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Long-term Retrospective Analysis of the Societal Metabolism of Cobalt in the European Union

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Corresponding Author:	María Fernanda Godoy León Ghent University: Universiteit Gent BELGIUM
First Author:	María Fernanda Godoy León, MSc
Order of Authors:	María Fernanda Godoy León, MSc
	Gian Andrea Blengini
	Cristina T. Matos
	Jo Dewulf
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Long-term Retrospective Analysis of the Societal Metabolism of Cobalt in the European Union

María Fernanda Godoy León [a], Gian Andrea Blengini [b], Cristina T. Matos [c], Jo Dewulf [a]

[a] Research Group Sustainable Systems Engineering (STEN), Ghent University, Coupure Links 653, 9000 Ghent, Belgium.
[b] Politecnico di Torino DIATI, Corso Duca degli Abruzzi 24, 10125 Torino, TO, Italy.
[c] A4F-Algae for Future, Estrada do Paço do Lumiar Campus do Lumiar, Ed. E – R/C 1649-038 Lisboa, Portugal.

Abstract

A proper understanding of the historical societal metabolism of cobalt (Co) in the European Union (EU) is lacking, resulting in a serious weakness in identifying potential sources of secondary materials, enhancing circularity, and improving forecasting assessments. A retrospective dynamic material flow analysis was performed to assess the stocks and flows of Co in the EU27, considering a number of Co-containing commodities and final metal products. Detailed results are provided for the year 2018, and the evolution of the stocks and flows over time is presented from 1955 to 2018. The results for 2018 indicate that the largest stock in the EU was the landfill stock, with around 166,000 metric tons of Co (35% of the total stock in that year), followed by the in-use stock, with around 157,000 metric tons of Co (33% of the total stock). From 1970 onwards, the in-use stock has doubled its size every 10 or 11 years and the landfill stock every eight years. A sensitivity analysis was performed with eight sets of parameters to determine their impact on the stocks in 2018. Six of them have a marginal impact on the stocks. The in-use stock and the stock of losses are mainly affected by the data uncertainty related to the end-use demand of Co and the lifetimes of the applications (between 4 and 22% in absolute terms for the in-use stock, and between 7 and 27% in absolute terms for the stock of losses).

Keywords: *Cobalt, Critical raw materials, Dynamic material flow analysis, Retrospective analysis, Recycling*

List of abbreviations

ΣF	: Cumulative flow
BGS	: British Geological Survey
Co	: Cobalt
CRM	: Critical raw material
D	: Downcycled
DRC	: Democratic Republic of Congo
E	: Extrapolation
EoL	: End-of-life
EoL-RR	: End-of-life recycling rate
EoS	: End-of-service
EU	: European Union
dMFA	: Dynamic material flow analysis
GDP	: Gross domestic product
ICT	: Information and communications technology
MC	: Model calculation

MFA	: Material flow analysis
MSA	: Material system analysis
NCA	: Battery cathode of nickel, cobalt, aluminium
NMA	: Battery cathode of nickel, manganese, aluminium
NMC	: Battery cathode of nickel, manganese, cobalt
OSR	: Old scrap ratio
OVC	: Output from the value chain
PCLR	: Pre-consumer loss rate
PET	: Polyethylene terephthalate
RESUCE	: Resource-Efficient Pathways towards Greenhouse-Gas- Neutrality
RPER	: Recycling process efficiency rate
SD	: Statistical data
SI	: Supporting information
SSP	: Self-sufficiency potential
T	: Tailings
TS-RIR	: Total scrap recycling input rate
UBA	: Federal Environment Agency of Germany
ULJAS	: Finnish customs databases
USGS	: US Geological Survey
W	: Waste
YoY	: Year-on-year

1. Introduction

For the last decade, cobalt (Co) has been considered a critical raw material (CRM) for the European Union (EU) since the first CRMs list was published in 2011. Its status has been affirmed in the three updates of the list (in 2014, 2017, and 2020). CRMs are characterised by having high economic importance for the EU and a high supply risk (European Commission, 2020a). In the case of Co, the particularly high importance is mostly related to its strategic use in the production of Li-ion batteries, which are key in the transition from fossil fuels to more sustainable sources of energy. The high risk is due to a particularly high concentration of primary supply in the Democratic Republic of Congo (DRC), a country considered politically unstable (World Bank, 2021b). In 2019, the DRC accounted for 71% of the global production of Co, followed by Finland, New Caledonia, Russia, and Canada (USGS, 2020).

The EU's list of CRMs was developed as part of the Raw Materials Initiative, launched by the European Commission in 2008. The initiative was based on three main pillars: ensuring a level playing field in terms of access to resources in third countries, fostering a sustainable supply of raw materials from European sources, and boosting resource efficiency and promoting recycling (European Commission, 2008). Later, in 2015, the Commission launched the EU action plan for the Circular Economy (European Commission, 2015), which included a number of measures to maintain the value of products, materials, and resources in the economy for as long as possible while minimising the generation of waste. CRMs were one of the five priority areas defined in the action plan. In 2019, a new action plan on circular economy was launched in March 2020, as part of the European Green Deal. This provides an action plan to boost the efficient use of resources by moving to a circular economy, and to restore biodiversity and cut pollution (European Commission, 2020c).

In this context, the European Commission has commissioned a high number of studies, aiming to better understand the societal metabolism of CRMs, particularly Co. Many of these studies have been developed with a lifecycle perspective using different tools, such as life cycle assessment and material flow analysis (MFA) (RPA, 2012; BIO by Deloitte, 2015; Alves Dias et al. 2018; Matos et al., 2020).

MFA studies can be carried out using static or dynamic models. The former are based on linear correlations and analyse the stocks and flows of a material within the system boundary for a year or at a given point of time in the past. The latter describes the behaviour of a system over a time interval, most applying lifetime distributions to the static flow of a material to analyse and forecast its stocks and flows over time (Elshkaki, 2007). One example of dynamic modelling is the MaTrace model (Nakamura et al., 2014; Godoy León et al., 2020), which tracks the fate of materials over time and across products. It also explicitly considers the losses incurred during the conversion processes.

For the EU, one of the most well-established static MFA studies is the MSA (material system analysis) study conducted by BIO by Deloitte (2015) on behalf of the European Commission in 2015. The study consisted of a map of the flows through the economy, including the inputs and movements within it, additions to stock, and end-of-life through either disposal or recovery. For Co, the assessment was done for 2012. A recent MSA study was published by Matos et al. (2020), which included an updated overview of the stocks and flows of Co in the EU for 2016 along with four other materials used in batteries (lithium, manganese, natural graphite, and nickel).

Since the publication of the first MSA, several other studies have used its results to estimate the current and future use of Co in the EU (Deetman et al., 2017; Monnet and Abderrahim, 2018; Bobba et al., 2019; Tercero Espinoza et al., 2019, Godoy León et al., 2020), some using a dynamic approach. However, little has been done in terms of retrospective analysis of stocks and flows of Co, which is fundamental to properly understand the societal metabolism of the metal in the region. At the EU level, to the best of the authors' knowledge, only Tercero Espinoza et al. (2019) estimated the historical Co demand in the EU (between 2000 and 2017). Other studies, such as Zeng and Li (2015) and Sun et al. (2019), have used dynamic MFA (dMFA) to trace Co stocks and flows in China and on a global scale, respectively. The former assessed the period 2005–2013 and the latter 1995–2015. Recently, Liu et al. (2021) developed a dMFA of critical metals for lithium-ion batteries in China for the period 2000–2018, in which Co was also assessed. For other metals (e.g. copper), there are long-term retrospective dMFA studies at the EU level (e.g. Ciacci et al. (2017), Soulier et al. (2018)), but that is not the case for Co. In one of our recent studies (Godoy León et al., 2021), long-term statistical data on Co production and trade at the EU level were analysed, acquiring and comparing data from different sources. The study focused on the production and trade flows of Co-containing commodities, with a critical analysis of the available data, but did not assess the full cycle of Co. Furthermore, it did not address other flows (e.g., flows of Co in final products and end-of-life flows), or how the stocks of Co have built up over time.

Therefore, there is a clear knowledge gap regarding the historical long-term societal metabolism of Co in the EU. However, such knowledge is crucial to understand shifts and trends in cobalt flows along its entire cycle, and to identify potential sources of secondary materials originating from earlier stock build-ups. This, in turn, is required to enhance circularity in the economy. Furthermore, it is also essential to improve forecasting assessments, which are key in discussions on managing the metal.

The objective of this work is to estimate long-term historical stocks and flows of Co in the EU27 in order to fill in the above-mentioned knowledge gap. A long-term retrospective dMFA was carried out, building on by the results of our aforementioned recent study (Godoy León et al., 2021). The model, data, assumptions, and results are presented in the following.

2. Methodology

2.1 System boundaries

The model was applied for the EU from 1955 to 2018. The acquired data from our previous study (Godoy León et al., 2021) covered the period 1938-2018. However, the most complete dataset was for the period 1955-2018, which is why the present assessment was done for that timespan.

