CRITICAL RAW MATERIALS IN THE CITY:

RECYCLING PERSPECTIVES FOR COBALT IN THE HAGUE

Thesis research project · Master Industrial Ecology

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ABSTRACT

Cobalt is one of the most important critical raw materials for emerging technologies. There are many incentives for analysis of this metal, from increasing demand for rechargeable batteries, rising prices and social issues involved. This paper is the first attempt to perform a substance flow analysis of cobalt at a city level. The analysis resulted in a generic cobalt city flow model that can be adjusted for another CRM or city. The model is meant to help create a better, more accurate national, and subsequently EU level, analysis. The generic city flow model is the first step to extrapolate the bottom-up approach to get reliable results on a broader scale. A case study for the city of The Hague quantified the main cobalt flows within the city. Based on the results it was possible to suggest policy recommendations regarding critical raw materials at an urban level. The main recommendations were the lack of specific data from several sectors and the need for collaboration between governments, statistical offices and entrepreneurs. Those actors should work together to create a database accessible for researchers. Figure 1 is a graphical abstract of the main research outcomes.

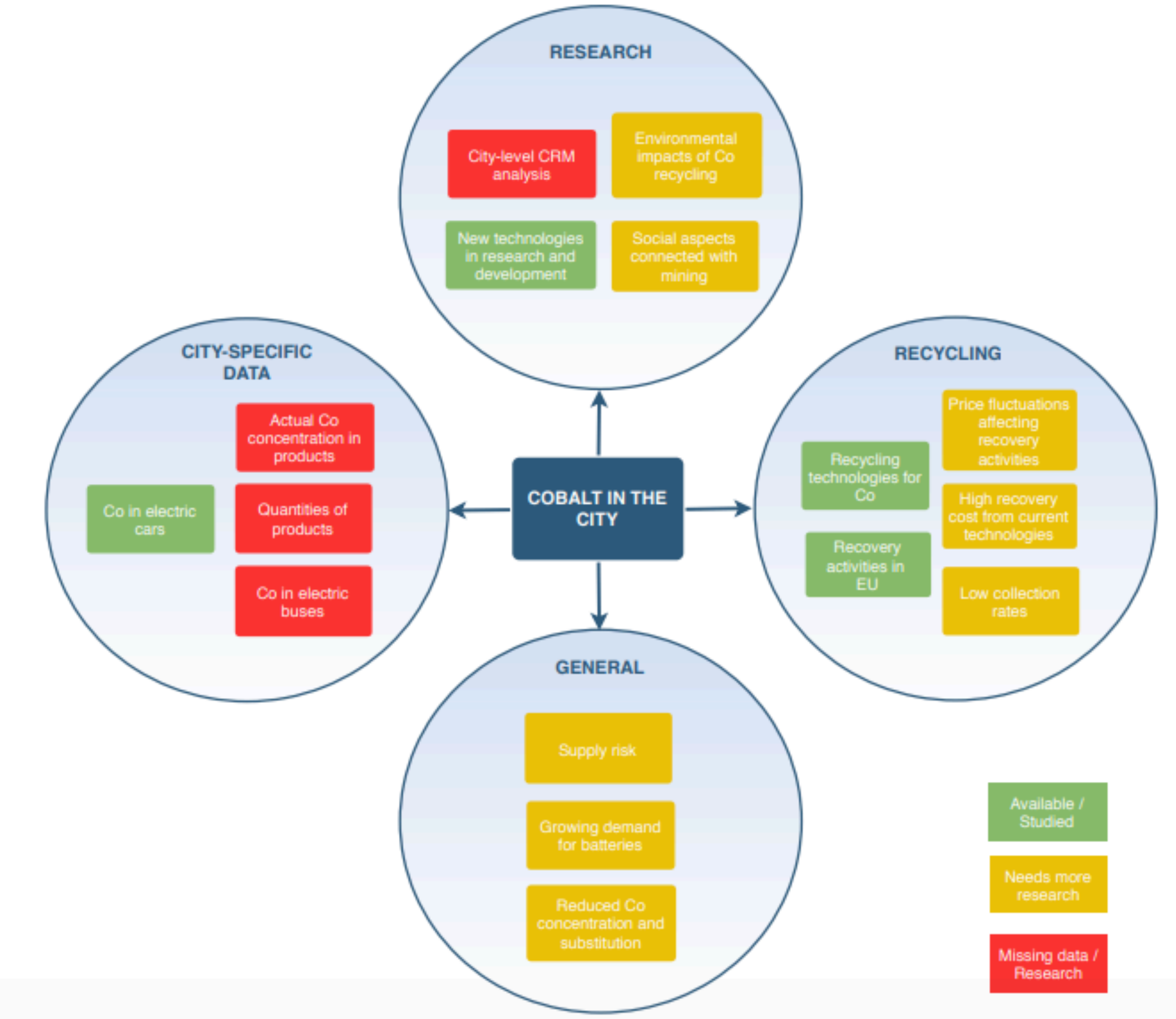

Figure 1. Graphical abstract of main results. The diagram summarizes main research outcomes regarding stocks, flows and recovery potential of cobalt on a city level. Colour code indicates the current status of each statement: green - information is already available, yellow - required more research, red - missing information or research on the topic

1. INTRODUCTION

Critical raw materials (CRM) are crucial for emerging technologies, which are important to increase number of sustainable innovations and develop more eco-efficient industries. Those new technologies often require substantial amounts of raw materials, which creates a challenge in ensuring their stable global supply. It can be observed that the European Union (EU) depends on importing critical raw materials for its domestic production.

1.1. RELEVANCE OF CRM

Raw materials can be obtained from two general sources: primary and secondary. Primary (virgin) raw materials are defined as natural materials extracted from the soil or harvested and processed to get new material or product. Primary raw materials are mined as a main product or a by-product of other material, usually in the form of ores or concentrates. Secondary raw materials have already been processed and used one or more times. Using processing technologies, they are recovered from used products or waste streams and prepared to be used again in the same or new application (OECD, 2008). Secondary resources of a specific material are therefore all end of life products containing this material. If the scope of analysis is limited to a city, this resource is often identified as urban waste. Another type of secondary resource is waste from processing materials (industrial waste), for example slag and sludge from smelting or flotation tailings. When the material of interest is deposited and stored, it becomes a historical waste. Landfill is also a part of historical waste, which can be a secondary resource of materials as well.

CRM are crucial for new emerging technologies, which are important to increase the number of sustainable innovations and develop more eco-efficient industries. Those new technologies often require substantial amounts of raw materials, often rare elements, which creates a challenge in ensuring their stable global supply. This is where the idea of a critical raw materials list comes into place. It can be observed that the EU is often depends on the import of critical raw materials for its domestic production. The aim of the critical raw materials list for the EU is to create incentives for production of those materials within Europe and open the door for new recycling and mining activities inside the EU (European Commission, 2017b). Those activities should contribute to decreasing Europe's material supply reliance on other countries. Moreover, the list should contribute to fulfilling industrial policy created by EU and strengthen industrial competition by taking action in different policy areas. The list of critical materials serves as a way to identify possible supply risks of materials important for the European economy, which often relies on import of materials required by industry.

The first critical raw materials list was created in 2011 and it is revised every 3 years. The criticality is assessed using a methodology created by the European Commission (EC). It is based on two parameters: Economic Importance and Supply Risk, for which values are determined for every raw material candidate. The first list identified 14 critical elements out of 41 non-agricultural and non-energy materials. The second analysis, in 2014, resulted in 20 raw materials as critical out of 54 candidates. The most recent assessment was performed in 2017 and resulted in 26 raw materials identified as critical out of 61 candidates (European Commission, 2017b). The increasing number of critical, or potentially critical, materials shows how the economic importance and supply risk levels for materials change over time. That the CRM list is flexible also indicates how industry's requirements for different materials can vary within short periods of time. Figure 2, below, presents the newest list of CRM in the European Union.

2017 Critical Raw Materials (26)			
Antimony	Gallium	Magnesium	Scandium
Baryte	Germanium	Natural graphite	Silicon metal
Beryllium	Hafnium	Natural Rubber	Tantalum
Bismuth	Helium	Niobium	Tungsten
Borate	HREEs	PGMs	Vanadium
Cobalt	Indium	Phosphate rock	
Fluorspar	LREEs	Phosphorus	

Figure 2. List of critical raw materials for the EU in 2017 (European Commission, 2017b)

Figure 3 gives a clear picture of how production of CRM is distributed around the world. When considering the global supply of CRM, China is by far the largest player in the market. This country supplies the world with the majority of critical materials. It is also worth noting that China is at the same time the biggest consumer of many of those materials (rare earth materials, antimony, magnesium, tungsten, natural graphite, etc.), which create competition for supplies with Europe and other economies (European Commission, 2017b).

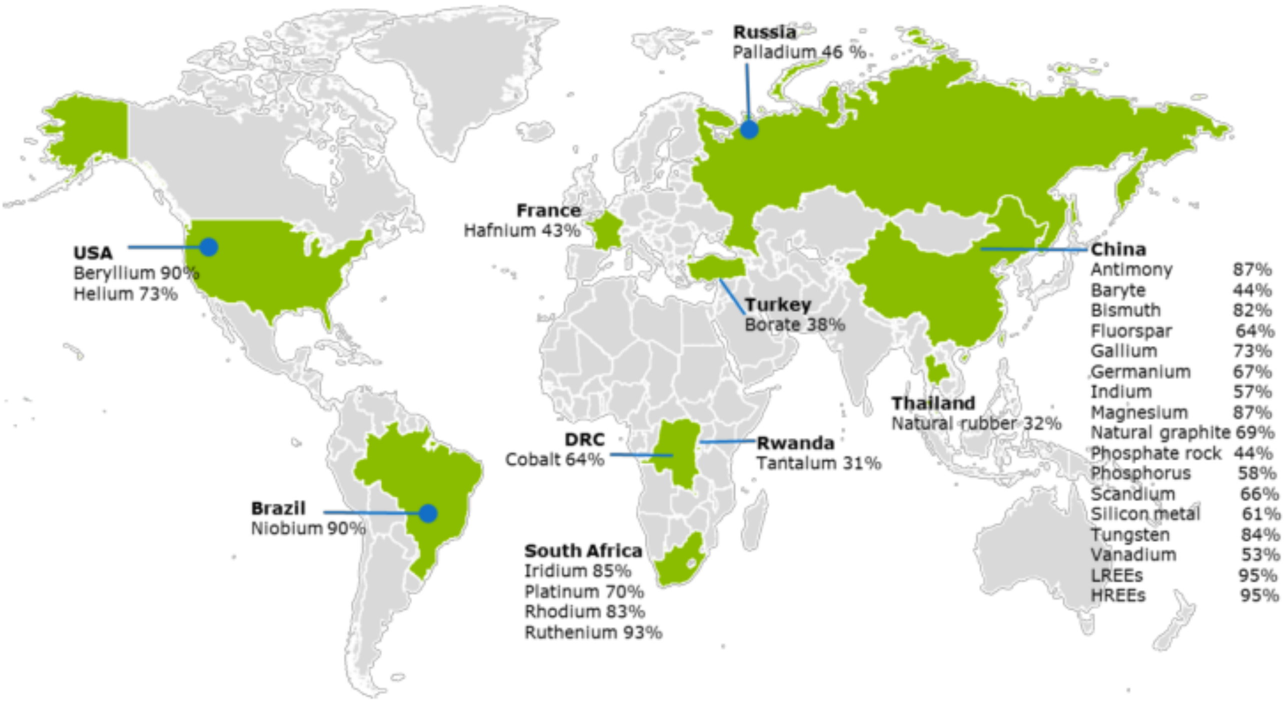

Figure 3. Global main suppliers of CRM (European Commission, 2017b)

1.2. URBAN MATERIAL FLOWS

The topic of material flows in a city can be found in the literature under several key words. Terms like urban metabolism, urban mining and urban material flows are present in many literature positions elaborating on circular economy and recycling. Together with concepts of zero waste, resource recovery and eco-design, they are increasingly used in many areas of industry (Cossu & Williams, 2015). This points out the relevance of taking care of primary reserves of materials and exploring the possibilities that secondary sources provide. With more extensive use of the above key words, the terminology should be consistent for all applications. Therefore, a short explanation of main terms is presented below (Figure 4), which also show clearly the position of city flows in general in the circular economy field.

Landfill mining is one of the sources for secondary raw materials. It includes recovery of precious materials from industrial processing waste and residues after mining, that have been deposited and not processed further. Those flows include, for example, mine tailings, manufacturing slags, landfills etc. Urban mining is a broader term, which also comprises recovery from any type of stocks (buildings, industries, infrastructure, products etc.). Materials recycling focuses on transforming waste into secondary raw materials, which can be used again to produce new items. Those materials are processed and brought back to the material cycle. Resource recovery includes materials recycling, but also energy produced by treating waste. Waste minimisation is comprised of strategies to avoid generating waste at the source. It includes optimization of used resources, reduction of hazardous materials use, reuse practices, conscious consumption and reduction of generating waste. Circular economy is a very broad term, which can be shortly described as cradle to cradle approach. It includes business models which support the reuse of products, reducing generation of waste and using more secondary materials for production, which also contribute to growth in job opportunities (Cossu & Williams, 2015).

Figure 4 Graphical representation of different terms concerning material recovery (Cossu & Williams, 2015)

Urban mines are getting increased attention, due in large part to increasing consumption and the population of cities. As a consequence, the amount of waste generated within cities is increasing as well, posing environmental concerns, but also creating market potential for materials that can be recovered. Moreover, considering the metal criticality, the importance of recycling waste gathered in urban mines is increasing (Sun, Xiao, Agterhuis, Sietsma, & Yang, 2016).

In the literature, material flow analysis (MFA) or substance flow analysis (SFA) is used as a tool to support policy decision making in the environmental management field. However, not many scientific papers focus on the actual potential of material recovery. Hendriks et al (2010) used the analytical tool to set priorities and improve effectiveness of material management in sustainability strategies. This analysis was performed for the city of Vienna since MFA is the right tool for analysis at the regional level. As the author claims, the MFA analysis is able to point out material accumulations which can either be environmental issues (hazardous materials stock) or sources of secondary materials. This information can serve as input for policy in order to implement precautions in material management.

Vienna's metabolism included multiple general anthropogenic flows going through the city, like water, energy, air, consumer goods, waste.

1.3. LITERATURE REVIEW ON THE CITY-LEVEL MFA

There are many scientific positions covering the state of the art of Rare Earth Elements (REE) recycling (Binnemans et al., 2013; Rademaker, Kleijn, & Yang, 2013; Sprecher et al., 2014; Yang et al., 2017). Plenty of research is focused on the material flows of REE, particularly those used in permanent magnets. One reason for that can be increasing global demand for this product, connected with a rapidly developing electric and hybrid vehicles industry, wind turbine industry as well as hard disc drives and other electronic equipment. In all of those applications, permanent magnets play an important role (Guyonnet, Planchon, Rollat, & Escalon, 2015; Rademaker et al., 2013). The studies analysed have a rather general scope, which is useful for governmental organisations to measure the level of materials used globally (Guyonnet et al., 2015). This perspective can demonstrate the most critical spots in materials flows and help tackle issues of material supply. Additionally, it can support environmental policy decision making on a European or even global scale (Hendriks et al., 2010).

There are few performed material flow analyses (MFA) for European cities. A study on urban metal flows was performed for Stockholm by Bergbäck et al (2000) to indicate environmental and resource problems. Analysis included following materials: cadmium, chromium, lead, copper, nickel, mercury and zinc. One of the outcomes of the study showed solid waste streams as the biggest source of metals in the outflow from the city. This confirms the relevance of waste in the urban metabolism and the opportunity for secondary raw material recovery. Another two papers focus on metals in the city of Cape Town, South Africa. Van Beers & Graedel (2003) analysed copper stocks, as well as their distribution and magnitude. The aim of this paper was to evaluate the secondary resources of copper after products bearing it become obsolete. In order to do so, first the main applications of copper in this city were identified, then the amounts of copper in use were quantified and the lifetime of each product was estimated. This resulted in quantified in use stock of copper and prediction of its future end of life (EoL) flows, using a model with a geographic information system. A more recent scientific paper by Mason-Jones & von Blottnitz (2010) elaborates on flows of nickel-cadmium batteries in Cape Town. The purpose of this analysis was to investigate use and disposal of end of life NiCd cells in order to quantify the flows of cadmium in the city. The method chosen for this paper was substance flow analysis, which serves as an example for conducting the present research.

