Supporting Information for

Decoding the Global Anthropogenic Cobalt Cycle: Metabolic Archetypes, Network Evolution And Circularity Potentials

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The *Data for Figures* and *Supplementary Data* are deposited in an external repository and are publicly available at Zenodo: https://doi.org/10.5281/zenodo.18983124.

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1. Supplementary methods

A complete supplementary data workbook containing the model parameter tables and the data underlying the figures is archived at Zenodo (DOI: 10.5281/zenodo.18983124). This workbook includes commodity metadata, cobalt content conversion factors, transfer coefficients, market shares, product lifetimes, recycling efficiencies, units, source references, assumptions, and applicable years.

1.1. Conceptual framework of the global cobalt material flow network

Figure S1 illustrates conceptual structure of the global cobalt material flow network (MFN). Building on the system-boundary and material-accounting definitions provided in Section 2.2.1 of the main text, this supplementary section further describes the stage-level organization of the system, the distinction among transformation, trade, loss, and recycling flows, and the role of in-use stock accumulation and end-of-life feedbacks within the trade-linked MFA framework.

The system is structured as a stage-resolved, trade-embedded, and partially closed material cycle that tracks cobalt from primary extraction to end-of-life (EoL) management while maintaining mass balance across all processes. The framework comprises five life-cycle stages: mining, refining & fabrication, manufacturing, in-use, and waste management.

The mining stage includes ore extraction and beneficiation, generating cobalt-containing raw materials. The refining and fabrication stage represents refining and chemical transformation processes, producing intermediate products such as cobalt metal, cobalt oxide, cobalt sulfate, and other cobalt salts. These semi-products are subsequently incorporated into final products during the manufacturing stage, including superalloys, batteries, cemented carbides, magnets, and chemical applications (Sun et al., 2019).

The in-use stage represents the only life-cycle phase in which cobalt stock accumulates in this study. All long-term material retention occurs in this stage, consistent with dynamic stock-driven modeling assumptions described in the main text. Outflows from the in-use stage correspond to EoL product retirements, which are determined by lifetime distributions.

No explicit stock accumulation is modeled for upstream production stages or downstream waste handling processes due to data unavailability.

The waste management stage receives EoL flows from each product category. A portion of these flows re-enters the refining & fabrication stage through recycling pathways, forming a partial closed-loop system. Recycling flows therefore reduce, but do not eliminate, the dependence on primary mining. The remaining fraction constitutes irreversible losses, which may occur during mining, beneficiation, refining, manufacturing, use, or waste treatment. Loss flows are explicitly represented to preserve mass balance across the system.

Four types of flows are distinguished in the framework: (i) transformation flows along the life-cycle chain, (ii) international trade flows occurring at raw material, intermediate, and final product stages, (iii) loss flows representing process inefficiencies and dissipation, and (iv) recycling flows connecting waste management back to fabrication and fabrication. Trade flows are modeled at each material stage, enabling the construction of stage-resolved, metal-equivalent bilateral trade networks.

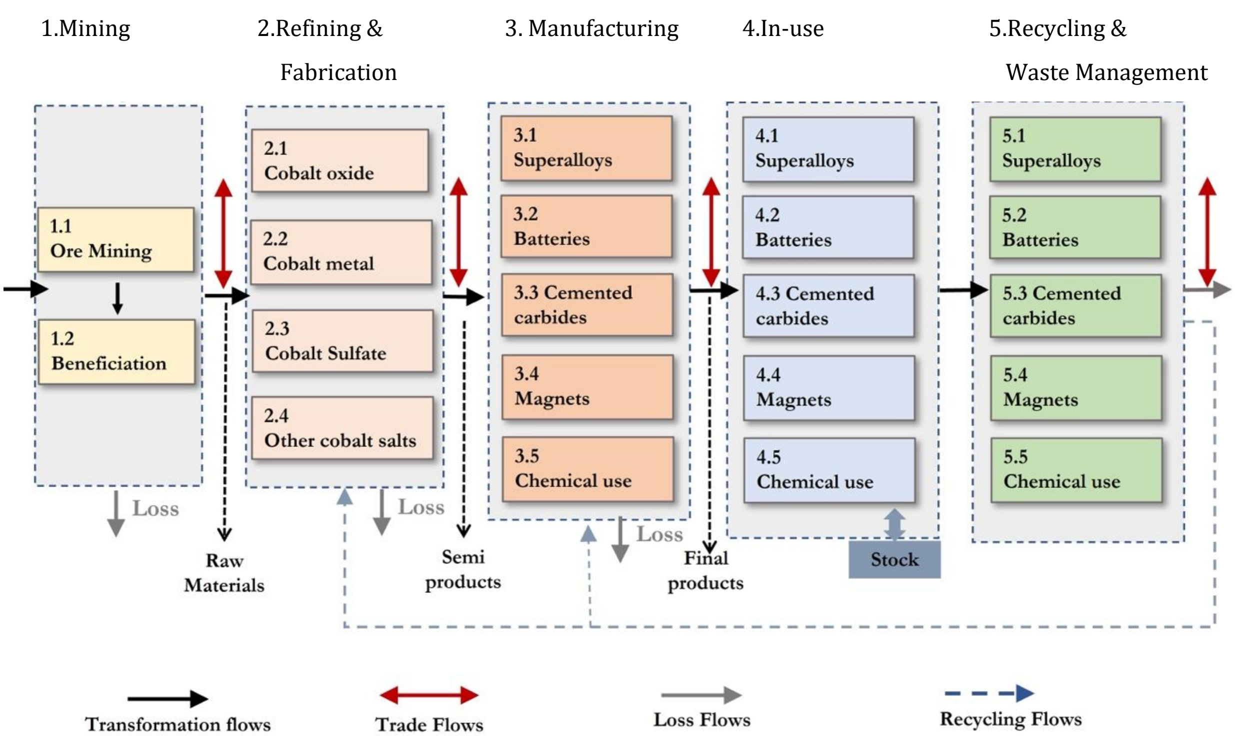

Fig. S1 Conceptual framework of the global cobalt material flow network.

Consistent with Section 2.2.1 of the main text, all flows are expressed in cobalt metal equivalents. Together, these elements provide the conceptual interpretation of Fig. S1 and the structural foundation for the coupled MFA–network analysis presented in the main text.

1.2. Processing and harmonization of bilateral cobalt trade data

Bilateral trade data were compiled from the BACI international trade database and concatenated into a unified annual panel covering all cobalt-related commodities. Reported trade quantities were cleaned by converting non-numeric or missing entries to null values and casting them into numeric format. Only HS codes corresponding to cobalt-containing materials were retained based on the predefined commodity classification table. To avoid duplication arising from parallel HS classifications, HS 810510 was consolidated into HS 810520, and duplicate entries sharing identical year, commodity, exporter, and importer were removed after sorting by quantity .

Trade quantities were converted to cobalt metal equivalents using commodity-specific cobalt content coefficients. For most commodities, cobalt content values were obtained from the commodity metadata table. For selected categories, additional adjustments were introduced to reflect compositional characteristics and temporal variation. Waste batteries (HS 854810) were assigned year-specific cobalt content coefficients to reflect changes in battery chemistry over 2010–2022. Lithium-ion batteries (HS 850760) were assigned a cobalt content of 6.8 percentage by weight battery for exports originating outside China, reflecting typical cathode chemistry assumptions. For cobalt mattes and intermediates (HS 810510/810520), a cobalt content of 99% by weight was applied to exports not originating from the Democratic Republic of the Congo to approximate refined cobalt purity. Cobalt metal equivalent flows were calculated as the product of reported trade quantity and the corresponding cobalt content coefficient.

Data consistency checks were implemented to prevent unrealistic spikes arising from reporting inconsistencies. Extreme outliers in bilateral cobalt metal trade (HS 810590) were conservatively capped at 1000 tonnes per flow. In addition, selected flows associated with known classification inconsistencies were removed to avoid double counting across intermediate and refined product categories.

To address mirror trade discrepancies inherent in bilateral reporting, net cobalt trade flows were constructed. For each year and commodity, reported exports from country *i* to *j* were paired with corresponding flows reported in the opposite direction. Net cobalt transfer was defined as the difference between the two reported flows, and only positive net values were retained. This procedure ensures that each country pair contributes a single directed flow representing net cobalt transfer in metal equivalents.

The resulting dataset consists of annual, commodity-specific, exporter–importer cobalt flows expressed in cobalt metal equivalents and serves as the trade backbone of the mass-balanced material flow analysis framework.

1.3. Construction of the supply-anchored trade-linked material flow network

To reconstruct a physically feasible representation of the global cobalt supply–demand system, we implement a supply-anchored and trade-linked MFA framework. The method integrates country-level production statistics, bilateral trade flows, and stage-specific transformation parameters to derive internally consistent material balances for each country–year node. The reconstruction proceeds sequentially along the cobalt supply chain, including mining, refining and fabrication, manufacturing, and end-use stages. International trade is explicitly embedded within each stage so that cross-border flows redistribute material but cannot generate additional supply.

Fig. S2 Computational implementation of the supply-anchored, trade-linked material flow (MFA).

All calculations are performed in cobalt metal equivalents. For each country i and year t, the available material at stage s is defined as the sum of domestic production and imports:

$$MA_{i,s,t} = P_{i,s,t} + \sum_{j} T_{j \to i,s,t}$$

where $P_{i,s,t}$ denotes domestic production and $T_{j \to i,s,t}$ represents imports from country j. Available material is allocated to exports, downstream transformation, and process losses:

$$MA_{i,s,t} = \sum_{k} T_{i \to k,s,t} + F_{i,s \to s+1,t} + L_{i,s,t}$$

where $F_{i,s \to s+1,t}$ represents the inter-stage transfer and $L_{i,s,t}$ denotes process losses. The computation of each component follows the algorithmic procedure described below.

1.3.1. Data integration and parameter calibration

The MFN construction begins by merging all input datasets into a unified country-year panel. Production statistics for mining and refining are combined with bilateral trade matrices and stage-specific category trade data. Transformation parameters include market shares describing the distribution of outputs across product categories and transfer coefficients representing process yields.

During preprocessing, several calibration procedures are applied to ensure parameter consistency. Market shares within each stage are normalized so that their sum equals unity for every year. This adjustment is necessary because the original statistics occasionally contain incomplete category coverage. Transfer coefficients are then applied to translate input material into effective outputs and process losses. All missing values are replaced with zeros to maintain a consistent mass-balance structure.

The resulting dataset contains, for each country–year observation, production data, net imports and exports for each stage, category-level market shares, and stage-specific transfer coefficients. These parameters serve as the basis for the subsequent stage-wise propagation of material flows.

1.3.2. Refining and fabrication stage

The refining and fabrication stage represents the first major transformation of mined cobalt into intermediate chemical and metallic products. Total material input to this stage is defined as the sum of primary consumption and secondary inputs. In the model implementation, primary consumption is constrained by observed refining production statistics. If the reported refining output exceeds calculated primary consumption, the latter is adjusted upward to ensure consistency with observed production levels.

Refining inputs are allocated across product categories according to their market shares. For each category c, production is calculated as:

$$Q_{i,c,t}^{prod} = C_{i,t}^{ref} \times MS_{c,t} \times TR_{c,t}$$

where $C_{i,t}^{ref}$ represents refining consumption, $MS_{c,t}$ is the market share of category c, and $TR_{c,t}$ denotes the transfer coefficient describing process yield (see Zenodo: https://doi.org/10.5281/zenodo.18983124 for data). Corresponding losses are calculated as:

$$L_{i,c,t} = C_{i,t}^{ref} \times MS_{c,t} \times (1 - TR_{c,t})$$

Total fabrication output is therefore the refining input minus the sum of category-specific losses. The resulting material becomes available for domestic manufacturing or export through international trade.

Net trade flows are incorporated by adding net imports of fabrication products to domestic production, thereby determining fabrication consumption within each country.

1.3.3. Manufacturing stage

Material entering the manufacturing stage is allocated among major end-use product categories, including battery materials, pigments and catalysts, magnetic materials, cemented carbides, superalloys, and other applications. Allocation again follows category-specific market shares and transfer coefficients.

For each manufacturing category k, production is determined by

$$Q_{i,k,t}^{man} = C_{i,t}^{fab} \times MS_{k,t} \times TR_{k,t}$$

where $C_{i,t}^{fab}$ represents fabrication consumption. Manufacturing losses are computed analogously using the complement of the transfer coefficient (see Zenodo: https://doi.org/10.5281/zenodo.18983124 for data).

Trade flows of manufactured products are incorporated by adding net imports of category-specific products. For battery products, net imports are further divided between lithium cobalt oxide batteries and ternary batteries according to their relative market shares. In addition, lithium cobalt oxide batteries are subdivided into laptop, mobile phone, and other electronic applications to support the downstream modeling of in-use stocks.

The total manufacturing consumption of cobalt in country i is then obtained by summing across all end-use categories.

1.3.4. Trade-linked calibration and mass-balance enforcement

A central feature of the framework is the explicit linkage between domestic material flows and bilateral trade statistics. Because trade data are often inconsistent with production statistics, the model applies a set of supply-anchored constraints to ensure physical feasibility.

First, export flows at each stage cannot exceed the material available from domestic production and imports. When such violations are detected, all export flows at the corresponding stage are, after anomaly screening, proportionally scaled down while preserving bilateral trade shares. For mining and refining & fabrication stages, zero domestic consumption is physically admissible. However, for final products, domestic consumption of zero almost always reflects data gaps or product classification masking rather than true zero consumption. To avoid zero-consumption conditions, a small positive lower bound (10-3 kg per capita per year) is imposed. This adjustment guarantees that international trade redistributes existing material rather than creating additional supply.

Second, countries without production capacity cannot be net exporters at the corresponding stage. In such cases, export flows are set to zero and the trade matrix is recalculated.

Third, when supply exceeds identifiable downstream uses, the surplus is not redistributed proportionally but is instead assigned to "Unknown" destinations. These cases represent material sources or destinations that cannot be reconciled with reported production and trade data and are retained for transparency and subsequent analysis. Typical situations include: (i) mining–refining linkage constraints, in which domestic mining output exists but cannot be matched to sufficient domestic refining capacity or identifiable exports, and the excess is assigned to an unknown destination; and (ii) unidentified refining source constraints, in which reported refining production exceeds identifiable mining and import inputs, and the deficit is recorded as an unknown import. These adjustments maintain mass balance while preserving transparency regarding unresolved data inconsistencies.

Additional calibration procedures are applied at the fabrication and manufacturing stages to ensure that exports do not exceed the combination of domestic production and imports. When such violations are detected, export flows are scaled proportionally across trading partners until the constraint is satisfied.

1.3.5. Integration with the global trade network

After country-level material balances are computed, the resulting flows are linked with bilateral trade data to construct the global material flow network. In this network representation, nodes correspond to country-stage combinations, while edges represent either domestic stage transitions or international trade flows. Vertical edges describe transformations along the supply chain, whereas horizontal edges capture the redistribution of material through international trade.

The final network therefore integrates three components simultaneously: physical production, stage-specific transformation processes, and cross-border trade. By anchoring all flows in observed upstream supply and enforcing mass-balance constraints throughout the calculation, the supply-anchored trade-linked MFA produces a globally consistent representation of cobalt flows across both production stages and international trade connections.

2. Supplementary Results

2.1. Global cobalt industry landscape

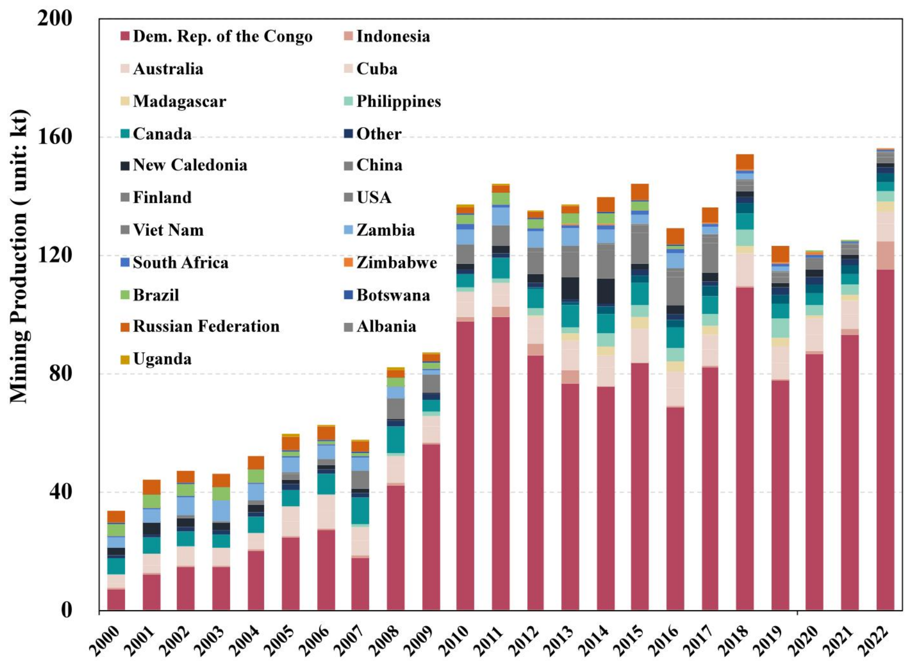

Fig. S3 Annual cobalt mining production by country (2000-2022).

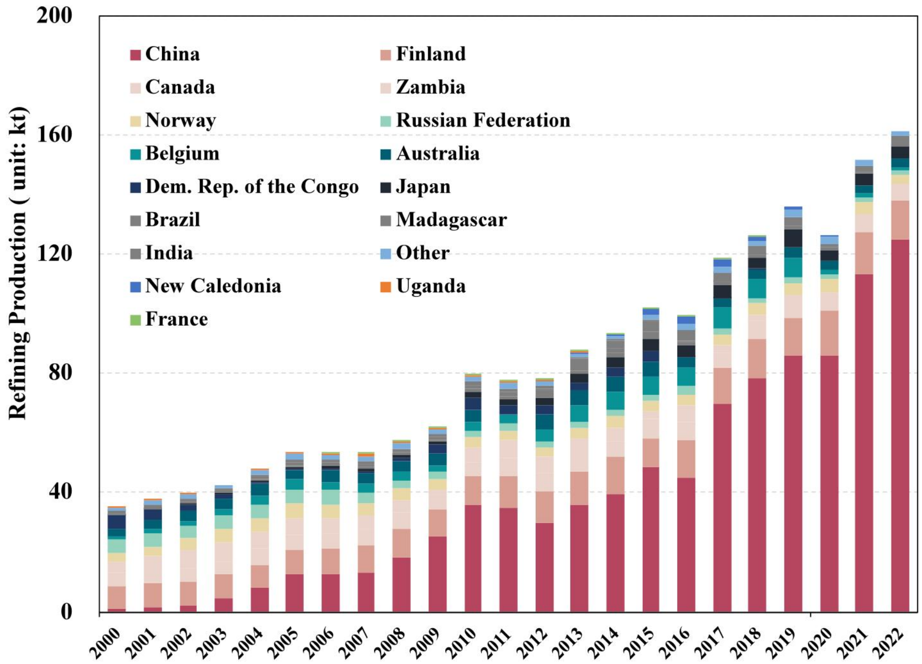

Fig. S4 Annual cobalt refining production by country (2000-2022).

2.2. Dynamic power shifts and community clustering

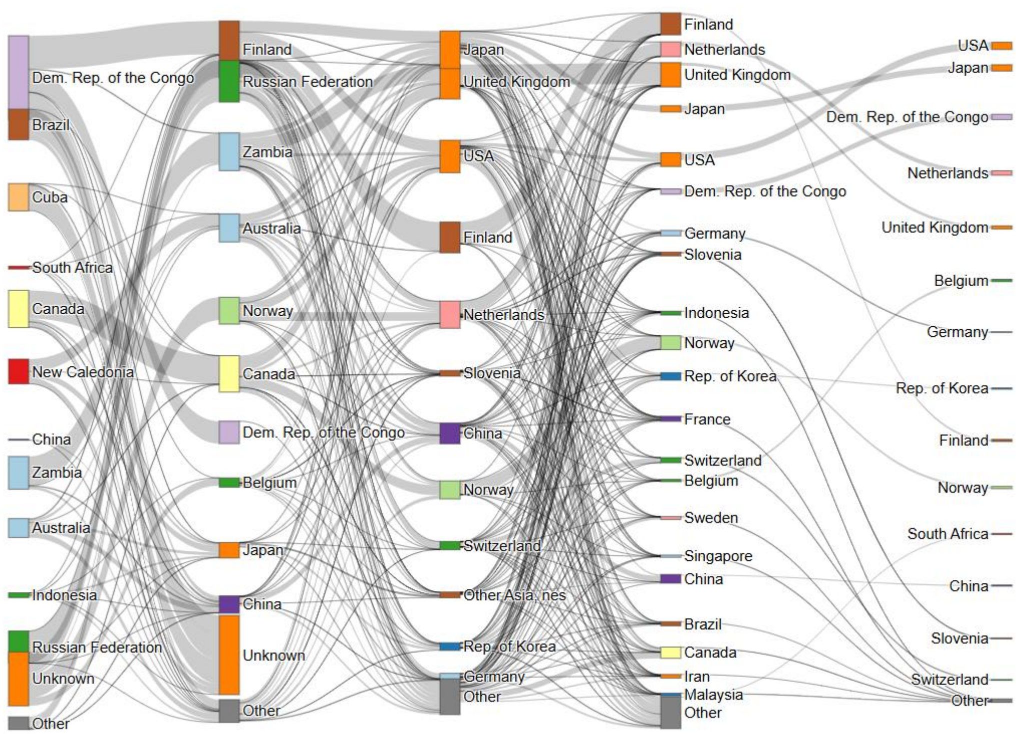

Fig. S5 Sankey diagram of regional cobalt mining, refining & fabrication, manufacturing, consumption (use), waste management, and trade throughout the entire material cycle in 2001.

