MICA
Minerals Intelligence Capacity Analysis

FACT SHEET

Material and Substance Flow Analysis (M/SFA)

Description of the method of Material and Substance Flow Analysis (M/SFA).

Scope (conceptual model & main characteristics)

Material Flow Analysis (MFA) is a group of methods analysing material flows in society with the aim to match the use of material resources and the release of wastes and pollutants with the capacity of the environment to provide these resources and to absorb the wastes and emissions. Within the MFA field, two variants can be distinguished that have a more specific scope and methodology: Economy-Wide Material Flow Accounting (EW-MFA), accounting for all material flows in national economies, and Material/Substance Flow Analysis (M/SFA), accounting or modelling the flows (and sometimes stocks) of individual materials, substances or groups of substances at different geographic scale levels. This factsheet will focus on Material/Substance Flow Analysis (M/SFA).

M/SFA analyses the flows and (sometimes) stocks of a material, substance (element or compound) or group of substances in, out and through a geographically bounded system. It systematically monitors or models the physical flows (in terms of mass units) of a material through the life cycle: extraction, production, fabrication, use, recycling, and final disposal. Flows (and sometimes stocks) through society or the economy are always included in the analysis. Flows (and sometimes stocks) in the environment are included in some cases, but often the analysis is limited to the economic system.

Older M/SFA studies have been conducted often with an environmental purpose. For a number of elements (individual heavy metals, nitrogen, phosphorus, carbon, chlorine compounds) and at different scale levels (national economies, groups of countries like the EU, continents, the world, but also regions and cities) (Bergbäck et al., 1997; van der Voet et al. (eds.), 2000). Such studies are still done, but recently the angle has shifted to materials supply, with a focus on metals and critical elements. The STAF project (Stocks and Flows project) of the Yale University (STAF, 2016) is an important research project in this area, which has generated many important publications (Graedel et al., 2004; Graedel et al., 2005; Yang et al., 2014; Johnson et al., 2005; Johnson et al., 2006; Wang et al., 2007; Reck et al., 2008; Reck et al., 2010; Eckelman et al., 2012; Mao et al., 2008; Nassar, 2013; Kavlak et al., 2013; Harper et al, 2012). Even more recent are the investigations of stocks in society, from the point of view of urban metabolism and urban mining (UNEP, 2010; Baccini & Brunner, 2012; Tanikawa et al., 2015; Krook & Baas, 2013).

The method is not standardized but some conventions are observed in the field. Brunner & Rechberger (2004) have developed a practical handbook of MFA, linked to the MFA software tool 'STAN' (see section 'operational tools').

Contexts of use, application fields	-> contexts (e.g., environmental, economic, social assessment) -> which types of stakeholder questions are concerned?

Types of applications:

M/SFA enables to spot the major flows and stocks, to signal future problems in an early stage, to trace the fate of inflows, to link specific pollution problems to their origins in society, and to assess the consequences of management changes. The main users of the M/SFA outcomes so far have been regional and national governments. It has been used for environmental statistics and to support resource and environmental policies. Since the 1980s M/SFA is used in a policy context in Austria, Denmark, Belgium, Sweden, the Netherlands, for example to monitor, analyze and forecast environmental problems related to those substances. Recently, the focus has been more on resource availability, specifically of critical materials. M/SFA is used to analyse global trade flows and to assess stocks of materials, mostly metals. These stocks are regarded as sources of (secondary) materials. The concept of urban mining is especially interesting from the point of view of moving towards a circular economy.

M/SFA can also be used at the company level, for example by industries or waste and sewage treatment plants, to identify the origin and fate of the throughput (bulk materials and/or substances). In the Netherlands and Germany M/SFA is used by farms to keep track of minerals (mineral bookkeeping).

M/SFA-studies exist in three types:

1. accounting
2. static/steady state modelling
3. dynamic modelling.

All three types have their own specific applications.

