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Using Dynamic Stock & Flow Models for Global and Regional Material and Substance Flow Analysis in the Field of Industrial Ecology: The Example of a Global Copper Flow Model

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Abstract:

Models of anthropogenic metal cycles quantify where metals are introduced into economies, how they are used, where they are stored and how they are recycled or discarded. Despite the rising amount of publications and research work in the field of Material Flow Analysis (MFA) and Substance Flow Analysis (SFA) in recent years, dynamic modeling approaches of anthropogenic metal flows have been heavily underrepresented. In this paper, we present a general methodology to simulate metal cycles over time based on a system dynamics approach. Using the example of a global copper flow model, we present the potential outcomes of dynamic metal cycles including the results of a stochastic uncertainty analysis of the recycling efficiency of postconsumer copper scrap.
In conclusion, we discuss the potential to enhance the material flow models and to link these cycles with further system dynamics models. For this purpose, we shortly present several ongoing projects.

Introduction: Substance Flow Analysis (SFA) and Industrial Ecology:

The demand for natural resources has been increasing steadily over the last decades, resulting from both the growing consumption in the established developed nations of the West and the economic rise of developing nations in Asia and South America. Due to this development a rising ecological damage can be observed. Against this background, the scientific field of Industrial Ecology was created at the end of the 1980s: Its new idea was an integral view on material flows used in industrial processes. Influenced by the principles of the natural ecosystem the goal is to use waste streams of one industrial process as input material for other processes, minimizing the losses of substances to the environment (Frosch, Gallopoulos 1989). In the best case, this leads to an industrial system with a full recycling and reuse of materials.

An important tool of industrial ecology is the Substance Flow Analysis (SFA): SFA can be seen as a specific instance of the more broadly defined Material Flow Analysis (MFA). A MFA has a defined system in focus, e.g. a geographical region or an industrial process, and tries to track and quantify the material flows both within the system and between the system and the environment (Bringezu, Moriguchi 2002). SFA on the other side is focusing on a specific substance and its way through an industrial process, respectively a value chain. According to the principle that input equals output a closed mass balance is attained in the end. Moreover, not only flows are of interest. Identifying material accumulations and their quantification is of significant importance, especially in the case of toxic substances (van der Voet 2002).

Besides the environmental aspect of detecting and quantifying material losses, another important more recent development has been paying attention to the SFA methodology: The increased demand of humanity for resources has led to a stronger competition on global raw material markets. In the case of energy resources this has already been observed for some time whereas for other raw materials, particularly metals, this development is new.

For the economies of high-technology countries with little national raw material resources such as Japan or Germany, a constant and secure supply with specific metallic raw materials is essential. Supply risks result not only from limited or regional concentration of resources but also from limited production capacities in the short term. Moreover, the distortion of competition caused by export restrictions and taxation of specific high-tech metals in several emerging countries are a serious threat to different industries as both higher prices and the limited availability of essential raw materials compromise their competitiveness (Glöser 2012) (BMWi 2010). One appropriate measure to reduce the supply risks of metals is a more efficient use of existing anthropogenic sources, e.g. production residues, post-consumer scrap or landfills (Goldmann 2010).

The SFA approach, carried out as a system dynamics model, offers a contribution to an improved material utilization by making the metal flows and anthropogenic stocks more transparent (Lifset et al. 2002). Based on this knowledge, losses can be minimized and tailor-made recycling methods can be developed for the discovered stocks. Apart from that, a model-based SFA is able to evaluate the effects of political instruments on the metal cycle through scenario simulations and analyses, e.g. the impact of a mandatory recycling quota on primary material demand. A further potential field of application for SFA models is the risk management of raw material-dependant companies such as car manufacturers (Konietzko 2011).

Summarizing SFA for industrial metals, metal life cycles quantify how much raw material is produced from primary sources (mining), how much is secondarily produced (recycling), how efficiently the material is processed during fabrication of products (new scrap), in which products and how long the metal remains in use (stocks in use), how much metal is contained in waste flows and how efficiently the metallic resource is recovered from scrap (recycling).

A general life cycle for an industrial metal with the different stages described above is depicted in Figure 1. Needless to say, each metal has its specific processing technologies and applications. However, general processes such as pyro- or hydrometallurgical processing or electrolytic refining, casting and alloying methods and further treatment like trimming, stamping or cutting are similar for most metals. Therefore, the general example presented in Figure 1 is applicable to numerous metals.

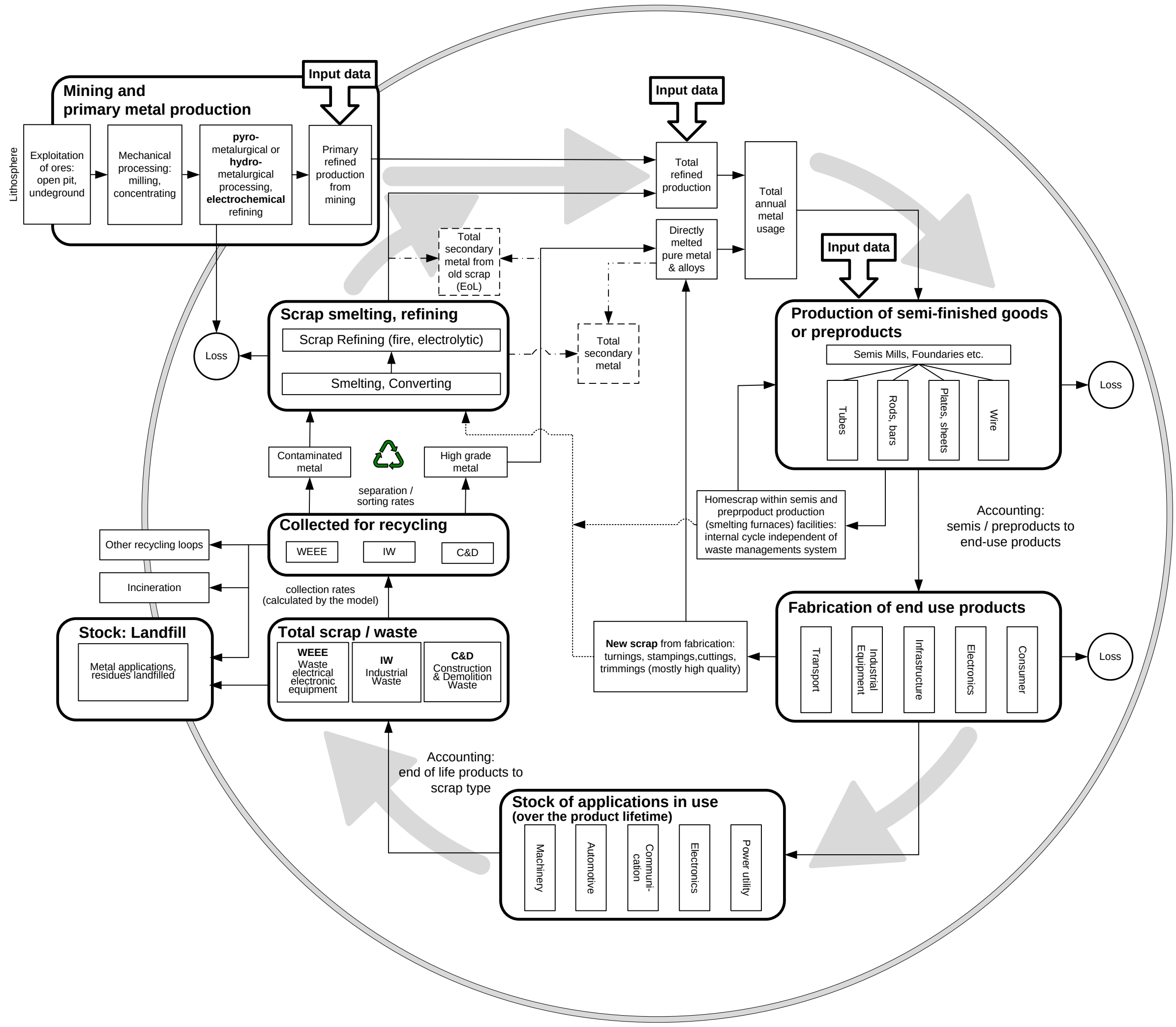


Figure 1 General life cycle of an industrial metal

In previous studies on metal cycles numerous approaches and methods were applied. Generally, one can distinguish between bottom-up and top-down approaches (Pauliuk et al. 2013). The bottom-up approach is based on empirical statistics of different products in use or in waste flows within a specific geographical region and assumptions of the average metal content per product (concentration) (Bergbäck et al. 2001). The top-down approach analyzes all flows into or out of a clearly defined system and aggregates stocks over time.

For dynamic models on a global or a regional level top down approaches are very well suited. However, in previous studies on metal cycles, dynamic approaches were strongly underrepresented (cf. Table 1).

Table 1 Methodological dimensions of previous studies (Chen, Graedel 2012). Literature review shows a significant lack of dynamic approaches when describing and analyzing metal cycles. Particularly on a global level, the system dynamics approach offers a highly valuable modeling environment for dynamic stock and flow models that can strongly contribute to an improvement of Substance and Material Flow Analysis.

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

As illustrated in Figure 2, in addition to the static and dynamic model dimension, a metal cycle can be characterized by the geographic region (spatial dimension) and the timeframe it refers to.