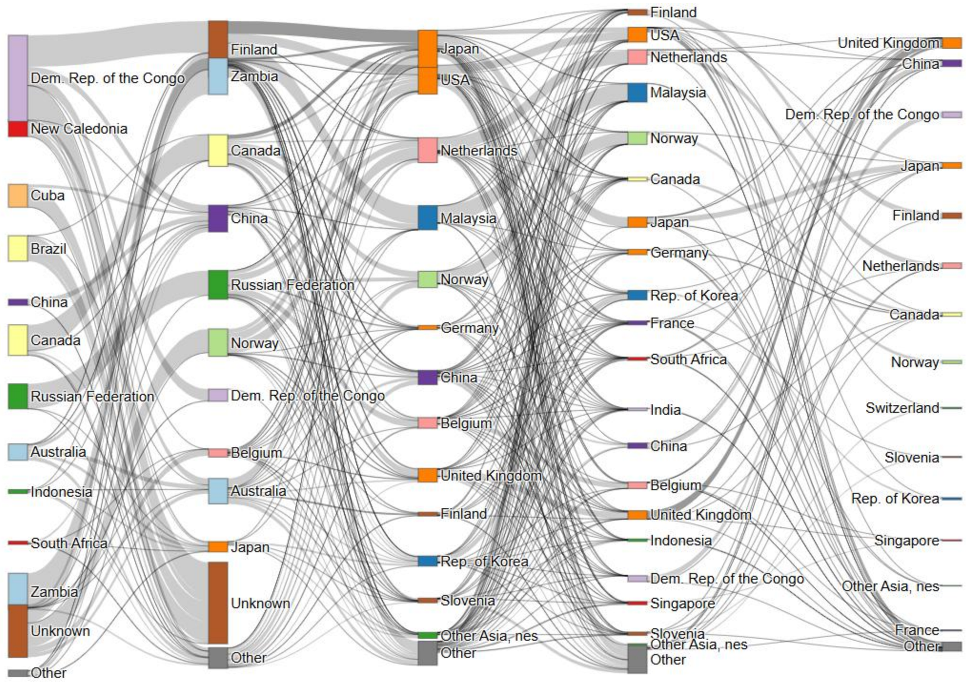

Fig. S6 Sankey diagram of regional cobalt mining, refining & fabrication, manufacturing, consumption (use), waste management, and trade throughout the entire material cycle in 2002.

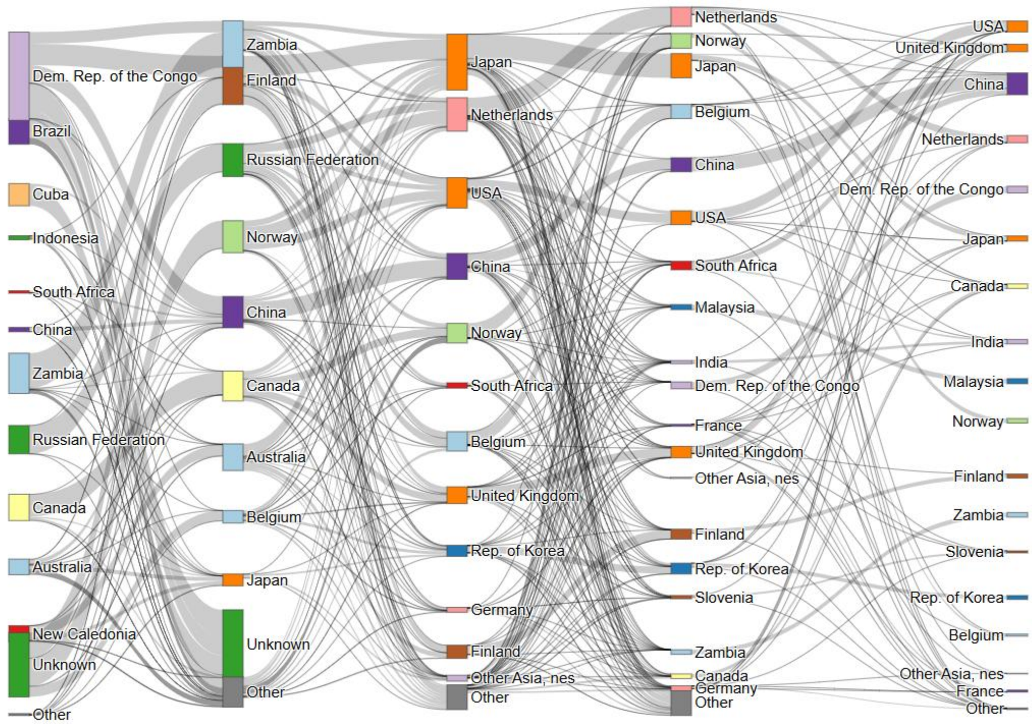

Fig. S7 Sankey diagram of regional cobalt mining, refining & fabrication, manufacturing, consumption (use), waste management, and trade throughout the entire material cycle in 2003.

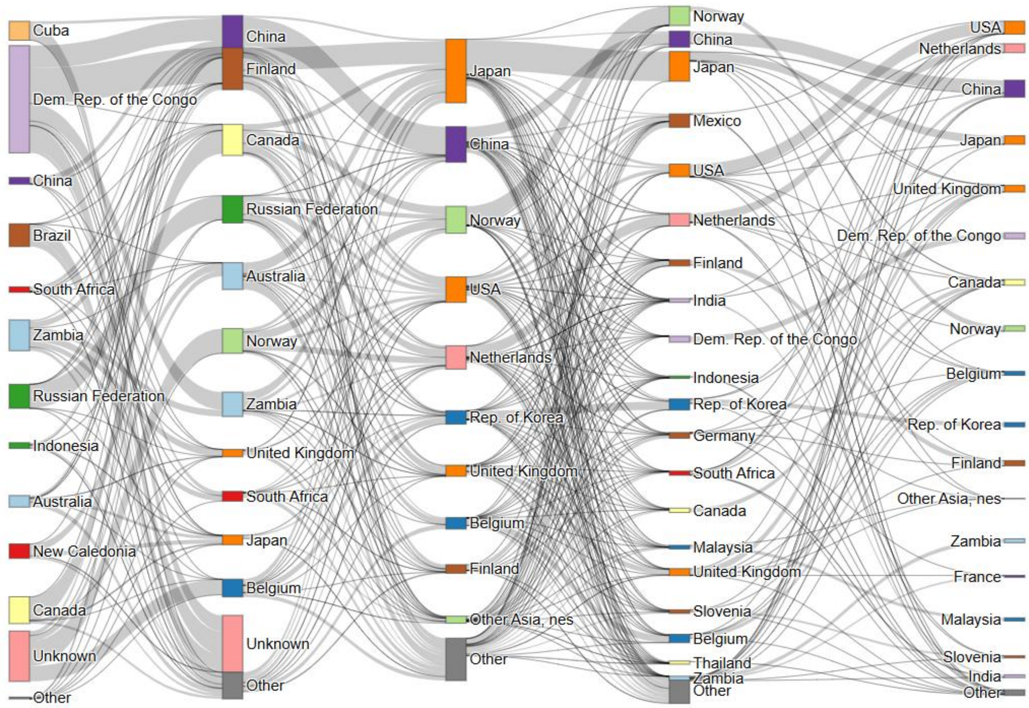

Fig. S8 Sankey diagram of regional cobalt mining, refining & fabrication, manufacturing, consumption (use), waste management, and trade throughout the entire material cycle in 2004.

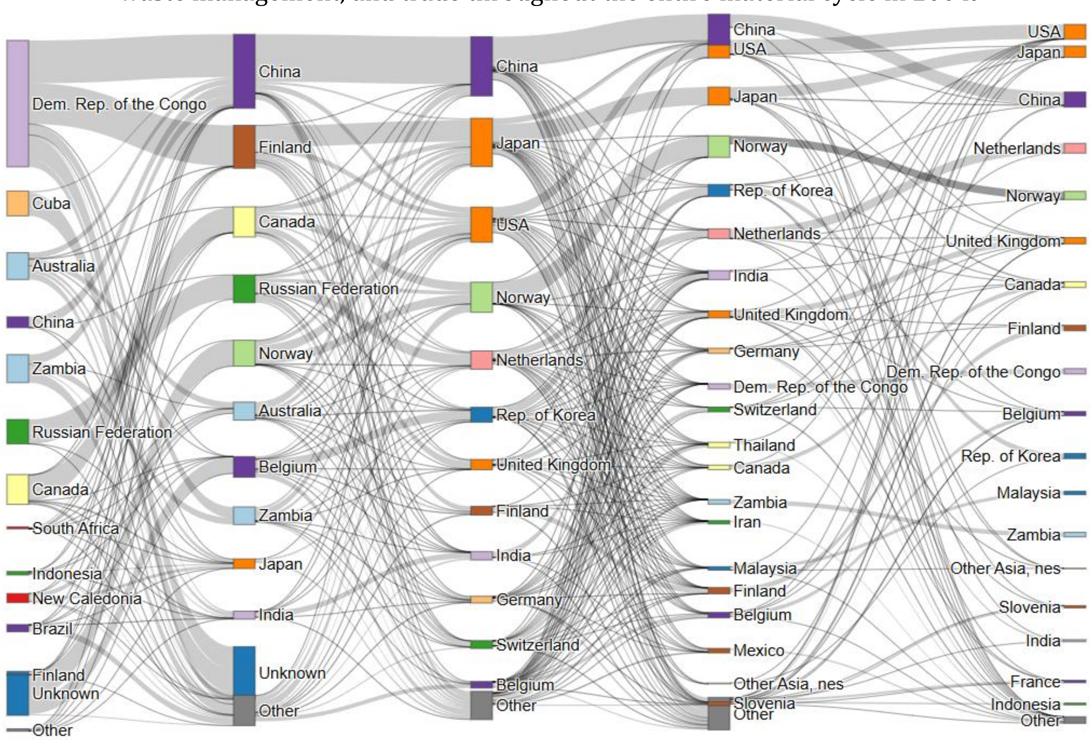

Fig. S9 Sankey diagram of regional cobalt mining, refining & fabrication, manufacturing, consumption (use), waste management, and trade throughout the entire material cycle in 2005.

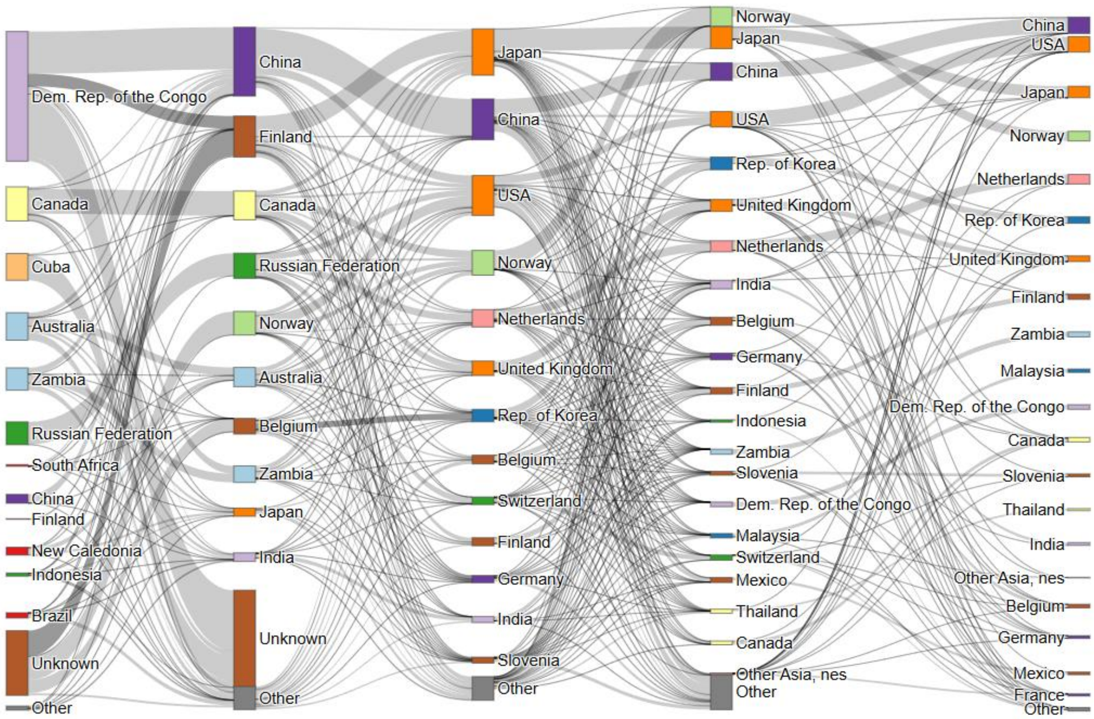

Fig. S10 Sankey diagram of regional cobalt mining, refining & fabrication, manufacturing, consumption (use), waste management, and trade throughout the entire material cycle in 2006.

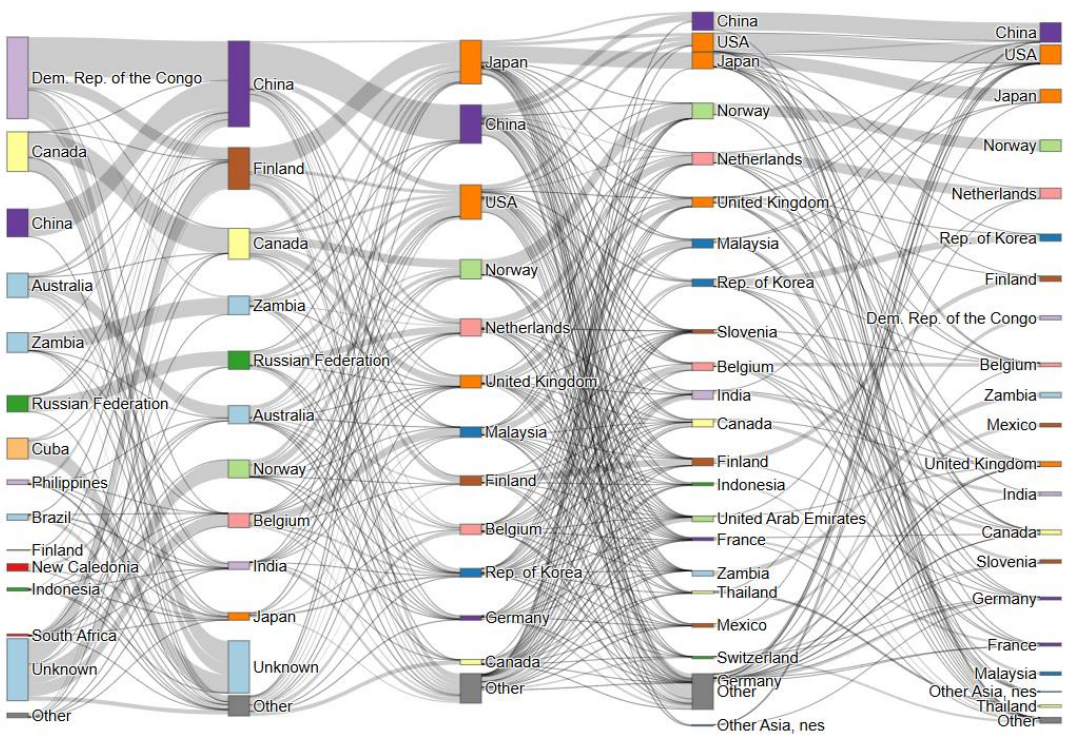

Fig. S11 Sankey diagram of regional cobalt mining, refining & fabrication, manufacturing, consumption (use), waste management, and trade throughout the entire material cycle in 2007.

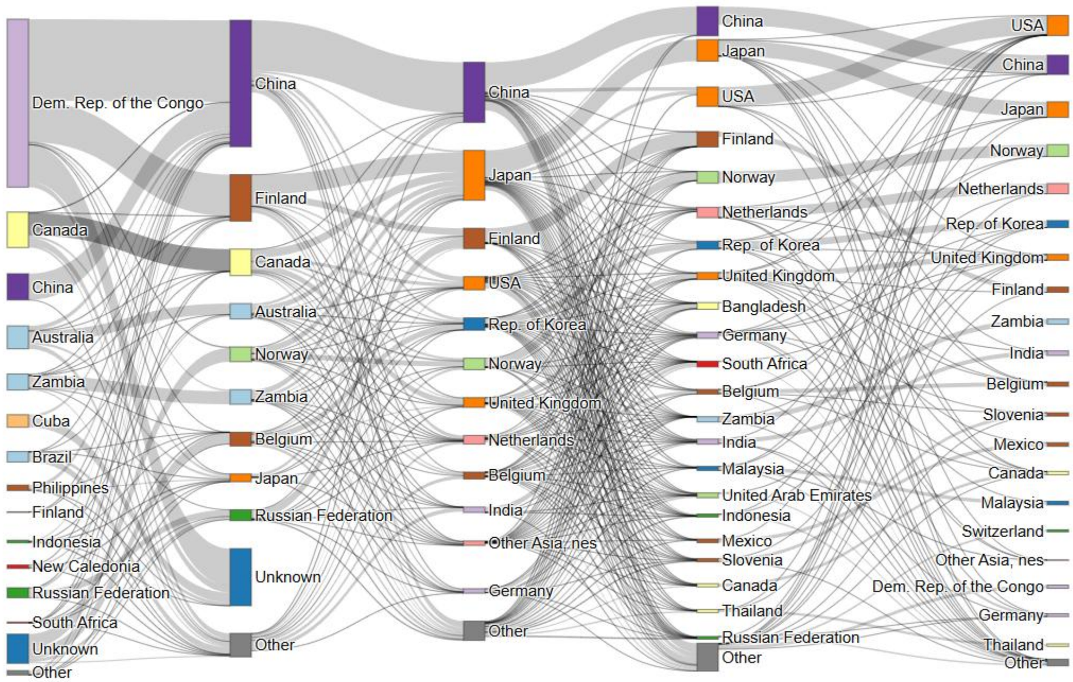

Fig. S12 Sankey diagram of regional cobalt mining, refining & fabrication, manufacturing, consumption (use), waste management, and trade throughout the entire material cycle in 2008.

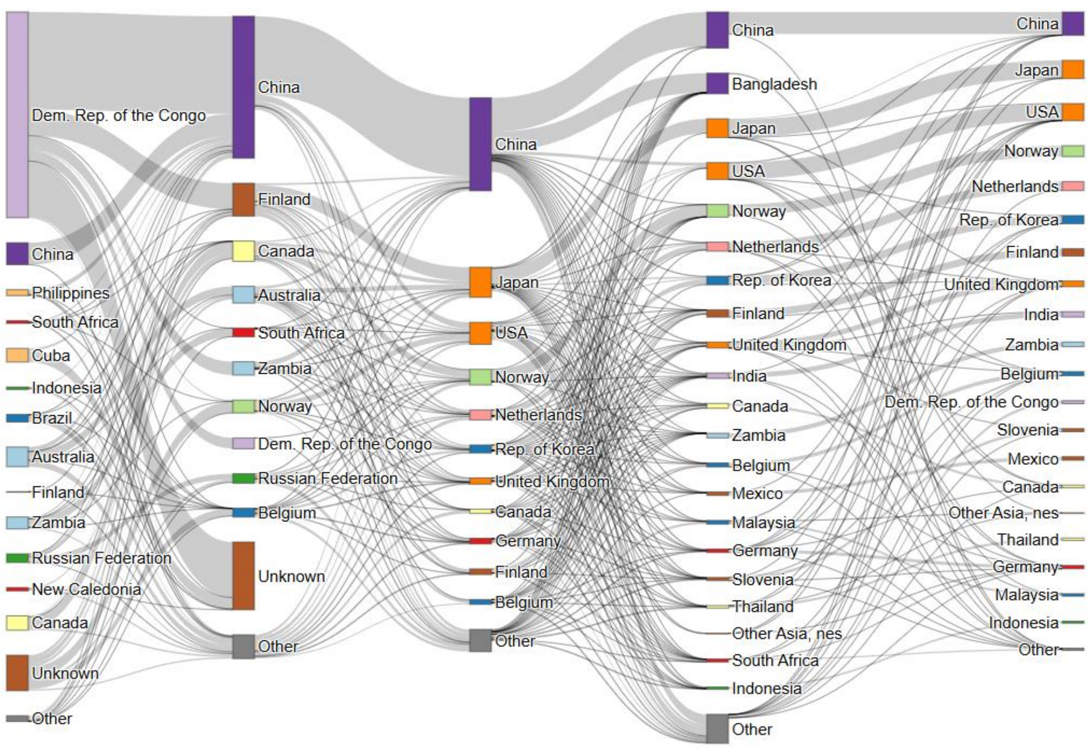

Fig. S13 Sankey diagram of regional cobalt mining, refining & fabrication, manufacturing, consumption (use), waste management, and trade throughout the entire material cycle in 2009.