Substance Flow Accounts are used to quantify and monitor substance flows and stocks (e.g. van der Voet, 1996; Van der Voet et al., 2000; Pacyna, 2009; Müller et al., 2014; Graedle et al., 2004; Graedle et al., 2005; Yang et al., 2014; Johnson et al., 2005; Johnson et al., 2006; Wang et al., 2007; Reck et al., 2008; Reck et al., 2010; Eckelman et al., 2012; Mao et al., 2008; Nassar, 2103; Kavlak et al., 2013; Harper et al, 2012)

- to get a complete overview of flows of substances in a specific region
- to find out how different flows are dependent on each other
- to find problem flows, identifying leaks,
- to monitor problem flows, spotting trends
- early warning

Static Substance Flow Models are used to evaluate the effects of policy measures (e.g. van der Voet, 1996; Van der Voet et al., 2000)

- tracing of origins in society of critical flows in the environment
- comparing management options, including problem shifting within the system between sectors or environmental emission compartments

Dynamic Material/Substance Flow Models are used to model substance flows over time. The stocks have an essential place in this, as in many cases stock dynamics determine flows, rather than the other way around. Such dynamic M/SFA models can also be used for forecasting. By combining demand projections with stock saturation per metal application, it is possible to estimate future flows (e.g. Elshkaki, 2007; Elshkaki & Graedel, 2013; Müller et al, 2006; Müller et al, 2014). Combining those demand scenarios with supply scenarios allows to include environmental aspects and comment on potential future supply problems.

Type(s) of data or knowledge needed and their possible source(s)	-> which types of data are needed to run the method, from which sources could they come… -> could be qualitative data or quantitative data, and also tacit knowledge, hybrid, etc.

Type of data:

An M/SFA-study requires data on flows and/or stocks included in the region under study. Mostly such data are collected on a case-by-case basis, preferably from statistical sources but sometimes also from grey literature and with the help of the companies involved. Flows and stocks refer to all kinds of commodities that the material is used in. In addition, M/SFA needs information on the content of the substances in those commodities. This information is more difficult to obtain, as the information on product composition is not standardly available. Especially for substances applied in tiny amounts, studies have to rely on the sparse literature or own estimates.

M/SFAs are compiled using many different sets of data, like:

- Data on extraction of resources
- Production data of (intermediate) materials and final products
- Trade data: imports and exports of ores, intermediate materials and final products
- Emission data on substances to air, water and soil
- Materials and product specifications, especially material content
- Data about stocks of materials and products in society (amount, composition, age, lifetime, etc.)
- Expert knowledge about behavior of substances in the environment, like deposition, volatilization, leakage, run off etc., often part of distribution models

Several relevant databases that can be used for the compilation of M/SFAs:

- Production and trade statistics, e.g. Europroms (Eurostat, 2016)
- Air emission accounts, like National emission accounts of UNFCCC (UNFCCC, 2016), National emission accounts of EMEP (EMEP, 2016), National Air emission accounts, by activity from EUROSTAT (Eurostat, 2016)

Data on product composition may be found in LCA databases (see factsheet on LCA) and dedicated studies on material en product composition (e.g. Buchert et al., 2012)

Detailed data on extraction of resources may be found at USGS commodity statistics. (USGS, 2016)

Model used (if any, geological mathematical, heuristic…)	-> e.g., geological model for mapping -> e.g., mathematical model such as mass balancing, matrix inversion, can be stepwise such as agent -based models, dynamic including time or quasidynamic specifying time series… -> can also be a scenario

For the accounting variant, flows and stocks are quantified based on data of commodities and the content of the material involved. Mass-balance is applied to each economic or environmental (sub)system. The choice for balancing item then is an issue.

Static models are derived by translating the account into a set of transfer coefficients which are used to redistribute the inflows over outflows (or, in some cases, the outflow over the inflows). Matrix inversion can be used to solve the set of equations, as a MFA system can be regarded as a specific type of input output model.

Dynamic Substance flow modeling makes use of additional information on stocks in society. There are various ways to combine stock and flow information. Most dynamic models use the life span of the commodities as a delay function:

outflow(t) = inflow (t – L), L being the life span of the commodity.

