpiling, expanding international investments, or eliminating export restrictions—can further consolidate their positions and the stability [14] of the current hierarchical multiple core–periphery structure and facilitate the dissemination of advanced manufacturing expertise to help resource-rich countries tap into midstream/downstream activities. However, in the foreseeable future, protracted geopolitical conflicts worldwide may persistently destabilize the global cobalt supply chain. The highly integrated dealers and suppliers built over decades hinder full decoupling, but they may partially take re-regionalization (reshoring or near-shoring [56]) actions to access a reliable cobalt supply in a future with competitive coexistence.

3.3. Evaluation of systemic risk

The systemic risk of the global cobalt supply chain network is evaluated based on two dimensions: systemic fragility and exposure rate. Systemic fragility measures the potential impact of a node's disruption on the overall network's robustness, with higher values indicating a greater likelihood of triggering catastrophic failures. In 2019, China (2.4) exhibited the highest systemic fragility, followed by the United States (1.7), Japan (1.3), Turkey (1.3), Belgium (1.0), France (1.0), the Netherlands (0.9), Congo (0.9), and India (0.9), among others (Supplementary Figs. S17 and S18). These countries are pivotal producers and consumers identified in the underlying supply chain network or in the avalanche network's core hubs. They are crucial in maintaining network structure and functionality. Therefore, calculated attacks on these nodes could have severe, irreversible consequences for the global cobalt supply chain, although such attacks are rare in practice. Meanwhile, random, dispersed shocks from other nodes could be absorbed and mitigated by these hubs, preventing localized disruptions from evolving into catastrophic failures. These results reflect the "robust-yet-fragile" nature—a common feature of heterogeneous networks [52]—of the global cobalt supply chain network.

As a prerequisite of cascading failures, countries with high systemic fragility tend to have higher exposure rates (see Quadrant I in Supplementary Fig. S19), which measure the probability of being affected by other nodes (Supplementary Figs. S17 and S18) but contradict their ability to absorb random disruptions. In comparison, countries with low systemic fragility but high exposure rate (see Quadrant IV in Supplementary Fig. S19) are particularly vulnerable to common random disruptions and lack resilience or effective responses. They are highlighted by the difference between exposure rate and systemic fragility (Fig. 5a), including small-scale resource-extraction countries, such as Indonesia, Kazakhstan, and the Philippines; refining and manufacturing countries, such as South Africa, Australia, Morocco, Madagascar, and Mexico; and import-processing countries, such as Norway and Canada. On the supply side, their low volumes result in a lack of economies of scale, hindering the establishment of long-term supply agreements. On the demand side, their low volumes and high import dependence weaken their bargaining power to secure raw materials and hamper their ability to navigate

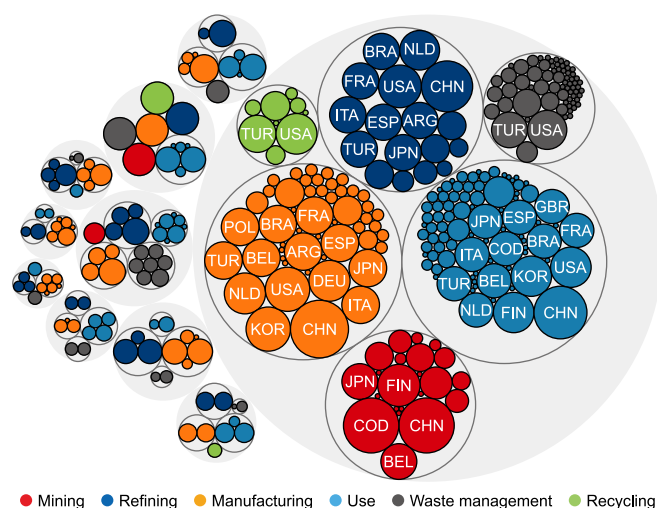


Fig. 4. Shock propagation patterns characterized by an avalanche network. The global cobalt supply chain avalanche network is clustered into communities (grey bubbles) and colored by layers or life-cycle stages. For visual clarity, only communities with more than six nodes are shown, and individual links are omitted because avalanche connections are much denser than the underlying supply chain links. Node size is proportional to systemic fragility, reflecting each node's impact on the whole supply chain network and serving as a proxy for link density. Each community exhibits a core–periphery structure, with larger nodes forming the core and smaller nodes forming the periphery. ARG: Argentina, BEL: Belgium, BRA: Brazil, CHN: China, COD: the Democratic Republic of the Congo, DEU: Germany, ESP: Spain, FIN: Finland, FRA: France, ITA: Italy, JPN: Japan, KOR: Korea, ITA: Italy, NLD: the Netherlands, POL: Poland, TUR: Turkey, USA: the United States of America. For visual clarity, nodes with systemic fragility below 0.3 are not labeled.

trade partnerships effectively.