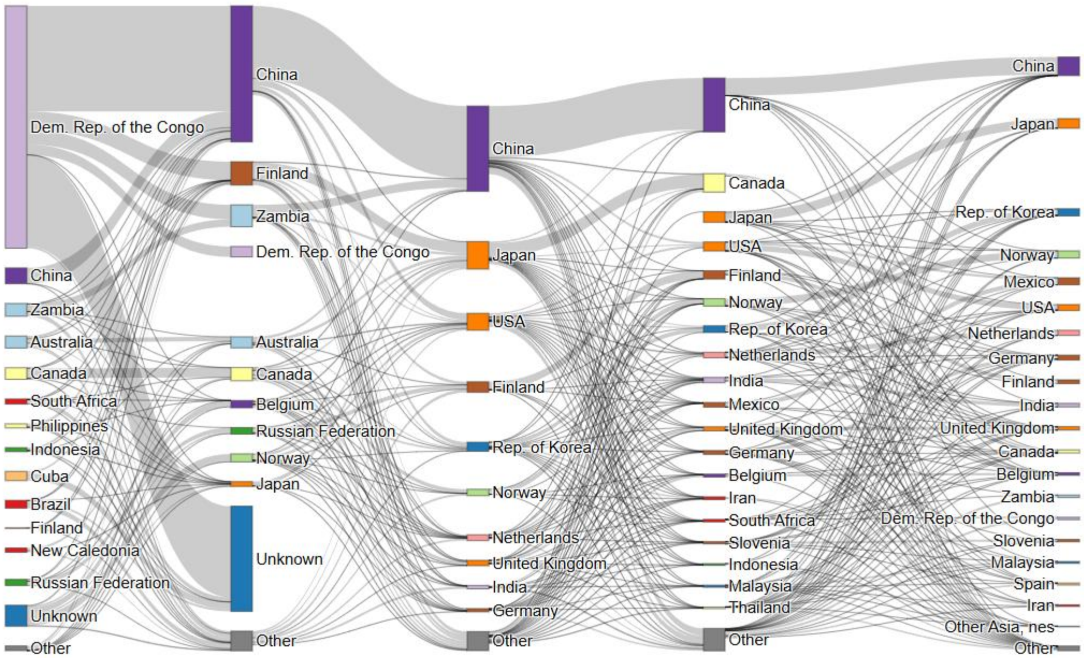

Fig. S14 Sankey diagram of regional cobalt mining, refining & fabrication, manufacturing, consumption (use), waste management, and trade throughout the entire material cycle in 2010.

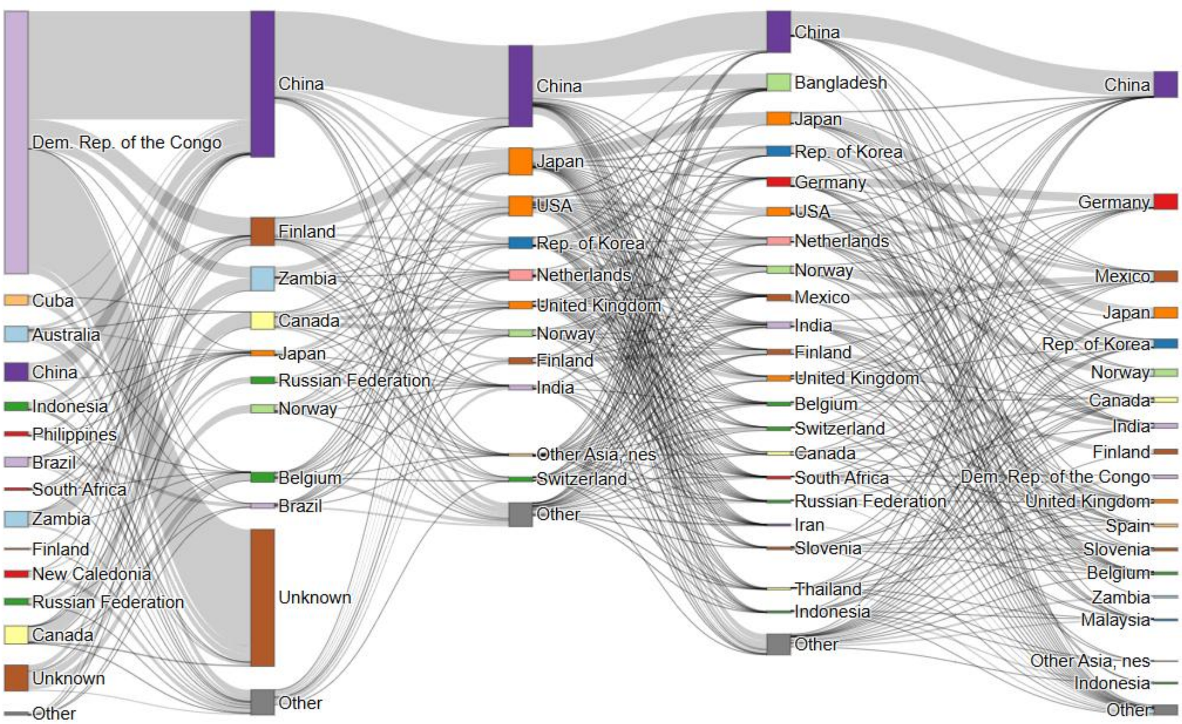

Fig. S15 Sankey diagram of regional cobalt mining, refining & fabrication, manufacturing, consumption (use), waste management, and trade throughout the entire material cycle in 2011.

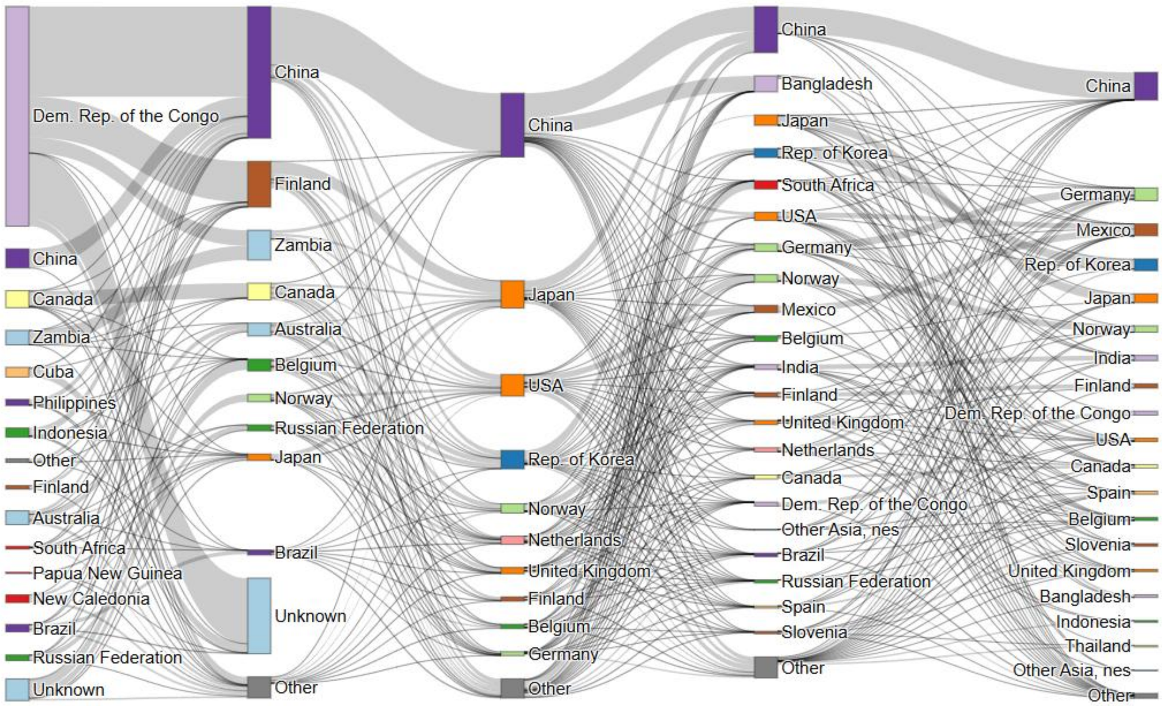

Fig. S16 Sankey diagram of regional cobalt mining, refining & fabrication, manufacturing, consumption (use), waste management, and trade throughout the entire material cycle in 2012.

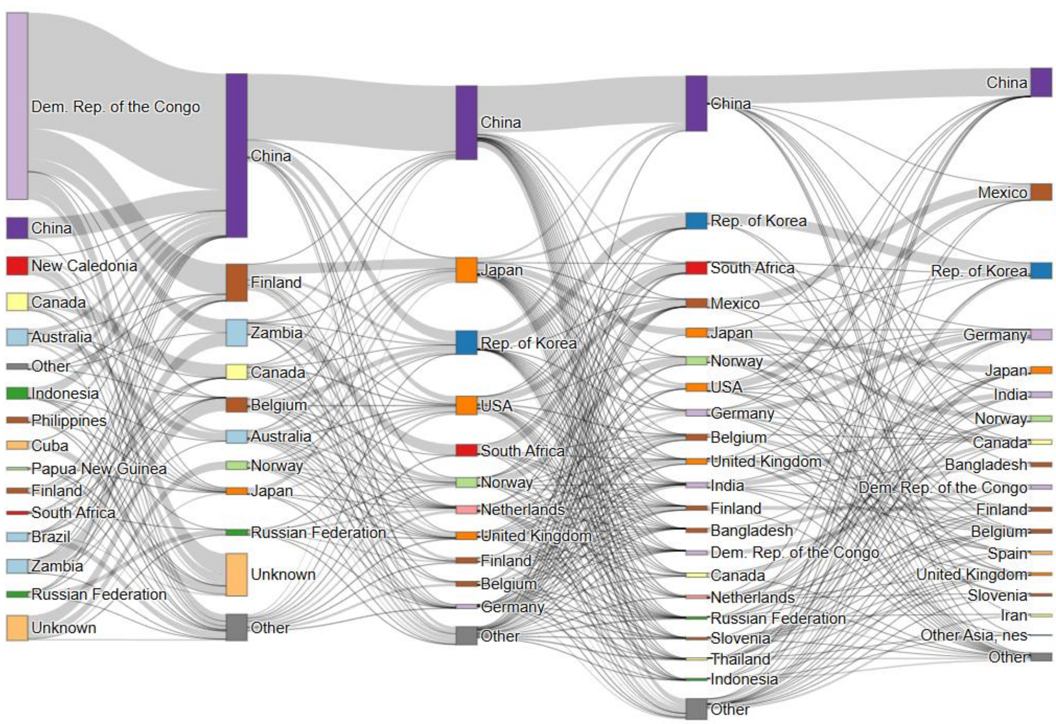

Fig. S17 Sankey diagram of regional cobalt mining, refining & fabrication, manufacturing, consumption (use), waste management, and trade throughout the entire material cycle in 2013.

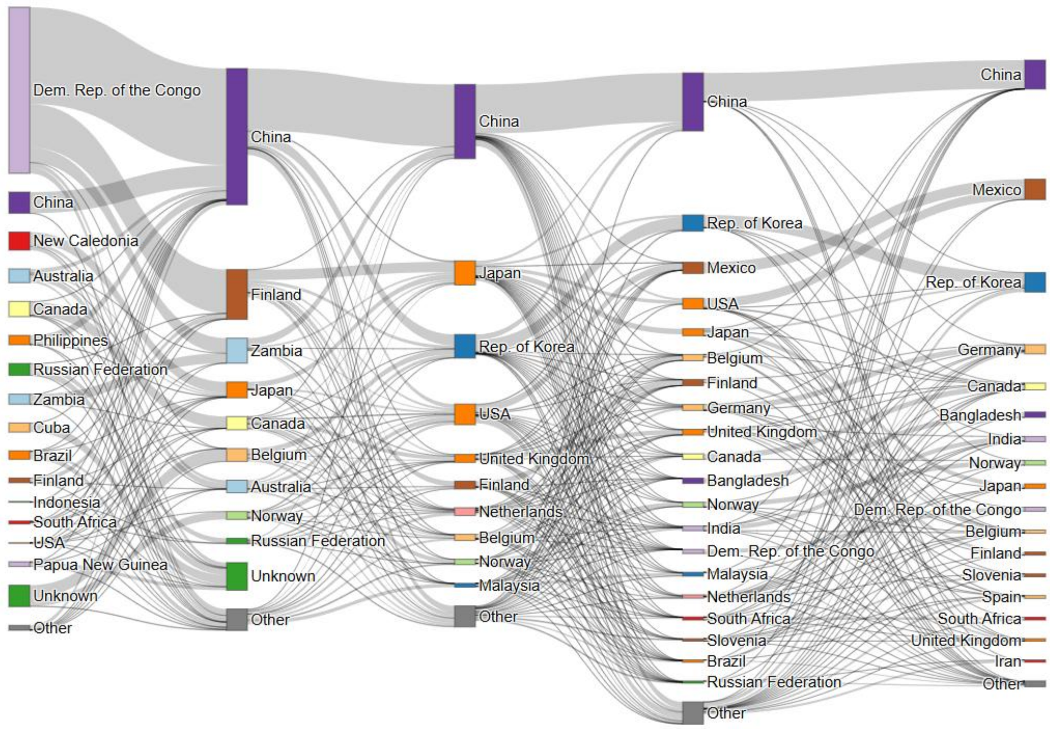

Fig. S18 Sankey diagram of regional cobalt mining, refining & fabrication, manufacturing, consumption (use), waste management, and trade throughout the entire material cycle in 2014.

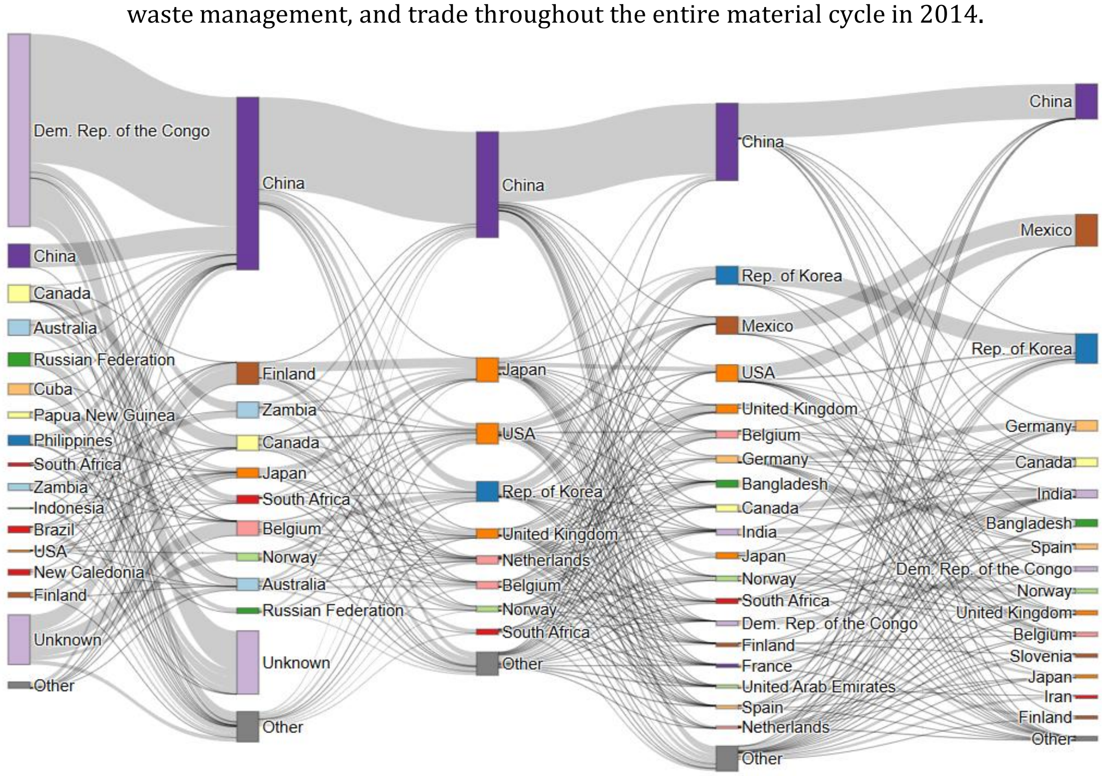

Fig. S19 Sankey diagram of regional cobalt mining, refining & fabrication, manufacturing, consumption (use), waste management, and trade throughout the entire material cycle in 2015.

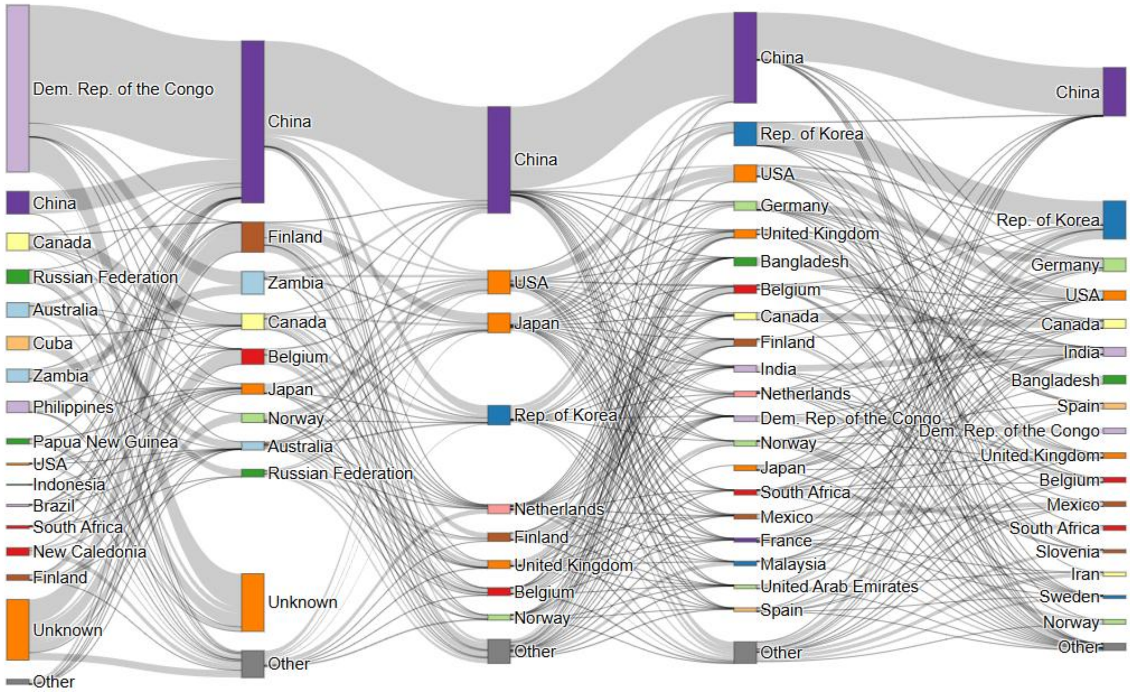

Fig. S20 Sankey diagram of regional cobalt mining, refining & fabrication, manufacturing, consumption (use), waste management, and trade throughout the entire material cycle in 2016.

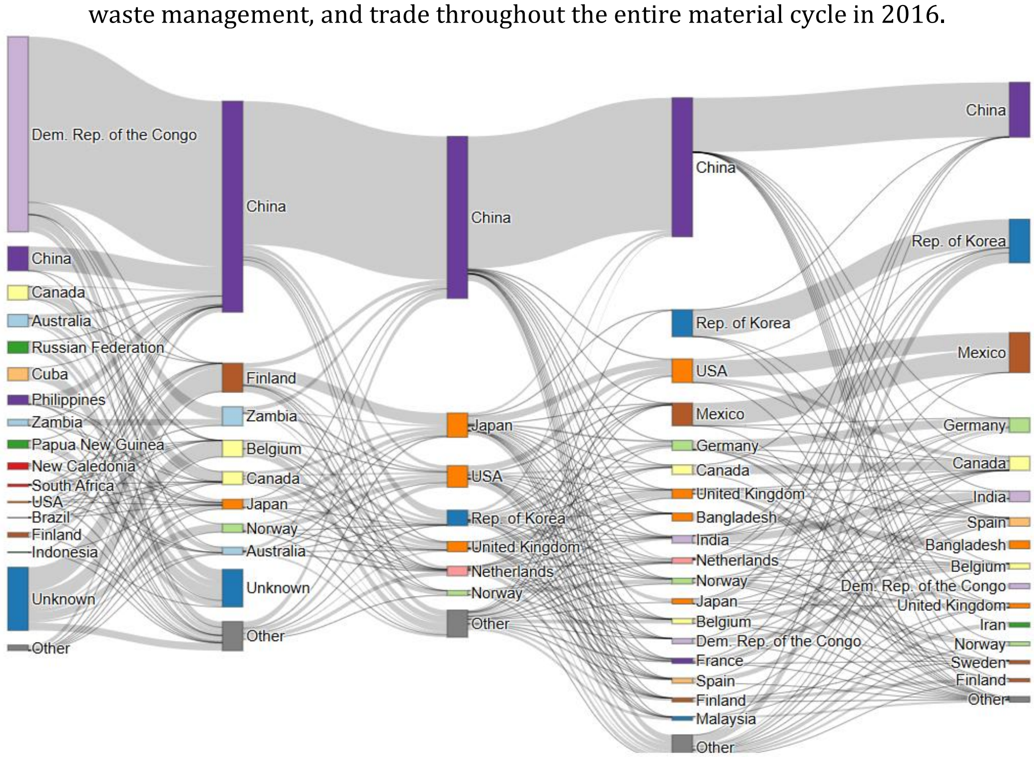

Fig. S21 Sankey diagram of regional cobalt mining, refining & fabrication, manufacturing, consumption (use), waste management, and trade throughout the entire material cycle in 2017.