In most cases this is combined with some life span distribution function to cover uncertainties.

System and/or parameters considered	-> **the system can be described by its boundaries.** These can refer to a geographic location, like a country, or a city, the time period involved, products, materials, processes etc. involved, like flows and stocks of copper, or the cradle-to-grave chain of a cell phone, or the car fleet, or the construction sector, or the whole economy… -> **parameters** could possibly refer to geographic co-ordinates, scale, commodities considered, genesis of ore deposits and others…

M/SFA analyses a geographically bounded system. Scale levels vary from the global level to the local level. Usually the system corresponds to administrative units such as countries, counties or municipalities. Sometimes other geographical systems are selected, such as river basins.

M/SFA follows a cradle-to-grave approach: all production and consumption processes within the region, connected with the substance (group), from the extraction of resources until the final disposal of waste are considered. The M/SFA sometimes includes the environment of the chosen region.

Within the economic system several subsystems might be defined, e.g. all sectors or industries within the geographical boundary of a country. M/SFA also includes flows between the economy and the environment, both extractions from the environment and emissions to the environment. Within the environmental system several subsystems might be defined, e.g. environmental compartments (air, surface water, groundwater, sea, sediment, agricultural soil, industrial soil etc.) within the geographical boundary of the system.

Time / Space / Resolution /Accuracy / Plausibility…	-> to which spatio-temporal domain it applies, with which resolution and/or accuracy (e.g., near future, EU 28, 1 year, country/regional/local level…) -> for foresight methods can also be plausibility,

	legitimacy and credibility…

M/SFA is specified in space and time. Usually flows are specified as kg / year, while stocks have the dimension kg at a specific moment in time. M/SFA accounting is used to observe trends and developments in the past by drafting accounts for a series of years. Static models represent the situation in one year, or an equilibrium situation in an undefined year in the future. Dynamic models can be used to forecast future flows and stocks in time series. A relatively new development concerns the monitoring or modelling of the development of specific stocks – both societal and environmental - over a more extended period of time, i.e., over decades or even centuries.

At the global level, M/SFA is used to specify international trade flows and to estimate global stocks (UNEP, 2010). Presently, scenarios are developed for several metals at the global level using dynamic M/SFA. The STAF project (STAF, 2016) focuses at the national and continental level, while attempting a global coverage. Within the EU the SOCOPSE project (Pacyna, 2009) can be mentioned, using M/SFA for river basin management plans throughout the EU. At a lower scale level, M/SFAs are performed for specific applications in a country to support material or resource policies, or it is used to specify stocks at city level to support urban mining and circular economy initiatives.

The level of detail and representativeness in terms of region and time will depend on the scope of the M/SFA case. There are no EU member states that perform M/SFAs for the total economy or parts of the economy on a regular basis, although many commission such studies occasionally.

Indicators / Outputs / Units	-> this refers to what the method is actually meant for. Units are an important part but that is most of the time not sufficient to express the meaning. For example, **the indicators used in LCA express the cradle-to-grave environmental impacts of a product or service**. This can be expressed in kg CO_2-equivalent. But also in €. Or in millipoints. Or in m^2year land use. -> for foresight methods the outputs are products or processes

All inflows and outflows of the (sub)systems in and between the economic system and environmental system can be used as indicators. Indicators for societal flows and stocks are relevant for early warning: inflows, accumulations, stocks. Other indicators refer to the management of the substances: resource efficiency, losses from the cycle, recycling rates. Indicators at the pressure level are the environmental interventions, i.e., the extractions and emissions. In M/SFA the flows can be followed further along the environmental cause-effect chain, thus linking the environmental interventions to some form of ERA (see ERA factsheet). Impact indicators can then refer to environmental concentrations and human intake. When a group of substances is considered, a translation is sometimes made to LCA impact categories (See factsheet on LCA). It is also possible to compare extraction flows with geological stocks, to comment on potential scarcity or criticality problems.

