# Part 1

# Background

# 1

# Assessment of European Demand for Mineral Resources by Material Flow Analyses: The Case of Cobalt

**Raphaël DANINO-PERRAUD[1], Maïté LEGLEUHER[2] and Dominique GUYONNET[2]**
[1]*LEO, University of Orléans, France*
[2]*Bureau de recherches géologiques et minières, Orléans, France*

## 1.1. Introduction

The growth of technological innovations in recent decades, especially in renewable energies (REs) and information and communication technologies (ICTs), has led to an ever-increasing consumption of elements of the periodic table used for very specific functions. This has led to concerns about the capacity of their producers to meet demand (Nassar *et al.* 2015). Energy storage systems, especially lithium-ion batteries, are particularly concerned by innovations in ICT and RE. Sold at 4 billion units in 2017 (5.5 billion in 2020) and with a growth of 11% per year (Berthoud *et al.* 2018), the smartphone is the symbol of a digital transition with a high technological content, using an ever larger and more complex combination of metals. For their part, energy transition policies, implemented by most industrialized countries, are also encouraging the use of such systems, whether for transportation (electric or hybrid vehicles) or for stationary use, in order to store electricity production from renewable and intermittent but low-carbon energies. These technologies use a number of raw materials, including lithium, nickel, and cobalt.

*Mineral Resources Economics 1*,
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Rising tensions over raw materials, particularly mineral raw materials in the early 2000s, due to growing consumption and a sometimes constrained geographical location, added to the problem of their supply. Criticality studies have, therefore, been carried out in Japan (JOGMEC 2019), Europe (European Commission 2008), and the United States (NRC 2008) to determine which mineral raw materials are essential for the economy but are subject to tensions, whether geopolitical or linked to limited production capacities. Among all these metals, cobalt has always been a concern, regardless of the country under study. This metal in fact represents a summary of the problems related to critical metals. It is essential and hardly substitutable with the same efficiency for key industrial sectors (superalloys for the aeronautics industry or batteries). Its consumption has quadrupled since the beginning of the 2000s, which has led to severe constraints on production. The latter has a limited geographical area, since 72% of mining production is carried out in the Democratic Republic of Congo (DRC), of which 10% to 15% is artisanal production, and 65% is refined in China (Darton Commodities 2019). The instability and corruption prevailing in Congo raise doubts about the country's ability to ensure sustainable production, which encourages price volatility.

The European Union (EU) is particularly vulnerable with respect to its critical metal supplies, as it produces only 2% of its consumption and more than 50% of the 16 of the 27 elements identified in 2017 are produced by China (European Commission 2019). It is for this reason that the Critical Raw Materials Initiative (European Commission 2019) was established in 2008, based on three pillars:

– sustainable production of mineral raw materials within the EU;

– control of EU supply routes;

– a resource efficiency[1] and recycling strategy (European Commission 2019).

While the first pillar is strictly internal, the second and third pillars require a better knowledge of the actors and also of cobalt flows and stocks at the international level.

Due to its ever-increasing consumption in energy storage systems, which are key to the energy transition, the choice of a flow analysis of cobalt at the EU level seems relevant. Combined with an analysis of the value chain at the global level, it would make it possible, as Nuss and Bengini (2018) point out, to understand and anticipate vulnerabilities, thanks to better knowledge of the origin of flows, and also to better

1 "Resource efficiency means using the Earth's limited resources in a sustainable manner while minimizing impacts on the environment. It allows us to create more with less and deliver more value with less input" (European Commission 2019).

manage them at the end of their lives through better knowledge of stocks in circulation. The exploitation of the urban mine could thus partially offset the deficit in primary cobalt production.

According to Brunner and Rechberger (2004), a material flow analysis (MFA) consists of a systematic evaluation, within a system defined in time and space, of the flows and stocks of a given product. It delivers a complete set of information on the latter. As such, it can provide a better understanding of the demand and use of cobalt in Europe. This metal has been less studied than other metals considered more important, such as nickel, copper, and aluminum (Gerst and Graedel 2008). In fact, we can list only seven material flow analyses dealing with cobalt since the late 1980s. In 2013, Asari *et al.* (2013) conducted an MFA of lithium-ion batteries in Japan for the period 2002–2010, revealing the low collection and recovery rate of cobalt. In 2012, through a dynamic method that allows for analyzing stock accumulation, Harper *et al.* (2012) focused on cobalt flows worldwide, then more specifically on their characteristics in China, Japan, and the United States, the three major countries in terms of consumption. For their part, Shedd and the United States Geological Survey (USGS) analyzed cobalt flows in the United States for the year 1992, focusing in particular on the rates of loss and recycling during the various production and use processes (Shedd 1993). Nansaï *et al.* (2012) worked on the origins and destinations as well as the cobalt contents of the different flows worldwide. Chen *et al.* (2019) insisted on the quantification and evolution of cobalt flows in China between 1994 and 2016 by analyzing the vulnerabilities they could reveal, while the consulting firm Deloitte (BIO by Deloitte 2015) carried out a dynamic MFA, but only showed data on incoming and outgoing flows at the EU level for the year 2012.

These various studies enable us to observe that there is no detailed (multiple year) dynamic cobalt MFA for the European Union, which was the third largest consumer of cobalt in the world in 2016 (between 15 and 20 kt), far behind China and in competition with the United States (Roskill 2016). We believe that such a work carried out for the years between 2008 and 2017 will, like the work of Chen *et al.* for China (2019), provide the necessary information for a better understanding of European consumption and vulnerabilities in cobalt supplies. This work is a prerequisite for a more efficient measurement of cobalt consumption and an improvement in the security of cobalt supplies. The first section presents an overview of the cobalt market, while the second focuses on justifying and presenting a combined value chain/material flow analysis methodology. Finally, the third section presents the results obtained and discusses their limitations.

## 1.2. Cobalt market: structure and operation

Cobalt takes its name from the prankster gnome of the German legends Kobold, accused from time to time of compromising the proper smelting of copper ores. Extracted at the same time as the latter, no process could isolate the cobalt or *a fortiori* prevent it from polluting the copper ore. The development of metallurgy and industrial chemistry from 1730 onwards made it possible to isolate it and then treat it after extraction, thus extending its lifecycle (Bihouix and Guillebon 2010). According to Nuss and Blengini (2018), there are four main stages in the lifecycle of a metal: extraction, transformation and refining, production and use, and the production and use of waste management (collection and recycling). Each step corresponds to one or two segments of the value chain.

### 1.2.1. *Diverse and highly concentrated resources*

Cobalt (Co) is the 27th element in Mendeleev's table. Fairly scarce in the Earth's crust (25 to 29 ppm), it is of average hardness and has a melting point of 1,495°C and a boiling point of 2,927°C. It is also a trace element essential to living beings, which is included in the composition of vitamin B12.

Cobalt is mainly exploited as a co-product of copper and nickel[2]. It is extracted from four types of deposits:

– stratiform copper deposits (the Copperbelt of DRC and Zambia);

– magmatic copper-nickel sulfide deposits with cobalt and subordinate platinoids (Norilsk in Russia, Sudbury in Canada, etc.);

– lateritic nickel deposits (New Caledonia, Cuba, etc.);

– hydrothermal deposits with cobalt dominant (Morocco), this last type of deposit being the only one where cobalt is exploited as the main metal.

In 2018, the USGS estimated the quantity of reserves at around 7 Mt (million tons) distributed between the DRC (3.4 Mt), Australia (1.2 Mt), Cuba (500 kt (kilotons)), Canada, the Philippines, Russia and Zambia (250 to 300 kt), with the remainder being shared by several countries including China, Indonesia, Madagascar, New Caledonia, and Finland. The resources were estimated at 25 Mt, mostly shared by the Democratic Republic of Congo, Zambia, Australia, Cuba, Canada, Russia, and the United States. According to the USGS, the concentrations of cobalt in polymetallic

2 According to Jebrak and Marcoux (2008), a co-product is "a metal recovered together with another metal in an industrial extraction process".

nodules and certain crusts on the ocean floor contain nearly 120 Mt. Nevertheless, the lack of knowledge of this type of deposit and the difficulties, both environmental and technological, make them unexploitable under present conditions (Shedd 2017)[3].

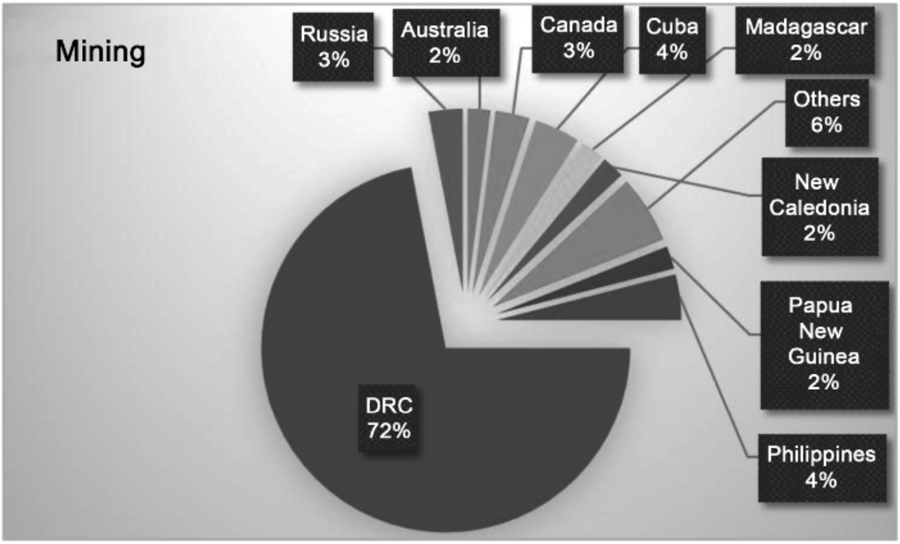
### 1.2.2. *Production and actors*

In 2018, cobalt mine production (see Figure 1.1) came mainly from the Democratic Republic of Congo (72% of production), while the EU had a small presence (1% of world production in Finland) (Alves Dias *et al.* 2018). Recent years have also seen the emergence of new players such as Madagascar, the Philippines, and Indonesia through nickel mining, while New Caledonia and Papua New Guinea are gaining momentum (Darton Commodities 2019; WMD 2019). When world production reached 140 kt in 2018, Glencore produced around 30 kt tons through four mines (Katanga and Mutanda in the Democratic Republic of Congo, Murin-Murin in Australia, and Sudbury in Canada), while seven Chinese companies (including China Molybdenum, Huayou Cobalt, Jinchuan, etc.) produced approximately 46 kt tons, mainly in the Democratic Republic of Congo through property buyouts or equity investments in projects. Companies such as Vale (Brazil), Implats (South Africa), Nornickel (Russia), ERG (Kazakhstan), Managem (Morocco), and Sumitomo (Japan) shared the rest of the market (Darton Commodities 2019).