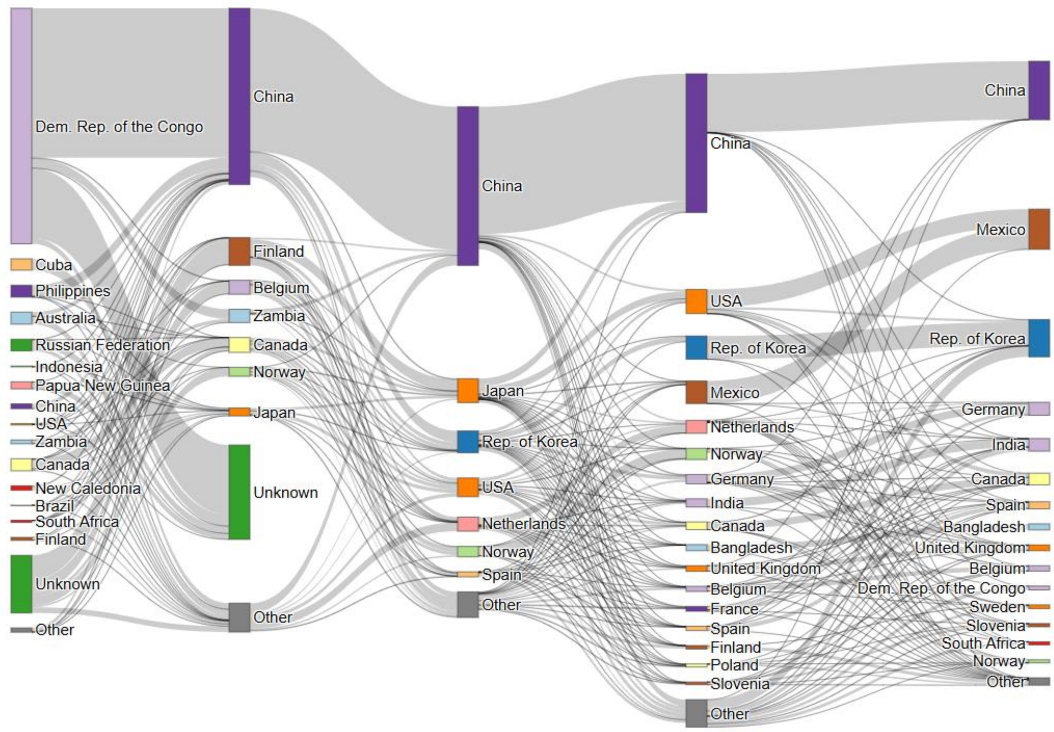

Fig. S22 Sankey diagram of regional cobalt mining, refining & fabrication, manufacturing, consumption (use), waste management, and trade throughout the entire material cycle in 2018.

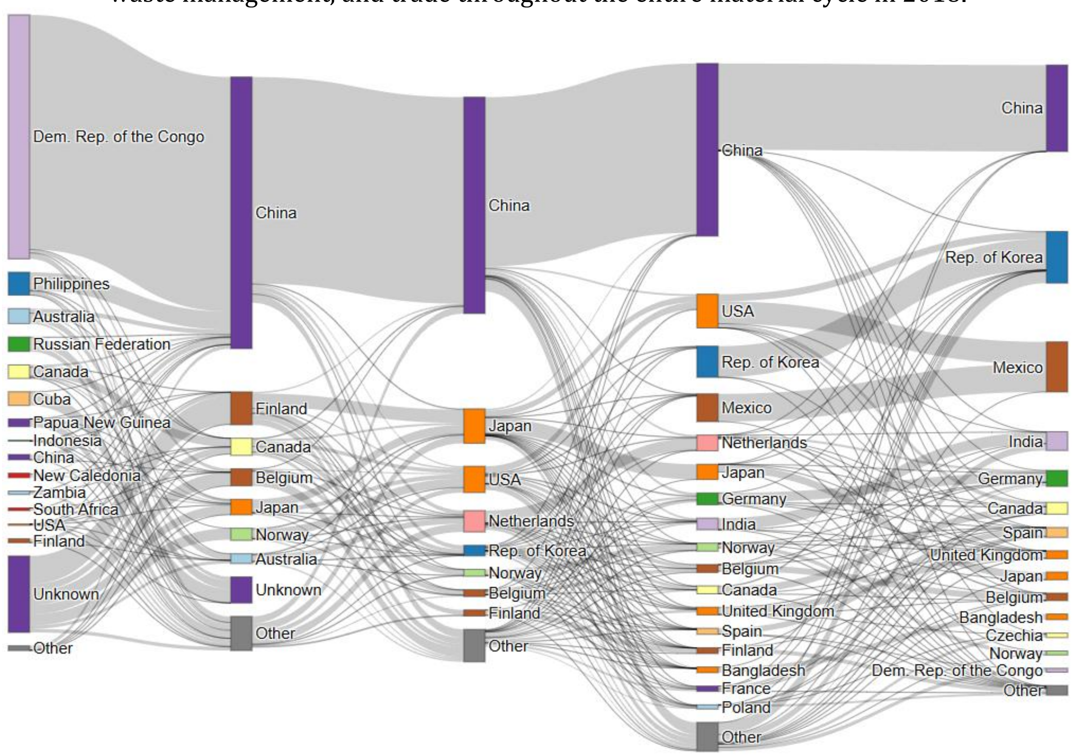

Fig. S23 Sankey diagram of regional cobalt mining, refining & fabrication, manufacturing, consumption (use), waste management, and trade throughout the entire material cycle in 2019.

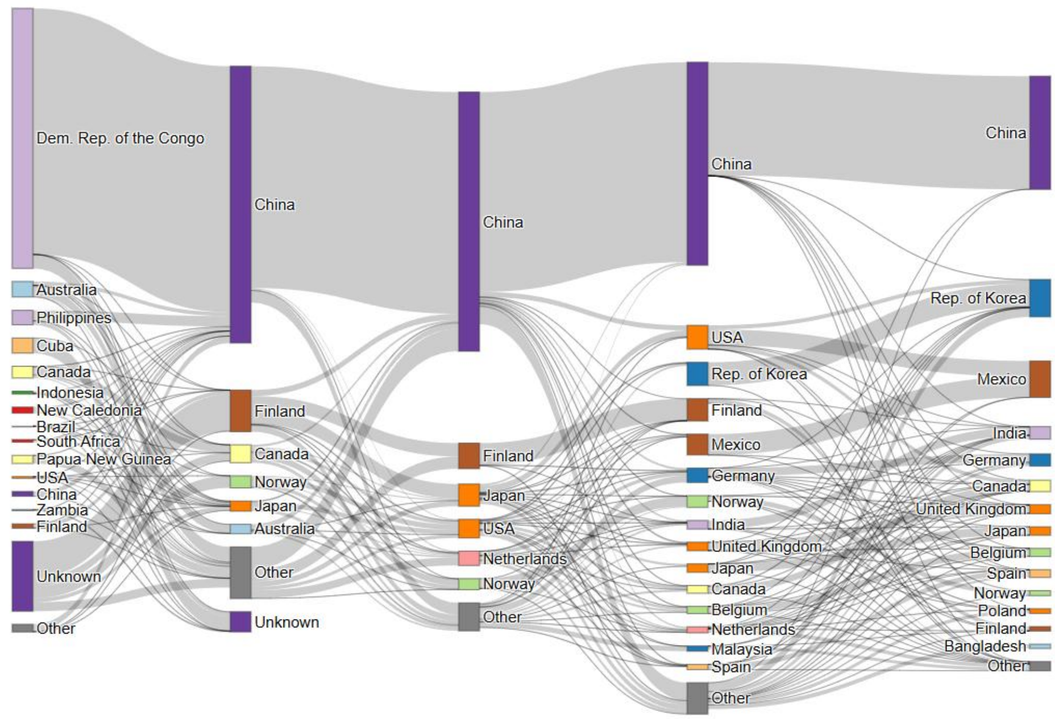

Fig. S24 Sankey diagram of regional cobalt mining, refining & fabrication, manufacturing, consumption (use), waste management, and trade throughout the entire material cycle in 2020.

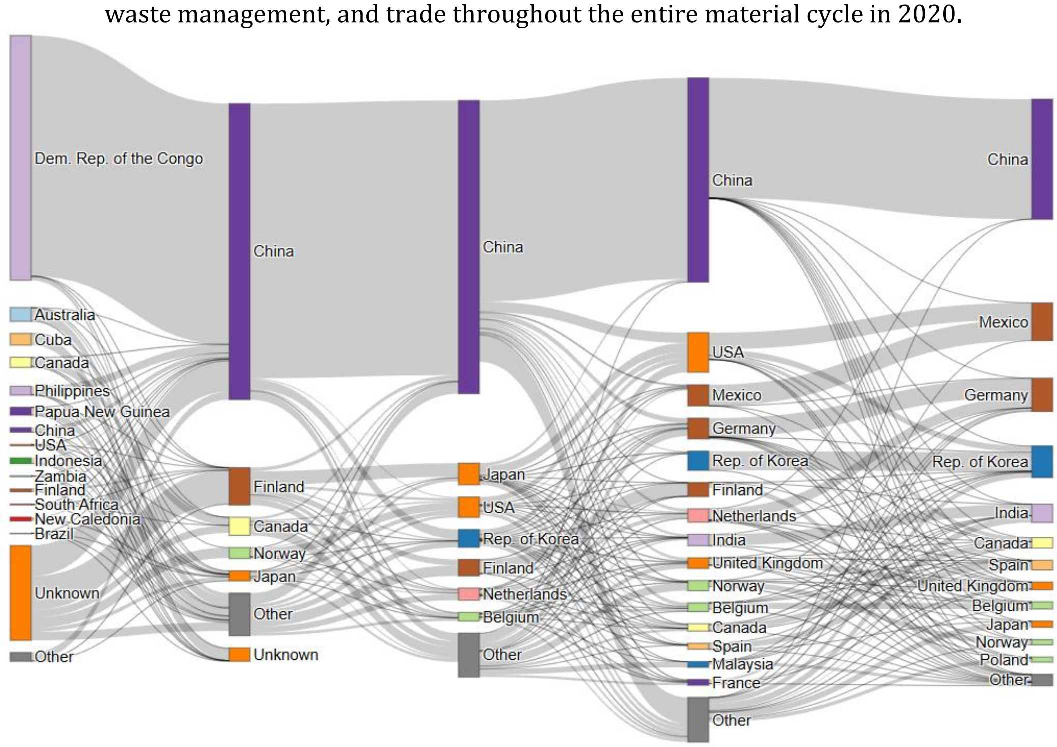

Fig. S25 Sankey diagram of regional cobalt mining, refining & fabrication, manufacturing, consumption (use), waste management, and trade throughout the entire material cycle in 2021.

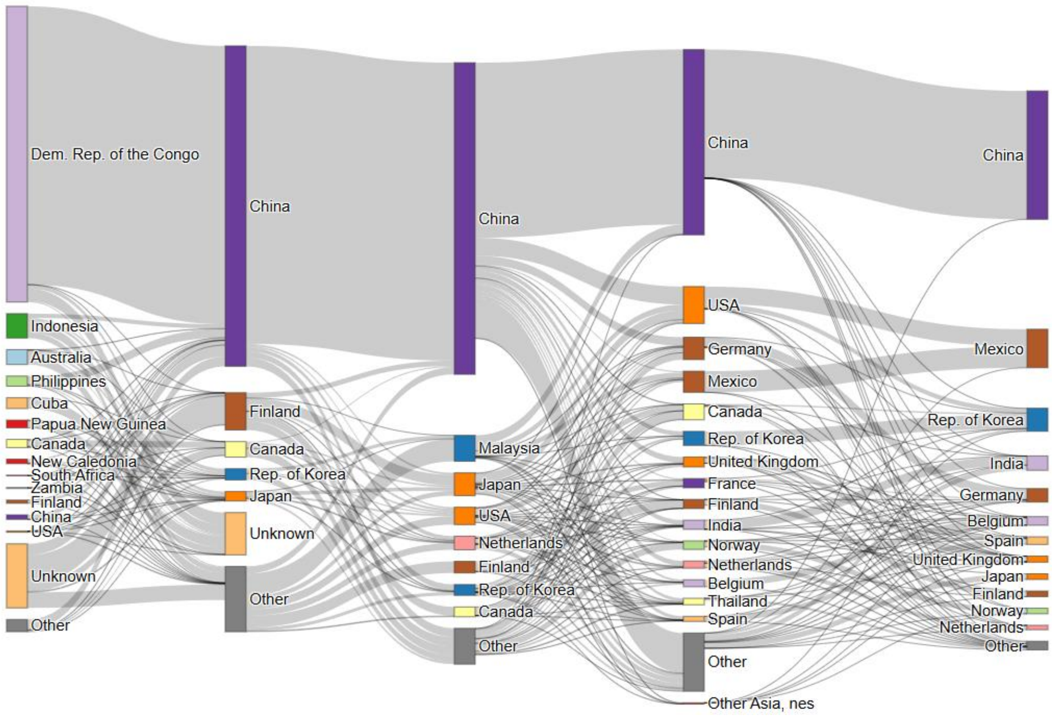

Fig. S26 Sankey diagram of regional cobalt mining, refining & fabrication, manufacturing, consumption (use), waste management, and trade throughout the entire material cycle in 2022.

2.3. Community detection results

Nodes with high PageRank values are labeled by country and stage, while smaller nodes are labeled only by stage. Node colors represent distinct communities, and node sizes are proportional to PageRank values. Stages 1–5 correspond to mining, refining & fabrication, manufacturing, use, and waste management & recycling, respectively.

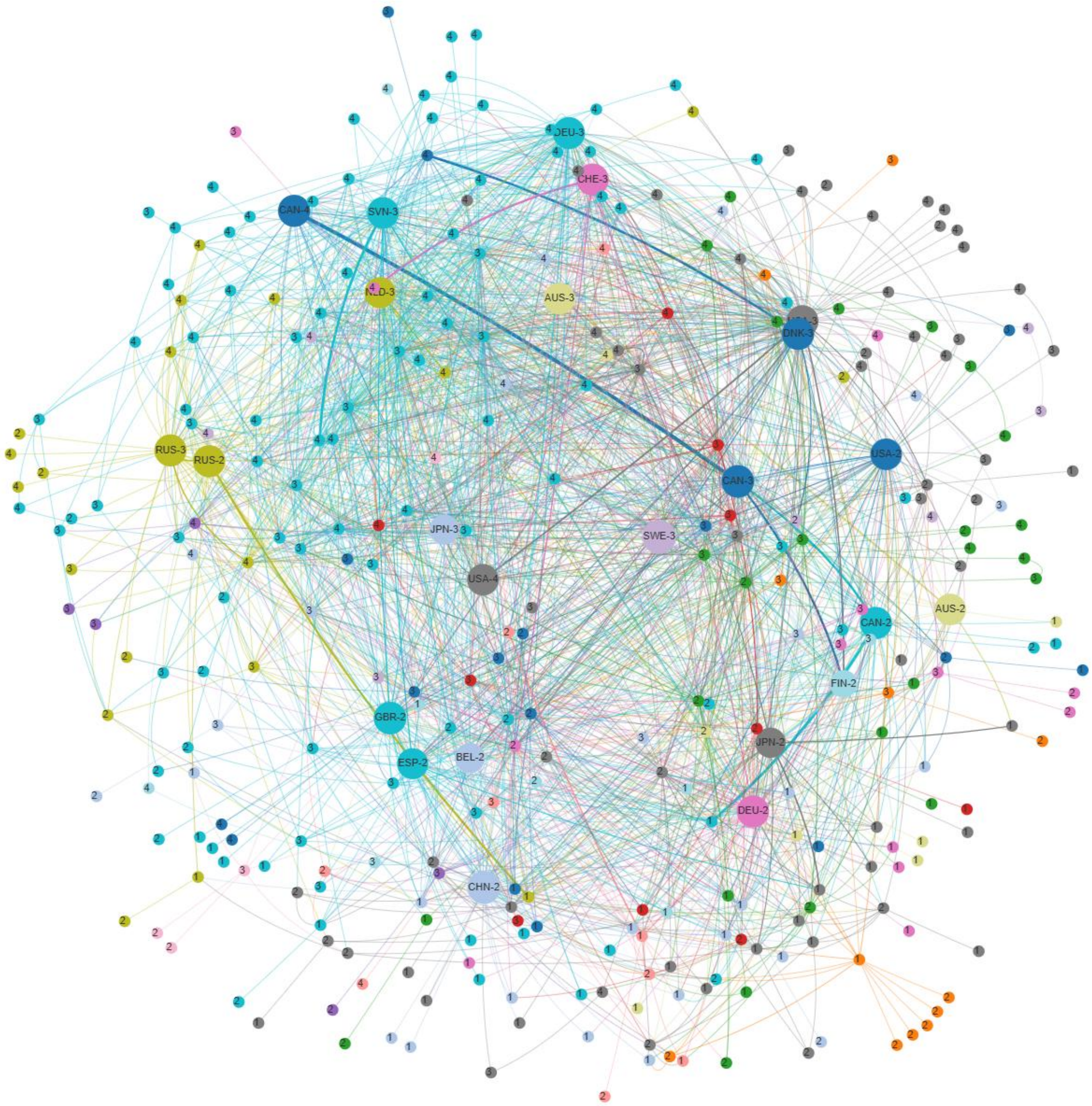

Fig. S27 Community detection results for the 2000 cobalt material flow network. Only edges with large trade volumes are retained.

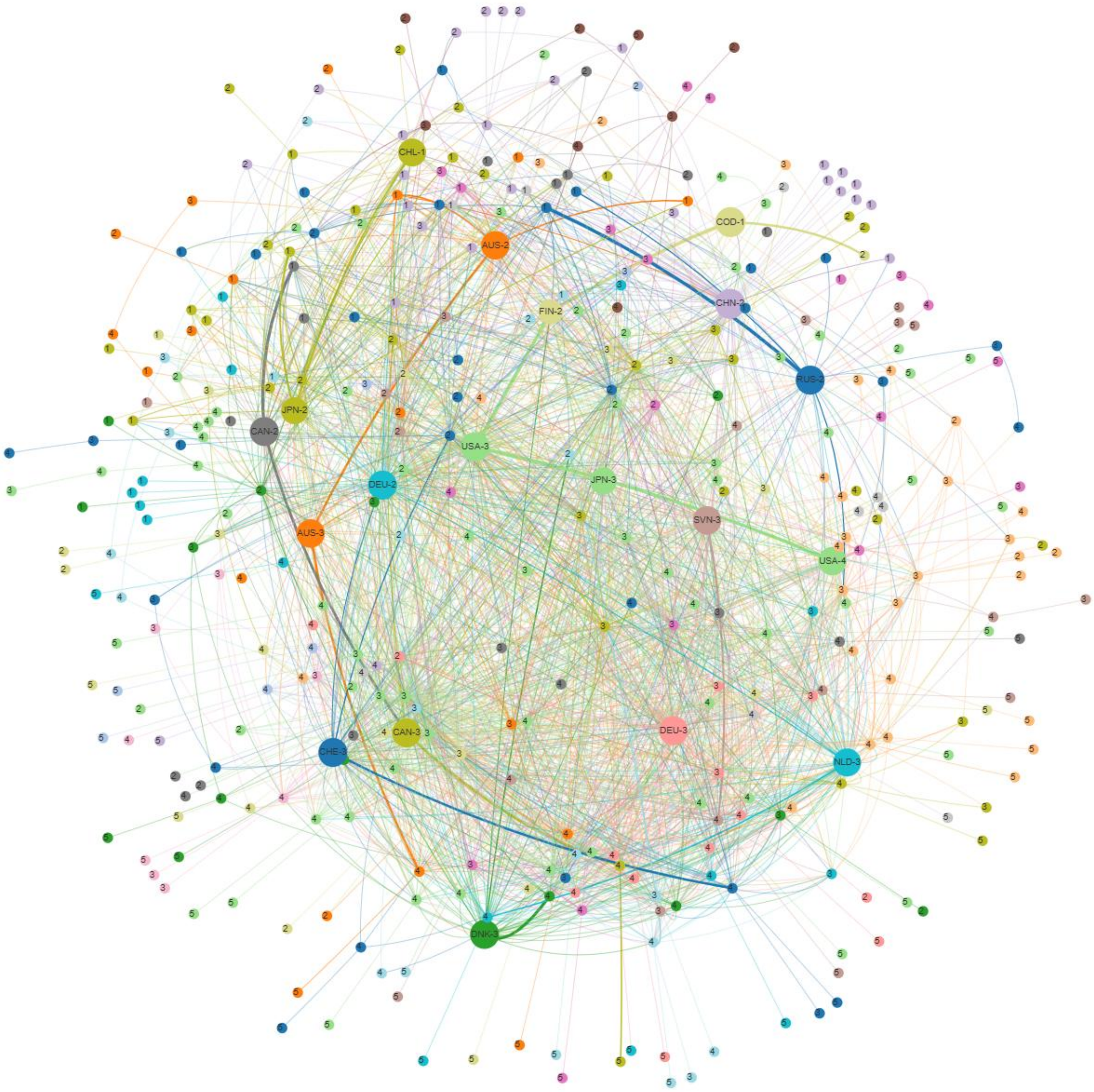

Fig. S28 Community detection results for the 2001 cobalt material flow network.