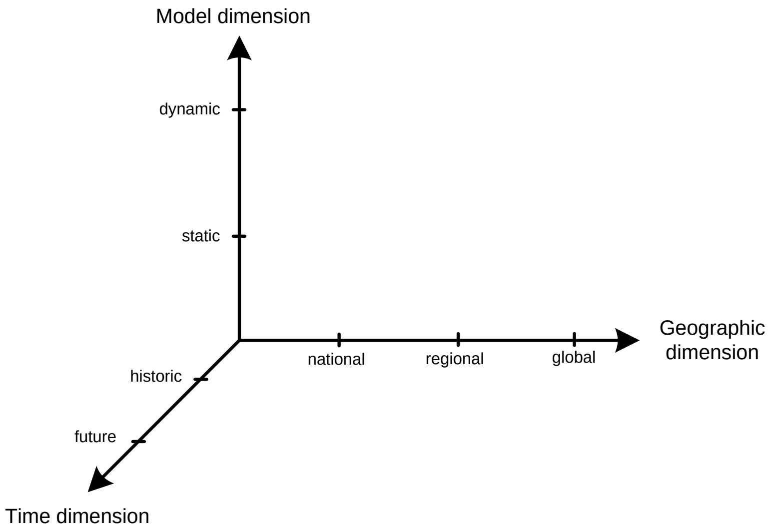
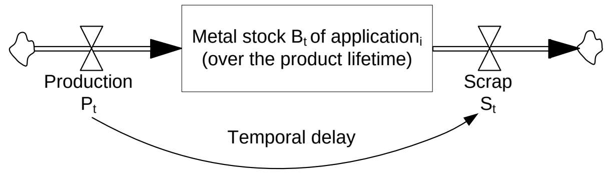


Figure 2 Dimensions of raw material cycles

Naturally, static bottom up studies -by evaluating empirical statistics on the use of specific products and by assuming raw material content in these products- are fundamental to generate basic estimates of stocks in use and material contents in waste streams and surely serve as data sources to validate dynamic top down approaches. Especially for studies referring to smaller spatial dimensions beyond national levels such as cities or regions bottom up approaches are essential due to the lack of production and trade data (cf. Bergbäck et al. 2001). Nevertheless, current raw material markets show high volatility over time both on the supply and the demand side which are not covered by static approaches. Moreover, a dynamic model provides relevant additional information compared to static approaches, e.g. material accumulations over time can be made transparent (Matsuno et al. 2012). In the field of industrial ecology, much more research work has to be done in the development of dynamic models. For specific forecasting methods dynamic bottom up approaches are useful (cf. Gerst 2009). However, particularly for dynamic material flow models on larger spatial levels such as models for countries, continents, or global models, top down approaches seem reasonable as reported production data are broadly available. As discussed in the following sections, the system dynamics approach offers a well suited environment to develop flexible dynamic top down models that meet current problems concerning the understanding of industrial demand and supply side dynamics and interactions.

System Dynamics as a powerful tool to simulate dynamic raw material cycles

The possibility to simulate different forms of delay functions is the most important component for the simulation of dynamic material flows and the stocking of metal over the useful lifetime of products. Feedback loops resulting in a system of first order differential equations are essential for the simulation of market dynamics and interactions (cf. section 4) but do not play a role for the dynamic material flow cycles described in this section. Figure 3 displays the basic methodology to aggregate metal stocks both using fixed average lifetimes and lifetime distributions. Typical functions of lifetime distributions from the field of safety and environmental engineering are shown in Figure 4.



System dynamics methodology:

$$B_t = \sum_{t=t_0}^{t} P_t - S_t + B_{t_0}, \text{ or } B(t) = \int_{t_0}^{t} (P(t)-S(t))\,dt + B(t_0)$$

Delay with fixed average lifetimes:

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

Delay with lifetime distributions (probability density functions):

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

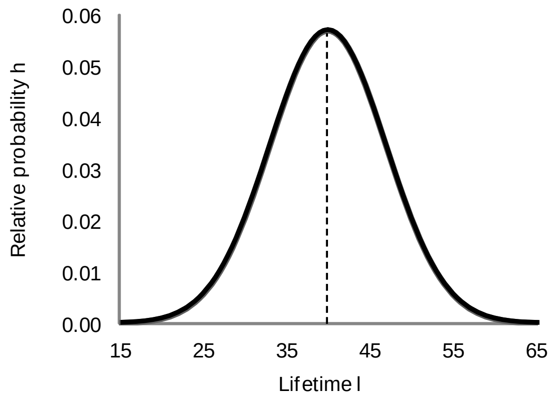


Figure 3 Basic methodology to estimate metal stocks in use and waste flows by using different forms of temporal delays

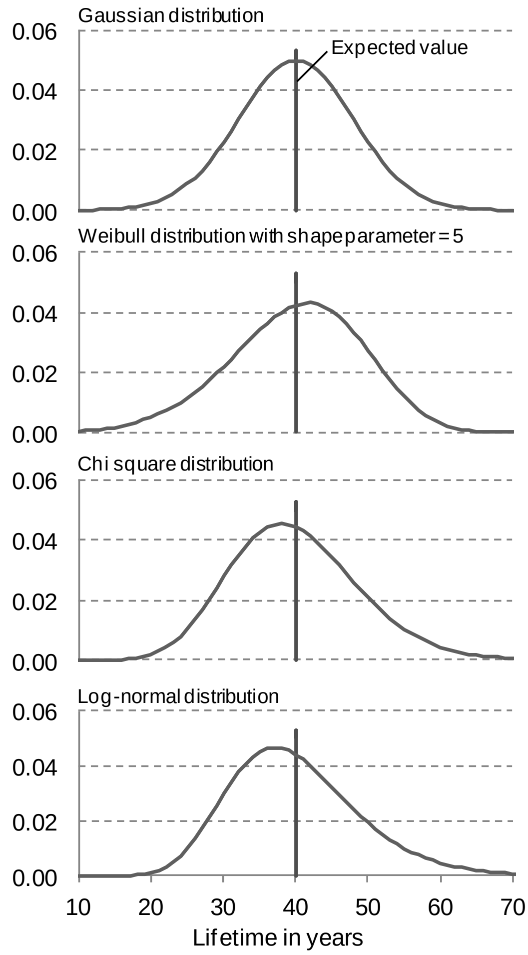


Figure 4 Typical lifetime distributions in safety and environmental engineering

The key input flows into a dynamic raw material cycle (mining, refined metal and semi finished goods) are marked in Figure 1. One of the main challenges when simulating dynamic material cycles is to keep a closed mass balance at every point in time. Hence, at every point in time the sum of primary production from mining and secondary production from recycling has to be in line with the total metal use for the production of semi finished goods or pre products. Therefore, we have developed a methodology to calculate the collection rate of scrap as a function of reported production data taking into account the efficiencies of scrap dismantling, separation and refining. The simplified methodology for the case of one single waste flow and one possible path to recycle post consumer scrap is described in Figure 5.

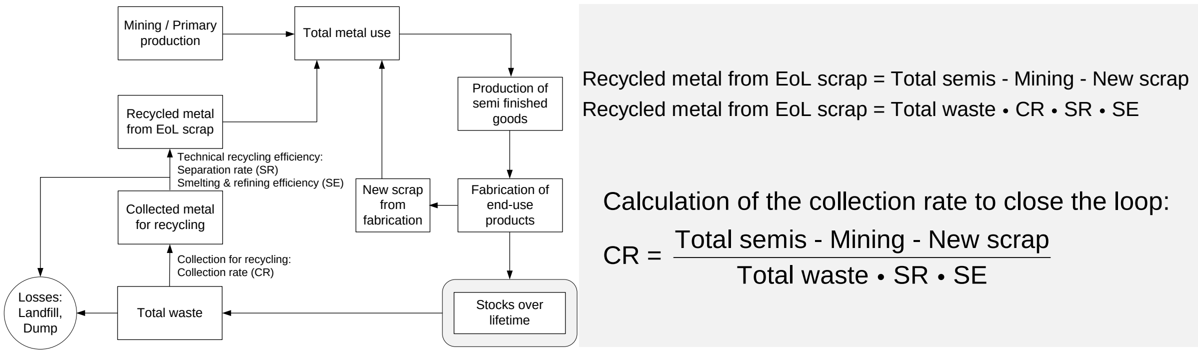


Figure 5 Simplified methodology to enable a closed mass balance by calculating the EoL Collection Rate as a function of production data

In the case of the global copper flow model described in the following section we distinguished between 6 different scrap types with different technical recovery efficiencies and took into account the fact that some of the high quality postconsumer scrap might be directly reused in smelting furnaces for semi-finished goods whereas the contaminated scrap is further treated in scrap smelters and refining facilities. However, the basic methodology described in Figure 6 remains similar to the simplified one in Figure 5.

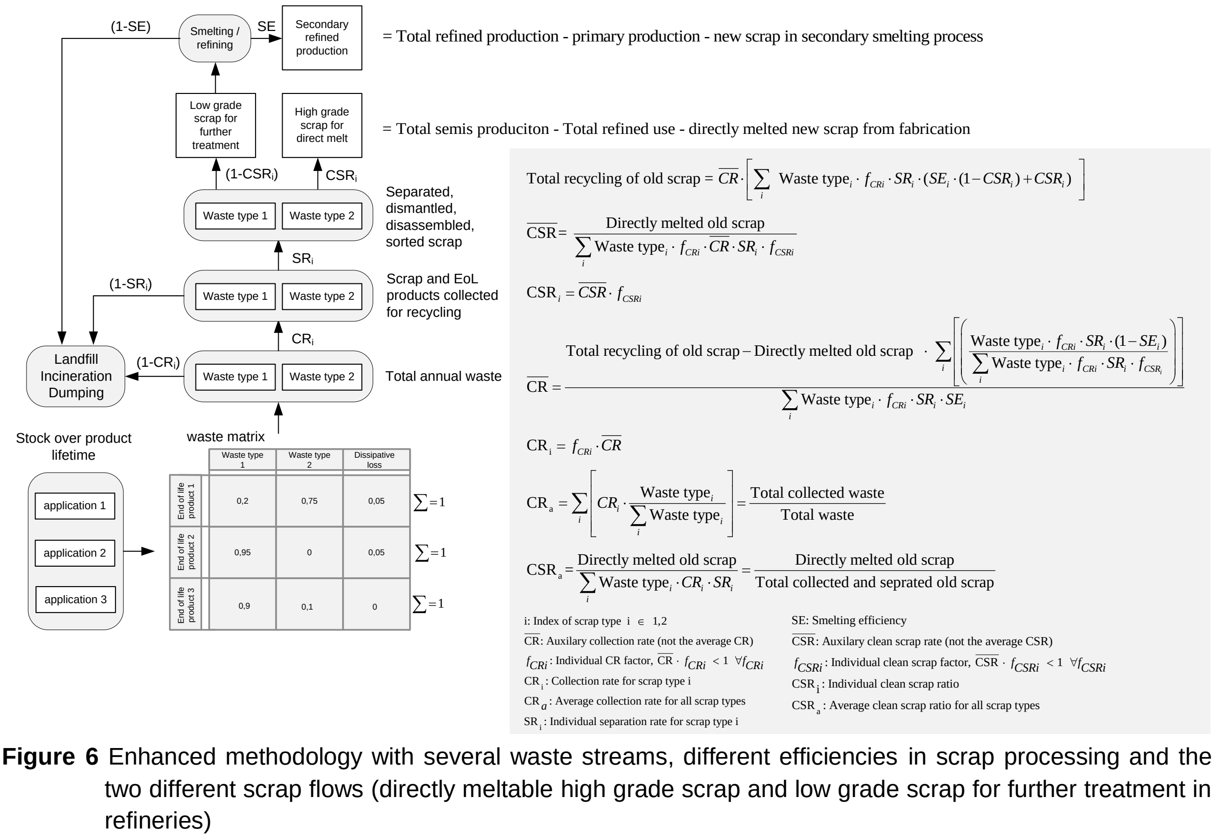


Figure 6 Enhanced methodology with several waste streams, different efficiencies in scrap processing and the two different scrap flows (directly meltable high grade scrap and low grade scrap for further treatment in refineries)