The 27 current member states were included in the analysis, including the period before they joined the EU. The analysed system considers the full life cycle of Co in the EU, from mining to recycling (see Figure 1), and takes into account the domestic production and international trade of a number of Co-containing commodities and final products (listed in the SI). These were established according to Matos et al. (2020). The commodities were classified as primary, secondary, semi-processed, and processed material. The final products containing Co were categorised in seven applications: batteries, catalysts, intentionally dissipative uses (modelled as pigments), hard metals, magnets, superalloys, and other uses (e.g. tool steels). Two sub-categories were studied for batteries: portable and mobility batteries. The focus was on Co-bearing rechargeable batteries. In the case of catalysts, three sub-categories were studied: for hydroprocessing, for hydroformylation, and for the production of polyester (PET) precursors. For intentionally dissipative uses, the focus was on pigments. A description of these applications can be found in Godoy León and Dewulf (2020).

2.2 Model, data, and assumptions

The model used to estimate the societal metabolism of Co in the EU27 is based on calculating material stocks and flows according to the law of conservation of mass. The model links the different phases of the life cycle of the metal through annually calculated material flows, considering a closed mass balance within one year and over time.

The input data of the model, specifically related to production and trade, included the sum of separately collected data for each of the 27 EU member states. Based on the available data, the model was developed for three periods: 1955–1987, 1988–2002, and 2003–2018. As can be seen in Figure 1 and Table 1, different types of input data for production and trade were required for each period. These were classified as statistical data (SD), model calculations (MC) (i.e. input data calculated through the model, such as when closing mass balances), and extrapolations (E) (i.e. extrapolated values from historical trends).

Table 1. Adaptations of the model according to the available data for the periods 1955–1987, 1988–2002, and 2003–2018 for each life cycle phase. E: Extrapolation, SD: Statistical data, MC: Model calculation, EoS: End-of-service. The trade refers to the numerated trade of Figure 1.

Period	Mining	Processing	Manufacturing	Use	EoS	Collection and Recycling
1955-1987	Production: SD	Trade1: MC Production: SD	Trade2: E Production: E	Trade3: E Stock: MC	Stock: MC	Production: MC Trade4–5: MC
1988-2002	Production: SD	Trade1: SD Production: SD	Trade2: SD Production: E	Trade3: E Stock: MC	Stock: MC	Production: MC Trade4–5: MC
2003-2018	Production: SD	Trade1: SD Production: SD	Trade2: SD Production: MC	Trade3: SD+MC Stock: MC	Stock: MC	Production: MC Trade4–5: MC

For the first period (1955–1987) a bottom-up approach (i.e. based on data at the product level, which are more disaggregated; for example 'Co ores and concentrates') was used for the mining phase, as statistical data on production were available. For the processing phase, statistical data were available for production but not for trade, which had to be estimated through the model. For the manufacturing and use phases, the trade was obtained from extrapolations. The flows and stocks of the following life cycle phases were obtained using the applied model through a series of parameters, such as lifetimes, hoarding rate and time, and collection rate of the different applications.

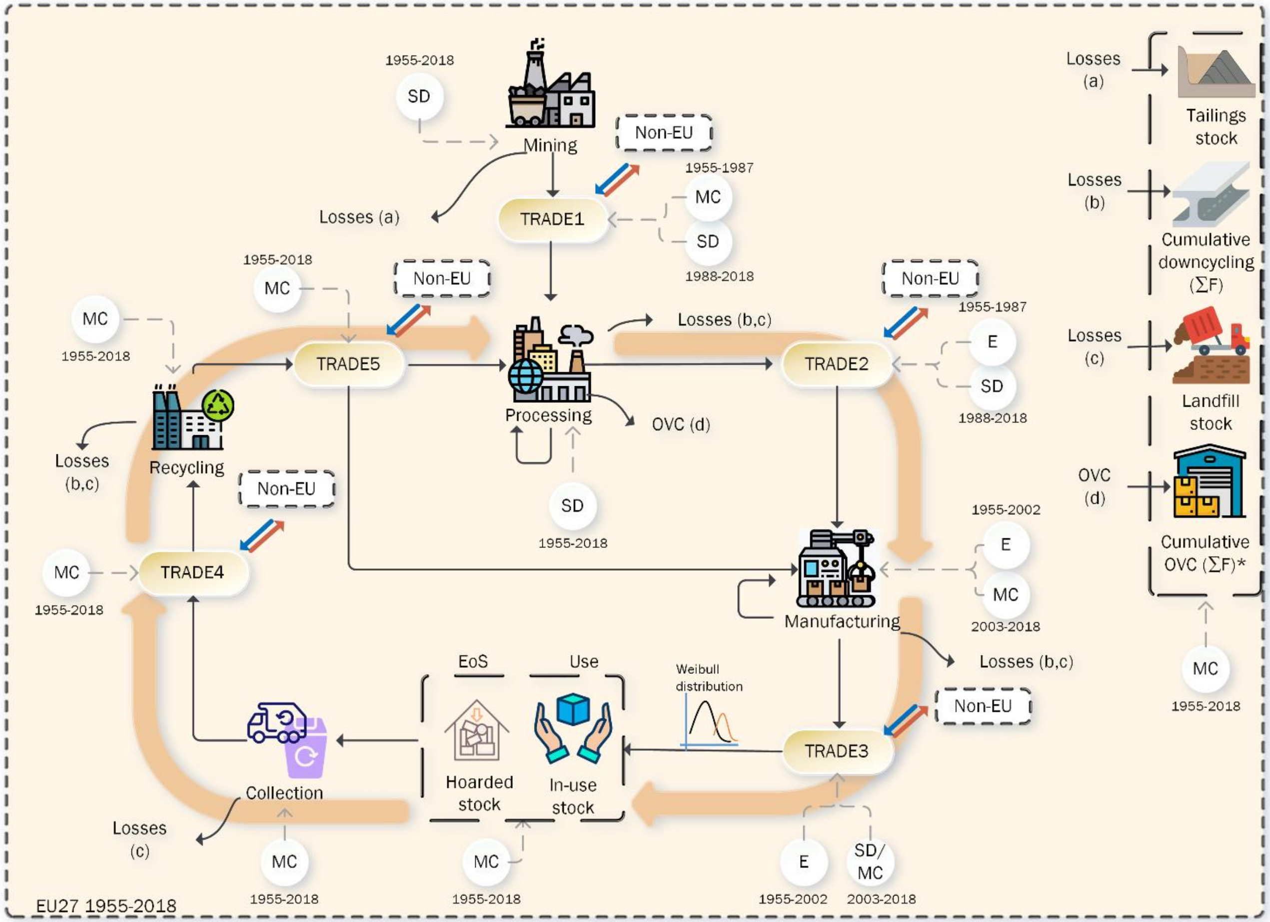

Figure 1. Overview of the methodology applied to model the Co stocks and flows in the EU between 1955 and 2018. The short-dashed line rectangle represents the system boundaries; the long-dashed line rectangle encompasses stocks or cumulative flows. Black arrows represent mass flows. Grey dashed arrows represent input of data for the trade and the production/stock of the life cycle phases (E: Extrapolation, SD: Statistical data, MC: Model calculation), which is given per period. The losses ((a) Mining waste, (b) Downcycled material, (c) Processing, manufacturing, collection, and recycling waste) and the output from the value chain (OVC (d)) go to their respective stocks. The numerated trade relates to Table 1. Input data related to the parameters of the model, such as processes efficiencies, collection rates, and hoarding rate and time, are not explicit in the diagram, but they are part of the model calculations (MC). Stocks and losses are also calculated from the model. EoS: End-of-service. Cumulative OVC refers to the stockpiling and/or confidential export aggregated over time. ΣF: cumulative flow.*

For the second and third periods (1988–2002, 2003–2018), a bottom-up approach was used for the mining and processing phases. Data on production and trade were reasonably available, and it was possible to estimate Co content due to the limited number of commodities in the EU. Regarding the manufacturing and use phase, production and trade were extrapolated for the second period. For the third period, a top-down approach (i.e. based on data at the EU level for more aggregated categories, such as 'Carbides whether or not chemically defined') was applied due to the large number of finished and semi-finished products and the lack of data related to their material content. For both periods, the following steps were calculated according to the model, based on collecting and recycling practices.

An exhaustive explanation of the bottom-up and top-down approaches is available in BIO by Deloitte (2015).

In addition, different datasets for the model parameters (e.g. lifetimes, collection rates, scrap recoveries) were used per period when data were available (see supporting information (SI)).

In the following, the model is explained per life cycle phase, along with its adaptations for each period. Figure 1 presents a summary of the used methodology, indicating the statistical data, extrapolation, and calculated data inputs.

2.2.1 Mining phase

For this phase, the produced material was obtained directly from the British Geological Survey (BGS, 2021) and the US Geological Survey (USGS, 2021). Due to the availability of data and the differences between the two sources, the data were used as follows. Data from BGS were used between 1955 and 1959 (no data were available from USGS), and data from USGS were used for the period 1962–1969 (no data were available from BGS). For the years 1960 and 1961 none of the sources reports data. The value for these years was assumed as the average value of the years 1959 and 1962. For the period 1970–2017, an average value between the data from BGS and USGS was used. For the year 2018, only data from BGS were used due to lack of data from USGS for that year (see SI). For the calculation of the waste produced in this phase, an extraction efficiency of 79% (BGS, 2021; BMLRT, 2021) was used for the studied period. Based on the annual waste production (loss (a) in Figure 1), the cumulative stock of tailings was calculated.