Fig. S29 Community detection results for the 2002 cobalt material flow network.

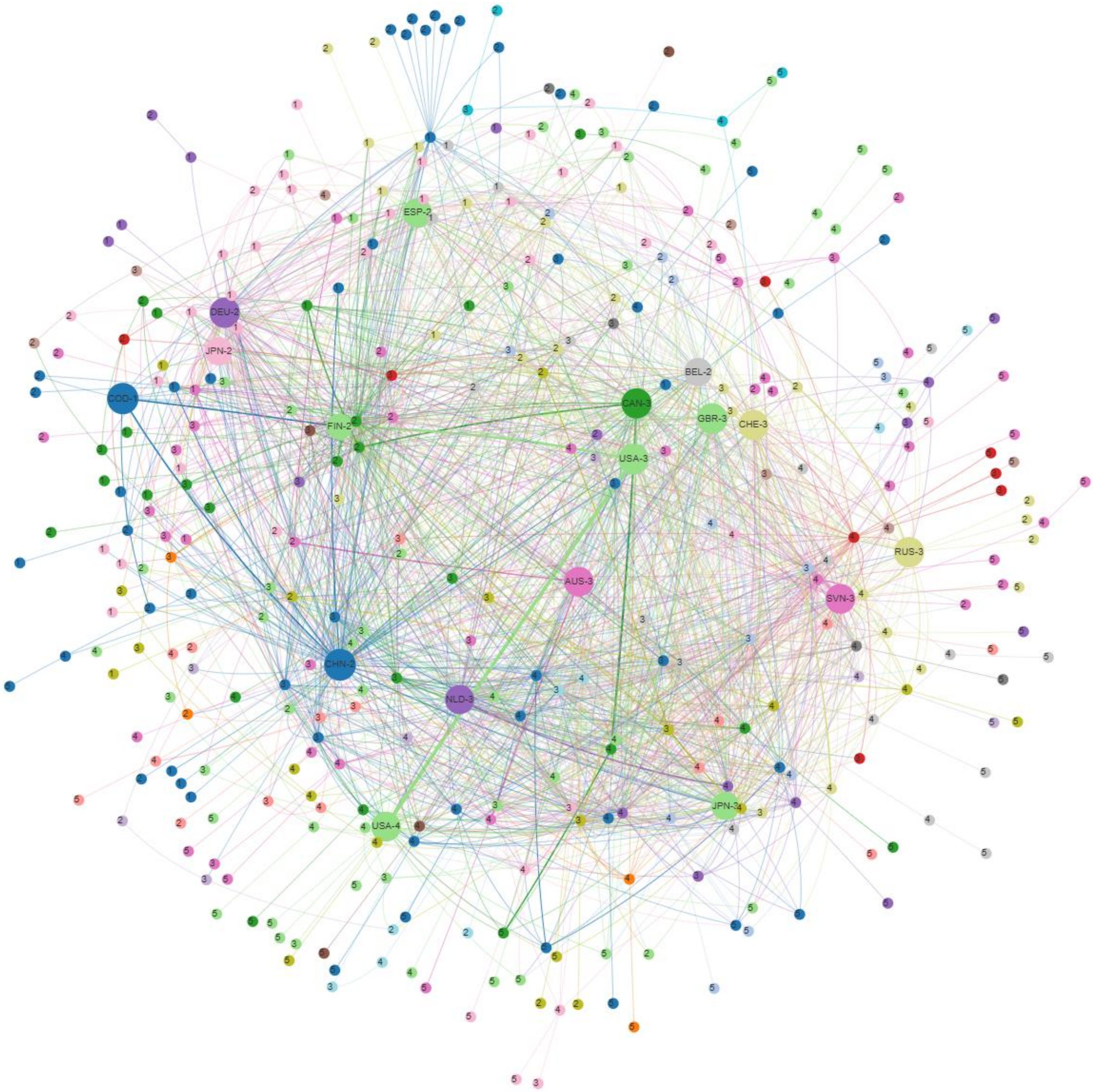

Fig. S30 Community detection results for the 2003 cobalt material flow network.

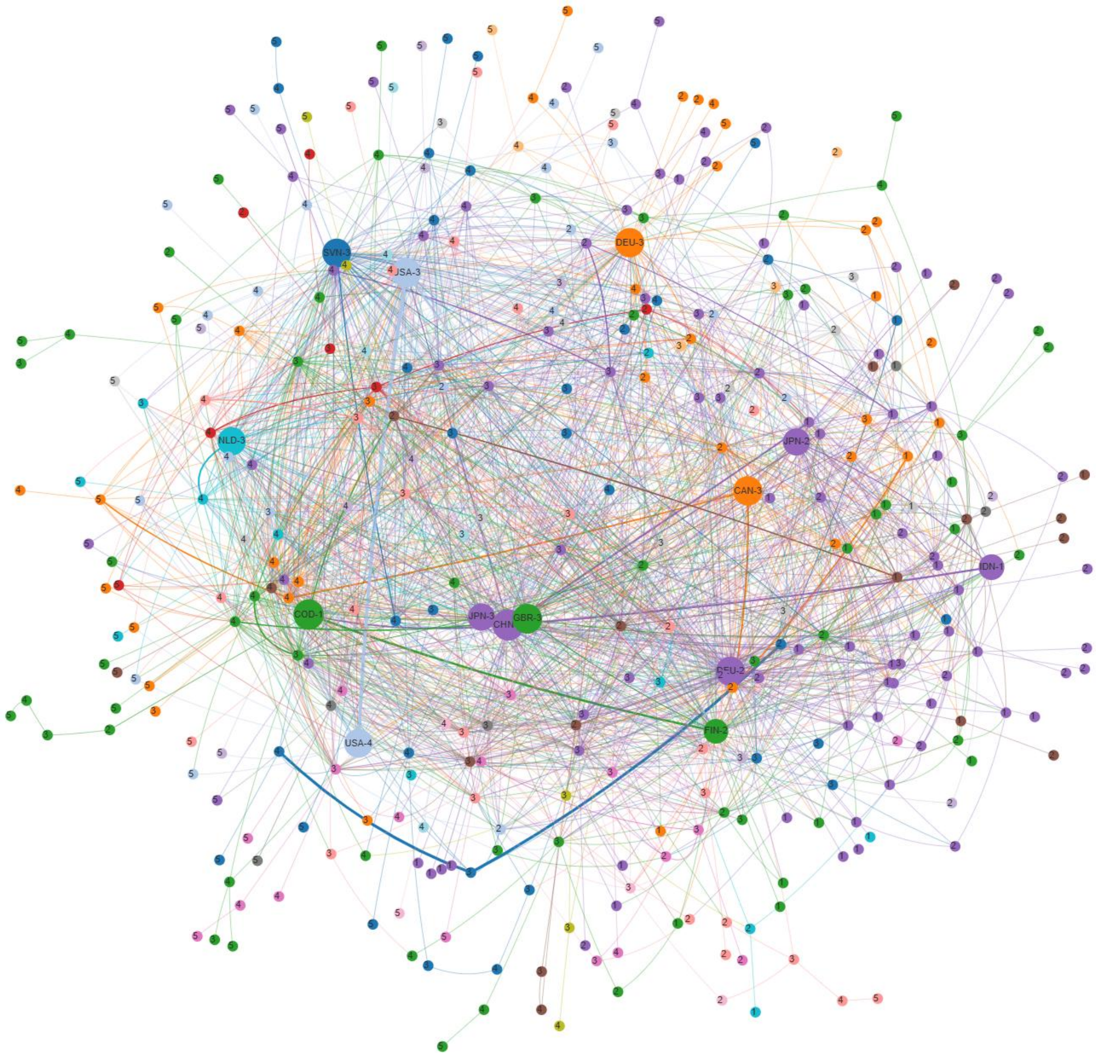

Fig. S31 Community detection results for the 2004 cobalt material flow network.

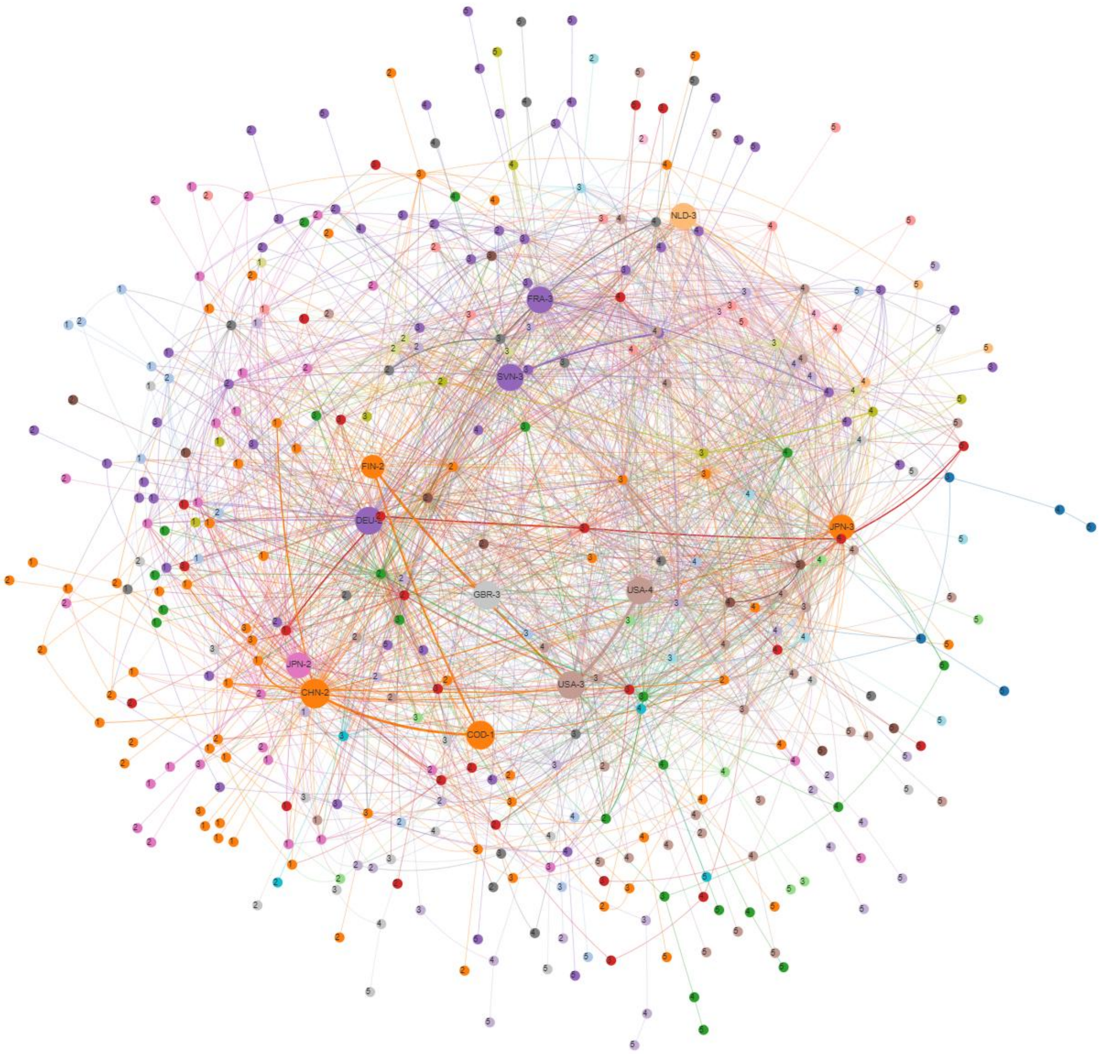

Fig. S32 Community detection results for the 2005 cobalt material flow network.

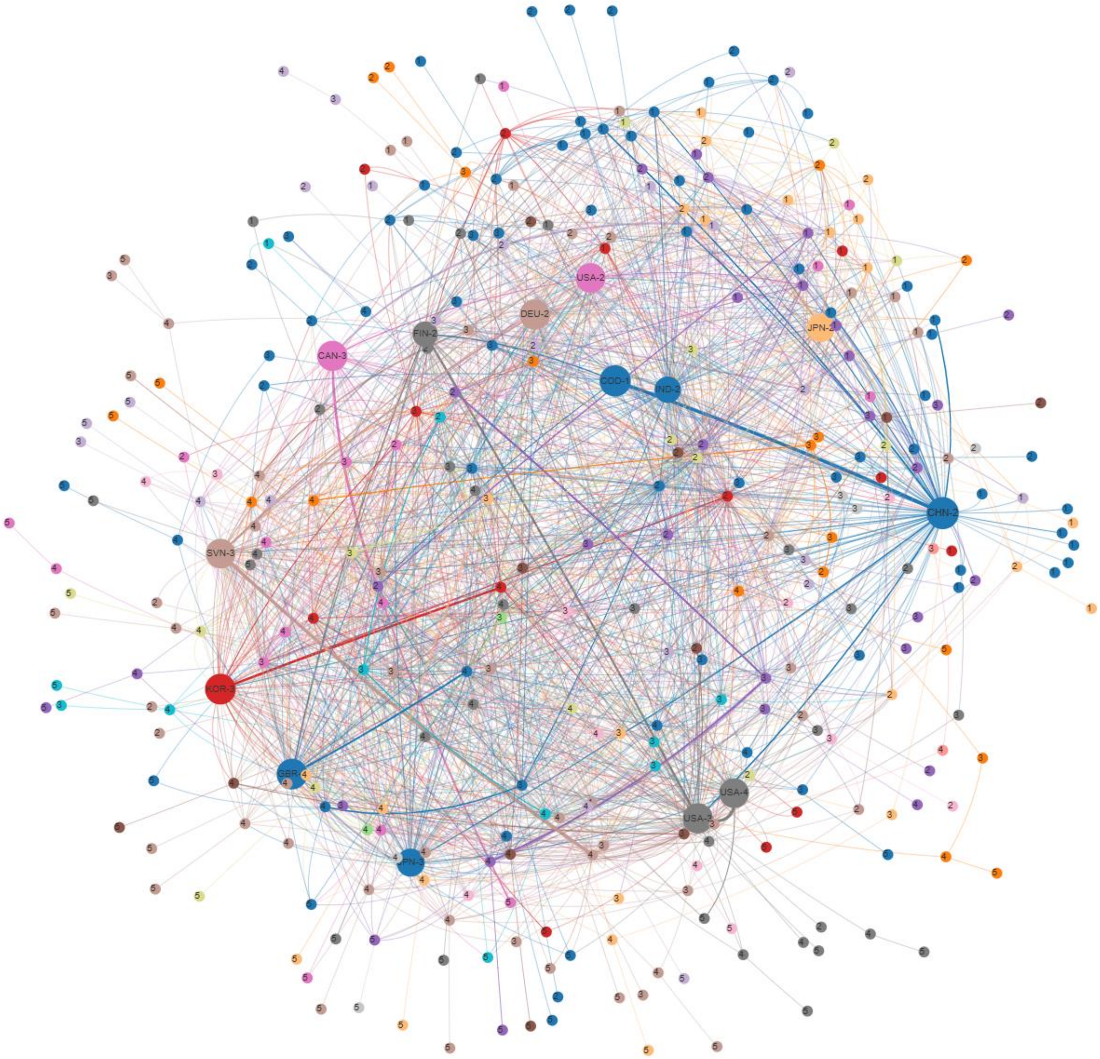

Fig. S33 Community detection results for the 2006 cobalt material flow network.

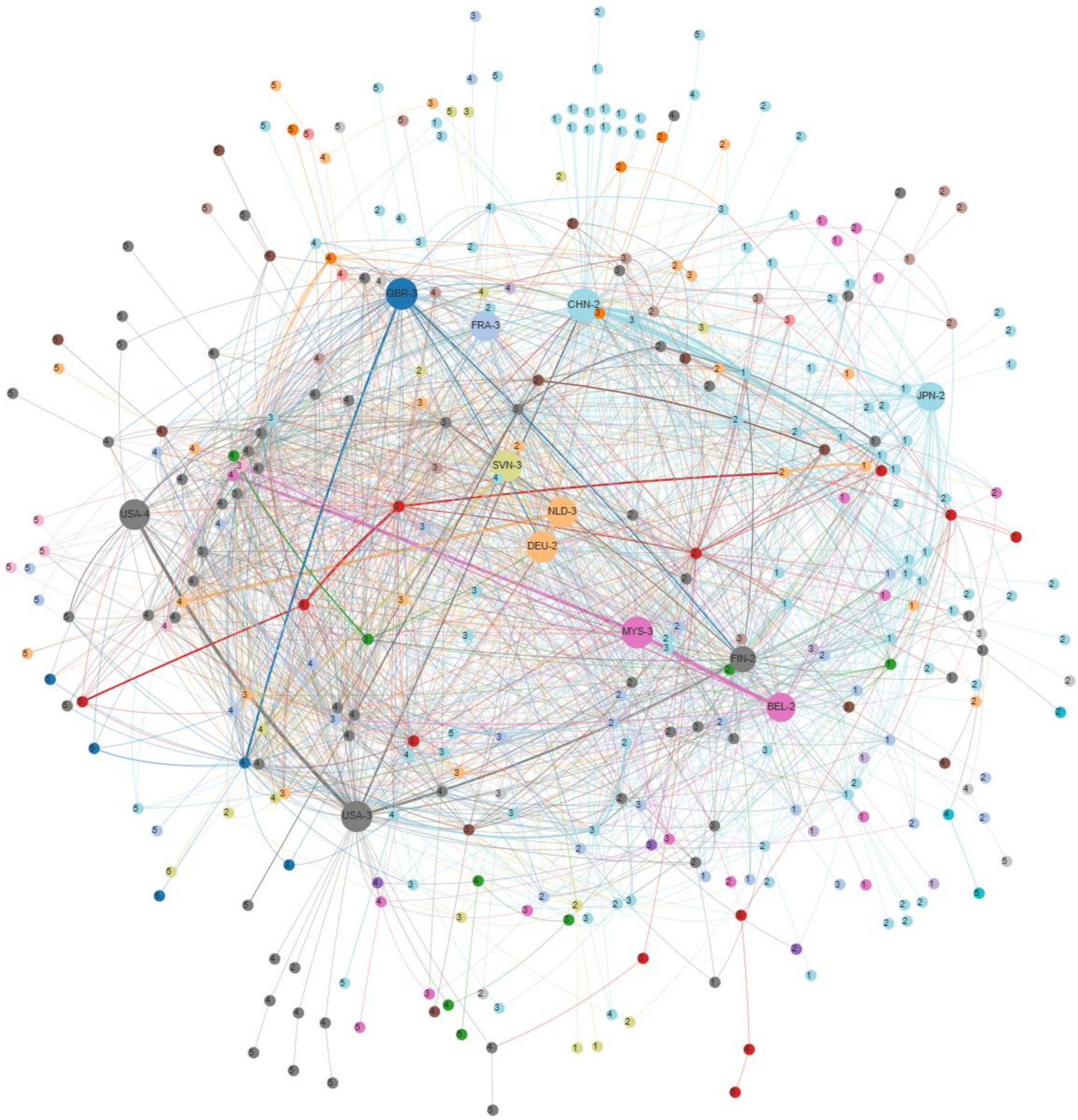

Fig. S34 Community detection results for the 2007 cobalt material flow network.

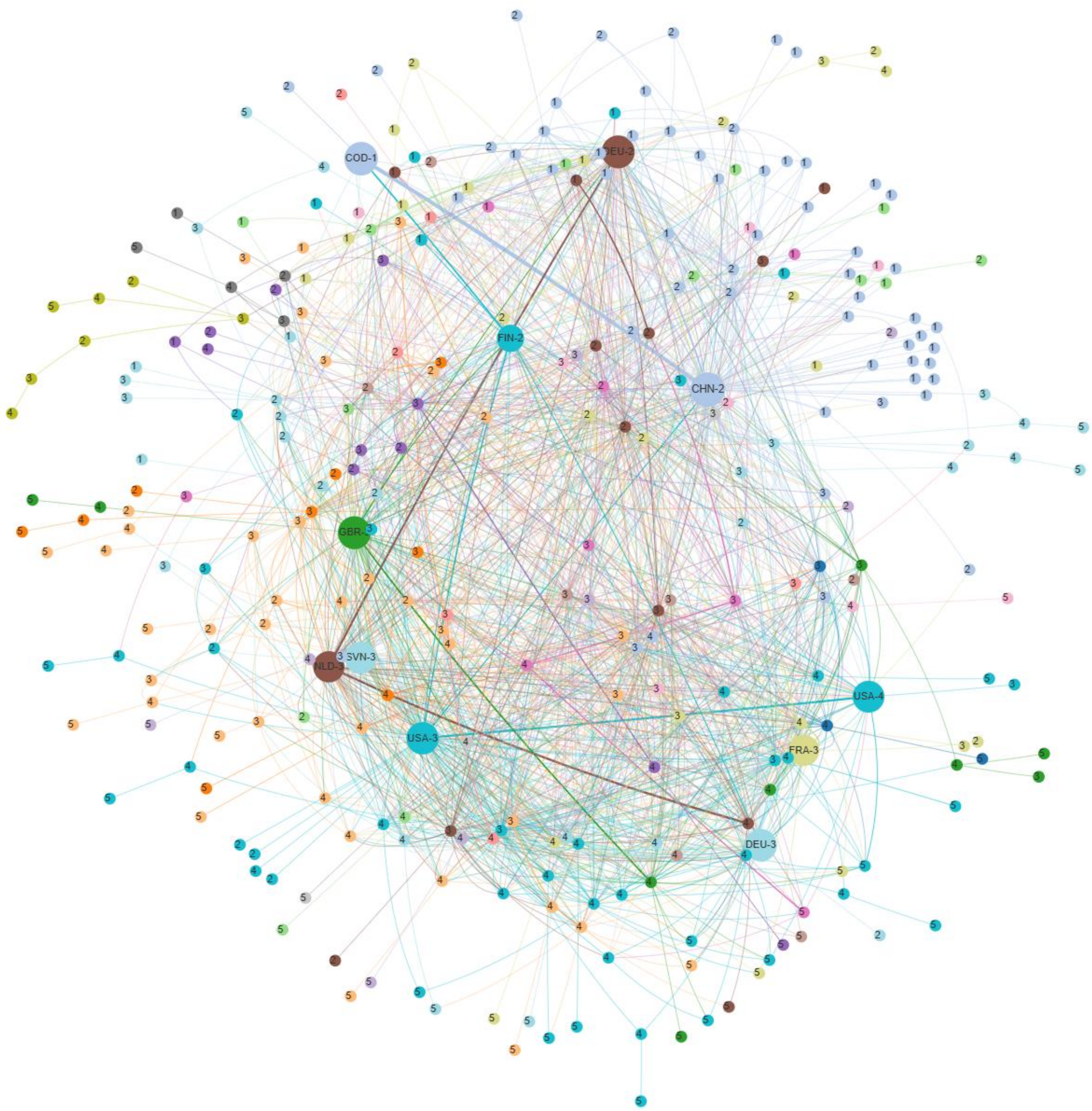

Fig. S35 Community detection results for the 2008 cobalt material flow network.