This principle was used for the copper flow model described below. Nevertheless, due to the similarity of most metal cycles, the core methodology is applicable to all other kinds of industrial metals.

Output of a dynamic metal cycle: the example of the global copper flow model

We applied the methodology described above to the global copper cycle. Therefore, mining and production data for the past 100 years (1910-2010) were necessary as several applications of copper, particularly in the field of building & construction and infrastructure have very long lifetimes (on average around 50 years). For the global copper flow model we considered 17 different end use sectors. A detailed description of the model and a discussion of the results have been published in a separate paper (Glöser et al. 2013). Herein, we intend to demonstrate the modeling possibilities and the potential outcome of such a metal cycle on the example of the global copper flow model. Figure 7 shows the structure of the model and the way it was implemented in a system dynamics software.

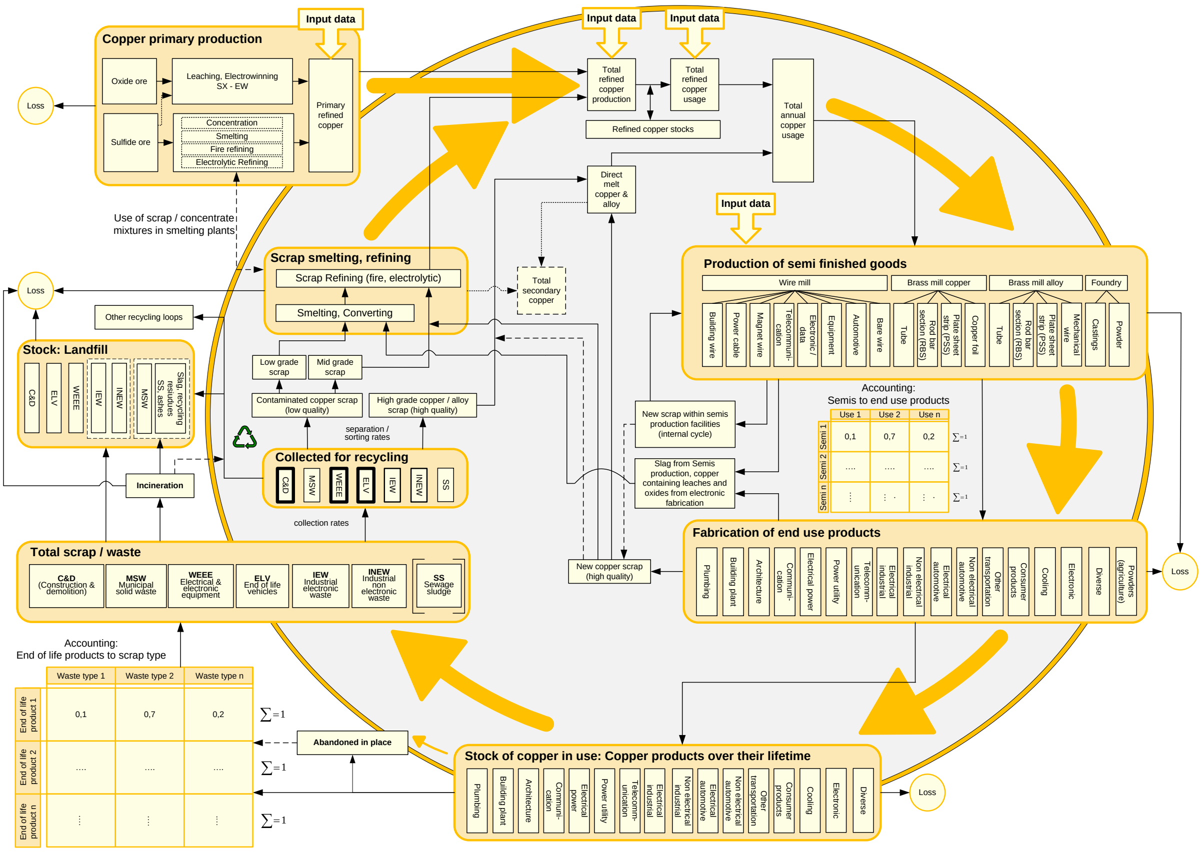


Figure 7 Structure of the global copper flow model [the model development was commissioned by the International Copper Association (ICA)]

The model was developed for a project commissioned by the International Copper Association (ICA) with the intention to get a better understanding of copper scrap flows and current global average recycling efficiencies of copper. Despite the industrial importance of copper -ranking third after steel and aluminum in terms of consumed tonnage- there is a lack of information concerning the material recovery from waste.

Several studies deal with the recycling of copper on a regional basis. However, uncertainties concerning copper content in trade flows and non reported exports of scrap are challenging when developing a dynamic model for a specific region. Therefore, we preferred to first run a global model which will be broken down into different regions as described later.

The calculation of relevant recycling indicators that can be extracted from the model is illustrated in Figure 8.

Recycling Input Rate (RIR)
= (r+d) / s

End of Life Recycling Input Rate (EoL RIR)
= o / s = RIR·OSR

Overall Processing Rate (Overall PR)
= (r+d) / (c+n)

Overall Recycling Efficiency Rate (Overall RER)
= (r+d) / (w+n)

End of Life Collection Rate (EoL CR)
= c / w

End of Life Processing Rate (EoL PR)
= o / c

End of Life Recycling Rate (EoL RR)
= o / w = EoL PR · EoL CR

Old Scrap Ratio (OSR)
= o / (r+d)

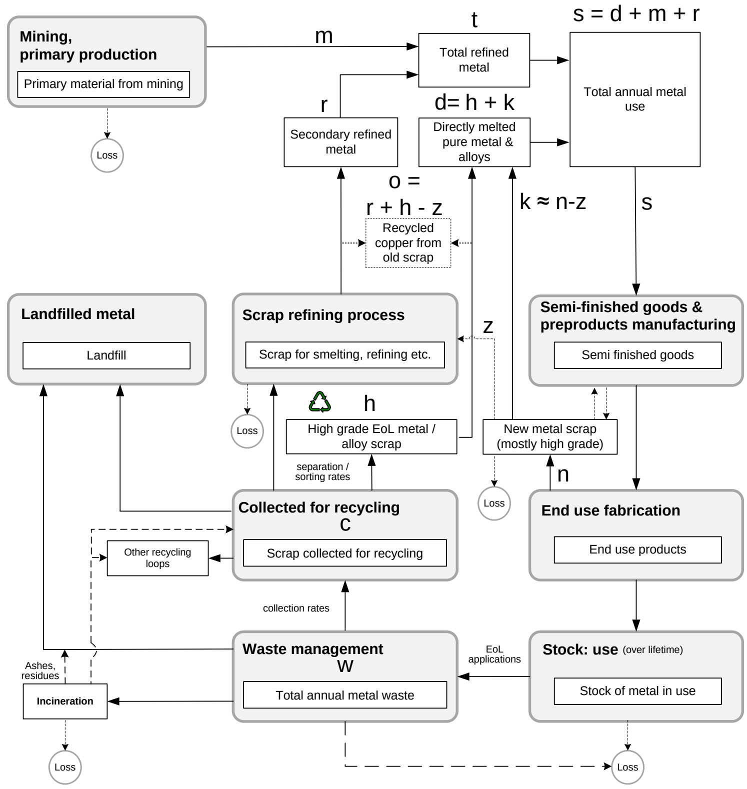


Figure 8 General calculation of different recycling indicators to quantify the performance of waste management and the recovery of raw materials from waste flows

Typical outcomes of a dynamic metal cycle are material stocks in use, stocks on landfills or discarded material and the development of waste flows. Figure 9 displays these results from the model.

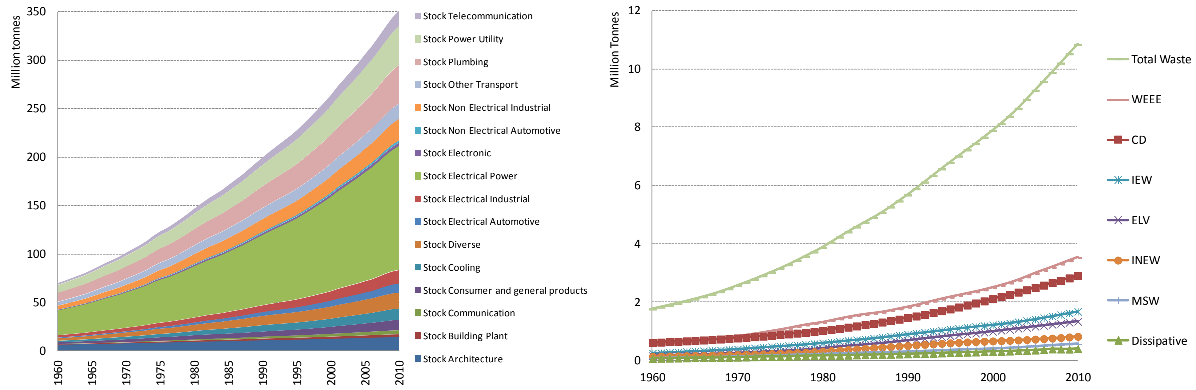


Figure 9 Development of copper stocks (left) in use and copper content in waste flows (right)
WEEE = waste electrical and electronic waste; CD = construction and demolition waste;
IEW = industrial electrical equipment waste; ELV = end-of-life vehicles;
INEW = industrial non-electrical equipment waste; MSW = municipal solid waste

In contrast to previous studies in which the conservation of mass over time was not always ensured, the methodology of calculating the collection rate of post consumer scrap as a function of production data guarantees a closed mass balance. However, the fluctuations due to market volatility are directly transferred to the collection rate. Hence, the different recycling rates fluctuate over time.