As I have noticed during the literature review, little focus is given to metal flows, especially critical metals and for European cities. There is still little understanding of CRM flows at city level. To the best of my knowledge, material flow analysis of cobalt was not performed before for any European city. I concluded that topic of specific metal flows at city level is not analysed thoroughly, which is the identified research gap.

The aim of this paper is to quantify cobalt flows in The Hague and to assess its recovery potential in order to enable circular economy starting from a city level. As can be derived from the literature review above, recycling is one of the solutions that can help overcome the supply concerns of cobalt.

The city flow model presented in this work is meant to be extrapolated in the future to other cities, then provinces and eventually countries. In my view, implementing actions from the bottom and building them up to global level can be less complex than top-down approach. Quantified metal stocks and flows within urban areas are based on locally gathered data and are more accurate than national statistics. The results therefore contribute to the increased accuracy of national or even global analyses. This can be done by extrapolating results based on population while considering the characteristics of a specific region or country. Analysing critical metals at city level is also important due to the growing population of cities, which means higher concentrations of consumer goods, vehicles and other Co-bearing products.

In order to fulfil the information gap, the following aspects will be discussed. First, a case study on cobalt flows in The Hague will demonstrate how much cobalt can be found in a typical European city. Based on the outcomes, the potential amount of recovered cobalt will be estimated and technologies for recycling will be evaluated. Discussion of the results will include the limitations and gaps in CRM recovery at city level. Lastly, based on the outcomes of analysis, policy recommendations will be given for cobalt recycling in The Hague and CRM recycling at city level in general.

2. COBALT

One of the most relevant CRM for sustainable technologies is cobalt (Co). It is mostly produced as a by-product of copper and nickel. Less than 6% of Co total primary production is mined as a main product. According to USGS, the world mine production reached 123 kt in 2016 and is estimated to be 110 kt in 2017. Figure 5 and Figure 6 depict historical world cobalt mine production and more recent values, respectively. Total world reserves are rounded up to 7 Mt (USGS, 2017). The largest global mine producers of cobalt are: Democratic Republic of Congo (DRC) with a 64% share, China with 5% and Canada with 5%. In Europe cobalt is presently mined in New Caledonia (France, not part of EU) and Finland, with a share of the global total of 2% and 1% respectively. In Finland, cobalt is mined in 4 plants and the production is around 1,200 tones. The EU's reliance on the import of cobalt ores and concentrates is estimated as 32% (European Commission, 2017a).

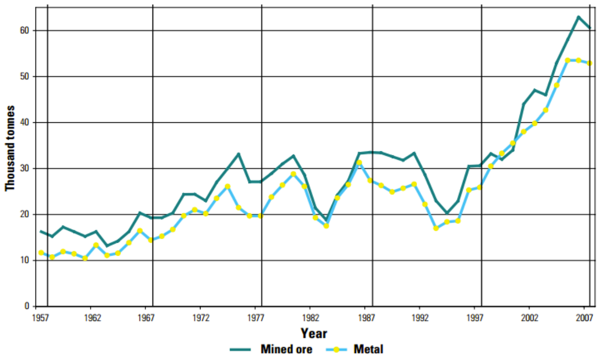

Figure 5. Historical world mine and refined cobalt production (British Geological Survey, 2009)

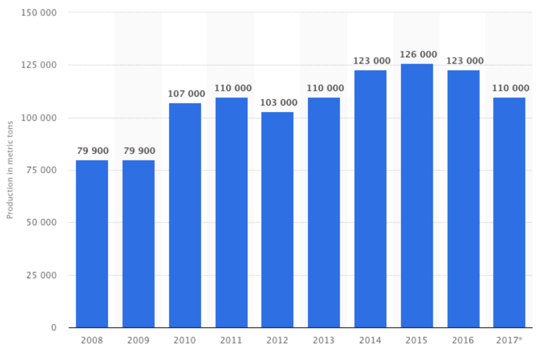

Figure 6. Recent world total cobalt mine production from 2008 to 2017 (*estimation) (Statista, 2018)

The supply of refined cobalt is shown in Figure 7. The chemical uses of this metal exceed the metal form. Secondary production is slowly growing; according to estimation it can reach 20 kt by 2025, while primary material supply is expected to stabilize (Hamilton, 2017).

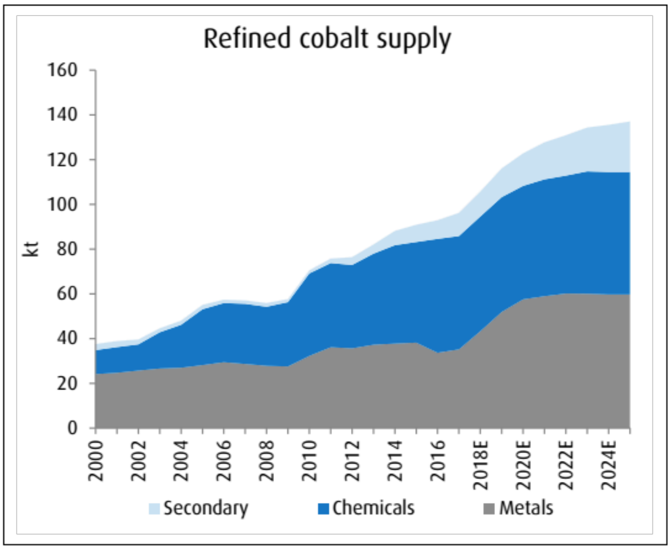

Figure 7. Supply of refined cobalt prediction distinguishing different forms in which cobalt is used (Hamilton, 2017)

Cobalt is used in a big range of end products in the form of cobalt metal or in multiple cobalt bearing chemicals. The biggest share is assigned to production of battery chemicals, namely in Ni-Cd, NiMH and Li-ion types. The second highest consumers are super alloys used mainly for jet engines. Cobalt is also used in hard materials for cutting tools, catalysts, pigments and ceramics, magnets, tyres adhesives and paint dryers, and multiple other small applications, for instance in biotechnology and electrolysis (European Commission, 2017a). Figure 8 shows the main global application of cobalt in 2015.

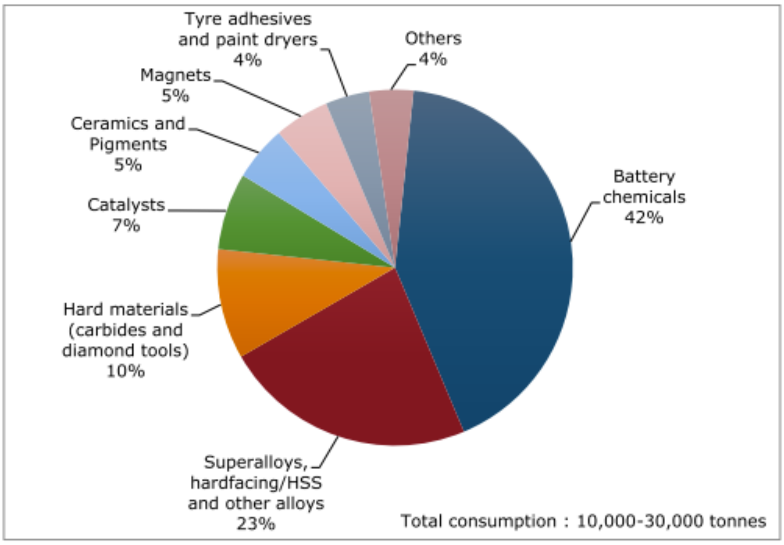

Figure 8. Global end use applications of cobalt in 2015 (European Commission, 2017)

Cobalt is such a valuable metal due to its properties, namely its high melting point and good corrosion resistance. This is crucial for withstanding the high temperatures in batteries as well as superalloys.

On average, a NiMH battery contains 15 wt% of cobalt, while the Li-ion battery uses up to 50 wt% of this metal (Ali, Toledano, Maennling, Hoffman, & Aganga, 2018). Together with growing demand, this high usage results in substantial accumulation of cobalt only in batteries, leaving out the remaining applications. The demand for cobalt embedded in the above-mentioned end uses is expected to grow substantially. One estimate suggests a growth of about 70% by 2020 (Martin, Rentsch, Höck, & Bertau, 2017). In particular, electric vehicles will contribute significantly to an increase in cobalt demand. The annual growth of cobalt use in rechargeable batteries was estimated at 13% over the last decade, which leads us to conclude that batteries will be the most important driver of future cobalt demand (Ali et al., 2018).

Another unfavourable aspect of cobalt demand is the level of difficulty and high cost of its separation from nickel and copper. All the issues mentioned above are likely to contribute to a disparity of supply and demand, particularly in the battery sector (Ali et al., 2018).

Figure 9 depicts historical cobalt price fluctuations. In recent years, cobalt price has almost tripled from nearly 15 $/lb (around 33 $/kg) in 2015 to over 43 $/lb (around 94 $/kg) in the beginning of 2018 (InvestmentMine, 2018). This metal is therefore very relevant for an analysis of a modern European city where the local government incentivises citizens to invest in electric vehicles by implementing subsidies (The Hague Online, 2016). Cobalt is mined almost exclusively as a by-product of other metals (copper and nickel), thus its supply highly depends on the production and prices of the host metals.

Figure 9. Historical cobalt price (InvestmentMine, 2018)

Lastly, social issues connected with cobalt primary production are an important element of sustainability and should not be left without attention in the material analysis. In the case of the DRC, while political conflicts and issues of corruption are experienced, there are social problems connected to cobalt production, mainly human rights abuses by child labour. Although DRC is entangled in political conflicts and struggle with corruption, cobalt coming from this country is not included in the "conflict minerals", because Co is mined as a by-product of copper which is not associated with conflicts in that region (Ali et al., 2018; European Commission, 2017a).

2.1. COBALT SUPPLY CHAIN

The analysis starts with a global picture of the cobalt supply chain with the distinction of different stages: production, use and end of life. Figure 10 below is a simplified diagram of the global cobalt supply chain in 2015 with a detailed description of use phase in The Hague. Numerical values are provided for several flows, where it was possible to obtain such data. To the best of my knowledge, there are no complete global or EU-level cobalt flow analyses that investigate each of the supply chain elements. Therefore, the quantitative data for product manufacturing, use and waste are not provided in the diagram below.

All stages of supply chain have waste flows, which are shown by curved arrows. Those are inevitable material losses due to physical limitations, tailings, slags and emissions, but their quantification is out of the scope of this study. Additional flows, including reuse and recycling of both old and new scrap, are indicated by loops.

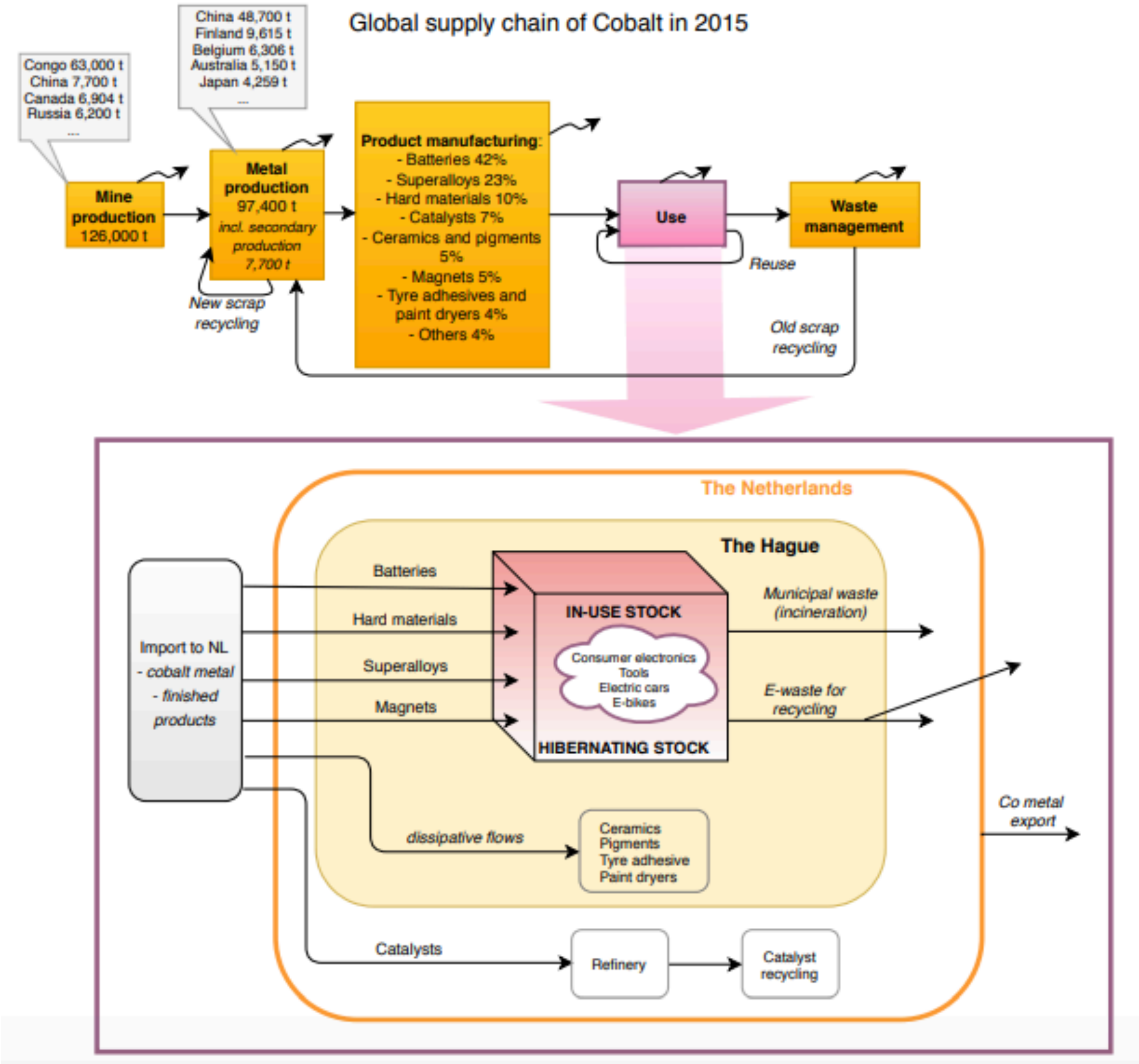

Figure 10. Global supply chain of cobalt in 2015 with focus on use phase in The Hague. Mining and refining data from Minerals Yearbook 2015 (Shedd, 2015)

Production

As mentioned, mining activities are undertaken mostly in Democratic Republic of Congo, where, in 2015, mine production reached 63 kt, more than a half of the world's total mine production (USGS, 2016). Other countries mining cobalt include China, Russia, Canada, Australia and other smaller contributors. Global mine production of this mineral summed up to 126 kt in 2015 and refining reached 97.4 kt (Shedd, 2015). The leader in refined cobalt was China, which was produced in large part from ore and partially from refined metal imported from the DRC. China is also the biggest consumer of cobalt with 75% of all Co used for battery production (USGS, 2016). In Europe, cobalt is refined in Belgium, Finland, Norway, France (Shedd, 2015). In 2015, 7.7 t of refined cobalt came from secondary production (Hamilton, 2017). It is unclear however, which part of this value comes from EoL products and which is from manufacturing scrap.