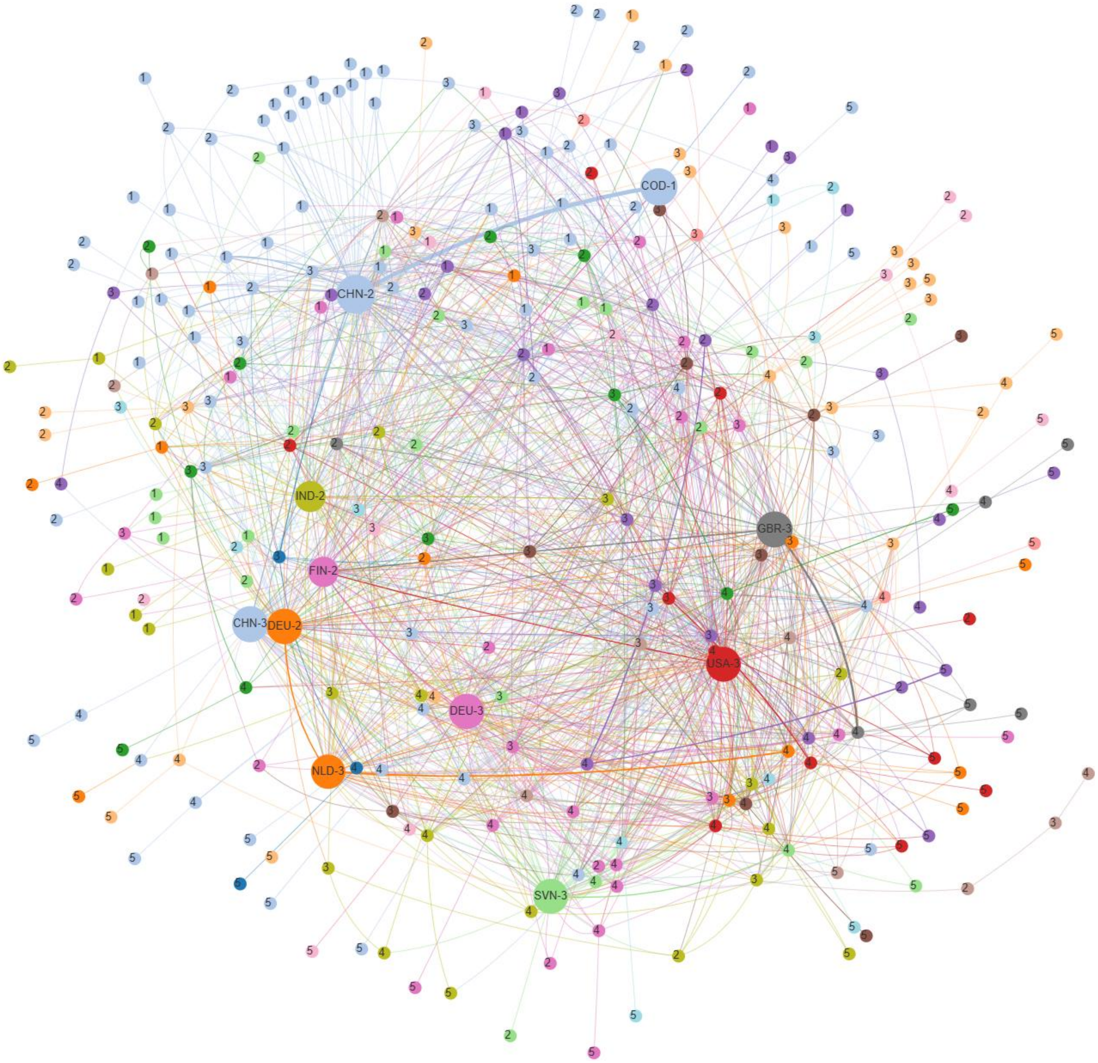

Fig. S36 Community detection results for the 2009 cobalt material flow network.

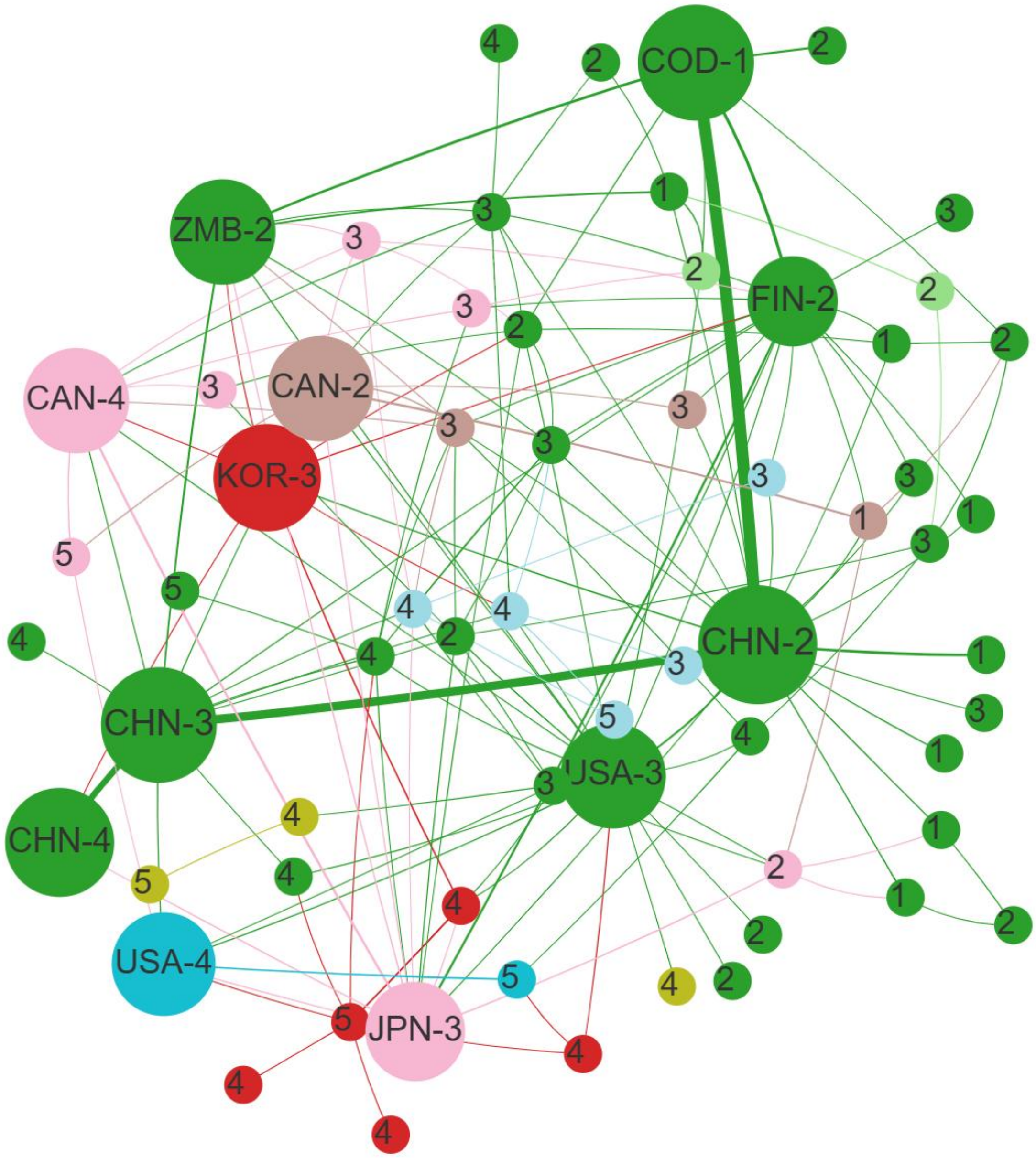

Fig. S37 Community detection results for the 2010 cobalt material flow network.

Fig. S38 Community detection results for the 2011 cobalt material flow network.

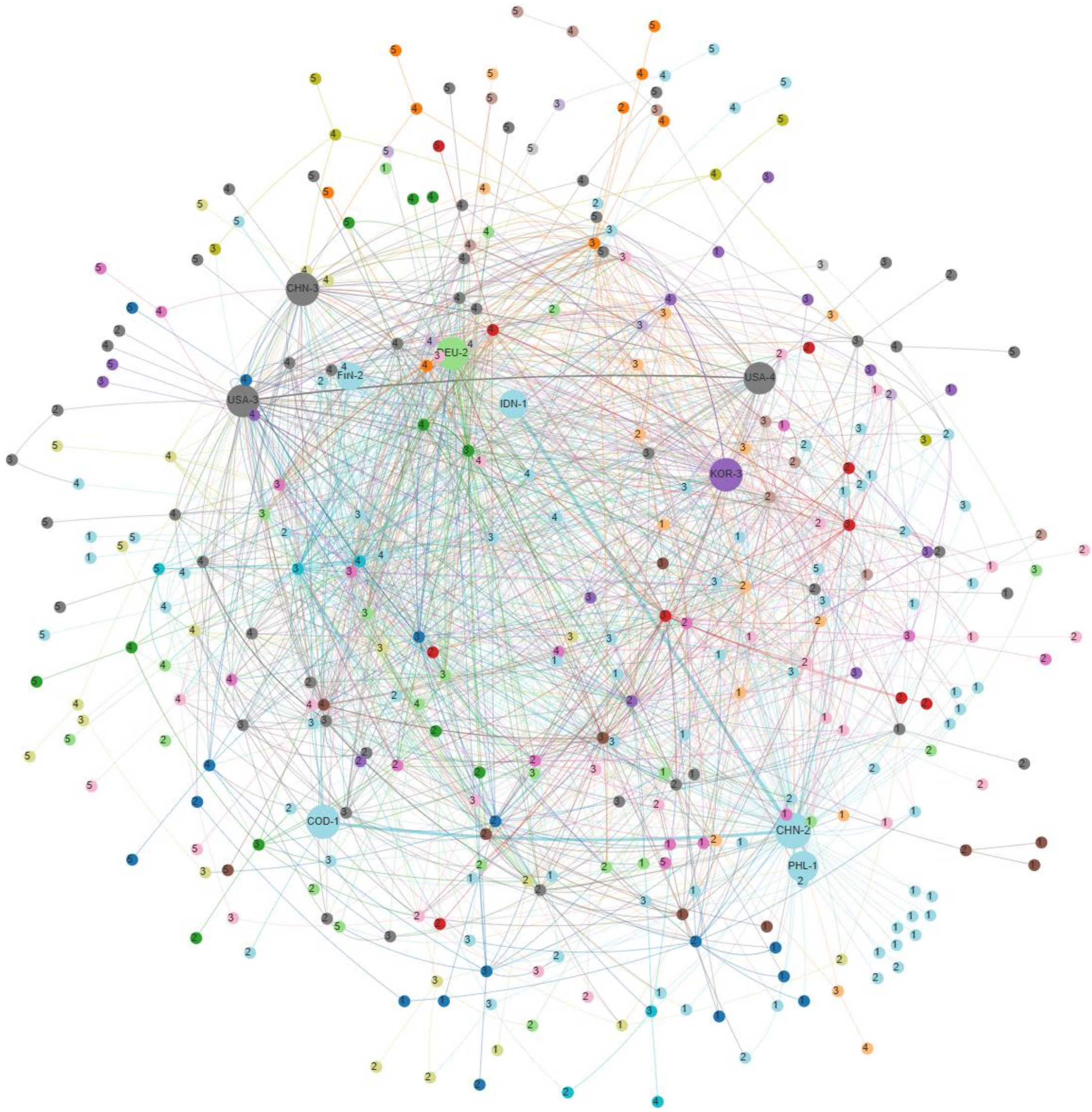

Fig. S39 Community detection results for the 2012 cobalt material flow network.

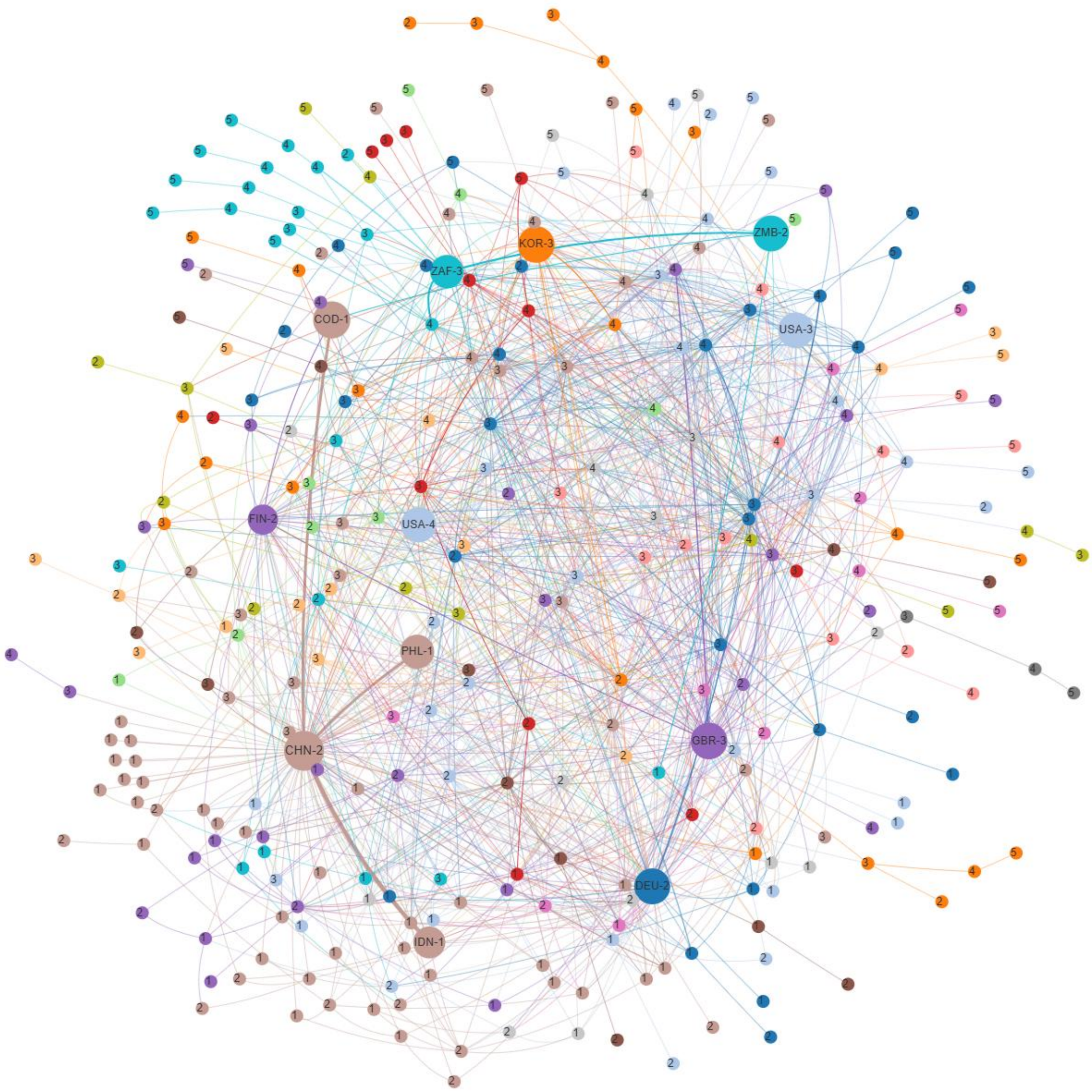

Fig. S40 Community detection results for the 2013 cobalt material flow network.

Fig. S41 Community detection results for the 2014 cobalt material flow network.

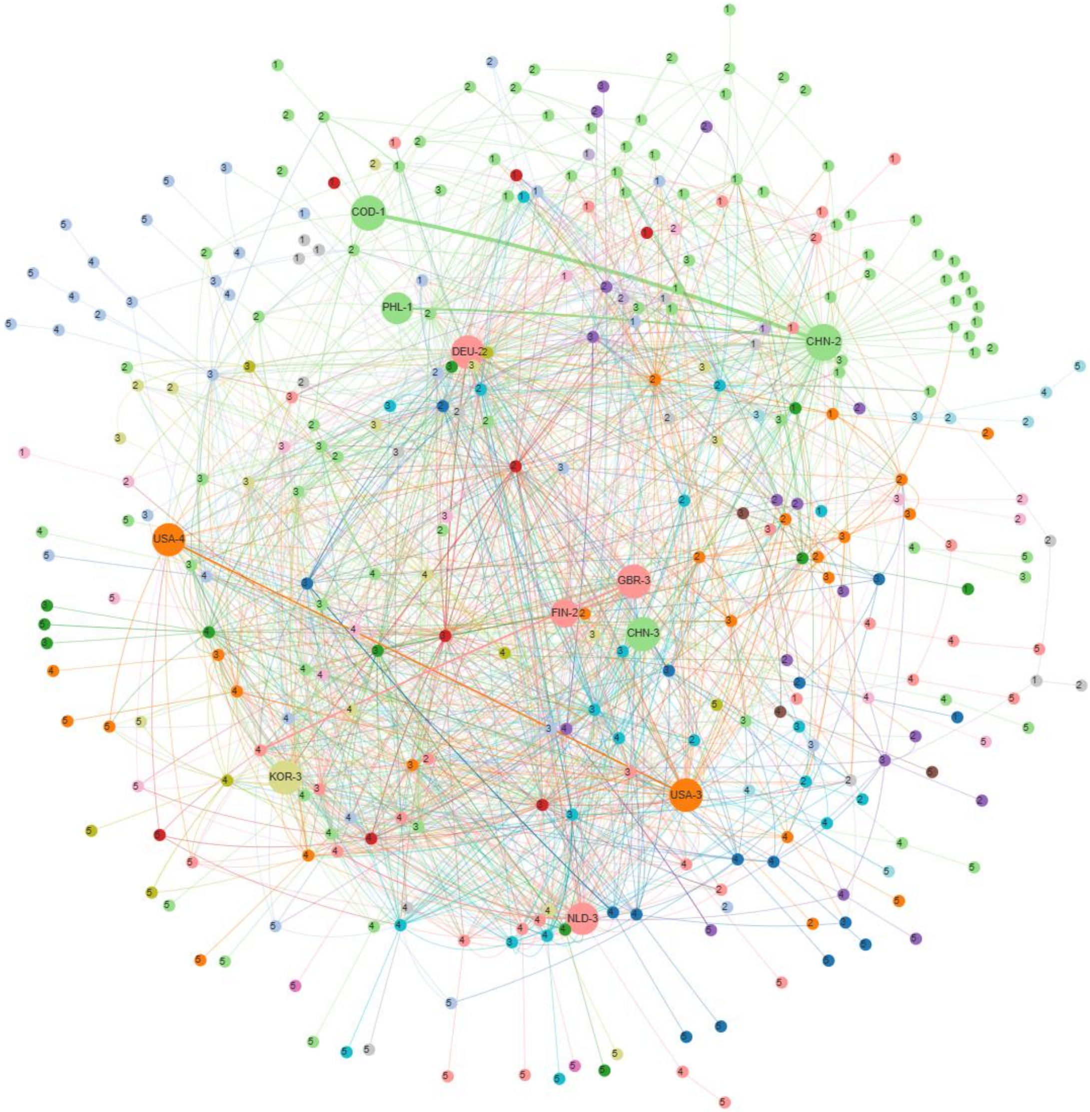

Fig. S42 Community detection results for the 2015 cobalt material flow network.