Approximately 126 kt of refined cobalt was produced in 2018 (see Figure 1.1), with China accounting for 65% of this production through companies such as Huayou Cobalt, Jinchuan Group, GEM, and Ganzhou Yi Hao. Europe is the second largest player in this segment, producing approximately 15% of the total in Finland at Kokkola (formerly Freeport MacRoan, now Umicore, 12%), in Belgium (Umicore, 1%) and at the Nikkelverk refinery in Norway (Glencore, 3%). It should be noted that the French company Eramet produces a few tons of cobalt from the processing of nickel mattes[4] at the Sandouville plant.

3 Resources and reserves represent “all known deposits that could be exploited when technical and economic conditions permit” and “the share of resources that can be technically and, above all, economically exploited”, respectively (Geldron 2017).

4 The Co production figures held by Eramet are unclear. Darton Commodities and Roskill indicated a few hundred tons in 2017 and 2018, but Eramet’s reference document does not mention this. Elementarium gave the figure of 48 tons of Co contained in cobalt chlorides in 2018. There would have been no production in 2017 due to the restructuring of the production line to process Finnish mattes.

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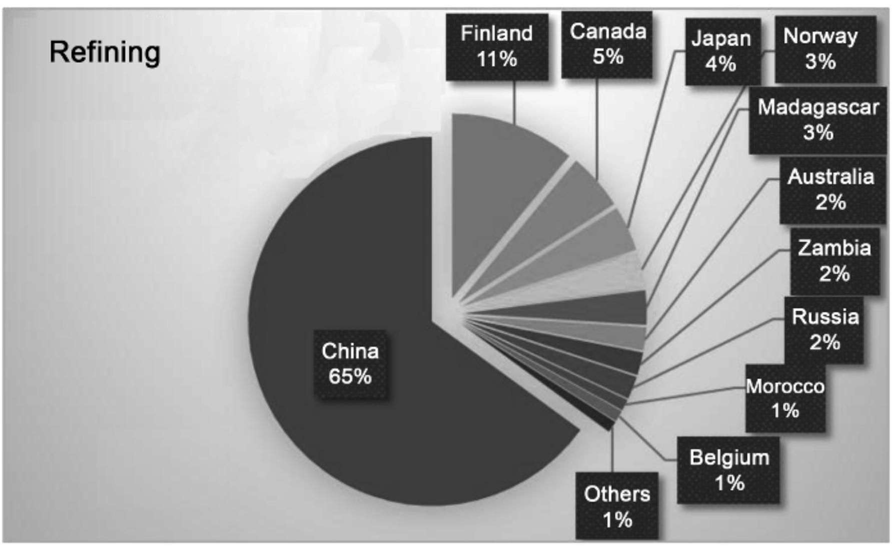



b)

**Figure 1.1.** *Cobalt mining and refining in 2018 (based on Darton Commodities (2019))*

Cobalt production has more than doubled in ten years from 59.6 kt in 2009 to 126 kt in 2018 (Shedd 2010, 2019). The consumption of cobalt has also changed significantly, with 34% of cobalt used in batteries in 2009 and 54% ten years later. Superalloys (aircraft engines and turbines for power plants) and cemented carbides (tungsten carbides, cutting tools, etc.) were still the second and third largest consumers of cobalt in 2018, although their share had decreased (see Figure 1.2).

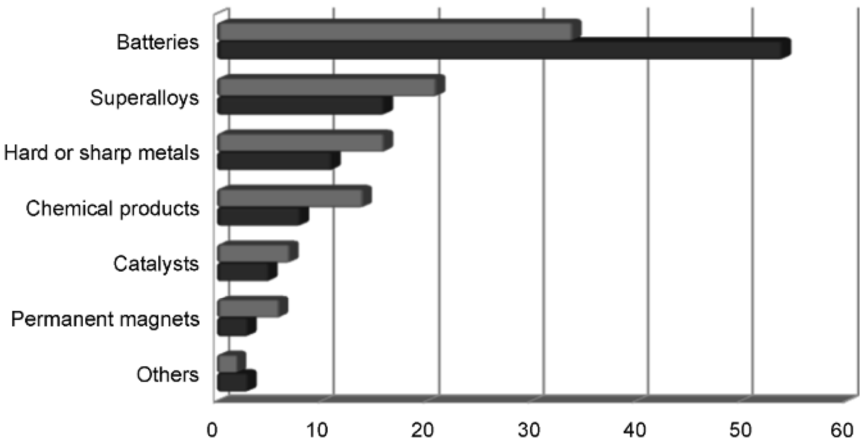



**Figure 1.2.** *Change in cobalt consumption between 2009 and 2018 (%) (based on Roskill (2016); Darton Commodities (2019))*

In 2013, the United Nations Environment Programme (UNEP) estimated that the end-of-life (EOL) recycling rate for cobalt reached 68% (Reuter *et al.* 2013). However, this figure is debatable since, as we shall see later, batteries are rarely collected and recycled, superalloys are not systematically functionally recycled[5], and dissipative uses (chemicals) cannot be recovered. For their part, Roskill (2017) and Darton Commodities (2018) indicated that the quantity of cobalt recycled was between 10% kt and 15 kt per year, that is between 10 and 15% of world consumption. This corresponds to another method of calculation, the consumption of recycled cobalt over total consumption (recycling input rate or RIR). In 2015, Deloitte gave an RIR of 35.5% for the EU. However, this was the share of recycling at all levels of the value chain (mine tailings, production offcuts, etc.) and not just end-of-life recycling. Finally, Harper *et al.* (2012) gave an EOL recycled content (RC) of 22%, adding 10% degraded recycling, or 68% cobalt lost from all end-of-life products containing it.

5 "Functional recycling is the part of end-of-life product recycling in which metals are separated and sorted to obtain recycled materials that can be used in the manufacturing process of a metal or alloy" (Centre national de la recherche scientifique 2016).

There are, therefore, several ways to calculate and understand the recycling rate, the figures of which are sometimes used without the necessary understanding of their meaning.

### 1.2.3. *A market undergoing profound change*

The last 20 years have seen a profound transformation of the cobalt market, both in the redistribution of its production and consumption. The Democratic Republic of Congo, which produced only 20% of cobalt in 2000 and 40% in 2009, now extracts 72%. China, which refined only one third of cobalt in 2009 (20 kt), has almost quadrupled its capacity (72.5 kt). China's rise in the cobalt value chain has also resulted in several asset acquisitions by Chinese companies, including China Molybdenum's acquisition in 2016 of the world's second largest cobalt mine, Tenke Fungurume (TFM). Refined production increased fivefold, while batteries accounted for more than half of consumption. This change in the market is leading to an in-depth transformation of refined cobalt production as the production of battery chemicals (sulfates) replaces cobalt metal. In 2019, the latter accounted for 70% of refined cobalt production (for more details on the different types of refined products, see Figure 1.3).

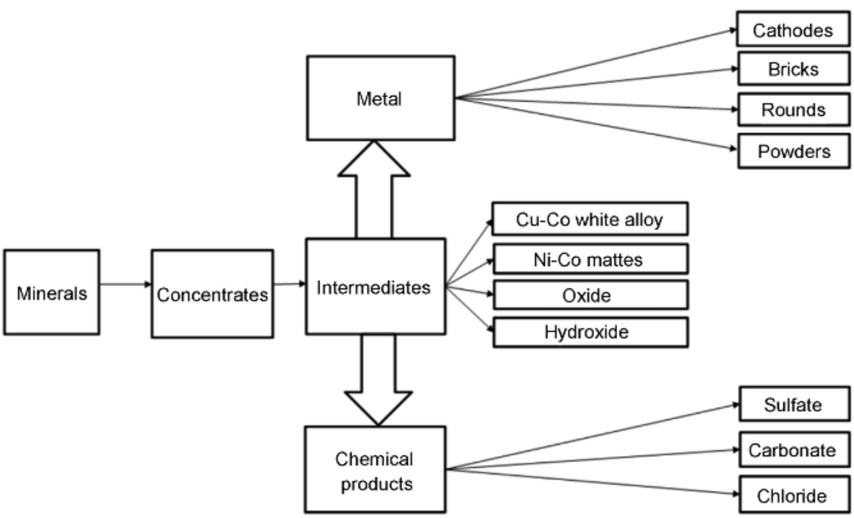



**Figure 1.3.** *Production of refined and semi-refined cobalt, by product type (according to Aurélie Gaudieux (BRGM))*

As a sign of its importance to the world economy, cobalt has been listed on the London Metal Exchange (LME) since 2010 to improve the transparency of its market and allow commercial players to hedge against price variations. After its price was stabilized at around $33,000 per ton in early 2017, cobalt reached its highest level in March 2018 ($95,000 per ton) and dropped to $55,000 per ton at the end of 2018 and $24,000 in April 2019. However, futures allowing for the quotation of cobalt use aircraft-grade cobalt cathode as the underlying asset (99.8% purity), given the extent of its past use. The increasing use of cobalt sulfate in batteries makes the quotation mechanism less relevant since the exchanges are made on chemicals and intermediate products (cobalt mattes, oxides, hydroxides, etc.) for further processing. The opacity of prices and quantities therefore persists.

