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Modeling material flows, cumulative material demand and market dynamics of industrial metals within a system dynamics framework

An overview of concepts and exemplary models

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Abstract:

A prerequisite for the implementation of targeted policies aiming at improving resource efficiency of industrial metals is a clear understanding of physical material flows and use patterns on the global and national level, including material distribution along the value chain and across economic sectors. This paper deals with different concepts for dynamic material flow modeling based on the System Dynamics approach. We present different exemplary outcomes of such material flow models for global and European copper flows. Using the commodity codes of trade data analyses for the European copper model as a connection point, we discuss a concept which links the material flow model to multisectoral economic models. The global copper flow model is finally supplemented by market dynamics in order to develop a flexible tool for global market forecasts, taking into account both restrictions of physical raw material supply and different forms of feedback effects on the supply and demand side of the metal market.

1. Introduction: life cycles, cumulative material demand and market dynamics of industrial metals

Against the background of continuously increasing human demand for non fuel metals and minerals and the associated environmental pollution, there is an urgent need for higher resource efficiency. Especially improvements in waste management and recycling can save resources and energy (Nuss and Eckelman 2014).

A further motivation to achieve higher resource efficiency is the growing competition regarding the access to raw materials and the control of raw material supply. In this context, a detailed knowledge of raw material dependencies by industry sector, sectoral interdependencies within an economy and cumulative raw material demand enable a better understanding of the economic importance of and the dependence on specific raw materials.

On the other hand, high market dynamics, cyclical market behavior and price volatility pose a severe challenge to raw material producing and processing industries as well as the recycling sector because price changes in procurement can not necessarily be passed on directly to the customer.

In this paper we provide different concepts and examples of how System Dynamics (SD) models can help to better understand and meet the aforementioned current challenges. Therefore, in the following section, we start with discussing concepts of dynamic material flow modeling and the simulation of product and material life cycles.

Taking commodity codes for trade data analysis as a connection point, we then present a concept of how to link dynamic material flow models on a national or multinational level with economic models based on input-output tables.

Subsequently, using the example of a global copper flow model, we describe how the material flow model may be enhanced by market dynamics in order to develop a useful tool for market analysis and price forecasts based on exogenous assumptions regarding the development of the global economy (global GDP).

2. Modeling physical material flows within the SD environment

The aim of modeling anthropogenic metal cycles is to quantify where materials are introduced into economies, how they are processed and used, where they are stored in society over the product life spans, and how they are recycled or discarded (see Figure 1 for a general metal cycle). Dynamic material flow analysis (MFA) is a concept that has gained wide acceptance in previous years in this area, sometimes also referred to as Substance Flow Analysis (SFA) when only one specific substance (e.g. one specific metal) is analyzed (Brunner 2012). A significant advantage of MFA is that it is a "systemic" approach: a system is defined which summarizes the raw material value-chain and the flows between items (processes) of this value chain (e.g., extraction, processing, manufacturing, use, waste management and recycling) are quantified. Performing calculations over a time window (dynamic analysis) provides an accounting of stock variations within the individual items of the value chain (e.g. in-use stocks) and captures the development of material flows over time.

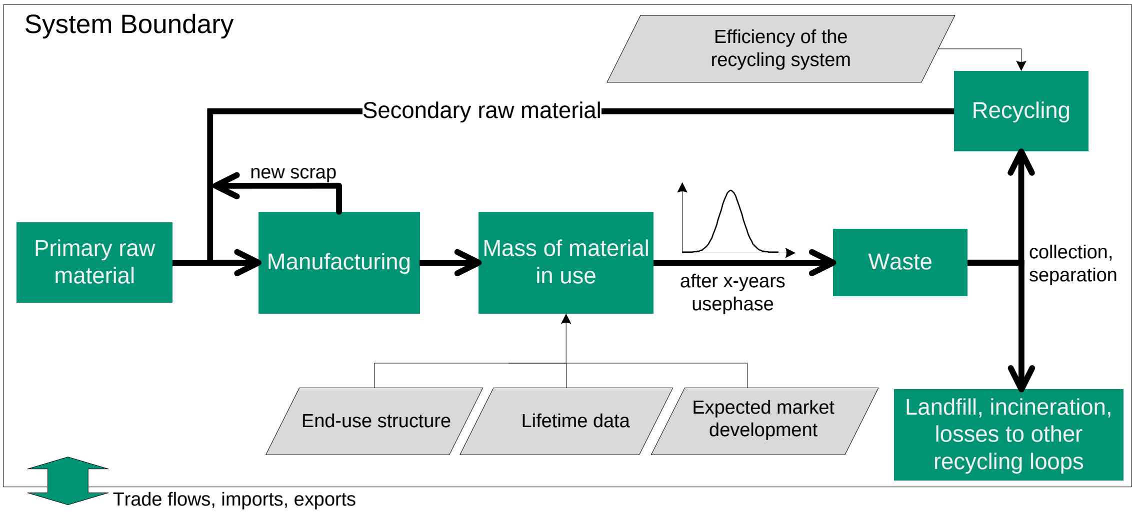


Figure 1 General simplified model structure of the life cycle of an industrial metal.

Despite the rising number of publications and research work in the field of Material and Substance Flow Analysis in recent years, dynamic modeling approaches of anthropogenic metal cycles are largely underrepresented compared to static analyses (Chen and Graedel 2012).

Table 1 A literature review of publications about anthropogenic material flow systems from 2012 shows a significant lack of dynamic approaches when describing and analyzing metal cycles and material flow systems (Chen and Graedel 2012).

Model dimensions	global	regional	national	total
static	47	105	791	943
dynamic	9	7	60	76
total	56	112	851	1019

This is due to both higher effort with respect to model development and extensive data requirements (Chen and Graedel 2012). However, analyzing past and future material use patterns, simulating material accumulation over time, determining resource efficiency and modeling product life cycles in order to assess recycling potentials and material stocks in society are scientific challenges at present that can only be met by dynamic modeling approaches. Müller et al. (2014) demonstrate the trend towards dynamic material flow modeling and the increasing role of dynamic approaches for the analysis of metal flow systems in recent years (cf. Figure 2).

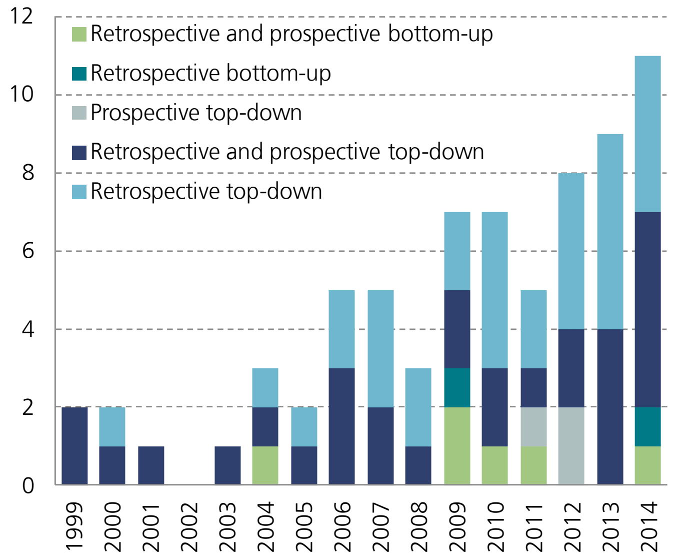
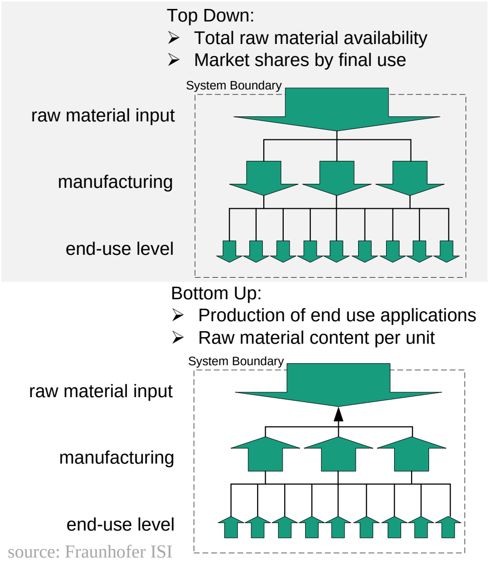


Figure 2 Number of publications on dynamic material flow models in previous years (cf. Müller et al. 2014, the values for 2014 were added by own literature research).



