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TRACING SUBSTANCES IN THE TECHNOSPHERE AND PRODUCTS

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Abstract

Material Flow Analysis (MFA) refers to several specific tools designed to trace the use of different materials and resources from micro- to macro scale. MFA tools also incorporate the different aspects and possibilities of tracing substances. Applicability and international state of the art of Substance Flow Analysis (SFA) and applicability of Life Cycle Inventories (LCI) are discussed in this paper. The article highlights the links between SFA and LCI, focusing on how the different substances or substance groups are traced at different levels of the socio-economic metabolism.

Keywords: Substance Flow Analysis (SFA), Life Cycle Assessment (LCA), Life Cycle Inventory (LCI)

1. Different Levels of Material Flow Analysis

The concept of Material Flow Analysis (MFA) refers to a number of methodologies (MFA tools) which can be used to provide information on industrial metabolism. Industrial metabolism is the way materials and energy are utilized by the economy, transforming them as inputs to products or services, and other outputs such as waste and emissions to the environment. MFA refers also to accounts in physical units (usually in terms of kilograms, as mass is the basic physical unit to characterize materials, and kilograms or metric tons are the measurement units for mass) comprizing the extraction, production, transformation, consumption, recycling, and disposal of materials, in the categories or notions of substances, raw materials, base materials, process flows, manufactured products, process residues and wastes, emissions to air, water and soil. MFA can be carried out at different levels, ranging from international, national and regional macro-scales, down to the community or company level micro-scales[1]. MFA-based analyses include approaches such as substance flow analysis, product flow accounts, material balancing, life cycle inventories and bulk material flow accounts for example. MFA tools are widely used in addressing different environmental problems.

[1]See the related article *Tracing material flows on industrial sites* by Kálmán KÓSI and András TORMA in the current issue of Periodica Polytechnica.

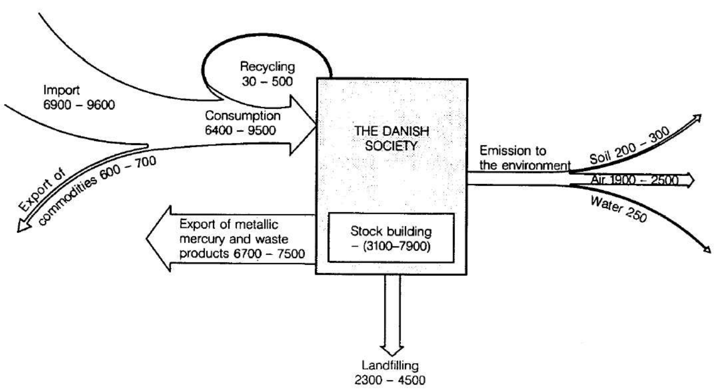
2. Tracing Substances by Substance Flow Analysis

After the recognition of environmental problems, and with the progress in environmental protection since the 1990s, SFA studies were first applied to trace and control the flow of hazardous substances. In general, SFA is applied for tracing the flow of a selected chemical (substance or group of substances) – e.g., heavy metals (mercury, lead, etc.), nitrogen, phosphorous, persistent organic substances, such as PCBs, etc. – through a defined system (e.g. society).

Most progressive research and methodology development is spearheaded by a limited number of research groups in a handful of countries in Europe. Austria, Denmark, Germany, the Netherlands, Norway, Sweden, and Switzerland are among the countries that are considered to be the most advanced in the field of SFA applications (BRINGEZU [2] and OECD [11]). Substances covered by the studies conducted in the above listed countries (HERCZEG et. al., [5]) are summarized in *Table 1*.

SFA has been used to determine the main entrance routes of different substances to the environment, the processes associated with these emissions, the stocks and flows within the industrial system, and the resulting concentrations in the environment.

Fig. 2 shows the results of a SFA performed for mercury in Denmark. The objective of the study was to describe developments in the use of mercury, as well as establishing the baseline consumption level prior to the enforcement of legislative restrictions on the use of mercury. The study covered a full analysis of the flow of mercury in the Danish society, including identification of applications and quantification of consumption, losses to relevant waste fractions, and emissions to the environment (air, water, soil) for each field of application (FEMIA and MOLL [4]).



(Source: MAAG et al. 1997 in FEMIA and MOLL [4])

Fig. 1. SFA for mercury (Hg), Denmark 1992/93 (all figures in kg per year)