Use

The main applications of cobalt were described above. For The Hague, the most relevant product flows are batteries, hard materials in tools, superalloys in electronics and magnets, as shown in the bottom of Figure 10, which describes the use phase. This view is meant to visualise main cobalt-related material flows in The Hague, as well as post-consumer waste management. A distinction was made between measurable flows of products found in the city, dissipated flows present in the city but not measured in this analysis and flows outside of The Hague. Ceramics, pigments, tyre adhesives and paint dryers are assigned to dissipative flows due to low concentrations used in products and difficulties with recovery of metal. Therefore, those flows are not considered in this analysis, since the cobalt embedded in them is not available for recycling (European Commission, 2017a). Products in stock were evaluated further in the analysis in order to quantify cobalt flows through the city. Hibernating stock is part of the products that are not used anymore, but not discarded either.

End of life

After the end of life, collected products containing cobalt can be reused or recycled. The number of products available for recycling depends on the efficiency of collection. It will differ among sectors, since in principle offices have higher collection rate than private households. During metal refining new scrap is generated, which can typically be reused directly in the processing site. Another aspect influencing metal recovery is the efficiency of recycling processes, as well as economics of recovery and physical limitations.

Waste flows leaving city borders are measurable and will be included in the analysis. There are two types of waste flows leaving The Hague considered in this analysis: end of life products that are collected in the city and sent outside of its borders, within as well as outside of the Netherlands, and products discarded in municipal waste stream that are incinerated within The Netherlands, but cobalt remaining in incineration residue is lost.

Tools and hard materials from the construction sector are returned to the producer after their end of life (Veelen, 2018). Input from one of the suppliers of tools for construction companies in The Hague indicates that diamond tools are produced by welding or brazing the cutting teeth (segments) to a steel tube for core bits or steel core for blades. Segments are manufactured using sintering process using a mixture of metal powder, including cobalt and synthetic diamond. It is also worth noting that, for roughly 20 years, producers of diamond tools gradually reduced the amount of cobalt used in metal powder due to high cost and environmental concerns. It is believed that current diamond tool segments do not contain more than 20% of cobalt. During the use phase core bits and blade segments are worn down over time. Material that is left is collected by the producer and recycled by general scrap metal recycling companies (Lavrysen, 2018). Based on this input, I assume that discarded tools contain trace amounts of cobalt and it is lost in the manufacturing of new components.

It is mandatory to recycle EoL vehicles according to European law. The vehicle post shredding residue is also recycled in a Dutch ARN facility in Tiel, which is able to recover minerals, fibres, plastic and metals. Among metals the main focus is on iron, stainless steel, aluminium and copper, since those are most commonly present elements (ARN, n.d.). There is no information on recovery of cobalt from EoL vehicles, therefore I assume it is lost in the residue.

A similar thing can be said for cobalt in municipal waste. ARN also treats spent car batteries, scooters and mopeds to avoid hazardous materials leaks to the environment, however there is no recovery of cobalt from those streams. There is no information available on what happens to the electronic waste after the collection point, therefore it is assumed that E-waste ends up in one of the recycling facilities and batteries are sent to specialised recovery plant, for example Umicore in Belgium.

3. COBALT RECYCLING

3.1. STATE OF THE ART IN COBALT RECYCLING

3.1.1. RECYCLING RATES

There are several definitions for recycling rates for metals, each of them looking at the recovery from a different perspective. *Old scrap collection rate* (CR) measures how much metal from collected EoL products was recovered and entered the recycling chain. *End of life recycling rate* (EoL-RR) refers to functional recycling, including recovery of pure metal and alloy. It is described as the amount of recycled metal (old scrap) of the total EoL product.

Functional recycling takes place when metal is separated from EoL products and re-enters the raw material production stream as a pure metal or alloy. It is important whether the scrap bearing the metal of interest is re-melted into the same alloy or class of alloys. In the case of cobalt, one example of functional recycling is spent battery treatment. Recovered cobalt is used again in cathodes for new batteries, which is described in more detail in the following subsection.

In another case, valuable metal in scrap can be used as a feed for a general material stream, where the qualities of the metal are lost in a lower-grade material. This situation represents non-functional recycling, where a material's primary function is lost (Graedel et al., 2011). Non-functional recycling happens when, for instance, scrap metal containing cobalt is not separated from other metal alloys and goes to a lower grade steel production where it is mixed with other steel elements. It is then an impurity lost in a residue slag.

In the metal production additional indicators are used. *Recycling input rate* (RIR) gives information on the amount of the secondary metal from scrap in the total input for metal production. Secondary metal comes from both old and new scrap in this indicator. RIR is the same as another metric, *recycled content* (RC). *Old scrap ratio* (OSR) represents the fraction of metal from old scrap in the recycling stream (old and new scrap).

There are several important aspects of recycling rates. First is the size of the collected scrap stream, and whether it is sufficient to provide input for recovery activities. In the case of old scrap, which is most relevant stream for the city level, the availability for recycling is affected by product lifetime and the amount of metal used in product manufacturing. Growing metal demand and prolonged product lifetime decrease the availability of old scrap for recycling, which is typically lower than metal required for product manufacturing resulting in lower RC.

Second, separation of different materials has influence if metal will be recycled functionally or non-functionally. Metal alloys with specific composition should ideally be separated from pure metals and recovered in different streams. Moreover, the quality of collected scrap, efficiency of manufacturing, and level of metal use influence recycling rates (Graedel et al., 2011).

End of life recycling input rate for cobalt in the EU is estimated at 35% (European Comission, 2016). UNEP estimated the end of life recycling rate at 68%, which is higher than in the case of other metals. Recycled content is estimated at 32%, which is a lower rate than most other metals (SETIS, 2016). Old scrap ratio is calculated as 50% (UNEP, 2011).

Several companies in Europe already recover cobalt from spent products. Umicore is a refining company with a facility in Olen, Belgium (refinery capacity 1.5 kt cobalt content) (Shedd, 2015), which recovers cobalt and other metals from scrap. Their recycling site can process the following types of waste products: batteries, hard metal tools and superalloys from aviation industry. Umicore is a cobalt powder market leader, which has announced investment in improvements to their refining and recycling facility in order to increase production of cobalt and increase its recycling from residues ("Umicore to upgrade cobalt recycling plant," 2015).

One more recycling facility in the EU is located in Kokkola, Finland. There, Freeport Cobalt produces several Co-bearing products used in chemicals (cobalt acetate, carbonate, hydroxide, oxide, sulphate and coarse grade cobalt powder), pigments, ceramics, batteries (cathodes in lithium ion and lithium polymer batteries) and metallurgy (for diamond tools and hard metal applications). They already recycle hard metal and battery scrap and are working on recovery of catalysts. Freeport Cobalt uses more than 50% of the recycled cobalt from domestic residues and by-products in the production feed. The facility uses hydrometallurgical circuits to extract and purify cobalt (Freeport Cobalt, 2015).

As it stands, recycling of cobalt is not profitable on a big scale (Ali et al., 2018). It is therefore recycled together with primary production, and the number of recycling plants is limited.

3.2. RECYCLING TECHNOLOGIES

There are several recycling technologies in place for cobalt recovery from urban mines. They can be divided into two categories: conventional and laboratory scale technologies. Conventional technologies are already used by industry for cobalt recovery and contribute to recycling rates described above. Laboratory scale are new technologies that are currently in a research and development phase.

The short overview of existing cobalt recovery technologies provided below is arranged based on the spent products containing this metal. Recovery of cobalt from other secondary sources like tailings, slags, other manufacturing residues and landfills are out of the scope of this research, since the focus is on recycling urban waste streams.

Cobalt is used in cathodes of Li-ion and NiCd batteries, as well as in both anode and cathode of NiMH batteries. The most Co-rich is the lithium-based battery, followed by NiMH and NiCd (Buchert, Manhart, Bleher, & Pingel, 2012; Zeng, Li, & Singh, 2014). Recycling company Umicore developed its own process for treatment of NiMH and Li-ion batteries with smelting techniques. Their process involves the use of an ultra-high temperature plasma torch to treat already separated Li-ion and NiMH batteries in the feed. The metal alloy resulting from it is further refined and treated with hydrometallurgical processes to obtain separated metals including Co, Fe, Ni and Cu, ready to be used in new cathodes (Umicore Battery Recycling, n.d.).

Batteries can be also processed hydrometallurgically by crushing with a hammer mill and subsequently sorting into different material streams. The cobalt cake remaining after processing contains up to 35% Co. Electrochemical treatment of used batteries involves dissolving cathode in acid and separating it with solvent extraction (Ferron, 2013).

Another interesting recovery alternative for Li-ion batteries is bioleaching. This method consists of a microorganism reaction leading to reproduction, which enables metal leaching from waste (Zeng et al., 2014).

Alloys are the second biggest cobalt application and can contain varying amounts of this metal. For instance, super alloy contains up to 39% Co, SmCo alloy includes 66% Co and soft magnetic alloy - 49% Co. Scrap alloys can be recycled on an industrial scale in sulphide smelter together with a new feed of cobalt sulphide. An electric furnace processes the material which results in matte, gas and slag. Slag is then purified and converted to obtain cobalt.

Hydrometallurgical treatment involves acid leaching, purification and separation of recovered metals, usually cobalt and nickel, but it depends on the composition of alloy (Ferron, 2013).

More recent research has shown a new method of cobalt recovery from super alloys. For this purpose, a double membrane electrolytic cell (DEMC) is used to obtain Co and Ni cathodes of high purity (Wang, 2006).

Hard materials include cemented carbides using cobalt as binding material in concentration 3-25%, and diamond tools, diamond saws and grinding wheels in particular (European Commission, 2017a; Wang, 2006). In the case of cemented carbide, cleaned scrap is melted in a vacuum furnace and cobalt is dissolved in molten zinc. After distillation, crushing and milling, the material is screened for Co separation (Ferron, 2013).

Catalysts for oil and gas refining, as well as catalysts used in plastics manufacturing, contain cobalt. To recover the metals from those applications, pyrometallurgical and hydrometallurgical methods can be used. Cobalt catalysts are treated in an electric arc furnace, where roasted and leached material is melted. This process results in an alloy with 12-17% Co and 36-43% Ni, which can be sold to Ni and Co refineries.

Cobalt catalysts can be processed hydrometallurgically by leaching with acid. As a result of this experiment, over 95% of Co was dissolved and precipitated to cobalt sulphide concentrate of high grade and sent to further processing (Ferron, 2013; Wang, 2006).

Cobalt used in pigments for paints, ceramics and glass is not recycled due to its high dissipation in those application and issues with collection (Ferron, 2013).

Cobalt is used in adhesives for rubber bonding in tyres, however there is no information regarding whether it is possible to recover cobalt from this application.

4. CASE STUDY DESCRIPTION

4.1. CITY OF THE HAGUE

The following analysis of statistical regional data will help to introduce the city, understand its underlying mechanisms and find motivation for the material flow analysis.

The Hague is one of the biggest cities in The Netherlands. The city was inhabited by nearly 532 thousand people at the beginning of 2018 and had over 257 thousand households in 2017 with an average of 2 persons per household. It is a diverse and modern city, which hosts about 100 international companies, 160 institutions and organisations and 115 foreign embassies (The Hague Convention Bureau, 2017). There are over 48 thousand businesses located in the city, mostly in the area of business services (over 14 thousand companies), trade and catering, industry and energy, as well as cultural and recreational services. In 2016, the municipality employed 273 thousand people, mostly in non-commercial (49%) and commercial (46%) services, industry and energy (4%). According to national statistics, 190,5 thousand motor vehicles were present in The Hague in 2017, mostly personal cars. The number of vehicles has been increasing by 1% since 2013, but the growth between 2016 and 2017 reached 6% (CBS, 2018a). The increase of car ownership can be an indicator of growing material requirement and future secondary material source.

One characteristic of The Hague is that it has the second highest number of branches in the Netherlands, second only to Amsterdam. The branch is understood as each separate terrain used by a company to carry out their activities. In 2015, there were over 68 thousand business locations in the municipality The Hague, mostly in the specialist business services category (25%). This category includes advising, research and other services that require high level of education and provide specific knowledge. Other sectors with high numbers of offices are trade, construction industry, culture, sport and recreation, information and financial services. Most of the branches have one actively working person (CBS, 2018a). That high number of offices can lead to assumptions about the high use of electronic devices in the city.

The city of The Hague was chosen as the subject of the substance flow analysis for several reasons. It is a modern European city with ambitious plans for sustainability. The city aims to become climate neutral by the year 2040, which is as many as 10 years earlier than the goal for the Netherlands. Those plans include a reduction of CO_2 emissions, implementing solutions to climate-proof the city, the expansion of sustainable district heating and the promotion of renewable energy (The Hague Convention Bureau, 2017). A raw material flow analysis previously performed for The Hague has investigated the consumption and waste processing in public administration and government services, construction, real estate and the trade sector. This analysis aims to give an improved understanding about were circular economy can have the highest impact. The research was performed for energy, biomass, minerals, chemicals, and metals streams by choosing the three most relevant products for each category (Winter et al., 2017). Moreover, The Hague seems very interested in gathering different kinds of data about the metabolism of the city. The municipality recognises the need for local data for the development of public services (CBS, 2017a). This was proved by the establishment of the CBS Urban Data Centre (UDC), a cooperation between Statistics Netherlands (CBS) and municipalities to collect microdata and use it effectively in local administration. The aim of UDC is to gather new data on a local level in order to help in areas of policy creation, businesses and new developments (CBS, 2017b). One centre was also launched in The Hague in September 2017, which aims to broaden the local data collection by connecting it with information already available at CBS.

That said, there is certainly room for improvement in material sustainability area. The city could benefit from knowledge on specific critical metal flows within their boundaries in order to assess the most efficient material use, and implement appropriate recovery schemes for secondary raw materials.

4.2. COBALT IN THE HAGUE

As already described, cobalt can be found in multiple products, mostly in batteries, super alloys and hard materials. This section elaborates on where cobalt can be found in The Hague. Specifically, I have investigated all products containing this metal and checked whether there is any trace of those items within the city. A literature review helped to create a list of all possible applications containing cobalt. The main sources of co-bearing products were: European Commission (2017), Harper, Kavlak & Graedel (2012), Huisman et al. (2017) and TNO (2017).

The first indication of potential applications of cobalt in The Hague was based on the outcomes of the ProSUM project (Huisman et al., 2017). From this study, flows of cobalt-bearing products that can be found in The Hague include electric vehicles and portable electronics using batteries in the offices and households. The second big stream of cobalt is expected to be electronics, where cobalt is used in multiple metal alloys and magnets. This category includes small appliances with batteries (computers, mobile phones) and tools, which are all relevant for this case study. The third big source of cobalt are vehicles which include electronic components and magnets used in drive motors (Huisman et al., 2017).

One potentially crucial flow of cobalt-bearing vehicles is the electric bus. It is potentially relevant to the research, because the applicability of the electric bus battery flow in the analysis depends on the specific battery chemistry. There are few Li-ion battery types used in heavy-duty applications: Nickel Manganese Cobalt Oxide (NMC), Lithium Titanate (LTO) and Lithium Iron Phosphate (LFP) (California Air Resources Board, 2016). However, only NMC has cobalt in the catalyst. It is important to note that batteries for heavy-duty vehicles (buses, trucks) have different requirements than light-duty equivalents (personal cars). Differences are in the expected lifetime, masses and driving cycles.