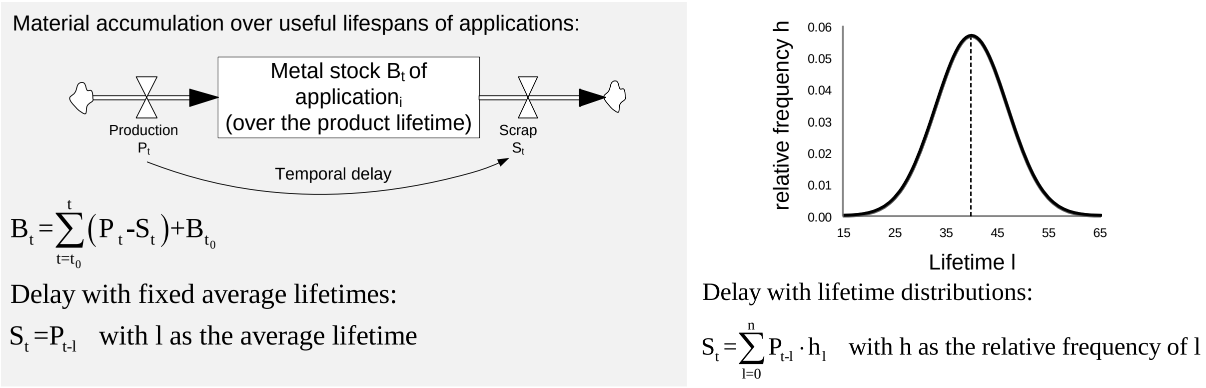
source: Fraunhofer ISI

Figure 3 Top-down and bottom-up approach to quantify material flows. Both concepts can be realized with the conceptual material flow models discussed below.

Especially when using the models for the identification of past and future trends in raw material supply and material use patterns, dynamic approaches are indispensable.

Figure 3 displays the difference between top-down and bottom-up approaches. On a global level, due to the broad availability of production and market data, top-down approaches have shown high suitability for dynamic material flow models (Glöser et al. 2013b). On a regional level, trade data and material contents within different commodities along the entire value chain have to be taken into account, which makes a product specific bottom up approach at least for the analysis of material flows across the system boundaries necessary. Technology based bottom-up models are suitable to analyze future demand due to the diffusion of new technologies (see for example (Angerer et al. 2009; Hoenderdaal et al. 2013; Habib and Wenzel 2014). For such analyses of future market developments and potential material constraints, SD models are highly suitable due to the possibility of combining material flows and market dynamics within a single model (Novinsky et al. 2014; Sprecher et al. 2015).

As described in the following section, the System Dynamics approach enables broad possibilities in simulating product life cycles and material flows reaching from simple material accumulation in a single stock to detailed aging chains modeling the aging process of consumer products. While single material flow models use the delay structure and stocks and flows within the SD environment to simulate material accumulation over use phases, they do not include any feedback loops. However, System Dynamics has proved highly suitable to model these dynamic material cycles (Bornhöft et al. 2013; Glöser et al. 2013c). Figure 4 displays the concept of material accumulation over the use phase of a product within a single stock. In this case a flow to flow relation is necessary to achieve a correct accumulation over the useful lifespan. In the simplest case this relation is realized with a fix average lifetime (Figure 4 left side), whereas lifetime distributions (Figure 4 right side) enable a more realistic modeling of product life spans.



$$B_t = \sum_{t=t_0}^{t} \left(P_t - S_t\right) + B_{t_0}$$

Delay with fixed average lifetimes:

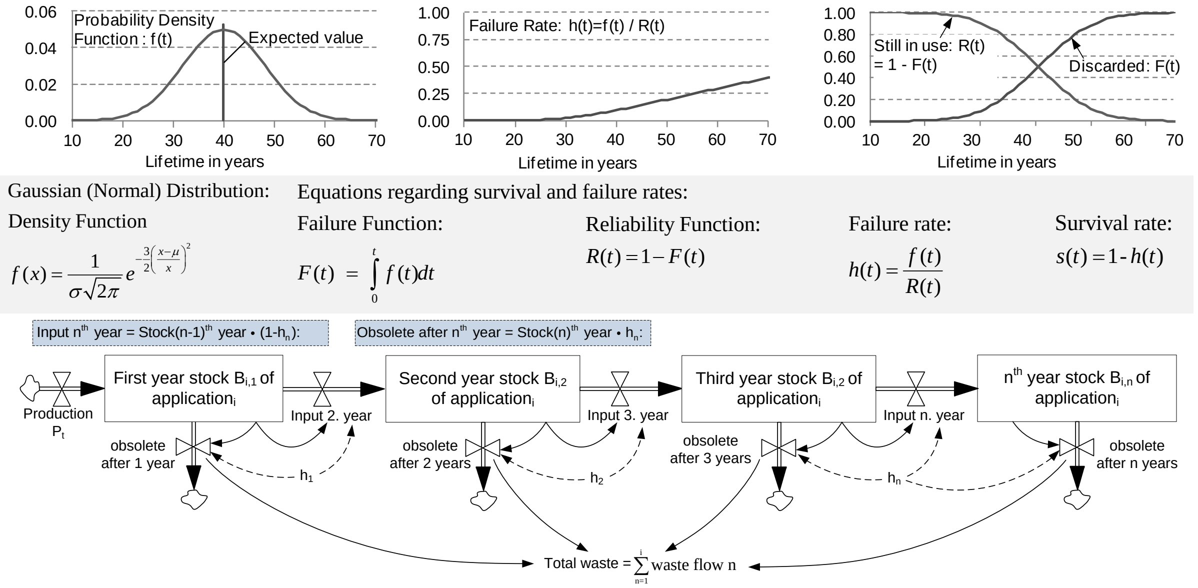
$S_t = P_{t-l}$ with l as the average lifetime

Delay with lifetime distributions:

$S_t = \sum_{l=0}^{n} P_{t-l} \cdot h_l$ with h as the relative frequency of l

Figure 4 Accumulation of material over the use phase within a single stock. In this case a direct flow to flow relation is necessary to ensure the correct stock accumulation over the product lifespan.

Typical shapes and density functions for lifetime distributions of technical products from the field of safety engineering are summarized in the appendix in Figure 20. While in the simple concept shown in Figure 4 the “stock in use” is entirely accumulated in a single variable and there is only one total end-of-life (EoL) material flow, the concept of an aging chain enables a detailed simulation of stock accumulation and waste flows by age (cf. Figure 5).



Gaussian (Normal) Distribution:

Density Function

$$f(x)=\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{3}{2}\left(\frac{x-\mu}{x}\right)^{2}}$$

Equations regarding survival and failure rates:

Failure Function: $F(t) = \int_{0}^{t} f(t)dt$

Reliability Function: $R(t)=1-F(t)$

Failure rate: $h(t)=\frac{f(t)}{R(t)}$

Survival rate: $s(t)=1-h(t)$

$\text{Input } n^{th} \text{ year} = \text{Stock}(n-1)^{th} \text{ year} \cdot (1-h_n)$:

$\text{Obsolete after } n^{th} \text{ year} = \text{Stock}(n)^{th} \text{ year} \cdot h_n$:

$\text{Total waste} = \sum_{n=1}^{i} \text{waste flow } n$

Figure 5 concept of the aging chain in order to achieve a detailed simulation of material stocks over time including the stock age and the age and composition of EoL material flows (Glöser and Hartwig 2015).

When examining use phases of metal applications in the field of building and construction or industrial applications, it is necessary to assume average life spans of 40 to 50 years with relatively broad distributions ranging from 20 to 80 years (see exemplary distribution in Figure 5). One way of simplifying the concept of the aging chain is to work with subscripts (arrays). This enables the realization of the aging chain displayed in Figure 5 within one stock variable and subscripts covering all age levels. Taking the SD software “Vensim” as an example, this concept is shown in Figure 6.

