Guideline on Material Flow Analysis (MFA).

IRT M2P – Gael FICK

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Presentation/objective of the guideline

The aim of this guide is to introduce companies to Material Flow Analysis (MFA) methodology. The methodology aims at assessing systematically flows and stocks of material(s) or substance(s) within a system defined in space and time.

First the methodology, its goals and some important vocabulary associated to the methodology will be presented. Some interesting examples of MFA use and applications at different levels will be introduced to show the potential of the methodology for companies.

Then, each individual step of the MFA process will be presented to describe how it can be implemented. Information on the practical implemention will be given, for outsourced MFA or for internal implementations.

Finally, further examples of the practical implementation of MFA will be given as well as possible use of MFA combined with other methodologies (such as LCA, cost benefit analysis).

Guidelines Material Flow Analysis – Table of contents

1. What is MFA?

What is Material flow Analysis ?

MFA is a systematic assessment of the flows and stocks of materials within a system defined in space and time.

It consists in quantifying and connecting the sources, pathways and sinks of one or several material over the defined system.

MFA results can be controlled easily by a simple material balance (law of conservation of matter)

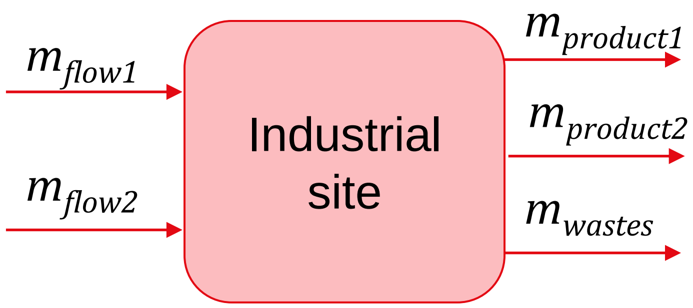
Brunner and Rechberger, 2004

1. What is MFA?
1.1 Definition

The law of conservation of matter enables two main modes of application to MFA studies:

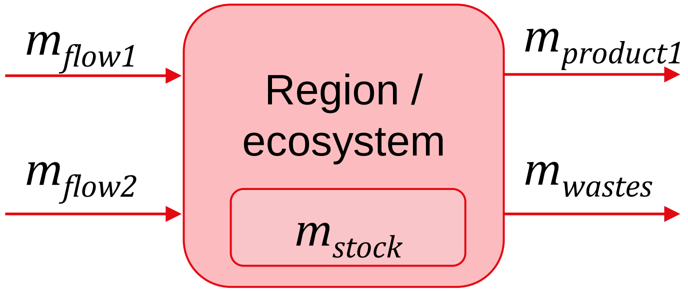
Control mechanism:

$$m_{flow1} + m_{flow2} \cong m_{product1} + m_{product2} + m_{wastes}$$



Quantification of unknown flow(s):

$$m_{stock} \cong m_{product1} + m_{wastes} - m_{flow1} - m_{flow2}$$



Vocabulary

System = set of material flows, stocks and processes within a defined boundary

Examples of systems:

- a production plant
- a geographical region
- a country

System boundaries = geographical and temporal

Matter = substances or goods

Substance = element (iron, aluminium, carbon) or molecule (CO2, H2O..)

Goods = substance or mixture of substances which have economic values (positive or negative)

Definitions from Practical Handbook of Material Flow Analysis – P.H. Brunner & H. Rechberger - 2004

Vocabulary

Process = transport, transformation or storage of materials (can be natural, man made or not)

Stock (unit of mass) = material reservoirs within the analysed system, can be constant, can increase (accumulation) or decrease (depletion)

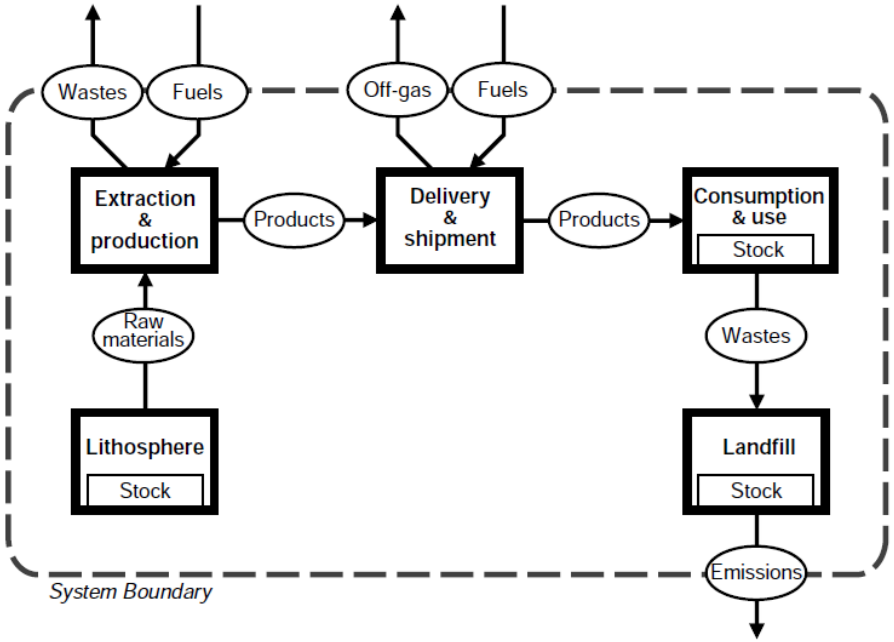
Processes are linked by **flows (unit of mass per unit of time)**

Material flows entering a process are named **inputs**, Material flows exiting are **outputs.**

Vocabulary

Activity = set of systems necessary to fulfil a particular need or perform a specific service

A AFM study can focus on a specific activity or on system regrouping several activities. For example, here is a system regrouping several activities to perform a specific service:



At product level

MFA can be used at product level to reduce its environmental impacts and material circularity via:

- Assessment of the overall material efficiency (amount of material used vs material in the final product)
- Identification and improvement of the main production phases responsible for material loss
- Evaluation of material dissipation stages (during use phase)
- Identification of possible utilisation of recycled material as raw material

At company level

MFA can be used at company level to improve material efficiency:

- Assessment of the overall material efficiency (amount of material used vs material in products)
- Help for resources and waste management
- Gather relevant data to set up industrial symbiosys with surrounding ecosystem/other companies