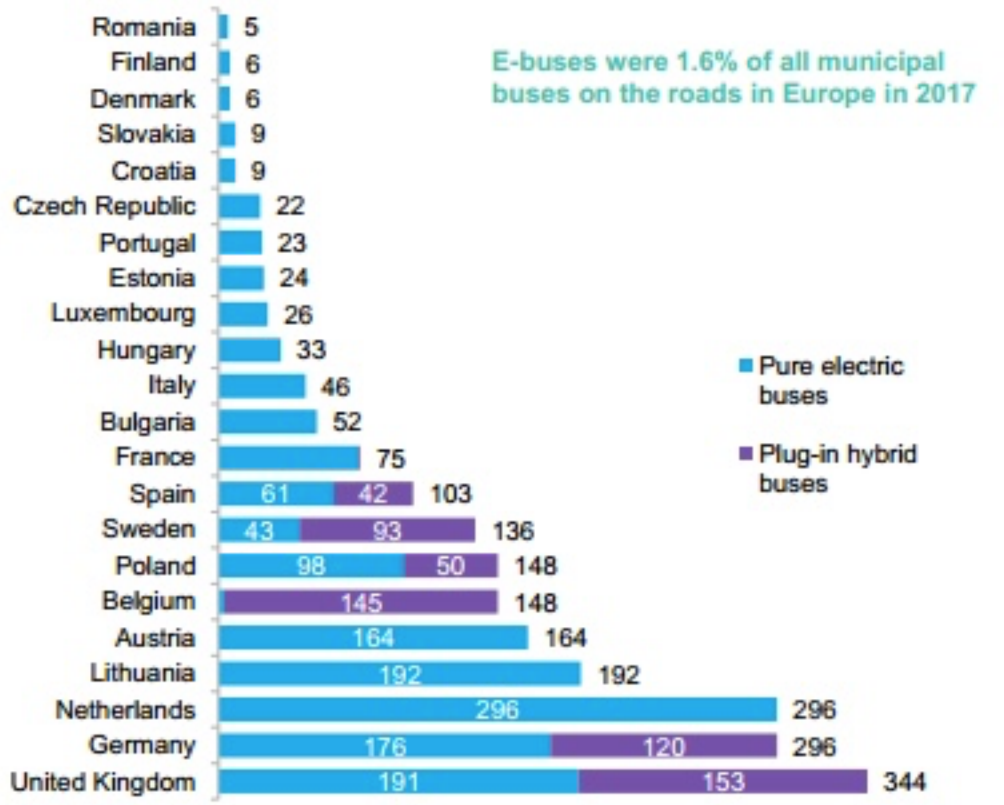

Figure 11. Electric bus fleets in Europe in 2017 (Bloomberg, 2018)

The Netherlands had the highest number of purely electric buses in Europe and second position in number of electric and hybrid electric buses used for public transport in 2017 (Figure 11) (Bloomberg, 2018). Europe's largest fleet of electric buses is being used in and around Schiphol airport near Amsterdam. Since March 2018, 100 electric buses ride in this area and this number is set to increase to 258 buses by the year 2021. The Dutch government has created a policy which claims that from 2025, only buses with zero harmful emissions can be bought (Schiphol Group, 2018). Furthermore, batteries in Dutch electric buses are charged only from renewable energy sources, mainly wind energy. The European leader in the electric bus industry claims that by 2021, the e-bus fleet will add up to 400 vehicles in different cities in The Netherlands (Transdev, 2018).

The Hague ordered 5 electric buses in January 2018 with the option for another 3 buses for emission free public transport. Although the city took the first step into creating an e-bus fleet, this flow is not considered in the present analysis since there were no electric buses in The Hague in 2015 (Automotive World, 2018).

5. METHOD AND DATA

5.1. METHOD

The research includes a case study on cobalt present in products and waste streams in The Hague using substance flow analysis. The SFA was performed in STAN software developed by the University of Vienna. The goal of the model is to obtain a quantitative indication of how much cobalt was accumulated in The Hague in 2015, and how much can be expected for recovery for this year. This information will be used in further steps of the analysis to draw conclusions and give policy recommendations. Substance flow analysis is an analytical tool to study stocks and flows of specific materials. The method is useful to show a raw material supply, where the biggest flows can be found and what are the hotspots in their flows throughout the economy. The identified hotspots serve as a potential for metal recovery in order to increase metal production from secondary resources. SFA is commonly used in the literature on metal flows, which means it is an accurate measure for this type of analysis (Guyonnet et al., 2015).

Since there is no standardised SFA methodology, the choice of method for this research was made based on a recent study conducted by researchers from Leiden University. In their work, the focus was on tantalum flows in Europe, for which the supply chain is not yet fully understood (Deetman, van Oers, van der Voet, & Tukker, 2017). The method applied is very clear and, as the authors claim, can be used for other materials, therefore it will be adapted to a smaller scale for cobalt in The Hague.

The first part of the analysis was performed based on the mentioned framework. The research started with creating a list of products containing cobalt that can be found in The Hague. The list includes inflows, in-stock items and outflows to determine recovery potential depending on the available data. The next step provided concentrations of cobalt in previously identified items based on a literature review. Subsequently, the amounts of items present in the city were estimated. This led to a calculation of cobalt stock in different products within the city. The methodology for those steps is depicted in Figure 12. After obtaining stocks of cobalt in the year 2015, inflows and outflows were calculated based on products' lifetime, collection rates and other available data. Hibernating stock was estimated based on the collection rate. It was assumed that most of the Co-bearing outflow that is not disposed for recycling is accumulated in hibernating stock. Results of the analysis were used as an input for a model which calculated the remaining values in the cobalt flows in the city.

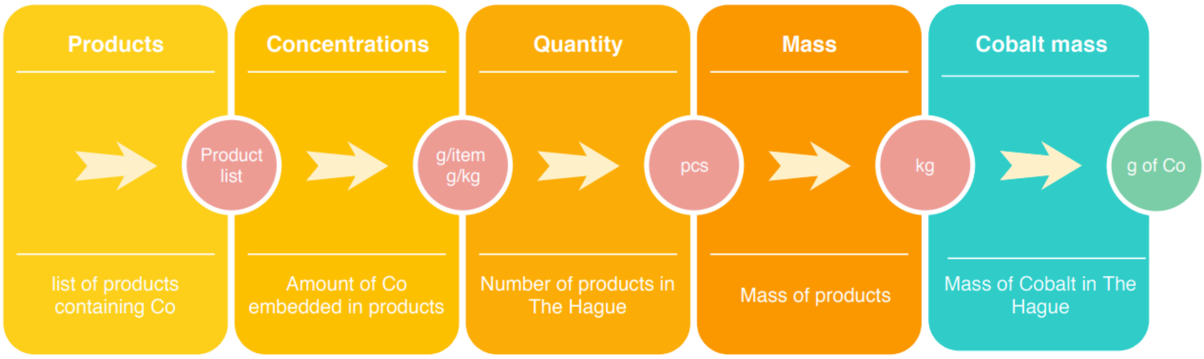

Figure 12. Methodology for obtaining amount of cobalt in products

5.2. DATA COLLECTION

The analysis of cobalt flows in The Hague is intended to be performed according to a bottom-up approach. This is done by estimating the actual amount of Co in the city based on specific data.

In general, the biggest groups of products considered in the analysis are small electronics, tools and vehicles, since those items can be found in the city flows. I made this assumption based on the literature review which indicated main products containing cobalt. Products that can be found in The Hague were selected according to my best knowledge. The full list of products can be found in the supporting information.

Various sources and statistics helped to determine actual number and mass of products, as well as concentration of Co in goods accumulated within the city. The concentration of cobalt in different products was obtained through literature review, in particular previous studies, MFA reports and websites. Substantial input was acquired from the website Grondstoffen Scanner, created by researchers from Dutch research institute TNO and other partners (TNO, 2017). This Raw Material Scanner includes a database of sectors, products and elements contained in them, as well as their concentration in each application. The source uses a Harmonised System (HS), which is an international standard for trade category codes. The tool helped select products that contain cobalt and are assumed to be found in The Hague.

Part of the information on Co-bearing products was obtained from local authorities. The municipality of The Hague provided number of electric cars registered in the city. From the data on electric vehicles, it can be observed that there is a clear trend of an increasing number of electric cars almost month by month (Figure 13). The average amount of electric cars in 2015 will give an indication of how much cobalt can be available for recovery in the future. It is not specified how many electric cars are owned by households and how many belong to the offices and construction sector. Therefore, the number of cars was distributed between those three sectors proportionally based on city population and number of employees.

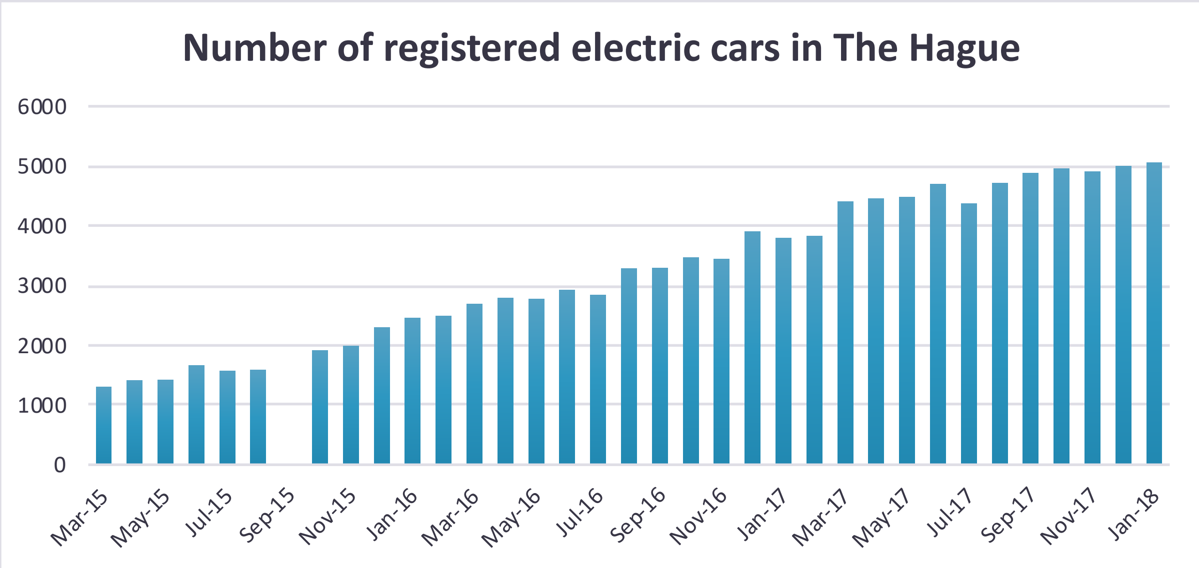

Figure 13. Number of registered electric cars in The Hague. Based on data from the Municipality

Depending on data availability, the bottom up approach may not be always possible. Therefore, in some cases, a top-down approach will be implemented using national datasets with adjusted values for the city level. While less accurate, it can nonetheless give an estimate on possible flows and fill in the gaps in data specific for The Hague. The estimation for the top-down approach is based on the population of the Netherlands and the number of citizens The Hague reported for the year 2015, taken from the national statistics. 2015 was chosen as a base for the material flow analysis since most of the collected data was available for that year. In case of lacking values for 2015, data for the closest available year was used in the analysis.

Where there was no possibility to obtain city-specific data, I investigated the market and used literature review to make estimations on products and concentrations of cobalt. Sales reports were used depending on their availability for the Netherlands or Europe. For most of the products there was national data available on penetration rates for household items. From this source a number of devices owned by a household or person was obtained and used as stock in the SFA model. Penetration rates for offices were determined based on number of pieces per inhabitant for The Netherlands from source (Van Straalen, Roskam, & Baldé, 2016). This value was used in the analysis and multiplied by the number of employees. Data on the number of employees in industries is based on labour statistics from the employment register of The Hague municipality provided by CBS for year 2015 (Rietveld, 2018). The part of this database used in the analysis can be found in Supporting Information.

In some cases, sales reports were used to determine inflows in the base year (2015). For several products the accumulated stock was calculated. An example is the amount of passenger cars that were registered until 1 January 2016. This information was assumed to indicate the stock of cars for 2015. Information on cobalt concentrations found in the literature were expressed in different units: g/item or g/kg. In the first case, accumulation of cobalt was determined by multiplying value for concentration with number of items found in The Hague. The second case required the use of additional parameter of a product's mass. This value was obtained from multiple sources.

To make the analysis as city-specific as possible, the analysis differentiates between following sectors: households, offices and the construction industry. Since the data availability for local product flows is very limited, looking at the city from a sector perspective will enable a more accurate estimation of flows in this particular city. Apart from households, sectors were chosen from the Dutch Standard Industrial Classification SBI 2008 (CBS, 2018b) after identifying where the highest number of Co-bearing products can be used. In households we can find multiple portable consumer electronics, as well as big amount of electric cars, motorcycles and electric bicycles. Offices are also a big source of electronic devices, such as laptops, desktop computers and mobile phones. The construction sector uses many different tools that contain cobalt in batteries and hard materials. A detailed list of included sectors can be found in Supporting Information.

For the end of life stage, there are differences in the collection rates between sectors. Typically, the collection rate of electronic devices is higher in offices than in private households.

All numerical values and their sources are described in detail in the Supporting Information.

6. RESULTS

6.1. GENERIC CITY METAL FLOW MODEL

The main result of the analysis is the generic model with disaggregated city flows of cobalt. The model serves as an indication of the approximate cobalt stock and flows through the city. It is based on city demographics and cobalt intensity per sector, calculated from the case study for The Hague. By changing information specific for each city, the model can be used for other urban areas. Parameters that can be adjusted are population, number of offices, number of employees per sector and the specific quantities of products, if known.

Figure 14 below depicts the main flows in The Hague and the sector disaggregation within the city, which are the elements of the model. Main inflows indicated for the Hague are: small electronics, tools, electric cars, cars, motorcycles and electric bicycles. Main outflows consist of collected E-waste, EoL vehicles and products that are disposed with municipal waste and therefore lost in incineration slag. There are four parameters that can be changed in the model according to data for specific city, shown in circles in the figure below. The two main parameters are population and the number of employees per sector, which need to be determined for a city. The number of electric cars and quantities of products can be changed if known. Otherwise values currently used for quantities of products based on penetration rates for The Netherlands are applicable for other cities. If the number of electric cars registered in a different city is not known, then the model will use an average value for the Netherlands.

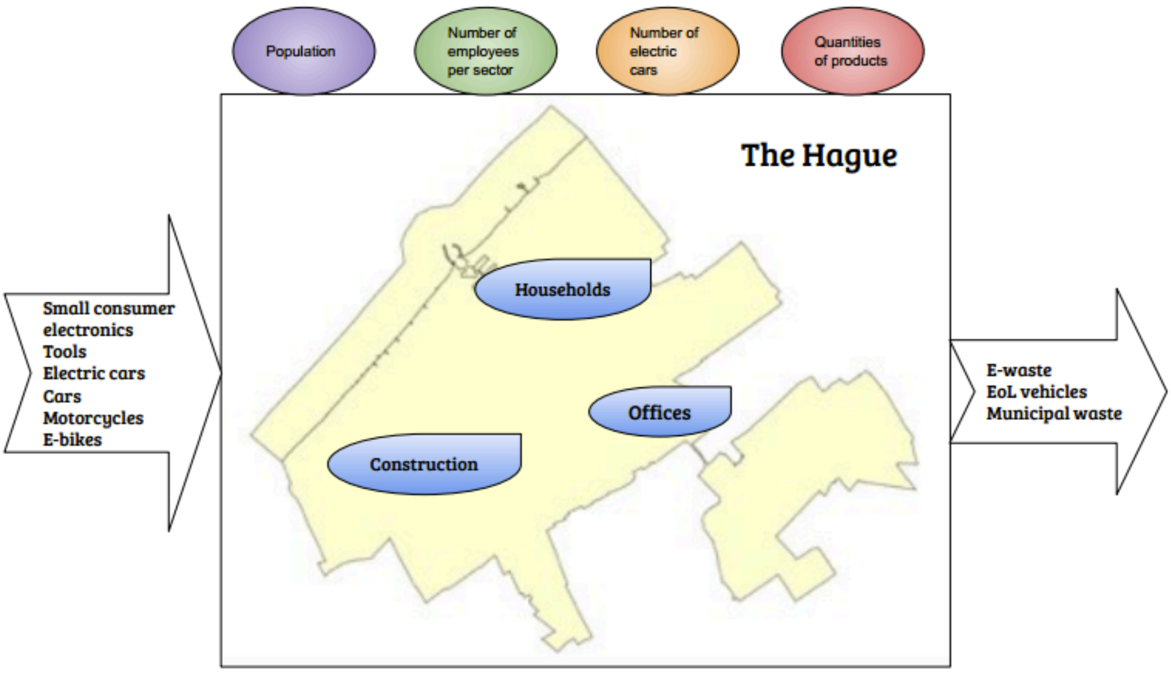

Figure 14. Diagram with flow groups and disaggregation within The Hague

Table 1 below, depicts the result of calculations for cobalt intensity indicators for each analysed sector in The Hague for the year 2015. This is a quantitative information on which sector has the highest impact on the cobalt stock in a city. Those indicators can be used instead of a detailed model for other cities after adjusting demographic parameters, such as the number of inhabitants and number of employees. It gives a quick and rough estimation on expected cobalt content in the analysed city.