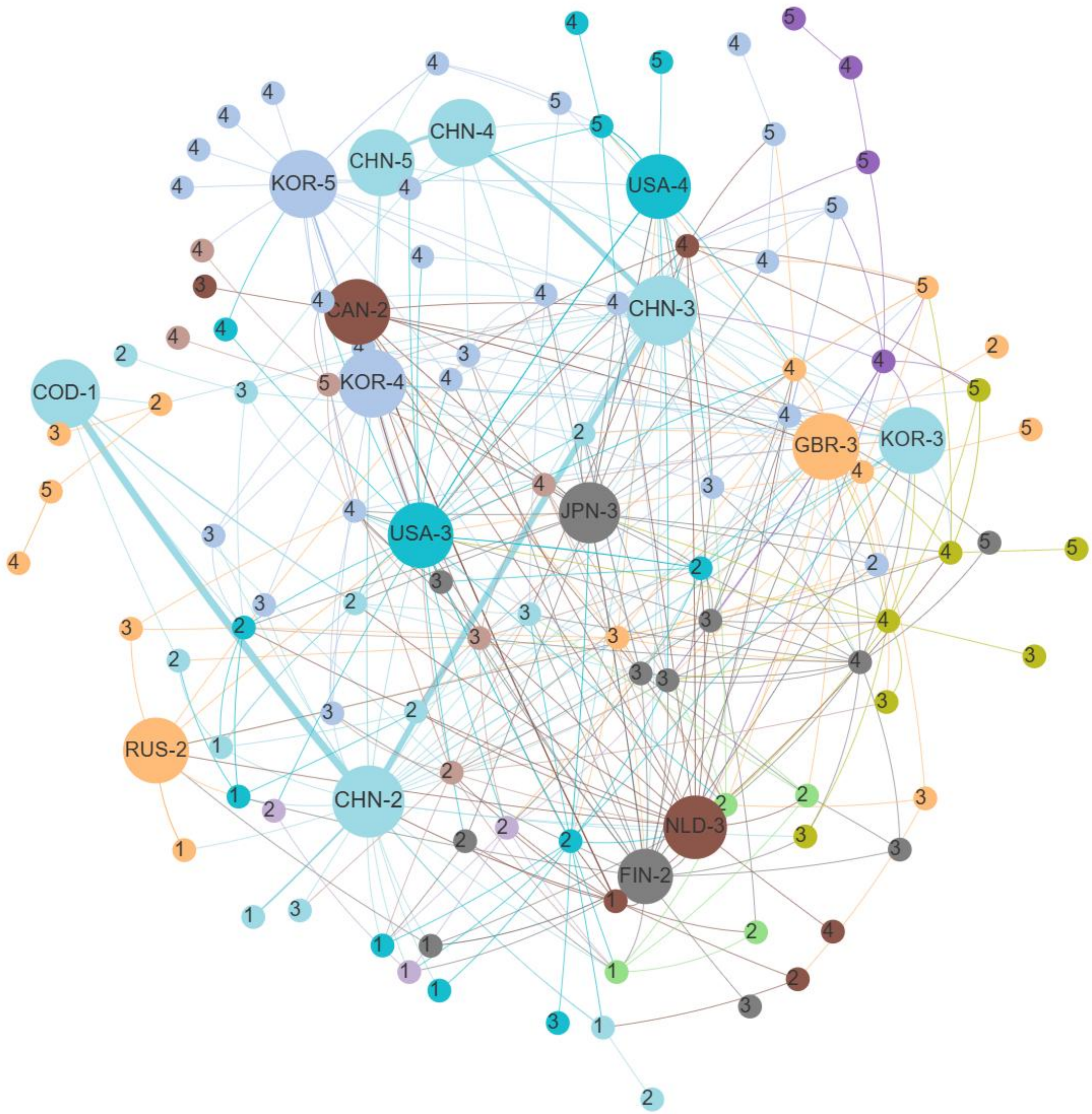

Fig. S43 Community detection results for the 2016 cobalt material flow network.

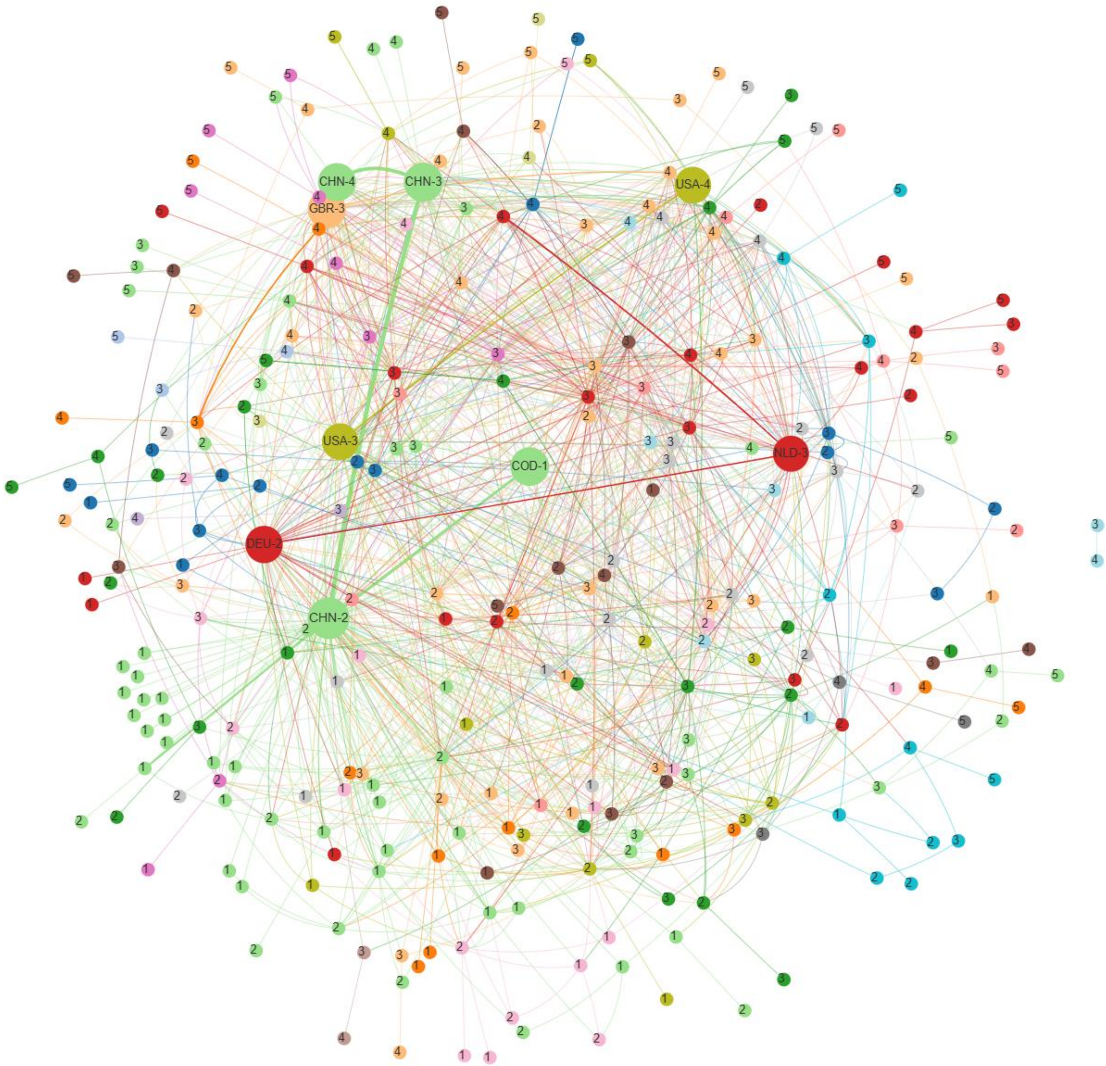

Fig. S44 Community detection results for the 2017 cobalt material flow network.

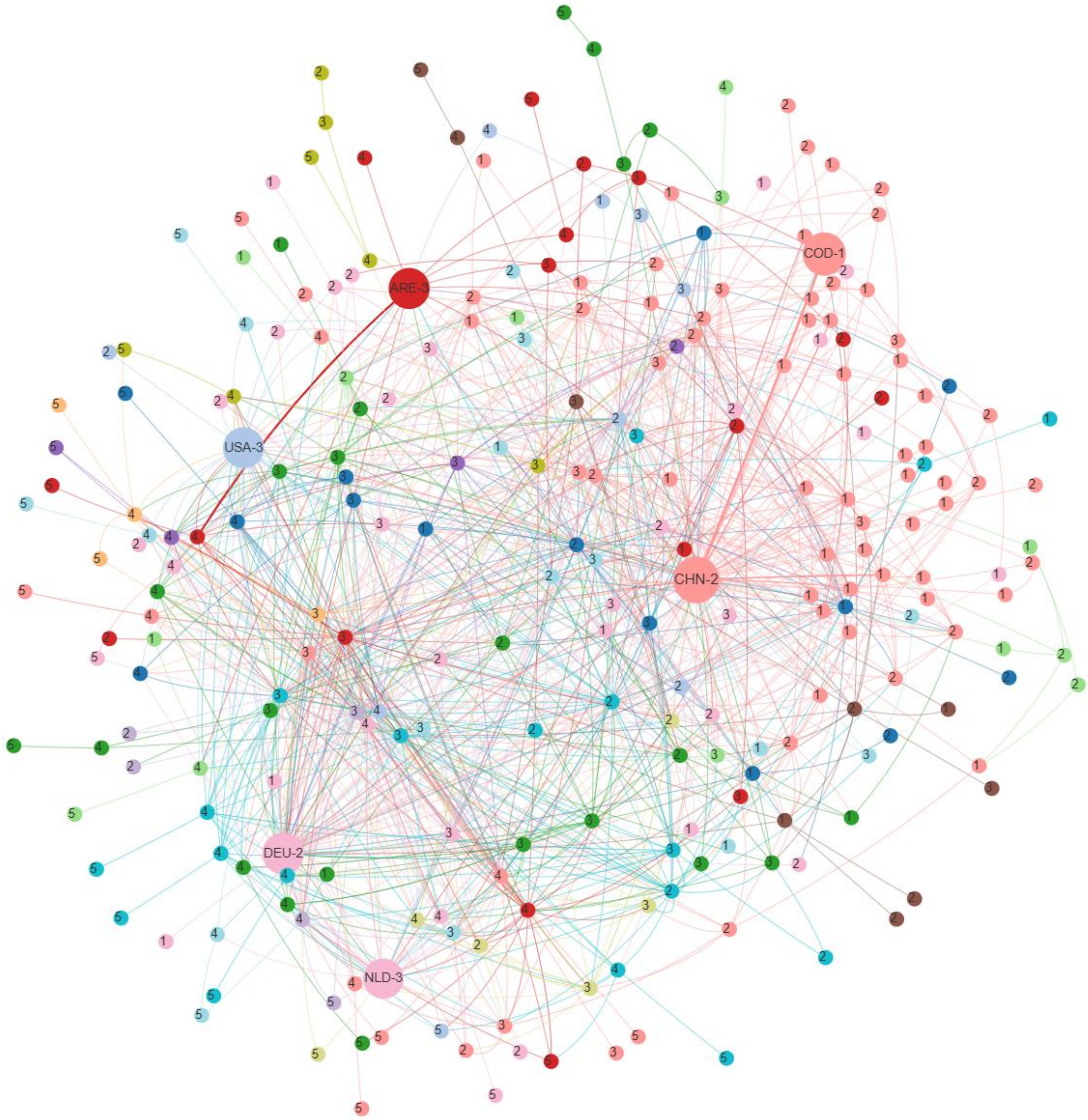

Fig. S45 Community detection results for the 2018 cobalt material flow network.

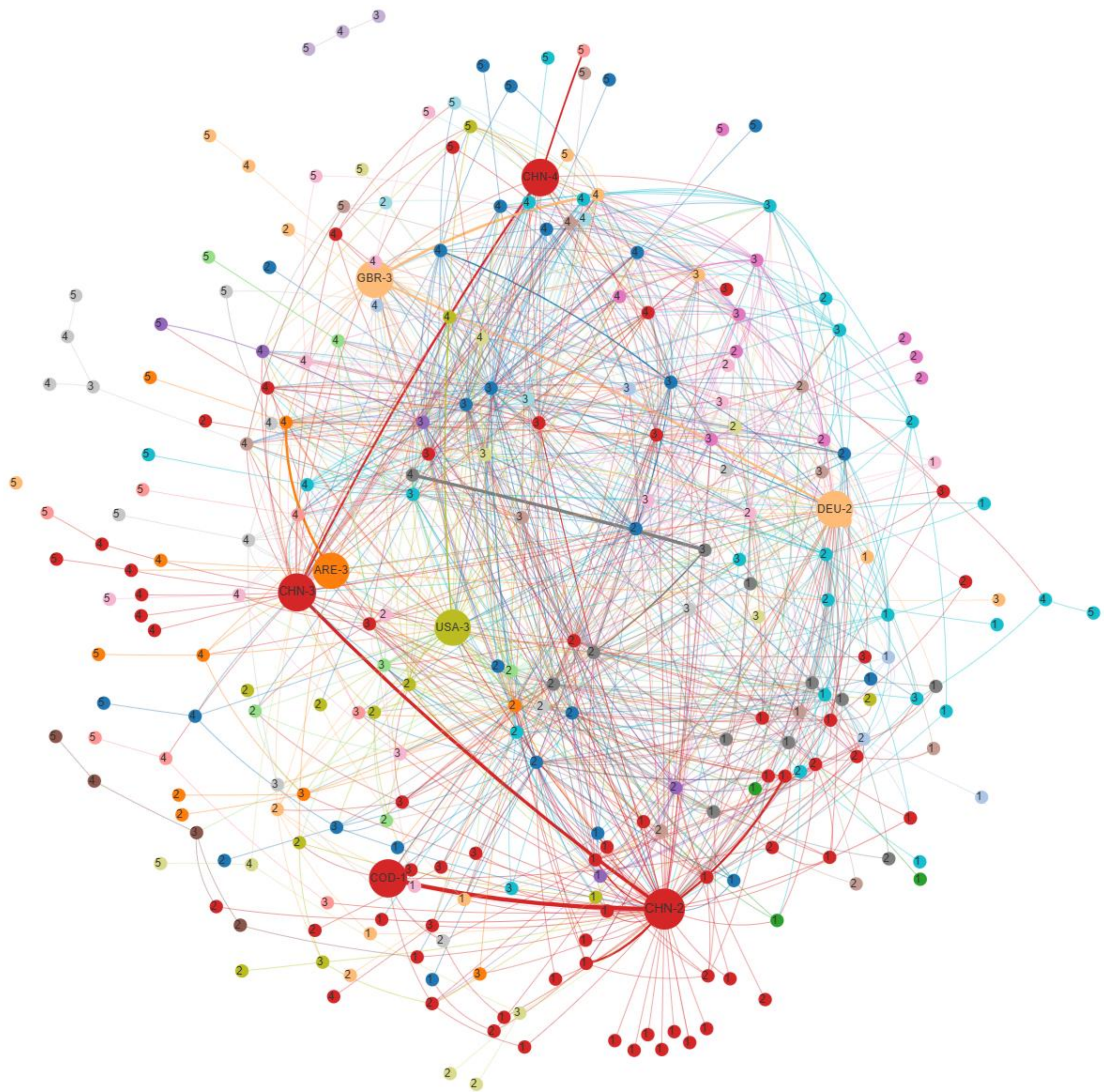

Fig. S46 Community detection results for the 2019 cobalt material flow network.

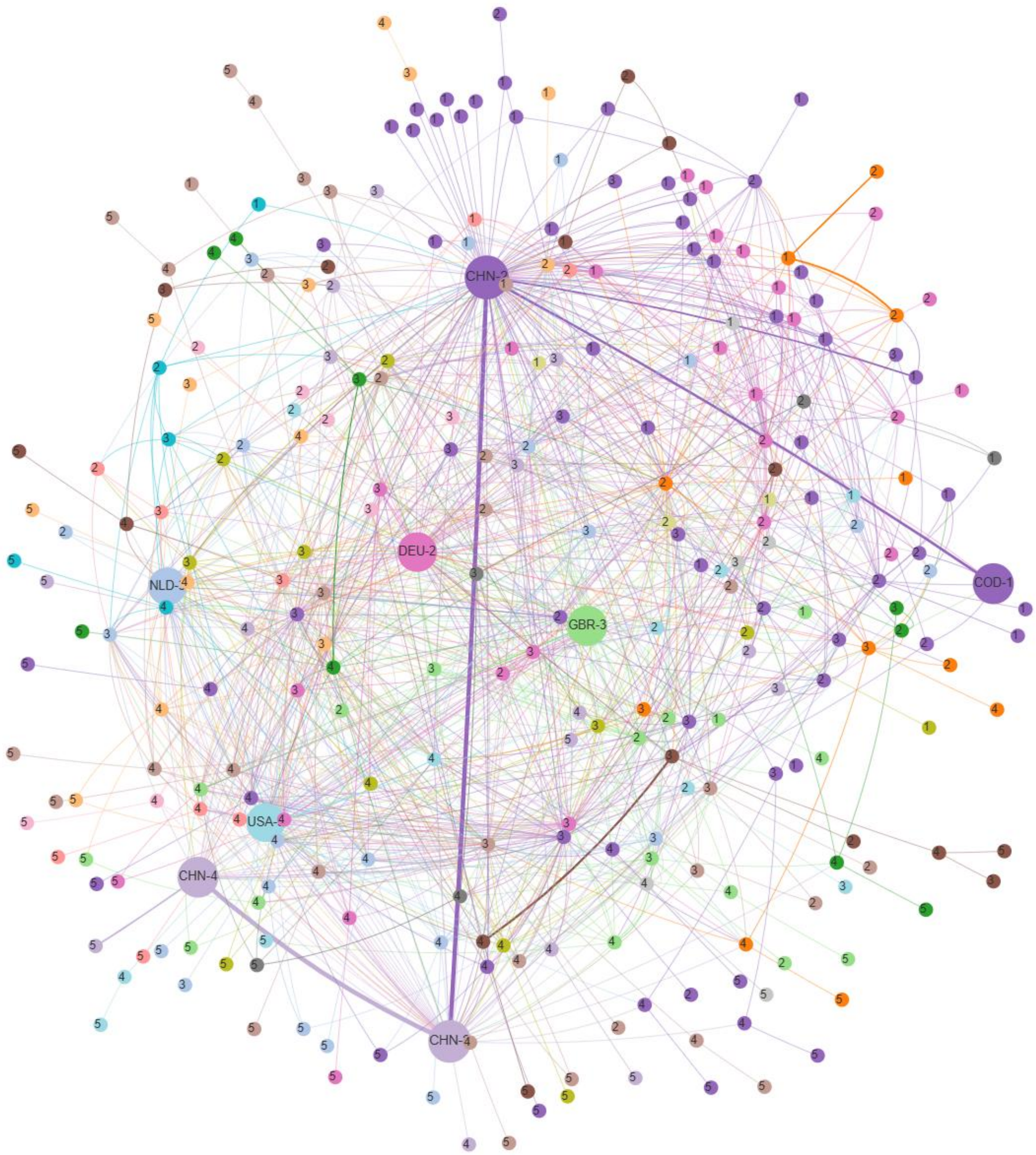

Fig. S47 Community detection results for the 2020 cobalt material flow network.

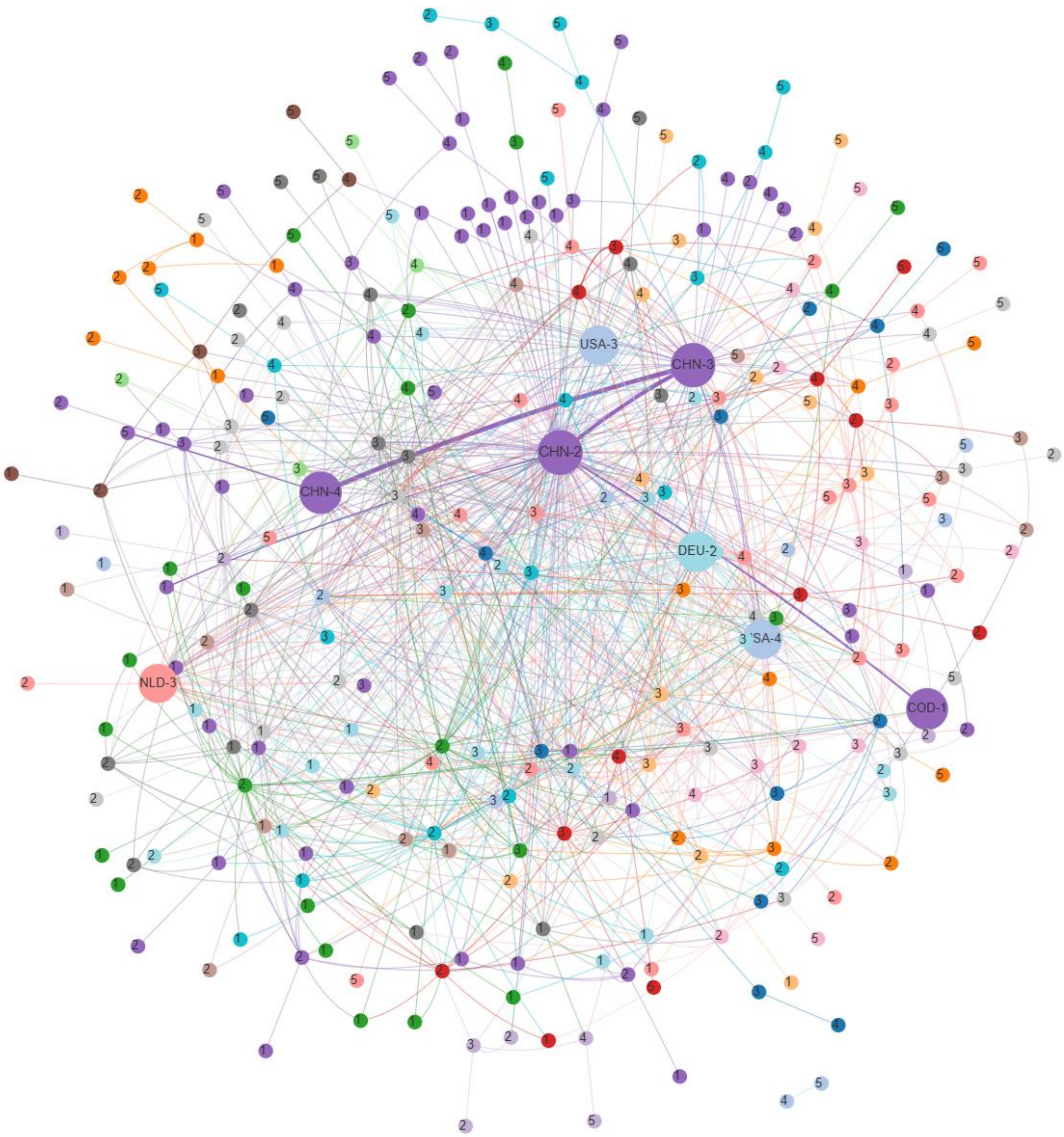

Fig. S48 Community detection results for the 2021 cobalt material flow network.

