



Full length article

Identifying supply risks by mapping the cobalt supply chain

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ABSTRACT

Cobalt is considered a critical raw material. Global cobalt demand is expected to quadruple in the next four decades, due primarily to lithium-ion battery demand. Uniquely, this study provides detailed geographically explicit data on the cobalt supply chain, with the aim of both determining how susceptible primary cobalt production is to supply chain disruptions, and to evaluate possible supply risks. We conclude that the risks for supply chain disruptions are high. Firstly, the cobalt market is highly concentrated, with more than half of the cobalt mined in the Democratic Republic of the Congo, and almost half of the cobalt refined in China. Secondly, almost all cobalt is mined as a by-product of copper and nickel. Finally, political stability in production countries is considered to be medium to very weak. There are also several factors in play that reduce supply risks. The concentration of the individual mines, refineries and companies remains under the threshold of a concentrated market, and the estimated 80 artisanal cobalt mines further diversify the mined supply. A network analysis shows the important position of companies with high betweenness and degree centrality. A disruption at these companies can affect the functioning of the overall supply chain. The geographic and a network visualization provide useful insights in the supply risks. Based on the analysis, we recommend to diversify cobalt production, through the development of mines, refineries, and efforts to ensure socially and environmentally sustainable artisanal mining.

1. Introduction

Cobalt is widely considered a critical material, and is used in many different sectors, ranging from chemical, metal and graphics industry, electronics to healthcare (Cobalt Institute, 2019). Cobalt is an essential component of the lithium-ion batteries used in almost all laptops, mobile phones and electric vehicles (McCullough and Nassar, 2017).

Several studies find that the demand for cobalt will significantly increase, due to demand for electric vehicles. Deetman et al. (2018) concluded that the demand for cobalt is expected to increase by a factor 10 to more than 20 towards 2050. Tisserant and Pauliuk (2016) expect a lower growth in cobalt requirements, but still foresee a quadrupling of demand in the next four decades. A 3 % annual growth rate of cobalt supply will be needed in order to satisfy the demand from electric vehicles alone, while electronic equipment is still by far the major market for lithium-ion batteries (Marscheider-Weidemann et al. as cited in Helbig et al. (2018)).

The increase in demand for cobalt leads to the question whether a major expansion of supply would lead to increasing supply risks. These risks are commonly studied in criticality assessments (e.g. Graedel et al. (2012), the European Commission (2017), the United States National Science and Technology Council (2016); Helbig et al. (2018); Cimprich

et al. (2017); Gemechu et al. (2017)). Supply risk can be described as the likelihood of a supply disruption (National Research Council, 2008). Disruptions in the supply chain can cause shortages, and subsequent rapid price increases (e.g. in the case of Neodymium prices increased with a factor 10, Sprecher et al., 2015).

Often used indicators of supply risk in criticality assessments include, but are not limited to, production concentration on a country- or company-level, country risk (e.g. in terms of political stability and governance quality), and by-product dependency (Achzet and Helbig, 2013; Graedel et al., 2015; Schrijvers et al., 2020). Depletion is not always included as indicator, as it is unlikely that physical scarcity will limit the access to materials in the foreseeable future (Coulomb et al. in Schrijvers et al., 2020).

Cobalt is mostly produced as a by-product. Several studies have suggested that the supply of by-products is inherently riskier than that of host metals, because their recovery is contingent upon the economic health of their corresponding primary commodity market (Hayes and McCullough, 2018; Sprecher et al., 2017b).

Production of cobalt is highly concentrated, with more than half of the world's cobalt being mined in the Democratic Republic of the Congo. Furthermore, mining in Congo can be problematic from a social point of view. Several reports by NGOs and academic studies provide

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evidence of cobalt-mining related to human rights violations and environmental negligence in the Katanga region of the Democratic Republic of the Congo (e.g. [Amnesty International, 2019](#); [Cheyns et al., 2014](#)). Besides industrial mining, an estimated 15–20 % of the total cobalt production in the Democratic Republic of the Congo comes from artisanal mining ([BGR, 2017](#)). The Centre for Research on Multinational Corporations (SOMO) estimated that 40,000 children work in underground tunnels, without protective equipment. Amnesty International reported that in one year 72 artisanal cobalt miners died in collapsed tunnels and other underground incidents ([SOMO, 2016](#)).

Besides further understanding the supply risks associated with cobalt, this study aims to advance the state of the art in contemporary criticality assessment. We do this by addressing two identified research gaps.

A first research gap is that production concentration is only measured on the country (and sometimes company) level. However, for minor metals a disruption at even a single mine can have an impact on the overall price of the mineral and the supply chain. For example, the closure of the Mutanda mine in 2019 removed around 20 % of the global cobalt supply ([WSJ, 2019](#)). Therefore, this study will examine the supply concentration not only on the country level, but also geographically map individual mines and refinery. We also geographically map these individual mines and refineries, and connect them to global trade flows.

A second research gap is the lack of assessment of linkages between companies, an exception being the network analysis of [Nuss et al. \(2016\)](#). Linkages between companies can impact supply chain disruptions. Therefore, we explore shareholder structures of the cobalt industry at the company level. We apply network analysis to identify important companies in terms of position and influence in the supply chain, and, in case of a disruption, to determine how this could impact the overall supply chain resilience.

Recent studies highlighted the importance of looking beyond mining, and also evaluating the refining stage of the supply chain ([Blengini et al., 2017](#), [Gemechu et al. in Nansai et al., 2017](#)). Several recent studies mapped cobalt trade flows between the mining and refining countries ([Nansai et al., 2014](#); [Sun et al., 2019](#)), highlighting the importance of exploring how linkages in the network can influence supply risk.

