A General System Structure and Accounting Framework for Socioeconomic Metabolism

By

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Ontology of Socioeconomic Metabolism

Part II: System Definitions and the General Accounting Framework

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Abstract:

A wide spectrum of models and model combinations exist to describe socioeconomic metabolism. These models use different terms and system representations. Often, they are used by separate scientific communities. This makes it difficult for practitioners to see the limitations of the different models, to compare them, and choose a model or a combination that is fit for purpose. To facilitate comparison and combination of models and model-independent handling of data, we analyze and compare the structure of the system descriptions of the different model families for socioeconomic metabolism.

We identify the explicit or implicit system structure of material flow analysis (MFA), life cycle assessment (LCA), input-output analysis (I/O) including waste-I/O, integrated assessment models (IAM), and computable general equilibrium models (CGE). We show that their system structure can be seen as special cases of a general system structure, which models socioeconomic metabolism as bipartite directed graph. The general system structure includes industries, markets, the use phase, products, waste, production factors, resources, and emissions. We derive an accounting framework for the general system structure in form of a generalized supply and use table. We demonstrate that bipartite directed graphs and supply and use tables are two equivalent representations of socioeconomic metabolism, and hence, the system structure determines the accounting framework and vice versa.

The general system structure and the accounting framework can facilitate the development of clear and unambiguous terminology and the comparison and selection of models.

Keywords: Socioeconomic Metabolism; Supply and Use Table; System of National Accounts; System Definition; Systems Theory; Bipartite Directed Graphs;
Introduction

A spectrum of model families to describe socioeconomic metabolism

Society faces the challenge of reconciling human development with physical constraints that arise due to the limited size of the natural environment (UN 2013). To tackle this challenge, society requires scientific knowledge of how human and economic development depends on and interacts with the natural environment. In other words, we need to understand and manage socioeconomic metabolism (Ayres and Simonis 1994; Fischer-Kowalski and Huttler, 1999; Fischer-Kowalski, 1997; Baccini and Brunner, 1991; Fischer-Kowalski, 1999; Pauliuk and Müller 2014). Different model families, which describe socioeconomic metabolism on different scales and with different degrees of physical and economic stringency, have evolved over the last decades (Pauliuk and colleagues 2014). These include material or substance flow analysis (MFA) (Baccini and Bader 1996), material flow accounting (Eurostat 2001; Fischer-Kowalski and colleagues 2011), process-based life-cycle assessment (LCA) (EU JRC 2010), input output analysis (I/O) (Miller and Blair 2009), integrated assessment models (IAM) (Loulou and colleagues 2005), and computable general equilibrium (CGE) models (Burfisher 2011).

To overcome the limitations of individual models and to tackle new research questions, a wide spectrum of combinations of different models has developed over the last decades. Examples for model combinations include economically extended MFA (Kytzia and colleagues 2004); the waste-input-output model (Nakamura and Kondo 2002; Nakamura and colleagues 2007); and approaches that combine detailed process descriptions with economy-wide IO models. The latter include hybrid LCA (de Haes and colleagues 2004; Suh 2004b; Strømman 2009), mixed unit I/O analysis (Hawkins and colleagues 2007), hybrid supply and
use tables and the IO models built upon them (Schmidt and colleagues 2010, 2012), and the hybrid I/O approach (Nakamura and colleagues 2008).

The models listed above differ in how they cover different physical and economic aspects of socioeconomic metabolism, countries or regions included, development over time, resolution of technical and natural processes, boundaries between man-made and natural environment, causal relationships between elements in the system, and model drivers. Moreover, the different models are maintained and developed by often separate scientific communities, which may lead to a lack of overview and transparency across fields. A sound comparison and systematization of the different approaches is needed to help users to understand and select the appropriate model or combination of models that is ‘fit for purpose’ (Keirstead 2014).

The need for an explicit system structure

Common terminology and uniform structure of accounting frameworks and models may facilitate model understanding and comparison. They may also strengthen the connections between separated research communities. In the first part of this paper (Pauliuk and colleagues 2014) we develop a general terminology of socioeconomic phenomena. We further argue that any system approach to describing socioeconomic metabolism can be structured as directed graph, which is an established concept in mathematics (Diestel 2012). The edges or arrows of the graph represent flows of objects and its vertices or nodes represent the processes in the system. A representation of the system structure of the different models as directed graphs would facilitate the comparison of different models. Such an overview is lacking, however.
Scope and research topics

- We show that, without loss of generality, system approaches of socioeconomic metabolism form bi-partite directed graphs, which is a special type of directed graph. We show that bipartite directed graphs and supply and use tables are equivalent representations of socioeconomic metabolism.

- We provide an overview of the system structure of MFA, LCA, I/O, Waste-I/O, IAM, and CGE models, and show that for each model, the system structure is a bi-partite directed graph or can be reshaped into one.