## 1.3. A method combining value chain analysis and material flow analysis

Studying the cobalt market requires a combination of two complementary methods – analysis of its value chain and analysis of material flows. To our knowledge, few authors have explicitly addressed the combined use of these two methodologies. A value chain analysis integrates the quantities produced and the products manufactured, whereas an MFA is based on the different stages of production of an element. These two methodologies have a common basis – the lifecycle of a component or product – from which they draw inspiration to define segments and linkages, flows, and stocks (Dahlström and Ekins 2006; Nuss and Bengini 2018). Value chain analysis focuses on analyzing an object, in this case the market for cobalt, its supply and demand structures, and its stakeholder strategies. It aims to study the creation of value throughout the process of transformation and distribution of a product, from the raw material to the final product. For its part, the MFA highlights the object of the analysis as such and therefore the origins and destinations of the flows, their constitution in different types of stocks, as well as their quantities and their future. It completes the analysis of the value chain by quantifying it while drawing inspiration from the latter's work to understand the evolution of stocks and flows of certain products (Gereffi *et al.* 2005; Dahlström and Ekins 2006; Machacek *et al.* 2017). Many authors are interested in these interactions between actors and materials. Thus, Saurat and Bringezu (2008, 2009) analyzed the constraints encountered by platinoid producers with regard to energy and pollution, while Mudd (2010) showed the determination of the industrial processes of nickel processing by the geological characteristics of the ores. For their part, Schmidt *et al.* (2016) have researched nickel and cobalt extraction and processing sites to analyze their impacts on the production of lithium batteries.

### 1.3.1. *Value chain methodology*

#### 1.3.1.1. *Value chain and competitiveness*

The concept of the value chain emerged from Wallerstein and Hopkins's (1977) work on primary commodity chains within "world systems" as well as from supply chain research (Dubois *et al.* 2004). Michael Porter created this concept in the context of globalization and increasing competition between developed and developing countries. In his mind, the value chain was to be a strategic tool for understanding and improving the competitive advantages of a company's three components: costs, organization, and technology. The acquisition of information, its analysis, and its application are the central elements of this tool to gain this competitive advantage (Porter 1985).

The value chain is nested within what Porter calls a multi-link value system. Indeed, the different activities within a given segment as well as the support functions are intralinked activities, unlike those between the different activities of a value chain, which are interrelated (Kaplinsiky and Morris 2001). Thus, the raw material extraction function is part of the battery value system, but is itself a value chain. A company can also operate on a single segment of a chain (horizontal operation) or on several segments (vertical operation) (Kogut 1985) (see Figure 1.4).

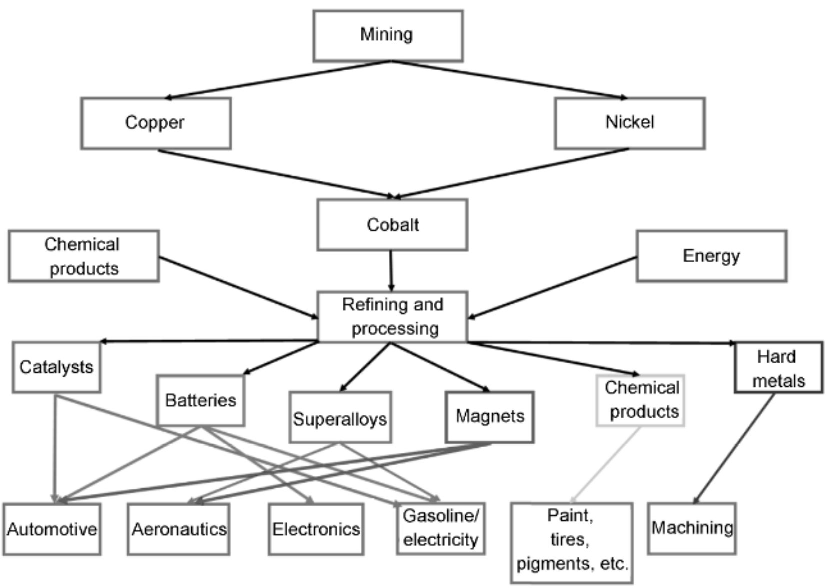



**Figure 1.4.** *Multi-linked cobalt value chain. For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

While corporate competitiveness is the central theme of Michael Porter's argument, he does not lose sight of the fact that nations are the main actors in the international system and that they are in economic competition with each other. While the firm creates the economic and strategic value, the nation must somehow give it the competitive advantage by offering it good conditions for development (Porter 1990). Analyzing the rare earths value chain, Machacek and Fold (2014) confirmed the central role of the state in its development.

### 1.3.1.2. *The value chain as a tool for economic development*

A process of disintegration of global value chains has been observed over the last few years (Gereffi *et al.* 2005). Indeed, companies have concentrated on their core competencies by outsourcing support functions or segments that are less economically profitable. For his part, David Humphrey (1995, 2010, 2013) noted this fragmentation in the mining sector, a consequence of the nationalization processes resulting from decolonization and then of the structural adjustment policies provoked by the raw materials crisis at the end of the 1970s. While it was the rule that refining plants and mines were located in the same geographical area under the same owner, the privatization of assets focused on the most lucrative segments, namely refining and processing (especially in Africa), while many mines, considered less profitable and riskier, remained state owned. The political-economic situation of the states concerned has been a decisive factor in the problem, their instability discouraging potential investors, most of whom are Western. However, the arrival of new Asian and Middle Eastern players has led to a new transformation of the metal industry (Machacek *et al.* 2017).

In a framework of economic development policy, Gereffi and Korzeniewicz (1994) considered value chain analysis as a tool for economic development. After an analysis of the value-added activities of a chain, the authors considered it necessary to focus on the actors and their capacities to appropriate this value even though production is geographically dispersed. This naturally raises the question of chain governance, which can take place at several levels (executive, legal, or legislative) and bring together actors from different horizons (companies, governments, NGOs, etc.) (Humphrey and Schmitz 2001).

While the two visions converge on the analysis of actors' strategies as an integral part of the analysis of value chains, Gereffi and Korzeniewicz (1994) add the notion of added value, linked to the technological mastery of different levels of production.

The latter is illustrated in Figure 1.5 and Table 1.1 (section 1.6), which show that the most advanced products, cobalt cathodes, powders, commercial oxides, and alloy parts (cobalt oxides and hydroxides, or products from cobalt matte flow and other cobalt metallurgy products) are also the most expensive and, therefore, the most value-creating. The degree of purification of cobalt is no longer the sole determinant of added value. This is also the case for the industry's ability to transform it into semi-finished and finished products, thanks to the mastery of specific and sophisticated technological processes.

On the other hand, the less advanced intermediate or primary products (nickel-based products, waste and scrap, certain products from the cobalt matte stream, and other cobalt metallurgy products, as well as ores and concentrates) are also the least expensive.

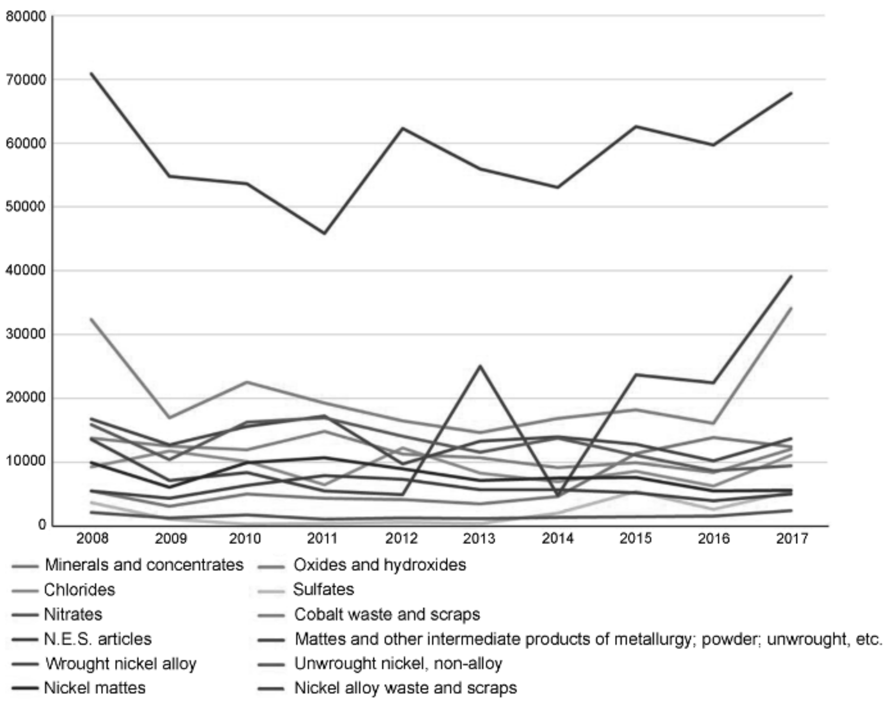



**Figure 1.5.** *Changes in import prices of intermediate products and refined products containing cobalt; 2008–2017 period (based on Eurostat (dollars)). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

### 1.3.2. *Material flow analysis, for a better understanding of cobalt demand*

#### 1.3.2.1. *Origins and characteristics of material flow analysis*

The origin of the MFA can be traced back to the work of a Paduan physician, Santoro Santoro, in the 17th century, whose aim was to measure human metabolism (Brunner and Rechberger 2004). It was, therefore, originally a tool used by the experimental sciences, as underlined by its constant analogy with biology, the MFA wanting to measure the metabolism of given spaces and in particular anthropogenic cycles (Allenby and Cooper 1994; Chen and Graedel 2012). Thus, the objective of an MFA is akin to examining anthropogenic stocks and flows of material materials at each level of their lifecycle in order to gain a better understanding of their status above ground (Nuss and Bengini 2018). In fact, it has a multidisciplinary vocation because human activities are placed in a larger ecosystem that supports them, notably through the flows of materials and energy that result from them. They must be measured against the political, social, and economic factors that underlie them, but also through their impacts on the environment (Lifset and Graedel 2002).