In summary, the aim of this study is to analyze the vulnerability of the primary cobalt production to supply chain disruptions, and to evaluate supply risks associated with the increased attention for responsible sourcing. We do this by geographically explicitly mapping the cobalt supply chain and companies, and applying supply risk indicators such as the diversity of supply, by-product dependency, political and environmental risks, and company linkages. For reasons of data availability, 2016 was taken as the base year.

Key innovative features of this study are that we add a level of detail to the analysis of diversity of supply, by making a network analysis of the linkages between mines and refineries and by adding the risk of global trade. These latter features transcend geographical country boundaries.

2. Methods and materials

2.1. Data sources

Country level mining and refining statistics are taken from the British Geological Survey ([BGS, 2018](#)), and compared with data from the United States Geological Survey (2017e). To identify the individual cobalt mines globally and the operators and shareholders involved, we used the following online sources; An online global overview of cobalt deposits ([USGS, 2017a](#)); company (annual) reports, a list of cobalt producing mines from [Mudd et al. \(2013\)](#), reports on cobalt from geological surveys, media articles, and reports of operators and websites that collect information on mines globally.

2.2. Supply risk indicators

Different methods were used to analyze supply risks, including the Herfindahl-Hirschman Index (HHI), the World Governance Index (WGI)

([Worldbank, 2019](#)), the Environmental Performance Index (EPI) and network analysis. The characteristics are visualised in a geographic map of mines and refiners and a network diagram of the companies involved.

The HHI is a method to measure the concentration in commodity markets but has also been used in previous studies as an indicator for supply diversity ([Silbergliitt et al., 2013](#)). The HHI is defined as the sum of the squares of the fraction of market share controlled by the 50 largest entities producing a particular product. The U.S. department of Justice developed guidelines to examine corporate mergers, and states that an HHI of between 1500 and 2500 signals a ‘moderately concentrated’ market, while an HHI above 2500 indicates a ‘highly concentrated market’ ([Silbergliitt et al., 2013](#)). Diversity of supply is part of the supply chain resilience framework, developed by [Sprecher et al. \(2015\)](#). Having high diversity in supply reduces the impact of disruptions and therefore increases resilience. Though it should be considered that the diversity of supply only increases resilience if actors have the capacity to switch in time between suppliers ([Sprecher et al., 2015](#)).

The WGI is used to measure the governance in a country, it ranges from approximately –2.5 (weak governance) to 2.5 (strong governance). Poor governance is a key factor in the determination of supply risks, because supply from countries exhibiting poor governance may be interrupted, e.g. through political unrest ([European Commission, 2014](#)). The WGI is used to evaluate a range of governance indicators, including Voice and Accountability, Political Stability and Absence of Violence, Government Effectiveness, Regulatory Quality, Rule of Law and Control of Corruption. In this study we will focus on the indicators for political stability and absence of violence (WGI-PV).

The EPI is used to measure countries’ policy performance on high-priority environmental issues ([Hsu, 2016](#)). The EPI ranks countries’ performance on high-priority environmental issues in two policy areas: protection of human health and protection of ecosystems. The country ranking includes scores from 0 to 100, with 0 indicating the lowest Environmental Performance and 100 indicating the highest Environmental Performance. New Caledonia is not included (separately from France) in the WGI or in the EPI.

Network analysis is used for understanding, designing, and managing supply chains ([Bellamy and Basole, 2012](#)). A network can be represented by a series of nodes and linkages in which the nodes represent an individual, a team, an organization, a community or a country and the linkages represent a relation between the nodes ([Sandru in Rodriguez-Rodriguez and Leon, 2016](#)). In the context of supply chain analysis, the use of network analysis is still relatively new. Today’s resource criticality assessments do not generally account for risk aspects related to the topology of the supply chains ([Nuss et al., 2016](#)). The network analysis is used to analyze the structure and mutual dependence of the companies in the network. The network is visualised with the software tool Gephi ([Gephi, 2019](#)). The network metrics degree centrality, betweenness centrality and closeness centrality are used to analyze the position and influence of the companies in the network. The degree centrality indicates the number of linkages per node. The closeness centrality indicates how close a node is on average to all other nodes in the network, so how closely a company is connected to all other companies. It is calculated as the average of the shortest path length from the node to every other node in the network ([Golbeck, 2015](#)). Betweenness centrality captures the role of a company in connecting other companies in the network. It is measured with the number of shortest paths that pass through the target node.

The trade of cobalt between mines and refineries was mapped with trade data from UN Comtrade ([UN Comtrade, 2019](#)). The data as reported by import countries are often different from those reported by export countries. In this analysis we only use the import data, because it is generally accepted that import data is usually more reliable because imports usually generate tariff revenues while exports do not ([Worldbank, 2010](#)). In order to exclude transit flows only those 13 importing countries were selected in which cobalt was refined. [Schmidt et al. \(2016\)](#) show cobalt intermediate products, such as mattes, are a

result of leaching and smelting processes that take place before cobalt refining. In the search for individual cobalt mines, we found that cobalt smelters or processing plants are often located at the mine site, see Figure S1 of the supporting information (SI). Therefore, to analyze the trade from countries with mines to countries with refineries we selected both the trade code for “cobalt ores and concentrates” as well as the code “cobalt: mattes and other intermediate products of cobalt metallurgy, cobalt and articles thereof” from the Comtrade data. These codes combine products with widely differing cobalt contents, therefore we have opted not to convert the volumes of the trade flows to their actual cobalt content, see also Table S1 of the SI.