Table 1. Cobalt intensity indicators in stock per sector in The Hague 2015

Sector	Co intensity	Unit	Population	Total Co stock [kg]
Households	0.12837	kg/inhabitant	514861 inhabitants	66,091
Offices	0.10436	kg/employee	62592 employees	6,532
Construction	0.10015	kg/employee	10343 employees	1,036
SUM [kg]				73,659

For The Hague, total in-use stock accumulated in the city summed up to 73.7 tons of cobalt embedded in a diverse range of products. The highest Co intensity was revealed in households (0.128 kg per capita) due to mostly electric cars, but also to battery-powered small appliances. Offices and construction sites have similar Co intensity of 0.10 kg per employee, although they are characterised by different end applications.

The entire model is available in the Excel file *Model final* attached to the Supporting Information.

6.2. CASE STUDY THE HAGUE

In this section results of the case study for The Hague will be analysed in more detail.

Results of the SFA analysis are depicted in the Sankey diagram shown below in Figure 15. The system boundary was set as city of The Hague. Values represent cobalt content embedded in products. Inflows are products entering the city, which subsequently enter the stock. Squares with Co stock in 2015 for each sector represent the old stock accumulated before the year of analysis and the delta stock, which is the sum of inflows in the year of analysis (2015). Old stock for each sector is much higher than the amount of cobalt in products that entered the city in 2015. Only households generate hibernating stock in this system, which is one of the assumptions in the model since offices and construction sectors do not accumulate used equipment. All flows and values presented on the diagram and assumptions made for their calculations can be viewed in Supporting Information.

The leading sector in cobalt concentration is households, which accumulate the highest stock of this metal through various products. The *Electric car battery* was far the biggest Co inflow into the city in 2015, representing 16.61 t of cobalt. The following streams are much smaller but still significant for the model: *E-bike battery (1.1 t)*, *Laptop (1.09)*, *Mobile phone (1.04 t), EEE in vehicles (0.68 t)*.The remaining cobalt mass is distributed between other small applications. Consequently, in the outflow from the city boundary, the highest amount of cobalt can be found in *EoL vehicles* (6.85 t), mostly due to batteries used in electric cars. A substantial flow is *E-waste from households* (0.67 t Co), where cobalt is dispersed in batteries of multiple appliances. Hibernating stock represents 0.64 ton of Co, which is difficult to reach and therefore not currently available for recovery.

In offices, the highest inflow are electric cars (2.02 t Co). Laptops and tablets contribute 0.2 t to Co stock in the city. Those application are also leading in E-waste generated in this sector.

The construction sector has the lowest influence on the cobalt stock, since the quantities of the metal in products is very low compared to other applications. The inflow of cobalt in electric cars is 0.33 t, while 0.1 t Co left the city in 2015.

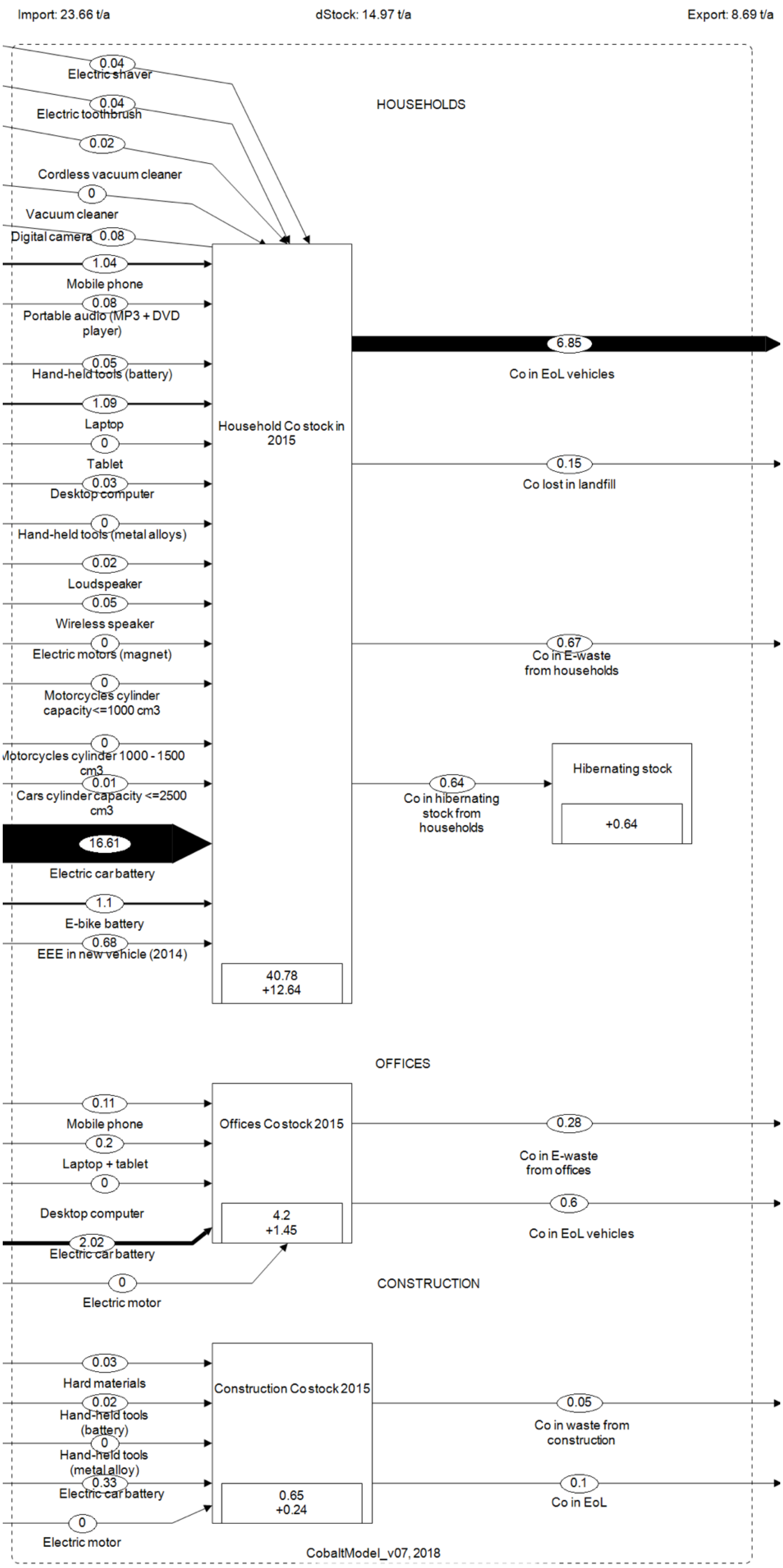

Figure 15. Sankey diagram of cobalt stocks and flows in The Hague from STAN software In 2015 (tons Co)

Figure 16 depicts flows in The Hague. The Sankey diagram was created using online tool for visualising results of analysis (SankeyMatic, 2018). It is clear that inflows of cobalt (23,664 kg) from different sources surpass the outflows (8,691 kg) for this year. This is the case due to the high and increasing inflow of electric cars, which have not yet reached their end of life phase. Due to the lifetime of electric cars batteries (8 years) and the fact that electric cars gained popularity relatively recently, the outflow of batteries from this source is yet to come. The difference between total inflow and total outflow is a contribution to the stock in 2015 (14,972 kg).

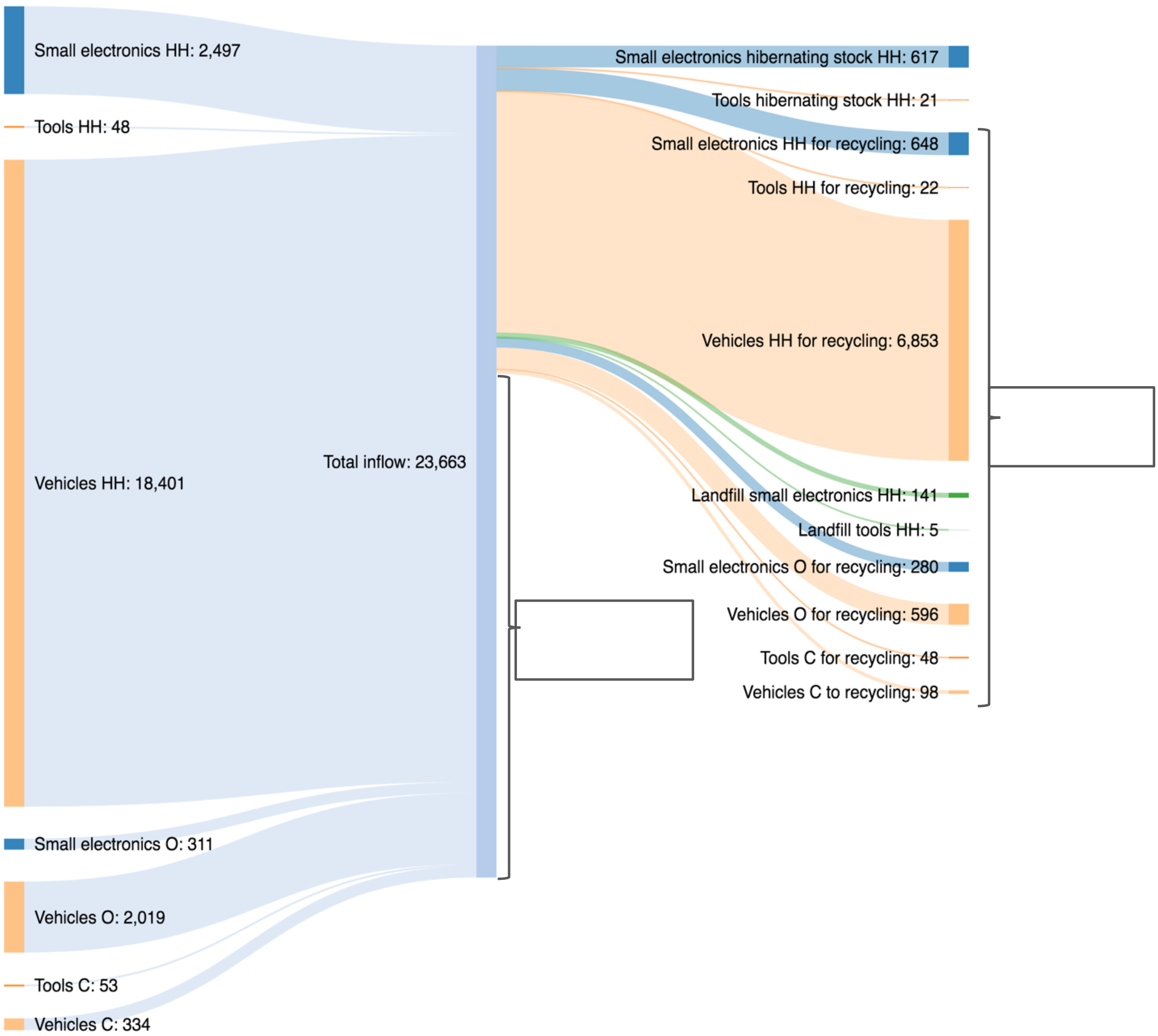

Figure 16 Sankey diagram of cobalt flows in The Hague in kg of Co (2015)

Sectors: HH-household, O – office, C - construction

6.2.1. COMPARISON BETWEEN SECTORS

Table 2, below, depicts the quantitative results for all flow types and sectors in The Hague considered in the analysis. As already observed in Figure 6, stock is the biggest accumulation of cobalt in the city for each sector. Households have the biggest potential for cobalt recovery, since the amounts of this metal in the end of life streams are the highest. Even though the collection rates for households are lower than for other sectors, the number of spent appliances creates high stream of Co-bearing products. It is assumed that offices and the construction sector do not generate hibernating stock and outflow to landfill.

Table 2. Aggregated results for each sector and flow in kg of cobalt (2015)

Flow	Households			Offices		Construction	
	Small electronics	Tools	Vehicles	Small electronics	Vehicles	Tools	Vehicles
Inflow	2497.03	48.44	18400.83	311.26	2019.48	53.25	333.71
Stock	3629.09	290.63	56712.36	1237.00	5294.82	160.95	874.94
Hibernating stock	616.89	21.26	-	-	-	-	-
Outflow	647.81	22.33	6853.24	280.13	595.67	47.93	98.43
Outflow to landfill	140.52	4.84	-	-	-	-	-

Interesting insights come from comparison of cobalt end applications distribution in the city and on global scale. Figure 17 shows main cobalt applications in the stock in The Hague for all sectors in 2015.

When comparing with global end use applications in 2015 (Figure 8), cobalt stock in The Hague consists of four largest end use groups. Those main groups account for roughly 75% of global uses. Similarly to global distribution, in The Hague the main application is battery, followed by superalloys. In the city, nearly 90% of all final products use cobalt in battery chemicals. In case of The Hague category *battery chemicals* includes all products using batteries, namely electric cars and small electronics. *Superalloys* bring together cobalt used in electronics in vehicles and alloys in hand-held tools. *Hard materials* in this research consist of tools used in construction sector. *Magnets* are used in loudspeakers, corded vacuum cleaners, car motors.

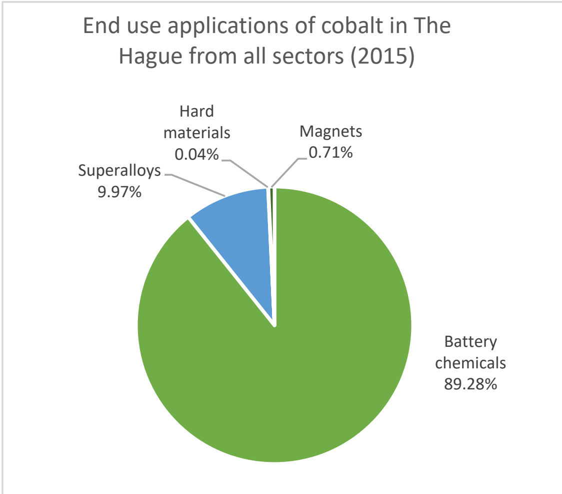

Figure 17. End use applications of cobalt in The Hague (2015)

Figure 18, below, shows applications with the highest cobalt stock in the city in 2015 for three sectors. From this graph it is clear that almost all of the cobalt in this sector comes from vehicles, mostly electric car batteries. Other products included in vehicles are E-bikes and electronics in cars. In households, electric car batteries are the leading application with 66 % share of Co city stock for the top 10 products.

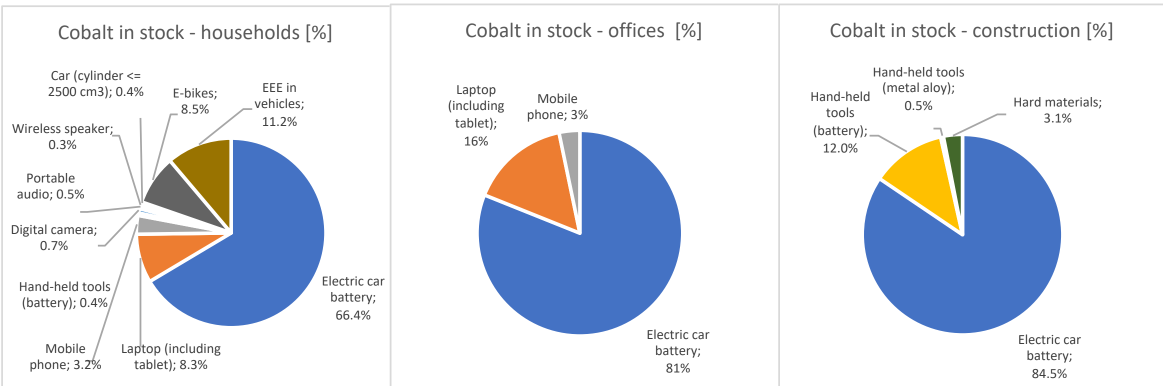

Figure 18. Products with the highest cobalt stock in households, offices and construction sector in The Hague (2015)

Stock of cobalt in offices is dominated by electric car batteries, followed by laptops and tablets.