MFA can be useful in economics because it allows for the incorporation of environmental or resource-related data into economic models (Fischer-Kowalski *et al.* 2011) or for measuring the impact of the economy on the environment (Ayres and Kneese 1969). MFA is also a tool with a geographical vocation, since it is necessary to determine its limits or boundaries, both territorial and between natural and political-economic systems (Fischer-Kowalski *et al.* 2011). This is why it can be used to measure the metabolism of a city (Wolflman 1965), an industry (Ayres and Simonis 1994), an economy (Fischer-Kowalski *et al.* 1998), or an anthroposphere (Baccini and Brunner 1991).

Several terms exist to qualify this methodology. While “MFA” is a generic term that we will continue to use throughout this chapter, substance flow analysis (SFA), applied to an element (chemicals or metal), or the analysis of a material in a system (AMS) are also concepts used (Stanisavljevic and Brunner 2014). In addition, two types of MFA are possible: dynamic when it integrates the temporal variation of flows and stocks (import, export, products, recycling, etc.), taking into account the lifetime of products in use (Guyonnet *et al.* 2014), or static (Müller *et al.* 2014). Thus, an MFA of cobalt carried out between 2008 and 2017 implies the use of commercial data up to 2000, since some products have a lifespan of eight years. This methodology also has to cope with certain constraints such as mass balance (what goes in at one place must come out somewhere or be stored) or model delineation and many uncertainties regarding the data incorporated in the models due to the lack of knowledge on flow compositions and their characteristics. Confrontation with other sources and discussions with experts are therefore necessary.

#### 1.3.2.2. *MFA steps*

Three steps are important to build an MFA and we will illustrate them by presenting the choices made for cobalt.

The first stage involves the selection of the product to be studied, while the second is concerned with the delineation of the study's scope and the third with the collection of the data required to conduct the study. Cobalt, a little-known metal subject to tension and essential for the energy transition, has emerged as a logical choice to conduct an MFA study. Moreover, despite numerous uncertainties about some data, it is a metal for which the quantities consumed are sufficiently large to provide quantified information. Thus, 140,000 tons were extracted in 2018 (according to the USGS), much more than gallium, germanium, or beryllium. Analyzing the state and evolution of stocks and flows, as well as the potential of the urban mine, is also an objective that has been built up gradually, in order to identify vulnerabilities and opportunities for the EU in the cobalt value chain. At the same time, the choice of the EU as a geographical border appeared logical since, apart from the MFA carried out by Deloitte for the year 2012, no MFA of cobalt had been carried out *a fortiori* dynamically and over several years, as we do for the period 2008–2017. We have chosen to deal only with flows entering and leaving the European Union and not with flows exchanged within the European Union by its members. This would have made the model more complex without adding value to the objectives. Finally, the data used for the MFA had to be sought and chosen. The Eurostat trade database provided the flows while several sources were used to estimate the quantities of cobalt contained in primary and refined flows, products, and waste.

A review of these tables shows that many elements are missing, particularly with regard to loss management throughout the process. We know, for example, that some occur during the manufacture of batteries, but we do not know the quantities. Concerning the cobalt content, certain rates had to be calculated from ranges reported in several documents, such as those for nickel and cobalt alloys, nickel and cobalt scraps, as well as the cobalt contained in aircraft engines or turbines for gas power plants. Finally, we have chosen to calculate the quantities of cobalt contained from fixed rates as Harper *et al.* (2012) did for cobalt in 2012 and tungsten in 2005 (Harper and Graedel 2008). Thus, several rates were available for cobalt ores and concentrates (Harper *et al.* 2012; Hannis *et al.* 2009; RMSA 2015; Darton Commodities 2018; Shedd 2019) or oxides and hydroxides (Roskill 2017; Darton Commodities 2018; Shedd 2019).

## 1.4. Results of and discussions on cobalt flow analysis in the European Union

This section discusses the results and limitations of the material flow analysis (see Figure 1.6). The analysis of the results deals with the evolution of flows, stocks, EU suppliers, and their significance in terms of value. Then, through several examples, the difficulties encountered and the choices made to de-emphasize them are discussed.

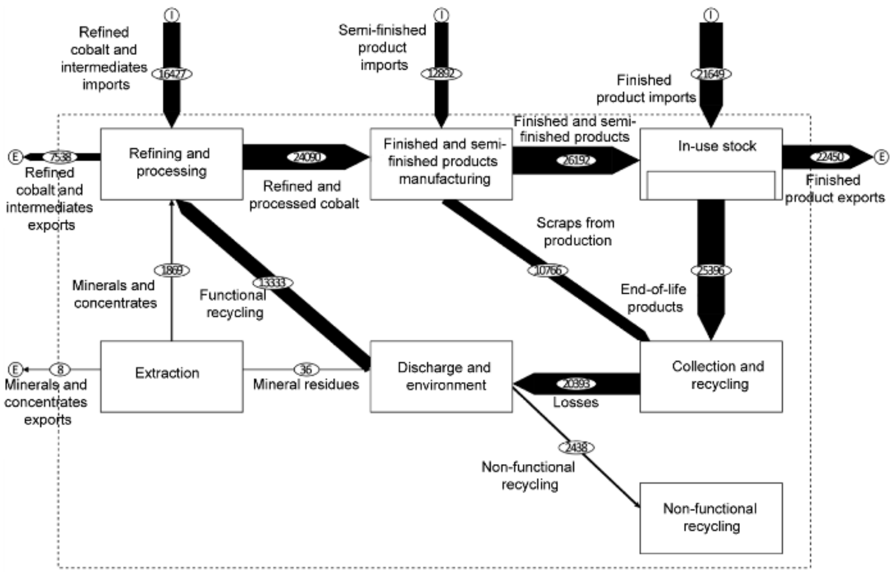



**Figure 1.6.** *Material flow analysis for cobalt in the EU in 2017 using STAN software (Brunner and Rechberger 2004)*

### 1.4.1. *Changes in flows and stocks: lessons from MFA*

Imports of refined products and finished or semi-finished products showed divergent trends during the 2008–2017 period. In fact, 20,201 tons were imported in 2008 in the form of ores, intermediate products, refined products, waste, and production scraps (23,032–25,396 tons for imports of finished and semi-finished products). In comparison, 16,396 tons were imported in 2017. Decreasing throughout the period, ores and concentrates were largely absent from European imports, while imports of high value-added cobalt items doubled. If the quantity of intermediate products of cobalt metallurgy is decreasing, this is not the case for their average value. Composed of different types of products (oxides, hydroxides, intermediates, concentrates, cathodes, powders, etc.) we see that the average value of products imported through this flow has increased between 2008 and 2017, not only because of the general increase in prices, but also and especially because imported products had a higher value added (disappearance of primary and intermediate products, increase in refined and processed products). While exports increased from 4,699 to 7,656 tons, the distinction is not so clear-cut, since the increase concerned both articles and commercial hydroxides, nickel mattes, or waste and scrap. These last three flows have a value less than half that of the first two (see Figure 1.7).

The amount of cobalt consumed by the European industry decreased from 29,210 tons in 2008 to 25,128 tons in 2017, despite the increase in consumption of products containing cobalt. A study of European manufactured production shows a significant drop in the production of semi-finished products (magnets and batteries), as well as finished products with lower added value (electronics). Production with high added value is either maintained (superalloys) or increased (electrical mobility). The case of the production of batteries and cells is singular. Indeed, while Asia produced more than 90% of the world's battery cells (Pillot 2017), Europe has expertise in their assembly, particularly for electric vehicles (Lebedeva *et al.* 2017) (see Figure 1.8).

The quantities of cobalt entering and leaving in the form of finished and semi-finished products have increased (23,032–25,396 tons for imports, 16,140–20,740 tons for exports). The significance of batteries in both exports and imports is still evident. Without data on this subject, but knowing the structures of the battery industry, it is reasonable to assume that the majority of European imports are in the form of cells and battery components, which are then assembled. Battery exports are mainly niche products for specialized industries, while electric vehicles remain an important export item (see Figure 1.9) (Lebedeva *et al.* 2017).

While Deloitte (2015) estimated the cobalt inventory in the European Union at 20,000 tons in 2012, our analysis leads us to suggest 47,717 tons and 54,195 tons of cobalt in use in 2008 and 2017. In 2008, approximately 30% of the European stock consisted of metal (cemented carbides, superalloys), while it only represented 24% in 2017. Even though the increase in electric mobility is visible (1,200 tons in 2008 versus 9,500 tons in 2017), batteries contained in electronic or household appliances remain the majority (see Figure 1.10).