Furthermore, there is considerable uncertainty among the input data, particularly concerning the assumptions of average lifetimes per sector and several technical efficiencies in product fabrication. To evaluate the uncertainties and to validate the calculation of recycling rates we chose a stochastic approach which may be interpreted as a variation of a Monte Carlo simulation. For all uncertain variables a specific range of possible values was defined. In each simulation run the variable value was randomly (evenly distributed) set from this range. The model was run 10^5 times extracting the calculated recycling efficiencies in each run. The results of the stochastic sensitivity analysis for the calculated recycling indicators are shown in Figure 10, Figure 11 and Figure 13.

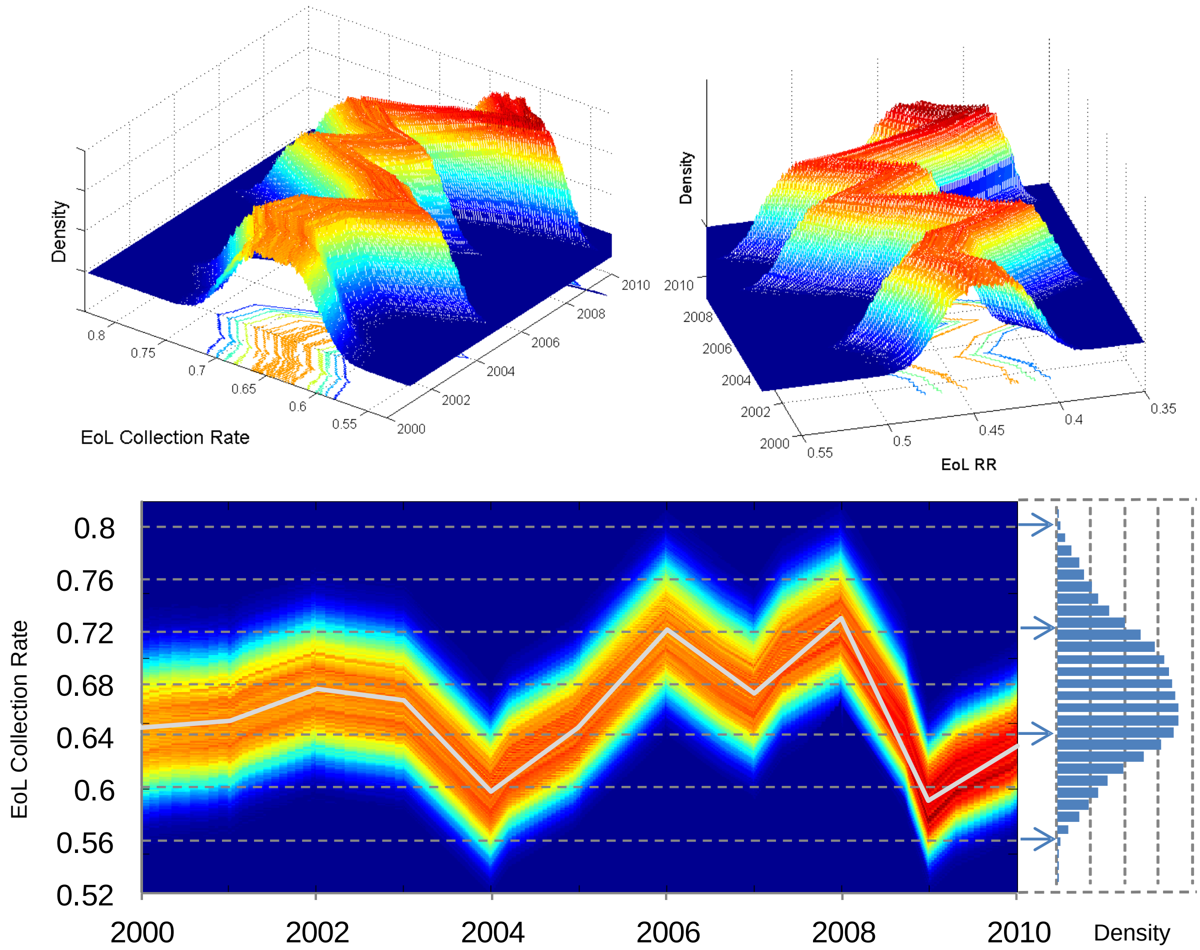


Figure 10 Results of the stochastic uncertainty evaluation for the quantification of recycling indicators - the example of the global EoL (End of Life) Collection Rate and the EoL Recycling Rate of copper

The basic advantage of this approach -compared with a simple simulation of maximum and minimum scenarios by setting all uncertain variables to their maximum or minimum value- is the possibility to extract density functions including both variations due to uncertainty and variations due to fluctuations over time (cf. Figure 10). Hence, we took into account that each uncertain variable may vary independently within the previously defined range but the likelihood that all uncertain variables take their maximum or minimum value at the same time is comparatively low. A comparable methodology to analyze uncertainty in system dynamics models has been presented by Pruyt (Pruyt 2007) and has been applied in numerous system dynamics models before (Auping et al. 2012). Figure 11 displays the density functions for all 8 recycling indicators, extracted in the manner described in Figure 10. The results show that due to uncertainty and market volatility it is not possible to make fixed statements about the exact recycling efficiencies of metals, neither on a global nor on a regional level. However, the approach presented in this study might help to get a better understanding of efficiency ranges of material recovery from waste.

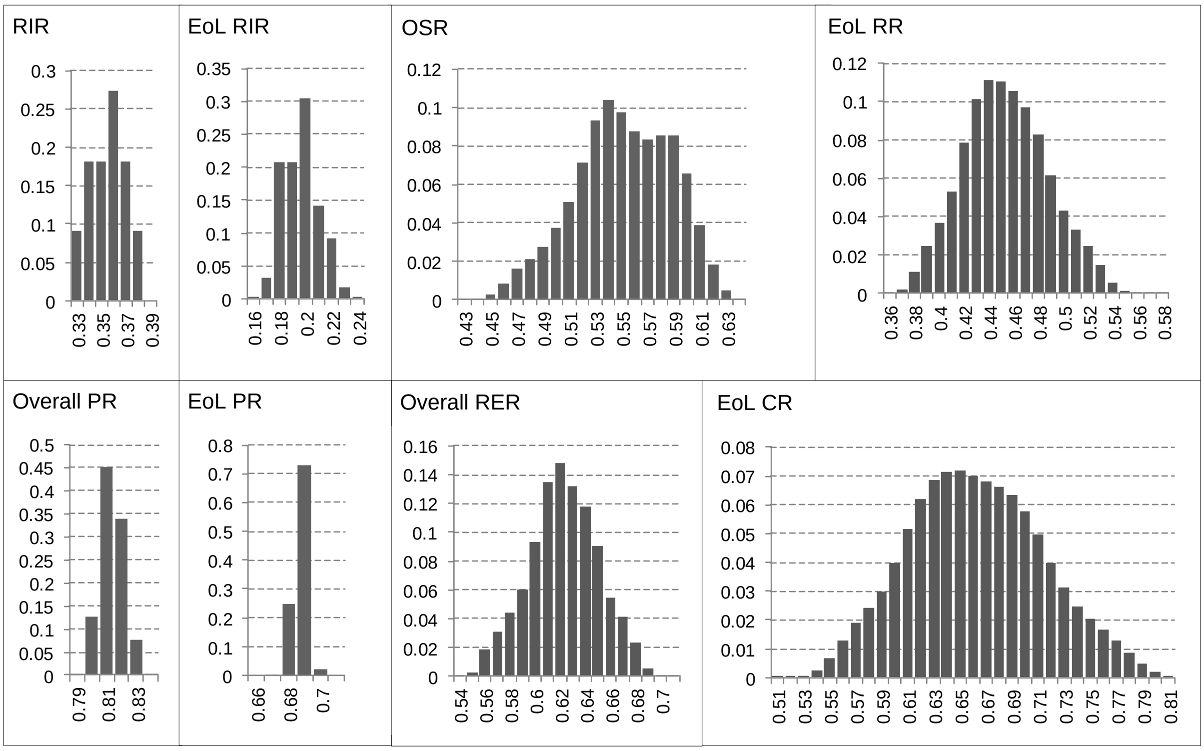


Figure 11 Aggregated results of the stochastic uncertainty analysis of all 8 global recycling indicators of copper

The effect of the stochastic uncertainty analysis on the estimation of copper stocks in use, waste flows and the estimation of aggregated material on landfills is illustrated in Figure 12.