2.2.2 Processing phase

For the processing phase, data on the produced material (processed Co) were obtained directly from the BGS and USGS databases. An average value was used for the years 1955 and 1956. For the period 1957–1962, data from BGS were used, and for the period 1963–2017, an average value between the data from BGS and USGS was used. For 2018, only data from BGS were used.

Regarding trade, the import and export of primary, secondary, and semi-processed Co were considered. The data were extracted from the Eurostat and UN Comtrade databases (Eurostat, 2021a; UN Comtrade, 2021). The data from these two sources are highly different for certain commodities (Godoy León et al., 2021), which is why both datasets were analysed separately. In addition, the import data in UN Comtrade were obtained with the member states as reporters and the export data with the member states as partners (for further explanation, see Godoy León et al., 2021).

Due to the lack of data on trade for the period 1963–1987, the net trade of all commodities was estimated based on a closed mass balance and the calculation of the domestic production of secondary Co from end-of-life (EoL) products. For the period 1988–2018, data for trade were obtained from both of the above-mentioned databases. In addition, the Finnish customs databases (ULJAS, 2021) was consulted for the trade of semi-processed Co.

As mentioned above, the input of domestic secondary material in this phase was estimated for each year of the studied period. An imbalance was detected for some years, where the inputs to the processing phase were higher than the outputs. The difference in output was called 'output from the value chain' (OVC). It consists of stockpiling, confidential exports (i.e. trade that is not publicly disclosed in the databases; see Godoy León et al., 2021), or a combination of both. Since the origin of this stream is uncertain, its accumulation over time is not considered a stock, and it is referred to only as a cumulative flow (see Figure 1).

For this phase, the production of processed material and waste was considered as well as the recovery of scrap and the downcycling of material. Downcycling, or non-functional recycling, refers to material that is incorporated into an associated large-magnitude material stream, ending up in low-end products where the original function is not required or as a contaminant (Buchert et al., 2009; Graedel et al., 2011; Zimmermann and Gößling-Reisemann, 2013; Zimmermann 2017).

Modified equations of the MaTrace model (Nakamura et al., 2014; Godoy León et al., 2020) were applied to estimate the flows of recovered scrap, waste, and downcycled material. These equations are based on the continuous internal reuse of scrap and depend on the processing efficiency and recovery rate of scrap. The original equations were extended to include primary material and trade of commodities. The derivation of the equations is presented in SI, along with the set of values used for the different parameters.

2.2.3 Manufacturing phase

Three sets of data were required for the manufacturing phase: the trade of processed material, the manufacturing share of the metal for each application, and the values for a number of parameters related to the calculation of waste and downcycled material.

Data from the Eurostat and UN Comtrade databases were considered for the trade. Due to the lack of data for the period 1955–1987, the net trade and manufacturing demand of these commodities were extrapolated. The extrapolation was performed using the available historical data from 1988 to 2018, considering exponential growth based on the conclusions of Krausmann et al. (2009). According to the authors, the 20th century was characterised by an exponential increase in global materials use (especially after WWII). This growth was driven by both population and economic growth, with a shift from the dominance of renewable biomass toward mineral materials (Krausmann et al., 2009). To validate this approach, the Co demand for manufacturing was compared to the GDP (gross domestic product) of the EU over time. The comparison showed similar results to those obtained considering exponential growth (see SI).

Regarding the manufacturing demand share of the different applications, no data were available for the EU before 2000. In the literature, the demand share was available for China (Zeng and Li, 2015), the USA (USGS, 2021), and the world (Sun et al., 2019). The share for China and the world were excluded, however, due to their high production of batteries, which are barely produced in the EU. The data available from the USA were selected as the most representative due to the similarity of its manufacturing sectors to those of the EU (National Research Council 1983; Sun et al., 2019) and their reasonably similar economic development (World Bank, 2021a). From 2000 onwards, the share was obtained from Roskill (2019), Tercero Espinoza et al. (2019), and Godoy León et al. (2020).

Finally, similarly to the processing phase, the recovered scrap, waste, and downcycled material produced during manufacturing were estimated using modified equations of the MaTrace model (Nakamura et al., 2014; Godoy León et al., 2020). The equations and set of values used for the different parameters are available in the SI.

2.2.4 Use phase.

For the use phase, the stock of in-use applications was modelled. To do so, the trade and lifetimes of the final products were required.

Regarding trade, for intentionally dissipative uses, hard metals, magnets, superalloys, and other uses, data were extracted from the Eurostat database, considering a number of finished or semi-finished products (see SI), with data available from 2003 onwards. For catalysts, a net trade of zero was assumed, as in Matos et al. (2020). In the case of portable and mobility batteries, the trade was estimated based on data of the ProSUM database (RMIS, 2019; Huisman et al., 2020). The database provides what was placed on the market from 2000 onwards.

Due to data gaps for most of the application before 2003, the final consumption of final products had to be estimated for the period 1955–2002. Based on Sun et al. (2019) and Matos et al. (2020), the EU was estimated to consume 30% of the global Co demand for final use in 2015. In addition, based on the work of Sun et al. (2019) (who provided the Co demand for 1995, 2005, and 2015) and Krausmann et al. (2009), the global Co demand for final use was extrapolated considering an exponential growth. Subsequently, the Co demand for the EU was estimated based on the extrapolated global demand and a share of 30%. To complement this assumption, the GDP of the EU was compared to the global GDP (World Bank, 2021a). It was found that between 1966 (EU's GDP is not available before this year) and 2002, the EU's GDP corresponded to between 21 and 29% of the world's GDP, with an average value of 26%.

Based on the end-use demand and the domestic manufacturing, the net trade of the applications was estimated. It is also important to note that the UN Comtrade database was not consulted for the trade of final products, as its available categories are more aggregated.

To estimate the in-use stock, a statistical probability distribution was used to model the lifetime of the different applications. These distributions are characterised by a probability density function, which describes the probability of events occurring over time. Here, the Weibull distribution was used, as it is widely used in life data analysis (Weibull, 2021). The considered lifetimes and parameters related to the Weibull distribution are available in the SI.

Two datasets were used for the lifetimes, one for the period 1955–1987 and another for the period 1988–2018. The ProSUM database was consulted for information on the waste generated in the EU27 from portable and mobility batteries, which was available from 2010 to 2018. Based on this information, the values of the lifetime of batteries were tuned (comparing the reported waste in the database with the values obtained by the model). Intentionally dissipative uses were modelled mainly as pigments, which is why this application was not dissipated during the use phase but assumed to be landfilled after its use.

Due to the lack of data from before 1955, it was assumed that the in-use stock before 1955 is negligible.

2.2.5 End-of-life phase

This phase is composed of three sub-phases: end-of-service (EoS), collection, and recycling. It is assumed that EoS products are hoarded by the user (i.e. dead storage of a product that has reached the end of its use, such as an old mobile phone kept in the attic (Wilson et al., 2017)) or are immediately disposed for collection. The stock of EoS products, called hoarded stock was calculated based on the Weibull distribution, hoarding rate, and hoarding period of each application. The annual addition of hoarded products to the stock and the collection and disposal of EoL products were calculated according to the equations of Godoy León et al. (2020). This phase also considers the trade of EoL scrap.

Next, the functional recycling and downcycling of Co from EoL products were calculated. For functional recycling, two routes were considered. The first involves a chemical process, through which batteries, catalysts, and hard metals are recycled. Co metal or a Co compound that can return to the processing phase are obtained from this route. The second route includes two different processes, where the recycled material goes directly to manufacturing. The first is the Zn process, through which hard metals are recycled. W-Co powder is obtained from this process, which is used in the production of new hard metals. The second process is remelting, where superalloys are recycled to produce new superalloys. The downcycling route is used for catalysts, magnets, superalloys, and other uses, and the recovered metallic fraction (including Co) is predominantly used in steel production (Godoy León et al., 2020).

The distribution of material in the different recycling routes is specified by an allocation matrix (see SI). An allocation matrix was used for the period 1955–2002 and for the period 2003-2018, according to the available data.

Given the purpose of this study, the recycling processes were not analysed in detail, as the model only requires efficiency of the whole phase (for further details, see Godoy León et al., 2020).

The mass balance of the system was closed by calculating the secondary material produced domestically from EoL products:

- For the period 1955–1987, the trade of the processing phase was estimated assuming no trade of secondary material (i.e. all domestic secondary material is used domestically, and there is no import).
- For the period 1988–2018, the input of domestic secondary material was obtained based on the mass balance between the production and trade of processed material. It was assumed that only recycled Co produced through the chemical process is traded (i.e. the recycled Co that returns to the manufacturing phase is used domestically). In case of obtaining a negative value, it was assumed that part of the input to the processing phase was stockpiled and/or left the value chain through confidential exports. In the event that the value was positive, the amount was compared with the secondary material produced from EoL products. The comparison made it possible to estimate the import or export of secondary Co.