- We propose a general system structure of socioeconomic metabolism in form of a bipartite directed graph and show that it includes the structures of the different modeling families of industrial ecology and the economic equilibrium models as special cases.

- We derive a general, multi-layer accounting framework for socioeconomic metabolism and show that it is equivalent to the general system structure.

- We explain how the general system structure and the accounting framework can help to establish and use clear and unambiguous nomenclature and facilitate the comparison and combination of different model families.

Bipartite directed graphs and supply and use tables

Figure 1a shows a directed graph with five transformation nodes or industries $t_1...t_5$, one node $e$ representing the environment outside the system boundary, and six different objects (resources, commodities, etc) $c_1...c_6$. The black arrows represent the flows within the system and the grey arrows the input and output to the environment. The 3D-array (Figure 1a, right)
is an alternative representation of this system, in consists of a stack of six matrices for the
flows of $c_1..c_6$ from and to the processes $t_1..t_5$ and $e$. Both representations are equivalent: the
array can be constructed from the graph by arranging the flows in matrix form, and the graph
can be constructed from the array by considering the row index as origin node and the column
index as destination node of each flow in the table. The 3D-array that describes the system in
Figure 1a can be called ‘traceable inventory’ because each flow can be traced back to the
industrial node where it was generated (Majeau-Bettez and colleagues 2014).

In reality the inter-industry flows of a certain commodity shown in Figure 1a are not
independent of each other. Commodities are scarce and the products consumed by one node
cannot be used by another. Industries and end users can often choose between different
suppliers and negotiate prices. There is hence a need to include processes that allocate scarce
commodities and resources across consumers. These processes are called distribution nodes,
market activities (Ecoinvent Centre 2014), or commodity nodes (Loulou and colleagues
2005).
Figure 1: Directed graphs and bi-partite directed graphs lead to different accounting frameworks. 

A directed graph consisting of arrows representing commodity flows between processes (nodes) can be represented as 3D array (origin x destination x commodity type). A bi-partite directed graph of process nodes (transformation T) and market nodes (distribution D) can be represented as supply and use table. In each case the graph and the tabular representations are equivalent, because one can be constructed from the other and vice versa without loss of information. The vectors \( g \) and \( q \) denote the total throughput of transformation and distribution nodes, respectively. The input-output structure of the transformation nodes is the same in both systems a) and b), but both systems are not equivalent.

The presence of distribution activities for all commodity types leads to a system where there is no direct exchange between industries because they place their output and buy their requirements on the markets. There is one market for each commodity or resource. Markets do not transform commodities, which is why there is not direct exchange between markets for different commodities. Graphs with two disjoint sets of nodes and arrows that only link nodes from different sets are called bipartite directed graphs, (Diestel 2012), (Figure 1b). The information contained in the graph in Figure 1b can be displayed in tabular form by recording all flows from industries to markets in a transformation output table and all flows from...
markets to industries in a transformation input table where the row numbers represent the distribution nodes and the column numbers the transformation nodes. Vice versa, the graph can be constructed from these tables by considering each number in the transformation output table as a flow between an industry node represented by the column number and a market node represented by the row number (the same with opposite flow direction for the transformation input table). The tabular system representing the bipartite directed graph is called supply and use table (SUT); it is a common representation of national economies used in the system of national accounts that allows for the accounting of co- or joint production (Baumgärtner and colleagues 2001; UN 2008). Bipartite directed graphs and supply and use tables are equivalent representations of the system structure of a model describing socioeconomic metabolism.

The system structure of models describing society’s metabolism

Material flow analysis and material flow accounting

The system definition of an MFA model contains a directed graph, where the processes (typically drawn as boxes) represent the nodes, and the arrows represent the flows (Baccini and Bader 1996; Baccini and Brunner 2012; Fischer-Kowalski and colleagues 2011). Explicit markets were introduced into MFA by Müller and colleagues (2006), but their use is neither a requirement nor always necessary. The systems used in state-of-the-art material flow analysis comprise entire material cycles including production; use; disposal; recycling; and trade at all stages (Figure 2) (Mao and colleagues 2008; Brunner and Rechberger 2004; Müller and colleagues 2006; Pauliuk 2013; Liu and colleagues 2012).
Figure 2: Common system definition of material flow analysis. (Mao and colleagues 2008; Brunner and Rechberger 2004; Müller and colleagues 2006; Pauliuk 2013). The large boxes represent industries or transformation process and the small boxes represent markets. The flows entering and leaving the markets in vertical direction represent trade flows between different regions.

The standardized system definition of material flow accounting (Eurostat 2001; Fischer-Kowalski and colleagues 2011) is an aggregated version of the scheme in Figure 2, where the entire region studied is modeled as a single transformation activity.