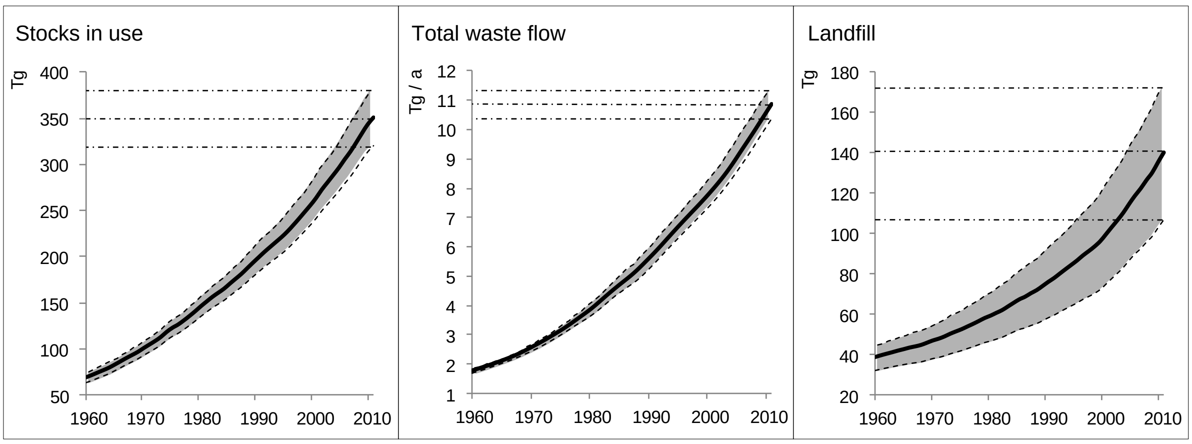


Figure 12 Effect of uncertainty on the estimation of stocks in use, total copper content in waste flows and landfilled (disposed) copper (cf. Figure 9).

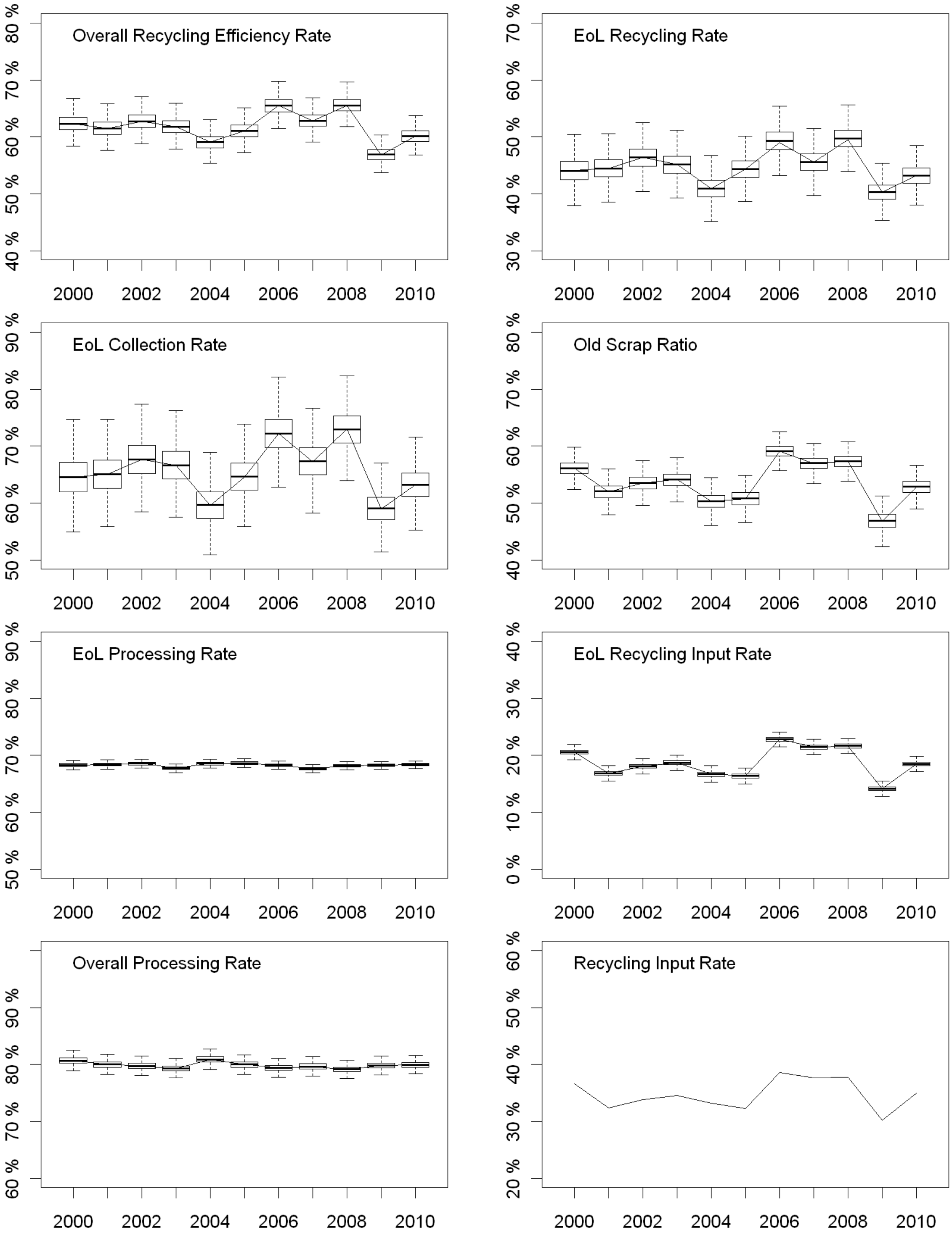


Figure 13 Results of the stochastic uncertainty evaluation in form of box plots over the timeline for each recycling indicator. Note that the Recycling Input Rate was not affected by the sensitivity analysis as this indicator only depends on historical production data which are well reported.

Potential enhancement of current models and future challenges of system dynamics in industrial ecology

Generally, the field of industrial ecology displays a severe lack of dynamic material flow models comparable to the copper flow model described in this paper (cf. Table 1). System dynamics models will certainly contribute to better understanding of metal cycles, especially when analyzing the strong market volatilities of the previous years and when running future scenarios. One of the key advantages of the system dynamics approach is its flexibility in model conception. In this section we shortly present several ongoing modeling activities in the context of dynamic raw material cycles.

An obvious extension of global material flow models is the inclusion of regional cycles and the connection of these cycles to the global model by means of foreign trade flows in each step of the value chain. In this case the challenge is to consider all relevant trade data. An advantage of running regional and global stocks and flows at the same time is the possibility to carry out plausibility checks by comparing global and regional figures. The basic principle of breaking down a global model into two regions is shown in Figure 14. Currently the global copper flow model presented above is broken down into different regions.

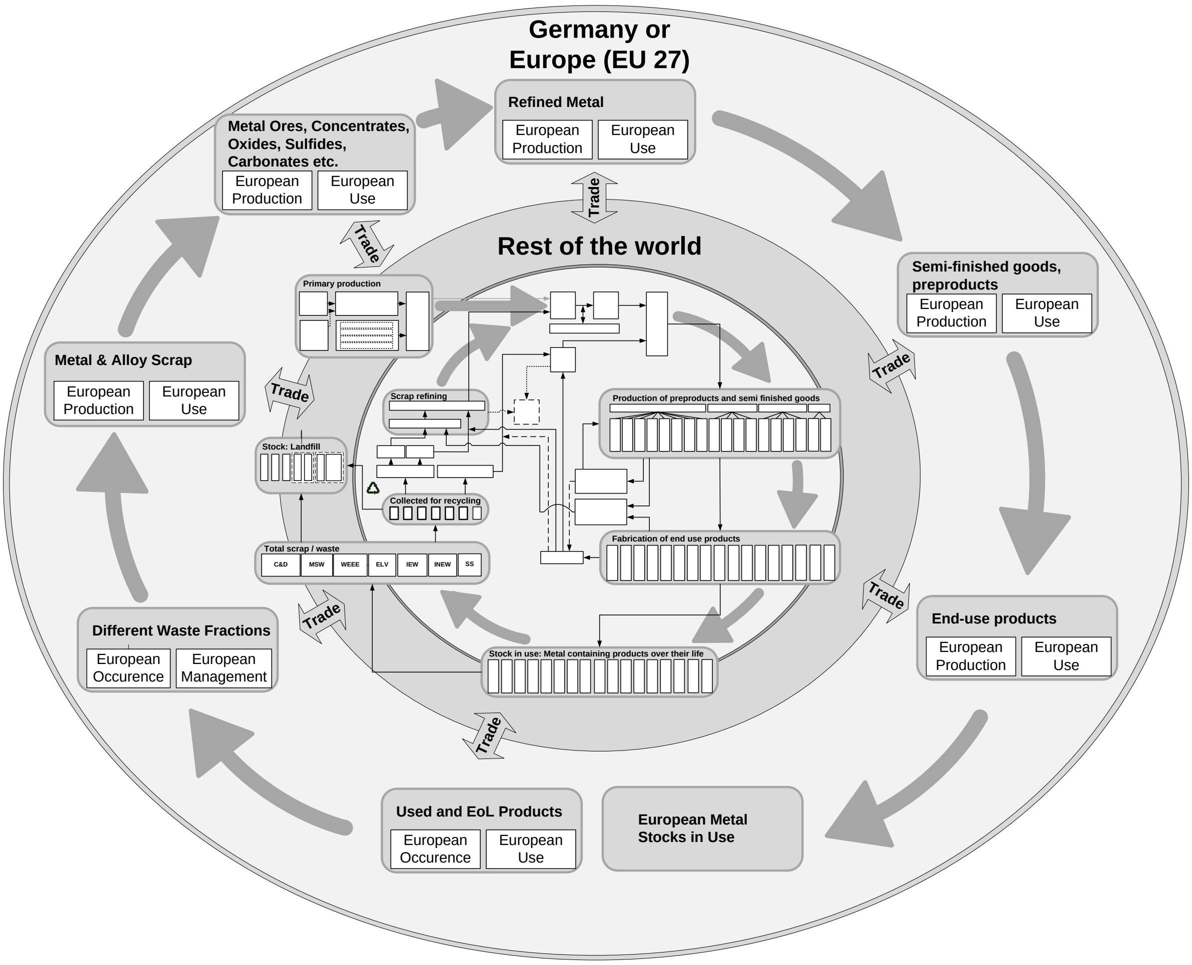


Figure 14 Breaking down a global model into a regional part and the rest of the world (RoW) and linking these partial models by means of foreign trade

A second enhancement of existing material flow models will be the connection of the lifecycles of different metals that show interrelations and interdependencies among each other (cf. Figure 15). Typical interdependencies among different metal markets may be for example:

1. Joint primary production if one metal (or mineral) is a byproduct of another metal (or ore) such as tellurium as a byproduct of copper production or gallium as a byproduct of bauxit refining for aluminium production.
2. One metal might be an alloying element of another and therefore, its demand depends on the demand of the main alloy constituent such as manganese for aluminium alloys (Hatayama et al. 2007) or nickel and chromium as important alloying elements of steel (Daigo et al. 2010).
3. One metal might be a substitute for another metal in specific technical applications such as aluminium as a substitute for copper in specific cables for electrical infrastructure.
4. The demand for several metals might depend on specific technologies such as lithium and cobalt for lithium ion battery production (Angerer et al. 2009).