For the construction sector, distribution of cobalt among applications is shown on the right side of Figure 18. Here as well, the batteries of electric cars are the main contributor to Co stock. In second place are batteries in hand held tools, followed by hard materials used in tools.

6.3. COMPARISON WITH ANOTHER CITY

6.3.1. AMSTERDAM

In order to validate the generic city model, it was tested by performing the analysis for another Dutch city. Amsterdam will be the example of such model application. Table 3 shows results for both cities which makes them easily comparable.

Table 3. Comparison of Co intensity in stock per sector for The Hague and Amsterdam

	The Hague				Amsterdam			
Sector	**Co Stock**	**Unit**	**Population**	**Total Co [kg]**	**Co Stock**	**Unit**	**Population**	**Total Co [kg]**
Households	0.12837	kg/capita	514861 inhabitants	66091.10	0.22525	kg/capita	1091000 inhabitants	245750.75
Offices	0.10436	kg/employee	62592 employees	6531.82	0.20176	kg/employee	78255 employees	15788.43
Construction	0.10015	kg/employee	10343 employees	1035.89	0.19755	kg/employee	13730 employees	2712.43
SUM [t]				73.66				264.25

Cobalt intensity for households is 1.75 times higher for Amsterdam. A similar difference can be seen for other sectors as well. This is due to the higher number of electric cars, the main contributor to cobalt stock. This indicator is different for each city because of the difference in numbers of electric cars. For The Hague, a specific number of cars was provided, while in the case study for Amsterdam, an average number for The Netherlands was used. The indicator for offices and construction are almost the same for The Hague. This trend is applicable also for Amsterdam. The overall mass of Co in Amsterdam is much higher comparing to The Hague.

Distribution of cobalt bearing products in both cities is shown in Figure 19. Main applications are the same for The Hague and Amsterdam, where batteries in electric cars are the major component. This category is substantially higher for the capital city.

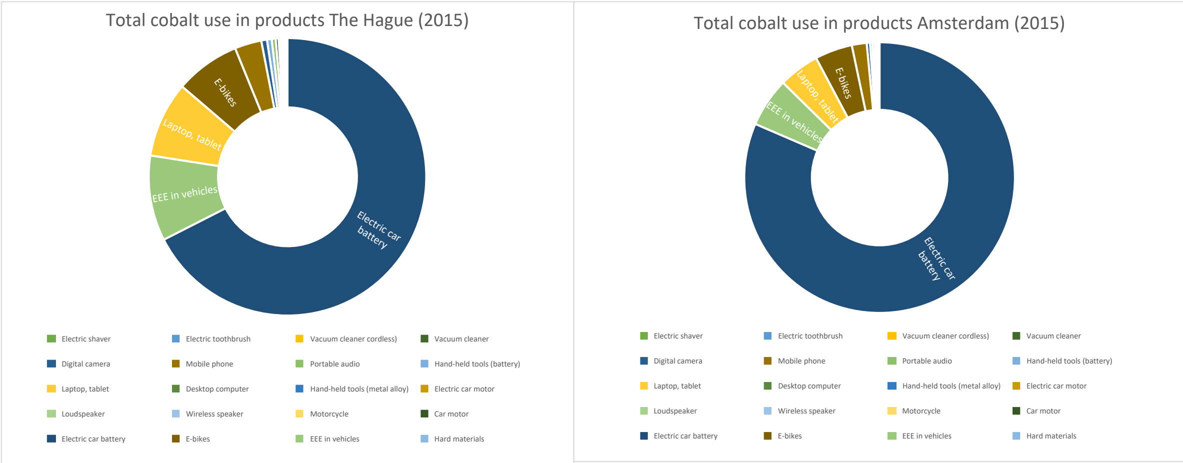

Figure 19. Total cobalt use in The Hague (left) and Amsterdam (right)

7. DISCUSSION

7.1. ANALYSIS OF RESULTS

This section will elaborate on the main findings of the analysis and their meaning for the recycling of not only cobalt, but also other critical raw materials. After analysing the results presented in previous section, several observations were made.

First of all, households are the main point for addressing cobalt recovery initiatives. This statement is supported by the highest cobalt intensity in this sector. Hibernating stock estimated as 0.64 t Co should be more easily available for recycling instead of being accumulated. In order to do so, inhabitants have to be incentivised to dispose of unused appliances in a proper manner. An initiative of another European city might inspire the collection of items in hibernating stock. In Szczecin, Poland, a university organised an event where a small flower was given for every used electronic item brought to the collection point (Głos Szczeciński, 2015). This way many citizens disposed of their spent electronic devices that were no longer used. Increasing collection rates in households would have a big influence on recycling potential in the city and would also reduce the generation of hibernating stock. Collection rate is a very important component of the recycling rate; that is the first step to successful metal recovery.

Regarding other analysed sectors, offices have the highest number of employees and subsequently more Co-bearing products in use. The highest number of offices is in specialist business services, including researchers and advisors. Therefore, potential for collection and recovery of cobalt is highest in this sector.

The stream that should be given most attention are batteries, especially from electric cars. This application contributes to the most cobalt stock already in the city in 2015. It is expected that the flow of electric cars is even higher, creating an important source for future recovery. That is supported by the number of electric cars registered in The Hague, which almost doubled comparing values for year of analysis (2015) and January 2018. Adding to that, the distribution of electric cars among different sectors was not known prior to conducting the research. Therefore, the assumption made about car division based on population and number of employees could be replaced with more accurate data.

Batteries in electric buses that were not quantified in this analysis will also strongly increase the overall cobalt stock in the city. The ambition of Dutch government to create emission free transport contributes to the increase of cobalt demand in this field. However, this application requires further investigation, since it is not clear which battery chemicals are used in batteries for electric buses already present in The Hague.

Recycling technologies, particularly for CRM, are known and yet still the recovery activities are rarely implemented. This is due to the difference between raw material cost and the higher cost of secondary metal production. In order to change that situation, more research is required to make the technologies more accessible.

I have created the generic city model with the purpose of applying it for other materials or cities, after implementing the necessary adjustments and incorporating elements specific for each material or city. The main idea behind the model is to improve the level of national and EU analysis of critical materials stocks and flows. In my view creating a system with a map of material flows for cities, followed by provinces and countries will be advantageous for the global overview of metal flows through the economy. The generic city flow model is the first step that should be taken to extrapolate the bottom-up approach in order to get reliable results on a broader scale.

For a quick estimation of cobalt stock in a city I calculated cobalt intensity indicator which can and should be used in other case studies. The intensity indicator was calculated based on the outcomes of case study for The Hague and determines the amount of cobalt per person or per employee for each sector. It is important to note that intensity indicator calculation involved making several assumptions for the specific city and it can give only a rough estimation in case of other urban areas.

There are several limitations identified for application of the model to other cities. Products using cobalt not present in The Hague were not included and need to be added for each city. This is the case for aircrafts, catalysts, gas turbine engines and chemical uses. Where there was no city-specific data, the model uses national average values which may not be accurate.

Due to the fact that there are no other city-level cobalt stock and flow quantifications in the literature, I was not able to validate the outcomes of my analysis. The only source that distinguishes material flows for elements (including cobalt) is ProSUM project, described in the Supporting Information. However, I decided not to use this source as a reference for comparison, due to its broader, national scope. The city level does not consider all possible cobalt applications, only those found in the specific city. Another reason were not transparent assumptions made in the ProSUM calculations, which made the results difficult to compare.

7.2. RECYCLING TECHNOLOGIES FOR COBALT RECOVERY

The most promising application for cobalt recovery are batteries used in electric cars and small electronics. This application represents the functional recycling of cobalt described in more detail in section *Cobalt recycling*. Batteries have relatively short lifespan, and considering the growing demand for electric cars, this application can be expected to provide a reliable stream of spent products for metal recovery. Batteries have a realistic recovery scenario since they are already recycled by at least two cobalt refineries in Europe.

Therefore, the recycling technology is already in place for this stream. Batteries are also a positive example of a functional recycling, where recovered metal does not lose its properties, and only plays the same role as a secondary raw material. As mentioned before, in battery recycling cobalt is extracted from spent products and used as a catalyst in new battery.

It is expected that the recycling of cobalt from alloys in hard materials used in tools manufacturing will be more challenging. This is due to difficulties in separation of materials. Moreover, diamond tools containing cobalt get worn down during use phase, therefore the remaining material does not have a high cobalt concentration. In the case of cobalt alloys, they are often recycled non-functionally together with other types of metal alloys, where valuable qualities of cobalt are lost.

7.2.1. GAPS AND LIMITATIONS FOR CRM RECYCLING ON A CITY LEVEL. IS CITY-LEVEL RECYCLING POSSIBLE?

There are several limitations for CRM recycling at city level, as well as on a global scale. In general, issues with metal recycling concern low collection rates and often lack of economic incentive due to the high recovery cost or low price for primary material. Another aspect of limiting recycling and implementation of circular economy is material complexity. New energy technologies use many different elements in low concentrations because together they provide better performance. From the end of life perspective, those alloys are difficult to process and recover the constituents. The reasonable way of treating those complex materials is reusing them in a new product with the same material composition (UNEP, 2013).

In order to recycle cobalt on a city level, there would need to be secured supply of waste containing it. As mentioned before, the Umicore refinery has capacity of 1.5 kt cobalt content, which includes both the production of primary metal and recycling. In order to make the recovery profitable, the recycling facility should have similar capacity which is challenging at an urban level. In The Hague, the total stock of cobalt that can be theoretically available for recycling after the end of life was 68 tones, which is as little as 5% of Umicore's capacity. It is important to note that most of this quantity is an old stock, which was accumulated during previous years. The yearly inflow to the city was just over 22 tons of Co. Therefore, city level recovery is not feasible at this point.

National level recycling could be a more feasible solution, but there are still questions whether every country should have a recycling plant for cobalt and possibly other CRM. This idea comes with substantial investment (building a facility, collection, separation of materials, treatment of hazardous substances, processing and purifying) that may be attractive for bigger countries, but difficult for smaller countries such as the Netherlands in terms of long-term profitability. In this case, it seems more reasonable to install a network of waste flows that come from all European countries to several facilities within EU, that can recover cobalt together with other valuable metals. This way, the capacity of the facility can be assured with less effort by combining EoL streams on a European level. Each country would need to contribute by increasing collection rates and store collected waste for a functional recovery later on. In order to avoid big investments, recovery activities should be undertaken by already existing cobalt refineries in Europe. That is happening already in Belgium and Finland, and there are at least two more refineries in Norway and France which could contribute and recycle cobalt from scrap together with the production of raw cobalt metal. This perspective requires thorough planning and cooperation between many countries but is the most feasible scenario at this moment.

An alternative solution for cobalt criticality and it's expected rapidly growing demand is the reduction of Co concentration and substitution. As mentioned before, there are already activities resulting in the lowering of the amount of cobalt used in hard materials for tools production. This was motivated by very high Co prices, lower availability and environmental issues. This is not happening in the tool industry alone; producers of batteries for electric vehicles are thinking about reducing cobalt content from one third Co in LI-ion nickel-cobalt manganese battery (NCM 111) to even one tenth Co in NCM 811 battery (Mining.com, 2018). Tesla has already reduced its Co concentration by 60% in the past several years. The company has announced further reduction in cobalt content with ambitions of eliminating Co almost completely (Barrera, 2018).

7.3. FURTHER RESEARCH

There are many issues directly connected with the topic of critical raw materials recycling. As a master thesis cannot investigate all associated aspects, the research boundaries and limitations are described here.

One of the topics outside of the boundary of this research is the environmental impact of metals' recovery. It is important to know whether the benefits of recovered materials are reduced by creating potentially negative environment impacts. This topic could be interesting as a further research.

Another interesting idea used in scientific research is the incorporation of geographic information system (GIS) mapping for more accurate analysis, where possible. This method has shown good results when incorporated in material flow analysis. Using existing geographical city maps, the estimation of cobalt content is expected to be more accurate. Furthermore, this approach lowers the possibility of overlooking important flows. An example of such analysis is the PUMA project performed for selected metals (copper, lead, aluminium) in buildings in Amsterdam, which assessed the potential of urban mine as a source of secondary metals (AMS Institute, 2016).

Finally, a more accurate city-specific quantification of product stocks (beyond demographics) would make the research closer to reality. Updated concentrations of cobalt in products could be based on a field study measuring actual values in items present on the market. This approach was not possible within the time frame of master thesis research. The new stream of electric buses should be included in future analysis, since they could be important contributors to the overall city stock.

Moreover, further analysis should include more accurate division of electric cars used by each sector. Distinguishing between different types of electric cars and detailed cobalt concentration depending on battery chemistry would give more accurate results.

8. CONCLUSION

Present study is an example of city-level substance flow analysis for critical raw materials. Main outcome of this research is a generic city flow model, which was used in a case study for cobalt in The Hague. The generic city model is meant to be applied for other materials or cities, after implementing necessary adjustments and incorporating elements specific for each material or city. The model will help to create a better national and subsequently EU level analysis. This can be implemented by creating a map of cities, followed by provinces and countries. The generic city flow model is the first step to extrapolate the bottom-up approach to get reliable results on a broader scale. For a quick estimation of cobalt stock in a city, cobalt intensity can be used. The intensity indicator was calculated based on the outcomes of case study for The Hague and determines the amount of cobalt per person or per employee for each sector.

I have concluded that the methodology differentiating between sectors of industry in the city applied in this analysis is appropriate for the limited level of city-specific data. This solution was the closest possible strategy within the time frame of thesis research project to estimate amount of cobalt flows in the city and assess recovery potential on urban scale.

One of the research aims was to assess recycling potential on a city level. Apart from recycling limitations applicable for all materials, namely low collection rate, material complexity, low concentration, lack of efficient and economically attractive recovery methods, there are gaps that I have identified for CRM based on the case study.

Based on the quantitative results and literature review I came to the conclusion that urban level recycling of cobalt is not feasible. This is mostly due to not sufficient end of life material input. Successful metal recovery requires constant inflow of scrap, which cannot be fulfilled at the moment. In my view, recovery of cobalt on European level with strong cooperation between countries is a promising recycling scenario. This statement is presumably true for other critical raw materials as well.

8.1. POLICY RECOMMENDATIONS

Based on the outcomes of the study, the following are policy recommendations for the municipality of The Hague and the Dutch government regarding cobalt flows in the city. Those recommendation are mostly also relevant for other critical metals. Figure 20 is a graphical representation of policy recommendations followed by more detailed description.

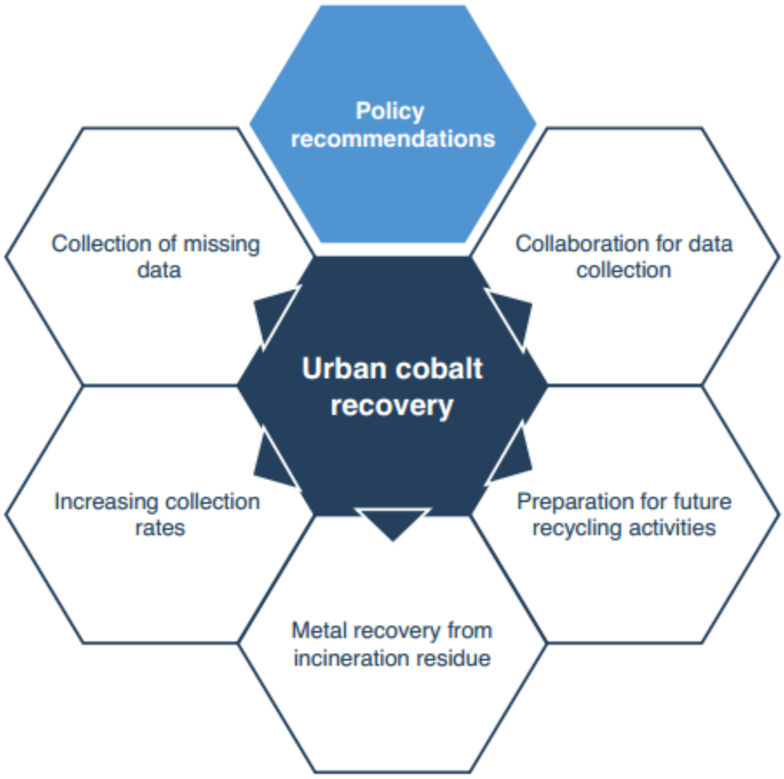

Figure 20. Policy recommendations for cobalt recovery on a city level

I. Collection of missing data

In order to improve the quality of material flow research for critical raw materials in the city, I advise to collect certain data.