Over the last two decades, the systemic fragility of the global cobalt supply chain network has exhibited a volatile yet upward trend (Fig. 5b), indicating an increasing potential for a localized disruption to spread globally and evolve into catastrophic failures. This trend generally aligns with the surging Herfindahl–Hirschman Index across the mining, refining, and manufacturing stages (Supplementary Fig. S11). Production concentration in the upstream or midstream and divergence between supply and demand have exacerbated global systemic fragility. Since 2011, underpinned by long-term industrial policies and substantial financial investments, China has surpassed the United States to become the most influential country in the cobalt supply chain network (Supplementary Fig. S20). In response to this shift, the United States and the European Union have taken a series of actions to enhance the reliability and resilience of their supply chains. As a result, the global exposure rate peaked in 2016 and has since declined (Fig. 5c). This decrease corresponded with the reduction in network intensity (Supplementary Fig. S21). Highly concentrated supply sources and excessive connectivity significantly increase the supply chain network's sensitivity to localized disruptions.

3.4. Discussion and policy implications

Our study integrated trade-linked MFA with a multilayer shock propagation model to identify how disruptions spread horizontally across economies and vertically through life-cycle stages. Using a two-step failure threshold design, we derived two systemic risk indicators—systemic fragility and exposure rate—to

network in 2019. Diffuse round: 12; Avalanche fraction: 25%. Nodes and links are colored according to the round in which they are activated. Link width is proportional to the cobalt flow volume on the corresponding multilayer network in 2019. Additional illustrative shock propagation processes originating from selected sources are presented in Supplementary Figs. S4–S7. c, Composition of avalanche fraction aggregated by life stage (left bar) and avalanche type (right bar). BEL: Belgium, CHN: China, COD: the Democratic Republic of the Congo, DEU: Germany, ESP: Spain, FIN: Finland, FRA: France, ITA: Italy, JPN: Japan, KOR: Korea, NLD: the Netherlands, USA: the United States of America.