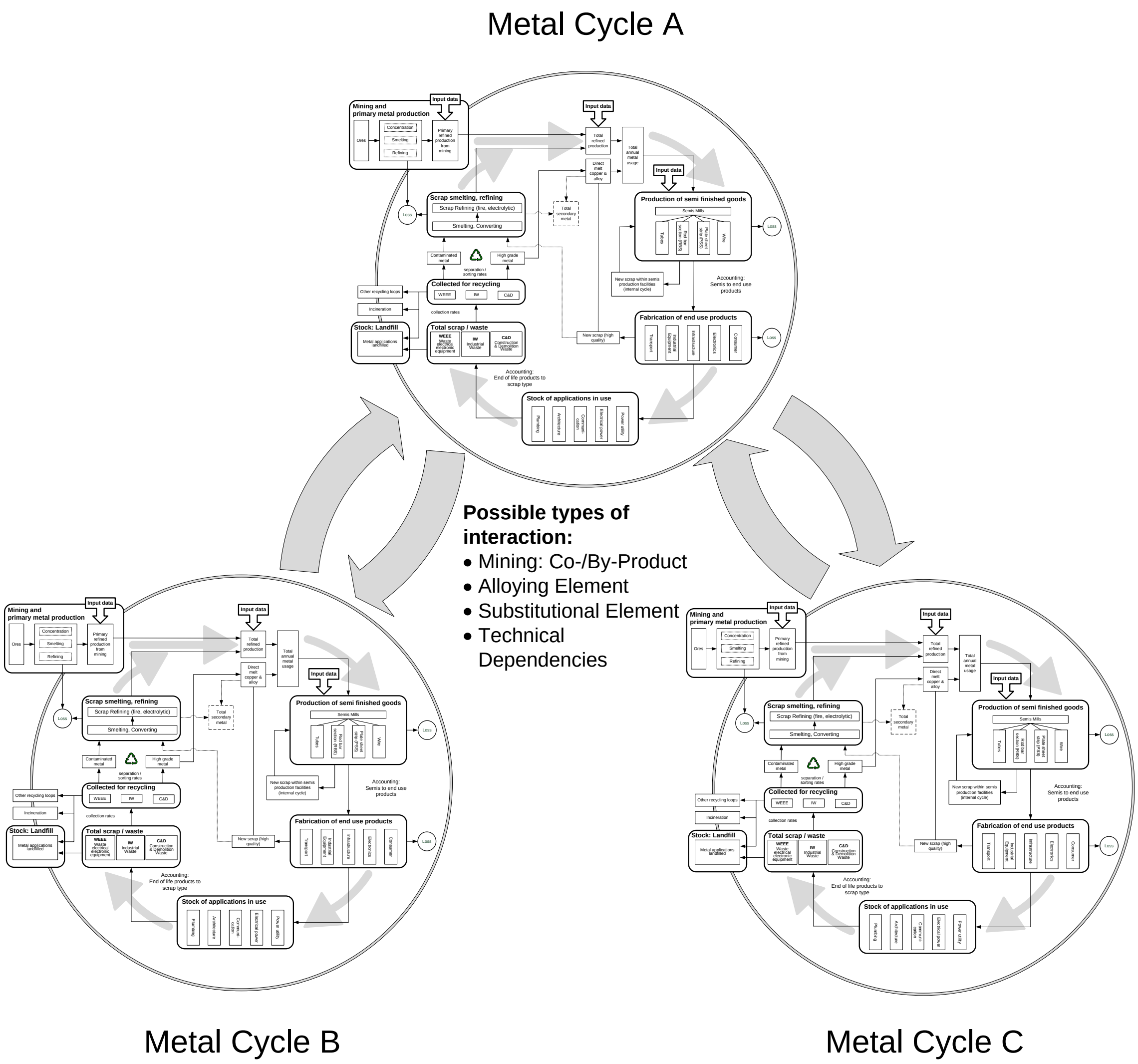


Figure 15 Coupling of different raw material cycles in terms of interdependencies concerning byproducts in mining and primary production, alloying elements, potentials of substitution and technical interrelations

In particular, the versatility of a system dynamics modeling approach -and the rich possibilities in combining the system dynamics principle with further approaches such as econometric structural equation models- forms a perfect basis to analyze raw material market dynamics and to combine physical material flow models with dynamic market models. When developing a qualitative causal loop diagram, one can imagine numerous feedback effects, particularly concerning feedbacks from the price level of a metal to both primary and secondary supply (mining & recycling) and to the demand side in form of higher resource efficiency and the potential use of substitutes.

A causal loop diagram of plausible interdependencies and feedback effects on raw material markets is illustrated in Figure 16.

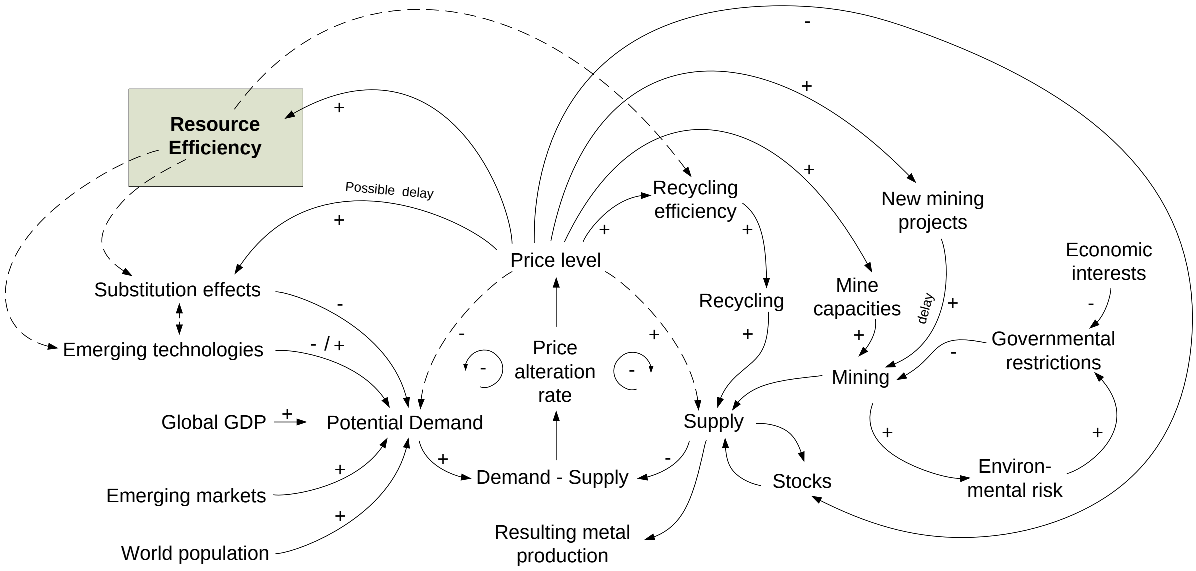


Figure 16 General causal loop diagram of potential interdependencies and feedback effects on raw material markets

The main challenge of this basic approach is to keep the specific market balanced despite external influences such as economic and technical development. However, the basic principle of a market equilibrium in microeconomics may be applied to a system dynamics model by negative feedback loops both on the demand and supply side as described in Figure 17.

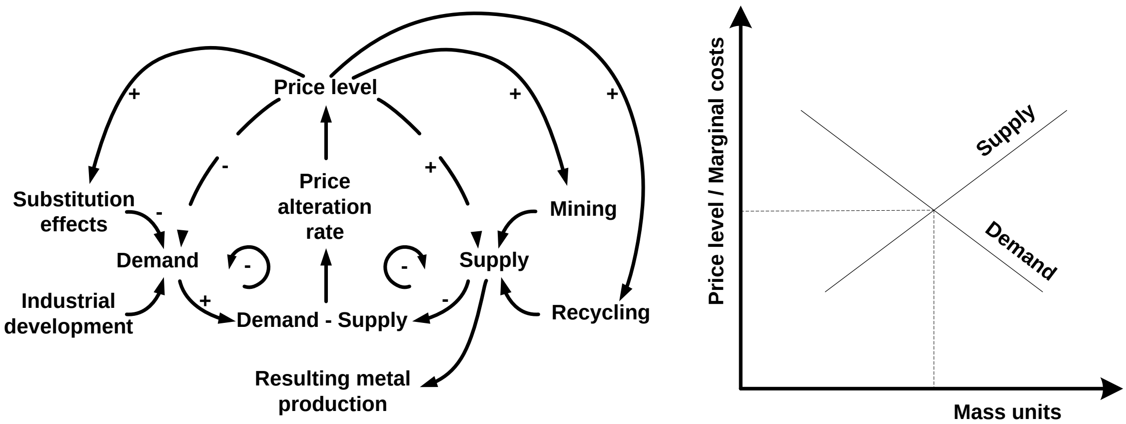


Figure 17 Negative feedback loops to keep the market balanced

Analyzing material needs in the context of economic development and assessing the feedback of potential material shortages and high raw material pricing on the development of specific technologies (concerning both high tech innovations and new recycling potentials) is one of the main future challenges of industrial ecology. We are convinced that both pure system dynamics models (consisting of delay functions and systems of first order differential equations) and hybrid models combining the system dynamics approach with econometric models will strongly contribute to a better understanding of current developments on raw material markets.