3. Results

In this section an overview of the data on the cobalt supply chain is presented, including the involved countries, the mines, refineries, the trade flows and the operator and shareholder companies. All data is reported for 2016, unless stated otherwise.

3.1. Geographic locations of cobalt mining and refining

3.1.1. Countries

Cobalt was mined in 21 countries, for a total production in the range of 123–128 kt, of which 69 kt was mined in the Democratic Republic of the Congo (BGS, 2018; USGS, 2017e). Cobalt was refined in 18 countries, with a total production of 98 kt, of which 45 kt was refined in China (BGS, 2018). The refined production is slightly higher than the estimation by the Cobalt Institute, which reported a total production of 94 kt from 17 countries, differing from the BGS by excluding New Caledonia (Cobalt Institute, 2018). The difference between mined production and refined production can be explained by losses during refining (BGS, 2018). See also Table S2 in the SI.

3.1.2. Cobalt mines

According to the USGS the total terrestrial cobalt resource is 25,000 kt (including past production) (USGS, 2017a), which is very similar to the terrestrial cobalt resource of 26,100 kt presented in the study by Mudd et al. (2013). The USGS (2017a) provides an overview of 214 cobalt deposits, of which most of the largest cobalt deposits are located in countries that have developed cobalt mines. In total 131 cobalt producing mines were identified, as well as the cobalt production per mine and the operator/shareholders companies of these mines. Production was only reported for 40 of these mines in 2016, which sums up to 104 kt. This is ~15 % to 20 % less than the total cobalt production estimated by the USGS (2017e) and BGS (2018). Of the identified production, 73 % comes from Africa, 11 % Oceania, 5 % North America, 4 % Central America, 3 % Asia, 2 % South America and 2 % Europe. Table 1 presents an overview of the cobalt producing mines in 2016, the SI provides all data. Mudd et al. (2013) published a paper listing the 30 producing cobalt mines and operators in 2011. Comparing these to the producing mines in 2016 with those in 2011, we found that five cobalt mines stopped production. For five other producing mines in 2011, no cobalt production was reported in 2016. Twenty new mines are added to the list from Mudd et al. (2013).

In the Democratic Republic of the Congo alone, an estimated 10,500 tonnes of cobalt originated from artisanal mining in 2015 (BGR, 2017). The BGR mapped around 80 artisanal copper-cobalt mines in this region (BGR, 2017).

Most of the mined cobalt production in 2016 (67 %) is from stratiform sediment hosted Cu-Co deposits, followed by Ni-Co laterite deposits (21 %) and magmatic Ni-Cu (Co-PGE) sulfide deposits (10 %) and finally by Polymetallic (Ag-Ni-Co-As-Bi) cobalt rich vein (2 %). 70 % of cobalt is produced as a by-product of African copper production. 20 % is a by-product of Nickel production, which takes place in almost all continents (including Africa). 8 % of cobalt is produced in mines that produce both nickel and copper, but where the main product is

unknown. Finally, 2 % of cobalt is mined as main product, at the Bou Azzer mine in Morocco.

The largest cobalt deposits can be found in the oceans. According to the USGS (2017a), legal, economic, and technological barriers have prevented exploitation of these cobalt resources. Advances in technology may soon allow production of these resources to be economically viable (USGS, 2017a). In addition, in 2020 a mining code will be finalized, that will put in place a process whereby contractors can apply for licenses to mine assigned ‘claim areas’ in parts of the international sea bed. However, the scarce data that exists, suggests that deep-sea mining will have devastating and potentially irreversible impacts on marine life (Hefferman, 2019).

3.1.3. Cobalt refineries

The Cobalt Institute (2018) lists the refined cobalt production of 14 companies in 17 countries in 2016. The production of the refineries in China (8 companies) and South Africa (1 company) is added from data from Al Barazi (2018) referring to refineries in 2017. This results in a total production of 101 tonnes at 23 refineries. Several other cobalt refineries were reported by the Responsible Minerals Initiative (2019), for example in the Republic of Korea, but no production was reported by these refineries for 2016. The exact locations are presented in Fig. 1.

3.2. Cobalt mine operators, shareholders and refineries

Table 1 shows the operators and shareholders identified per mine site. In total 34 cobalt mine operator companies were found (producing in 2016), of which some companies operate multiple mines. In total 35 shareholder companies were found with shares in mine operator companies, some mine operator companies are the main shareholder, while other operator companies have different owners. Comparing the list of cobalt companies in 2011 from Mudd et al. (2013) with 2016, there were at least 10 additional companies and there were some changes in ownership, including that the Freeport owned Tenke Fungurume mine was taken over by China Molybdenum and Glencore fully acquired Xstrata in 2013. Most of the mines kept the same main operator and shareholder.

We identified 23 refinery companies that produced cobalt (Table 2). Of these 23 refineries, 13 are owned by identified shareholder companies (Al Barazi, 2018). The linkages between the refineries and shareholders are based on this ownership.