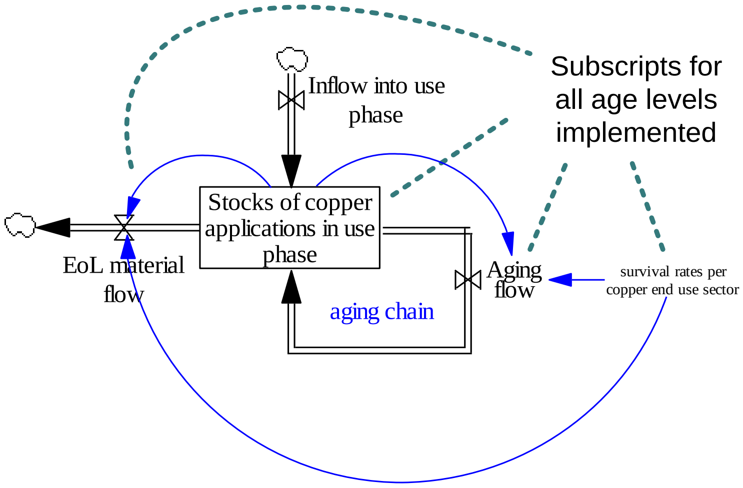


Figure 6 Implementing the aging chain with subscripts (arrays)

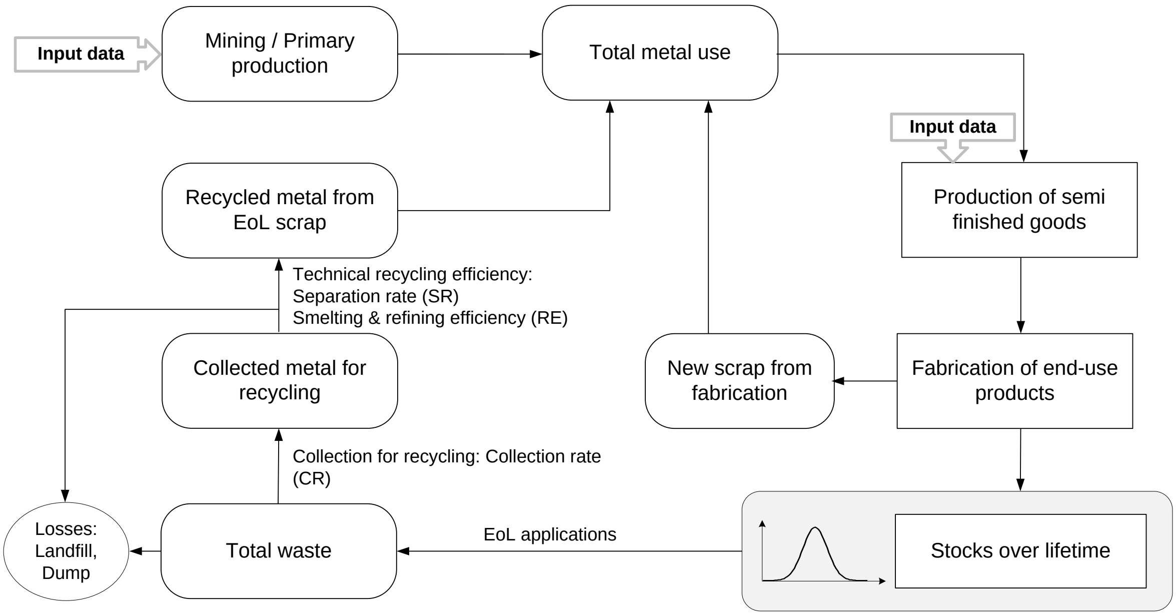
The methodologies of material flow modeling using SD software as described above are generally applicable for simulating all kinds of material flow systems and product life cycles. Such models are necessary to identify and communicate further recycling potentials and to quantify their contribution to improving resource efficiency. While the example of the copper cycle as described below already shows a relatively established recycling system with comparatively high recycling rates, the majority of technology metals are poorly recovered from waste flows. This is partly due to economic feasibility but also due to a lack of knowledge about material dispersion in society and poor performance of collection and waste management. Dynamic material flow models comparable to the exemplary copper flow models described below will contribute to a better understanding of recycling potentials. Next to focusing on specific materials and analyzing their routes through the technosphere, such models may also be used for the simulation of the use phase of entire electronic products such as cell phones, tablets or laptops containing all kinds of different high-tech metals. In the following section we provide examples of a global and a European copper flow model.

The examples of a global and a European model of copper stocks and flows

The global copper flow model simulates the entire copper life cycle from mining and refining over the fabrication of semi-finished goods to the end use of copper over product life spans and the recycling of copper scrap. The model builds upon historical production data going back 100 years which is necessary due to the long use phases of different copper applications, especially in the field of building and construction. In a second step, a separate European model was realized, taking into account trade flows along the entire value chain. The intention behind the development of this material flow model is the analysis of the performance of copper recycling on a global and regional level.

A detailed description of the global material flow model is provided by Glöser et al. (2013a). In this section we only give a short overview of this dynamic material flow model applied to simulate the global and European anthropogenic copper cycle.

As shown in Figure 7, the copper flow model takes mining and production data of semi finished goods as the major input flows. While these two flows are well reported on a global level, the occurrence of copper containing scrap and waste flows is unknown as there are no statistics of satisfactory detail of waste occurrence on a global level. Therefore, this flow is simulated based on historic fabrication data and lifetime distributions in the different sectors using the concept of an aging chain as describe above. The fabrication efficiency of copper (and the related occurrence of production residues or new scrap) and the mine production as well as the total metal use are relatively well reported and thus, as described in Figure 7, the total amount of effective recycling from EoL scrap can be calculated from these data. By adjusting the collection rate of EoL scrap to the historic production data, a closed mass balance is achieved over time (cf. equations in Figure 7).



Basic concept of keeping a closed mass balance over time:
the collection rate of metal scrap is adjusted to production data

$$\text{Recycled metal from EoL scrap}_t = \text{Total metal use}_t - \text{Mining}_t - \text{New scrap}_t$$

$$\text{Recycled metal from EoL scrap}_t = \text{Total waste}_t \bullet \text{CR}_t \bullet \text{SR}_t \bullet \text{RE}_t$$

Calculation of the collection rate to close the mass balance:

$$\mathbf{CR_t} = \frac{\mathbf{Total\ metal\ use_t - Mining_t - New\ scrap_t}}{\mathbf{Total\ waste_t \bullet SR_t \bullet RE_t}}$$

CR: Collection Rate SR: Separation Rate RE: Refining Efficiency

Figure 7 Enabling a closed mass balance over time by defining the global collection rate of EoL (End-of-Life) copper scrap as a function of reported global production data.

As several model assumptions such as the average useful lifetimes of different product groups or the fabrication efficiencies leading to new scrap occurrence are subject to a certain degree of uncertainty, we performed a stochastic sensitivity analysis as described in Figure

8. This leads to a better understanding of the effect of data uncertainty on the calculated recycling indicators. Different probability distributions over uncertainty intervals (cf. Figure 8a) enable a detailed analysis of data uncertainties and sensitivities which is a point that was not sufficiently addressed in several previous studies (Laner et al. 2014).