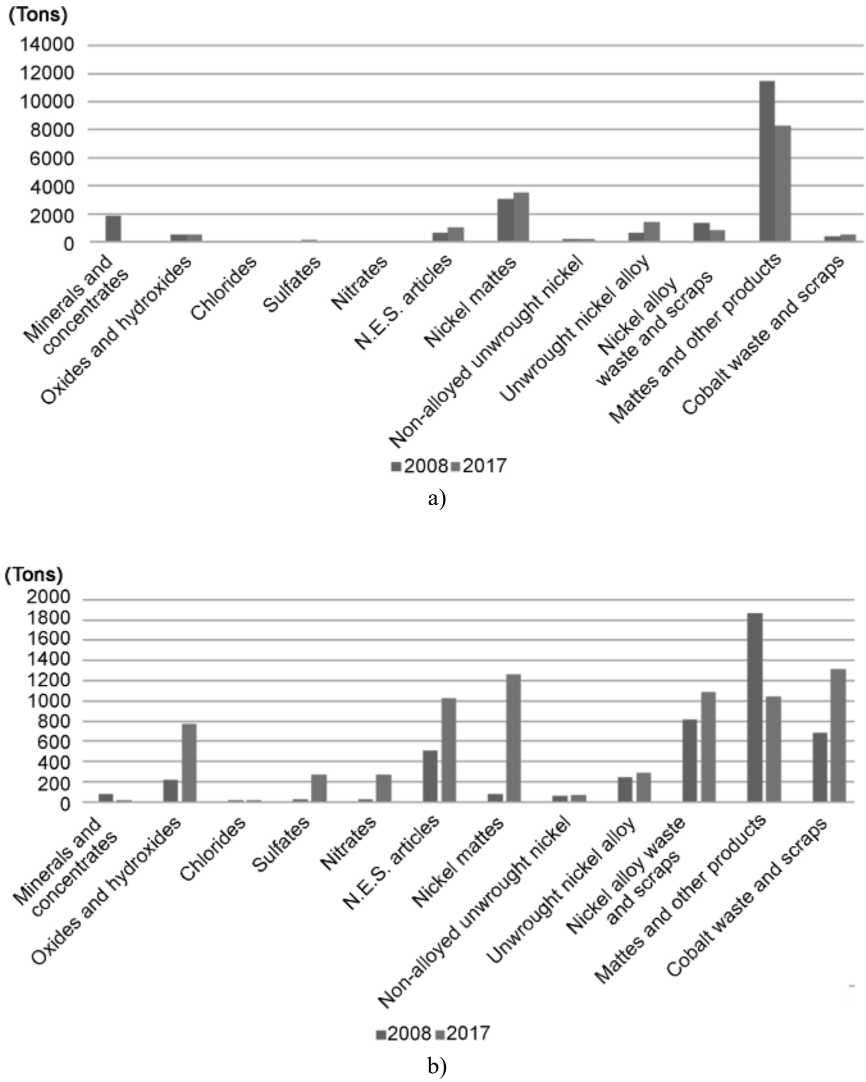



**Figure 1.7.** *Structures of cobalt imports (a) and exports (b) in the form of ores, intermediate products, refined products, waste and scraps for production in the EU, 2008/2017 (tons). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

While exports of cobalt and nickel production scrap and off-cuts increased between 2008 and 2017 (see Figure 1.7), this is not necessarily a good news story for European industry, which simply does not have the industrial or contractual capacity or interest to process them[6]. Furthermore, in 2017, we estimate that 3,532 tons of cobalt were functionally recycled, or about 20% of the end-of-life material. Around 8% was recycled in a degraded manner (1,378 tons) while 72% was lost (12,293 tons). These results are similar to those of Harper *et al.* (2012) and Chen *et al.* (2019). With an RIR of 29.5%, we are below Deloitte's calculation for the European Union in 2012 (34%).

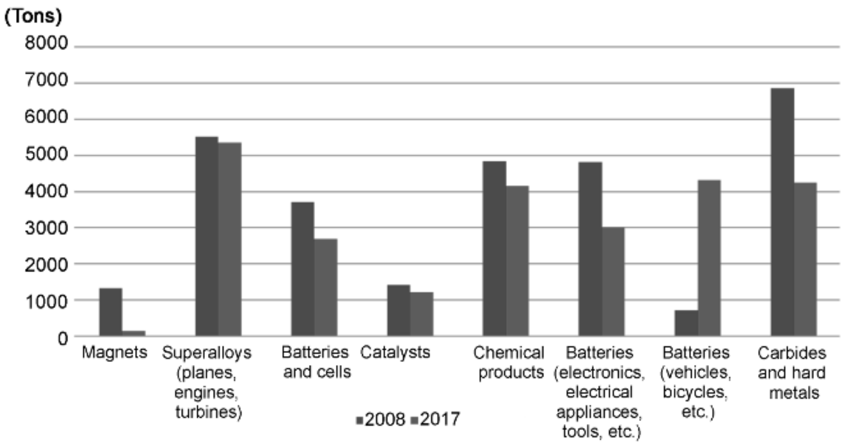


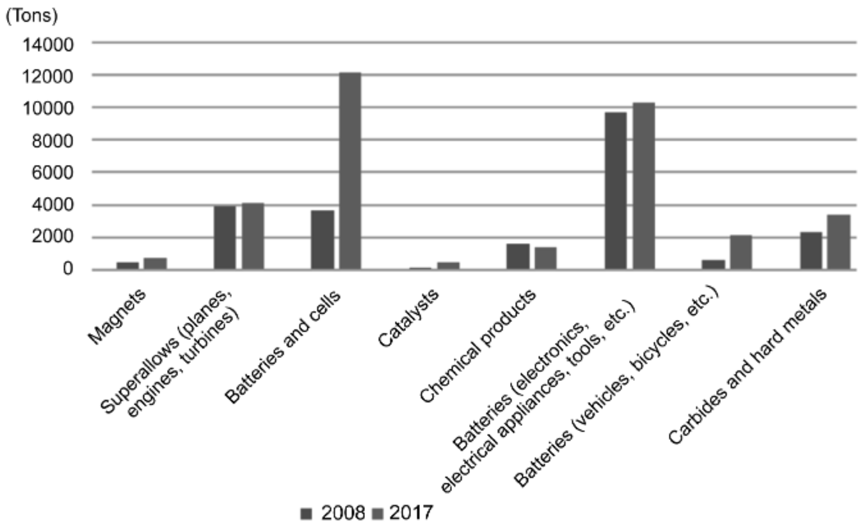

**Figure 1.8.** *Production of finished and semi-finished products containing cobalt in the EU, 2008/2017 (tons). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

Waste management therefore raises questions both in terms of organization and information. For example, production waste and scrap metal are poorly documented. Thus, it is difficult to test their traceability as well as their content; the latter determines whether or not they can be functionally recycled. In the case of the recycling of finished products, there is, for example, an important difference between batteries for electronics and batteries for mobility, both in terms of design and life span and the quantity of metals contained. Collection and recycling are only worthwhile if there is sufficient critical mass to ensure the cost effectiveness of the process.

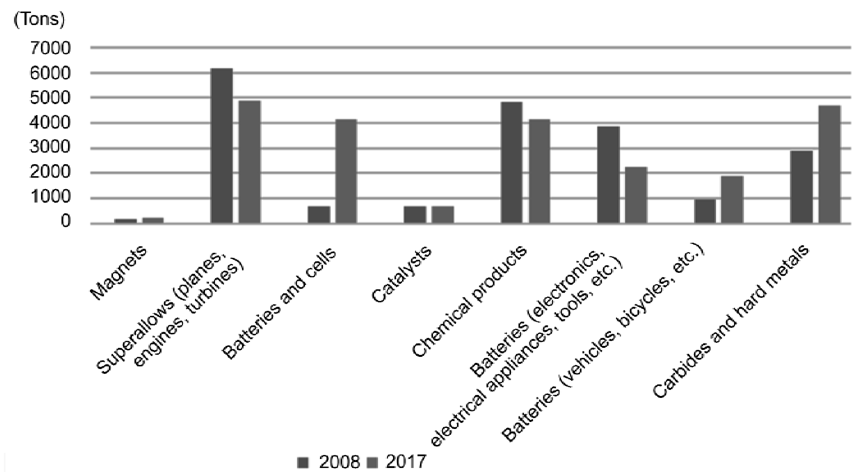
At the moment, due to the battery stock structures in Europe, dominated by electronics with a low collection rate, the recycling system is still too complex. However, the emergence of batteries in electric vehicles by 2020–2025 and the revision of the battery directive in 2021 could accelerate recycling. Also, a solution

6 The market for production scrap containing rare minerals is characterized by return-to-prime-supplier clauses, such as the titanium market (Louvigné 2015).

will have to be found to the volatility of metal prices, which makes any investment in this type of structure uncertain. Better hedging on futures markets could be a solution to this problem (Fizaine 2018).




a)




b)

**Figure 1.9.** *Imports (a) and exports (b) of finished and semi-finished products containing cobalt, 2008/2017 (tons). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

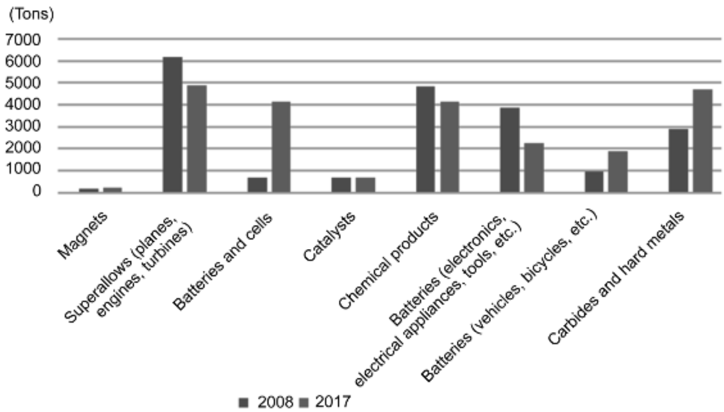



**Figure 1.10.** *"In-use stock" of cobalt, 2008/2017 (tons). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

### 1.4.2. *Value chain partnerships and flow analysis assistance*

The evolution of trade relations between the European Union and its partners in primary, intermediate, and refined products depends on the industrial policies of these different countries. Thus, China has become one of the major players on the cobalt market since the early 2000s, while Madagascar and Mexico have emerged very recently as complementary producers, essential in a strategy of supply diversification. Others, such as Indonesia and the Philippines, are in the process of becoming major producers of nickel with associated cobalt.