3.3. Trade flows

In total there were 12 flows of cobalt ores and concentrates, with a total weight of 140 kt, and 84 flows of cobalt mattes and intermediate products, with a total weight of 190 kt (Comtrade 2016). Based on a refined production of 98,000 tonnes, the overall average cobalt content of all these trade flows together was around 30 %. The largest exporter of cobalt products is the Democratic Republic of the Congo, with 88 % of the exports. This is followed by Zambia (4 %), South Africa (2 %), New Caledonia (2 %), Finland (1 %) and Canada (1 %). All these countries also have cobalt mines. Some countries with high mined production have a relatively low export, e.g. China (0.09 %) and Australia (0.4 %), simply because the cobalt products are domestically refined. The largest importer of the cobalt products is China (97 %), followed by Japan (2 %). All other countries import less than 1 %. China and Japan also have relatively high refined production (46 % and 4 % of global production). A few inconsistencies in the data are described in the SI. A visualization of the geographic supply chain is presented in Fig. 1. The graph shows 40 cobalt mines, 23 refineries, and intermediate product trade flows between the countries (trade flows < 50 tons are excluded).¹

¹ A satellite map of the individual mines and refineries can be accessed through <https://drive.google.com/open?id=1rTyWBKil47jPwsNyYMDjrMaJgcREYzj2&usp=sharing>

Table 1

Global overview of cobalt mines, mine operators and shareholders producing cobalt in 2016.

Sources: 24 hGold (2019a), 24 hGold (2019b), Africa Rainbow Minerals (2018), Al Barazi (2018); Australian Mine Atlas (2019); Australian Mining (2018); BGR (2017); BGS (2019); Boliden (2017); Catalogo de Mineracao Brasil (2017); Chemaf (2018), China Nonferrous Mining Corporation Limited (2018), CongoMines (2018); Coral Bay Nickel Corporation (2018); Eagle Mine (2018); Eramet (2010), 2019; Eurasian Natural Resources Corporation (2017); Glencore (2016); Government of the Philippines (2018); Highlands Pacific (2019); Horizonte Minerals (2018); Indian Bureau of Mines (2017); Investing News (2018); Investor Intel (2016); KPMG (2013); Lundin Mining (2017); Managem Group (2016); Mindat (2019a, b, c), Mining Data (2019a, b, c, d), Mitsubishi Corporation (2009); Mudd et al. (2013); Natural Resources Canada (2018); Nornickel (2018); Ontario Prospectors Association (2016); Pacific Islands Report (2010); PWC (2012); Sheritt International (2017); USGS (2017a), b; USGS (2017c, d); USGS, 2017e, Vale (2016); Wikipedia (2018c); Yle (2018); ZCCM Investment Holdings Plc (2018). A list of all company reports reviewed can be found in table S6 in the SI.

Country	Cobalt production in 2016 (BGS, 2018)	Mine	Deposit type	Cobalt production in 2016 (*) (metric tonnes)	Total per country	Operators (**)	Shareholders (**)			
Dem. Rep. of Congo (DRC/COD)	68822	Mutanda North (ex-Kansuki), Mutanda South,	Stratiform sediment-hosted Cu-Co	24500	64698	Mutanda ya Mukonkoto Mining (Mutanda)	Glencore			
		Tenke Fungurume: Fwaulu, Fungurume, Kansalawile, Kwatebala, Mambilima, Mwadinkomba, and Tenke.	Stratiform sediment-hosted Cu-Co	16053		Tenke Fungurume Mining (Tenke)	China Molybdenum (Molybdenum), Gecamines (Gecam), Lundin Mining Corporation (Lundin)			
		Luiswishi	Stratiform sediment-hosted Cu-Co	6200		Huayou Cobalt (Huayou)	Huayou Cobalt (Huayou)			
		Kakanda, Lwita Est, Mukondo Mountain	Stratiform sediment-hosted Cu-Co	5100		Boss mining (Boss)	Eurasian Natural Resources Corporation (ENRC)			
		Etoile, Etoile HMS 1,	Stratiform sediment-hosted Cu-Co	3800		Shalina Resources Ltd (Shalina)	Chemaf (Chemaf)			
		Ruashi Mine	Stratiform sediment-hosted Cu-Co	3264		Metorex (Metorex)	Jinchuan Group (Jinchuan)			
		Kamoto, Kananga, KOV, Mashamba Est, T17, Tilwezembe	Stratiform sediment-hosted Cu-Co	2901		Katanga Mining Limited (Katanga)	Glencore (Glencore)			
		Usoke	Stratiform sediment-hosted Cu-Co	2400		Chemaf (Chemaf)	Chemaf (Chemaf)			
		Luisshia	Stratiform sediment-hosted Cu-Co	480		Miniere du Sud Katanga (Katanga S)	Entreprise General Malta Forrest (EGMF), Gecamines (Gecams)			
		Total								
China (CHN)	10500	Kalatongke	Magmatic Ni-Cu(Co-PGE) sulfide	106	188	Xinjiang Xinxin Mining Industry (Xinjiang)	Xinjiang Xinxin Mining Industry (Xinjiang)			
		Yuanjiang Total	Ni-Co laterite	82		Yuanjiang Nickel (Yuanjiang)	Yuanjiang Nickel (Yuanjiang)			
Canada (CAN)	6969	Raglan	Magmatic Ni-Cu(Co-PGE) sulfide	1000	6046	Glencore (Glencore)	Glencore (Glencore)			
		Voisey's Bay	Magmatic Ni-Cu(Co-PGE) sulfide	887		Vale (Vale)	Vale (Vale)			
		Sudbury	Magmatic Ni-Cu(Co-PGE) sulfide	882		Vale (Vale)	Vale (Vale)			
		Thompson	Magmatic Ni-Cu(Co-PGE) sulfide	700		Vale (Vale)	Vale (Vale)			
		Copper Cliff North	Magmatic Ni-Cu(Co-PGE) sulfide	606		Vale (Vale)	Vale (Vale)			
		Nickel Rim South	Magmatic Ni-Cu(Co-PGE) sulfide	100		Glencore (Glencore)	Glencore (Glencore)			
		Total								
		Australia (AUS)	6012	Murrin Murrin		Ni-Co laterite	2800	4175	Minara Resources (Minara)	Glencore
				Brolga and Dingo Dam mine		Ni-Co laterite	1850		Queensland Nickel Group (Queensland)	Queensland Nickel Group (Queensland)
				Ravensthorpe (Bandalup)		Ni-Co laterite	920		First Quantum Minerals (First QM)	First Quantum Minerals (First QM)
Savannah	Magmatic Ni-Cu(Co-PGE) sulfide			476	Panoramic Resources (Panoramic)	Zeta Resources (Zeta)				
Total										