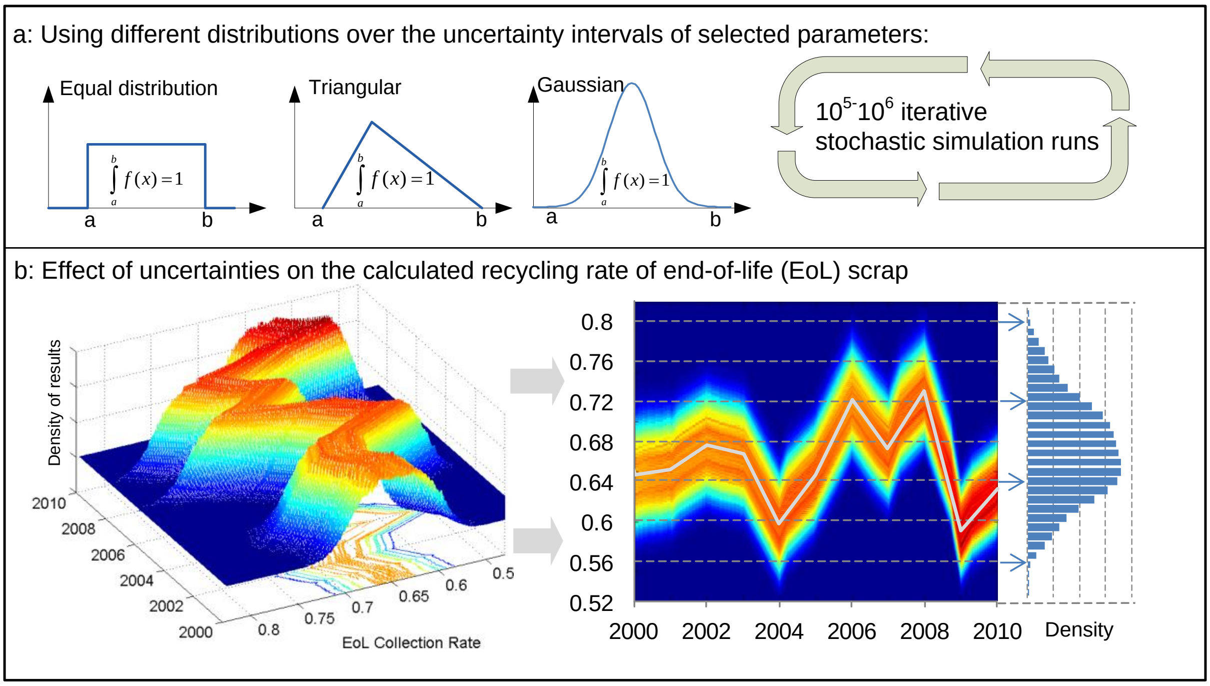


Figure 8 Analyzing the effect of data uncertainty on the calculated collection rate (CR) of copper from waste flows (Glöser et al. 2013a).

Furthermore, the material flow models enable the quantification of copper stocks in use and waste flows as well as losses to landfills or to the environment (see Figure 9).

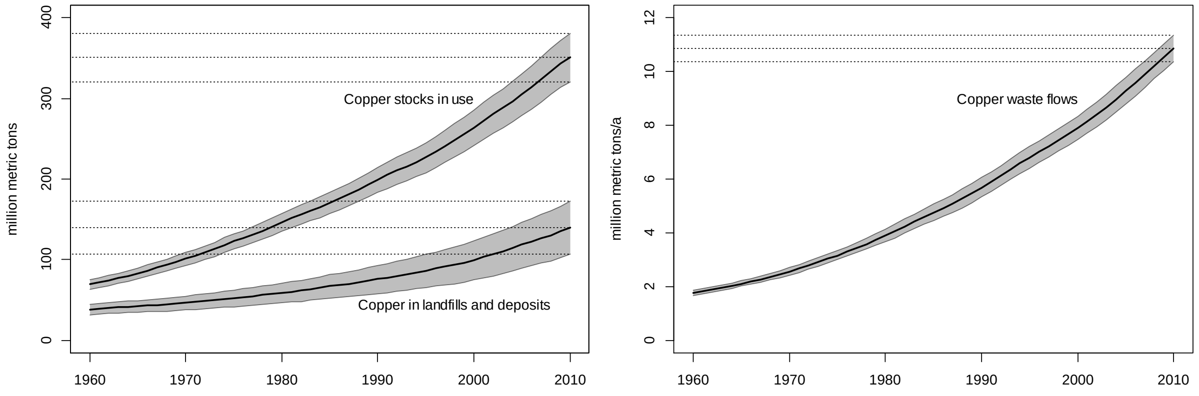


Figure 9 Further results from the global copper flow model are for example the accumulation of material stocks in use, material content in waste flows or cumulative losses to the environment.

The global aggregated copper cycle for the base year 2012 in the form of a Sankey diagram is depicted in Figure 10.

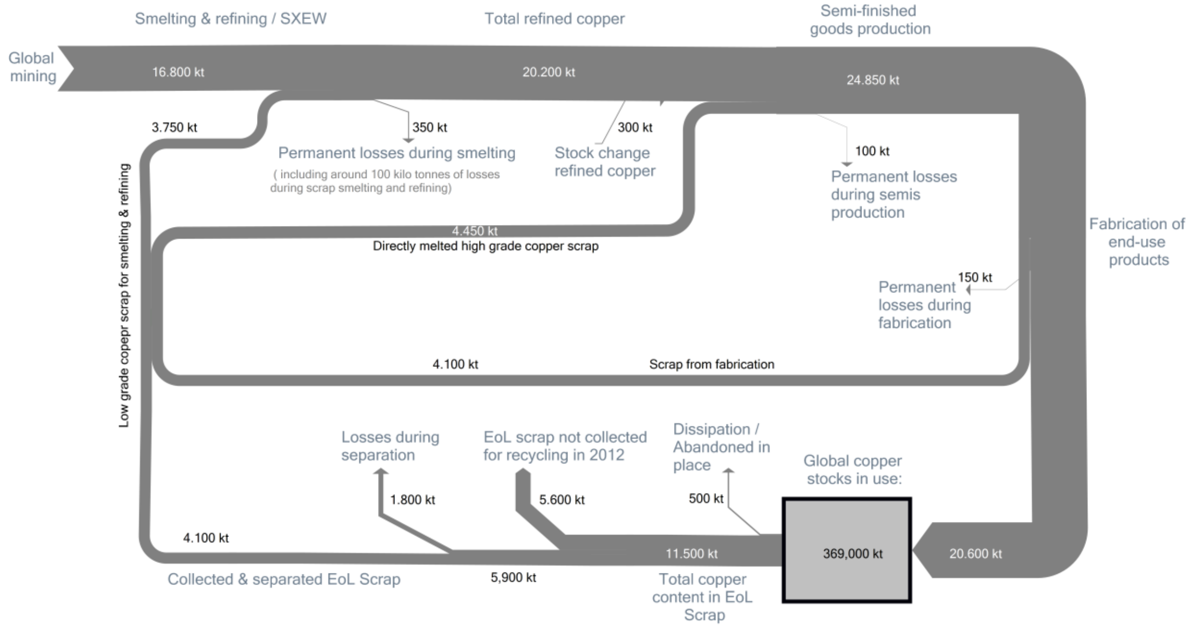


Figure 10 Accumulated global material cycle of copper for the base year 2012.

The European model follows the same concept as the global model with respect to implementation except for the additional consideration of trade flows. As mentioned before, the challenge for regional modeling is the consideration of trade data along the entire value chain. For the analysis of the European copper cycle, a detailed assessment of trade data was necessary. Therefore, all HS[1] codes of commodities containing copper were identified and an estimation of average copper content per commodity was made based on existing literature (Kupfer im regionalen Ressourcenhaushalt - Ein methodischer Beitrag zur Exploration urbaner Lagerstätten 2006) and further research.

While we identified around 350 commodity codes based on the HS system being relevant for the copper material flow analysis, Table 2 summarizes several codes in the first steps of the value chain.

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[1] The **H**armonized **S**ystem is a global standard for commodity specification in trade data

Table 2 Exemplary copper containing commodity codes (according to the Harmonized System, HS)

HS Code	Description	copper content
260300	Copper ores and concentrates	30%
740200	Unrefined copper, copper anodes, electrolytic refining	95%
740311	Copper cathodes and sections of cathodes unwrought	100%
740710	Bars, rods & profiles of refined copper	100%
262030	Ash or residues containing mainly copper	10%
740400	Copper/copper alloy waste or scrap	90%
⋮ ⋮ ⋮	⋮ ⋮ ⋮	⋮ ⋮ ⋮

The resulting cumulative European trade balance of copper flows based on the trade data analysis along the value chain in shown in Figure 11.