These upsurges are often characterized by the implementation of commercial policies that encourage the development of local industry. China has implemented a 25% tax on exports of ores and concentrates, while refined products are taxed little or not at all. Similarly, the Philippines and Indonesia have implemented a quota system on the export of nickel ores that encourages Chinese industries to invest in local processing capacity (Le Gleuher 2017). For their part, the Democratic Republic of Congo and Russia are also looking to move up the cobalt value chain, the former by introducing an export ban on ores and concentrates in 2013, and the latter by building a refinery to produce cobalt ingots (99.5% cobalt content) rather than exporting concentrates to Finland (Roskill 2017; Darton Commodities 2018, 2019). A few years after the Congolese decision, an analysis of Congolese production and exports shows that the Democratic Republic of Congo exports few ores but more intermediate products, such as white alloys and cobalt hydroxides. Russia on the other hand no longer exports concentrates, but ingots and intermediate products (mattes and other nickel-based products).

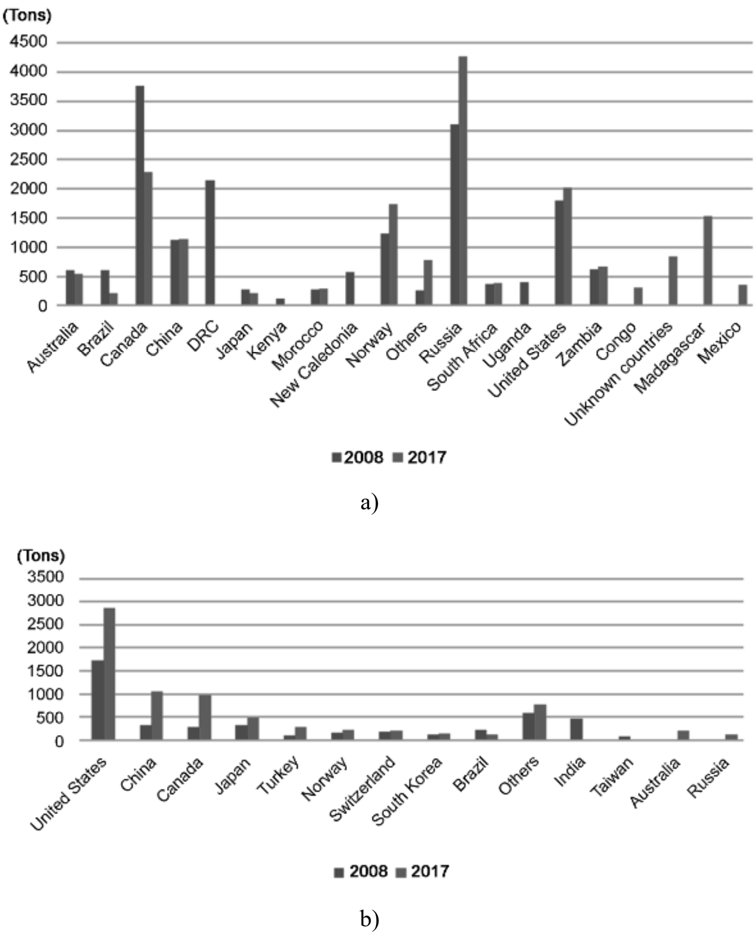



**Figure 1.11.** *Main EU suppliers (a) and customers (b) for primary, intermediate, and refined products, 2008/2017 (tons). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

In terms of exports, we can note that the four major customers of the European Union are industrialized countries, which confirms the higher value of European exports. On the other hand, in terms of imports, the Democratic Republic of Congo, Brazil, Kenya, and Uganda are no longer among the European Union's major suppliers for various reasons (see Figure 1.11). Brazil, for example, has been hit hard by the decline in the price of nickel and has reduced or stopped production, which has inevitably influenced the production of cobalt. Uganda, on the other hand, stopped producing cobalt due to the depletion of its stocks based on the mining of

Kilembe tailings. Ugandan production could resume in the coming years, but it will be based on copper mining. For its part, the Democratic Republic of Congo now supplies very little cobalt to the European Union (64 tons in 2017). This state of affairs could be the consequence of two different European policies: one a policy of sanctions against Congolese leaders because of human rights violations and the other more coercive on transparency and responsible cobalt production, linked to the European policy on “blood minerals“. However, beyond the lack of data to confirm its assertions, Congolese production transits through certain countries, including Norway, where Glencore has a refinery, which tends to qualify the previous observation.

Understanding the value chain of cobalt-producing countries such as Australia, Canada, Russia, and New Caledonia helps to understand the type of products they can export and their cobalt content. Al Barazi (2018), for example, gave an estimate of the cobalt content of nickel mattes, depending on the country and the type of original ore. He also highlighted the type of products manufactured by the Canadian and Australian mining industries (cathodes or briquettes, 99.5% cobalt content), which allows for a fair analysis of the supplies of these two countries in the flow of “cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; cobalt powder”, which contains several types of products of different values, without mentioning them.

The lack of data concerning the cobalt content, the imprecision of certain sources, and sometimes even their excessive variety, was a real challenge for the creation of an MFA. This was particularly true for the flow of “cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; cobalt powder”. As we have shown for some flows (cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; cobalt powder; as well as the various chemicals containing cobalt), the data for cobalt content were missing, and so they had to be estimated on the basis of assumptions derived from the literature. Some insertion errors in the databases were also found. Between quantities that are sometimes too large to be accurate (cobalt chloride for 2013 and 2014 imported by Denmark) and the lack of clarity and consistency in the indicators (carbides by weight, in kilograms, in tons, or in pieces?), the consequences on the calculation of flows can be significant. Uncertainty about the data led us to choose set limits for the calculation of cobalt content, lifetimes, or recycling rates, rather than variable limits. In our opinion, the latter choice would have made the calculation more complex without necessarily giving additional guarantees in terms of the veracity of the results. This was notably the case for concentrates and cobalt ores with contents ranging from 3% to 10% (Hannis *et al.* 2009; Darton Commodities 2019) or hydroxides ranging from 20% to 72% (Darton Commodities 2019; Shedd 2019).

Further down the value chain, there was a lot of information about the cobalt content of batteries, but barely applicable through the use of Eurostat trade statistics.

Indeed, while the data in the literature provided the amount of cobalt contained per piece or per kilowatt-hour (Kwh) (Buchert *et al.* 2011; Harper *et al.* 2012; Nordic Council of Ministers 2015; Pillot 2017), Eurostat only provides quantities in tons or hundreds of kilograms. Similarly, the database does not indicate the type of batteries (NMC, NCA, LCO, etc.) present in the flows. Concerning the recycling of superalloys, only Shedd (1993) gives useful information on the subject, which was confirmed to us by discussions with professionals. In view of the lack of information available for chemicals, we decided to divide the flows into two: the cobalt and titanium sulfate flows and the barium, beryllium, cadmium, cobalt, nickel, and lead nitrate flows. In the same way, it was not possible to calculate precisely the amount of cobalt contained in manufactured products or imported and exported products. When in doubt, we used data from Deloitte (2015), which indicated that 17% of the cobalt end products manufactured in the European Union were chemicals, as were 7% of the products consumed.

## 1.5. Conclusion

This MFA of cobalt for the European Union made it possible to identify methodological points and interesting results. First of all, the analyses of value chain and material flows seem to be complementary and allow for a better understanding of stocks, flows, and their evolution through a global vision of the strategies of actors and market transformation. Beyond the strictly quantitative results, MFA also revealed the qualitative aspect of stocks and flows: types of products, types of suppliers, and their evolutions. Through their analyses, we also see that the European industry is increasingly focusing on high value-added segments, which still raises some questions about its industrial strategy. Indeed, activities upstream in the value chain (e.g. extraction, refining, etc.) are decreasing while downstream activities are increasing, which places the European Union in a situation of dependence both in terms of resources for cobalt and battery technologies. This is particularly visible in the recycling segment, which is struggling to take off despite its growing importance and the growing number of questions about it. While there is some interest in the former urban mine operation, transforming the status of waste into a resource, we are still far from its optimal use, in particular because of the many uncertainties as to the revenues from such processes. As shown by the numerous customs barriers on the export of waste of different metals (OECD 2014), waste is gradually becoming a strategic resource but still has little economic value.

