Part II: Methods

Methodology1: Basics of industrial ecology data and accounting
IEooc_Methods1_Lecture1

Basic concepts, definitions, and methodology of material and energy flow analysis (MEFA)

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Content:

• Definition and basic methodology of MEFA

• Indicator elements

• Units of measurement

• Indicator definition

• Practical examples and MEFA software STAN
Definition of Material Flow Analysis (MFA)

The accounting of energy and material flows and stocks in SES represents the basis for quantitative systems analysis.

The established methods for this accounting are called material flow analysis (MFA), substance flow analysis (SFA), and energy flow analysis (EFA). All three methods follow the same principles but differ in their subject of study.

Material flow analysis (MFA) is the systematic assessment of the flows and stocks of materials within a system defined in space and time.

Brunner and Rechberger 2004

Throughout this course, we use the term MFA as umbrella for material and substance flow analysis.

**What is a material?**

In material flow analysis, *materials* comprise (chemical) substances and goods. ‘*Material*’ ist ein Sammelbegriff für (chemische) Substanzen und für Güter.

<table>
<thead>
<tr>
<th>Substances</th>
<th>Goods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Any chemical element or compound</td>
<td>Tangible items with potential economic value</td>
</tr>
<tr>
<td>Substances have a unique chemical constitution, are homogenous, and flow through both, the technosphere and the natural environment.</td>
<td>All human artifacts and products are goods. Substances turn into goods when regarded as commodities.</td>
</tr>
<tr>
<td><strong>Examples:</strong> Cd, C, Ag, CO₂, NH₃, Polypropylene, H₂O</td>
<td><strong>Examples:</strong> drinking water, plastics, TV sets, automobiles, garbage, sewage sludge, timber, CO₂ and ammonia (when traded as commodities)</td>
</tr>
</tbody>
</table>
Basic MEFA methodology. Or: How does MEFA work?

It’s very simple!

A MEFA includes an abstract representation of the system studied as collection of processes (with stocks). The processes are linked by flows, they are separated from the environment through the system boundary.
The basic elements of a system definition

System boundary: Chemical element x, country y, year z.

System boundary:
Shows what processes are part of the system studied. System needs to be specified in space and time.

Process: Element of a system were material or energy is transformed, stored, or distributed.

Stock: Storage of material, products, or energy. A stock is always associated with a process. It is measured at a given point of time t. 'snapshot'

Flow: Transport of material products, or energy across the system. A flow always connects two processes or one process with the environment. It is measured over an interval \([t_1,t_2]\).
System variables and parameters

System boundary: Chemical element x, country y, year z.

Stocks, stock changes, and flows together form the **system variables**.

**Stocks:** $S_1$, $S_3$.

**Stock changes (net addition to stock):** $\Delta S_1$, $\Delta S_3$.

**Flows:** $F_{01}$, $F_{12}$, $F_{20}$, $F_{23}$, $F_{31}$, $F_{30}$

A **parameter** is an additional variable that couples different system variables through equations:

For example:

$F_{23} = k \cdot F_{12}$

$\Delta S_1 = 0.15 \cdot F_{12}$

$\Delta S_3 = 0$
Example of a correctly defined MFA system, not quantified

System boundary: Cadmium, EU28, 2014

1. Mining
   \( S_1 \Delta S_1 \)

2. Production/Manufacture
   \( F_{0-2} \)
   \( F_{1-2} \)
   \( F_{4-2} \)

3. Use
   \( S_3 \Delta S_3 \)
   \( F_{2-3} \)

   \( F_{4-0} \)

5. Obsolete stock
   \( S_5 \Delta S_5 \)
   \( F_{3-4} \)
   \( F_{3-5} \)

Use ‘0’ if the flow enters or leaves the system!
Example of a correctly defined and quantified MFA system

For mass, energy, sometimes monetary values, the process and system-wide balance holds:

\[ \text{Input} - \text{Output} = \text{Net Stock Change} \]

Process 1: \( F_{01} + F_{31} - F_{12} = \Delta S_1 \)
Process 2: \( F_{12} - F_{23} - F_{20} = 0 \)
Process 3: \( F_{23} - F_{31} - F_{30} = \Delta S_3 \)
System: \( F_{01} - F_{20} - F_{30} = \Delta S_1 + \Delta S_3 \)

For a fully quantified system:

\#System variables = \#balance equations + \#parameters + \#Measurements
An alternative system representation: Sankey diagrams

A Sankey diagram is a special representation of a quantitative systems diagram. **Sankey diagrams** are flow diagrams, in which the width of the arrows is shown proportionally to the flow quantity. Processes (events) are usually shown as bars.

**Figure 1** Left: Sankey diagram with splitting of an energy flow. Source: Tafel 1924, figure 11. Right: Sankey diagram with fanning and relative data. Source: Gueldner 1913, figure 12.

Source: DOI: 10.1111/j.1530-9290.2008.00015.x
Examples of a Sankey diagram: Material Flow Analysis of steel

From Cullen et al. (2012). [http://dx.doi.org/10.1021/es302433p](http://dx.doi.org/10.1021/es302433p)
Common mistakes when defining MFA systems

Don’t!