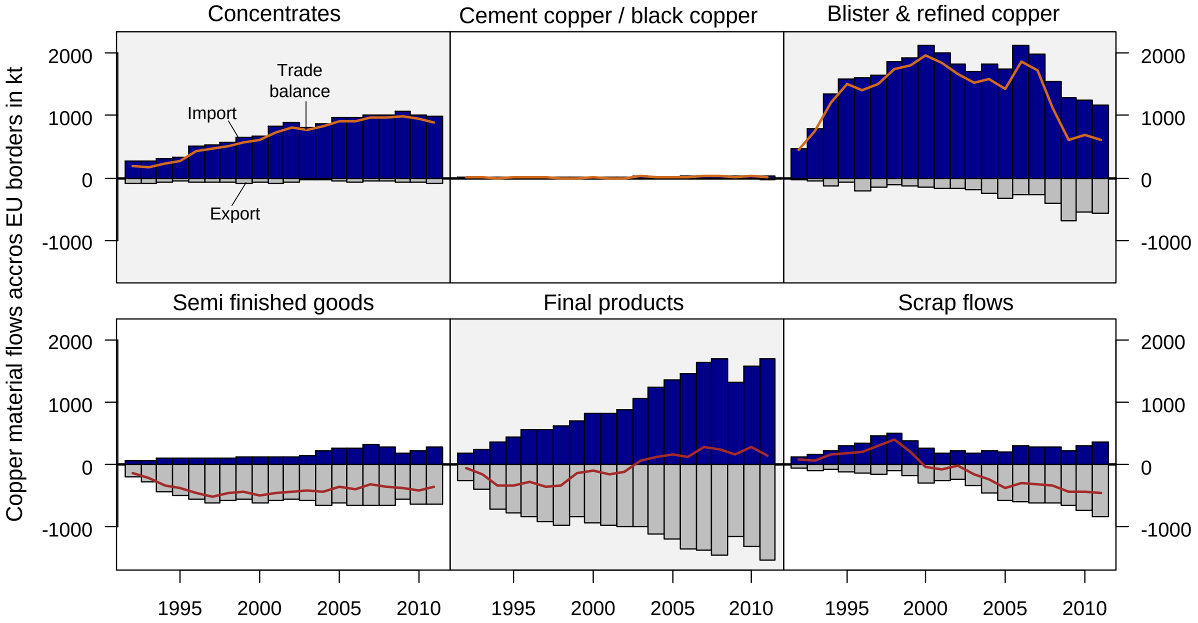

Figure 11 Trade flows across EU borders (Glöser et al. 2014).

Figure 12 displays the corresponding Sankey diagram of the European copper cycle for the base year 2012 including the cumulative trade flows.

The aforementioned material flow models are suitable tools to simulate material and product life cycles and to analyze the current performance of waste management and the recycling system. However, both for the regional and the global models there are further possibilities for enhancements and interconnections, which we discuss in the following sections. The detailed analysis of material contents on a product level for the trade flow assessment in the European model (based on HS commodity codes) can be used as a connection point for regional economic models building upon input-output tables. This link for the regional (at the

EU level) copper flow model is discussed below. Regarding the global copper cycle, we built a model of market dynamics around the material flow model in order to analyze historic and future market developments. This is described in section 4.

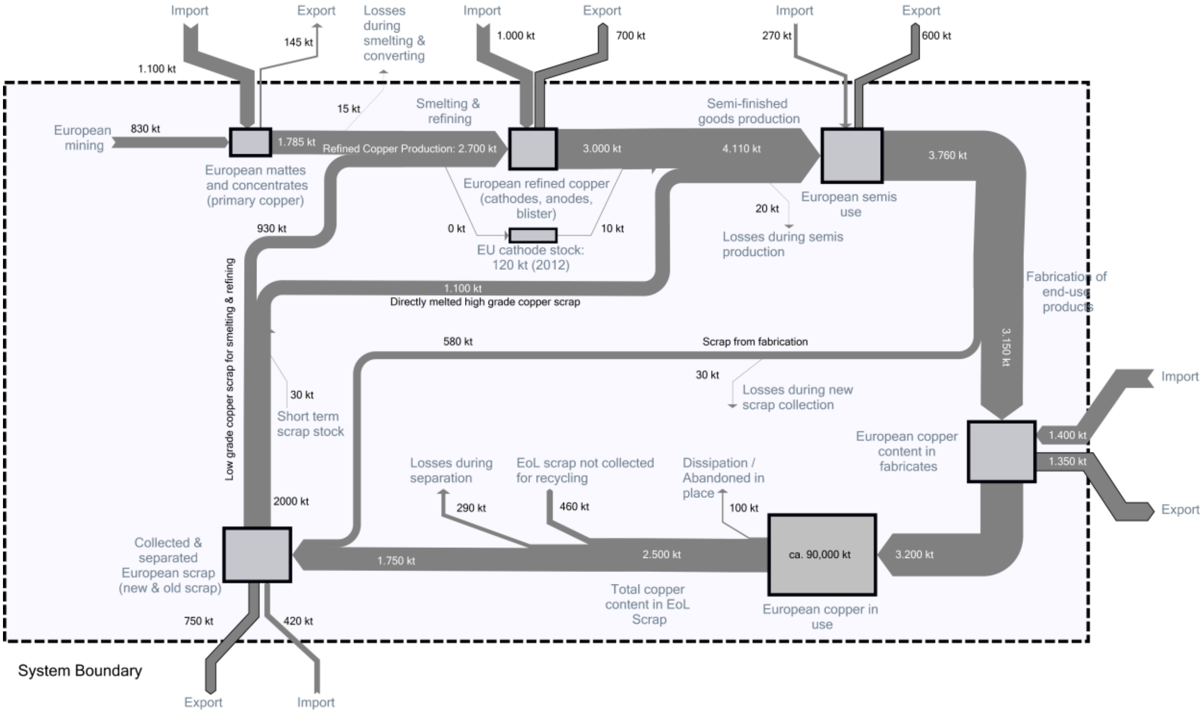

Figure 12 Cumulative European (EU27) material flows for the base year 2012 (cf. European Copper Institute ECI)

3. Linking regional material flow models with economic input-output tables – a conceptual approach

The physical system of material flows and the economic system are deeply interconnected: material flows are strongly driven by economic activity while the economy depends heavily on material inputs. As was already pointed out by Duchin (1992a), in order to be able to adequately inform policies related to raw materials, it is necessary to have a detailed understanding of the interplay between material flows and economic dynamics, particularly on the level of individual economic sectors This understanding can be furthered by combining material flow analysis with input-output analysis and thereby utilizing the relative strengths of both approaches.

Input-output analysis is well suited to capture the interconnectedness of sectors within an economy, thereby allowing for the calculation of indirect and cumulative deliveries between sectors. For instance, sectors which do not directly demand high material inputs, such as services, may nevertheless display considerable indirect material requirements. As Beylot and Villeneuve (2015) have shown for the case of copper, the overall dependence on copper may be higher for such sectors with only indirect material demands than for sectors which directly receive copper inputs but have low upstream copper requirements along the value chain.

While input-output models are capable of portraying such value chain effects, the standard versions published by statistical offices are generally too aggregated for a detailed analysis of material or substance flows. The economic transactions between sectors portrayed in these monetary input-output tables are thus an inadequate representation of physical transactions of materials. This is illustrated in Figure 13, which on the one hand displays monetary intermediate deliveries of the nonferrous metals sector (in which the majority of semi-finished copper products are produced) according to the German Input-output table of 2012 (Destatis 2014), and on the other hand copper flows from this sector to other sectors based on a substance flow analysis of copper for the same year. The relative distribution of inputs from the nonferrous metal sector to other sectors differs significantly from the distribution of semi-finished copper products.

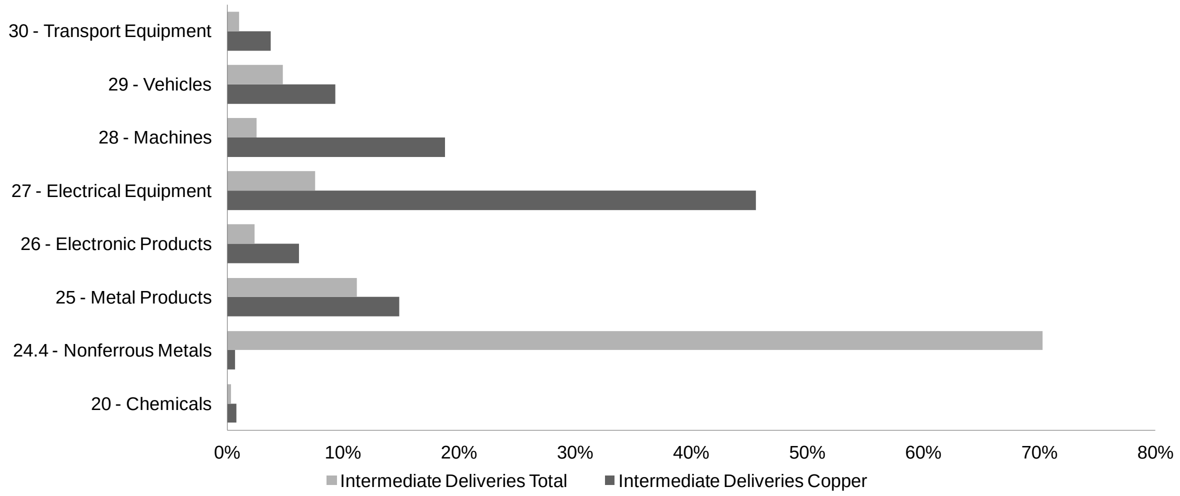

Figure 13: Comparison of total and copper intermediate deliveries from the nonferrous metals sector to relevant other sectors (in NACE Rev. 2 classification) for Germany in 2012

The knowledge of material/substance flows on a product level (through HS, CN or CPA codes respectively) can thus be used as a connection point between material flow and economic input-output models. The connection between commodity codes for trade data analysis (HS, CN), data from the European Prodcom database (CPA) and NACE[2] sectors (which form the basis of EU input-output tables and those of its member states) is shown in Figure 14.