A basic modeling approach which includes physical raw material cycles, econometric aspects and feedbacks from higher material pricing is shown in Figure 18. Such dynamic market models are planned to be applied to different metal cycles, bearing in mind that each market has its own peculiarities which may require adjustments to this basic approach in order to better capture its dynamics in the model.

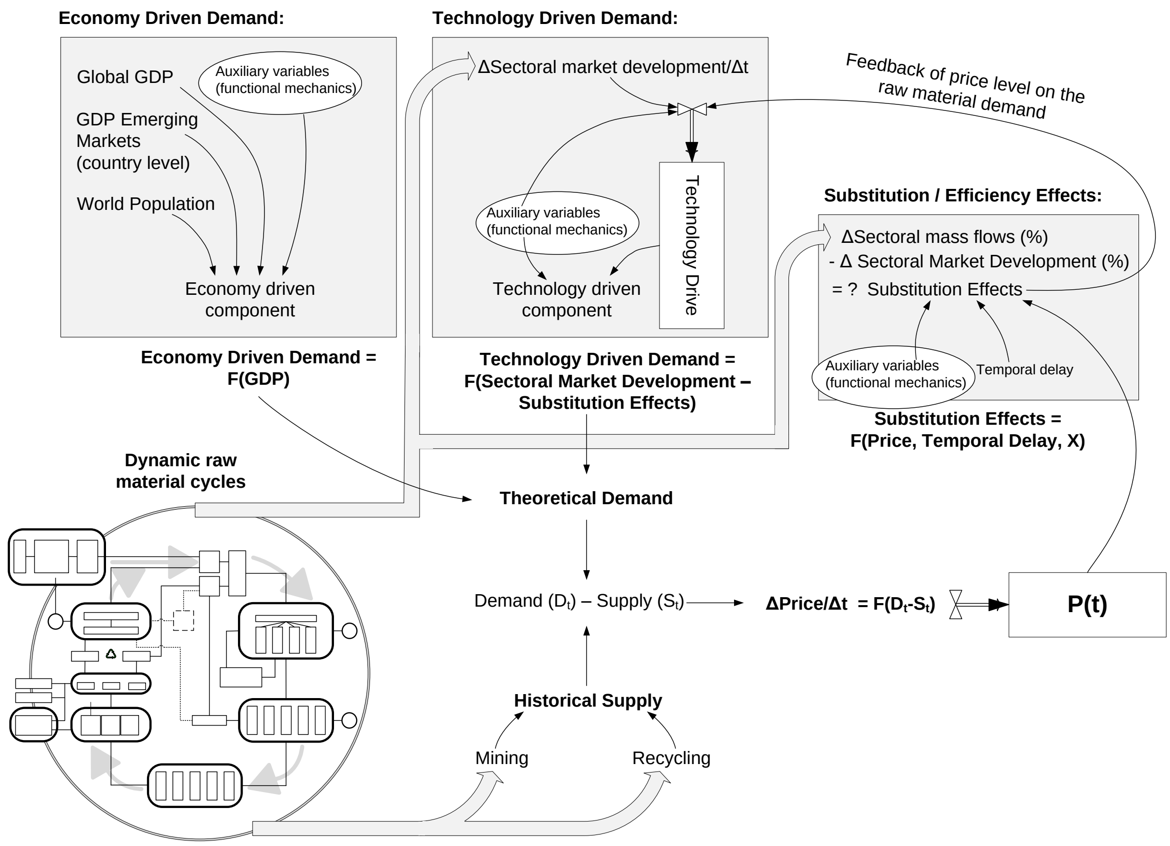


Figure 18 Linking physical material flow models with macro economic and technical demand drives and analyzing the feedback of higher raw material pricing on raw material demand through substitution effects

The specific effect of electro mobility diffusion (battery electric vehicles and hybrid vehicles) on the demand for battery raw materials (lithium and cobalt) and the feedback of potential raw material shortages on the market diffusion of alternative drives has been analyzed in previous studies (Kühn, Glöser 2013, 2012) and is currently improved as shown in Figure 19. Generally, the effect of emerging technologies on raw material demand and the feedback of potential raw material shortages on the market penetration of new technologies can be well simulated with a system dynamics approach and should be further analyzed, particularly for those raw materials for which the demand is driven by one specific technology.

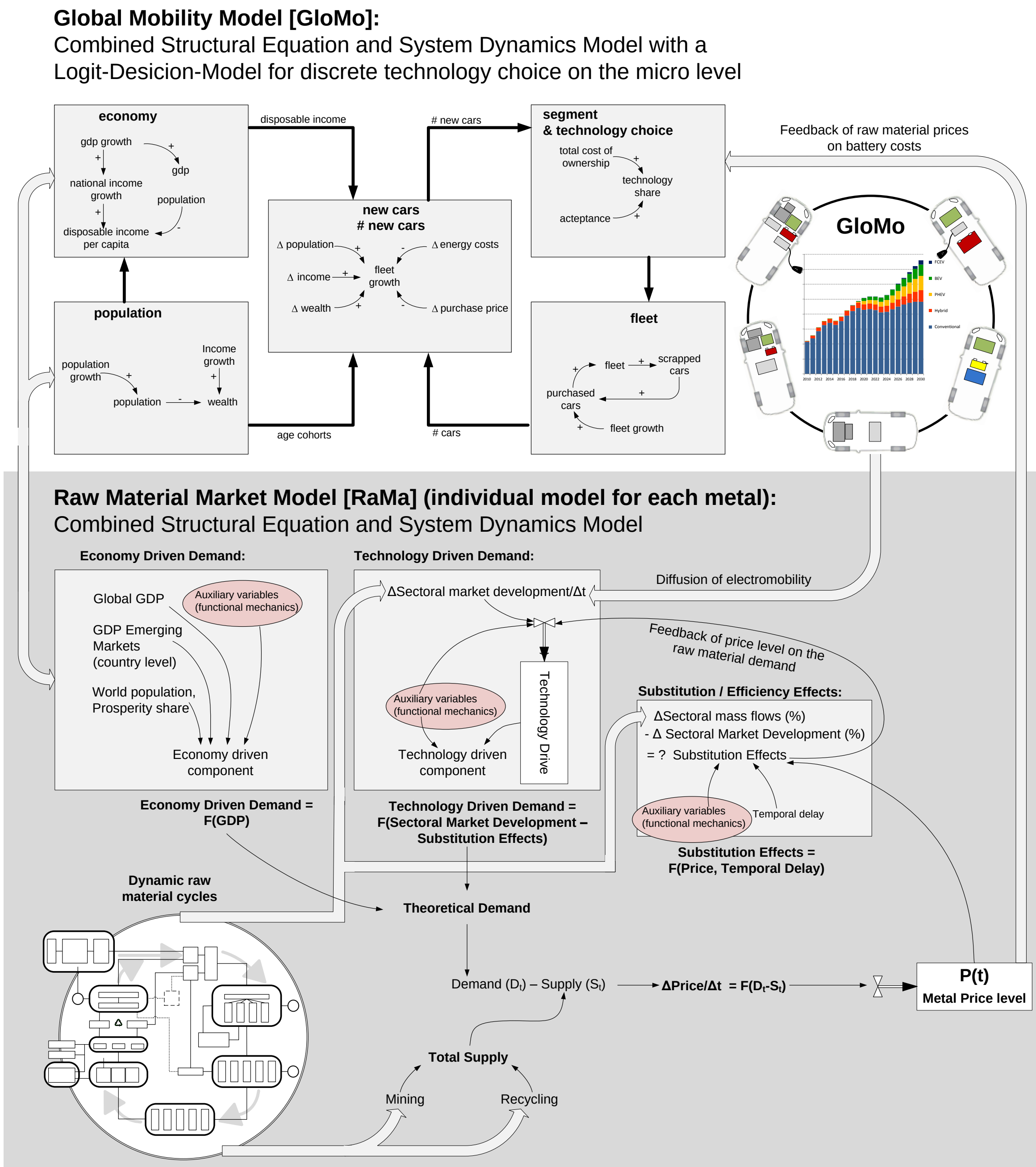


Figure 19 The effect of the diffusion of alternative drives (hybrids, plug-in-hybrids and battery electric vehicles) on the demand for battery raw materials (lithium & cobalt) (Kühn, Glöser 2013, 2012).

Raw material criticality measures the potential impact of supply disruptions or raw material shortages on an economic system and may therefore be interpreted as an abstraction of classical risk assessment in a risk matrix (cf. Figure 20 (Glöser 2012), (Eggert et al. 2007)).
In the context of increasing supply risks of essential metals and minerals the systematic evaluation of raw material criticality has been the basis for numerous studies in recent years (Nassar et al. 2012), (Sievers und Tercero 2012), (Erdmann et al. 2011), (Gandenberger 2011), (U.S. Department of Energy 2010), (Ad-hoc Working Group on defining critical raw materials 2010), (Eggert et al. 2007). However, these studies are static analyses for one base year and do not take into account the rapid changes and dynamics both on the supply and demand side of current raw material markets.