2.2.6 Losses

The losses, shown in Figure 1, consist of the mining waste (loss (a)); the processing, manufacturing, and recycling waste due to the inefficiencies of the processes (loss (c)); the collection waste due to non-selective collection (loss (c)); and the downcycled material produced in processing, manufacturing, and recycling (loss (b)). The mining waste accumulates in the tailings stock, and the waste produced by inefficiencies and non-selective collection accumulates in the landfill stock. The downcycled material is dispersed in the technosphere and does not accumulate in a specific stock. For this reason, the accumulation of this stream was not called stock but cumulative flow. Nevertheless, it is considered part of the lost stock, as the Co ending in this compartment is not currently being qualitatively recycled.

2.3 Indicators

Six indicators were calculated in order to characterise the Co cycle in the EU: total scrap recycling input rate (TS-RIR), old scrap ratio (OSR), end-of-life recycling rate (EoL-RR), recycling process efficiency rate (RPER), self-sufficiency potential (SSP), and pre-consumer loss rate (PCLR). The former four come from UNEP (2011) and Tercero Espinoza and Soulier (2018), while the latter two come from Eurostat (2021b) and Matos et al. (2021). These indicators measure different aspects of the metal cycle, such as the amount of reused scrap. The descriptions and equations of the indicators are available in the SI.

2.4 Sensitivity analysis

A sensitivity analysis was performed to assess the impact of the main assumptions of the model. These were related to the following parameters or calculations: the manufacturing demand between 1955 and 1987, the manufacturing demand share between 1955 and 1999, the trade of catalysts between 2003 and 2018, the end-use demand between 1955 and 2002, the export of functionally recycled material between 1955 and 1987, and the extraction efficiency for the complete studied period.

In addition, two other parameters were assessed due to their importance in other dMFA studies (Soulier et al., 2018; Godoy León et al., 2020): the lifetime of applications and the collection rates. These are key parameters required to model in-use stocks and flows of secondary materials and the available information on these parameters bears considerable uncertainty.

Due to the lack of statistical measures of the uncertainty of the input values (i.e. the type of distribution they follow and/or the spread), a simple sensitivity analysis was performed where each parameter was changed individually over a certain range. The results were compared in terms of the in-use stock, OVC cumulative flow (stockpile and/or non-EU exports), hoarded stock, and lost stock (tailings, landfill, and downcycled).

Table 2 lists the assessed parameters or calculations, how they were established or calculated for the base case, and how they were modified in the sensitivity analysis.

*Table 2. List of parameters or calculations assessed in the sensitivity analysis. *Considering the main applications in 2000 (superalloys, hard metals, and intentionally dissipative uses). The difference in percentage is distributed equally among the other applications (when applicable, e.g. mobility batteries were not considered before 2000). **Maximum possible of 100%.*

Parameter/Calculation	Base case	Range in the sensitivity analysis
Manufacturing demand (1955–1987)	Extrapolated assuming exponential growth	±50% of the extrapolated value
Manufacturing demand share (1955–1999)	Same share as in the USA	±50% for main applications*
Trade of catalysts (2003–2018)	Net trade of zero	±50% net trade
End-use demand (1955–2002)	30% of the global Co demand	±50% of the base case
Trade of functionally recycled material (1955–1987)	Net trade of zero	±50% net trade
Lifetime of applications (1955–1987)	See SI	±50% of the base case
Collection rates (1955–1987)**	See SI	±50% of the base case
Extraction efficiency (1955–2018)	79%	±25% of the base case

3. Results and discussion

In this section, we present the results obtained from the dMFA of Co in the EU27 from 1955 to 2018. Different aspects are analysed, such as the Co demand over time, the Co cycle for specific years, and how the cumulative stocks are built up over time. We finish this section by presenting the results and a discussion on the sensitivity analysis. The results are presented in metric tons (t).

3.1 Demand of cobalt over time

The evolution of the EU27 demand for Co over time was analysed, comparing the results obtained from the UN Comtrade and Eurostat databases separately. Figure 2 shows the demand for the processing, manufacturing, and end-use phases. Here, demand is understood as apparent consumption (also known as domestic material consumption, DMC), which is defined as 'production+imports-exports' (Fastmarkets RISI, 2021; United Nations, 2021).

The demand over time in both cases is similar for the processing phase, as in general the datasets from both sources do not present substantial differences (Godoy León et al., 2021). For the manufacturing and end-use phases, however, the differences are significant. For example, for 2018 the manufacturing and end-use demands obtained with the UN Comtrade dataset are 49 and 44% lower, respectively, than the demands obtained using the dataset from Eurostat. This is mostly explained by the substantial differences in the trade of processed material, as UN Comtrade reports considerably higher values for the export of that type of commodity (Godoy León et al., 2021). This is related to confidential exports from Finland, a topic that will be discussed in the next section.

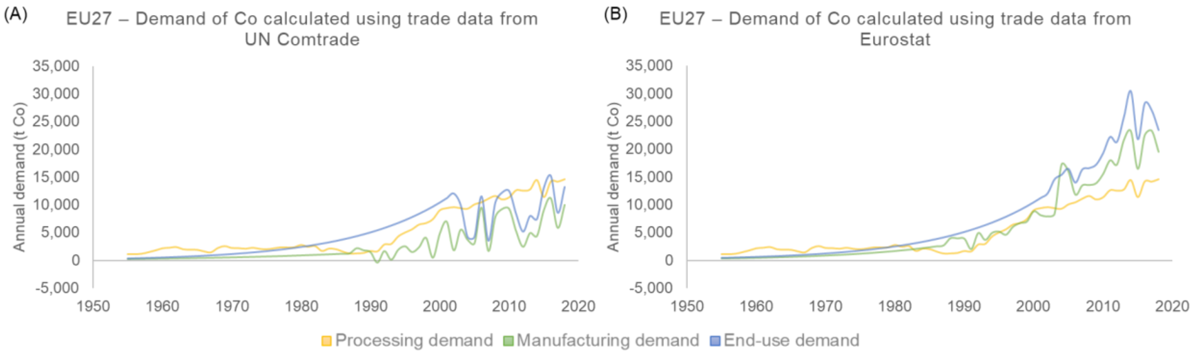

Figure 2. Annual Co demand for processing, manufacturing, and end use in the EU27 between 1955 and 2018, according to the data obtained from UN Comtrade and Eurostat.

For more information regarding the analysis and comparison of both datasets, we refer the reader to our previous study (Godoy León et al., 2021).

In addition, some inconsistencies are found in the demands obtained with the UN Comtrade dataset. For instance, the manufacturing demand is zero or even negative for some years. Moreover, the processing demand for the period 2012–2016 is higher or almost equal to the end-use demand, which conflicts with the findings of Matos et al. (2020). The demands obtained with the Eurostat dataset do not present these inconsistencies.

Furthermore, the manufacturing demand obtained with both datasets is compared to the annual price of Co (see SI). The demand obtained with the dataset from Eurostat is better correlated with the fluctuations of the market. Based on these arguments, the following sections focus on the results obtained with the Eurostat dataset. For the UN Comtrade dataset, the results are shown in the SI. This decision is also supported by the recent study of Watari et al. (2020), in which data from the UN Comtrade database were avoided due to inconsistent trade data between countries.

Focusing on the evolution of demand according to the Eurostat data (Figure 2(B)), it has increased overall over time. The demand for processing increased at a high rate between 1990 and 2000, with an average year-on-year (YoY) change of 21%, but for the period 2000–2018 it shows a relative stagnation, with an average YoY change of 4%. For the manufacturing and end-use demands, a more constant increase is observed. The manufacturing demand shows an average YoY change of 16% between 1990 and 2000 and of 9% between 2000 and 2018. Meanwhile, the end-use demand shows an average YoY change of 7% between 1990 and 2000 and of 6% between 2000 and 2018. Nevertheless, the studied demands (Figure 2) reveal a lower increase rate between 2000 and 2018 compared with the previous decade. This will be further discussed in the next section.

3.2 Cobalt cycle in the EU

For the sake of simplicity, the Co cycle in the EU was analysed in detail for three years: 1988, 2003, and 2018, as shown in Figure 3. These years were chosen to obtain a fair overview of the dynamics of Co over time in the studied period, based on the data availability for the periods described in section 2.2.The full results are presented in the SI. For each year, the flows entering and leaving each life cycle phase are presented along with the net trade and accumulated stocks. First, the cycle for the latest year will be analysed in detail, followed by a comparison between the cycles of the three years.

