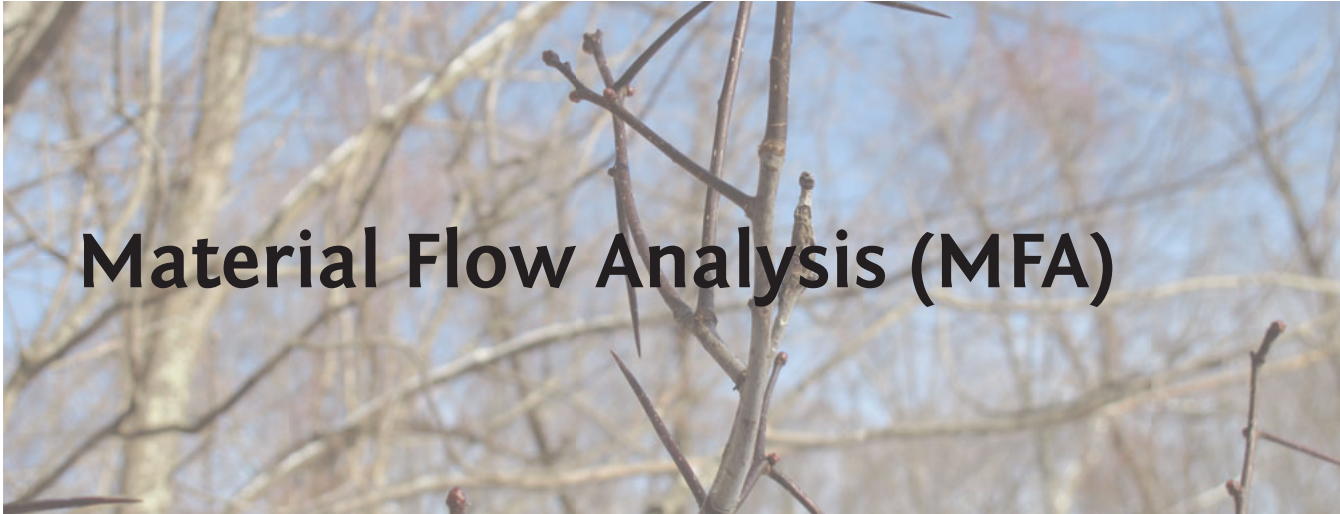




Material Flow Analysis (MFA)

Material flow analysis (MFA) is a method to describe and analyze the material and energy balance of a firm, a region, or a nation. It is based on the law of matter conservation and is defined by a geographic system boundary, a time span within which the analysis is performed, processes which depict human activities, and flows of goods, matter, or energy between these processes.

In the twenty-first century the material throughput of industrial societies (i.e., the amount of physical material moving through societies, and the energy expended to produce it) is not sustainable and cannot continue as such at a global level without causing severe damage to the life-sustaining functions of the ecosystem. Material flow analysis (MFA) is a method that provides an understanding of the underlying physical processes of the material and energy flows and supports the development of policies to minimize the key material and energy flows.

History

The origin of MFA can be traced to ancient Greece, where the law of conservation of matter (i.e., input into a process equals the output of the process) was first communicated more than two thousand years ago. The eighteenth-century chemical engineer Antoine Lavoisier was the first person to provide the experimental evidence for the conservation of matter in chemical processes. This knowledge was then applied in chemical engineering during the twentieth century.

Only in 1965 was MFA applied to larger systems such as cities. Since then MFA studies have been made at various scales, from businesses and firms to densely populated regions in developed countries, to entire nations. MFA has also been adapted to analyze environmental problems in developing countries and to trace pollutants through watersheds.

Methods

Two main types of MFA can be distinguished: economy-wide MFA (EMFA) and general MFA. EMFA studies the total material flows through a nation or a region. It provides an overview of all annual material inputs and outputs of an economy, including inputs from the national or regional environment, and outputs to the environment, as well as the physical amounts of imports and exports (Eurostat 2009). The accounting is made in physical units, usually tonnes per year. It includes “sectors” such as biomass, fossil fuels, construction materials, industrial materials and ores. A standardized methodology allows for historical and international comparisons.