(continued on next page)

Table 1 (continued)

Country	Cobalt production in 2016 (BCS, 2018)	Mine	Deposit type	Cobalt production in 2016 (*) (metric tonnes)	Total per country	Operators (**)	Shareholders (**)
Brazil (BRA)	3600	Vermelho	Ni-Co laterite	2500	2500	Horizonte Minerals	Horizonte Minerals Plc (Horizonte)
Cuba (CUB)	3694	Moa Bay	Ni-Co laterite	3694	3694	Sherritt International (Sherritt)	Government of Cuba (Gov Cuba), Sherritt International Corp (Sherritt)
Zambia (ZMB)	4725	Chambishi	Stratiform sediment-hosted Cu-Co	2997		Chambishi Metals plc Zambia (Chambishi)	China Non-ferrous Mining (CHN non-ferrous), ZCCM Investments holding (ZCCM)
		Nchanga, Konkola	Stratiform sediment-hosted Cu-Co	1700		Konkola Copper Cobalt Operation (Konkola)	Vedanta Resources (Vedanta), ZCCM Investments holding (ZCCM)
		Total			4697		
New Caledonia (NCL)	4350	Goro (VNC)	Ni-Co laterite	3188	3188	Goro (VNC) (Goro VNC)	Vale (Vale)
Madagascar (MDG)	3370	Ambatovy	Ni-Co laterite	1309	1309	Ambatovy (Ambatovy)	Sherritt International (Sherritt)
Philippines (PHL)	2554	Rio Tuba Nickel mine and Rio Tuba Processing Plant, Coral bay Nickel Corporation and Taganito	Ni-Co laterite	2600	2600	Rio Tuba Nickel Mining Corporation/ Coral Bay Nickel Corporation (Rio Tuba)	Nickel Asia (Nickel Asia)
Finland (FIN)	2308	Kevitsa	Magmatic Ni-Cu(Co-PGE) sulfide	420		Boliden (Boliden)	Boliden (Boliden)
		Sotkamo (formerly Talvivaara)	Black-shale-hosted Ni-Cu-Zn-Co	20		Terraflame Mining (Terraflame)	Terraflame and Solidium (Terraflame)
		Total			440		
Papua New Guinea (PNG)	2191	Ramu	Ni-Co laterite	2191	2191	Highlands Pacific (Highlands)	China Metallurgical Group Corporation (China Metallurgical), PNG Government (PNG Gov)
Russia (RUS)	2100	TAIMYR PENINSULA: Talnakhskoye, Oktyabrskoye Fields	Magmatic Ni-Cu(Co-PGE) sulfide	2040	2040	Norilsk Nickel (Norilsk)	Norilsk Nickel (Norilsk)
Morocco (MAR)	2081	Bou Azzer	Polymetallic (Ag-Ni-Co-As-Bi) and other cobalt-rich veins	2081	2081	Compagnie de Tifnout Tiranimine (CTT)	Managem Group (Managem)
South Africa (ZAF)	1101	Nkomati	Magmatic Ni-Cu(Co-PGE) sulfide	1065	1065	Africa Rainbow Minerals (Africa Rainbow)	Norilsk Nickel Africa (Norilsk), Africa Rainbow Minerals (Africa Rainbow)
United States (USA)	690	Eagle	Magmatic Ni-Cu(Co-PGE) sulfide	650	650	Eagle Nickel-Copper Mining (Eagle)	Lundin Mining (Lundin)
Indonesia (IDN)	350	Halmahera/Weda Bay	Ni-Co laterite	400	400	Eramet (Eramet)	PT Antam (PT Antam) Mitsubishi Corporation (Mitsubishi)
Zimbabwe (ZWE)	409	Trojan Mine at Bindura and Shangani Mine	Magmatic Ni-Cu(Co-PGE) sulfide	800		Bindura Nickel Corporation Ltd. (Bindura)	Bindura Nickel (Bindura)
		Mimosa	Magmatic Ni-Cu(Co-PGE) sulfide	88	888	Impala Platinum Holdings Ltd (Impala)	Aquarius Platinum (Aquarius)
Botswana (BWA)	248	Selebi-Phikwe Mines	Magmatic Ni-Cu(Co-PGE) sulfide	400	400	Bamangwato Concessions (Bamangwato)	Government Botswana (Gov BWA), Norilsk Nickel (Norilsk)
Vietnam (VNM)	132	Ban Phuc nickel mine and plant, Tha Koa concession	Magmatic Ni-Cu(Co-PGE) sulfide	277	277	Asian Mineral Resources Limited (Asian Mineral)	Asian Mineral Resources (Asian Mineral)
Total	126206				103339		

* Some companies were operator or shareholder of the mine in a different year or produced the cobalt in a different year (2015 or 2017), these are included for mines where no specific data was found for 2016.