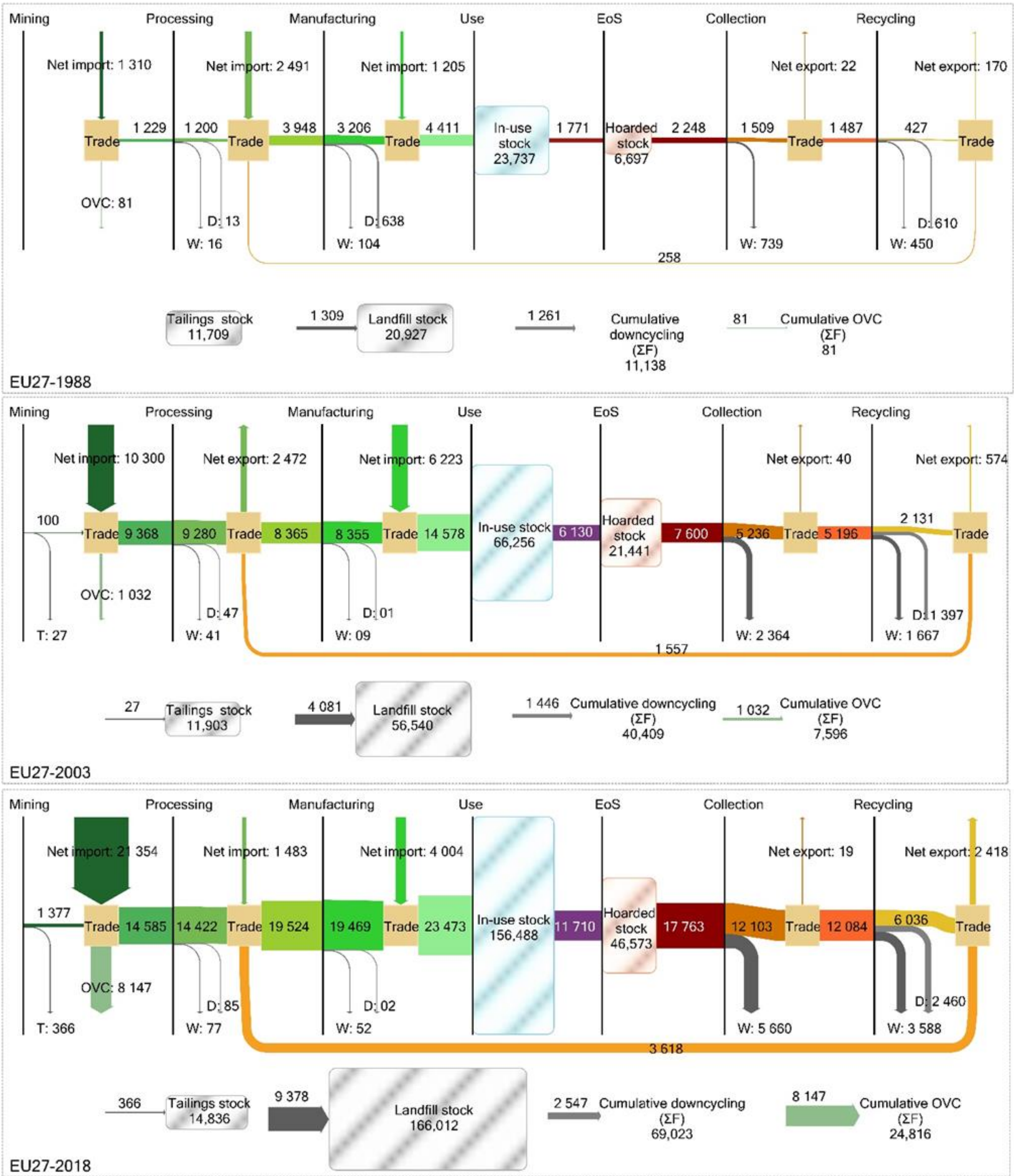

Figure 3. Co cycle in the EU27 in 1988 (A), 2003 (B), and 2018 (C). Values are shown in metric tons (t). Collection includes what is released after hoarding and what is immediately collected at the end-of-service (EoS). D: downcycled, OVC: output from the value chain, T: Tailings, W: waste. Differences of 1 metric ton can be encountered due to approximations. Green is used to represent pre-consumer flows, and red to orange is used to represent post-consumer flows. ΣF: cumulative flow.

3.2.1 Cobalt cycle in 2018

In 2018 (Figure 3(C)), around 1,700 t of primary Co were mined in the EU (specifically in Finland), and about 1,400 t were extracted as Co concentrates. The cycle of this year was characterised by net imports to the processing, manufacturing, and use phases and net exports from the collection and recycling phases. Overall, 24,400 t of Co were imported to the EU, mainly as semi-processed material. Domestically, around 14,400 t of Co were embedded in processed material and 19,500 t in final products. Around 23,500 t of Co were added to the in-use stock, which was about 157,000 t of Co in

2018. In addition, 46,600 t of Co were stored in the hoarding stock. About 18,000 t of Co were disposed, of which 68% (12,000 t) were selectively collected for recycling. From the recycling phase (which also includes the pre-treatment phase), 6,000 t were functionally recycled, 2,500 t were downcycled, and 3,600 t were disposed as waste. From the functional recycled material, 60% was used domestically, returned to the manufacturing phase, and the rest was exported.

Finally, for 2018 there was an output from the value chain of 8,100 t of Co, which plausibly was stockpiled or left the EU though confidential exports. Considering this flow, by 2018 there were almost 25,000 accumulated metric tons of Co whose fate is unclear.

3.2.2 Evolution of the cobalt cycle

A number of points arise from Figure 3. First, it is clear that in the last 30 years the Co stocks and flows in the EU have increased substantially. For instance, from 1988 to 2003 the inputs to the processing, manufacturing, and use phases increased by 6.6, 1.1, and 2.3 times, respectively. From 2003 to 2018, these inputs also increased considerably, but in general at a lower rate (56, 133, and 61%, respectively). For the phases related to the end of life, a similar behaviour is observed. In particular, the functionally recycled material used domestically increased by 13 times between 1988 and 2018.Second, the EU has become more reliant on imports of materials, especially for the processing phase. The net import to this phase increased by 6.9 times between 1988 and 2003 and by 1.1 times between 2003 and 2018. In addition, the import of semi-processed Co rose steeply at the end of the 1990s and in the middle of the 2010s. At the end of the 1990s, this was probably due to the higher demand of processed Co for its use in rechargeable batteries (Shedd, 1997). A plausible reason for the increase in the middle of the 2010s was the construction of gigafactories for battery production in different parts of Europe (Climate Home News, 2020). This occurred in the context of the European Battery Alliance (EBA), aiming to boost the production of electric cars in the continent (EBA, 2021). This indicates that, in the last decade, Co has been stockpiled in the EU. Indeed, Figure 3(C) shows that the OVC stream was 8,100 t of Co in 2018, which was calculated based on the imbalance between the inputs to the processing phase and final production, creating an excess of Co material. This imbalance could be partly explained by stockpiling, to avoid possible uncertainties in the Co market. However, another plausible reason is the existence of confidential exports of semi-processed material with the commodity code CN81052000, which are not reported in Eurostat and are aggregated in the ULJAS database for all countries. From the UN Comtrade database, it is possible to determine that Japan, Russia, and the USA are the main importers of the commodities with the code CN81052000. All these countries have Co refining capabilities, and the ratio of value imported versus mass is lower or equal to the price of refined Co. Therefore, it can be expected that some of the volumes imported from Finland to these three countries are of intermediate Co commodities, that is, ‘semi-processed materials’. More details regarding the evolution of the trade are available in the SI and in a previous study (Godoy León et al., 2021).

Third, in line with higher inputs and outputs within the system, the Co losses have also increased. A decrease in the losses is only observed between 1988 and 2003 for the manufacturing phase, due to improvements in the efficiency of the processes. The larger losses are for the collection and recycling phases, where the total losses increased by 6.7 and 4.7 times, respectively, between 1988 and 2018. While the model takes into account higher collection rates over time, the collection losses still increase due to higher consumption and subsequent disposal of EoL products. This means that efforts to increase the circularity of Co in the EU should be focused on both differentiated collection and recycling.

Finally, regarding the functional recycling and downcycling of Co, both of corresponding flows have increased in time. However, as Figure 4 shows, the share of functionally recycled material has increased over time, while the share of downcycled material has decreased. For instance, in 1960 the share was 10% of recycled Co and 90% of downcycled Co (without considering the produced waste). By 2000, the share was 50/50, and in 2018 the share was 71% of recycled Co and 29% of downcycled Co. This change is due to a shift in the end-use demand, as for some applications the corresponding

EoL products are more downcycled than others (e.g. magnets are fully downcycled while superalloys can follow both routes, mostly depending on the Co price).

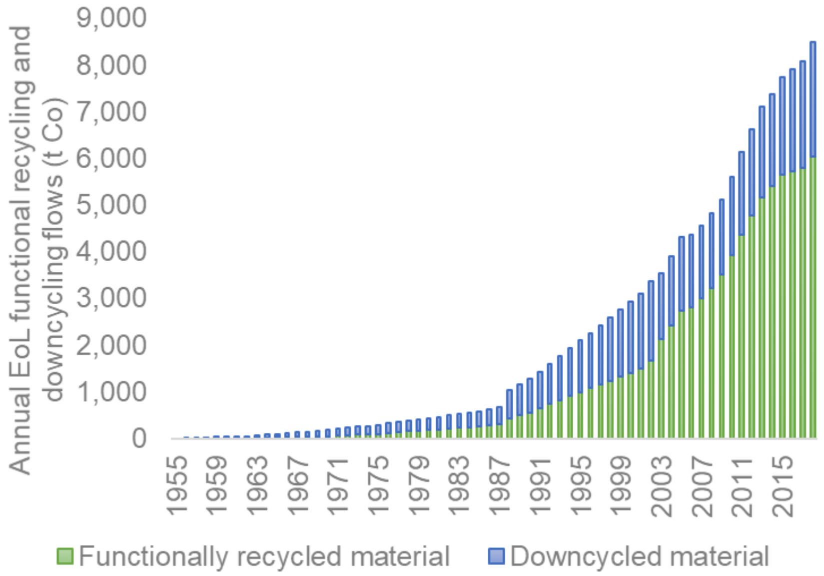

Figure 4. Annual flow of functionally recycled and downcycled Co from EoL products between 1955 and 2018.