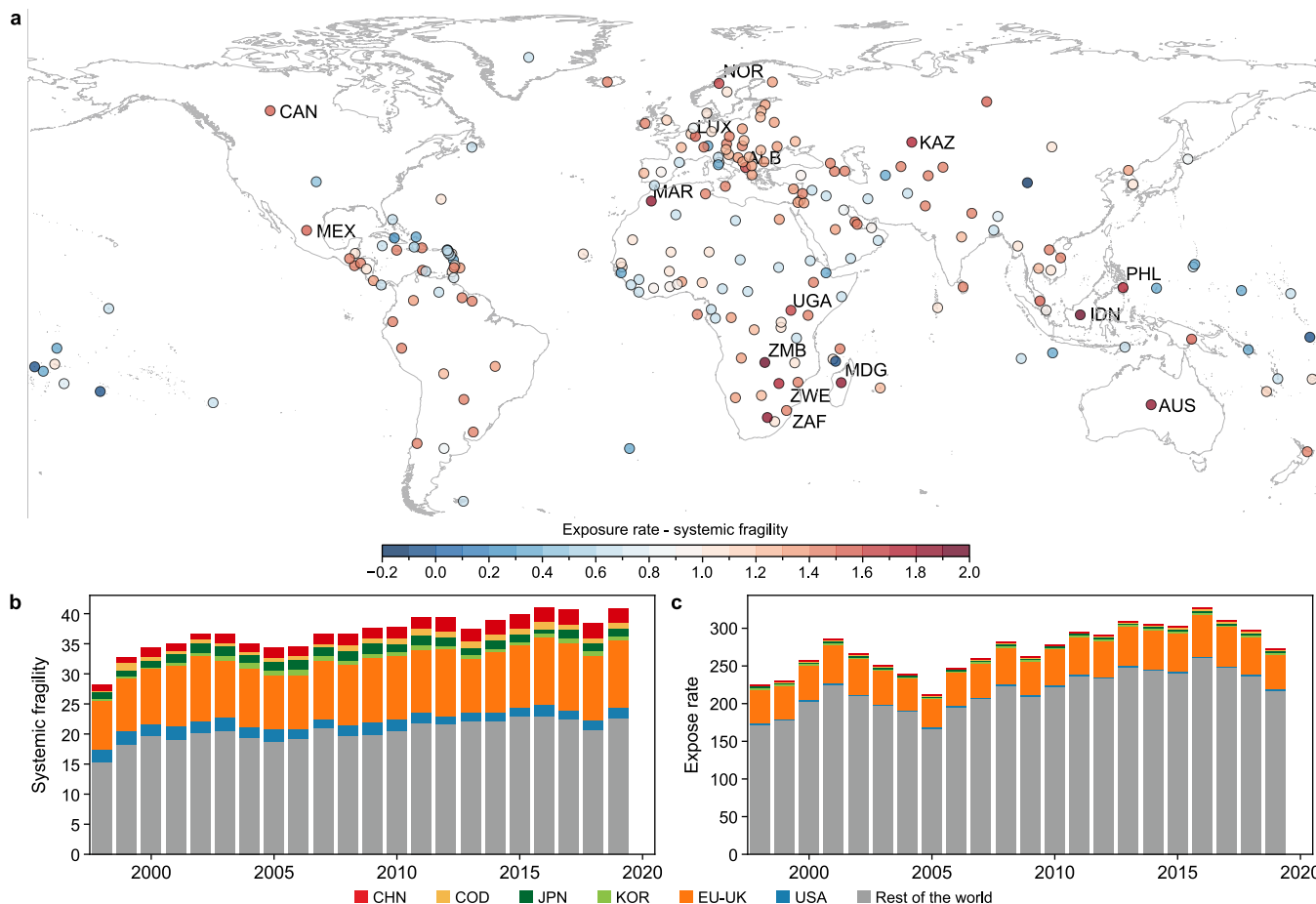


Fig. 5. Systemic risks of the global cobalt supply chain network. **a**, Differences between exposure rate and systemic fragility in 2019. Countries exhibiting high systemic risk but limited resilience or responses capacity are identified by a large disparity between the exposure rate and systemic fragility. **b**, Evolution and composition of global systemic fragility from 1998 to 2019. **c**, Evolution and composition of global exposure rate from 1998 to 2019. Additional maps of systemic fragility and exposure rate for 2000, 2005, 2010, 2015, and 2019 are presented in [Supplementary Figs. S13–S17](#). ALB: Albania, AUS: Australis, CAN: Canada, CHN: China, COD: the Democratic Republic of the Congo, JPN: Japan, KAZ: Kazakhstan, KOR: Korea, EU-UK: the European Union and the United States of Kingdom, IND: India, LUX: Luxembourg, NOR: Norway, MDG: Madagascar, MEX: MAR: Morocco, Mexico, PHL: Philippines, UFA., Uganda, USA: the United States of America, ZAF: South Africa, ZWE: Zimbabwe, ZMB: Zambia.

quantify disruption-generating and disruption-receiving risks in the global cobalt supply chain network, uncovering mechanisms missed by single-layer or trade-only multiplex networks. Specifically, the systemic risk of the global cobalt supply chain network is concentrated at the mining stage, but it accumulates predominantly at the refining-manufacturing bridges. Alternating horizontal/vertical and direct/indirect shock propagation pathways lengthen cascades, expose multistage knock-ons, and produce abrupt, nonlinear failures, yielding a four-fold denser avalanche network than the underlying supply chain. These mechanisms imply that unchecked interventions often relocate rather than remove risk, highlighting the need for system-level approaches to predict, simulate, manage, and respond to the risks of supply chain networks. In short, national strategies are necessary, but coordinated efforts and close collaboration of multiple stakeholders are more important and efficient. Building on these insights, we propose five policy priorities to improve the resilience of cobalt or LIB supply chains.

Further mapping and understanding of the LIB and battery material supply chains. Mapping the supply chain is a stepping stone for effective supply chain management. Recent years have seen increasing efforts to improve the visibility and traceability of supply chains for LIBs and related critical minerals, from an economy-wide scale [57] to national [12,41] (Fig. 2 for cobalt) and firm levels [58]. These periodic assessments provide valid

implications for long-term policies [59,60], yet they may struggle to counteract short-term or emergent disruptions. With the rapid advancement of big data analytics, the real-time tracking of supply chains and the monitoring of suppliers' performance are receiving increasing attention, but data limitations still constrain them. Integrating these fragmented and incompatible supply chain datasets requires collaborative efforts among governments, intergovernmental and nongovernmental organizations, the private sector, and academia. Blockchain technology, a decentralized data storage system, is a promising means of sharing these datasets with transparency, traceability, and security. Digitized documentation [61]—namely, material passports—makes it easy and inexpensive to track the provenance of materials, components, semis, and final products. Complementarily, isotope "fingerprints" provide an independent, reliable, and tamper-proof means of examining document-based traceability [62].