General MFAs provide a more fine-tuned analysis categorized in terms of substances, materials, or goods through a firm, region, or nation. An analysis applied to a single material or substance is called a substance flow analysis (SFA) and uses the same key terms and components. The focus of an MFA thus involves optimizing the management of resources (e.g., wood or copper) within a country, region, or economic sector, or it involves reducing the flow of potentially harmful substances (e.g., heavy metals) to the environment. Thereby the pathways of the substances within the selected system are

analyzed as well as their chemical, physical, and biological transformations. Both MFA and SFA are similar in that they define spatial and temporal system boundaries and that they consider the principle of conservation of mass or matter.

Economy-Wide Material Flow Analysis

The standardized methodology provided by Eurostat (2009) gives detailed instructions on how the system is defined, how stocks and flows are calculated, and which indicators can be derived from the stocks and flows.

The main variables considered (see also Eurostat 2001; Eurostat 2009) include the inputs, factors within the economy, and outputs:

Inputs

- Imports: Traded and imported commodities from basic commodities to processed products in tons.
- Domestic extraction (DE): Annual amount of solid, liquid, and gaseous raw materials (excluding water and air) extracted from the natural environment within the system boundaries, and used as material factor inputs in production.
- Input balancing items: Water and air, which have to be considered for the material balance.

Within the Economy

- Net Additions to Stock (NAS): Physical growth of the economy. NAS includes the amount of new construction materials used in buildings and infrastructure; material included in existing durable goods such as cars, household appliances, and furniture; and materials incorporated into new durable goods. In principle, old materials are disposed of and enter the DPO (domestic processed output; see next item), while new materials are consumed and enter the stock. Another factor is residence time, the amount of time in which a material or product remains in the system.
- Domestic processed output (DPO): Measures the total mass of waste materials generated along the value-added chain, including resource extraction, processing, manufacturing use, and waste management. DPO includes emissions to air, water, and landfill.

Outputs

- Exports: Traded and exported commodities, from basic commodities to processed products in tons.
- Output balancing items: Water and CO₂, which have to be considered for the material balance.

The national material balance equation is then defined as follows:

$$\text{DE} + \text{Imports} + \text{Input Balancing Items} \\ = \text{Exports} + \text{DPO} + \text{Output Balancing Items} + \text{NAS}$$

From the above measured variables several indicators can be defined (see Eurostat 2009). Here only a few are mentioned:

- Domestic material consumption (DMC): DMC relates to the material inputs into a region/nation that remain there until they are released to the environment. DMC “measures the annual amount of raw materials extracted in a national economy, plus all physical imports minus all physical exports” (Eurostat 2009). DMC is defined in the same way as other key physical indicators such as total primary energy supply (TPES). That implies that the term “consumption” as used in DMC relates to “apparent consumption” and not to “final consumption.”
- Physical trade balance (PTB): PTB is calculated as physical imports minus physical exports. It is, thus, defined reverse to the monetary trade balance (which is exports minus imports), taking account of the fact that in economies money and goods move in opposite direction. A physical trade surplus indicates a net import of materials, whereas a physical trade deficit indicates a net export.

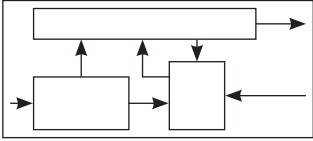
These indicators can be related to other indicators such as GDP (gross domestic product) and land area.

- Material intensity: The ratio of DMC to GDP.
- Area Intensity: The DE or DMC to total land area ratio. The ratio between material flows and total land area indicates the scale of the physical economy related to its natural environment.
- Domestic Resource Dependency (DE/DMC): The ratio of domestic extraction to domestic material consumption is an indicator for the dependence of the physical economy on domestic raw material supply (see Weisz et al. 2006).

MFA and SFA

Due to the diversity of questions that can be answered with MFA and SFA, no completely standardized methodology exists yet. The key terms and definitions for MFA, however, apply for almost any MFA or SFA performed. (See table 1 on the next page.) The balance time is usually one year, and the measured unit a physical mass unit.

TABLE 1. Key Terms Used in Material Flow Analysis

Key Terms	Definition	Graphical Representation	Mathematical Interpretation
Activity	Human actions to satisfy their needs (e.g., feeding, cleaning)		Functional subsystem of an MFA system
MFA system	Open system composed of processes and goods, through which material and energy flow		A specifically defined spatial and temporal unit in which the material and energy flows are measured
System boundary	Delimits the MFA system		Defines the MFA system geographically and within time
Process (stock)	Transport, transformation or depositing of elements and goods		Balance volume (a spatial unit which is balanced for a specific time period and for which mass conservation applies)
Good/Materials (flow)	Materials are used for activities valued by humans		Carrier of specific “matter”
Element	Chemical elements or compounds		Elements (i.e., components of materials)

Source: Adapted from Baccini and Bader (1996).