For better understanding of cobalt flows throughout the city, more transparency is needed in product composition. I encountered difficulties in obtaining information on exact *concentration of cobalt* in specific items on the market. This can be fulfilled by a detailed research gathering this information directly from producers or by measuring the weight of cobalt separated from carrying it product. This data should be regularly updated considering changes in product design and already mentioned trend in lower cobalt usage in some products.

Regarding material flow quantification, the missing data points are exact *numbers of devices* identified as containing cobalt. It is crucial element of the analysis determining the magnitude of cobalt concentration. The information on quantity of products should be collected for all sectors within the city.

As I have shown in this report, *distribution of products* among sectors have big influence on final results. It should be more accurate in order to address future recovery activities to appropriate sector.

II. Collaboration for data collection

Local data collection needs improvement in order to perform research for cobalt recovery potential. There should be more cooperation between government, industry, enterprises, research centres and academia in order to make a detailed and more accurate analysis possible. Those actors should work together on acquisition of local data on cobalt content in products and waste flows and create a database accessible for researchers. An example of this initiative is a secured online platform, where all actors involved in local flow of products containing cobalt (producers, importers and users) can provide information on number and type of devices, lifetime and disposal of their products. Authorised researchers in cooperation with local government and statistical bureau should have access to this information for their analysis and present results to the interested parties. This idea can be extended for other materials relevant for the city or country. The municipality should incentivise other actors to provide input from their side.

Moreover, the data already gathered by local authorities and CBS should more easily available for research. For this reason, it is advised to create more cooperation between CBS, the Municipality, academia and research institutes.

III. Increasing collection rates

High collection rates are the first crucial step to successful material recovery. Therefore, an effective collection scheme through policy regulations should be implemented. The scheme would be applicable to the city, as well as on a national level, bringing all cities together in this effort.

IV. Preparation for recycling activities

Regarding recycling, the city should collect electronic scrap and store it until the quantity is enough to recycle it. At that time the material should be sent to the closest refining facility with recycling plant to recover the secondary metal. It is important to trace the cobalt flow from recycling to avoid downcycling the metal in lower quality alloys. A way to ensure cobalt is not lost during recovery is the implementation of certificates that go together with the scrap until the metal is separated.

V. Metal recovery from incineration residue

Metal recovery from incineration residue requires more attention from authorities. The part of the metal waste that ends up in municipal waste should be separated during waste collection activities. If a part of the metal is still incinerated with waste, it can be recovered from the incineration slag. This type of recovery is already in place for many metals in production facilities.

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10. SUPPORTING INFORMATION

Data from CBS used for analysis in The Hague

Data presented below was used in the analysis of The Hague presented in section Case study description of the main paper. Information from CBS websites originally is available in Dutch; therefore, the content was translated into English using Google Translate platform.

Table S1a. Number of businesses per industry for 2015 (source: CBS)

	Region		
Business locations; control, industry, region	**The Netherlands**	**Amsterdam**	**Agglomeration 's-**
Industry	Branches		
A Agriculture, forestry and fishing	71260	1290	2010
B Minerals extraction	470	25	40
C Industry	63555	4175	1805
D Energy supply	1070	75	15
E Water companies and waste management	2155	145	70
F Construction industry	148495	9790	8410
G trade	262240	22590	10960
H Transportation and storage	38985	4975	1405
I Horeca	55210	6295	2745
J Information and communication	80005	12935	4405
K Financial services	117085	11900	4490
L Rental and trade of real estate	26610	2995	1530
M Specialist business services	301240	39985	16920
N Rental and other business services	66960	7620	4035
R Culture, sports and recreation	91120	17965	4600
S Other services	92330	7820	4655
Extraterritorial organizations	5	0	0
SUM	**1418795**	**150580**	**68095**

The term *branch* is understood as "Each separate space, terrain or complex of spaces or grounds, used by a company for carrying out the activities. Every company consists of at least one branch" (CBS, 2017).

Category *M Specialist business services* mean "Advising, research and other specialist business services". It includes "specialized professional scientific and technical activities. These activities require a high level of education and provide specific knowledge" (CBS, 2017).

Table S1b. Number of employees per industry and per legal form for The Hague in 2015 (source: CBS)

	Region: Agglomeration 's-Gravenhage (CR)								
Business locations; size, legal form, industry, region	**Branches**	**Location size**				**Legal form**			
Industry		0 employed persons	1 working person	2 to 10 working persons	10 or more employees	One-man business	VOF, CV and partnership	NV's en BV's	Other legal forms
A Agriculture, forestry and fishing									
B Minerals extraction	2010	10	1665	300	30	1625	280	105	0
C Industry	40	0	25	5	10	10	0	30	0
D Energy supply	1805	45	1225	395	135	1075	215	505	15
E Water companies and waste	15	0	10	5	0	0	0	10	0
F Construction industry	70	5	40	15	10	30	0	30	10
G trade	8410	60	7350	865	135	6975	650	770	15
H Transportation and storage	10960	390	6360	3505	705	5345	1950	3550	115
I Horeca	1405	85	950	280	90	845	230	285	45
J Information and communication	2745	110	1265	1160	210	1375	725	605	35
K Financial services	4405	60	3655	515	180	2870	350	1110	70
L Rental and trade of real estate	4490	755	3105	510	115	230	125	4000	135
M Specialist business services	1530	75	1045	350	60	435	225	800	70
N Rental and other business services	16920	405	14440	1690	390	10980	1010	4710	225
R Culture, sports and recreation	4035	105	2765	815	350	2475	410	1080	70
S Other services	4600	35	4085	380	100	3665	245	300	390
Extraterritorial organizations	4655	60	3625	810	160	3240	345	175	895
SUM	68095	2200	51610	11600	2680	41175	6760	18065	2090

All numerical data used in the analysis:

Table S2. Products and respective components used in the analysis

Component \ Product group	Small electronics												Tools	Vehicles				
	Electric shaver	Electric toothbrush	Vacuum cleaner (cordless)	Digital camera	Mobile phone/ smartphone	Portable audio (MP3 + DVD player)	Laptop	Tablet	Loudspeaker	Wireless speaker	Desktop computer	Vacuum cleaner	Hand-held tools	Electric car	Car	Motorcycle <1000 cm3	Motorcycle 1000-1500 cm3	E-bike
Battery	x	x	x	x	x	x	x	x		x			x	x		x	x	x
Magnet									x		x	x			x	x	x	
Electronics/ Metal alloys													x	x	x			

Table S3. List of products containing cobalt and respective concentrations

Name	Value	Unit	Source	Description	
Cobalt concentration in products					
Electric shaver	0.706	g/item	(Sommer, Rotter, & Ueberschaar, 2015)	Batteries; calculated based on total Co in products in Germany, which was divided by the amount of sold products	
Electric toothbrush	0.867				
Vacuum cleaner (cordless)	2.647				
Digital camera	2.958				
Mobile phone	5.002				
Portable audio (MP3 + DVD player)	3.086				
Radio set	0.324				
Video camera	13.062				
Hand-held tools (battery) [2)]	4.720				
Laptop	13.860				
Vacuum cleaner	0.000005	g/kg	(TNO, 2017)[5)]	Magnet	
Tablet	*0.0322*	kg	Battery weight: (Dell, 2018)	*Calculated*: concentration from Table 4.1 (14wt%); battery weight (0.23 kg)	
Desktop computer	0.0157	%	(Harper, Kavlak, & Graedel, 2012b)	Used in structural components, housing, cathode ray tube, and printed wiring board	
Hand-held tools (metal alloy) [2)]	0.18	g/item		Assumed 50% by weight of each tool is made of high-speed steel, which contains 7.67% cobalt	
Hard materials	3.7	%		On average tools are made of 48 wt% hard steel (average of 10 products), which contain 7.67% cobalt[6)]; 3.7% Co/item	
Portable electric lamp	0.18	g/item			
Drills	0.025	%			
Electric motors	0.000009	g/kg	(European Commission, 2017a);	Magnets	
MRI	0.002940	g/kg	(TNO, 2017);		
Microphones	0.41454	g/item	(Adams Magnetic Products, n.d.)		Contains samarium permanent magnet with 63 wt% cobalt[4)]
Loudspeaker	0.41454	g/item			
Guitar pickup	0.41454	g/item	(Chemicool, 2012); (Adams Magnetic Products, n.d.)		

Name	Value	Unit	Source	Description
Wireless speaker	2.958	g/item		Battery; Assumed same weight as digital camera
Motorcycle (cylinder <=1000cm3)	0.000736	g/kg	(TNO, 2017)1)	New vehicles with a cylinder capacity of up to 1000 cm3 3); assumed it's including battery
Motorcycle (cylinder 1000-1500 cm3)	0.000325			New motor vehicles with a cylinder content between 1000 and 1500 cm3 3); assumed it's including battery
Car (cylinder <= 1500 cm3)	0.002044			New cars with a cylinder capacity of up to 1500 cm3
Car (cylinder <= 2500 cm3	0.000744			New cars with a cylinder capacity of up to 2500 cm3
Car (cylinder > 2500 cm3)	0.010792			New cars with a cylinder capacity of at least 2500 cm3
Motor vehicles with an electric motor	0.003587			
HEV battery	1.8	kg/item	(Harper, Kavlak, & Graedel, 2012b)	Value for HEV
Electric car battery	21.6			For Tesla model S: battery pack weights 540 kg; 4 wt% of battery is Co (Table 4) resulting in 21.6 kg Co per battery pack
E-bike battery	*0.132*	kg	Battery weight: (Hollandbikeshop, 2018)	*Calculated*: concentration from Table 4.3 (4wt%); battery weight (3.3 kg)
Average new vehicle (2014)	50	g/item	(Restrepo et al., 2017)	Mostly in permanent magnet in electronic power steering motor
Average vehicle in stock (2007)	30	g/item		
Average End of Life vehicle (2000)	20	g/item	(Restrepo et al., 2017)	Mostly in alternator and speakers

Comments:

1) There was a confusion, whether source (TNO, 2017) uses comma as separator for decimals or thousands. I assumed, that it separates decimals. For simplicity of calculations, unit of numbers was changed from g/tonne into g/kg by dividing the value by 1000.

2) Hand-held tools batteries and metal alloys are considered separately; this category is including drilling machines, saw and others)

3) Types of motor vehicles (motorcycle, truck) were assumed based on the cylinder capacity range.

4) Loudspeakers, microphones and guitar pickups contain samarium permanent magnet with 63 wt% cobalt; the concentration was calculated from average magnet weight (0.658 g) and its cobalt content

5) The source uses Harmonised System, international standard trade category codes

6) High speed steel used in tools can contain 5, 8 or 10% cobalt depending on the type of steel (BandSawHub, 2016; Lenox, 2018; Wikipedia, 2018a). Average of those values (7.67%) was used in the analysis. Average HSS in tools calculated based on (Harper, Kavlak, & Graedel, 2012a)

Table S4. Cobalt concentration in batteries and their typical applications

Lp	Name	Value	Unit	Source	Description
1	Li-ion Lithium cobalt oxide (LCO)	14	Wt %	(Sommer et al., 2015) *(Battery University, 2017)*	*Laptops, mobile phones, cameras, tablets*
2	Li-ion Nickel Cobalt Aluminum Oxide (NCA)	2.5			*Medical devices, industrial, electric powertrain (Tesla)*
3	Li-ion Nickel Manganese Cobalt Oxide (NMC)	4.0			*E-bikes, medical devices, EVs, industrial*
4	Li-ion other types	0			-
5	NiCd	1.0			-
6	NiMH AB5	3.0			*Portable devices*
7	NiMH other types	3.0			
8	Other batteries	0			-

Information on exact type of lithium ion battery used in a device is not easily available. Therefore, the type of Li-ion battery will be assumed based on their typical applications found in the literature.

Table S5a. Penetration rates of electrical appliances in Dutch households (%)

Name	Value	Source	Description	
2012 per household				**Per person[1)]**
Electric toothbrush	36.36	(Tselekis, 2012)		16.76
Vacuum cleaner (cordless)	15.91			7.33
Vacuum cleaner	100			46.08
Laptop	166			76.50
Desktop computer	50			23.04
DVD player	45.50		Assumed for portable audio	20.97
Home audio	91		Assumed for loudspeaker	41.94
Electric shaver	50	(Teschke & Riedel, n.d.)	For US, 2002	23.04
Digital camera	70	(Statista, 2018a)	For Great Britain, 2013	32.26
Hand-held tools	25	assumed		11.52
2015 per person				
Smartphone	81	(Deloitte, 2016)	NL	-
Tablet	62.5			
Wireless speaker	12			
Car	50.4	(CBS, 2018a)		
New motorcycles with a cylinder capacity of up to 1000 cm3	2.8458	calculated	From Table 9 and population	
New motorcycles with a cylinder capacity between 1000 and 1500 cm3	0.97481			
Electric car	0.9136	CBS	For Netherlands 2015; Including plug-in hybrid electric cars: 155950 electric cars in 2015 divided by population in NL	
E-bikes	8.2	calculated	From Table 9 and population	

1) Penetration rate was recalculated from households to per person unit by dividing the value by number of residents per household. In 2015 there were 2.17 people per household in the Netherlands (Statista, 2018c).

Table S5b. Penetration rates in other sectors (in 2018 per employee)

Name	Value [%]	Source	Description
Offices			
Laptop	118	(Van Straalen, Roskam, & Baldé, 2016)	Including tablets
Desktop computer	43		
Mobile phone	68		
Tablet	-		
Construction			
Hard materials	106.25	(Van Straalen et al., 2016)	Average value between penetration for household tools (drills, saws, high pressure cleaners) 2.41 pcs and professional tools (for welding, soldering, milling) 0.10 pcs. Assuming not all tools contain cobalt, the number was multiplied by 0.85. Hard steel alloys in tools (band and circular saw blades, drawing and extruding dies, pressing, stamping, and punching tools, tools for tapping and threading, drills)
Hand-held tools	255		Based on data from (Veelen, 2018) on average 3 hand held devices are used per person. Considering 85% of employees work physically, penetration rate is 2.55 pcs/employee

Source (Van Straalen et al., 2016) provides values in pieces per inhabitant for The Netherlands, in distinction with Table 5a above, which shows values for households. Those values were chosen to calculate the amounts of products for other sectors.