Table 1. Summary on substances studied by SFAs in selected countries

Country	Substances and/or group of substances investigated
Austria	• SFA studies exist for the chemical industry on: fibre, fertilizer and plastic industry. • PCB, zinc (Zn), Silver (Ag) in wastewater in the city of Vienna. Lead (Pb), Nitrogen (N) and biotic carbon (C) balance of Vienna.
Denmark	• metals and heavy metals: aluminium (Al), arsenic (As), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni), tin (Sn) • organic substances: azo colorants, AMPA, brominated flame retardants, CFCs, HCFCs, HFCs, chloroparaffins, chlorophenols, dichlorofemethane, dioxins, orghanotin, flurocyclobutane, fluoroethane, fluorohexane, fluoropropane, formaldehyd, methylbromide, nonylphenols and nonylphenolethoxylates, PCB/PTB, phthalates, sulfphur-hexafluoride, tetrachloroethylene, trichloroethylene
Germany	• endocrine disrupting industrial chemicals: Bisphenol A; Dibutylphathalat, Benzylbutylphathalat; Nonylphenol, Alkylphenolethoxylate, • heavy metals: lead Pb, copper Cu, cadmium (Cd), aluminium (Al), • nutrients: nitrogen (N), phosphorus (P), potassium (Na), • chlorine (Cl) and PVC.
The Netherlands	• heavy metals: copper (Cu), zinc (Zn), lead (Pb), chromium (Cr), mercury (Hg), cadmium (Cd), nickel (Ni) • nutrients: nitrogen (N) and phosphor (P), • chlorinated compounds and plastics (PVC).
Norway	• heavy metals: chromium (Cr), arsenic (As), copper (Cu), lead (Pb), nickel (Ni), zinc (Zn), • tin organic substances and • organic compounds: Tetra chloroethene, Chlorophenols, Carbon tetrachloride, Trichloroethene, Absorbing substances, Dioxins, Nonylphenol and nonylphenoletoxylates, brominated flame retardants, phtalates and chloroparaffins, Short chained chlorinated paraffins, Brominated flame retardants, Biocides and biocidal products, Muskxylenes, perflouroalkylsulfonates (PFAS). • Few chemicals with endocrine effects, Hazardous substances in toner powder for laser printers and copying machines, PCB in building materials: grouting, concrete admixture, floor covering and paint/marine coating, chemicals used in development and management of transport works, endocrine disrupters in cleaning and car maintenance products, paints and varnishes.
Sweden	• heavy metals (cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni), zinc (Zn) and antimony (Sb), • organic substances (polybrominated diphenyl ether (PBDE), polycyclic aromatic hydrocarbons (PAH), alkylphenolethoxylate (APA), Di(2-ethylhexyl) phthalate (DEHP) and perfluorooctane sulfonate (PFOS) (currently ongoing study for Stockholm 2005–2007)
Switzerland	• heavy metals: cadmium (Cd) • organic compounds: vinylchlorid, halogenated solvents, dioxins and furans, polybrominated flame retardants, chlorinated paraffins. • other compounds: nitrogen (N), metallic/non-metallic substances in waste electronics.

Source: HERCZEG et. al., [5]

As it can be seen from the figure, SFA is tracing the substance pathway through the economic and natural systems by revealing information on the *origin of a certain* *harmful substance*, its *applications* in the economic system, and *where it ends up*. Substances may cause a problem *(e.g. adverse human health impacts)*, when they are released to the environment e.g., through emissions or wastes.

A SFA identifies these entry points and quantifies how much of and where the selected substance is released. Policy measures may address these entry points e.g., by end-of-pipe technologies. The general aim of SFA is to identify the most effective intervention points for pollution prevention policies. SFA aims to answer the following questions according to Femia and Moll (FEMIA and MOLL [4]):

- Where and how much of substance *X* is flowing through a given system?
- How much of substance *X* is flowing to wastes?
- Where do flows of a substance *X* end up?
- How much of substance *X* is stored in durable goods?
- Where are potentials to utilize substance *X* more efficiently in technical processes?
- Where are options for substituting the harmful substance?
- Where do substances end up once they are released into the natural environment?

The impact of substance-specific findings is not restricted to government policy but includes industry itself, especially when related to certain products.

The strength of SFA is that it provides systematic, physical, quantitative information to design substance management strategies, in order to keep under control a certain harmful substance. SFA may reveal potentials to utilize substances more efficiently in technical processes and may help to identify options for substituting the harmful substance. However, the application of SFA is limited, because the substance needs to be identified as being relevant (i.e., it is not a tool to prioritize substances), and has no consideration of 'hidden flows' associated with foreign trade (FEMIA and MOLL [4]).

Although, there is no formally standardized methodology accepted so far, SFA methodologies established by academia are available. In general SFA studies comprise the following three-step procedure according to van der VOET *et alia*, (OECD [11]).

(1) *Definition of the System*

The system must be defined with regard to space (e.g. a city, province or country), function, time and materials. If necessary, the system can be divided into subsystems. To define the SFA system, choices must be made with regard to spatial demarcation, functional demarcation, time horizon, and materials to be studied.

(2) *Quantification of the Overview of Stocks and Flows*

The various categories of related processes, stocks and flows (of the studied substance) belonging to the system must be specified.

(3) *Interpretation of the Results*

Finally, these result in a flow chart: the specification of the 'network of nodes' as illustrated in *Fig. 2*. This is an elegant method to visualize the often complex processes, tracing mass/volume of the substances in question.

When an SFA is to be carried out it involves the identification and collection of data on one hand, and modelling on the other. Three models are applied in the SFA studies: accounting, static modelling and dynamic modelling (OECD [11]).