Returning to Figure 3, it is noteworthy that between 2003 and 2018 the flows of Co in general increased at a lower rate compared to the previous 15 years. This could indicate saturation of Co in the EU. For example, Tsiropoulos and colleagues indicate that the electronics market has gradually slowed, and it is expected to saturate further in the coming years (Tsiropoulos et al., 2018). However, the demand per capita (see SI) on average has increased at a similar rate; between 1988 and 2003 the average annual growth rate of the demand per capita was 7.2%, and between 2003 and 2018 it was 7.4%. Furthermore, when comparing the end-use demand to GDP (known as resource intensity, i.e. how much material is required to create one unit of monetary value (Krausmann et al., 2018), the resource intensity has increased over time, from 0.7 g Co per €1,000 of GDP in 1995 to 2.1 g Co per €1,000 of GDP in 2018. This means that the EU's economy has become more intense in the use of Co over time.

To complement the discussion, Figure 5 shows the evolution over time of the manufacturing and use of applications in the EU27. The values correspond to the average value per decade. Once again, both the manufacturing and use skyrocket starting in the 1990s. In both cases, the main applications are intentionally dissipative uses, hard metals, and superalloys. In addition, Figure 5(A) shows that in the last eight years the manufacturing of magnets and catalysts represents the highest increase (on average 4.5 and 3.3 times, respectively), followed by mobility batteries and intentionally dissipative uses (on average 2.5 times). Regarding the use (Figure 5(B)), the highest increase is seen for mobility batteries and magnets (on average 11 and 6.3 times, respectively), followed by catalysts and intentionally dissipative uses (on average 3.3 and 2.3 times, respectively).

There are different reasons for this pattern. Recent advances in defence and aerospace have escalated the global demand for magnets (Sinha et al., 2017), which could explain the noticeable increase in both manufacturing and use of this application in the EU. In the case of superalloys, the increase in both manufacturing and use has mainly been due to the increasing demand for superalloys in aerospace. In 2017, the global commercial and military aerospace markets were estimated to account for 67% of the total superalloy demand. Since 2010, the global demand for superalloys has increased, not only due to the higher production rate of aircrafts but also due to the so-called new-generation engines. However, the strong aerospace demand has been offset by a sharp drop in the demand for industrial gas turbines used in power generation due to the global rise in renewable energy from solar and wind generation (Darton Commodities Limited, 2018). Although the demand for superalloys in aerospace is forecasted to further increase in the coming decades (Airbus, 2017; Darton Commodities Limited, 2018), there are some factors that could cause the demand to remain constant or even decrease, specifically legal and environmental drivers related to aviation (Monnet and Abderrahim, 2018). Direct emissions from aviation account for about 3% of the EU's total greenhouse gas emissions and more than 2% of the global emissions. Furthermore, to date aviation emissions are already around 70% higher than in 2005, and it is predicted that by 2050 they could grow by over 300% (European Commission, 2020b). As some specialists have already indicated (Capoccitti et al., 2010; Bock and Burkhardt, 2019), improving technological or logistical aspects, such as fuel efficiency, engine technology, and traffic management, might not be enough to stop this trend. Hence, if governments enforce stronger measures for climate change mitigation, a decrease in demand could occur.

In the same context of climate change mitigation, the demand for batteries has changed and is expected to change further. The increasing use of mobility batteries is in line with the EU's policy objective of reducing greenhouse gas emissions from transport. Based on the Paris Agreement's goals and the EU Batteries Alliance, different studies and reports forecast that the Co demand for this sector will continue increasing at both the EU and global levels (Alves Dias et al., 2018; Deetman et al., 2018; IEA, 2018; Neef and Thielmann, 2018; Tercero Espinoza et al., 2019). According to recent data, in 2030 the use of Co for mobility in the EU will be between 29,000 and 53,000 t of Co, of which the EU will manufacture 20,000 to 47,000 t. This means that between 2018 and 2030 the demand will increase between 3,700 and 8,900% for manufacturing and between 3,600 and 6,700% for use. However, based on the research of new battery chemistries, other scenarios foresee a decrease of the demand of Co in batteries. For example, the Federal Environment Agency (UBA) of Germany assumed in its RESUCE (Resource-Efficient Pathways towards Greenhouse-Gas- Neutrality) study (Günther et al., 2019) that lithium-sulphur batteries will fully replace lithium-ion batteries containing Co from 2040 onwards. Lithium-sulphur batteries are already in the market, and are one of promising candidates for next-generation energy storage device due to the sulphur cathode material with low cost and nontoxicity (Zhou et al., 2019). Another cathode chemistry was recently developed (Li et al., 2020) based on nickel, manganese, and aluminium, abbreviated NMA. The Co-free cathode material presents overall attractive electrochemical properties, which were benchmarked against NMC and NCA for lithium-ion batteries. According to the authors, this research opened a new space for cathode material development for next-generation high-energy, Co-free lithium-ion batteries.

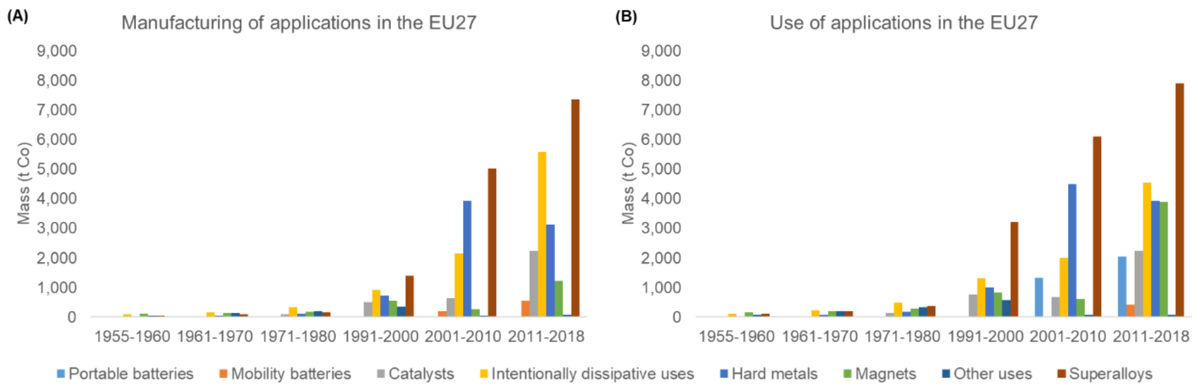

Figure 5. (A) Manufacturing of applications of Co in the EU. (B) Use of applications of Co in the EU.

The evolution of the societal metabolism of Co can also be analysed through comparison of the calculated indicators, which are presented in Figure 6. For the indicators TS-RIR and SSP, the results are shown from 1988 onwards due to data availability related to the trade of commodities.

The RPER has fluctuated between 35 and 50%, showing the lowest values between 1970 and 1990. This behaviour is mainly due to the temporal evolution of the demand of final products, which affects the amount of scrap recovered from the processing and manufacturing phases, and the amount of scrap recovered from EoL products. From 2002 onwards, the modelling assumes a higher recovery of scrap from the manufacturing phase and a lower rate of downcycling for superalloys, which results in higher values of the RPER after 2000. The EoL-RR has increased steadily over time, meaning that more secondary Co has been recovered from domestically collected and imported EoL products. Nevertheless, there is room for improvement to increase the circularity of Co, as in 2018 the EoL-RR was estimated at 34%.

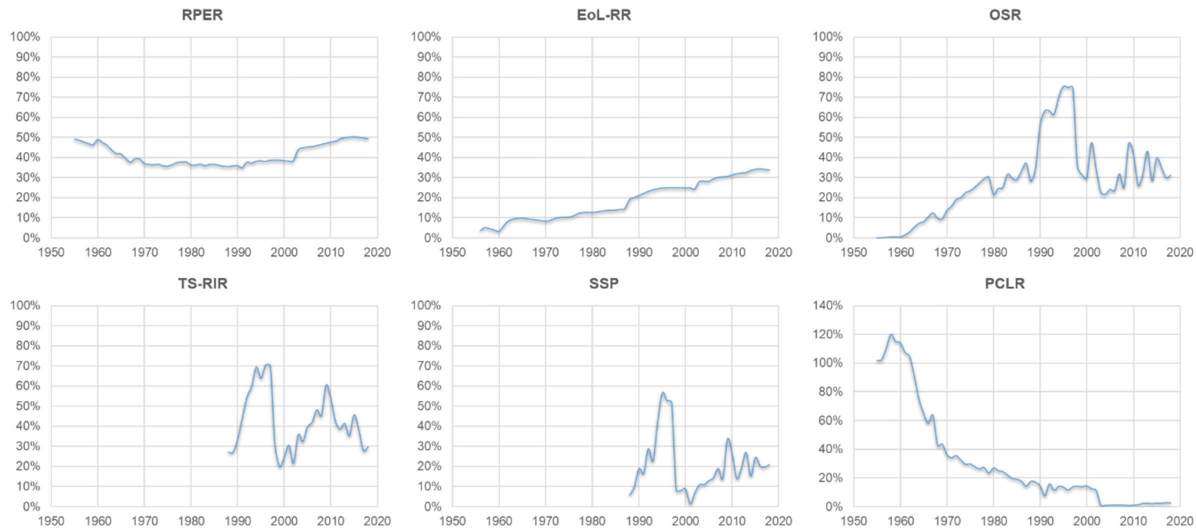

Figure 6. Value for the set of indicators in percentage (%). Recycling process efficiency rate (RPER), end-of-life recycling rate (EoL-RR), old scrap ratio (OSR), total scrap recycling input rate (TS-RIR), self-sufficiency potential (SSP), and pre-consumer loss rate (PCLR).

