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Dynamic analysis of European copper flows

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ABSTRACT

A dynamic material stock & flow model for the European Union (EU28) is presented and discussed. Detailed results are provided for the period 1990–2014 including trade flows, while the modelling period extends from 1910–2014 using extrapolation based on economic growth in order to better depict the build-up of long-term stocks (especially building & infrastructure). Model results indicate a total copper stock in use of approx. 82 million tonnes of copper in 2014, with a net addition to stock on the order of 500 thousand tonnes. Comparison with different country studies reveals different dynamics in Eastern and Western Europe. Eight recycling indicators are presented for 2014 and the latest 10-year period. In 2005–2014, ≈50% of copper refined and remelted in the EU was from secondary sources (recycling input rate), ≈50–60% of which were post-consumer (old) scrap (end of life recycling input rate 25–30% depending on the assumed composition of traded scrap). Uncertainties in the input parameters were explored using a stochastic method with 10.000 simulation runs.

1. Introduction

Copper is essential for numerous applications in modern society, ranging from energy production and transmission, architectural uses, water and heating pipes to all kinds of electronic components used in consumer electronics, home appliances and vehicles (Lossin, 2006). Along with the constantly growing usage of copper, its good recyclability transforms manufacturing scrap and discarded products into important material sources, contributing close to 30% of copper supply worldwide in 2014 (secondary refined copper for cathodes and directly remelted copper for the production of semi-finished goods; ICSG, 2016). In view of its contribution to supply and environmental benefits of copper recycling (Ayres, 1997), it is important to develop a quantitative understanding of the anthropogenic copper cycle in order to provide reasonable estimates of copper availability from secondary sources and to identify areas of improvement.

Tracing material flows through a system using the principle of closed mass balances is the core of substance flow analysis (SFA). SFAs, when carried out dynamically, enable also the simulation of material accumulations in stocks over time (van der Voet, 2002) and provide the quantitative basis for the assessment of anthropogenic metal cycles. We recently presented a dynamic SFA model for copper at the global level (Glöser et al., 2013b). However, as the production of copper, the fabrication of products and the final use are not equally distributed throughout the world, the structure of the copper flows differs depending on the geographical region (Graedel et al., 2004). Copper is accumulated in areas where end-use products are extensively used, whereas metal extraction from ore to a large extent takes place in Latin American countries and the fabrication of copper products is concentrated in large manufacturing centers (ICSG, 2016; Tercero Espinoza and Soulier, 2016; UNEP, 2010). Regional SFAs are needed in order to understand and depict these geographical differences as the level of detail in global approaches is limited. For this reason, a number of copper cycles have been developed for the city, country and regional level (Amneklev et al., 2016; Bertram et al., 2002; Bonnin et al., 2013; Chen et al., 2016; Chen and Graedel, 2012; Ciacci et al., 2017; Daigo et al., 2009; ICSG, 2005; Rauch et al., 2007; Tanimoto et al., 2010; van Beers et al., 2003; van Beers and Graedel, 2003; Vexler et al., 2004; Zhang et al., 2014, 2012).

A closer examination of copper stocks and flows in Europe is valuable for several reasons: First, Europe with its broad industrial basis covers the whole value chain of copper starting with metal production through the fabrication of semi-finished goods and end-use products of copper and copper alloys. In addition, Europe has a well developed recycling infrastructure including public collection systems and capable recycling companies. Furthermore, an information deficit specifically for stocks and flows of non-energy raw materials has been identified in the current discussion on resource efficiency, circular economy and criticality in the EU (Blengini et al., 2017; EIP Raw Materials, 2013; Goldmann, 2010a,b; Nuss and Blengini, 2017). In particular for copper,

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previous studies on Europe provide mostly static snapshots for stocks and flows of the mid 1990s and early 2000s (Gerst and Graedel, 2007; Graedel, 2002; Ruhrberg, 2006; Spatari et al., 2002). Dynamic approaches on copper flows have been developed for European countries such as for France (Bonnin et al., 2013) and Switzerland (Bader et al., 2011; Wittmer and Lichtensteiger, 2007), and more recently for the EU (Ciacci et al., 2017). In this article, we present a detailed dynamic top-down copper flow model for the European Union based upon the most recent data on copper trade and copper usage covering the period from 1990 to 2014.

The work presented here extends the results of Glöser et al. (2013a) and provides a more differentiated view of the EU copper cycle than available to date. As global trade has been increasing significantly over the last 20 years, import and export flows are of particular relevance. Thus, several hundred trade codes were identified as being relevant for copper, enabling an illustration of copper imports and exports on a unique level of granularity. Together with detailed information on the production of copper, semi-finished and end-use products provided from the copper industry, the best available data basis is used as input for the model. As one result of the model, recycling rates for the regional copper cycle (cf. Tercero Espinoza and Soulier, 2017b) are either comprehensibly derived from the simulated mass flows or, for technical scrap processing, based on an in-depth analysis of the scrap type specific separation processes.