Additional indicators can be derived using and combining a selection of the flows, e.g. total of emissions per total input as an indicator for the closedness of the economic system etc.

The indicators are expressed in mass units per year. To make comparisons between countries possible indicators also can be expressed per capita (material intensity).

When combined with monetary flows related to the same system boundaries, the M/SFA indicators can be expressed as eco-intensity indicators expressing for example the emission or extraction (in kg) per value added (in euro).

Treatment of uncertainty, verification, validation	-> evaluation of the uncertainty related to this method, how it can be calculated/estimated

The scope of the M/SFA is quite narrow: only flows and stocks of a specific substance. While this can be used to support a resource policy, it must be clear at all times that the consequences of that policy will be much broader and won't show up in the M/SFA.

Because of the diverse nature of sources and the varying quality and availability of data, MFA results are inherently uncertain (e.g. uncertainties of concentrations of elements in ores, materials and products; interpretation of production and trade statistics; illegal trade, losses in industrial processes etc.). Uncertainty analyses have received increasing attention in recent MFA studies, but systematic approaches for selection of appropriate uncertainty tools are missing. Laner et al. (2014) reviews existing literature related to handling of uncertainty in MFA studies and evaluates current practice of uncertainty analysis in MFA. Based on this, recommendations for consideration of uncertainty in MFA are provided. In Patrício et al. (2015) a quantification of the uncertainty in nationwide, regional, and urban MFA methodologies is provided. Also the ASTER project (Systemic Analysis of Rare Earth Elements – flows and stocks) started in 2012 aims to take into account uncertainty analysis in MFA. (ASTER, 2016)

Additional uncertainties will pop up in the modelling applications, since process characteristics become very important. Whereas the steady state analysis has a robustness of its own - in the steady state situation, the outflows can be described solely as a function of the inflows – the dynamic type of analysis is rather sensitive to flow and process data errors. The instrument mostly used to assess the robustness of the outcomes is a sensitivity analysis.

Main publications / references	-> e.g. , ILCD handbook on LCA, standards (e.g. , ISO) -> can include reference to websites/pages

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Related methods	-> List of comparable methods, their particularities... (or a link to one or several other fact sheet(s))

Compatibility with other types of information:

M/SFA can be combined with risk assessment tools.

In dynamic M/SFA regression methods are used to forecasting demand projections and stock saturation of substances. The simplest way to estimate the future magnitude of any variable is to extrapolate from the situation in the recent past. For example the analysis of the historic demand for metals can be carried out using regression analysis, with per capita GDP, the level of urbanization, population, and time as explanatory variables.

M/SFA can also be combined with LCA to link the material flows to their (potential) environmental impacts (see separate factsheet on Life Cycle Assessment).

Substance flow accounts and economy wide – material flow accounts (EW-MFA) are different methodologies that belong to the same family of Material Flow Accounts. They both monitor material flows in physical units, mass (kg) of substances, raw materials, products, wastes and emissions related to economic activities in a geographical region, comprising extraction, production, consumption, waste disposal.

Some examples of operational tools (CAUTION, this list is not exhaustive)	-> e.g., software… Only give a listing and a reference (publication, website/page…) -> **should be provided only if ALL main actors are properly cited**

Software availability:

M/SFA accounts are often conducted with the help of general database and spreadsheet tools such as Excel and Access. For steady state and dynamic modelling, various research groups involved in M/SFA use their own models, often also based on spreadsheets. The only generally available MFA software tool is the STAN tool, developed by the Technical University in Vienna. STAN is software tool that can be used for both accounting and static modeling M/SFA. If used for accounting, users can enter known data in the model and missing data will be estimated on the basis of the mass-balance principle. In static modeling so-called transfer coefficients (TCs) are used to redistribute the inflows over outflows. See http://www.stan2web.net/ for more details.

Key relevant contacts	-> list of relevant **types** of organisations that could provide further expertise and help with the methods described above.

There is no institution for M/SFA studies. Such studies are conducted by a large number of research groups in all parts of the world.

Glossary of acronyms /abbreviations used	-> Definition