System of National Accounts (SNA), System of Environmental-Economic Accounting (SEEA), and the FORWAST/CREEA system of SUTs

The system of national accounts (UN 2008) describes international standards for the accounting of the monetary aspects of socioeconomic metabolism in form of SUTs, and the SEEA (UN 2012) describes a compatible accounting framework for physical aspects of society’s metabolism and natural assets. Both frameworks record industry output in supply tables \( V \) and industry input in use tables \( U \). External input to industries is recorded as value added \( v \), and output to end users is called final demand \( y \). The SUT provided by the SNA can be recast into an equivalent bi-partite graph. Figure 3a shows a simplified representation of this graph using the notation used in MFA. Here, the left box represents the different industrial nodes and the right one the different market nodes.
Waste generation and the FORWAST and CREEA systems: To add resources, waste, or emissions to the SUT, different extensions of the system in Figure 3a have been proposed. Here we present the FORWAST and CREEA system, which not only includes the economic flows in the classical SUT, but also the use of natural resources $R$, emissions to the environment $B$, Waste generation $W_V$ and use $W_U$, imports $N_c(n)$ and exports $N_c(e)$, and stock changes in both industries ($\Delta S$) and markets ($S^*$) (Schmidt and colleagues 2010, 2012). All flows are recorded in a supply and use table and therefore, the system structure is a bipartite graph (Figure 3b). The flows in the SUT can be recorded in multiple units to represent monetary, mass, energy, or carbon aspects of the flows. When comparing system structures a) and b), we found that Schmidt and colleagues did not consider value added $v$, which is required to establish the monetary industry balance. It is therefore shown in brackets in Figure 2b.

Leontief, Ghosh, and waste I/O models

Leontief and Ghosh I/O models: SUTs are the main data source for I/O models. To create an I/O model from the supply and use tables $V$ and $U$ a 1:1 correspondence between industries and products needs to be established by introducing additional modeling assumptions, so-called constructs (Majeau-Bettez and colleagues 2014; Miller and Blair 2009). Irrespective of which construct is applied, the resulting I/O model can always be recast as symmetric SUT, where the supply table is the diagonalized output vector $\hat{x}$ and the use table is the inter-industry flow matrix $Z$. Even though the number of industries or products may change when applying a construct to the SUT, the system structure remains a bi-partite graph (Figure 3c). In the supplementary material we show that markets play an important role in Leontief I/O models: their balancing equation is identical with the Leontief primary model.
d) The waste-input-output model (WIO) (Nakamura and Kondo 2002) can be derived from a supply and use framework (Lenzen and Reynolds 2014). Its system structure is a bipartite directed graph (Figure 3d). The WIO model comprises primary industries and markets for main products, markets for different types of waste, and waste treatment activities. From Figure 3d we see that the waste treatment part of the WIO model is a mirror-inverted IO model with waste flowing into treatment activities. A detailed description of the system structure of the WIO model, including the definition of all system variables, is contained in section 2 of the supplementary material. The industries in the original WIO model are not balanced. We therefore introduced value added for primary industries \([v_i]\) and emissions to nature for waste treatment industries \([B_{ii}]\) to the system structure in Figure 3d.

In section 3 of the supplementary material we present and discuss the graphs behind the different approaches for dealing with waste in physical I/O models that have been proposed by Hubacek and Giljum (2003), Suh (2004a), Dietzenbacher (2005), Xu and Zhang (2009), and Dietzenbacher (2009). We show that making explicit the graphs that lie behind the different approaches can help to understand the differences between the approaches and select a correct accounting and model structure.
Figure 3: a) The system structure behind the supply and use table of the system of national accounts; b) The extended coverage of exchanges with the environment developed under the EU FORWAST and CREEA projects in form of hybrid SUTs (Schmidt and colleagues 2010, 2012); c) The system structure of Leontief and Ghosh I/O models; d) The system structure of the waste-input-output model (Nakamura and Kondo 2002). Parts a) and b) show the system structure of accounting frameworks, and parts c) and d) the system structure of I/O-models. The variables are explained in the text.
Life cycle assessment

Explicit system definitions in form of directed graphs are part of good practice in LCA (EU JRC 2010) but there is no standardized system structure for LCA. There are structural similarities between LCA and IOA, however, including the application of supply-and-use tables and Leontief I/O models in both fields (Suh and colleagues 2010; de Haes and colleagues 2004; Suh and colleagues 2004; Stromman and colleagues 2009). Even though markets are often not explicitly modeled in LCA, the application of I/O models in LCA implies their presence because of the bipartite property of the system structure of I/O models. Markets connect the different industrial activities in the supply chain of a product. In EcoInvent 3, markets are activities that “do not transform inputs, but simply transfer the intermediate output of one or more transforming activities to the activities that consume this intermediate exchange as an input” (Ecoinvent Centre 2014).