** Abbreviations of the companies are made and included in this table for the network analysis (Fig. 2).

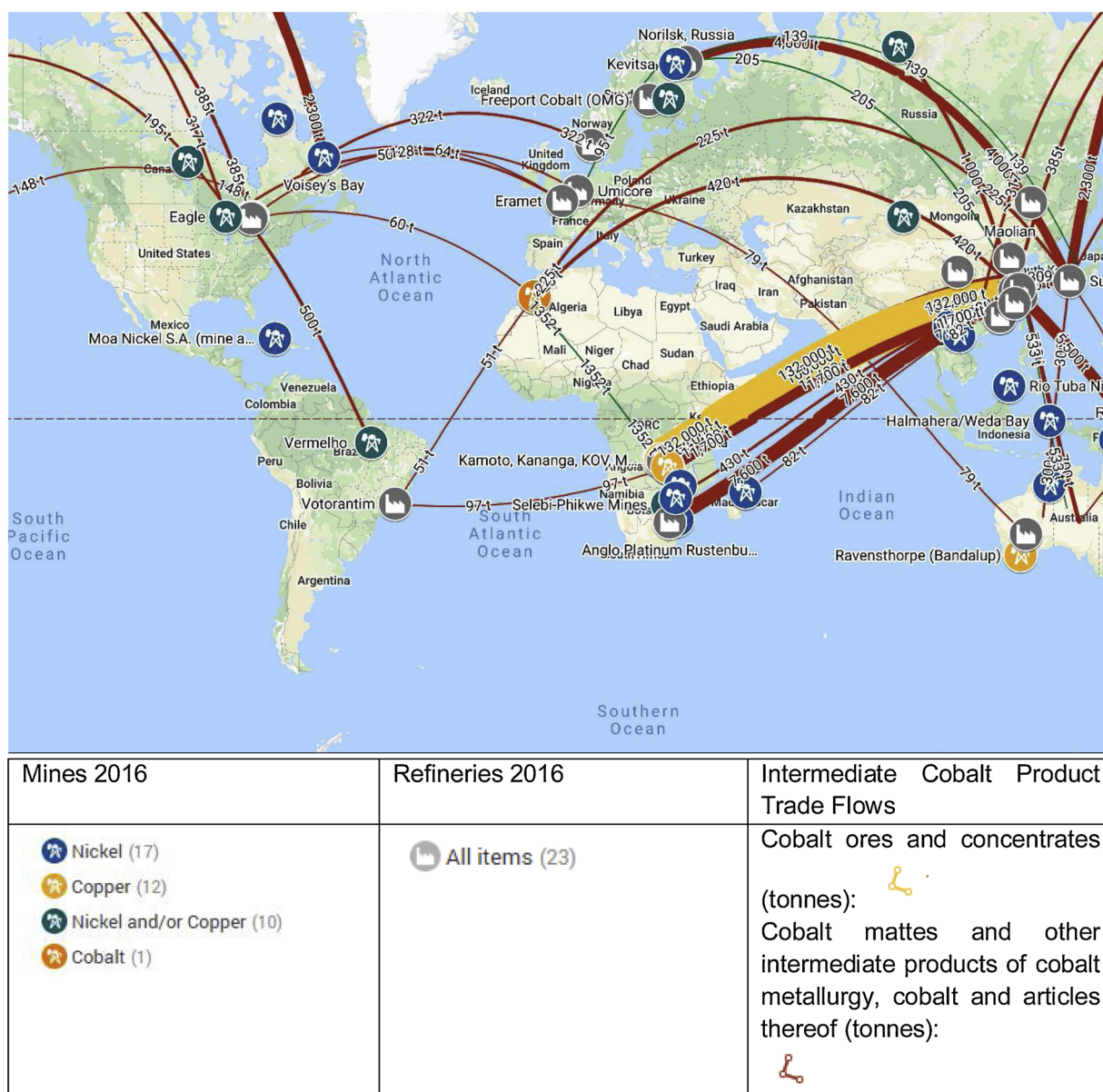


Fig. 1. Geographic cobalt supply chain: intermediate cobalt product flows.² To see all the trade quantities per flow, the interactive map can be accessed through https://drive.google.com/open?id=1AzOy8Cula_nQJDNeLS5BTBtFEO_3JDD&usp=sharing. The direction of the flows can be found on the interactive map by clicking on the flows to see the origin and destination country.

3.4. Diversity of supply

Cobalt mines can be found on all continents, but there is a concentration of mines in the African copper belt, in the Democratic Republic of the Congo and Zambia. More than half of the mined cobalt production in 2016 originated from the Democratic Republic of the Congo (~54 %), followed by China (~8 %), Canada (~5 %) and Australia (~5 %). On the country level, the HHI index for the mined cobalt supply is 3082 for 2016, indicating a highly concentrated market, and therefore a high risk for supply. The concentration of the individual mines is much lower with a HHI of 974, as some countries have multiple mine sites, which makes the supply more diversified.

Cobalt refineries are also located on each continent, but there is a

concentration of refineries in China. Of the refined supply ~46 % originates from China, ~13 % from Finland, ~6 % from Canada and ~6 % from Belgium, 5 %~ from Zambia with the remaining 24 % of the refined supply coming from 12 other countries. The HHI index for the refined cobalt supply is: 2451, which is just under the threshold for a highly concentrated supply. The HHI of the individual refineries is much lower, 730, particularly the supply within China is more diversified since there are eight cobalt refineries in China. A disruption at a single mine or refinery would therefore only pose a small risk for global supply. But a disruption at the country level could seriously impact the global cobalt supply both for mined (the Democratic Republic of the Congo) and refined (China) production.