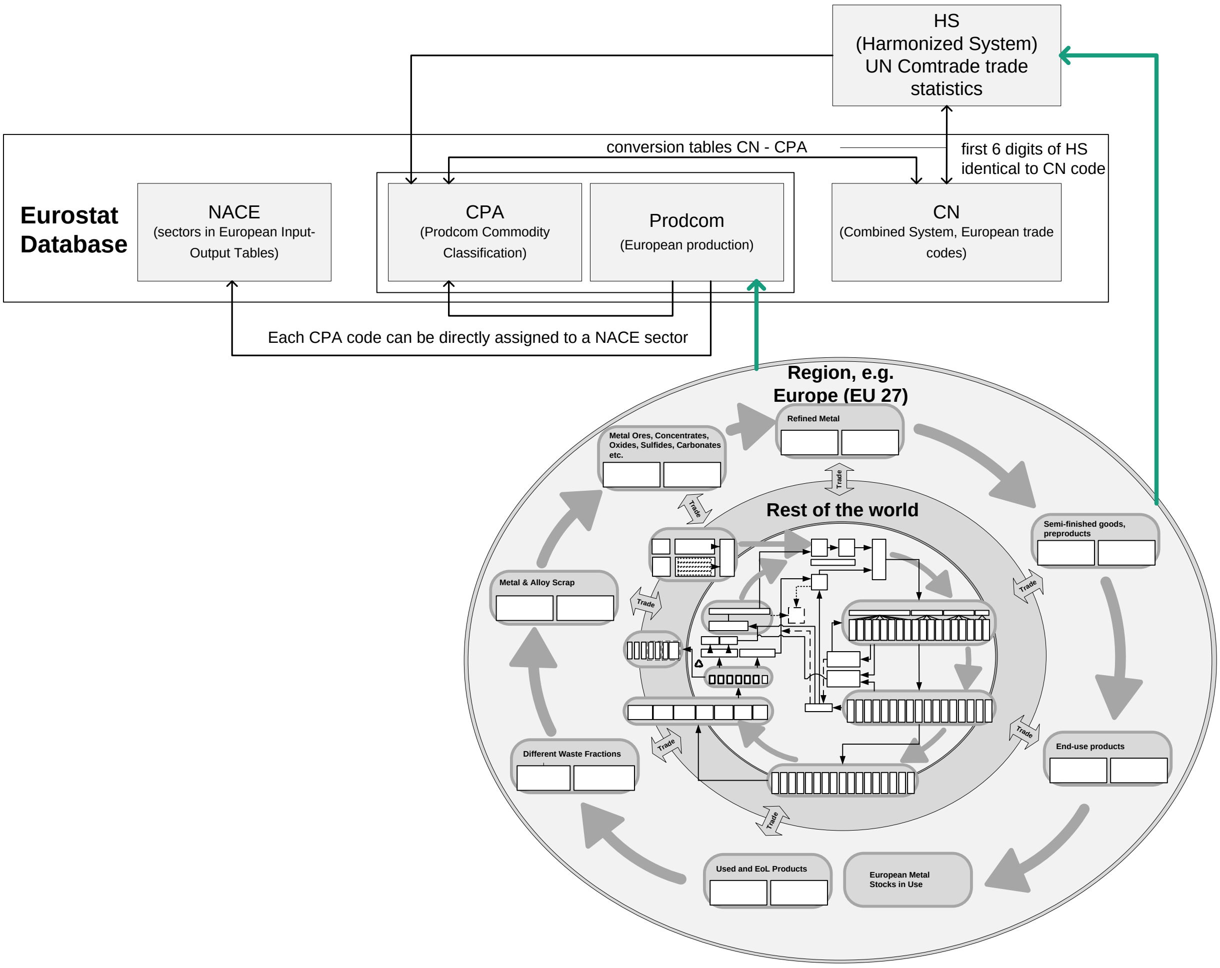

Figure 14 Connection between trade data (HS, CN), production data (CPA) and the European industry activity classification (NACE).

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[2] European industrial activity classification (Activités economiques dans les communautés europeennes)

A number of studies have developed hybrid approaches which generally consist of a combination of input-output analysis and life cycle assessment, and mostly focus on specific processes (e.g. Joshi 2000, Suh 2004, Suh et al. 2004, Acquaye et al. 2011, Wiedmann et al. 2011, Liu et al. 2012). Here, a methodology is briefly presented which combines input-output analysis with material flow analysis on the national level. This approach leaves the standard input-output tables intact and uses satellite matrices that display physical material flows as a function of economic flows of the input-output table. Because copper containing products display a wide range of copper contents relative to their respective prices, these matrices are defined on the product level. For each product the material flows are assigned to the individual intermediate deliveries between the production sectors as well as the components of final demand of the input-output table.

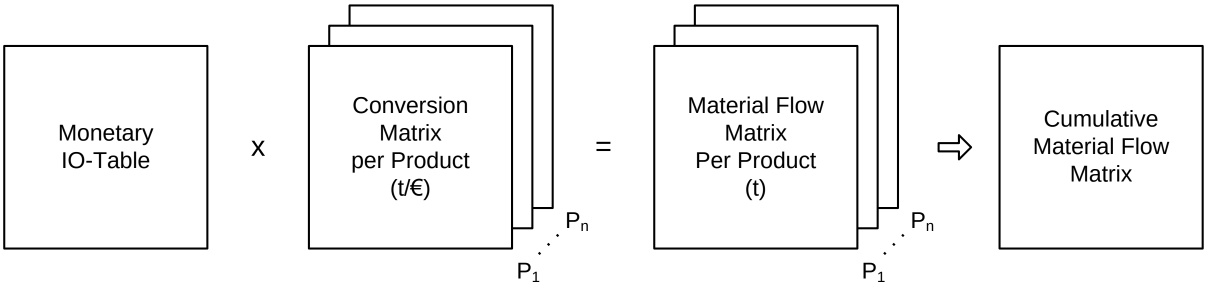


Figure 15: Schematic representation of conversion matrices.

Each intermediate delivery and each final demand transaction of the economic model is thus matched with a product flow. The product flows, together with information on material content and value added can then be used to deduct physical material flows. This link between the economic and the physical spheres can be used in two ways: to analyze the effects of economic developments on material use patterns, and to analyze the macroeconomic effects of changes in material use, for example through efficiency gains. While the former is an established research topic, the latter has not been researched comprehensively, possibly due to a lack of suitable methodologies. The approach presented above may prove to advance this field of research.

4. Modeling the dynamics in metal markets based on global material flows

While the dynamic material flow models described in section 2 only use the stock and flow structure of the SD approach to simulate aging chains, material life cycles and stock accumulation over time, they do not include any feedback loops. However, especially for global material flow models covering global supply from primary (mining) and secondary (recycling) sources and global material use patterns, an enhancement of the models with market dynamics seems reasonable. This enables the development of a tool for market analysis covering both physical material flows and feedback effects including typical delay structures in commodity markets. As summarized in the causal loop diagram in Figure 16, there are numerous feedback effects.