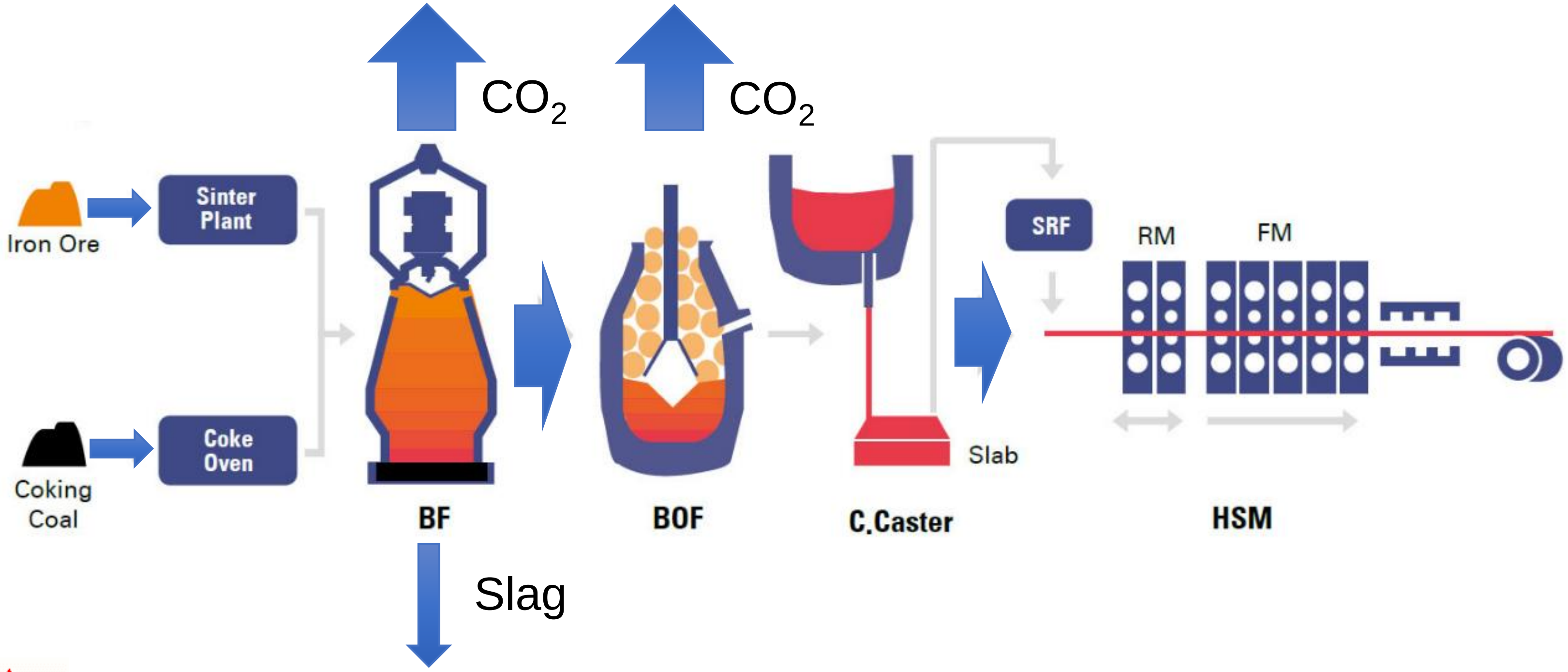
At regional level

MFA can be used at regional level to:

- Assess overall material balances (resources consumption and wastes production)
- Assess the pollution (and its evolution) of a specific region/geographical zone with toxic substances or elements by tracing the main inputs (emissions from industrial plants, transportation modes....) and outputs (evacuation through river flows, winds, absorbtion in biomass...)

At company level

- MFA helps focusing on major sources and flows to increase material efficiency and reduce costs
- MFA ensures transparent information when production volumes evolve (using mass balance)



Emission and waste quantities are linked to inputs/outputs by coefficients which can be verified

However, MFA is not sufficient for environmental management, other tools need to be used in order to change the process as efficiently as possible (for example LCA, Cost benefit analysis…)

Picture from: https://newsroom.posco.com/en/the-evolution-of-the-steel-production-process/

At regional level

Examples of MFA to identify and quantify the sources of pollutants (heavy metals) and their accumulation at regional level.

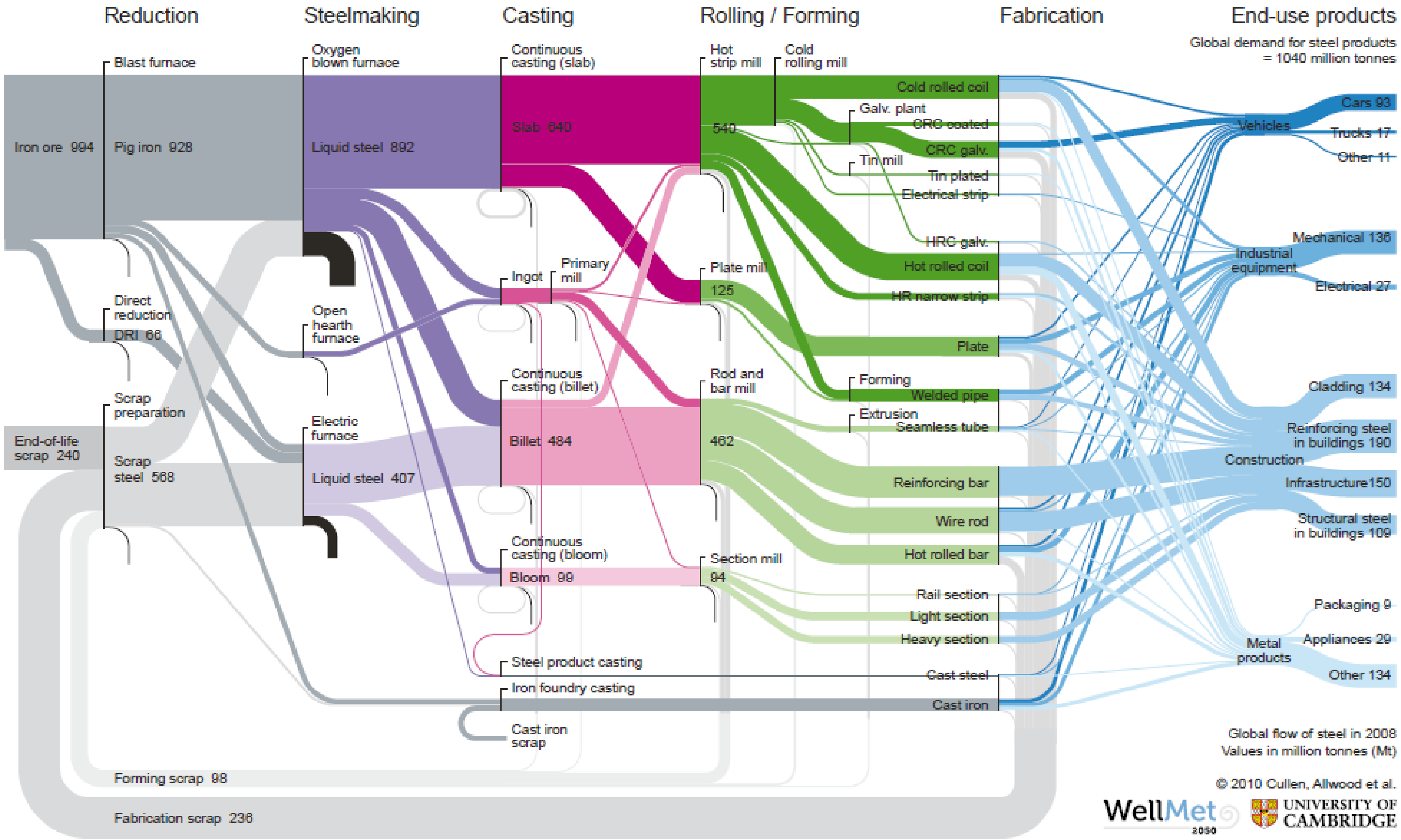
The first study was carried out by Huntzicker et al. (1972), on lead emissions from cars in the Los Angeles basin, to show the main sources, pathways and sinks of lead. this study enabled to identify the emissions from cars as a significant (the main) sources, showing the need for lead ban in automotive fuel

Another study was performed on lead in LA in 1998 (Lankey et al.), measuring the concentrations and granulometric distributions of lead particles in the atmosphere and evaluating the deposition rates. This study showed two main results:

- The ban on lead in automotive fuels (1975) successfully reduced the input of lead in the LA basin
- There was still lead in LA atmosphere 20 years after the ban, because ongoing road traffic would create resuspended dust, assessed as a significant secondary source of lead, which would decrease slowly over time.