Integrated assessment (IAM) and general equilibrium models (CGE)

IAMs combine models of socioeconomic metabolism with climate models (Pindyck 2013). To better understand the relation between the industrial ecology models and the way socioeconomic metabolism is modeled in IAMs we analyze the system structure of IAMs. Some documentations of IAMs explicitly mention the divide between industries and markets (‘commodity nodes’) in their systems, e.g., the MARKAL and TIMES model family (Loulou and colleagues 2005). This divide leads to a bipartite directed graph as system structure, which has long been recognized in the IAM community. Figure 6 shows a typical system drawing of socioeconomic metabolism in an IAM. IAMs also contain dynamic models of in-use stocks of capital and consumer goods as part of their description of socioeconomic metabolism (Loulou and colleagues 2005).
Figure 4: A bi-partite graph, consisting of technologies (process nodes, drawn as boxes) and markets (commodity nodes, drawn as vertical lines) represents the system structure of socioeconomic metabolism in integrated assessment models. After Loulou and colleagues (2005).

CGE models stem from the neoclassical economic tradition. Their system structure is given by a social accounting matrix (SAM), which is a matrix that describes the spending of each activity (column account) and the source of income to each activity (row account) (Burfisher 2011). Depending on the scope of the model, the agents include production activities (industries), households, or the government. The social accounting matrix is constructed from supply and use tables similar to the construction of I/O models, and, according to our comments on Figure 3c, the system structure of CGE models is therefore a bi-partite graph.

Table 1 summarizes our findings on the system structure and the coverage of different activity groups and extensions by the different model families. It shows that none of the different fields and accounting frameworks covers the entire socioeconomic metabolism on both the monetary and the physical layer. Several models used in industrial ecology have a bipartite system structure, but markets are implicit.
Table 1: Graph type (D: directed, B: bipartite), coverage of different activity groups, and inclusion of social and environmental extensions of the different accounting and model frameworks. Notes: I): implicit, part of system structure but not recognized as separate activity; a) aggregated together with main industries or markets; b) included in models with closure for labor or capital service; Color code: monetary layer: red; physical layer: blue; both layers: green.

<table>
<thead>
<tr>
<th>Graph type</th>
<th>Use phase</th>
<th>Product Industries</th>
<th>Waste treatment industries</th>
<th>Product markets</th>
<th>Waste markets</th>
<th>Factors</th>
<th>Emissions</th>
<th>Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>MF accounting</td>
<td>D,(B)</td>
<td>X (all merged into one activity)</td>
<td>---</td>
<td>---</td>
<td>(merged)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>MF analysis</td>
<td>D,(B)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>---</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>SNA+SEEA</td>
<td>B</td>
<td>X</td>
<td>X</td>
<td>X(^a)</td>
<td>X</td>
<td>---(^f)</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>FORWAST/CREEA IO</td>
<td>B</td>
<td>---</td>
<td>X</td>
<td>X(^f)</td>
<td>---(^a)</td>
<td>---</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>EE-IO</td>
<td>B</td>
<td>---</td>
<td>X</td>
<td>X(^a)</td>
<td>---(^a)</td>
<td>X(^b)</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>WIO</td>
<td>B</td>
<td>---</td>
<td>X</td>
<td>X(^f)</td>
<td>---(^a)</td>
<td>---</td>
<td>---</td>
<td>X</td>
</tr>
<tr>
<td>LCA</td>
<td>D,(B)</td>
<td>X</td>
<td>X</td>
<td>X(^f)</td>
<td>---(^a)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>IAM</td>
<td>B</td>
<td>X</td>
<td>---</td>
<td>X</td>
<td>---(^a)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>CGE</td>
<td>B</td>
<td>X</td>
<td>---(^a)</td>
<td>---(^f)</td>
<td>---(^a)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

The general system structure of socioeconomic metabolism

The different industrial ecology and economic models of socioeconomic metabolism share a common system structure, which can be presented as bipartite directed graph. (In models without bipartite structure markets can be introduced without loss of generality by re-routing each inter-industry flows through a commodity node.) The systems presented above cover several types of transformation activities: primary industries, waste treatment activities, and the use phase. They contain up to five categories of object flows, for which markets can be introduced: products, waste, natural resources, emissions, and man-made production factors or value added. The latter are called factor markets (Samuelson and Nordhaus 2005; Duchin 2009). We now propose a general system structure of socioeconomic metabolism as bipartite directed graph that contains all three types of transformation activities: the use phase, primary industries producing goods and services, and waste treatment industries; and markets for each of the five object flow categories: natural resources, goods or products, waste, emissions, and
man-made production factors. Each of the three transformation processes is connected to all five distribution activities.