Building a global critical mineral alliance to manage mining activities. Mineral extraction is the first step in the cobalt—and thus LIB and EV—supply chain and is potentially associated with serious ESG issues. Thus, it is essential to reach consensus on international targets for global mineral extraction to minimize ESG impacts while ensuring a reliable supply of critical minerals. The current lack of consensus often leads to mismatched upstream supply and downstream demand, causing market fluctuations. On the supply side, major miners are rapidly scaling up production to

meet the surging material demand for LIBs and EVs. For example, a cobalt deficit of 8 kt in 2021 was quickly filled, leading to a surplus of 18 kt in 2023 [63]. The oversupply situation is particularly acute for lithium and nickel, with surpluses of 65 and 221 kt, respectively, in 2023 [63]. These changes will weigh on critical mineral prices and lead to the suspension of mineral project development. Therefore, we argue for a critical mineral alliance to bridge information between upstream supply and downstream demand to reduce redundancies. On the demand side, the main consumers rely highly on mineral imports, making them vulnerable to supply disruptions. To mitigate this, China [64], the United States [65], Japan, and Korea are establishing or expanding strategic stockpiles to create a buffer against potential shortages and long-term import dependencies. Increasing stockpile competition for national security places an additional burden on mineral extraction, undermines developing countries' access to minerals, and potentially slows or suspends global mitigation progress. Therefore, we argue for a critical mineral alliance to develop joint emergency assistance, including sharing strategic stockpiles and coordinating alternative supply routes.

Building an LIB industry supply chain alliance to ensure a smooth transition. Underpinned by decades of industrial policies and investment, China has emerged as the global leader in the entire supply chain for critical minerals and LIBs, with around 70% of lithium and cobalt refining capacity, and cathode, anode, and battery cell production capacity, located in China [66]. This growing role of China has sparked resentment and raised concerns in the West. The European Union has refining and processing capacity in Belgium, France, and the Netherlands, but securing mineral sources will be the main challenge. To secure access to critical minerals, they diversify sources and expand partnerships to reduce strategic dependencies [67]. From an interconnected network perspective, however, greater connectivity does not necessarily imply greater resilience [52]. As illustrated in this study, a highly interconnected supply chain is susceptible to cascades of supply shocks. The United States, on the other hand, takes a more radical approach to revitalizing domestic production and reshaping its supply chain [68] to exclude its geostrategic competitor, China. However, excessive and rapid decoupling will fragment the global supply chain, raise costs, and slow the low-carbon transition, as evidenced by analogous research on lithium [25]. Altering direct connections—whether adding links to diversify or removing links to decouple—can reconfigure hidden indirect dependencies and reroute exposure paths, but if they are not carefully designed, such changes may inadvertently elevate systemic risk. Our approach provides a framework for simulating the impact of decoupling and introducing new partnerships by removing or adding linkages and adjusting the import or export volumes of the underlying supply chain network to balance efficiency and resilience (Fig. 3). In the future, the likely transition from globalization centered on growth and efficiency to a fractured system centered on competition and security will still require international cooperation and coordination to ensure a smooth transition.

Establishing an early warning mechanism for impending risks. Owing to the alternating direct and indirect cascades, microscopic failures may not increase linearly but instead accumulate and abruptly lead to catastrophic failures, making them difficult to prevent or mitigate. The robustness or resilience of the global supply chain relies on the relationships within communities and their connections to other parts of the network. The hierarchical, multiple core–periphery structure of the avalanche network (Fig. 4) helps reveal the risk propagation mechanism and identify potential risk sources: hub communities and hub nodes. These hubs are good at holding network structure and functionality, as they limit or absorb the impact of localized disruptions,

but they also quickly amplify localized avalanches from themselves to the whole network [52]. Therefore, we propose a two-step approach to providing early warnings. The first step is to monitor the state of the hub nodes in each community. If the relative decrements caused by local disruptions exceed the failure threshold identified by dynamic criticality, catastrophic failures will occur abruptly. Thus, we set a proportion of 10% of the relative decrements—around two times the average systemic values (Supplementary Fig. S22)—as the warning value of the hub nodes. When disruption occurs, governments and markets work to maintain supply chain stability by releasing stockpiles or inventories, increasing imports, and reducing exports. The second step is to monitor overall community changes during this adjustment process and set the 35% of the relative decrements—the average exposure rates (Supplementary Fig. S22)—as the warning value for hub communities. A local avalanche within communities may not propagate to the entire network, depending on the strength of intercommunity connections. This two-step approach could help identify and mitigate risks before they lead to widespread disruptions.