Finally, an examination of the evolution of the European Union’s trading partners does not make it possible for us to observe, to a certain extent, the effectiveness of the industrial policies pursued in different countries or, conversely, to illustrate the limits they encounter. The case of the Democratic Republic of

Congo demonstrates this clearly. Despite the development of high taxation and tariff barriers, the country is struggling to gain ground because of its overly limited infrastructure and a corrupt political-administrative system. The presence of Russia as the European Union's leading supplier of cobalt also raises the question of the relationships that the latter can establish with its partners. In fact, despite the obvious tensions between the two and the policies of reciprocal trade sanctions, for several years now the latter have not concerned the supply of cobalt as much as other metals such as titanium. It is not for us to answer this question in this chapter; however, this situation illustrates the ambiguities linked to such dependence on a country with which there is no shortage of points of conflict.

## 1.6. Appendix: quantities of cobalt contained in primary and refined streams, recycling rates, and cobalt waste management

| Nomenclatures | Products | Cobalt content (average) |
|---|---|---|
| HS 26 05 00 | Cobalt concentrates and ores | 7% |
| HS 28 22 00 | Cobalt oxides and hydroxides | 72.9% |
| HS 28 34 29 20 | Barium nitrate, beryllium, cadmium, cobalt, nickel, and lead | 22.5% |
| HS 28 27 39 30 | Cobalt chloride | 26.6% |
| HS 28 33 29 30 | Cobalt and titanium sulfate | 26.9% |
| HS81 05 30 00 | Cobalt waste and scrap | 37%[7] |
| HS 81 05 20 00 | Cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; cobalt powder | 3%–99%[8] |
| HS 81 05 90 | Cobalt, N.E.S. articles | 99%[9] |
| HS 75 03 00 90 | Nickel alloy wastes and scraps | 7% |
| HS 75 01 | Nickel mattes | 1%–5% |
| HS 75 02 10 00 | Nickel alloy, not forged | 0.5% |
| HS 75 02 20 00 | Non-alloyed and non-forged nickel | 1.5% |

**Table 1.1.** *Cobalt contained in primary and refined flows (%)*[10]

7 Personal calculations based on Shedd (1993), Audion *et al.* (2013); Roskill (2017), Al Barazi (2018), Alves Dias *et al.* (2018), Darton Commodities (2018), Ladenberger *et al.* (2018), and the European Commission (2019).

8 Personal calculations based on the origin and prices of flows as well as Roskill (2017), Al Barazi (2018), and Darton Commodities (2018).

9 Personal calculations based on flow prices.

10 According to Shedd (1993) Audion *et al.* (2013), Roskill (2017), Al Barazi (2018), Alves Dias *et al.* (2018), Darton Commodities (2018), Ladenberger *et al.* (2018), and the European Commission (2019).

| Products | Cobalt content (average) | Service life (years) |
|---|---|---|
| Superalloys | 250 kg/piece | 5 |
| Cemented carbides | 11% | 1 |
| Hard or sharp metals | 11% | 3 |
| Catalysts | 2.75% | 5 |
| Electronic batteries: nickel-cadmium (Ni-Cd) | 1% | 3 |
| Electronic batteries: nickel-metal hydride (NiMH) | 3% | 3 |
| Electronic batteries: lithium-ion (LIB) | 9% | 3 |
| Batteries (transport) | 30% | 8 |
| Magnets (AlNiCo, Sm-Co) | 24.5%–66% | 5 |
| Chemical products | No data | 1 |

**Table 1.2.** *Cobalt contained in manufactured product flows*[11]

| Products | Collection rates | Functional recycling | Degraded recycling | Untreated |
|---|---|---|---|---|
| Superalloys | 100% | 50% | 30% | 20% |
| Cemented carbides | 100% | 15% | 75% | 10% |
| Hard metals | 100% | 55% | 20% | 25% |
| Catalysts | 90% | 75% | No data | 32% |
| Electronic batteries | 10% | 80% | No data | 92% |
| Batteries (transport) | 80% | 80% | No data | 64% |
| Magnets | No data | 10% | 6% | 84% |
| Chemical products | 0% | 0% | 0% | 0% |

**Table 1.3.** *Recycling rates for manufactured products containing cobalt*[12]

11 According to Shedd (1993), Buchert *et al.* (2011), Harper *et al.* (2012), Graedel *et al.* (2015), Roskill (2017), Huisman *et al.* (2017), and Ladenberger *et al.* (2018).

12 According to Shedd (1993), Harper *et al.* (2012), Blandin (2015), Roskill (2017), and Heelan *et al.* (2016).

| Products | Wear and tear losses | Falls | Collection | Recovery | Degraded recycling | Untreated |
|---|---|---|---|---|---|---|
| Superalloys | No data | 66% | 70% | 70% | 20% | 10% |
| Cemented carbides | 16% | 5% | 35% | 100% | No data | No data |
| Metals | 16% | 5% | 35% | 100% | No data | No data |
| Catalysts | 6% | No data | No data | No data | No data | No data |
| Batteries (electronics and transport) | No data | No data | No data | No data | No data | No data |
| Magnets | No data | No data | 10% | No data | No data | No data |
| Chemical products | 100% | 0% | 0% | 0% | 0% | 0% |

**Table 1.4.** *Management of losses during the manufacturing process*[13]

## 1.7. References

Al Barazi, S. (2018). Rohstoffrisikobewertung: Kobalt. Document, Deutsche Rohstoffe Agentur (DERA), Berlin.

Allenby, B.R. and Cooper, W.E. (1994). Understanding industrial ecology from a biological systems perspective. *Environmental Quality Management*, 3(3), 343–354.

Alves Dias, P., Blagoeva, D., Pavel, C., Arvanitidis, N. (2018). Cobalt: Demand-supply balances in the transition to electric mobility. Report, Publications Office of the European Union, Luxembourg.

Asari, M. and Sakai, S.I. (2013). Li-ion battery recycling and cobalt flow analysis in Japan. *Resources, Conservation and Recycling*, 81, 52–59.

Audion, A.S., Hocquard, C., Labbé, J.F., Dupuy, J.J. (2014). Panorama mondial 2013 du marché du cobalt. Report, Bureau des recherches géologiques et minières (BRGM), Orléans.

Ayres, R.U. and Kneese, A.V. (1969). Production, consumption and externalities. *American Economic Review*, 59(3), 282–296.

Ayres, R.U. and Simonis, U.E. (1994). *Industrial Metabolism: Restructuring for Sustainable Development*. United Nations University Press, Tokyo.

Baccini, P. and Brunner, H.P. (2012). *Metabolism of the Anthroposphere: Analysis, Evaluation, Design*, 2nd edition. The MIT Press, Cambridge.

13 According to Shedd (1993).

Berthoud, F., Bihouix, P., Fabre, P., Kaplan, D., Ducasse, A., Lefèvre, L., Monnin, A., Ridoux, O., Vaija, S., Vautier, M., Verne, X., Efoui-Hess, M., Kahraman, Z., Ferreboeuf, H. (2018). Lean ICT : pour une sobriété numérique. Report, The Shift Project, Paris.

Bihouix, P. and de Guillebon, B. (2010). *Quel futur pour les métaux ? Raréfaction des métaux : un nouveau défi pour la société*. EDP Sciences, Les Ullis.

BIO by Deloitte (2015). Study on data for a raw material system analysis: Roadmap and test of the fully operational MSA for raw materials. Prepared for the European Commission, DG GROW.

Blandin, M.C. (2016). 100 millions de téléphones portables usagés : l'urgence d'une stratégie. Rapport d'information fait au nom de la mission d'information n° 850 sur l'inventaire et le devenir des matériaux et composants des téléphones mobiles. Report, Sénat, Paris.

Brunner, P.H. and Rechberger, H. (2004). *Practical Handbook of Material Flow Analysis.* CRC Press, Boca Raton.

Buchert, M., Jenseit, W., Merz, C., Schüller, D. (2011). Verbundprojekt: Entwicklung eines realisierbaren recycling-konzepts für die Hochleistungsbatterien zukünftiger Elektrofahrzeuge – LIBRI. Teilprojek: LCA der Recyclingverfahren. Report, Öko-Institut, Darmsatdt.

Centre national de la recherche scientifique (2016). Le recyclage des métaux [Online]. Available at: https://ecoinfo.cnrs.fr/2014/09/03/3-le-recyclage-des-metaux/ [Accessed 31 August 2019].

Chen, W. and Graedel, T.E. (2012). Anthropogenic cycles of the elements: A critical review. *Environmental Science and Technology*, 46(16), 8574–8586.

Chen, Z., Zhang, L., Zu, Z. (2019). Tracking and quantifying the cobalt flows in mainland China during 1994–2016: Insights into use, trade and prospective demand. *Science of the Total Environment*, 672, 752–762.

Dahlström, K. and Ekins, P. (2006). Combining economic and environmental dimensions: Value chain analysis of UK iron and steel flows. *Ecological Economics*, 56, 507–519.

Darton Commodities (2019). Cobalt market review 2018–2019. Report, Darton Commodities Ltd, Guildford.

Dubois, A., Hulthén, K., Pedersen, A.C. (2004). Supply chains and interdependence: A theoretical analysis. *Journal of Purchasing & Supply Management*, 10(1), 3–9.

European Commission (2008). Initiative "matières premières" – répondre à nos besoins fondamentaux pour assurer la croissance et créer des emplois en Europe. Report, Commission au Parlement et au Conseil, Brussels.

European Commission (2019). Critical raw materials [Online]. Available at: http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_fr [Accessed 31 August 2019].

European Commission (n.d.a). Policy and strategy for raw materials [Online]. Available at: https://ec.europa.eu/growth/sectors/raw-materials/policy-strategy_en [Accessed 31 August 2019].