- Branching of flows between processes 1, 2, and 3. Unclear which flow the symbol ‘B’ refers to.
- The stock at the right sight has no process it belongs to and no symbol/name.
- The stock change $\Delta S_3$ is missing.
- Regional scope is not displayed in the system definition
- There is no symbol/name for the flow from process 2 to the unnamed stock.

Do!


Working with indicator elements

Conducting and MFA for all goods, substances, and elements in a system is too much work and not necessary in most cases.

System can be sufficiently characterized by using selected chemical elements for which the mass balance holds in all processes.

Such elements are called indicator elements.

<table>
<thead>
<tr>
<th>Problem setting</th>
<th>Indicator element</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHG emissions/ climate change</td>
<td>C</td>
</tr>
<tr>
<td>Eutrophication/Überdüngung</td>
<td>P, N</td>
</tr>
<tr>
<td>Steel cycle</td>
<td>Fe, Ni</td>
</tr>
<tr>
<td>Dioxine and other VOCs</td>
<td>Cl</td>
</tr>
<tr>
<td>Heavy metal pollution</td>
<td>Pb, Cd</td>
</tr>
</tbody>
</table>
Units of measurement

Flows measure the amount of material moving between two processes during a certain time interval. They are commonly expressed as rates (amount per time).

Stocks measure the amount of material in a process at a given time.

Common units of measurement

<table>
<thead>
<tr>
<th>Quantities → System variable</th>
<th>Mass (of good, substance, or chem. element)</th>
<th>Energy</th>
<th>Quantity</th>
<th>Money</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flows</td>
<td>kg/yr, Mt/yr, Gt/yr</td>
<td>TJ/yr, EJ/yr</td>
<td>1/yr</td>
<td>€/yr</td>
</tr>
<tr>
<td>Stock changes (same as flows)</td>
<td>kg/yr, Mt/yr, Gt/yr</td>
<td>TJ/yr, EJ/yr</td>
<td>1/yr</td>
<td>€/yr</td>
</tr>
<tr>
<td>Stocks</td>
<td>kg, Mt, Gt</td>
<td>GJ, TJ, EJ</td>
<td>1</td>
<td>€</td>
</tr>
</tbody>
</table>

Units: All SI and related units are OK. Non-standard units (ha, barrels, ...) should be used with great care.

Note: Often, though, flows are reported not as rates but as amount-type variables. E.g., steel production Germany 2014: 43 Mt instead of 43 Mt/yr. This is not formally correct but tolerated. It may lead to trouble when making calculations, so beware!

http://physics.nist.gov/cuu/Units/units.html
Multi-layer system descriptions

Environment ↔

- Emissions layer
- Energy layer
- Materials layer
- Final products layer

Humans ↔

- Service layer

Source: PhD thesis Stefan Pauliuk
A major advantage of an explicit system definition is the clear definition of performance indicators.

**Efficiency** $\eta = \frac{\text{useful output}}{\text{total input}}$

Process 2: $\eta_2 = \frac{F_{20}}{F_{12}}$

Process 1: $\eta_1 = \frac{F_{12}}{F_{01}}$ OR $\eta_1 = \frac{F_{12}}{(F_{01} + F_{31})}$

System: $\eta_s = \frac{F_{20}}{F_{01}}$

**Emissions/waste intensity** $b = \frac{\text{waste}}{\text{useful output}}$ OR $\frac{\text{waste}}{\text{total input}}$
Exercise: IEOoc_Methods1_Exercise1

Defining and locating indicators in a system definition

Goal: Establish a system definition to allocate quantitative information that is given as text. Define and calculate indicators base on the system definition.
Examples. The standard MFA model of a material or product cycle

Source: PhD thesis Stefan Pauliuk
More examples of MFA systems

MFA can be applied to any material, on any spatial and temporal scale. MFA is the most general of the quantitative systems analysis methods.

- **City level**: Phosphorous, Beijing
- **Regional level**: Lead, Bunz Valley, Switzerland
- **National level**: Steel, China
- **Plant level**: Energy, paper mill
- **Global level**: Neodymium

Source: DOI: 10.1126/science.1217501 / DOI: 10.1021/es201904c / Brunner&Rechberger Ch. 3
Example: Country-Scale or economy-wide MFA: An entire national economy is modeled as one process

- **DMI** (Direct Material Input) = Domestic Extraction + Imports
- **TMR** (Total Material Requirement) = DMI + Domestic Hidden Flows + Foreign Hidden Flows
- **DPO** (Domestic Processed Output) = DMI – Net Additions to Stock – Exports
- **TDO** (Total Domestic Output) = DPO + Domestic Hidden Flows
- **NAS** (Net Addition to Stock) = DMI - DPO - Exports

Source: Matthews et al. 2000
Example: MFA for studying the circularity of an economic region

Source: DOI: 10.1111/jiec.12244
What distinguishes MFA from other quantitative systems approaches?

(1) The *entire system is quantified* for one or more materials.

(2) The *system quantification is valid for a certain time period* (measurement interval) and regional scope.

(3) *All processes within the system must be balanced*.

For comparison: Points (1) and (3) do not hold for an LCA.
The STAN Software for MFA

Available free of charge at http://www.stan2web.net/

- Draw system as Sankey diagram
- Check mass balance
- Reconcile data (estimate missing flows and adjust flow values to fit the mass balance)
- Share data on web repository
- Overview of MFA methodology and glossary of terms