(1) *Accounting (or Bookkeeping)*

is the first way to 'model' the system. The input for such a system are the data that can be obtained from trade and production statistics, and, if necessary, further detailed data to be recovered on the content of the specific substances in those recorded goods and materials. Emissions and environmental fluxes or concentration monitoring can be used for assessing the environmental flows. The accounting overview may also serve as an identification system for missing or inaccurate data. Missing amounts can be estimated by applying the mass balance principle. In this way, inflows and outflows are balanced for every node, as well as for the system as a whole, unless accumulation within the system can be proven. This technique is most commonly used in material flow studies, and can be viewed as a form of descriptive statistics. There are, however, some examples of case studies that specifically address societal stocks, and use these as an indicator for possible environmental problems in the future (OECD [11]).

(2) *Static Modelling*

is the process when the network of flow nodes is translated into a mathematical 'language', actually a set of linear equations which are describing the flows and accumulations as dependents on each other. Emission factors and distribution factors over the various outputs for the economic processes, and partition coefficients for the environmental compartments, can be used as variables in the equations. A limited amount of substance flow accounting data is also required for a solving of the set of linear equations, but the modelling outcome is determined largely by the substance distribution pattern. Static modelling can be extended by including a so-called *origin-analysis* in which the origins of one specific problematic flow can be traced at several levels. Three levels may be distinguished:

- direct causes, derived directly from the nodes balance (for example, one of the direct causes of cadmium load in soil is atmospheric deposition);
- the economic sectors, or environmental policy target groups, directly responsible for the problem, identified by following the path back from node to node to the point of emission (for example, waste incineration is one of the economic sectors responsible for the cadmium load in soil);
- ultimate origins, found by following the path back to the system boundaries (for example, the extraction, transport, processing and trade of zinc ore is one of the ultimate origins of the cadmium load in soil).

Furthermore the effectiveness of abatement measures can be assessed with static modelling by recording timelines on substances (OECD [11]).

(3) *Dynamic Modelling*

is different from the static SFA model as it includes substance stocks accumulated in society, as well, in various materials and products in the households and across the built environment.

Stocks play an important role in SFA in the prediction of future emissions and waste flows of products with a long life span. For example, in the case of societal stocks of PVC, policy-makers need to be supplied with information about future PVC outflows, as today's stocks become tomorrow's emissions and waste flows. Studies have been carried out on the analysis of accumulated stocks of metals and other persistent toxics in the societal system. Such build-ups can serve as an 'early warning' signal for future emissions and their potential effects, since one day these stocks may become obsolete and recognizably dangerous – as has happened with asbestos, CFCs, PCBs and mercury in chlor-alkali cells. As the stocks get discarded, they end up as waste, emissions, factors of risks to environment and population. In some cases, this delay between inflow and outflow can be very long indeed. Stocks of products no longer in use, but not discarded yet, are also important: old radios, computers and/or other electronic equipments stored in basements or attics, out-of-use pipes still in the soils, old stocks of chemicals no longer produced but still stored, sometimes in large quantities, such as lead paints and pesticides. These 'hibernated stocks' are estimated by OECD [11] to be likely very large. To estimate future emissions, which is a crucial issue if environmental policy-makers are to anticipate problems and take timely, effective action, such stocks cannot be ignored. Therefore, when using MFA or SFA models for forecasting, the stocks should play a vital part. Flows and stocks interact with each other; stocks grow when the inflows exceed the outflows of a (sub)system, and certain outflows of a (sub)system, are disproportional to the stocks. For this dynamic model, additional information is needed with regard to the time dimension of the variables: the life span of applications in the economy, the half life of compounds, the retention time in environmental compartments and so forth. Calculations can be made not only on the 'intrinsic' effectiveness of packages of measures, but also on their anticipated effects in a specific year in the future, and on the time it takes for such measures to become effective. A dynamic model is therefore the most suitable for scenario analysis, provided that the required data are available or can be estimated with adequate accuracy (OECD [11]).

3. Tracing Substances in Products by Life Cycle Inventory

Life Cycle Assessment (LCA) is to assess environmental aspects and potential impacts of products, processes and services during the whole life cycle. This type of assessment is often referred to as 'cradle to cradle' approach, as it covers extraction and process of raw materials, production, transport and distribution, use, reuse, recovery and disposal of products. The aim of LCA is to determine impacts of various products to the environment.

In order to assess the above aspects, the material and energy streams of the life cycle stages must be identified. This procedure requires having all these streams accounted via a bottom-up approach, creating a material (and energy) balance for every stages of the life cycle in the form of a Life Cycle Inventory (LCI).

As parts of the international ISO 14000 series, ISO 14040–14043 standards aim to describe the methodology, providing a framework for LCA studies.

According to the mentioned ISO standards, a complete LCA is carried out in four stages (*Fig. 2*): Goal and scope definition, inventory analysis, impact assessment, and interpretation.