Imposing a "systemic risk tax" for an already evolving risk. Unlike mandatory administrative orders, financial instruments can achieve supply chain adjustments more naturally and smoothly. In financial networks, economists have proposed "systemic risk tax" [69]—a macroprudential regulation tool—to offset systemic risks. This approach imposes additional taxes on transactions and investments, thereby elevating systemic risk. However, quantifying systemic risk levels and contributions remains challenging. Our approach provides a framework for quantifying the risk contributions of countries (Fig. 5) or even firms and could work as the foundation for implementing a supply chain systemic risk tax. A calibrated levy could discourage high-risk configurations and incentivize firms to adopt risk-reducing actions, such as diversifying supply sources, pursuing new mining exploration, developing cathode substitution technologies or alternative materials, and supporting recycling and recovery infrastructure.

While this integrated analysis provides valuable insights into global cobalt supply chain resilience, uncertainties in the data and limitations in the model remain. On the data side, our model successfully traced approximately 80% of cobalt flows within and across economies, but the remaining 20% of untraced flows may significantly alter the network topology. To evaluate the potential impact—although these flows are difficult to observe directly—we virtually backfilled the missing data, linked it to the remaining refining capacities, and then reevaluated the systemic risk on the backfilled network. Relative to the baseline, systemic fragility remained robust (~2%), whereas the exposure rate appeared conservatively underestimated (~5%), especially for some small economies (Supplementary Figs. S23 and S24). On the modeling side, shocks are highly simplified as fractional supply shortages or demand reductions; many real-world disruptions (e.g., trade restrictions, sanctions, natural disasters, pandemic shutdowns, and local conflicts) and responses (e.g., stockpile adjustment, diversifying sources, and decoupling) can be mapped into these forms by altering the underlying multilayer network. Given the dense interconnections and interdependencies of the multilayer system, such interventions may improve robustness for certain regions, but they rarely eliminate risks, typically redistributing risks unevenly across the global network [25]. This underscores the need for a careful and thorough evaluation of network topology and systemic risk. In response, stockpiles are demonstrated effectively through buffer capacity adjustments, but we have not yet explicitly simulated inventory dynamics. More broadly, this model does not capture adaptive responses, including price-mediated restructuring of supply, consumption, or trade, governmental

interventions, and substitution effects. These limitations highlight priorities for future work integrating explicit inventory and policy responses, modeling substitution pathways, and incorporating price-driven network adaptation.

4. Conclusions

Our results revealed an interconnected, integrated global cobalt supply chain network, coupled with concentrated supply sources and a mismatch between supply and demand. First, such a cobalt supply chain network is robust yet fragile—that is, robust to common random shocks from nodes with low systemic fragility but fragile to targeted attacks from nodes with high systemic fragility. Countries with low systemic fragility but high exposure rate are particularly vulnerable to common random disruptions and lack resilience or effective responses. Second, the systemic risk of the global cobalt supply chain network is concentrated at the mining stage but predominantly accumulates at the refining–manufacturing bridges. Alternating horizontal/vertical and direct/indirect shock propagation pathways lengthen cascades, expose multistage knock-ons, and produce abrupt, nonlinear failures, yielding a four-fold denser avalanche network than the underlying supply chain. Third, systemic risk exhibited a volatile but upward trend over the last two decades. Together with a hierarchical multiple core–periphery structure, these features highlight the fact that national strategies are necessary but insufficient; effective resilience requires stage-aware, multilateral cooperation and system-level coordination.

CRediT authorship contribution statement

Xin Ouyang: Writing - Original Draft, Visualization, Software, Methodology, Investigation, Formal Analysis, Data Curation. **Litao Liu:** Writing - Review & Editing, Supervision, Funding Acquisition, Conceptualization. **Qiance Liu:** Writing - Review & Editing, Validation, Formal Analysis. **Wu Chen:** Writing - Review & Editing, Validation, Formal Analysis. **Chao Wang:** Validation, Formal Analysis. **Xun Pang:** Validation, Formal analysis. **Canfei He:** Validation, Formal Analysis. **Gang Liu:** Writing - Review & Editing, Writing - Original Draft, Visualization, Validation, Supervision, Project Administration, Methodology, Investigation, Funding Acquisition, Formal Analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix B. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ese.2025.100654>.

Appendix A. Supplementary data

Methodology details include the anthropogenic cycle or trade-linked material flow analysis model of cobalt, and results details

include cobalt flows in the global cobalt supply chain network, as well as shock propagation processes and properties, systemic risks, and uncertainty analysis.

The simulation codes and illustrative examples are available at <https://github.com/IE-XinOuyang/Multilayer-Linear-Threshold-Model>.

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