Regarding the OSR, an increasing trend is observed between the 1960s and end of the 1990s. After the 2000s, the OSR fluctuates, with an average value of 32%. This behaviour is explained by the change in the demand of final products, shifting to applications from which more new scrap can be recovered during the processing and manufacturing phases. The TS-RIR shows an increasing trend between the end of the 1980s and the end of the 1990s and between the beginning of the 2000s and the end of the 2000s. The behaviour of this indicator is mainly influenced by trade dynamics, as it depends on the import of processed and semi-processed material. In addition, as with RPER and OSR, it is affected by the change in the demand of final products. The SSP also shows an increasing trend between the end of the 1980s and the end of the 1990s and between the beginning of the 2000s and the end of the 2000s. Afterwards it fluctuates, with an average value of 21%. In 1995, it reached its peak at 57%. High values of this indicator are due to a high return of recycled Co from EoL products to the processing and manufacturing phases. The input of primary material is generally negligible.

Finally, it is observed that the PCLR has decreased over time. However, even though efficiency improvements were made to the model when possible, the main reason for this decrease is an increasing end-use demand. This result has to be considered carefully since the EU also relies on imports in the use phase, but the PCLR only reflects domestic pre-consumer losses, and it does not consider the losses occurring outside the EU. The value of the PCLR in the 1950s is higher than 100%. This is related to the export of processed material. In that period, the processing losses were high due to the production of processed Co that was subsequently exported, with the total losses surpassing the amount used domestically in final products.

3.3 Anthropogenic and lost stocks over time

In this section, the cumulative stocks and flows of Co are discussed. Figure 7 presents the accumulation between 1955 and 2018 for six different destinations of Co: in-use (stock), OVC (cumulative flow), hoarded (stock), tailings (stock), landfill (stock), and downcycled (cumulative flow) (see section 2.2 for an explanation of each).

In 2018, the landfill stock was the largest, with around 166,000 t of Co, representing 35% of the total accumulation in that year. The main contribution to this stock comes from the non-selective collection; in 2018, almost 100,000 t of Co were stocked in landfills due to this stream. The second biggest stock or cumulative flow was the in-use stock, which was around 157,000 t of Co in 2018 (33% of the total accumulation). The smallest stock or cumulative flow in 2018 was the tailings stock and the cumulative output from the value chain, representing 3 and 5% of the total accumulation in that year, respectively.

The in-use stock increased at an average rate of 33% per year between 1955 and 1960, 11% per year between 1961 and 1970, and about 7% per year from 1971 until 2018. In other words, after 1970 the in-use stocks doubled in size every 10 or 11 years.

The cumulative OVC (which refers to stockpiled Co and/or Co that has left the EU through confidential exports) started to build up in the late 1980s, but only at the end of the 1990s did it become substantial, with around 4,000 t of Co in 1999. In 2006, it doubled (about 8,000 t of Co), and in 2017 and 2018 a high value chain output was estimated, increasing the cumulative flows to 17,000 and 25,000 t of Co, respectively. Here it is important to mention that the model does not consider 'de-stockpiling' since, to the best of the author's knowledge, there is no information available.

The hoarded stock doubled its size every 8 to 11 years between 1970 and 2010, growing at an average value of 8% per year. However, between 2010 and 2018 its average growth rate decreased to 3.6% per year. This decrease was due to a shift in the end-use demand for applications with lower hoarding rates and/or hoarding times. Between 2012 and 2018, the end-use demand for mobility batteries, catalysts, intentionally dissipative uses, and magnets increased, with a decrease in the demand for portable batteries, hard metals, and superalloys. The latter are indeed the applications with the highest hoarding rates and/or hoarding times.

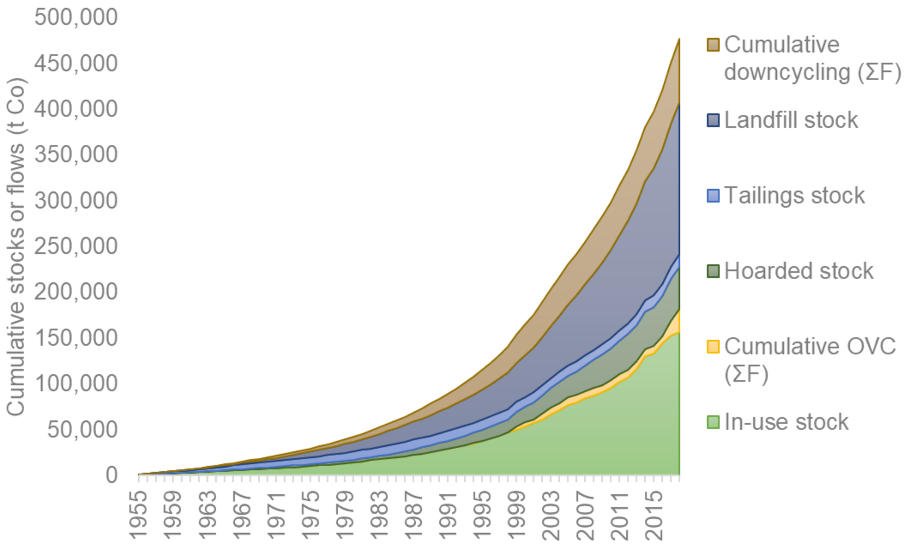

Figure 7. Cumulative stocks or flows of Co in the EU27 from 1955 until 2018. OVC: output from the value chain. ΣF: cumulative flow.

The tailings stock has evolved according to the periods in which primary material was produced domestically (for more details, see Godoy León et al., 2021), but in general after 1970 it increased at a rate between 1 and 6% per year. Only between 1955 and 1967 did it show higher growth rates, between 11 and 61% per year.

Regarding the landfill stock, it exhibits a similar behaviour to that of the in-use stock; it increased at a higher rate between 1955 and 1960 (49% in average per year), decreasing between 1961 and 1970 and stabilising after 1971 (25% on average per year between 1961 and 1970 and 9% on average per year between 1971 and 2018). This means that the landfill stock doubled in size on average every eight years. Finally, the cumulative downcycling flow, which refers to the aggregated flow of Co lost by downcycling, increased at an average rate of 41% per year between 1955 and 1960, 18% per year between 1961 and 1970, 10% per year between 1971 and 2002, and 4% per year between 2003 and 2018. The lowest rate after 2002 was due to the higher recovery of Co from functional recycling, specifically from EoL superalloys.

The main products of the in-use stock in 2018 were intentionally dissipative uses, superalloys, magnets, and hard metals: 29, 26, 19, and 15% of the total stock in-use, respectively. The high volume of stock observed for products containing superalloys is consistent with the higher lifetime characteristic of these products. One important consequence of this result is that, for more than a quarter of the actual in-use stock, Co could be retained in use within products with lifetimes as high as 30 years. Regarding batteries, the high expected demand for electric vehicles will increase their in-use stock in the near future. According to RMIS (2019), the stock of Co in mobility batteries will more than double in 2021, compared to the values reported in 2016. In contrast, a high volume of the in-use stock (29%) is embedded in products in dissipative uses, which means that part of this amount will be lost from the Co cycle after use (some dissipative uses are landfilled after use, while others are dissipated in the environment).

It is important to keep in mind that the presented stocks and cumulative flows do not consider inputs before 1955. Nevertheless they would not likely contribute significantly to the current stocks and cumulative flows, mainly due to the magnitude of the Co flows before the 1990s.

In terms of circularity, it was observed that the efforts should be focused on differentiated collection and recycling. In addition, the in-use and hoarded stocks and related flows provide information about how much Co will be available in the coming years. For example, the amount of Co in the hoarded stock (about 47,000 t of Co) at the current collection and recycling rates could be sufficient to cover the need for processed Co for a whole year. In terms of the EoL flows, in 2018 the hoarded and the non-selectively collected Co could have covered around 70% of the processed Co demand, increasing the self-sufficiency of the EU from 21 to 80%. In both examples, it is assumed that the recycled Co has sufficient quality for all the applications. These results are relevant for policy decision-making, especially regarding the new Circular Economy action plan of the EU (European Commission, 2020c). One of the pillars of the plan is circularity in production processes, which promotes the use of digital technologies for tracking, tracing, and mapping of resources. In addition, the plan is focused in key product value chains, such as ICT (information and communications technology), and batteries and vehicles.