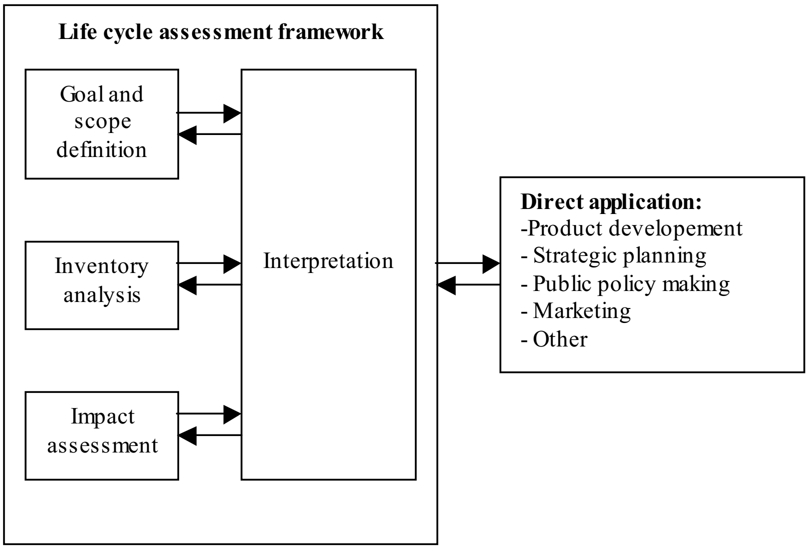
Goal and scope definition: The first step of the LCA is to define the goal and scope of the study and setting up functions of the product, functional unit and reference flows. Furthermore system boundaries must be drawn in a way, which ensures that inputs and outputs at its boundary are elementary flows. (ISO 14041 [14])

Inventory analysis (LCI): Inventory includes all the flows crossing the system boundary during the life cycle stages, recording the quantity of material and energy inputs and outputs. (ISO 14041 [14])

Impact assessment (LCIA): Impact assessment is to condense and explain the LCI results, while carrying out an assessment considering environmental aspects. (ISO 14042 [15])

Interpretation: The final stage is to check the *results of LCI and of LCIA*, examine and interpret the results according to the goals and scope defined earlier. This stage includes addressing significant aspects, evaluation (and control) of results and drawing conclusions and proper decision-making in accordance with the goal and scope definition) (ISO 14043 [16])

Applications of LCA: LCA results may be applied at both macro- and micro levels. As the assessment provides possibilities to compare inputs and outputs



Source: ISO 14040, [13]

Fig. 2. Phases of a complete LCA

of alternative products, processes or services, LCA approach can serve as a framework in environmental policy for developing new instruments, directives or tools, such as:

- indirect, economic instruments: subsidies, taxes and refund systems;
- development and implementation of management techniques (e.g. eco-labelling).

As a design tool, LCA is applied at micro level to develop and improve products. In the long term, this helps in environmental risk management, can facilitate product management contributing to improved competitiveness.

Practice shows a broad variability in LCAs: often a single stage of the life cycle or only one significant process is being studied. Studies are often terminated at the LCI or LCIA stage. The reason is that carrying out a complete LCA has a very high resource, data and time demand and requires sound expertise. Therefore, in practice only a simplified LCA is carried out.

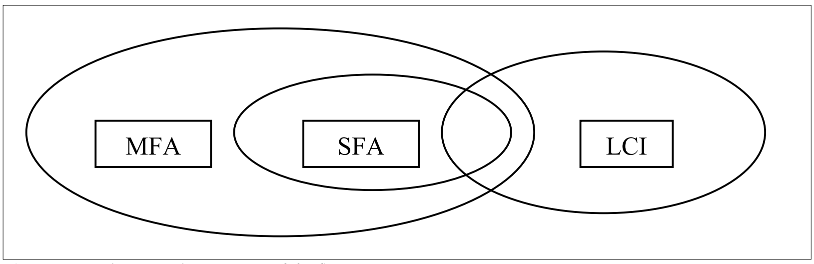
LCI is not simply the direct physical link to SFA, but also the most crucial stage of the LCA. Generally, LCI is the most widely applied result of the assessment.

Life Cycle Inventories are based on appropriate data collection and calculation procedure. Collecting data is a complex and precise task. Quality and reliability of the data, which may be measured, calculated or estimated is a critical point of the assessment: lack of sound data may lead to absolutely misleading results.

LCI analyses unit process, so drawing of specific process flow diagrams that outline all unit process that will be modelled, including interrelationships. Description of each unit process and the listing of data categories associated with each unit process, description of data collection techniques and data calculation techniques for each data categories are given then. (ISO 14041 [14]) Therefore, assembling a complete LCI, appropriate data are required for all processes of the life cycle stages.

4. Physical Links between SFA and LCI

As discussed in the above sections, SFA and LCI studies provide information with different aspects on how substances are streaming in the socio-economic metabolic processes. The aim of our present article is to demonstrate the physical links between these two different MFA tools. *Fig. 3* is representing the relation of different MFA tools including SFA and product specific Life Cycle Inventories (LCI).