The estimated 80 artisanal mines help diversify the mined production (Fig. S2 in the SI). The share of artisanal cobalt production in the Democratic Republic of the Congo depends on developments in the industrial cobalt sector as well as the international market (BGR, 2017). Between 1998 and 2006 (a period of civil war and mismanaged state-controlled mines) nearly 90 % of the total Congolese cobalt production

² The intermediate cobalt product flows (HS 2605 plus HS 8105) represented in this analysis are trade flows between countries, flows between actual mines and refineries are unknown.

Table 2
Refined cobalt production per company in 2016 (the Cobalt Institute, 2018; Al Barazi, 2018).

Refinery	Country	Cobalt Refined Cobalt Production 2016 (kt)
Quzhou Huayou Cobalt New Material Co., Ltd. (Quzhou)	China	13000
Freeport Cobalt (Freeport)	Finland	11187
Jiangsu Cobalt Nickel Metal (Jiangsu)	China	9500
Zhejiang Huayou Cobalt Co.,Ltd. (Huayou)	China	9150
Umicore (Umicore)	Belgium	6329
Lanzhou Jinchuan Advanced Materials Technology Co., Ltd. (Jinchuan)	China	5800
Ganzhou Tengyuan Cobalt New Material Co., Ltd. (Tengyuan)	China	5600
Chambishi Metals plc Zambia (ERG) (Chambishi)	Zambia	4725
Gangzhou Yi Hao Umicore Industry Co. (Gangzhou Umicore)	China	4401
Sumitomo (Sumitomo)	Japan	4305
NPMC International Cobalt (NPMC)	Canada	3693
Nikkelverk, Raglan, Sudbury (Glencore) (Nikkelverk GI)	Norway + Canada	3500
Ambatovy (Ambatovy)	Madagascar	3273
Minara (Glencore) (Minara GI)	Australia	3200
Norilsk, Russia (Norilsk)	Russia	3092
Vale (Vale)	Canada	1851
CTT (CTT)	Morocco	1568
Nanjing Hanrui Cobalt (Nanjing)	China	1100
Maolian (Maolian)	China	900
Anglo Platinum Rustenburg (Anglo Platinum)	South Africa	700
Gecamines (Gecams)	Dem Rep of the Congo	400
Votorantim (Votorantim)	Brazil	400
Eramet (Eramet)	France	119
Total refined production		101,486

Abbreviations of the companies are included for the network analysis (Fig. 2).

originated from the artisanal sector (BGR, 2017). This illustrates that artisanal mining can – at least partly – compensate for a shortage in industrial supply. This is in line with Mancheri et al. (2018), which find that artisanal tantalum supply makes the supply chain more flexible, as the production is spread over hundreds of sites and able to respond much more rapidly to price fluctuations than industrial mining, which require significant capitalization and years to significantly increase production.

The visualization of the company network (see Fig. 2) provides an overview of the companies and the cobalt production locations in 2016.

Fig. 2 clearly shows that global cobalt mining is dominated by a limited number of mine operators (mainly in the Democratic Republic of the Congo) and shareholders. Cobalt refining is concentrated in China, but more evenly distributed in terms of the number of companies involved.

Glencore is the largest shareholder, Mutanda ya Mukonkota Mine operator and Tenke Fungurume Mining the largest operators and Freeport Cobalt and Huayou cobalt the largest refineries. Besides these large producers, the production is more diversified. This is also confirmed by the HHI of the companies, which is 990 of the operators, the 1360 of the shareholders and only 730 of the refineries.

3.5. Company linkages

Network analysis is used to find the most important actors related to the position of the actors in the network. This is also called the centrality, the position in the network (Lee and Sohn, 2015). Three types of centrality will be measured, the degree centrality, closeness centrality and the betweenness centrality. The analysis is of the linkages between the companies (mine and refinery operators and shareholders). Most shareholders only have one link (share) to one operator company. Only Glencore has shares in five mine operator companies and Vale, Chemaf, Gecamines, Lundin Mining in two mine operators. Overall, if a company with many linkages fails it may be more likely to result in a disruption of the global cobalt supply than when a company with only a few linkages fails (Nuss et al., 2016).

The companies with the smallest closeness centrality are the mine shareholders: Glencore, Huayou Cobalt and Gecamines, the mine operators: Mutanda ya Mukonkota Mining, Huayou Cobalt and Tenke

Fungurume Mining, and the refineries: Gecamines, Minara Resources, Zhejiang Huayou Cobalt. Companies with smaller closeness centrality are connected to shorter supply chains (i.e. on average less ‘hops’ to get from one actor to another’ and it is therefore it may be less likely that a disruption in physical or information flows occurs (Nuss et al., 2016).

The companies with the highest betweenness centrality are the shareholders: Glencore, Huayou Cobalt and Vale, the mine operators: Mutanda ya Mukonkota Mining, Huayou Cobalt and Glencore, and the refineries: Zhejiang Huayou Cobalt, Quzhou Huayou Cobalt New Material and Minara Resources. Companies with high betweenness centrality can function as bridges between other companies/countries and shorten the pathways between different companies. In this manner companies have (indirect) linkages to other companies through these ‘bridges’ that make the supply chain more resilient. Highlighting these nodes is important as the removal of these nodes can affect the functioning of the overall supply chain (Nuss et al., 2016). The network analysis also shows the multinational companies are vertically integrated, and own both cobalt mines and a refinery (e.g. Glencore, Vale, Norilsk Nickel, Chambishi Metals).