All flows and stocks that are part of the general system structure are listed and explained in Table 2. Notation was chosen according to the common use in the system of national accounts, the waste input-output model, and the FORWAST/CREEA system of hybrid supply and use tables. Industries and use phase use natural resources ($R_l, R_k, R_w$) and emit flows to nature ($B_l, B_k, B_w$), and the use phase supplies capital service and labor, which is distributed to industries on the factor markets ($f, F_l, F_k$). Industries supply products and waste ($V, W_V$ for the primary industries and $G, V_k$ for the waste treatment processes) and consume products and waste ($U, W_U$, for the primary industries and $T, U_k$ for the waste treatment processes). The use phase consumes products and supplies end-of-life products to the waste markets ($Y_p, Y_w$).

Industries, markets, and the use phase contain stocks, which are to be interpreted as materials and supply or work in progress for industries, inventories for markets, and in-use stocks for the use phase, respectively. We consider industrial capital to be part of the use phase. This allocation of capital follows the traditions of the system of national accounts, where the gross fixed capital formation is part of final demand that leaves the industrial system, and MFA, where the use phase comprises all anthropogenic stocks. The system variables describe the social metabolism of one region, and several regions or countries can be considered by introducing trade flows between them ($N_p, E_p, N_w, E_w$), which connect the markets of different regions with each other.
Table 2: List of system variables and examples for the general system structure (Figure 5), the general accounting framework (Figure 6), and the balancing equations (1)-(6). Matrices are shown as capital letters, vectors as bold lowercase letters, and indices as subscripts.

### Indices

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number and index of products</td>
<td>$p$</td>
<td>Passenger cars, mobile phones</td>
</tr>
<tr>
<td>Number and index of waste types</td>
<td>$w$</td>
<td>Municipal solid waste, blast furnace slag</td>
</tr>
<tr>
<td>Number and index of primary industries</td>
<td>$I$</td>
<td>Electricity generation from hydropower</td>
</tr>
<tr>
<td>Number and index of waste treatment industries</td>
<td>$K$</td>
<td>Incinerators, secondary steel making</td>
</tr>
<tr>
<td>Number and index of factors, resources, and emissions, respectively</td>
<td>$f, r, b$</td>
<td>Value added, iron ore in ground, CO$_2$ to air,</td>
</tr>
<tr>
<td>Number and index of final use</td>
<td>$u$</td>
<td>Households, government, industries</td>
</tr>
<tr>
<td>Number and index of different regions</td>
<td>$m$</td>
<td>Countries, world regions</td>
</tr>
</tbody>
</table>