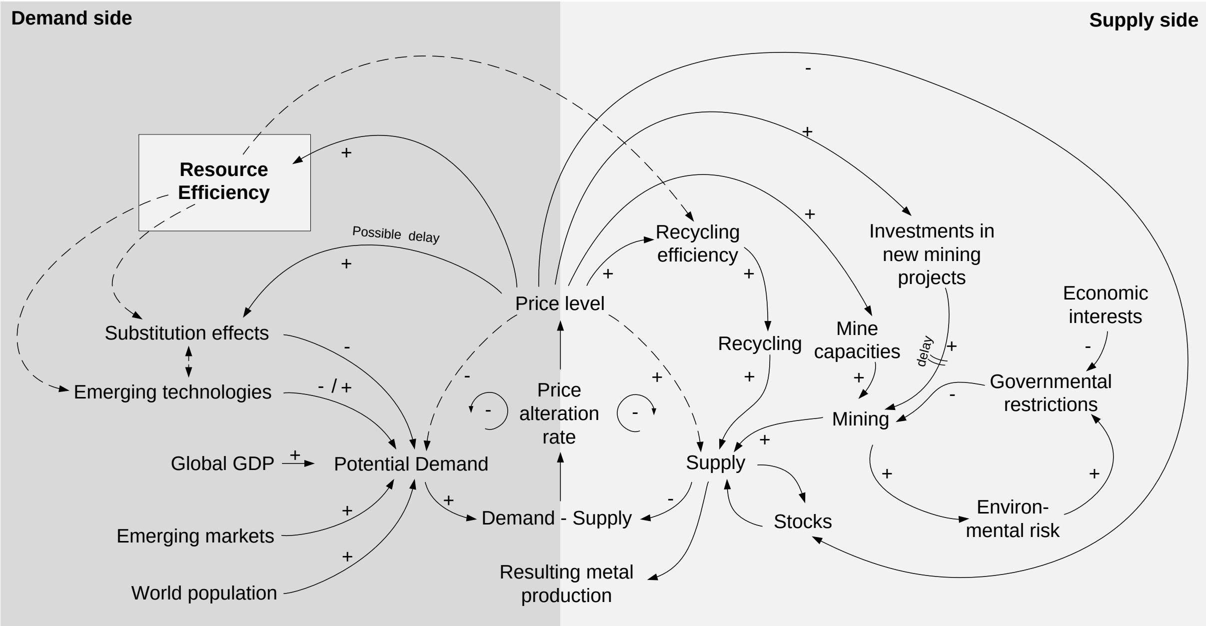


Figure 16 General causal loop diagram of a commodity market taking into account demand and supply side feedback effects (Glöser and Faulstich 2012).

A major feature of industrial metal markets which is identified as the main reason for cyclical market behavior is the delayed adjustment of supply due to long planning and construction phases of new mining projects (Humphreys 2012). As the investments in new production capacities are highly correlated with current price levels resulting from adaptive forecast behavior which is in contrast to rationality, the delay in supply adjustments leads to cyclical market behavior. As demonstrated with the simple model in Figure 17, the SD approach is highly suitable to model these delays in supply adjustment.

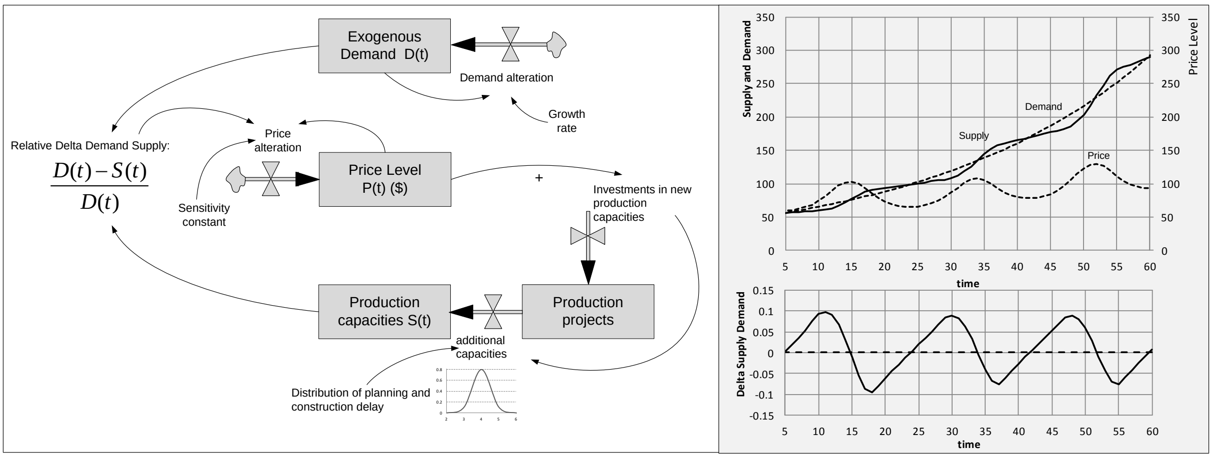


Figure 17 Simple exemplary model of price fluctuations due to delayed supply adjustment (Glöser and Hartwig 2015).

The example of a copper market model based on the global material flow model

The basic concept of the exemplary model shown in Figure 17 was implemented into an enhanced market model for copper as illustrated in Figure 18. While a detailed description of this model is published in Glöser and Hartwig (2015), here we provide a short overview of this model aiming at highlighting the possibilities of System Dynamics for market analysis.

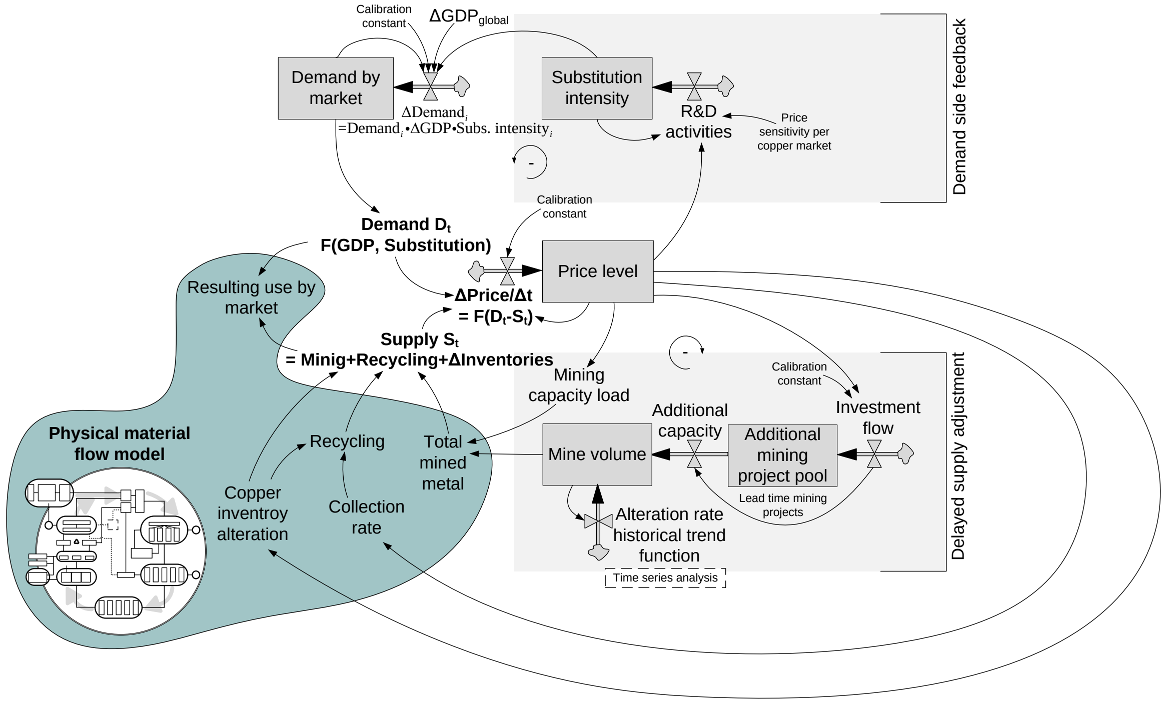
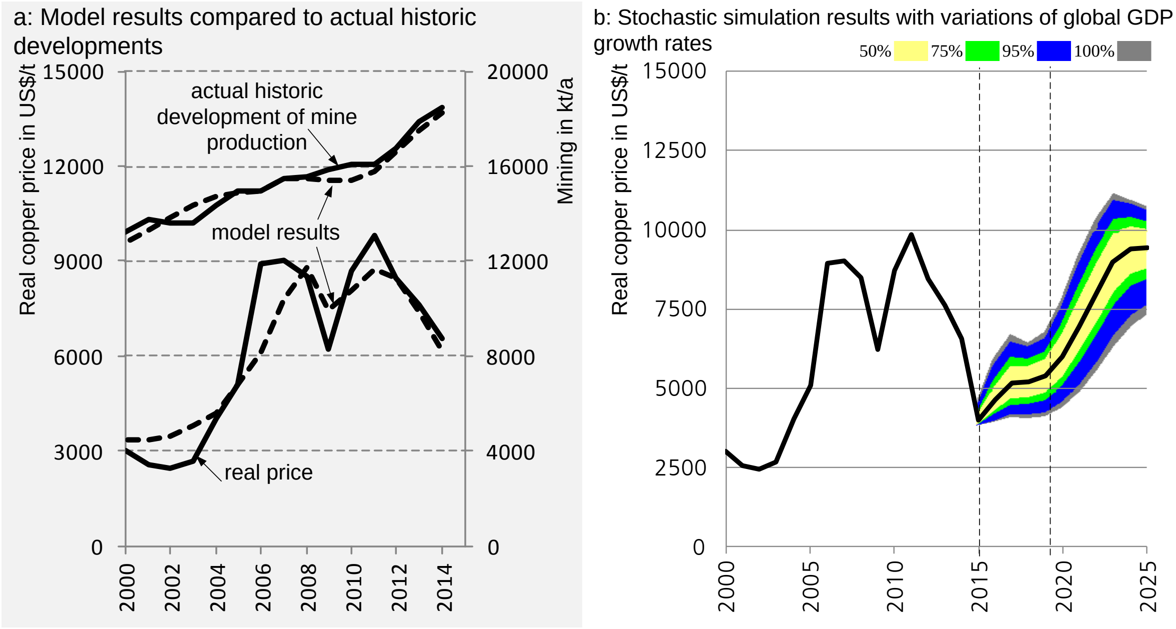