The overall centrality in the network can also be measured with a network analysis, but will need to be compared to other metal supply chains to indicate the level of risk. There are no other studies identified that made a network analysis of the companies in a specific metal supply chain.

3.6. Host metal markets

70 % of cobalt is currently mined as by-product of copper, and 20 % as by product of nickel. In 2016, cobalt production had a value of around USD 3.5 billion. This is insignificant compared to copper (around USD 97 billion) and nickel (around USD 20 billion) (USGS, 2017f, g; Infomine, 2019; Ycharts, 2019). For mines where cobalt provides only a minority of the revenue, cobalt processing generally begins only after the host metal has been concentrated and extracted (BGS, 2009). A high degree of dependence on the minerals production to the production of a “host” metal indicated a high supply risk (Yuan et al., 2019). Additionally, the fact that cobalt is mainly a by-product of copper and nickel production reduces the elasticity of cobalt supply (Mining, 2017). However, due to the high demand projections for

findings are that the cobalt supply chain of 2016 is significantly less concentrated than that of rare earths was in 2008. This is true for both mining (HHI of ~3100 for cobalt compared to ~9500 for rare earths), and refining (HHI of ~2500 for cobalt compared to ~6000 for rare earths). Interestingly, Sprecher et al. (2017a) found that over time the HHI of mining went down, while the HHI of refining went up. This changing over time of which particular step in the supply chain is most critically concentrated could also apply to cobalt. More research in the direction of how both criticality and resilience can change over time is necessary.

There were some limitations to the production reported on the country level by the geological surveys. The BGS (2018) notes that firstly, sometimes mined and refined production are not strictly separated. Secondly, there is frequently a considerable disparity between the cobalt content of ore raised and cobalt actually recovered. Some mine operator companies and their shareholders might not report the cobalt in ore raised if the cobalt will not be recovered. Finally, some numbers of mine production are based on estimates only and could therefore be different in reality. The production of cobalt per country differs also per source, for example comparing the cobalt production per country from the USGS (2018) to the BGS (2018) the production differs for each country and can be up to three times as high. Both data sources are taken into consideration and compared.

The combination of the geographic map and the network analysis create a comprehensive picture of the upstream cobalt supply chain. This includes information on the company level and geographic level on the diversity of the production, the production of companion minerals (copper or nickel mines) and on the supply of the mineral by risk countries or risk suppliers. A limitation of the network analysis is the lack of data available on the actual supplier and buyers relations. This could give more insight into the supply risk connected to the linkages. Some companies also aim to become more transparent with providing information on their suppliers. For example, both Samsung (2016) and Apple (2017) produced a list of their cobalt smelters/refineries. It is recommended for future studies to extend the geographic map and company network analysis with this type of information beyond cobalt mining and refining. While the present research has a clear relationship to previous research on supply chain resilience when it comes to diversity of supply, the other resilience mechanisms (substitution, recycling and stockpiling) have not been explored.

Finally, as the data in this study is based on public information, it can be reproduced for other minerals. It is recommended to map and analyze this information for other minerals, particularly the geographic map and the network analysis can be compared to find differences and to identify mineral specific characteristics.

5. Conclusion

In this study we analyzed the cobalt supply chain for the reference year 2016, in order to assess possible supply chain disruptions.

We conclude that the risk of supply chain disruption is high. The supply of cobalt is strongly concentrated, both at the mining and refining stage. 98 % of cobalt is mined as a by-product of copper and nickel. Finally, there is a weighted weak governance performance in the mining countries and almost weak governance performance in the refining countries. The origin of supply for the global markets is also concentrated.

There are also some factors that reduce the supply risks. Though the mined and refined production is concentrated on the country level, the concentration of the individual mines, refineries and companies remains under the threshold of a concentrated market. In addition, the estimated 80 artisanal mines diversify the mined supply. While the mining of cobalt can have severe environmental impacts, the relatively low environmental performance of mining countries could indicate a lower supply risk as cobalt deposits with high environmental impacts may still be developed or expanded. The latter is an example of how

resilience and sustainability do not necessarily go hand in hand.

This study identified specific companies in the cobalt supply chain that have a high degree centrality and betweenness centrality and low closeness centrality. A disruption at these companies creates a high risk to affect the functioning of the overall supply chain, as these companies function as 'bridges' between countries and companies. The large shareholder companies in the network are vertically integrated and own both mines and refineries. A supply chain could be more resilient if there are overall short supply chain paths (low closeness centrality), many companies 'serving as bridges' (high betweenness centrality) and an even distribution of degree centrality. The risks of the linkages are dependent on market dependent supplier buyer relations, when companies have multiple shareholders and multiple buyers and suppliers, this could decrease overall supply risks.

To increase supply chain resilience, we recommend to diversify the mined and refined cobalt production. More than 150 cobalt deposits are currently not mined, some of which some are in countries that currently do not have cobalt mines. Another option would be to explore deep sea mining, but there are significant concerns about environmental impacts and additional research into the ecological impact is needed. Finally, artisanal mining can play an important role in the diversity of supply. Efforts to ensure socially and environmentally sustainable artisanal mining could increase supply chain resilience. Ways to achieve this include the development and improvement of ASM sustainability certification schemes, and due diligence practices that promote responsible sourcing.

In this study we showed that by using multiple visualizations of a supply chain network can be used to gain useful insights in the resilience of the supply chain. This overview can be used as a tool by companies and policy makers to identify bottlenecks and constraints, as well as to identify the risks are for supply disruption.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.resconrec.2020.104743>.

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