### System variables

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Size</th>
<th>Example</th>
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</thead>
<tbody>
<tr>
<td>Supply of products by primary industries (Supply table)</td>
<td>$V$</td>
<td>$p \cdot I$</td>
<td>Supply of wheat by agricultural sector</td>
</tr>
<tr>
<td>Use of products by primary industries (Use table)</td>
<td>$U$</td>
<td>$p \cdot I$</td>
<td>Use of electricity by car manufacturing sector</td>
</tr>
<tr>
<td>Treatment of waste type by waste treatment industry</td>
<td>$T$</td>
<td>$w \cdot K$</td>
<td>Amount of municipal solid waste sent to landfills</td>
</tr>
<tr>
<td>Generation of waste type by waste treatment industry</td>
<td>$G$</td>
<td>$w \cdot K$</td>
<td>Amount of slag generated by incinerators</td>
</tr>
<tr>
<td>Generation of waste type by primary industry</td>
<td>$W_v$</td>
<td>$w \cdot I$</td>
<td>Amount of fabrication scrap generated by car industry</td>
</tr>
<tr>
<td>Use of waste type by primary industry</td>
<td>$W_U$</td>
<td>$w \cdot I$</td>
<td>Use of old car tires in cement kilns</td>
</tr>
<tr>
<td>Use of products by waste treatment industry</td>
<td>$U_K$</td>
<td>$p \cdot K$</td>
<td>Use of electricity in car shredders</td>
</tr>
<tr>
<td>Supply of products by waste treatment industry</td>
<td>$V_K$</td>
<td>$p \cdot K$</td>
<td>Supply of electricity by incineration plants</td>
</tr>
<tr>
<td>Factor use by primary and waste treatment industries, and total</td>
<td>$F_I, F_K, F_u$</td>
<td>$f \cdot I, f \cdot K, f \cdot u$</td>
<td>Labor costs in incineration plant</td>
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<tr>
<td>Use of natural resources by primary and waste treatment industries, use phase, and total</td>
<td>$R_I, R_K, R_u$</td>
<td>$r \cdot I, r \cdot K, r \cdot u, r \cdot l$</td>
<td>Use of mineral resources, harvested biomass, or air</td>
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<tr>
<td>Emissions by primary and waste treatment industries, use phase, and total</td>
<td>$B_I, B_K, B_u$</td>
<td>$r \cdot I, r \cdot K, r \cdot u, r \cdot l$</td>
<td>Emissions of CO$_2$</td>
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<tr>
<td>Net stock additions on product and waste markets ($p,w$), primary and waste treatment industries ($I,K$), and the use phase ($u$)</td>
<td>$\Delta S_{x, y} = p, w, I, K, u$</td>
<td>$p \cdot I, w \cdot I, l \cdot I, l \cdot K, l \cdot u$</td>
<td>Build-up of inventories of primary aluminum on markets</td>
</tr>
<tr>
<td>Stocks on product and waste markets ($p,w$), primary and waste treatment industries ($I,K$), nature (N), and the use phase ($u$)</td>
<td>$S_{x, y} = p, w, I, K, N, u$</td>
<td>Not specified</td>
<td>Inventories of primary aluminum on markets</td>
</tr>
<tr>
<td>Final demand for products</td>
<td>$Y_p$</td>
<td>$p \cdot u$</td>
<td>Final demand for passenger cars</td>
</tr>
<tr>
<td>Supply of post-consumer waste</td>
<td>$Y_u$</td>
<td>$w \cdot u$</td>
<td>EOL-cars sent to shredders</td>
</tr>
<tr>
<td>Imports of products and waste</td>
<td>$N_p, N_w$</td>
<td>$p \cdot m, w \cdot m$</td>
<td>Import of passenger vehicles or obsolete electronic equipment</td>
</tr>
<tr>
<td>Exports of products and waste</td>
<td>$E_p, E_w$</td>
<td>$p \cdot m, w \cdot m$</td>
<td>Export of passenger vehicles or obsolete electronic equipment</td>
</tr>
<tr>
<td>Industry throughput, primary and waste treatment, use phase throughput</td>
<td>$g_I, g_K, g_u$</td>
<td>$I \cdot l, K \cdot l, u$</td>
<td>Total throughput through passenger car manufacturing, Total throughput through incinerator</td>
</tr>
<tr>
<td>Market throughput, products and waste</td>
<td>$q_p, q_u$</td>
<td>$p \cdot l, w \cdot l$</td>
<td>Total turnover of passenger cars or municipal solid waste</td>
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</tbody>
</table>
We now arrange the eight activities to a bipartite directed graph (Figure 5). The so-obtained general system definition is the simplest representation of socioeconomic metabolism as bipartite graph that contains the use phase and two groups of industrial activities, one for converting natural resources into useful products and one for treating waste and end-of-life products, and that exchanges objects with nature in both directions. This dichotomy of industries reflects that any economic activity leads to wanted and unwanted output (Baumgärtner and colleagues 2001).

The scheme in Figure 5 defines which activities are studied and how they are connected. It does not represent a fully specified system definition or even a model, however, because this would require specific choices of the boundary between nature and anthroposphere, on spatial and temporal boundaries including the accounting period, the asset and production boundaries (UN 2008), the classification of products and activities studied, the layers or units that are quantified, and a set of model equations.
Figure 5: The general system structure of socioeconomic metabolism. Each of the boxes with a solid line represents a group of activities, and the number of activities depends on the classification depth. The flows represent vectors such as the total emissions $b$, or matrices such as the supply table $V$. The system structure is a bipartite directed graph: Each flow connects a dark grey transformation process with a light grey distribution process.

<heading level 2> The relation between the general system structure and the accounting frameworks and model families of socioeconomic metabolism

The following statements were obtained by comparing Figures 2-4 and Table 1 with Figure 5. The MFA system in Figure 2 is compatible with the general system structure: the waste treatment processes in Figure 2 have been moved to the left side of the use phase. Trade
between regions at all stages is considered as well. The general system structure is more comprehensive, however: while typical MFA systems contain only a few industries of interest, the general system contains all industries and all variables necessary for a complete physical and economic description of socioeconomic metabolism.

The system structures of the standard SUT and the Leontief I/O model (Figure 3a and 3c) are covered by the general system structure. The use phase including capital stocks is usually not included in this model class. Non-product flows including waste, resource use, and emissions can be appended by adding impact flows or ‘environmental stressors’ per unit of monetary output. This is common practice in environmentally extended IO analysis (Leontief 1970, 1972; Miller and Blair 2009).

The FORWAST/CREEA system includes a balanced physical representation of all industries. The use phase is not included. In the description of the CREEA SUT, waste treatment and recycling activities are not treated separately from the primary industries, but they are disaggregated from the SNA data and treated as separate entities in the implementation of the framework (Schmidt and colleagues 2012).