The key terms outlined for an MFA also apply to a substance flow analysis (SFA), which focuses on a single material or substance.

Furthermore, most researchers agree that an MFA consists of the following five iterative steps as proposed by Peter Baccini and Hans-Peter Bader (1996):

1. Definition of the system: In this step the system boundaries are set, that is the geographical space and the time span within which the analysis is performed are defined. Then the processes depicting the relevant transformation, transport and deposition processes within the system are defined, and the flows between the processes are identified. It is recommended that a graphical representation of the system is made. If stakeholders are included in a transdisciplinary process, they can be asked to validate the definition of the system.
2. Data collection or measurement: In this step the flows of goods/substances and the stock changes of processes are quantified. One common source is statistical data from government and multilateral agencies. Alternatively, specific flows of goods can be measured, for example with a household consumption survey (Binder et al. 2001). If environmental processes are included in the analysis, measurements within the environment might also be required, such as the concentration of elements in soil and water (van der Voet 1997).
3. Calculating the material or substance flows: In this step, based on the data obtained, the whole material flow system is calculated and, if possible, so are the critical flows validated through secondary calculations. As with the EMFA, the mass balance principle applies. That is: the output is equal to the input plus changes in stock.
4. For dynamic analyses the residence time in the stock has to be considered (Baccini and Bader 1996; Binder et al. 2001; 2004).
5. Representation and interpretation: In the final step the results are represented in a material flow diagram and interpreted with respect to the research question set in the beginning of the analysis. For the representation, open-source software STAN can be used (Tu Wien 2011). Alternatively, there are also some commercial software packages available, SIMBOX (EAWAG 2009) and GABI (PE International AG).

MFA and Life Cycle Assessment (LCA)

MFA and LCA are similar methodologies. Whereas MFA studies the material flows within a firm, region or nation, LCA studies the environmental impact of a

TABLE 2. Main Differences Between MFA and LCA

	MFA	LCA
Goal	Analyzes the flows of material and energy through a firm, region, or nation, and thus includes several products	Compares the environmental impact of different products through their whole lifespan
System boundary	Defined in geographic terms, and hence any materials and goods required for producing imported goods are not considered.	Defined through the functional unit as life span of a product, including the origin of its components. From cradle to grave.
Assessment	There is no specific assessment procedure included. Some authors favor the comparison of the anthropogenic flows to the geogenic flows. Others opt for comparing the change in material throughput over time.	LCA assesses the whole chain from the point of view of a functional unit. The process is divided into a LCI (life cycle inventory) without assessment and the assessment part. There are databases that support the assessment process (see ecoinvent 2012).

Source: author.

An MFA studies the material flows within a firm, region or nation, while an LCA studies the environmental impact of a specific product from cradle to grave.

specific product from cradle to grave. They differ in the goal setting, the system boundaries, and the assessment process. (See table 2 above.)

MFA and Sustainability

An MFA can contribute in different ways to a transition towards sustainability. First, it serves to identify the key flows originating from human activities and affecting the environmental issue at hand. It thus addresses the question: *how do different human activities affect the environmental problem to be solved?*

The answer to this question is a prerequisite for a development toward sustainability. If we do not understand which human activity contributes, and to what extent, to a certain environmental problem, we will not be able to develop sound measures that tackle the problem at its core. In particular, with respect to the following areas, MFA has been shown to provide significant inputs:

- **Consumption:** Researchers have shown that analyses of different activities regarding the consumption of resources such as water, energy, and materials provide specific knowledge on where the focus of sustainable measures to address overconsumption should be (Brunner and Baccini 1992; Daxbeck et al. 1997; Binder et al. 2004);
- **Pollution:** The key issue here is to identify the origin and to trace the pathway of pollutants through the whole system being analyzed. This is particularly

relevant when talking about water contamination, CO₂ emissions, and waste production (e.g., to trace pollutants through watersheds or urban regions). Another aspect to consider is the ratio between household and industrial pollution and regional assimilative capacity (Ayres et al. 1985; Lohm et al., 1994; van der Voet et al. 1994; Kleijn et al. 1994; Frosch et al. 1997);

- **Optimization of industrial processes:** Some authors have found that MFA allows for identifying the flows of energy and materials through all the industrial processes. The approach supports the analysis of trade-offs regarding the optimization of resources (e.g., energy, materials, water) and between resource optimization and economic optimization. Perhaps surprisingly, in most cases they found that both resource and economic improvements had been reached (Ayres 1978; Erkmann 2003; Henseler et al. 1995; Kytzia et al.);
- **Global element flows:** National and international flows of copper and zinc have recently been established. This provides the basis for planning against resource scarcity (Graedel et al. 2002; Gordon et al. 2003; Spartari et al. 2003).