(Source: Helias et. al., 1997, modified)

Fig. 3. Relation of SFA to MFA and LCI

The above illustrated relation is trivial: materials (*traced by MFAs*) including chemical substances (*traced by SFA*) are used in industrial processes and many of them are components of various products (*traced by LCI*) which are used by the socio-economic sub-system of the planet.

Fig. 4 demonstrates the physical links of material/substance flows. Three different levels are defined and linked on the figure:

- Macro level;
- Micro level;
- Material (substance) level.

Number of enterprises (micro level units): $\sum \; E\_1 - E\_1$
Material flows including input and output flows are analysed at all levels:
Input $\sum \; M\_i1 - M\_ij$
Output $\sum \; M\_o1 - M\_ik$
Material flows include the basic elementary flows and product flows as well.
Materials (including products) might contain several different compounds

(such as substances).
If the studied materials or products include compounds, then these compounds are to be analysed individually (*by SFA*). $\sum C\_1 - C\_m$
When the material is homogenous, it is built up of a single compound only (M_x). $\sum C\_1 - C\_m = 0$

Legends:

E:	Enterprises (micro level units)
M_i:	Material input flows (all levels)
M_o:	Material output flows (all levels)
C	Compound flows (e.g. substances)

Macro Level Material Flows

Macro level material flows may be accounced by Economy-Wide Material Flow Accounts (EW-MFA), National Account Matrixes Extended with Environmental Accounts (NAMEA) or by the System of Integrated Environmental and Economic Accounts (SEEA). SFA studies provide information on the flows of selected substances only: besides input and output substance flows and addition to stocks (*accumulation*).

Micro Level Material Flows

Micro level MFA tools include corporate material balances and input-output analysis: these mass balances are set up to describe a site or corporate level metabolism (usually for a time period of 1 year in practice) including all input and output material flows of the system. These site level Input-Output Analysis usually include energy balances as well.

As shown in *Fig. 4* when analysing an industrial site (E_1 for example) all material inputs ($\sum M\_i1 - M\_ij$) and outputs ($\sum M\_o1 - M\_ok$) are drawn up. Material flows are usually identified by defining processes (modules) of the site or factory determining individual flows of each module. This bottom-up approach then will enable us to compose the full material flow balance of the site. Relevant data may be gathered from the corporate accounting or controlling system for example. Corporate MFAs may also include individual substance flows at site level. Data on substances might be twofold:

- Unbound or free substance: when the material and the substance are the same in chemical terms: for example a site producing active carbon might have losses during the production processes, being emitted to the environment. An

SFA analysing carbon flow should include these losses in the overall mass balance, as the subject of the two different analysis are identical in *chemical* terms.

- Bounded substance: when a piece of data gathered from a corporate mass balance is set up for a compound which is not a single substance, but may include a substance subject to an SFA. Keeping the above example, the same site may apply the carbon activation process using natural gas for heating. Among the output flows carbon dioxide (CO_2) will appear as a result of burning. In this case carbon is not being emitted on the site in form of pure carbon (C), but it is included in the substance subject to the SFA.

Material Processes

Mass or material balance can be interpreted for products, too. In broader sense, product balances are the LCIs set up according to the life cycle approach. LCI includes all data on material and energy inputs and outputs of a product during its life cycle. Though, the balance may be set up only for a stage of the life cycle, e.g. for the *use* of the product.

Product level MFAs include not only input and output flows, but accumulation in the products (or *the product* itself). These flows in *Fig. 4* are input ($\sum M\_i1 - M\_ij$) and output ($\sum M\_o1 - M\_ok$) flows, and compounds ($\sum C\_1 - C\_m$) of the material (or product). Obviously, flows of substances include the flows in different stages of the product life cycle as well.

5. Physical Links between SFA and LCI Applications: an Example on Germany

The following example on Germany is to illustrate the physical links and relationship discussed in the previous section. Our example is based on the results of the substance balance from SFAs of selected metals (copper) in the German economy, and the LCI of a car (VW Golf A4 model) manufactured in Germany. Latter includes some of the metals studied by the SFA study as well. The substance we selected to demonstrate the physical link is copper (Cu), a widely used metal.

Available studies show, that SFA (among several additional, such as policy aspects) provided several product, trade and consumption related information as well. Examples for these aspects are e.g. PCB, lead and zinc studies in Austria and the Netherlands, studies on silver in Vienna or SFAs on PCB, CFS, metals and heavy metals in Denmark (HERCZEG et. al [5]). These applicability issues proved, that SFA studies:

- can help identifying the products in which the substance is present;
- can identify the overall amount of the substance used;

- can help tracing the consumption and emission resulting from the presence of the substance as a trace element or contaminant in fossil fuels, wood, cement etc;
- can help identifying emissions and losses to air, soil wastewater, solid waste, and hazardous waste from manufacturing processes and use of finished goods, by use areas;
- can help understanding the use of the group of substance;
- can provide information on the application and consumption of finished goods by use areas;
- can help trace substance import and production;
- can help carrying out a detailed analysis of the international market and trends in consumption;
- can provide information on international market and trends in consumption at an overall level (used as background information);
- can provide information on production, import/export, and processing of raw materials and semi-manufactured goods.