The WIO system comprises all flows of the industrial metabolism (all processes covered by the system in Figure 3d) except man-made factors and emissions. Waste treatment processes are kept separate from the primary industries. The use phase and the markets for factors, natural resources, and emissions, are not included.

Life cycle inventories of product systems include a description of the flows occurring in production, use, and disposal of the products studied, and after including market transactions, the generalized version of a life cycle inventory matches the general system structure in Figure 5. In-use stocks are often not modeled explicitly, which is not necessary if only one
product is studied. Similar to MFA systems, LCA systems contain problem-specific subsystems of socioeconomic metabolism.

The general system structure of IAMs shown in Figure 4 comprises industries and product markets as bipartite graph and is therefore included in the general system structure. The same applies to CGE models because they have the same system structure as the supply and use tables they are constructed from.

A generalized accounting framework of socioeconomic metabolism

Proper accounting of socioeconomic metabolism should precede modeling (Majeau-Bettez and colleagues 2014). Process balances are central to testing the validity of a dataset describing socioeconomic metabolism. Next to the monetary process balance, different physical balance can be imposed for energy, total mass, or mass of carbon. We define the throughput for primary industries $g_I$, product markets $q_p$, waste treatment industries $g_K$, waste markets $q_w$, and the use phase $g_u$. For a balanced system, the sum of all inputs, the sum of all outputs and the throughput equal for each activity. Stock changes are included and treated as if they were outputs (Figure 5). For each activity, we arrange the input and output flows as supply and use table (Figure 6), which consists of a transformation process use table and a transformation process supply table. Summing up all rows yields the industry throughput, and summing up all columns gives the market throughput. The general SUT in Figure 6 extends the classical monetary SUTs (European Commission 2008), by adding resources, waste, and emissions. If the system is quantified for different units, e.g., mass and monetary value, the SUT can have multiple layers (not shown in Figure 6) and different industry and market balances can be checked at the same time. The general multi-layer SUT was developed from the hybrid SUTs used for the FORWAST and CREEA projects (Schmidt and colleagues...
2010, 2012). We added the use phase as transformation process, separated waste treatment activities from the main industries, and included post-consumer waste.

**Figure 6.** The general accounting framework (supply and use tables) of socioeconomic metabolism.

This framework was developed from the FORWAST hybrid SUT (Schmidt and colleagues 2010, 2012). The general accounting framework, the general system structure in Figure 5, and the balancing equations (1)-(6), are equivalent representations of the general bipartite system with three transformation activities (column account) and five market activities (row accounts). Note that none of the matrices in the system is square in general. All symbols are introduced in Table 2.

**The balancing equations of socioeconomic metabolism**

Equations (1-3) represent the balance for the five distribution process groups: product markets (1), waste markets (2), and the three markets for factors, resources, and emissions (3). In all equations, \( i \) stands for a summation vector of ones with the length \( x \).

\[
U \cdot i_t + U_K \cdot i_K + Y_p \cdot i_u + E_p \cdot i_m + \Delta S_p = q_p = V \cdot i_t + V_K \cdot i_K + N_p \cdot i_m \quad (1)
\]

\[
W_U \cdot i_t + T \cdot i_K + E_w \cdot i_m + \Delta S_w = q_w = W_v \cdot i_t + G \cdot i_K + Y_w \cdot i_u + N_w \cdot i_m \quad (2)
\]

\[
F_i \cdot i_t + F_K \cdot i_K = f \\
R_i \cdot i_t + R_K \cdot i_K + R_u \cdot i_u = r \\
B_i \cdot i_t + B_K \cdot i_K + B_u \cdot i_u = b 
\quad (3)
\]
The second group of equations represents the balance of the two transformation process groups: primary industries (4), waste treatment industries (5), and the use phase (6). Equations (4-6) can only be established when a common unit is used across the entire supply and use table, for example mass or monetary value.

\[ i_p^T \cdot U + i_w^T \cdot W_0 + i_f^T \cdot F_I + i_r^T \cdot R_I = g_I = i_p^T \cdot V + i_w^T \cdot W_I + i_b^T \cdot B_I + \Delta S_I \]  (4)

\[ i_p^T \cdot U_K + i_w^T \cdot T + i_f^T \cdot F_K + i_r^T \cdot R_K = g_K = i_p^T \cdot V_K + i_w^T \cdot G + i_b^T \cdot B_K + \Delta S_K \]  (5)

\[ i_p^T \cdot Y_p + i_r^T \cdot R_u = g_u = i_w^T \cdot Y_w + i_b^T \cdot B_u + \Delta S_u \]  (6)

Note that equations 1 to 6 are vector equations. Equation 1, for example, contains \( p \) equations, one for each product group.