2. Methods

The presented copper flow model for the EU28 is based on the underlying principles of calculating material stocks and flows as applied in the previously published global copper flow model (Glöser et al., 2013b). As in the global case, the regional model consists of five different lifecycle stages: (1) primary production, (2) semi-finished goods fabrication, (3) manufacturing and (4) usage of finished products and finally (5) the recycling of scrap. The model links these different stages through annually calculated material flows taking into consideration a closed mass balance not only within one year but also over time. The model's input data, especially on production and trade, is the sum of separately collected data for each of the 28 EU-countries. Using this method, we are able to simulate the copper flows even in a time before the EU in its current form existed. Implemented in the system dynamics (SD) software Vensim®, it is possible to trace the copper production in any year since 1990 and to follow it on its way through the cycle, allowing among others the derivation of relevant recycling indicators. The detailed model structure as it has been implemented in the SD-software is shown in Fig. 1.

2.1. Trade

The most obvious difference between global and regional MFAs is the occurrence of imports and exports which have to be considered at every stage of the material cycle. Data for this were extracted from the UN Comtrade database (UN Comtrade, 2016) using values reported by the EU28 Member States. The UN Comtrade database is well suited for this purpose due to its wide coverage of international trade flows. It uses ≈5000 commodity codes based on the Harmonized System (HS) to classify traded products. For the regional copper flow model, ≈370 commodity codes of copper-containing products have been identified and an individual estimate of their copper content has been assigned to every code. The commodity codes, their assumed copper content and the copper cycle stage at which they are implemented in the model are listed in the supplementary information (Table S1).

In the case of Europe, the EU28 foreign trade as a whole is only reported back to the year 2000 in Comtrade. Trade flows back to 1990 were calculated manually from individual country data reported in Comtrade by accounting imports (M) and exports (X) for each EU country i and each trade code h with partner countries p. For imports, this was done following Equation (1). An equivalent expression was used for exports.

$$M_{\text{EU}} = \sum_{i} \sum_{h} \left[\left(\sum_{p} M_{i,h,p} - \sum_{p \in \text{EU28}} M_{i,h,p} \right) \times C_h \right] \tag{1}$$

where C_h denotes the estimated copper content of commodity h as reported in Table S1 in the supplementary material.

2.2. Simulation

Starting point of the model calculations is the domestic EU copper concentrate production plus imports minus exports of concentrate which is then converted and refined to copper cathodes. Furthermore, a small stock of copper cathodes has been implemented. Data on production of concentrates and the fabrication and stock of cathodes is taken from several external sources (BGR, 2012; Cochilco, 2015; ICSG, 2010; USGS, 1994). After considering the trade balance for refined copper, the model simulates production and usage of copper for semi-finished goods in the EU. A detailed matrix provided by the copper industry is used to allocate 18 different categories of semi-finished goods to 17 end-use applications on a yearly basis. The structure of the allocation matrix is shown in Figure S1 in the supplementary material. As there is no perfectly efficient production process, the model considers individual fabrication efficiencies for each end-use product which account for the new scrap flow of copper after being summed up.

A certain share of the manufactured end-use products is then exported while the rest is put on market for domestic use together with imported goods from non-EU countries.

The copper containing end-use products are then put on market and enter the European anthropogenic copper stock. The time span of how long the copper remains in the stock is determined by product lifetime distributions and their corresponding application-specific failure rates. They ensure that—with growing probability—in every year after being put on market a certain amount of products leaves the end-use stock. This principle, known as aging chain methodology, is a useful tool for dynamically estimating stocks and has already been implemented in the field of population research (Eberlein et al., 2012; Krejčí and Kvasnička, 2012) and for product lifetime calculations such as for automobiles (Kagawa et al., 2015). More details on the average lifetimes used in the model and the implementation of aging chains can be found in Table S2 and Figure S2 of the supplementary material to this paper.

After having left the stock at the end of their lifespan, the end-of-life products are allocated according to the matrix in Table S3 to six different types of post-consumer copper scrap (post-consumer and old scrap are used as synonyms) (ICSG, 2005; Ruhrberg, 2006): Construction and demolition waste (C & D), municipal solid waste (MSW), end-of-life vehicles (ELV), waste electrical and electronic equipment (WEEE), industrial electrical waste (IEW) and industrial non-electrical waste (INEW). These scrap types are processed with individual efficiencies after collection (see Tables S4–S9). The amount of collected material is determined by the secondary material needed in order to meet reported copper production which cannot be completely satisfied by primary material. Thus, the EoL collection rate (EoL CR) is a result—not a given—in this work, and is also the model's key parameter to ensure a closed mass balance at every time step. Note that multiplying flow (e) in Fig. 2 by $1 - \mathit{EoL\ CR}$ leads to flow (f). It is generated according to the following Eqs. (2) and (3):

$$\text{Secondary Cu for production} = \underbrace{\text{Refined Cu production} - \text{Primary Cu use}}_{\text{2ary refined Cu}} + \underbrace{\text{Semis fabrication} - \text{Refined Cu use}}_{\text{direct melt}} \tag{2}$$