At international level

Overall flows of steel in the world in 2008

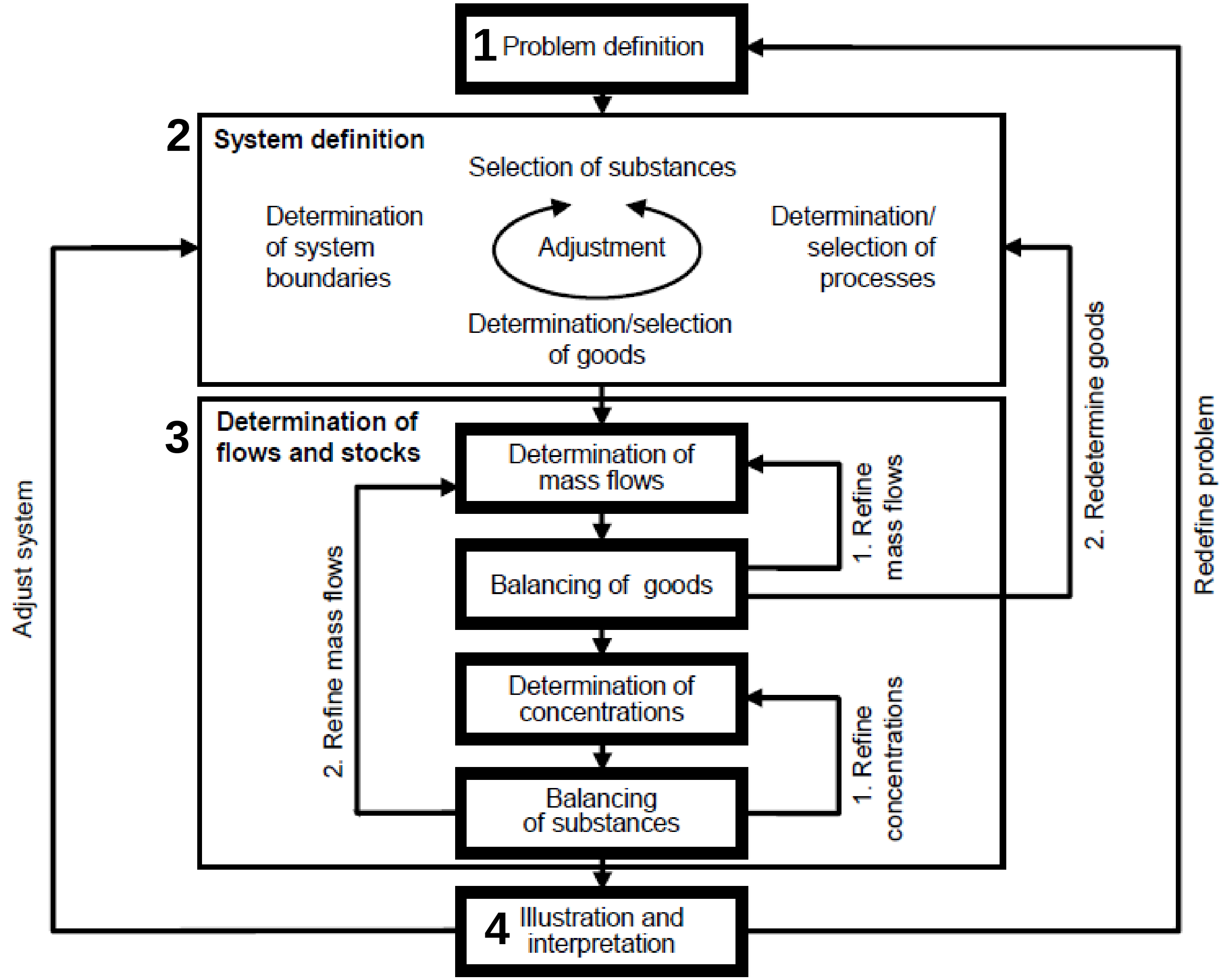


Allwood, JM and Cullen, J, 2012. Sustainable Materials – With Both Eyes Open.

2. Practical implementation

Overall MFA process

MFA is an iterative process, each step needs to be confronted to actual needs and objectives of the study (defined in problem definition).



Procedure/diagram defined in Practical Handbook of Material Flow Analysis – P.H. Brunner & H. Rechberger - 2004

Problem identification

First step in MFA process: definition of the problem

- Explain what are the objectives of the study, what are the questions which need answering and why.
- What is the context?
- Who are the stakeholders?

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System definition > Selection of substances

Different approaches to selected the substance(s) :

1. Regulation based selection: substances involved in Clean Air Act aux US, directive Cleaner Air For Europe, REACh (…) or using standards with regulated substances.
    - In that case, substances are usually well known and documented
2. Focus on main substances found in the main flows of the goods considered in the study:
    - Regroup imports and exports goods by type (solids, liquids, gases)
    - Select main flows of each group to reach > 90% (weight) of each group.
    - Evaluation of the ratio of concentration of substances in goods over respective concentration in geogenic materials (Earth crust for solids, hydro for liquids and atmosphere for gases)
    - Select substances whose ratio is > 10, if none, use the substances with highest ratios
3. The study deals specifically (defined at *problem definition* step) with one or more substances, then the these substances alone will be investigated.
4. For limited/small systems, MFA can try to cover all possible substances consumed, produced or emitted within the system

Partly from Practical Handbook of Material Flow Analysis – P.H. Brunner & H. Rechberger - 2004

System definition > Perimeter

The system must be defined in space and time:

Often no choice for the spatial boundaries

- Spatial boundaries are defined in the scope: region, plant/company boundaries,..
- Perimeter of available data, statist

Ideally:

- Choose the smallest and most uniform system as possible
- Include all processes and flows relevant to the study

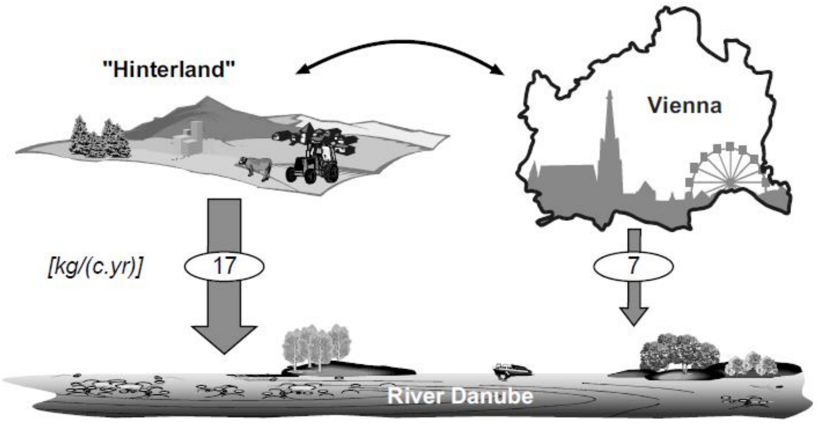


FIGURE 2.16 Nitrogen flux in kg/(capita·year) to the river Danube from the city of Vienna and the corresponding hinterland.[124]

Example of Vienna: using the boundaries of the city to perform its Nitrogen Flow Analysis would lead to underestimate significantly the flows as the main emissions occur at hinterland level to provide food for the inhabitants

From Practical Handbook of Material Flow Analysis – P.H. Brunner & H. Rechberger - 2004

System definition > Perimeter

In an MFA study, the system is the object of the study.