Table S6. Number of personal computers per household in 2012

Name	Value	Unit	Source	Description
Desktop PC and laptops	2.15	pcs	(Nakono, 2018)	Number of personal computers installed in the Netherlands per household

Table S7. Data from The Hague municipality

Time frame	Value	Unit	Source	Description
E-waste from households in The Hague				
2015	1058	ton	Ger Kwakkel, The Hague	Include different electric devices: refrigerators, microwaves, phones, radio, computers etc.
2016	1131			
2017	1079			
Population and households				
Population of the Netherlands	17069297	Inhabitants	(World Population Review, 2018)	For 2018
Population of The Hague	514861	inhabitants	CBS	For 2015
Number of households in Netherlands	7722600		(Eurostat, 2017)	For 2016
Number of households in municipality The Hague	253420	households	CBS	

Table S8. Number of registered electric cars in The Hague

Time frame	Value [pcs]	Source
Mar-15	1309	Ger Kwakkel, Municipality The Hague
Apr-15	1417	
May-15	1424	
Jun-15	1662	
Jul-15	1574	
Aug-15	1588	
Oct-15	1912	
Nov-15	1988	
Dec-15	**2302**	
Jan-16	2458	
Feb-16	2491	
Mar-16	2694	
Apr-16	2790	
May-16	2772	
Jun-16	2924	
Jul-16	2838	
Aug-16	3286	
Sep-16	3289	
Oct-16	3467	
Nov-16	3443	
Dec-16	3903	
Jan-17	3797	
Feb-17	3828	
Apr-17	4457	
May-17	4480	
Jun-17	4702	
Jul-17	4375	
Apr-17	4457	
May-17	4480	
Jun-17	4702	
Jul-17	4375	
Mar-17	4408	
Apr-17	4457	
May-17	4480	
Jun-17	4702	
Jul-17	4375	
Aug-17	4714	
Sep-17	4885	
Oct-17	4959	
Nov-17	4905	
Dec-17	5002	
Jan-18	5055	

Table S9. List of calculated quantities of products in households in The Hague

Name	Quantity [pcs/person]	Unit	Source	Description
Electric shaver	126710	Pcs	-	1)
Electric toothbrush	92143.51	Pcs		
Vacuum cleaner (cordless)	40319.12	Pcs		
Digital camera	177394	Pcs		
Mobile phone/Smartphone	417037.41	Pcs		
Portable audio (MP3 + DVD player)	115306.1	Pcs		
Vacuum cleaner	253420	Pcs		1)
Hand-held tools	63355	Pcs		1)
Laptop	420677.2	Pcs		1)

Name	Quantity [pcs/person]	Unit	Source	Description
Tablet	321788.13	pcs		1)
Desktop computer	126710	Pcs		1)
Electric motors	2302			From Table 9 for December 2015
MRI	6	pcs	(HMC, n.d.); (Hagaziekenhuis, n.d.)	5 hospitals in DH (Municipality Den Haag, 2017) have at least 6 MRI scanners
Loudspeaker	230612.2	pcs	-	1)
Wireless speaker	61783.32	pcs		1)
New motorcycles with a cylinder capacity of up to 1000 cm3 (inflow)	227.91	pcs	(BOVAG-RAI, 2017)	Motorcycles; Calculated based on motorcycle sales in the Netherlands for 2015 (7556 pcs)
New motorcycles with a cylinder capacity of up to 1000 cm3 (stock)	14651.94	pcs	(Statista, 2018d)	From number of registered motorcycles in NL in 2016 (485759 pcs)
New motorcycles with a cylinder content between 1000 and 1500 cm3 (inflow)	111.21	pcs	(BOVAG-RAI, 2017)	Motorcycles; Calculated based on motorcycle (with cylinder capacity >1000 cm3) sales in the Netherlands for 2015 (3687 pcs)
New motorcycles with a cylinder content between 1000 and 1500 cm3 (stock)	5018.94	pcs	(Statista, 2018d)	From number of registered motorcycles in NL in 2016 (166394 pcs)
New cars with a cylinder capacity of up to 2500 cm3	259489.94	pcs	-	1)
Electric car battery (stock Dec 2015)	2302	pcs		From Table 8 for December 2015
Electric car battery (inflow 2015)	878	pcs		From Table 8: (difference between December 2015 and March 2015)
E-bike battery (inflow)	8324.98	pcs	(BOVAG-RAI, 2017)	Calculated based on E-bike sales in the Netherlands for 2015 (276,000 pcs) and population
Number of E-bikes (stock)	42228.18	pcs	(CBS, 2015)	Calculated from number of E-bikes in NL in 2014 (1,400,000)
Cars (inflow 2015)	13553.74	pcs	(Statista, 2018b)	EEE in cars; From passenger cars sold in NL in 2015 (449350 pcs)
Cars (stock 2015)	259489.94	pcs	-	EEE in cars; 1)
Cars (EoL)	2810.66	pcs	(Eurostat, n.d.)	1) EEE in cars; From EoL vehicles 121603 tonnes recycled in NL in 2014, divided by car weight (1305 kg)

Comments:

1) Calculated from penetration rates (Table 5) and number of households/inhabitants in The Hague (Table 7)

For other sectors values were calculated based on penetration rate and number of employees/branches.

Table S10. Weights of products

Name	Weight	Unit	Source	Description
Electric shaver	-	-	-	Not required for the analysis
Electric toothbrush				
Vacuum cleaner (cordless)				
Digital camera				
Mobile phone				
Portable audio (MP3 + DVD player)				
Radio set				
Video camera				
Hand-held tool (battery)				
Laptop				
Tablet				
Desktop computer	9.53	kg	(HP, 2018)	
Hard materials	0.78	kg	-	Calculated average weight (from band saw blade 100g, circular saw blade 2 kg, straight saw blade 235g)
Hand-held tools (metal alloys)	-	-	-	-
Portable electric lamp				
Vacuum cleaner	6	kg	(Bestlist, 2018)	Weight for vacuum cleaner of 700W
Electric motors	12.25	kg	(Automation Direct, n.d.)	Approximate weight of general purpose AC motor
Generators				
MRI	9525.44	kg	(Block Imaging, 2014)	MRI GE Openspeed model with magnet strength 0.7 T
Microphones	0.000658	kg	(Master Magnetics, 2018)	Magnet weight
Loudspeaker	0.000658	kg		Magnet weight
Guitar pickup	0.000658	kg		Magnet weight
Wireless speaker	0.45	kg	investigation	
New vehicles with a cylinder capacity of up to 1000 cm3	195	kg	(MCS, n.d.-b)	Weight for motorcycle Honda CB 400X
New motor vehicles with a cylinder content between 1000 and 1500 cm3	223	kg	(MCS, n.d.-a)	Weight for motorcycle BMW R 1200GS Adventure
New cars with a cylinder capacity of up to 1500 cm3	1205	kg	(Parkers, 2018)	Average weight for 1000 and 1500 cm3
New cars with a cylinder capacity of up to 2500 cm3	1305	kg	(Parkers, 2018)	Weight for cylinder capacity 2000 cm3
New cars with a cylinder capacity of at least 2500 cm3	-	-	-	-
Motor vehicles with an electric motor	2108	kg	(Electriauto, 2018)	Tesla model S (2015)
Electric car battery	540	kg	(Wikipedia, 2018b)	
E-bike battery	-			Not required for the analysis

Comments:

- Car weights are for a model Audi A3 SE with different engine cylinder capacities. Source: (Parkers, 2018)
- Weight of permanent magnets in loudspeakers, microphones and guitar pickups was not available, therefore it was assumed 0.658 g for a samarium cobalt disc magnet of diameter 64 mm and thickness 25 mm (Master Magnetics, 2018).

Table S11. Sectors from SBI 2008 used in the analysis (CBS, 2018b)

Group	2-digit sector name
F	41 Construction of buildings and development of building projects
	43 Specialised construction activities
G	45 Sale and repair of motor vehicles, motorcycles and trailers
J	58 Publishing
	59 Motion picture and television programme production and distribution; sound recording and
	60 Programming and broadcasting
	61 Telecommunications
	62 Support activities in the field of information technology
	63 Information service activities
K	64 Financial institutions, except insurance and pension funding
	65 Insurance and pension funding (no compulsory social security)
	66 Other financial services
L	68 Renting and buying and selling of real estate
M	69 Legal services, accounting, tax consultancy, administration
	70 Holding companies (not financial)
	71 Architects, engineers and technical design and consultancy; testing and analysis
	72 Research and development
	73 Advertising and market research
	74 Industrial design, photography, translation and other consultancy

Table S12. Product lifetimes

Name	Lifetime [years]	Source
Electric shaver	2	Assumed same as for electric toothbrush
Electric toothbrush	2	(Cox, Griffith, Giorgi, & King, 2013)
Vacuum cleaner	6	(Minerals4EU, 2015)
Digital camera	6	(Cox et al., 2013)
Mobile phone/Smartphone	2	(Cox et al., 2013)
Portable audio (MP3 + DVD player)	4	MP3 player (Cox et al., 2013)
Hand-held tools	6	Power tools (Cox et al., 2013)
Hard materials	1	(Harper et al., 2012a)
Laptop	5	(Tecchio et al., 2018)
Tablet	3	(Tecchio et al., 2018)
Stationary computer	6	(Tecchio et al., 2018)
Electric motors (magnet)	8	(Herb Weisbaum, 2006)
MRI	11.4	(Diagnostic Imaging, 2014)
Loudspeaker	4	Assumed same as for MP3 player
Wireless speaker	4	Assumed same as for MP3 player
New vehicles with a cylinder capacity of up to 1000 cm3	20	assumed
New motor vehicles with a cylinder content between 1000 and 1500 cm3	20	assumed
New cars with a cylinder capacity of up to 2500 cm3	20	assumed
Electric car battery	8	(Harper et al., 2012b)
E-bike battery	4	(E-BikeKit, 2018)
Car	20	assumed

Collection rates

Collection rate for portable batteries placed on the market in The Netherlands in 2015 reached 46.1% (Stibat, 2015). The source does not specify type of batteries included in this statistic or in which devices they were used. Considering that there is no other more accurate data available, in the present analysis this value will be used for all applications using batteries in households. The same value was assumed by author for loudspeakers, desktop computers and vacuum cleaners due to lack of another source.

The part of the waste flow that is not collected but ends up in municipal waste and embedded cobalt is eventually lost was assumed as 10%. It is assumed that products in other sectors than households do not end up in municipal waste stream.

The remaining products that are not used anymore, but also are not collected as accumulated in hibernating stock.

Table S13. List of products found in The Hague in 2015 and the amount of cobalt in them [g]

Name	**Concentration [g/item]**	**Cobalt mass [g]**				
		STOCK	INFLOW	OUTFLOW	Outflow to landfill	Hibernating stock
HOUSEHOLDS						
Electric shaver	0.706	83748.53	41874.26	19304.04	4187.43	18382.80
Electric toothbrush	0.867	74814.04	37407.02	17244.64	3740.70	16421.68
Vacuum cleaner cordless)	2.647	99895.96	16649.33	7675.34	1664.93	7309.05
Vacuum cleaner	0.00003	7.12	1.19	0.55	0.12	0.52
Digital camera	2.958	491306.52	81884.42	37748.72	8188.44	35947.26
Mobile phone	5.002	2086021.12	1043010.56	480827.87	104301.06	457881.64
Portable audio (MP3 + DVD player)	3.086	333184.16	83296.04	38399.47	8329.60	36566.96
Hand-held tools (battery)	4.72	279952.58	46658.76	21509.69	4665.88	20483.20
Laptop	13.86	5459019.70	1091803.94	503321.62	109180.39	47930.93
Tablet	0.0322	10361.58	3453.86	1592.23	345.39	1516.24
Desktop computer	1.49621	177486.38	29581.06	13636.87	2958.11	12986.09
Hand-held tools (metal alloy)	0.18	10676.16	1779.36	820.28	177.94	781.14
Electric car motor	0.000009	0.22	0.08	0.03	-	-
Loudspeaker	0.41454	89512.74	22378.19	10316.34	2237.82	9824.02
Wireless speaker	2.958	182755.06	45688.77	21062.52	4568.88	20057.37
Motorcycles cylinder <= up to 1000 cm3	0.14352	2102.84	32.71	105.14	-	-
Motorcycles cylinder between 1000 and 1500 cm3	0.072475	363.75	8.06	18.19	-	-
Car (cylinder <= 2500 cm3)	0.97092	251943.98	12597.20	12597.20	-	-
Electric car battery	21600	43553437.72	16611606.57	5444179.71	-	-
E-bikes	132	5574119.55	1098897.98	1393529.89	-	-
EEE in vehicles	30	7330387.90	677686.93	2810.66	-	-

SUM	-	66091097.59	20946296.28	8026700.99	254546.68	1117459.90
OFFICES						
Mobile phone	5.002	212897.93	106448.96	95804.07	-	-
Laptop (including tablet)	13.86	1023679.64	204735.93	184262.34	-	-
Desktop computer	0.0157	422.56	70.43	63.38	-	-
Electric car battery	21600	5294820.88	2019484.25	595667.35	-	-
Electric car motor	0.000009	0.03	0.01	0.00	-	-
SUM stock	-	6531821.03	2330739.57	875797.14	**-**	**-**
CONSTRUCTION						
Hand-held tools (battery)	4.72	124488.35	20748.06	18673.25	-	-
Hand-held tools (metal alloy)	0.18	4747.44	791.24	712.12	-	-
Hard materials	2.89	31715.52	31715.52	28543.96	-	-
Electric car battery	21600	874941.40	333709.19	98430.91	-	-
Electric car motor	0.000009	0.0045	0.0017	0.0005	-	-
SUM stock	-	1035892.71	386964.01	146360.24	**-**	**-**
TOTAL stock The Hague		73658811.34	23663999.86	9048858.37	254546.68	1117459.90

Missing inflows were calculated dividing number of items in stock by their lifetime.

Comparison with ProSUM

The ProSUM (Huisman et al., 2017) analysis was performed on a country level for Europe and for many elements, including cobalt. Starting from there, for the purpose of current study, the amounts of cobalt embedded in three main categories: batteries, EEE and vehicles were scaled down from values for The Netherlands. Based on number of inhabitants in The Hague the amount of cobalt in products was then determined. This will help to demonstrate if the results are comparable and how sensitive the used data is.

Figure below presents results of disaggregated ProSUM values from national to a city level. This data can be compared with results for households from current analysis to observe if the scale of cobalt content in products is comparable.

After comparing results of the analysis on a city level with disaggregated values from national analysis, there are few observations. First, both approaches have different assumptions and most likely include different flows. Categories used in ProSUM analysis are aggregated and there is no possibility to check which items were included. Therefore, it is difficult to compare them directly. Second, taking national values and disaggregating them into a city using number of inhabitants is inaccurate, since it does not take into account specifics of a city. What is more, there is no distinction between urban and rural area, which can show substantial differences in number of appliances in households, consumer behaviour in terms of usage and disposal of products or presence and size of other sectors.

Table S14. Cobalt in households the city calculated based on ProSUM project

Category	Component	Co mass per capita NL [ton/capita]	Total mass The Hague [ton]
Placed on the market in 2015			
Batteries	Battery NiMH	8.2019E-07	0.422281832
	Battery Li-ion rechargeable	1.9333E-05	9.953786029
Vehicles	Battery electric/Fuel cell	*5.4135E-09*	*0.002787211*
	Hybrid electric	*2.2302E-08*	*0.011482567*
	Plug-in Hybrid electric	*1.8389E-08*	*0.009467559*
	Diesel	-	-
	Petrol	*5.5667E-07*	*0.286608712*
EEE	Temperature exchange equipment	3.3185E-08	0.017085644
	Screens	1.0662E-08	0.005489664
	Lamps	1.7471E-06	0.899490464
	Large equipment	9.6801E-09	0.004983891
	Small equipment	4.49E-08	0.023117397
	Small IT	5.3371E-07	0.27478482
SUM	-	-	11.91136579
Waste in 2015			
Batteries	Battery NiMH	8.2019E-07	0.422281832
	Battery Li-ion rechargeable	5.8585E-06	3.016298797
Vehicles	Battery electric/Fuel cell	-	-
	Hybrid electric	-	-
	Plug-in Hybrid electric	-	-
	Diesel	*5.2199E-08*	*0.026875222*
	Petrol	*5.173E-07*	*0.266339184*
EEE	Temperature exchange equipment	2.8773E-08	0.01481419
	Screens	1.7376E-07	0.089463422
	Lamps	8.8844E-07	0.457421713
	Large equipment	1.0694E-08	0.005506103
	Small equipment	6.1001E-08	0.031407151
	Small IT	4.3025E-07	0.221516984
SUM	-	-	4.551924596

Comments:

- national data divided by inhabitants
- In italics: data for year 2014

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