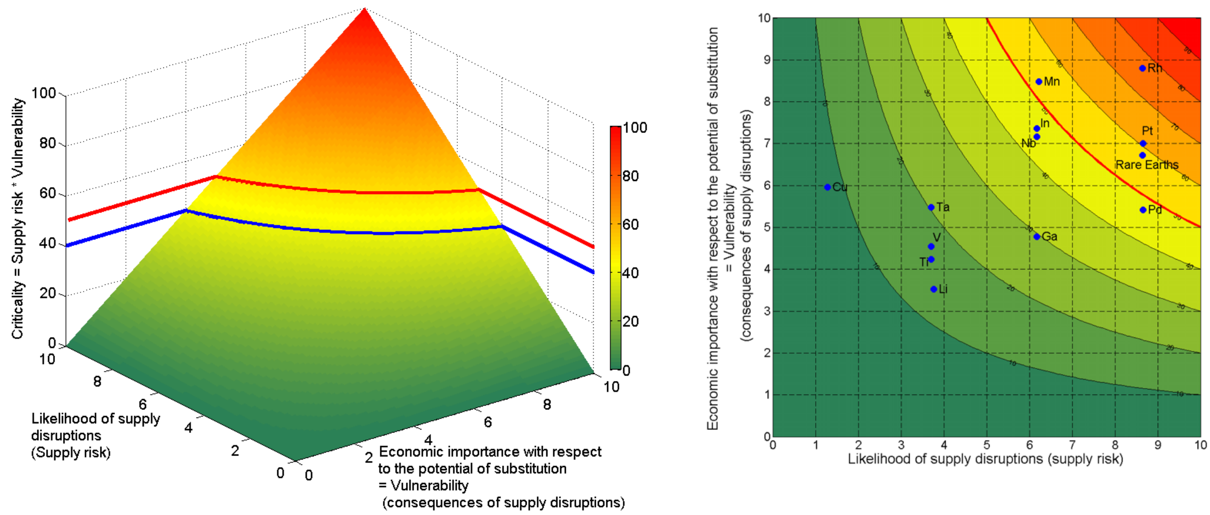


Figure 20 Basic methodology of raw material criticality assessment and results of a study performed by the US National Research Council in 2007 (Eggert et al. 2007).

Based on a model combining physical material flows and market development, raw material criticality can be assessed over time. By simulating future scenarios, potential bottlenecks in raw material supply may be identified. We are currently developing a model to assess raw material criticality over time as illustrated in Figure 21 and Figure 22 (cf. Glöser 2012). The interaction between different metal cycles as discussed above may also be included in such a system dynamics approach.

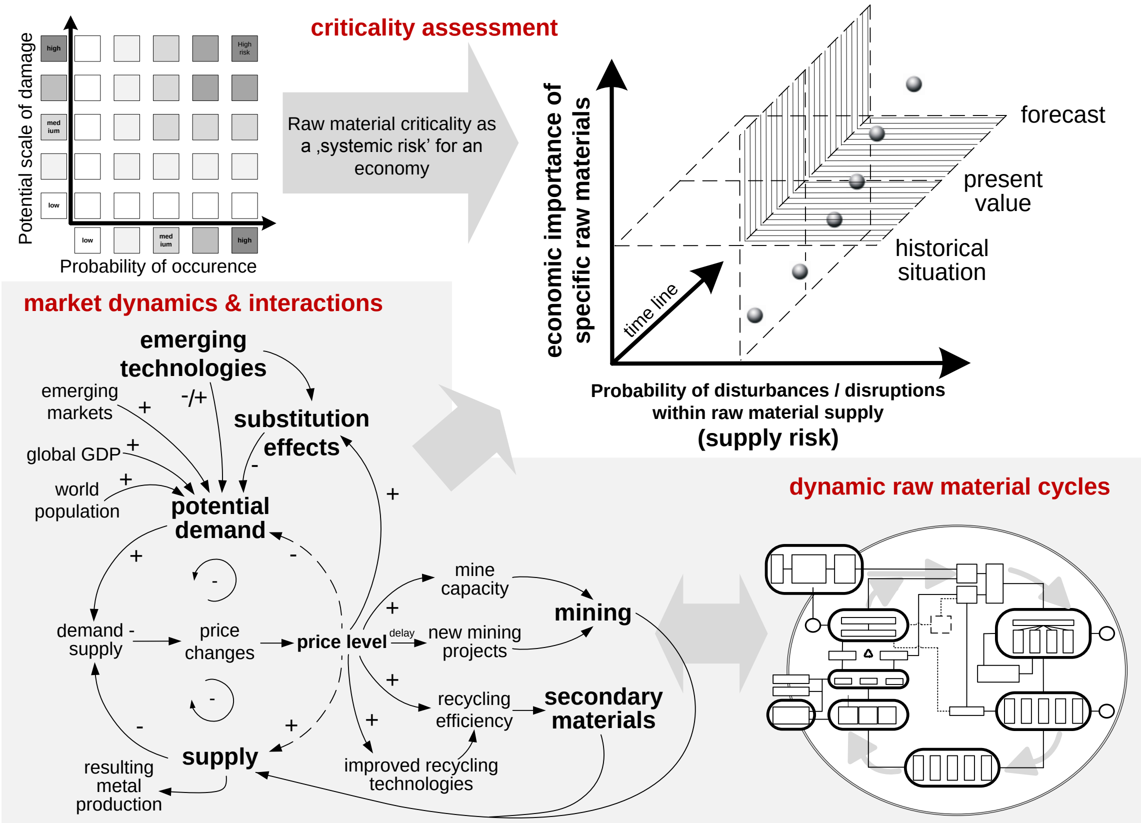


Figure 21 Extracting raw material criticality over the timeline within a dynamic market model (Glöser 2012)

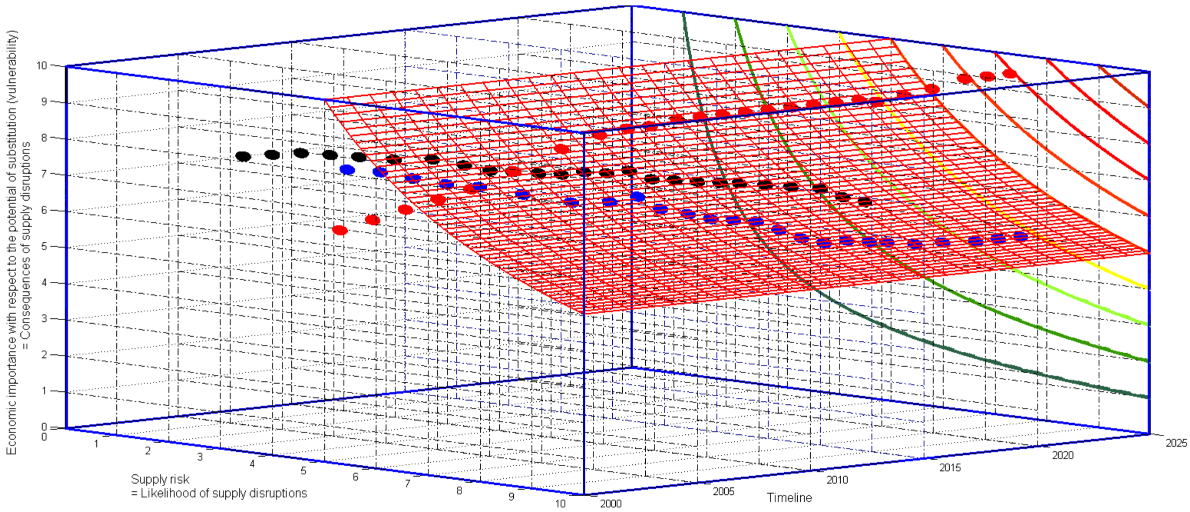


Figure 22 Assessing the criticality matrix for each year on the timeline: historical data, present values, forecasts

As mentioned previously, one of the main future challenges of industrial ecology is simulating material flows with respect to economic development. Thus, the linkage of material flow models and economic models. The main problem is that most macro and meso economic models such as Input output models are based on monetary units. There are approaches to create 'ecological input output tables' which include physical material flows. However, in a market model including both price levels and physical material flows a linkage to existing input output models seems feasible with less effort as described in Figure 23. Nevertheless, our approaches of linking material cycles with economic models are still at the beginning of the development phase.

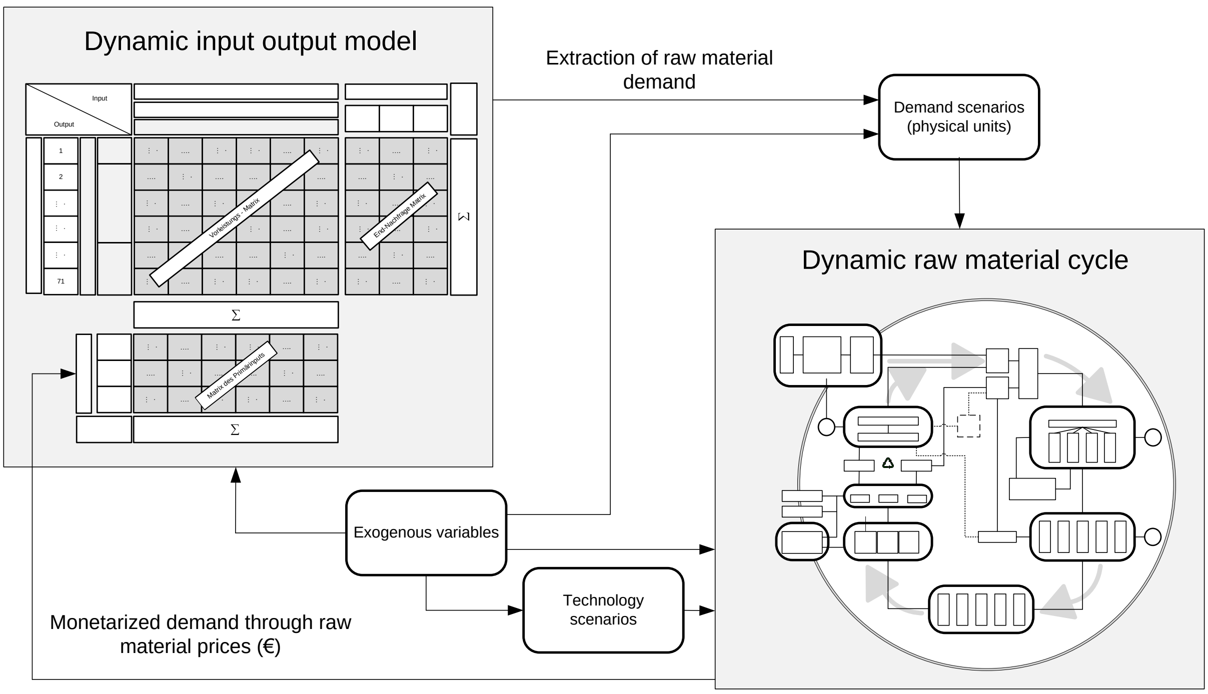


Figure 23 Linking material flow models with monetary macro (meso)-economic input output models

Acknowledgments:

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Literature

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