It is defined by a group of elements, by interactions between these elements and by **boundaries defined in space and time**.

An **opened system** interacts with its surrounding external environment (imports or exports of energy and matter)

A **closed system** is completely isolated, with no flows of matter or energy through its boundaries.

A system can consist in one single process or a group of processes.

! The definition of the system must not be neglected, a poor definition can result in issues for performing the study or lead to poor quality results !

System definition > Temporal & spatial boundaries

Temporal boundaries should be chosen according to the objectives of the study:

From 1s for a combustion process to more than 10 000 years for landfilling issues (e.g. nuclear)

Usual temporal boundaries: 1 hour, 1 day or 1 year.

For common economic activities, data are usually available on a yearly basis.

Geographic/spatial boundaries are usually given by spatial boundaries of the processes investigated:

- For a company: the production site
- A whole region or a country for specific economic activity
- The world…

It is possible to define abstract spatial boundaries to study specific part of economy.

Identification of flows, stocks and processes

First, a rough assessment of the system has to be performed:

- General information on the flows from literature, statistics, experts, etc.
- Small flows (< 1%) are neglected at this stage (but should be included in next phases)
- Limit the number of processes included max 15
- Check the mass balance:

$$\sum_{k_I} \dot{m}_{input} = \sum_{k_O} \dot{m}_{output} + \dot{m}_{storage}$$

! Mass balance should check for the flows of goods at system level AND at each process level !

If inputs and outputs don’t balance: there are either missing flows or processes or they contain errors!

From Practical Handbook of Material Flow Analysis – P.H. Brunner & H. Rechberger - 2004

Determination of mass flows, stocks and concentrations

Sources of data for mass flows:

- Databases, scientific literature, books…
- Direct/indirect measurements onsite
- Governmental statistical data (at region, at nation, at world level)
- Statistics from industrial associations
- Consumer organisations

These sources can provide data and information on:

- productions
- consumptions
- sales

Flows can also be estimated on the basis of:

- Specific assumptions
- Cross-comparison with similar systems
- Proxy / indirect data

Data on wastes and pollutant emissions (at air/soil/water) are usually gathered by national and international agencies on energy and environment control.

Determination of mass flows, stocks and concentrations

The flows of substances are calculated on the basis of the flows of goods and substance concentrations in these goods:

i = 1, …, k : number of good

j = 1, …., n : number of substance

$$\dot{X}_{ij} = \dot{m}_i \cdot c_{ij}$$

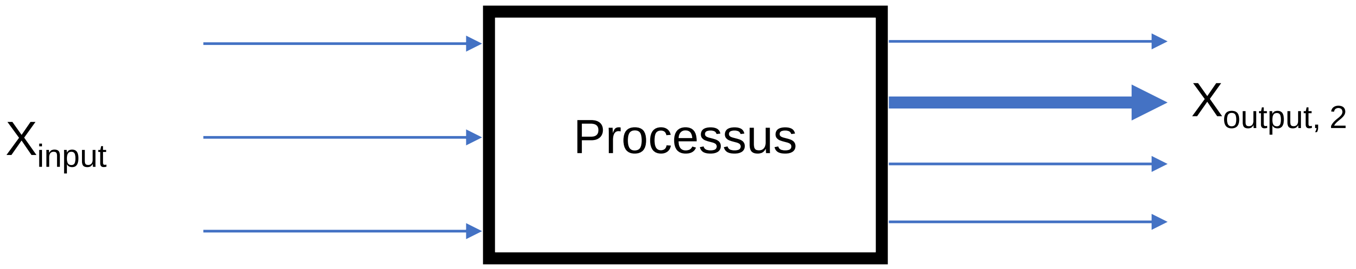
As for the flows of goods, inputs and outputs for substances should balance. If not the case:

- Check the mass balance for goods (should already be done)
- Probable issue in concentrations

Note: MFA studies often show errors/uncertainties of around 10% between inputs and outputs

Transfer coefficient

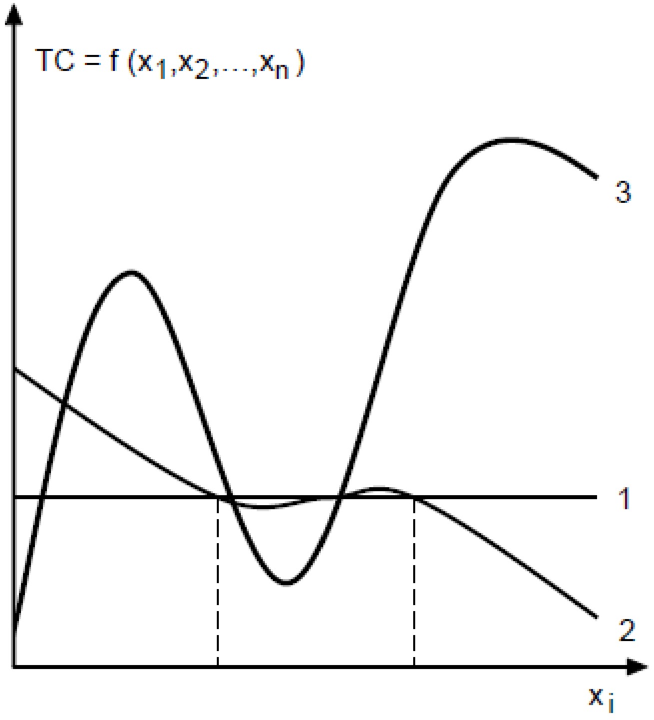
Transfer coefficients describe the distribution of substances/material in a process



$$TC_i = \frac{X_{sortie,i}}{\sum_{i=1}^{k\ entree} X_{entree,i}}$$

$$\sum_{i=1}^{k\ output} TC_i = 1$$

Avec
k_{input} = number of input flows in the process
k_{output} = number of output flows in the process



TC can be strongly or not dependant on input values, can be linear or not.

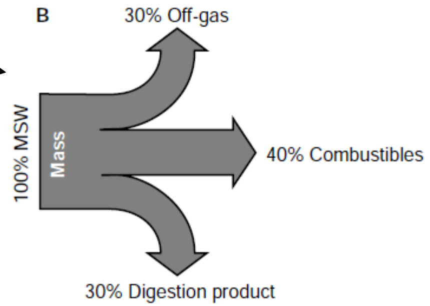
Presentation of the results

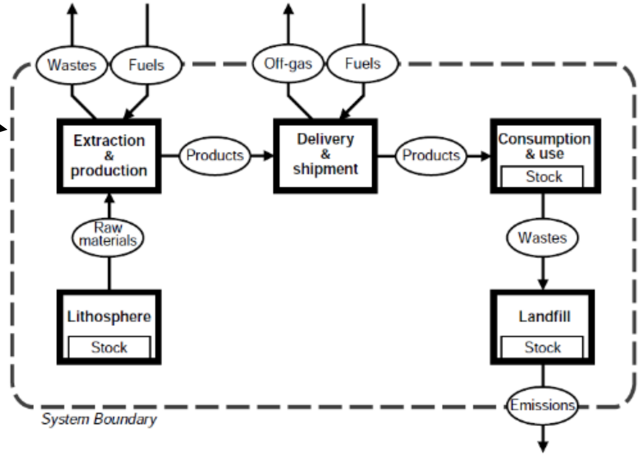
Presentation must be adapted to the audience. The level of details and the type of diagram used will depend on whether the audience is:

- LCA/MFA experts
- Decisions-makers
- General public

As much as possible, use illustrations with diagrams:

- Flowcharts with all processes, flows, import/exports…
- Curve
- Sankey diagrams





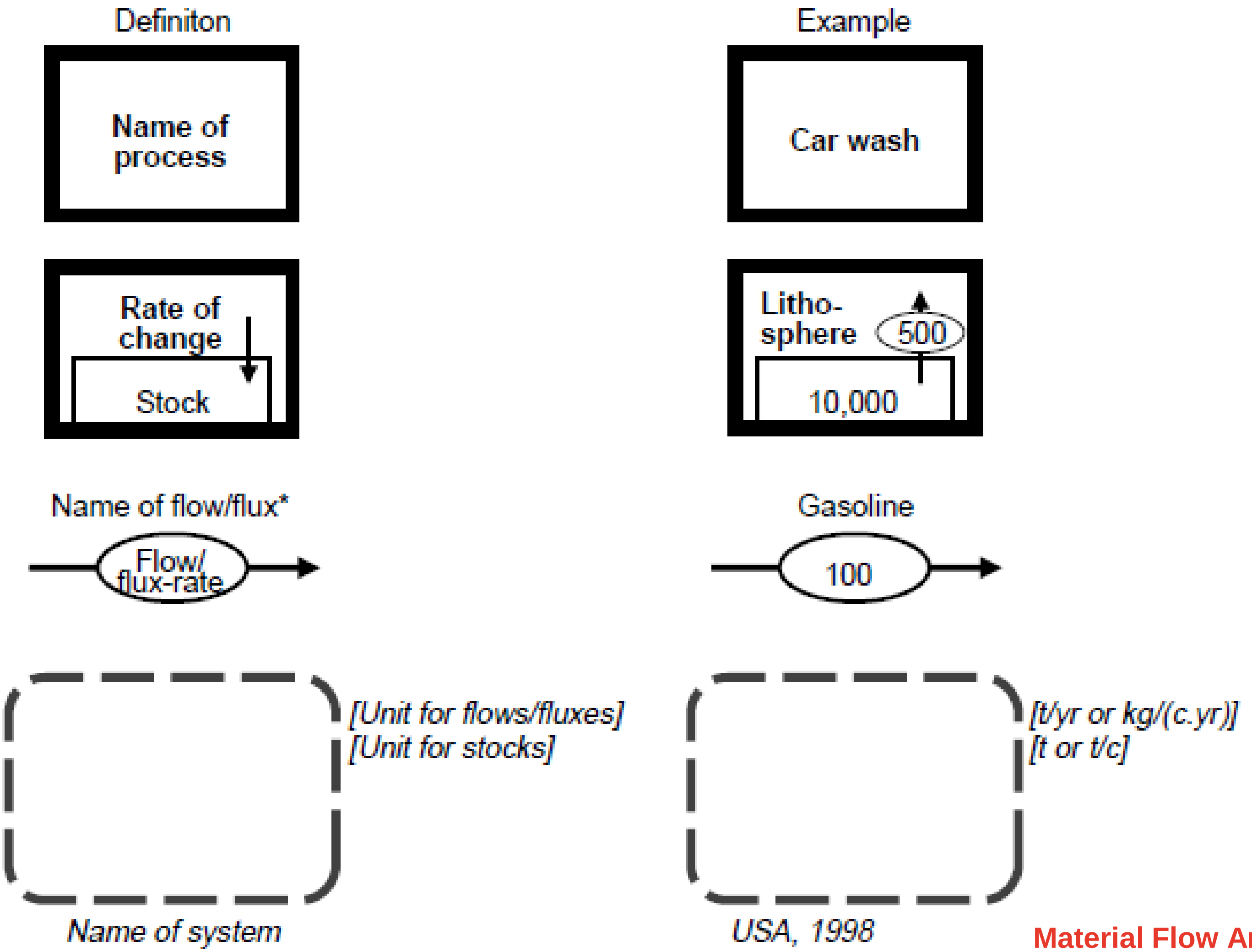
Presentation of the results > Using flowcharts

Process

Stocks + rate of change

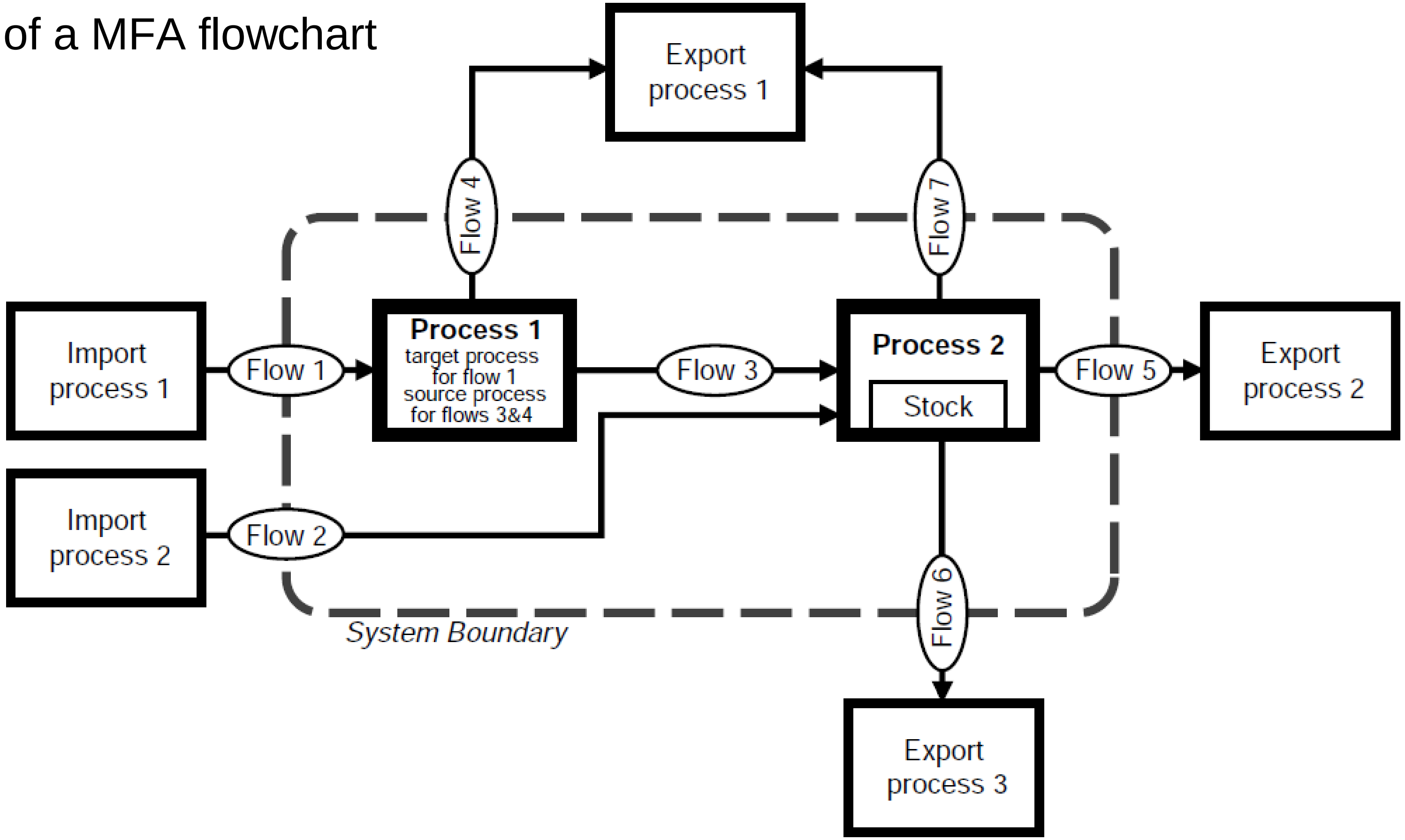
Flows

System boundaries



Presentation of the results > Using flowcharts

Example of a MFA flowchart



PRODUCE

Material Accounting

Performing Material Accounting (MA) means focusing only on main relevant flows and stocks:

- Helps identify quickly future or potential issues or opportunities
- Systematic implementation helps follow the evolutions

The first step of a Material Accounting study is a MFA. Once MFA is performed:

- Material accounting objectives have to be defined
    - Reducing or increasing specific flows
    - Improving the control of pollution
    - Optimizing a technology / process
- Relevant processes, flows and stocks are chosen to achieve the objectives. They should be easily measurable (e.g. processes with constant transfer coefficients)

- Systematic evolution: confrontation overtime of the results and their evolution with the objectives

Evaluation of MFA results

MFA results can sometimes be hard to interpret/exploit

Example:

A MFA shows that a region will be entirely depleted in a specific resource within 50 years if we keep the current consumption level.

- Should it be alarming or not? 50 years = long or short?

It is thus useful to associate MFA to indicators or specific methods to interpret the results and assessment their importance. Several methods exist:

- Material-Intensity per Service-Unit (MIPS)
- Sustainable Process Index (SPI)
- LCA
- Exergy
- Cost Benefit Analysis (CBA)

PRODUCE

Method Material-Intensity per Service-Unit (MIPS)

This concept, developed by Smidt-Bleek, measures the overall flow of material associated to the production, consumption and end of life of a product or service.

- It consists in assessing what is known as the « ecological rucksack » of the product/service

For this method, only inputs are considered to avoid double-counting.

Authors/designers of this methodology suggest to regroup inputs into 6 categories (see table).

Main issue: there is no distinction between the actual type of materials.

Material Intensity for Materials and Products Compiled Using the MIPS Concept

	Abiotic Materials, t/t	Biotic Materials, t/t	Water, t/t	Air, t/t	Soil, t/t	Electricity, kWh/t
Aluminum	85	0	1380	9.8	0	16,300
Pig iron	5.6	0	22	1	0	190
Steel (mix)	6.4	0	47	1.2	0	480
Copper	500	0	260	2	0	3000
Diamonds [a]	5,300,000	0	0	0	0	n.d.[b]
Brown coal	9.7	0	9.3	0.02	0	39
Hard coal	2.4	0	9.1	0.05	0	80
Concrete	1.3	0	3.4	0.04	0.02	24
Cement (Portland)	3.22	0	17	0.33	0	170
Plateglass	2.9	0	12	0.74	0.13	86
Wood (spruce)	0.68	4.7	9.4	0.16	0	109
Paper clip	0.008	0	0.06	0.002	n.d.[b]	n.d.[b]
Shirt	1.6	0.6	400	0.06	n.d.[b]	n.d.[b]
Jeans	5.1	1.6	1200	0.15	n.d.[b]	n.d.[b]
Toilet paper	0.3	0	3	0.13	n.d.[b]	n.d.[b]
Tooth brush	0.12	0	1.5	0.028	n.d.[b]	n.d.[b]

Note: Updated data may soon be available at www.mips-online.info.

Method Sustainable Process Index (SPI)

Concept developed by Narodoslawsky and Krotscheck: assess ground surface required to add a process or a service into the biosphere under sustainable conditions. The objective is to translate all flows of energy and matter into units of surfaces, which are then added.

Comes from the fact that the only true renewable energy is solar energy. Solar energy available on earth is limited by its surface, which is then the only limited resource available.

It is calculated using 5 variables: $$A_{tot} = A_R + A_E + A_I + A_P + (A_{ST})$$

A_R = Raw materials
A_E = Energy
A_I = Infrastructure
A_P = Processing wastes and emissions
A_{ST} = Staff

Exergy

Exergy measures the maximum quantity of work which can theoretically be obtained from a resource (energy and material) by bringing it to equilibrium with respect to its surrounding environment, and with reversible processes (no loss from friction, heat…).

It is an extensive property of matter, and unlike energy, there is no conservation law for exergy

- It is either consumed of destroyed due to the irreversibility of real processes.

Exergy is considered as an interesting indicator for environmental impacts: the more exergy a material or an energy does have, the more its thermodynamic state deviate from environmental equilibrium (the highest damages potential it has).

However, exergy balances have one major weakness: they usually are dominated by energy flows, material flows usually play lesser roles in exergy balances, meaning that they can seem less important.

PRODUCE

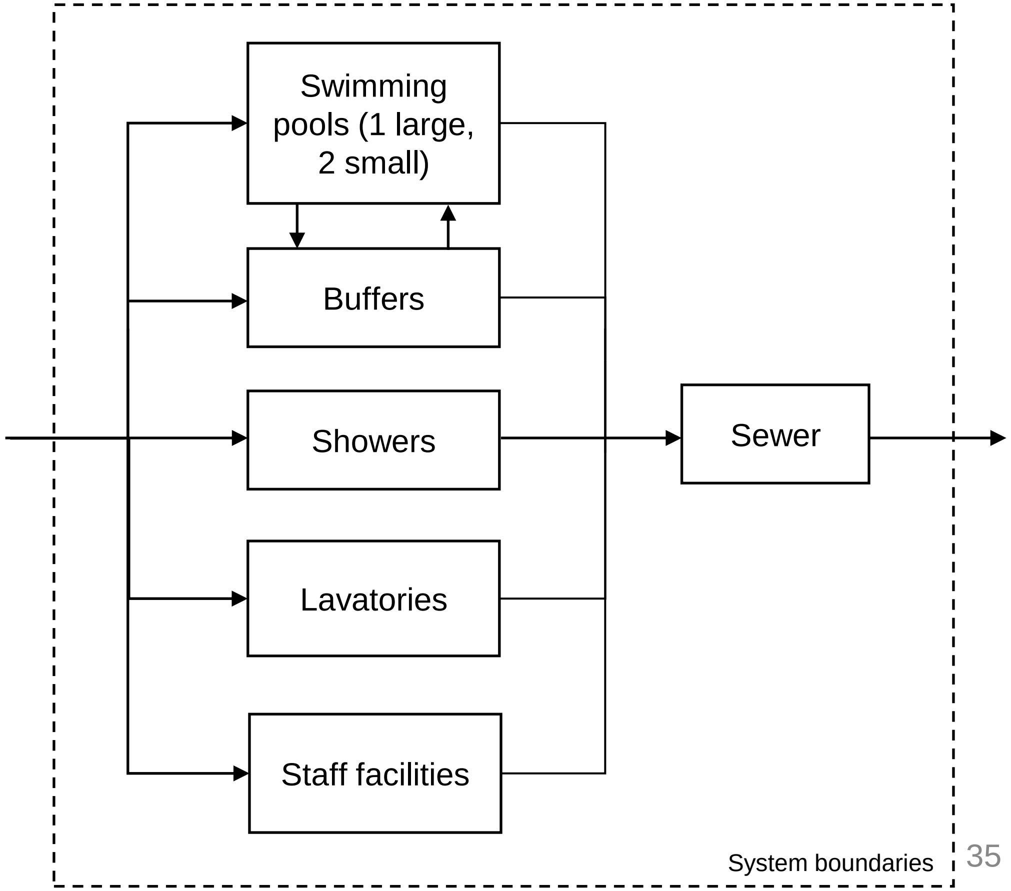
Example 1

A municipal pool, knows how much water it uses on a yearly basis but would like to have a more precise idea of its main water uses and identify if there are leaks or if optimizations are possible.