3.4 Limitations and sensitivity analysis

The calculation of the presented stocks and flows is subject to limitations. For instance, production–inventory problems are not considered. Here, it is assumed that the amount produced is equal to the demand. This aspect is more related to the management of single companies, but it could be considered in future research to determine how it affects the stocks and flows of Co.

Other limitations are related to the assumptions considered in the study. For example, the tailings were calculated using a constant value of 79% for mining extraction, which is a considerable assumption since the ore grade and extraction efficiency can vary over time according to the characteristics of the mine and available technology. Due to data unavailability, the in-use flows and stock were calculated using extrapolated values for the manufacturing and end-use demand, assuming exponential growth between 1955 and 1987 and between 1955 and 2002, respectively; this is in addition to assumptions related to the share of manufacturing demand and the trade of catalysts. Similarly, the EoL flows and related stocks and cumulative flows were estimated assuming relatively constant values of the lifetime and the collection rate of the applications. All of these assumptions may have a low or high impact on the final results. This impact was examined through a sensitivity analysis (Figure 8).

Eight sets of parameters were analysed (see Table 2). Figure 8 presents the results when the value of the parameters changes by ±50% (±25% for the extraction efficiency) compared with the base case.

The results indicate the variation of the in-use stock, cumulative OVC, hoarded stock, and lost stock (including the cumulative downcycling flow) in 2018. The results related to the net trade of functionally recycled material are not shown in Figure 8 since the value of that parameter does not influence stocks in 2018 but rather the trade of primary and semi-processed Co between 1955 and 1987. Between these years, the trade of these commodities varies on average 3.8% compared with the base case (3.8% higher when there is a net export of recycled Co, and 3.8% lower when there is a net import of recycled Co).

Figure 8. Variation in the percentage of the in-use stock, cumulative OVC (output from the value chain), hoarded stock, and lost stock in 2018 when changing the value of seven sets of parameters. Above, the value of the parameters decreased by 50% (25% for extraction efficiency); below, the value of the parameters increased by 50% (25% for extraction efficiency). Man. demand: Manufacturing demand, Man. share: Manufacturing demand share, Catal. trade: Net trade of catalysts. ΣF: cumulative flow.

Regarding the other seven sets of parameters, those with the highest influence on the 2018 stocks are the end-use demand of Co and the lifetimes of the applications. The rest of the assessed parameters have a minor impact on the stocks (less than 10% in absolute terms). The end-use demand of Co mainly affects the lost stock, which decreases (increases) by 27% compared with the base case when the value of the end-use demand decreases (increases) by 50%. A higher Co demand by end-users implies higher flows of EoL Co. Indeed, it is observed that the losses that increase the most are those related to non-selective collection, recycling waste, and downcycled material in the recycling phase. Since the value of the end-use demand changes between 1955 and 2002, its effect on the in-use stock in 2018 is marginal (around 4%); by 2018, many of the applications that entered the use phase during that period have already reached their EoL.

Related to the lifetime of the applications, when their value decreases by 50%, the in-use stock in 2018 decreases by 15%, and the lost stock increases by 7%; when their value increases by 50%, the in-use stock increases by 22%, and the lost stock decreases by 11%. If the lifetime of the applications increases, they remain in the in-use stock longer, making it bigger over time; in addition, fewer EoL products are produced, decreasing the EoL losses (and the other way around). Even though the lifetime values only change between 1955 and 1987, the change is strong enough to influence the in-use stock in 2018. This means that the in-use stock is more sensitive to a change in the lifetimes than to the end-use demand.

A comparison of our findings with those of previous studies can help us to understand the accuracy of the data. As indicated in section 1, Bio by Deloitte (2015) and Matos et al. (2020) assessed the stocks and flows of Co in the EU28 in 2012 and in the EU27 in 2016, respectively. When comparing our results with those of BIO by Deloitte, some differences are found in the processing and manufacturing phases. According to that study, in 2012 the EU28 produced around 15,000 t of refined Co and manufactured around 11,000 t of Co in final products. Our results show that in 2012 the EU27 produced around 12,400 t of refined Co and manufactured 17,800 t of Co in final products. However, for the use and collection phases, the differences are smaller. For example, the end-use demand and the collection of EoL products each show a difference of about 6% between both studies. When compared with the results of Matos et al. (2020), the differences are lower for the processing and manufacturing phases (0.1% and 7%, respectively) but higher for the use and collection phases. For 2016, Matos et al. (2020) estimated that the EU27 consumed around 33,000 t of Co in final products, and 20,000 t of Co were collected in EoL products. Our calculations show that in 2016 the EU27 consumed 28,300 t of Co in final products, and 16,600 t were collected.

There are various reasons for these differences. First, the geographical coverage is different, as BIO by Deloitte developed the study for the EU28 whereas this study was developed for the EU27. Second, the data used in the three studies are different; for instance, here we used analysed and complemented statistical data on the production and trade of the different commodities and applications. In BIO by Deloitte and Matos et al., the considered statistical data were not scrutinised. In addition, both previous studies were developed using a static approach whereas we used a dynamic approach. This made it possible to introduce lifetime distributions and estimate stocks and flows considering changes in the past. For example, in BIO by Deloitte and Matos et al., the calculation of the collection of EoL products depended on constant annual growth rates of consumption and on the manufacturing and trade flows of the applications of the assessed year. In other words, it was assumed that the production and trade of the applications in the past follow the same trend as in the present. Here, the dynamics over time were considered in the calculation.

Despite these differences, the values in this research, in general, vary less than 20% from those of the previous studies, which is acceptable given the data availability and quality. However, there is an important discrepancy in the estimated downcycled Co. On one hand, BIO by Deloitte did not consider any downcycling of the metal. On the other hand, Matos et al. estimated the downcycled flow as 4,000 t of Co, which is almost 85% higher than the flow estimated here. This difference mainly comes from the estimation of EoL magnets, which is 75% higher in Matos et al. In the authors' opinion, this flow was overestimated in Matos et al. due to the applied methodology. Consequently, it is recommended that in future research EoL flows should be estimated using a historical dynamic approach.

4. Conclusions

A dynamic material flow analysis (dMFA) was applied for long-term retrospective assessment of the cobalt (Co) societal metabolism in the EU27. The assessment was done between 1955 and 2018.

It was found that the Co stocks and flows have increased substantially over time. For example, between 1988 and 2003 the inputs to the processing phase increased 6.6 times. Between 2003 and 2018, the inputs to the different phases also increased considerably, but generally at a lower rate. Nevertheless, when comparing the end-use demand per capita it can be seen that, on average, it increased at a similar rate between 1988 and 2003 (7.2%) and between 2003 and 2018 (7.4%). In addition, the growth rates indicate that the Co demand is growing at a considerably faster pace as GDP and as a consequence, the EU's economy has become more intense in the use of Co over time, from 0.7 g Co per €1,000 of GDP in 1995 to 2.1 g Co per €1,000 of GDP in 2018.

The EoL stocks and flows have also increased over time. In particular, the flows of functionally recycled and downcycled Co have increased significantly, although the share of functionally recycled material has increased, while the share of downcycled material has decreased. This change has been mainly due to shifts toward some applications for which EoL products are often downcycled. In 2018, the share was 71% of functionally recycled Co and 29% of downcycled Co.

According to the results, the landfill stock was the largest one in 2018, with around 166,000 t of Co, accounting for 35% of the total stock in that year. The main input to this stock was the non-selective collection, which in 2018 had stocked about 100,000 t of Co in landfills. In terms of circularity, landfills might be both a big opportunity and a challenge for the recovery of Co in the coming years. According to Dewulf et al. (2021), in the best scenario material could start to be recovered from landfills in the coming decades. If the entire landfilled stock of Co could be identified, accessed, and recovered, and assuming a hypothetical efficiency of 50%, it could cover the EU27 material demand for about four years (assuming a demand of 20,000 t of Co, as in 2018). In a similar vein, in 2018 the hoarded and non-selectively collected Co could have covered around 70% of the processed Co demand, increasing the self-sufficiency of the EU from 21 to 80%. Therefore, it is clear that enhancing selective collection and switching from downcycling to recycling is key for increasing the circularity of Co, reducing supply risks at the same time.

This work is novel in multiple ways. First, it is the first long-term retrospective dMFA of Co developed for the EU. Second, it offers an updated view of the metabolism of Co in the EU27 for 2018. Third, the calculation of stocks in previous assessments was based on assumptions and applied values of market levels some years before the assessment. Here, historical long-term statistical data were applied. In addition, data from the Eurostat and UN Comtrade databases were used separately, comparing the results when using one or the other, and substantial differences were identified.

The results of our research can be useful for policy makers, industries, and researchers. They establish how the stocks have built up over time and where the main reserves of secondary Co in the EU are located, which could be exploited in the coming years. In addition, they indicate where efforts should be made to increase the circularity of Co, decreasing dependency on imported material. Finally, the results could be used in a prospective dMFA, modelling different scenarios to determine the potential future of Co in the EU in the coming decades.

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