A research (ERDMANN et. al [3]) project carried out by the German Institute for Futures Studies and Technology Assessment investigates options and instruments to support a sustainable usage of non-renewable scarce resources with a focus on copper (Cu) and lead (Pb) based on data from 1999. Compared to other mass metals these are outstandingly scarce. However, the average input rates of secondary copper and lead in total production achieve only about 55% in Germany.

The research report includes the substance flow summaries for two selected metals and mass flow diagrams that display usage patterns, value chains and interfaces between main actors.

Fig. 5 above demonstrates the substance flow nodes drawn up after the SFA carried out for copper (Cu) use in Germany: by tracing lead flows through the technosphere in Germany, the network of nodes clarifies, that 1.705.000 tons of copper products (with 90–96% copper content) are being produced. This includes 125.000 tons used for can manufacturing.

The nodes include four main categories: primary supply, process, use (including stocks) and recycling and waste management. In *Fig. 5*, spatial and quality changes can be traced by following the network of nodes.

Spatial changes include streams within the system boundary (Germany) as well as exports and imports (which are the streams through the system boundary).

Quality changes include the changes where copper turns to be ‘visible’ in the system: being used or processed by physical and/or chemical means and which products contain copper.

This way, the copper flow analysis also makes it visible, that automotive industry (incl. car manufacturing, water and railway transport equipments) uses 3.099 tons of copper (BAW [1]; data from 1999).