An MFA expert is called to perform an quick analysis of the flows of water over a period of a year.

Problem deifnition:
Objectives: identify main water flows and look for possible optimization

System definition:
Scope: physical boundaries of the pool over a period of 1 year see flowsheet
Substance: water



Example 1 (solution)

Determination of the flows and stocks:

The manager knows its annual consumption (measured) : 24 260 m3
The specific consumption for each “process”, can be estimated:
Pools: 4 500 m^3 (volume of the pools * number of drainings)
Buffers: 500 m^3 (volume of the buffers * number of drainings)
Showers: 15 000 m^3 (number of visitors * average consumption for a shower)
Lavatories: 1 800 m^3 (number of visitors * average consumption)
Staff facilities: 300 m^3 (estimation on the basis of previsou figures and staff number)

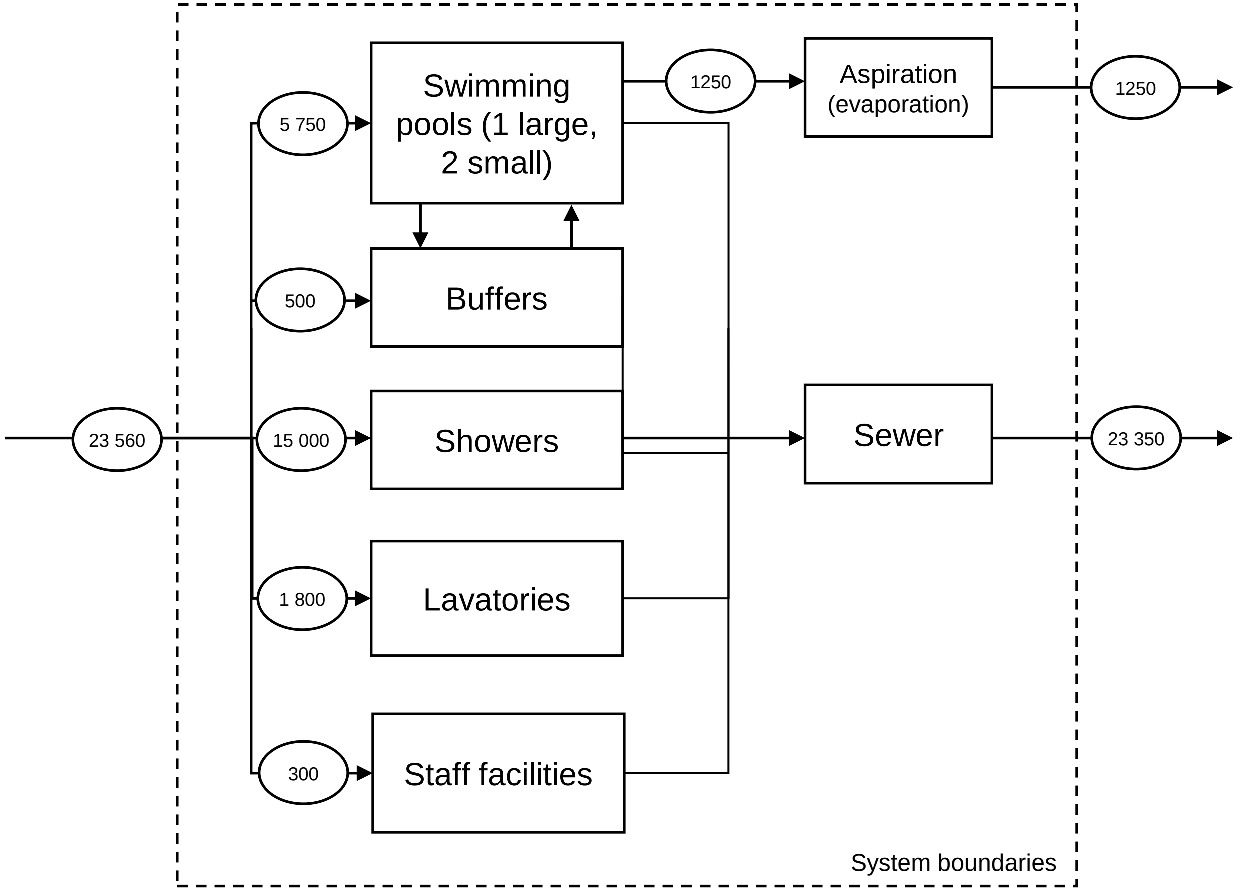
Mass balance between input (measured) and output (calculated)
 discrepancy of 1 910 m^3

After a more careful study of the layout and the pool, this discrepancy could be explained by water evaporation from the pools, then extracted by the aspiration system.
There exists a formula to estimate the evaporation rate of free surface/pools. Using air and pool temperatures with such formula, gives an estimation of 0,16 m^3 lost through evaporation each hour (on average) **1 250 m^3 close to the discrepancy**

Example 1 (solution)

Illustration of the results and first conclusions – updated flowsheet

The mass balance is not verified but the error is quite small (<5%), which can come from the different estimations made. Current state of the pool doesn't seem to show any major leaks.



One example of optimization could potentially be performed by re-using the pool water (currently disposed after the yearly drainings), this would however need additional systems for filtration, etc, to prevent any health issues.

This was an example of a quick study, however, to refine these results, a more precise data collection process could be used.
For example, flowmeters could be set up at each exit points (or at least at sewer) to verify these estimations and confirm the overall volumes of effluent.

Example 2: Additive manufacturing of titanium parts

For the production of aeronautic parts, additive manufacturing of metallic part is investigated to replace conventional machining processes.

Is this production process interesting from an environmental and circularity point of view, compared to current practices?