The balancing equations (1-6) can be read from the general system structure in Figure 5 and from the general SUT in Figure 6. Vice versa, the general system structure and the general SUT can be constructed from the balancing equations: Writing the balancing equations in tabular form leads to the SUT, and interpreting each equation as balance of a process will, after re-arrangement, lead to the general system definition of socioeconomic metabolism (Figure 5).

The general system structure and the general SUT are different representations of the balancing equations of the activities (1-6). All three representations are equivalent. This equivalence facilitates the understanding, construction, and comparison of different models as practitioners can choose between graphical system definitions, supply and use tables, and the balancing equations without losing information.
How can the concepts developed here be used in future work?

Working with different model families

Accounting of and modeling socioeconomic metabolism is becoming more comprehensive as physical and economic aspects are quantified in parallel and with different levels of resolution. Comparing the structure of different accounting frameworks and models allows practitioners to better understand the connections and similarities between them. A graphical representation of the system structure reveals the function of the different process groups and makes implicit processes explicit. This process facilitates understanding and it helps practitioners to choose between or combine different accounting frameworks and models. This may prove especially helpful when working across fields that follow a different accounting and modeling tradition, e.g., MFA and IAM models.

Use of clear nomenclature

The graphical representation of the system structure reveals how the different flows in the accounting frameworks and models are connected to each other. It allows modelers to clarify the meaning of terms by referring back to the system structure. This is helpful for the development and use of clear terminology, and we provide two examples:

1) In bipartite systems, supply and use are relative, and one should use more specific terms, e.g., "industry supply" for the traditional supply table to avoid confusion with "market supply".

2) Balancing equations should be named after the processes they apply to and which unit they are in: ‘market balance in monetary units’, ‘industry balance for total mass’, etc. Terms like
‘material balance’ for the market balance in monetary units or ‘financial balance’ for the
industry balance in monetary units as used by Jansen and ten Raa (1990) may lead to
confusion since these terms do not refer to a specific choice of units as the names suggest, but
to specific processes (markets and industries).

<heading level 2> Specification of accounting rules

For models that include waste, by-products, or emissions (joint production), it is important to
distinguish between industry throughput and usable output when defining technical
coefficients. When stocks or inventories are present, it matters whether additions to stock are
accounted for at the input or the output side of a process, and both methods will lead to
different accounting frameworks. In bipartite graphs and SUTs, there are two ways of
accounting for inventories: they can be placed in industries and on markets. Both ways of
locating inventories are possible and they can be used in parallel, thus allowing for a more
complete description of industrial metabolism than a single method could do (cf. sections S1-3 and S1-4 of the SI)

<heading level 2> SUTs and the general database of socioeconomic metabolism

Bipartite graphs contain both industrial and market activities. We therefore believe that they
are better suited as common foundation for integrating the different modeling families and for
interdisciplinary research on socioeconomic metabolism than directed graphs. Industries are
commonly studied by engineers and economists, and markets by economists, psychologists,
and sociologists. Moreover, a directed graph with traceable industry-industry transactions can
always be transformed into a bipartite graph by adding auxiliary market nodes that interrupt
each inter-industry flow. These auxiliary markets for individual flows can be further
aggregated to commodity markets.
A general database of socioeconomic metabolism, as described in part I, should distinguish between relational properties of the object flows and intrinsic properties of the objects so that practitioners are able to track commodity flows from suppliers to consumers (relational properties) and to consider markets of specific commodity groups (defined by intrinsic properties). This feature would combine the traceability of inter-industry flows and the more convenient bipartite system structure with industries and markets. Traceability is important for modeling footprints and supply chains, and market modeling is needed when modeling price formation and scarcity.

Accounting sociometabolic phenomena in SUTs is a first major step that allows for balanced accounting of joint production on any number of layers using a bipartite system structure. The use of SUTs like the one shown in Figure 6 allows for integrating industrial ecology concepts into any form of environmental-economic accounting and it would facilitate data exchange between different fields. Establishing SUTs as common accounting framework would require a change of common practice in MFA and LCA, though SUTs have been implemented in the latest version of EcoInvent (Swiss Centre for LCIs 2014).

Conclusion

The graph approach to socioeconomic metabolism helps to clarify a number of seemingly unrelated issues from a system structure perspective in a clear and intuitive manner. This includes the role of the implicit markets in I/O models; the distinction of useful process output and process throughput in accounting frameworks; and the identification of two complementary ways of accounting for inventory changes, which resolves the conflict between the SNA and FORWAST accounting frameworks.
The equivalence of process balancing equations, system structure, and SUT may prove useful to strengthen the modeling community of industrial ecology, because it allows practitioners to reduce misconception and pathologic modeling by choosing the tool they feel most comfortable with.

The common system structure paves the way for integrating industrial ecology concepts in more mainstream economic modeling. Vice versa, it enables IE practitioners to apply more explicit and realistic modeling of markets, especially for large scale models.

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