A second way in which MFA contributes to a transition toward sustainability is as a precautionary tool. That is, MFA can be used to identify potential environmental problems before they escalate, which might occur if the current behavioral patterns continue or new ones are adopted, and to test potential measures to improve the situation. Hence

a dynamic modeling approach is of special interest. The following research questions are addressed: *What are the potential environmental problems emerging from current or envisioned patterns of material use? What is the potential of (technical) measures for improving the current situation?*

Examples for the application of dynamic models include development of the photovoltaic market, building management, and cascade flows of used goods. The dynamic behavior of material or substance flows in human-environment systems can be simulated using mathematical models. These approaches have been applied in diverse fields by a number of researchers. Claudia R. Binder (1996), in solo research and again with her colleagues (Binder et al. 2001) modeled the dynamics of material use for different scenarios of furniture consumption. Daniel Beat Mueller (1998) analyzed the dynamics of forest and wood management for the lowlands of Switzerland. Marcus Georg Real (1998) developed a method for evaluating metabolism in the large-scale introduction of renewable energy systems. C. Zeltner and colleagues (1999) modeled the dynamics of copper flows in the USA; René Kleijn and colleagues (2000) looked at delayed behavior of PVC in durables related to waste production; and Ester van der Voet and colleagues (2002) used this model to predict future emissions.

Finally, MFA can be used to monitor the development of the system. This is done by calculating the MFA on a yearly basis. The following two-part research question is addressed: *How is the development of the system with respect to sustainable standards? To what extent has it been improving?*

The answer to this question is one area of application for the economy-wide MFA (EMFA). In this context, the DMC calculated with the EMFA methodology is viewed as the “material GDP” of a country (Eurostat 2009) and allows comparing countries with respect to their material intensity (Direct Material Consumption/GDP). When the material intensity decreases, it is a sign of de-materialization, or of

shifting material-intensive activities to other economies, especially rapidly developing ones such as China. Another important application for this methodology is development over time. Thereby one is able to track the material changes within specific transitions, such as from agricultural societies to industrial society (Fischer-Kowalski and Haberl 2007).

Linking MFA to Other Approaches

A significant number of approaches can be linked to MFA. Most of them stem from economics, as the structures of analysis of MFA and economic methodologies, such as input-output analysis and general equilibrium models, are quite consistent with each other. (For a review see Binder 2007a.)

In addition, a few approaches have been developed which link stakeholders/actors behavior to material flow analysis and provide information on how the material flows can be steered in the social system (Binder 2007b; Lang et al. 2006). They have been applied to the area of waste management (Lang et al. 2006; Binder and Mosler 2007), regional management of wood flow (Binder et al. 2004), and phosphorous management (Lamprecht et al. 2011) among others.



MFA: Quo Vadis?

MFA is an excellent tool in sustainability research: it provides an overview over the physical characteristics of a system. As the processes can be related to human activities, the results of an MFA can be linked to economics as well as actor-oriented analyses. This makes the tool particularly interesting for combined modeling endeavors in which changes in human behavior can be analyzed with respect to their environmental impact. For policy makers this tool is of relevance as it provides a base for designing policies, it supports the monitoring process, it is

relatively easy to communicate, and it considers to a large extent the complexity of the system analyzed.

Claudia R. BINDER
University of Munich

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See also Agenda 21; Biological Indicators (*several articles*); Community and Stakeholder Input; Development Indicators; Ecosystem Health Indicators; Environmental Performance Index (EPI); Genuine Progress Indicator (GPI); Global Environment Outlook (GEO) Reports; Global Reporting Initiative (GRI); Human Appropriation of Net Primary Production (HANPP); $I = P \times A \times T$ Equation; Land-Use and Land-Cover Change; Life Cycle Assessment (LCA); Life Cycle Costing (LCC); Life Cycle Management (LCM); National Environmental Accounting; Regional Planning; Systems Thinking

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