European Commission (n.d.b). Une Europe efficace dans l'utilisation des ressources [Online]. Available at: https://ec.europa.eu/eurostat/fr/web/europe-2020-indicators/resource-efficient-europe [Accessed 31 August 2019].

Fischer-Kowalski, M. (1998). Society's metabolism. The intellectual history of materials flow analysis, Part II. *Journal of Industrial Ecology*, 2(1), 107–136.

Fischer-Kowalski, M., Krausmann, F., Giljum, S., Lutter, S., Mayer, A., Bringezu, S., Moriguchi, Y., Schuetz, H., Schandl, H., Weisz, H. (2011). Methodology and indicators of economy wide material flow accounting. *Journal of Industrial Ecology*, 15(5), 855–876.

Fizaine, F. (2018). Toward generalization of futures contracts for raw materials: A probabilistic answer applied to metal markets. *Resources Policy*, 59, 379–388.

Geldron, A. (2017). L'épuisement des métaux et minéraux : faut-il s'inquiéter ? Report, Agence de l'environnement et de la maîtrise de l'énergie (ADEME), Angers.

Gereffi, G. and Korzeniewicz, M. (1994). *Commodity Chains and Global Capitalism*. Praeger Edition, Westport.

Gereffi, G., Humphrey, J., Sturgeon, T.J. (2005). The governance of global value chain. *Review of International Political Economy*, 12(1), 78–104.

Gerst, M.D. and Graedel, T.E. (2008). In-use stocks of metals: Status and implications. *Environmental Science and Technology*, 42(19), 7038–7045.

Graedel, T.E., Harper, E.M., Nassar, N.T., Nuss, P., Reck, B.K. (2015). Criticality of metals and metalloids. *Proceedings of the National Academy of Sciences (PNAS)*, 112(14), 4257–4262.

Guyonnet, D., Planchon, M., Rollat, A., Escalon, V., Tuduri, J., Charles, N., Vaxelaire, S., Dubois, D., Fargier, H. (2015). Material flow analysis applied to rare earth elements in Europe. *Journal of Cleaner Production*, 107, 215–228.

Hannis, S. and Bide, T. (2009). Cobalt: Commodity profiles. Report, British Geological Survey (BGS), Keyworth.

Harper, E.M. and Graedel, T.E. (2008). Illuminating tungsten's lifecycle in the United States: 1975–2000. *Environmental Science and Technology*, 42(10), 3835–3842.

Harper, E.M., Kavlak, G., Graedel, T.E. (2012). Tracking the metal of the goblins: Cobalt's cycle of use. *Environmental Science and Technology*, 46(2), 1079–1086.

Heelan, J., Gratz, E., Zheng, Z., Wang, Q. (2016). Current and prospective Li-Ion battery recycling and recovery processes. *Journal of the Minerals, Metals and Materials Society*, 68(10), 2632–2638.

Hopkins, T.K. and Wallerstein, I. (1977). Patterns of development of the modern world system. *Fernand Braudel Center*, 1(2), 111–145.

Huisman, J., Leroy, P., Tertre, F., Ljunggren Söderman, M., Chancerel, P., Cassard, D., Løvik, A.N., Wäger, P., Kushnir, D., Rotter, V.S., Mählitz, P., Herreras, L., Emmerich, J., Hallberg, A., Habib, H., Wagner, M., Downes, S. (2017). Prospecting secondary raw materials in the urban mine and mining wastes. Final report, ProSUM, Brussels.

Humphrey, J. and Schmitz, H. (2001). Governance in global value chains. *Institute of Development Studies (IDS)*, 32(3), 19–29.

Humphreys, D. (1995). Whatever happened to security of supply? Mineral policy in the post-cold war world. *Resources Policy*, 21(2), 91–97.

Humphreys, D. (2010). The great metals boom: A retrospective. *Resources Policy*, 35(1), 1–13.

Humphreys, D. (2013). Minerals: Industry history and fault lines of conflicts. In *Conflict and Cooperation in Global Resource*, Dannreuther, R., Ostrowski, W. (eds). Palgrave Macmillan, London.

Jebrak, M. and Marcoux, E. (2008). *Géologie des ressources minérales*. Ressources naturelles et faunes, Quebec.

JOGMEC (Japan Oil, Gas and Metals National Corporation) (n.d.). History of JOGMEC [Online]. Available at: http://www.jogmec.go.jp/english/about/about003.html [Accessed 31 August 2019].

Journal officiel de l'Union européenne (2017). Règlement d'exécution (UE) 2017/1925 de la Commission du 12 octobre 2017 modifiant l'annexe I du règlement (CEE) n° 2658/87 du Conseil relatif à la nomenclature tarifaire et statistique et au tarif douanier commun. European Commission, Brussels.

Kaplinsky, R. and Morris, M. (2001). A handbook for value chain research. International Development Research Center (IRDC), 113.

Kogut, B. (1985). Designing global strategies: Profiting from operation flexibility. *Sloan Management Review*, 26(4), 15–28.

Ladenberger, A., Arvanitidis, N., Jonsson, E., Arvidsson, R., Casanovas, S., Lauri, L. (2018). Identification and quantification of secondary CRM resources in Europe. Solutions for critical raw materials – A European Expert Network (SCREEN). Report, European Union, Paris.

Le Gleuher, M. (2017). La Chine de plus en plus dépendante de ses importations de nickel [Online]. Available at: http://www.mineralinfo.fr/ecomine/chine-plus-en-plus-dependante-importations-nickel-diversifie-approvisionnement-poursuit [Accessed 31 August 2019].

Lebedeva, N., Di Persio, F., Boon-Brett, L. (2017). Lithium ion battery value chain and related opportunities in Europe. Technical report, Joint Research Council (JRC), Publication Office of the European Union, Luxembourg.

Lifset, R. and Graedel, T.E. (2002). Industrial ecology: Goals and definitions. In *A Handbook of Industrial Ecology*, Ayres, R.U., Ayres, L.W. (eds). Edward Elgar Publishing, Cheltenham.

Machacek, E. and Fold, N. (2014). Alternative value chain for rare earths: The Anglo-deposits developers. *Resources Policy*, 42, 53–64.

Machacek, E., Richter, J.L., Lane, R. (2017). Governance and risk-value construction in closing loop of rare earth elements in global value chain. *Resources*, 6(4), 59.

Mudd, G. (2010). Global trends and environmental issues in nickel mining: Sulfides versus laterites. *Ore Geology Reviews*, 38(1–2), 9–26.

Mueller, E., Hilty, L.M., Widmer, R., Schluep, M., Faulstich, M. (2014). Modeling metal stocks and flows: A review of dynamic material flow analysis methods. *Environmental Science and Technology*, 48(4), 2102–2113.

Nansai, K., Nakajima, K., Kagawa, S., Kondo, Y., Su, S., Shigetomi, Y., Oshita, Y. (2014). Global flows of critical metals necessary for low-carbon technologies: The case of neodymium, cobalt, and platinum. *Environmental Science and Technology*, 48(3), 1391–1400.

Nassar, N.T., Graedel, T.E., Harper, E.M. (2015). By-product metals are technologically essential but have problematic supply. *Science Advances*, 1(3).

NRC (National Research Council) (2008). *Minerals, Critical Minerals, and the U.S. Economy*. The National Academies Press, Washington.

Nuss, P. and Blengini, G.A. (2018). Towards better monitoring of technology critical elements in Europe: Coupling of natural and anthropogenic cycles. *Science of the Total Environment*, 613–614, 569–578.

Pillot, C. (2017). The worldwide rechargeable battery market 2016–2025. Report, Avicenne Energy, Nice.

Porter, M.E. (1985). *Competitive Advantage: Creating and Sustaining Superior Performance*. The Free Press Edition, New York.

Porter, M.E. (1990). *The Competitive Advantage of Nations.* The Free Press Edition, New York.

Roskill (2017). Cobalt: Global industry, market and outlook to 2026, 13th edition. Report, Roskill.

Reuter, M., Oyj, O., Hudson, C., Van Schaik, A., Heiskanen, K., Meskers, C., Hagelüken, C. (2013). Metal recycling: Opportunities, limits, infrastructure. A report of the Working Group on the Global Metal Flows to the International Resource Panel. Report, United Nations Environment Program (UNEP), Nairobi.

Saurat, M. and Bringezu, S. (2008). Platinum group metal flows of Europe, Part I. Global supply, use in industry, and shifting of environmental impacts. *Journal of Industrial Ecology*, 12(5–6), 754–767.

Saurat, M. and Bringezu, S. (2009). Platinum group metal flows of Europe, Part II. Exploring the technological and institutional potential for reducing environmental impacts. *Journal of Industrial Ecology*, 13(3), 406–421.

Schmidt, T., Buchert, M., Schebek, L. (2016). Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. *Resources Conservation and Recycling*, 112, 107–122.

Shedd, K.B. (1993). The material flow of cobalt for the United States, Information Circular 9350. US Bureau of Mines, Washington.

Shedd, K.B. (2010). Cobalt. United States Geological Survey (USGS), Mineral Commodity Summaries, Reston.

Shedd, K.B. (2017). Cobalt. United States Geological Survey (USGS), Mineral Commodity Summaries, Reston.

Shedd, K.B. (2019). Cobalt. United States Geological Survey (USGS), Mineral Commodity Summaries, Reston.

Stanisavljevic, N. and Brunner, P. (2014). Combination of material flow analysis and substance flow analysis: A powerful approach for decision support in waste management. *Waste Management & Research*, 21(8), 733–744.

Wolfman, A. (1965). The metabolism of cities. *Scientific American*, 213(3), 178–193.