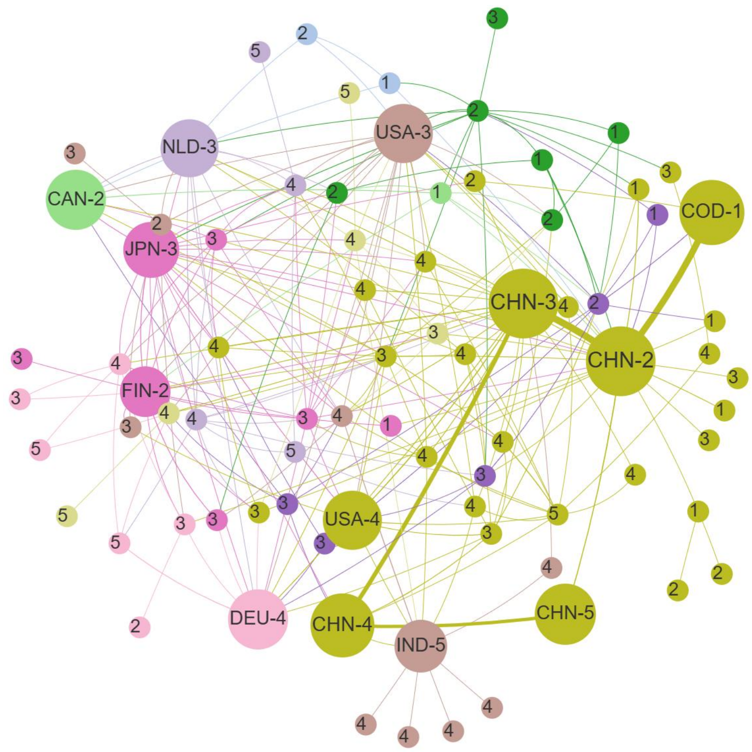

Fig. S49 Community detection results for the 2022 cobalt material flow network.

2.4. Heatmaps of PageRank values

	ARE	AUS	AUT	BEL	BRA	CAN	CHE	CHN	COD	DEU	ESP	FIN	FRA	GBR	IDN	IND	JPN	KOR	MEX	NLD	NOR	PHL	POL	RUS	SVN	USA	ZAF	ZMB
Mining	0.0	5.6	0.0	0.0	4.6	7.3	0.0	6.4	55.8	0.0	0.0	0.8	0.0	0.0	3.9	0.0	0.0	0.0	0.0	0.0	0.0	2.4	0.0	3.5	0.0	0.0	1.5	7.2
Refining & Fabrication	0.5	9.7	0.6	7.1	5.0	14.2	2.0	89.0	4.0	2.6	2.5	23.6	1.7	2.6	0.5	6.1	6.3	2.6	0.7	0.7	6.6	0.7	0.6	6.8	0.5	2.8	3.9	16.9
Manufacturing	0.7	0.9	1.6	4.1	1.8	3.6	2.8	61.0	0.5	5.6	2.7	10.4	4.2	7.5	1.2	4.8	29.3	10.8	1.1	7.1	5.1	1.9	1.1	1.1	3.3	23.9	2.3	0.0
In-use	3.0	2.8	2.1	4.9	2.6	13.9	2.9	24.9	2.5	6.1	3.5	6.6	1.8	6.2	3.2	6.4	4.5	9.6	3.8	6.3	6.2	2.0	2.0	3.3	4.3	11.7	3.0	2.5
Waste management & Recycling	1.9	1.6	1.9	2.8	1.5	2.9	1.6	8.1	2.7	5.2	2.8	2.4	1.1	3.0	1.8	3.2	4.2	6.1	5.1	3.4	4.0	1.3	1.5	1.7	2.9	5.0	1.3	2.7

Fig. S50 Heatmaps of PageRank values (×1000) by country and stage in 2010.

	ARE	AUS	AUT	BEL	BRA	CAN	CHE	CHN	COD	DEU	ESP	FIN	FRA	GBR	IDN	IND	JPN	KOR	MEX	NLD	NOR	PHL	POL	RUS	SVN	USA	ZAF	ZMB
Mining	0.2	3.3	0.3	0.9	2.1	4.0	0.2	4.7	21.0	1.0	1.2	1.3	0.5	0.8	16.3	0.6	0.5	0.2	0.6	0.7	0.7	6.1	0.2	2.0	0.2	1.6	3.8	5.2
Refining & Fabrication	0.4	2.4	1.4	7.1	2.9	5.9	1.3	67.4	1.5	14.3	4.2	18.2	3.0	3.5	0.7	7.3	8.6	5.6	2.7	3.5	4.0	0.8	0.9	3.7	3.7	7.2	2.8	7.7
Manufacturing	3.5	3.5	6.3	1.8	7.5	7.2	5.8	11.7	0.3	8.0	4.6	0.6	8.2	15.4	3.0	6.2	9.3	6.9	2.1	14.7	0.9	2.9	3.1	5.5	12.2	23.1	6.0	1.9
In-use	2.5	3.6	2.6	0.8	5.1	5.2	2.9	2.4	0.9	1.6	0.9	0.5	4.6	7.2	2.6	3.5	1.9	2.5	1.3	1.9	0.5	1.7	1.9	3.6	1.5	12.7	3.5	2.2
Waste management & Recycling	0.7	1.9	0.2	0.2	1.4	2.2	0.2	0.7	0.8	0.4	0.4	0.3	1.4	0.4	0.6	1.2	0.5	0.2	0.6	0.3	0.3	0.2	0.2	1.0	0.5	1.3	0.8	0.4

Fig. S51 Heatmaps of PageRank values (×1000) by country and stage in 2011.

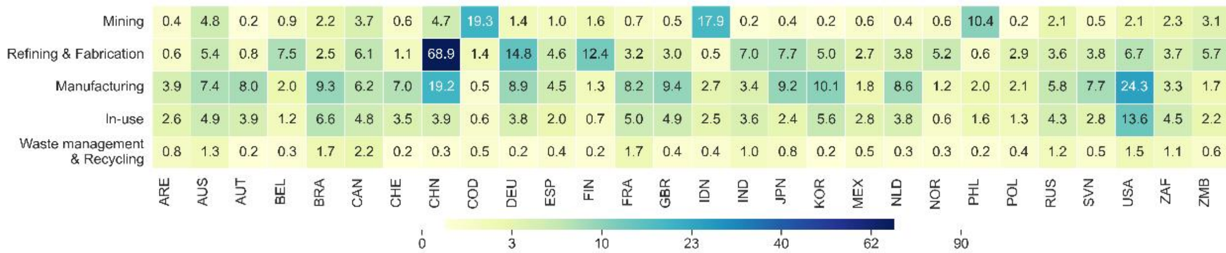

Fig. S52 Heatmaps of PageRank values (×1000) by country and stage in 2012.

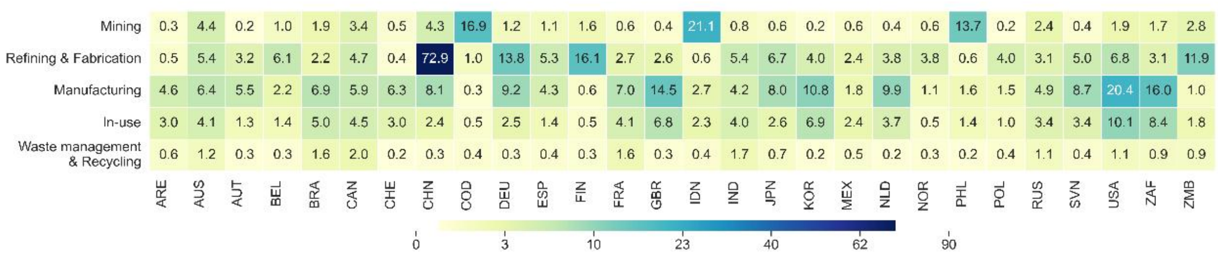

Fig. S53 Heatmaps of PageRank values (×1000) by country and stage in 2013.

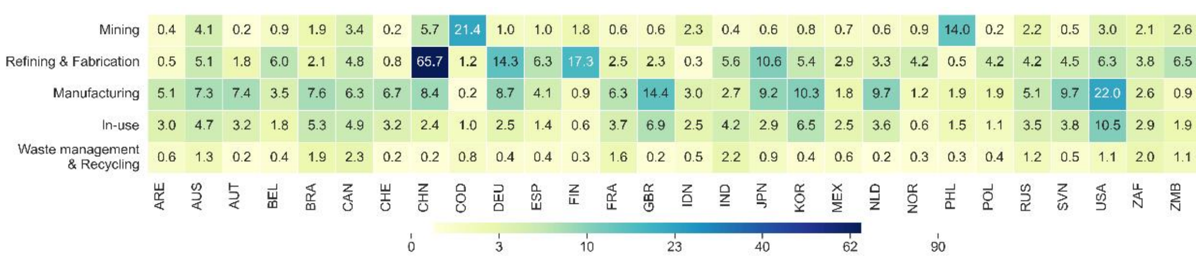

Fig. S54 Heatmaps of PageRank values (×1000) by country and stage in 2014.

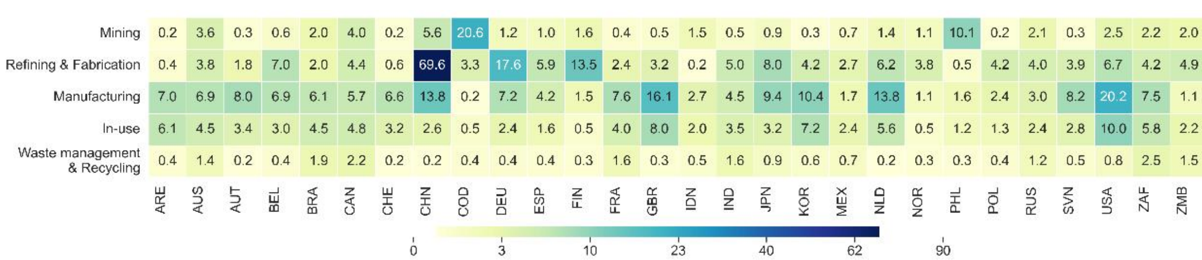

Fig. S55 Heatmaps of PageRank values (×1000) by country and stage in 2015.

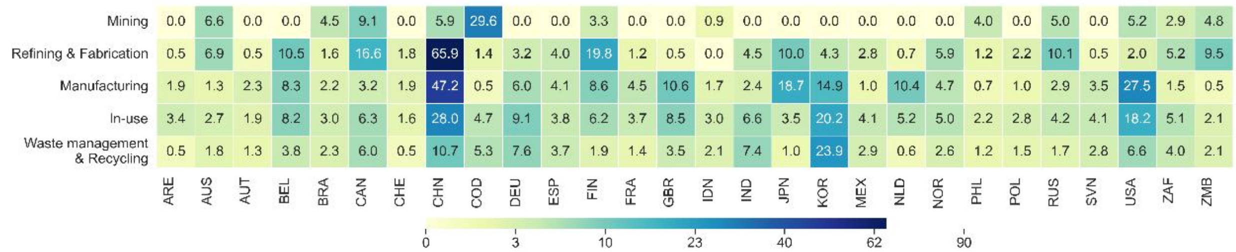

Fig. S56 Heatmaps of PageRank values (×1000) by country and stage in 2016.

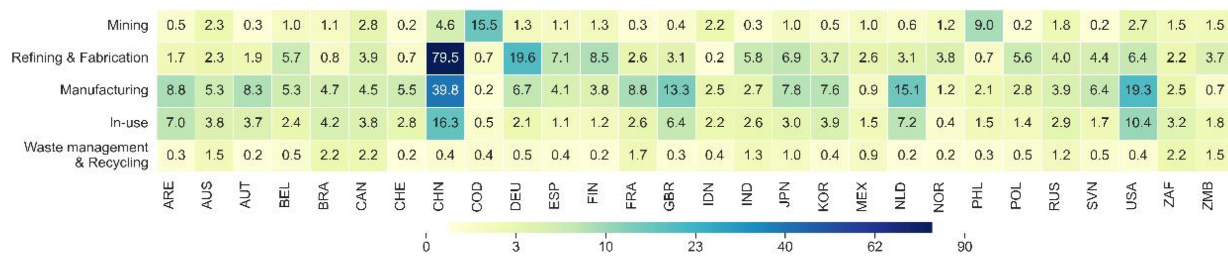

Fig. S57 Heatmaps of PageRank values (×1000) by country and stage in 2017.

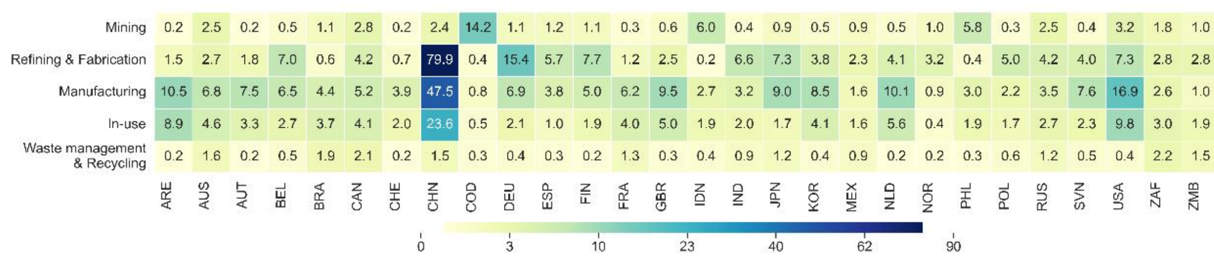

Fig. S58 Heatmaps of PageRank values (×1000) by country and stage in 2018.

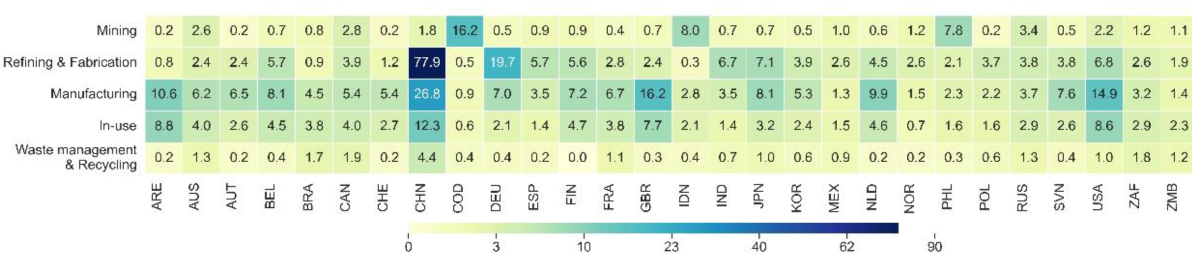

Fig. S59 Heatmaps of PageRank values (×1000) by country and stage in 2019.

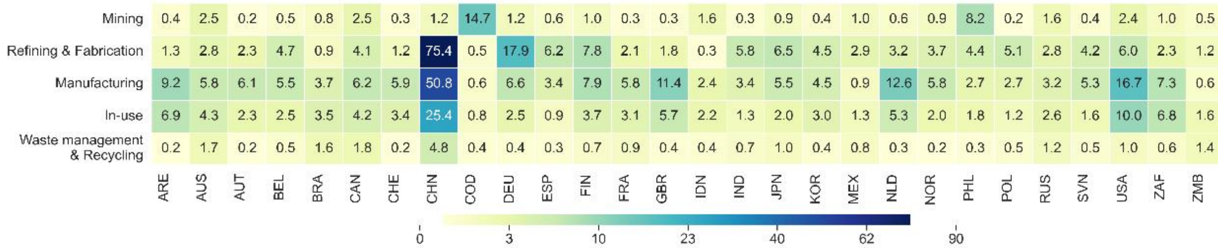

Fig. S60 Heatmaps of PageRank values (×1000) by country and stage in 2020.

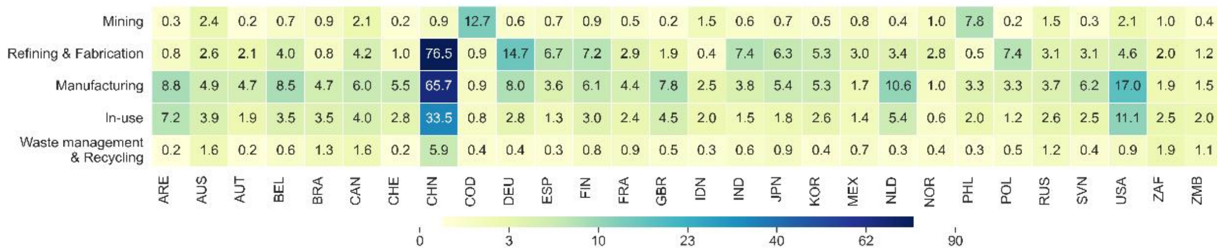

Fig. S61 Heatmaps of PageRank values (×1000) by country and stage in 2021.

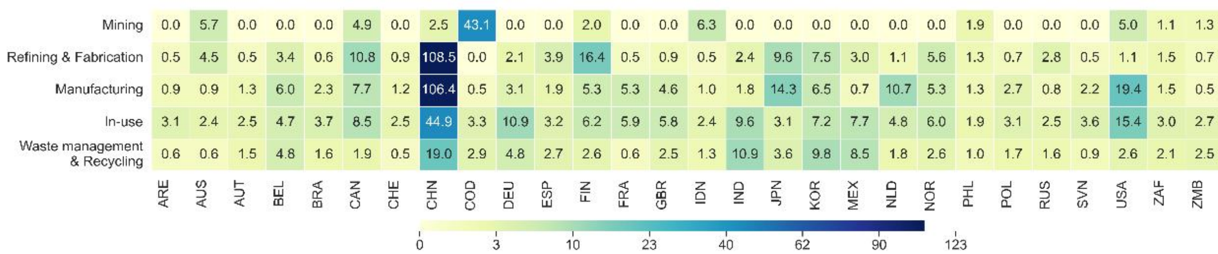

Fig. S62 Heatmaps of PageRank values (×1000) by country and stage in 2022.

2.5. Country- and region-specific metabolic archetypes

We further analyzed cobalt consumption patterns for three major consuming regions, i.e., China, the United States, and Europe (Fig. S63). The consumption structures of the United States and Europe are similar, with batteries gradually replacing conventional end uses since the early 2000s and accounting for 91% and 83% of total cobalt consumption in 2022, respectively. In China, rapid economic growth and the promotion of 3C products since 2007 have driven a steep rise in battery-related cobalt demand, reaching 64% of total consumption in 2022. Meanwhile, cobalt demand for conventional end uses in China remains notable, mainly superalloys (14%) and cemented carbides (6%). China's total in-use cobalt stock reached 310 kt in 2022, 64% of which was embedded in batteries, with 50 kt of scrap generated that year (51% battery) (Fig. S64). For comparison, in-use cobalt stocks in the United States and Europe were 63 kt and 156 kt, respectively, with 76% and 74% contained in batteries, roughly evenly split between LCO and NCM/NCA types. Finally, the annual scrap generation in the United States and Europe reached 8.1 kt and 23.4 kt, respectively.

Fig. S63 Evolution of in-use cobalt stocks and end-of-life (EoL) flows by product category (2000–2020) across China (a, d), the United States (b, e), and Europe (c, f). Panels (a–c) show in-use stocks, while panels (d–f) show EoL cobalt flows.

Fig. S64 Evolution of cobalt apparent consumption by end-use product category (2000–2020) across China (a, b), the United States (c, d), and Europe (e, f). Panels (a, c, e) show absolute consumption, while panels (b, d, f) show market shares by product category.

Fig. S65 Trade structure of cobalt by region and by stage (a, b), and by product category (c, d). Panels (a, b) show exports, while panels (c, d) show imports.

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