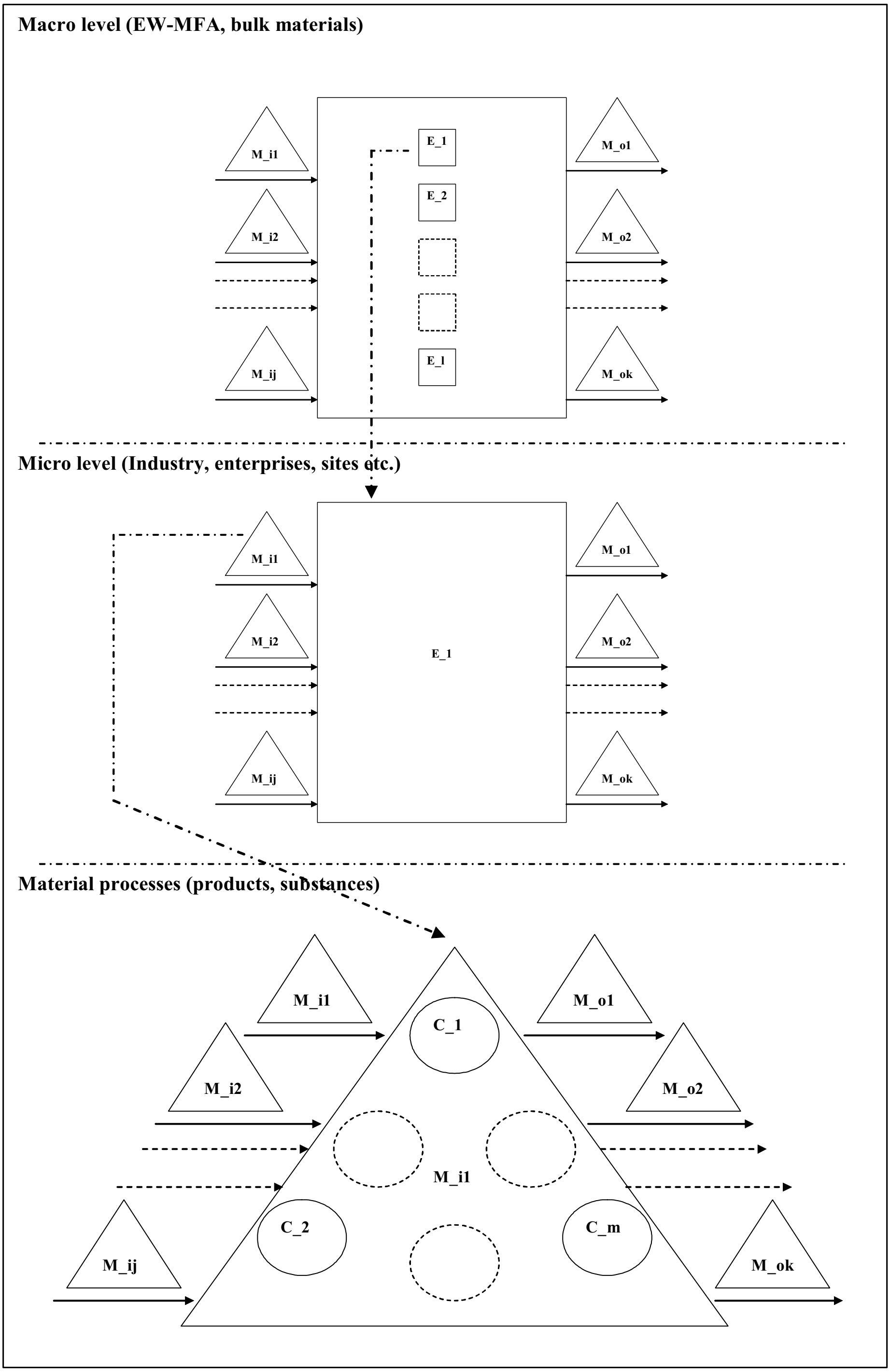
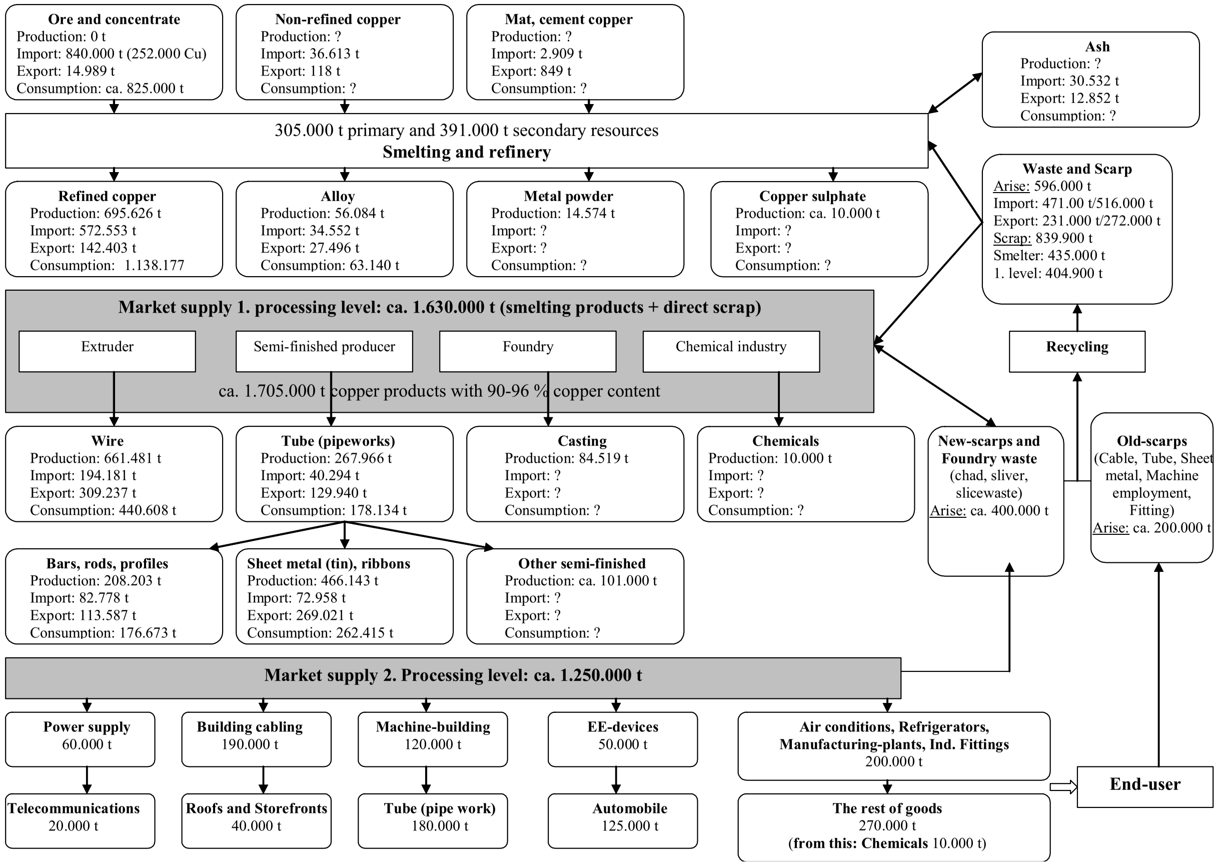


Fig. 4. Material flows between different levels of industrial metabolism

Table 2. Life Cycle Inventory (LCI) – including Copper (Cu) – of the VW Golf A4 model