Figure 18 Copper market model combining physical material flows and market dynamics.

The copper market model combines the material flow model described above with the major feedback effects on raw material. As each copper end-use sector has different substitution potentials and thus reacts differently to price changes, the demand in each sector is calculated individually based on exogenous GDP development and the substitution intensity which is directly influenced by the price level.

The material flow model provides specific supply data regarding both recycling, taking into account total scrap availability and mining data influenced by the delayed capacity building from investments in new mining projects. This combination of physical material flows with dynamic aspects of market adjustment mechanisms forms a flexible tool for advanced market analyses.

The model was calibrated to historic copper price and mining development in order to analyze its ability to reproduce real market behavior based on past GDP development (cf. Figure 19a). We performed a first copper price forecast based on expected global economic development published by the World Bank (Global Economic Prospects 2015). With a stochastic variation of future GDP growth rates, this model can be use as a forecasting tool of copper price development (cf. Figure 19b).


a: Model results compared to actual historic developments

b: Stochastic simulation results with variations of global GDP growth rates

Figure 19 Results from the copper market model.

Needless to say, this highly simplified model only captures few relations and correspondences in the copper market; hence the results must be treated with some reservation. However, it underlines that the System Dynamics approach combining time delays and feedback effects is highly suitable to model raw material markets taking into account physical material flows and market dynamics. In our opinion, the possibility of a more systemic approach and flexibility in varying exogenous variables for sensitivity analyses makes System Dynamics superior to econometric analyses such as auto regression or structural equation models which are widely used by market analysts.

5. Summary and conclusions

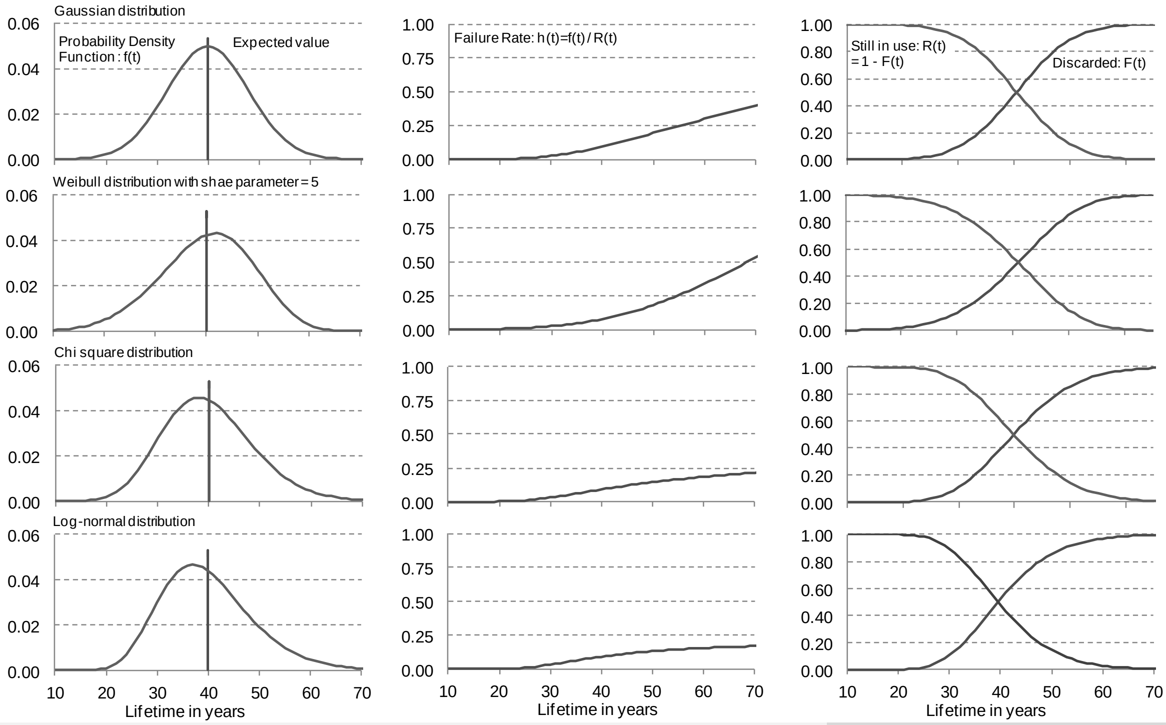
With this paper we intended to give insight into different ongoing SD modeling work in the field of industrial metals material flows, cumulative material use and market dynamics. The System Dynamics approach provides different advantages for describing raw material systems such as the broad possibilities of modeling both physical material flows and market dynamics caused by partly delayed feedbacks due to price alterations.

Regional material flow models on national or multinational levels require a detailed analysis of commodity trade and production data. This forms a connection point to sectoral economic models building upon input output tables. While regional material flow models may be linked to macro-economic models providing a better understanding of demand by sector or cumulative material use respectively, global material flow models can form the basis for market analysis tools covering physical restrictions in material supply from primary and secondary sources and dynamic market behavior.

The examples provided in this paper are limited to copper as an exemplary industrial metal, however, the modeling concepts discussed here may be transferred to all kinds of further commodities and raw materials.

Besides the modelling of industrial metals markets as performed on the example of the copper market in this paper, SD models based on global material cycles can be applied for advanced scenario analysis taking into account restrictions from the supply side. Particularly for the analysis of future raw material demand driven by the diffusion and dissemination of emerging technologies such models are useful. These advanced scenario analyses taking into account different forms of feedback effects are in contrast to simple separate supply and demand side forecasts and a subsequent comparison of both timelines.

6. Appendix



Typical lifetime distributions in Safety and Quality Engineering (probability density functions):

Gaussian (Normal) Distribution:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{3}{2}\left(\frac{x-\mu}{x}\right)^2}$$

Weibull Distribution:

$$f(x) = \frac{b}{T}\cdot\left(\frac{x}{T}\right)^{b-1}\cdot e^{-\left(\frac{x}{T}\right)^b}$$

with t,T,b ≥ 0 b as Shapefactor and T as Characteristic Time

Chi-squared Distribution:

$$f(x) = \frac{x^{\left(\frac{n}{2}-1\right)} e^{-\frac{x}{2}}}{2^{\frac{n}{2}}\Gamma\left(\frac{n}{2}\right)}$$

x > 0 with Γ as the Gammafunction: $\Gamma(n+1)$=n!

log Normal Distribution:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma x} e^{-\left(\frac{(\ln(x)-\mu)^2}{2\sigma^2}\right)}$$

Equations regarding survival and failure rates:

Failure Function:

$$F(t) = \int_0^t f(t)dt$$

Reliability Function:

$$R(t) = 1 - F(t)$$

Failure rate:

$$h(t) = \frac{f(t)}{R(t)}$$

Survival rate:

$$s(t) = 1\text{-}h(t)$$

Figure 20 Typical lifetime distribution functions from the field of safety and quality engineering (Kahle and Liebscher 2013) .

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