Primary resources Ore	Production materials+ car	Production gas + oil	Use car	Energy source	Production materials+ car	Production gas + oil	Use car
Bauxite 21% Al [kg]	25			Primary energy [GJ]	86	34	325
Lead ore [kg]	740			Quota from			
Chrome [kg]	6			Brown-coal [GJ]	4	2	1
Iron [kg]	1476			Coal [GJ]	27	9	5
Copper [kg]	**78**			Natural gas [GJ]	29	21	317
Nickel [kg]	2			Crude oil (rock oil) [GJ]	15	1	1
Platinum ore [kg]	2000			Nuclear energy [GJ]	9		
Zinc [kg]	(740+5)			Hydro power [GJ]	2		
Limestone [kg]	666						
Rock-salt [kg]	100		7				
Water [m^3]	57	23	15				
Emissions into the air							
CO_2 [tn]	4	2	23	H_2SO_4 [g]	1.2		
CO [kg]	23	1	16	HCl [g]	154	65	4
Non-Methan VOC [kg]	6	94	7	HF [g]	39	9	2
CH_4 [kg]	17	0.3	3	H_2S [g]	4	0.1	0.3
NO_x [kg]	9	12	3	C_6H_6 [g]	4	1	470
N_2O [kg]	0.3		6	PAH [g]	0.6		2
NH_3 [kg]			0.9	**Cu [g]**	**3**		**0.9**
SO_2 [kg]	15	12	3	Mn [g]	2		
Particle/dust [kg]	8	2	0.6	Heavy metals [g]	15		2
Emissions into the water							
AOX [g]	4	0.1	0.6	Na^+ [g]	26	5	260
COD [g]	800	93	290	Fe [g]	6	80	1
BOD [g]	120	16	42	**Cu [g]**	**0.1**	**0.8**	**2**
TOC [g]	440	50	110	Zn [g]	2		2
Total N [g]	18	0.1	5	Heavy metals [g]	22	1	9
Phenols [g]	1	1	0.6	HC [g]	110	700	250
Cl^- [g]	1200	29	63	Oils [g]	9		
PO_4^{3-} [g]	6	2	1.4	PAH [g]	0.6	8	
SO_4^{2-} [g]	850	720	22				
Emissions into the soil							
Ash [kg]	21	10	3	Cr-slag [kg]	105		
Liquid waste [kg]		0.5		**Cu-slag [kg]**	**25**		**1**
Solid waste [kg]	150	1	30	Ni-slag [kg]	12		
Tyre abrade [kg]			12	Paint sludge [kg]	3		
Communal waste [kg]	85		85	Ore deposits [tn]	8		
Special waste [kg]	5		11	Tailing [tn]	3		

AOX Absorbable Organic Halogens
BOD Biochemical Oxygen Demand
COD Chemical Oxygen Demand
TOC Total Organic Compounds
VOC Volatile Organic Compounds
Source G. W. SCHWEIMER et al [6]



Source: ERDMANN et. al. [3]

Fig. 5. Copper flow analyses in Germany

We note that average lifetime in use of copper in products is approximately 10–12 years. Use of copper in transport equipments has a very low emission level. So, after having copper built into parts of machines, they re-appear after 10–12 years as wastes without significant emissions while being used.

While the SFA traces the route of copper (Cu) streams through the German economy, we emphasize the physical link to a product using copper as a part of the product. The car manufacturer Volkswagen AG has carried out an LCA already for some of the products: studies on Golf A3, 3 Liter Lupo and SEAT Ibiza was followed by an LCA for Golf A4. The study covers only the LCI, as data non-availability caused a complete LCA impossible to be carried out.

The functional unit of the assessment is a 1999 model VW Golf A4, (4 doors sedan with 1.4 litre 55 kW Otto and 1.9 litre 66 kW Diesel engine with a 5 gear manual transmission).

System boundaries include the direct processes related to the production.

Table 2 includes the material used for the use and production of the model VW Golf A4.

Data on copper use are highlighted in *Table 2* below. The table accounts the following copper streams and the selected product life cycle stage:

- Input: Copper in ores: 78 kg
- Output: Emissions into the air: $\sum$ Cu = 3.9 g
  Emissions into the water: $\sum$ Cu = 2.9 g
  Emissions into the soil: $\sum$ Cu-slag = 26 kg

The team has used the Microsoft EXCEL 5.0, GABI 2.0 and TEAM 3.0. softwares to facilitate the analyses. Most of the data were available at the company (though not all in the most appropriate form) so only a few measures had to be made in order to satisfy data demand of the LCI. Finally, the inventory includes 900 materials and products, 500 basic processes and 58 plans.

- Data on accessory parts are based on mass calculations by C++ Programme;
- Data on use are based on measures and data of NEDC (New European Driving Cycle) and the '*Unregulated Exhaust Gas Components of Modern Diesel Passanger Cars*' (NEUMANN et. al [10]).

Examples on material use:

- Data on engine oil, brake oil and filters are based on the scheduled maintenance;
- Data on tyres (lifetime in kms) are based on the data from suppliers;
- Data on batteries (lifetime in years) are based on the data from suppliers;
- Data on car cosmetics (cleaning and painting materials lifetime) are based on car washing enterprises;
- Data on transmission parts manufacturing are factory data from Kassel;
- Data on energy are from the Wolfsburg site annual energy records;
- Data on wastewater and waste are from the Wolfsburg site monitoring data;

Summarizing the physical links demonstrated between the SFA and LCI (both identified as different MFA tools) the first example provided information on the flows of copper in the German economy (based on data from 1999), while the second example was to show how copper use was accounted in a car manufacturing procedure.

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