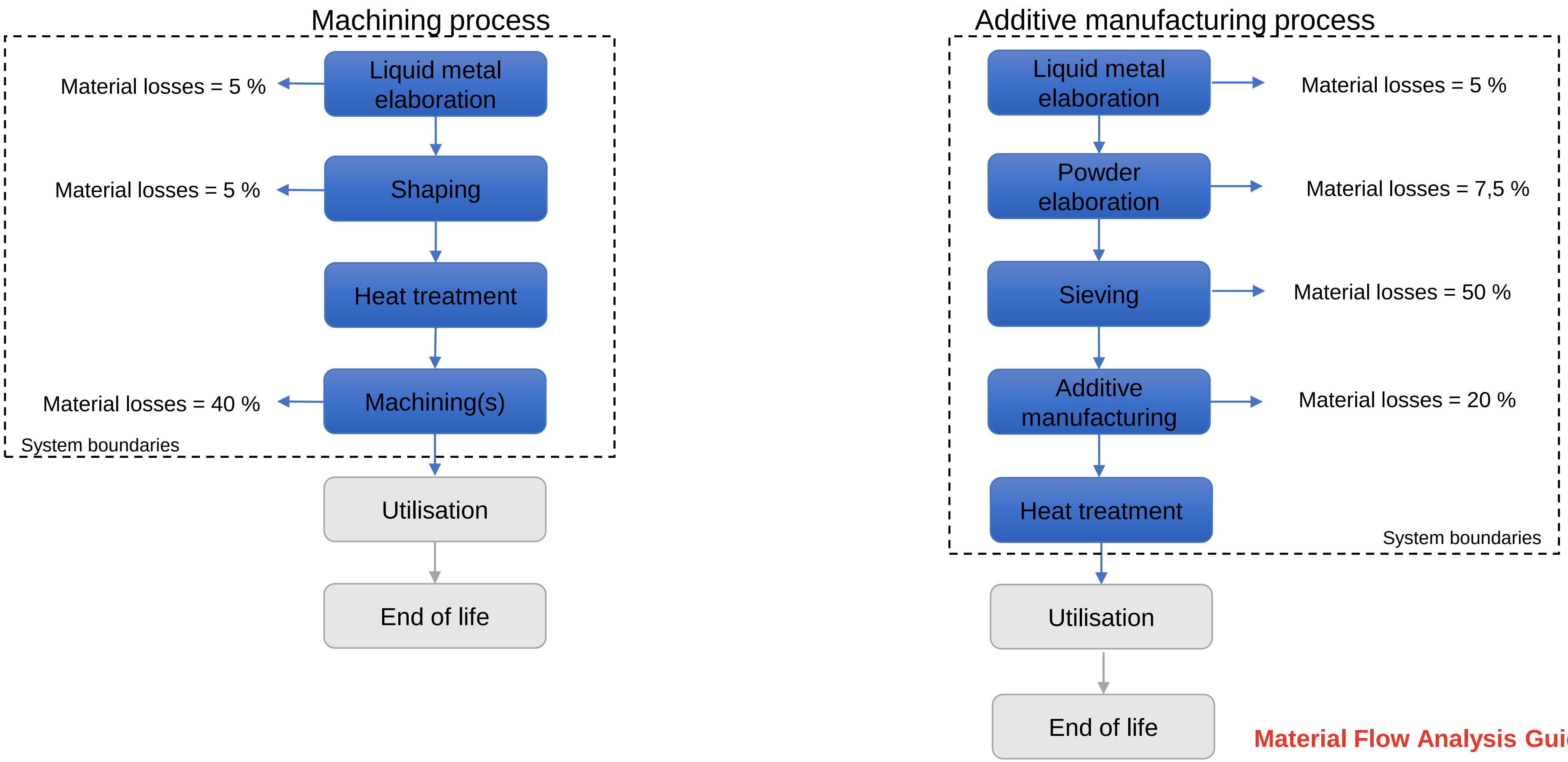
Performing an MFA of both production processes can then help assess their environmental impact as well as the actual raw material consumptions and process losses.

Problem deifnition:
Objectives: compare two production routes and assess their raw material consumptions / production losses
System definition:
Scope: processes from the metal elaboration to the finished parts – for 1 kg of part
Substance: metal used for the part manufacturing process (titanium)

Determination of the flows: each unit process from the elaboration of the metal to the finished parts are studied individually and their respective yield are identified (see next slide)

Example 2: Additive manufacturing of titanium parts

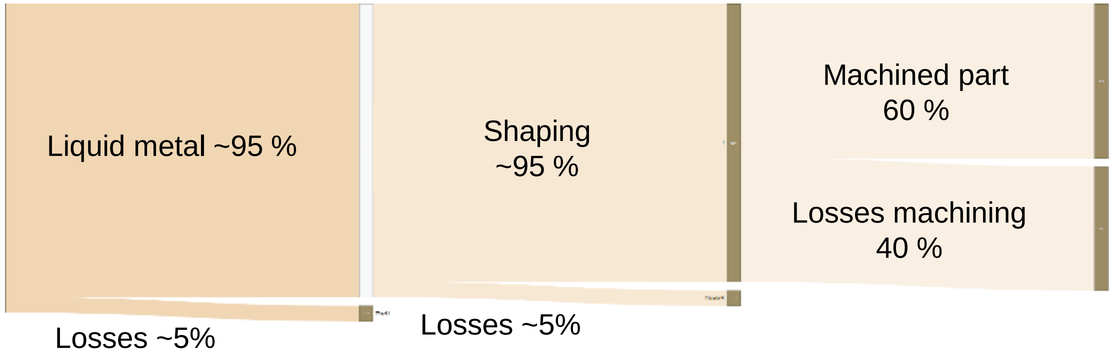
Comparison of both production routes – system definition and determination of flows



Example 2: presentation of the results using Sankey diagrams

Machining process

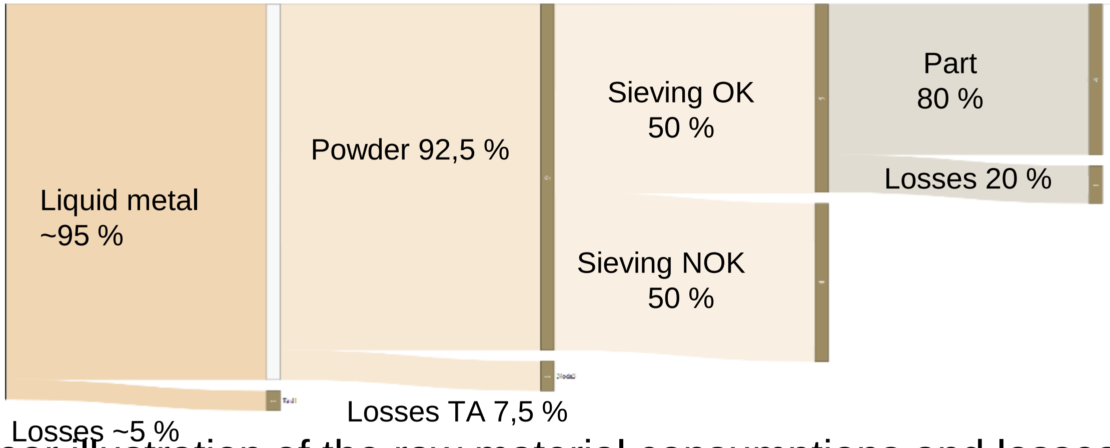
1,85 kg metal



1 kg finished part

Additive manufacturing

2,85 kg metal



1 kg finished part

Sankey diagrams give a clear illustration of the raw material consumptions and losses associated with these two routes. These results can be used in several different ways:

- Select the more relevant production process
- Identify the process(es) which need improvement to reduce the loss of material.
- Translate material flows into environmental impacts (requires knowledge on impacts of each unitary process) – (See LCA section)

PRODUCE

Outsourcing MFA studies

Few consulting agencies perform this kind of study, but most usually perform Material Flow Cost Accoutning (focused on the costs).

Actual Material Flow Analysis are usually performed by Research centers and academic laboratories (e.g. NTNU in Norway, Delft University in Netherlands, Bordeaux University in France, etc.)

Costs for an MFA will vary strongly depending on the scope (10 000 to > 50 000 €).

Even for outsourced MFA, internal resources (human resources) are required for data collection, more specifically for:

- Identification of relevant internal contacts
  - production manager,
  - Environmental/waste manager,...
- Identification of available data on internal processes
- Discussion with suppliers on the possibility to have information on their products / processes and with customers on their practices with the product (lifespan, consumption habits...)

Developing internal skills for MFA requires:

Human resources - between 1 to more than 6 months FTE, depending on the scope and objectives

- Internal human resources
  - production manager,
  - Environmental/waste manager,...
- Collection of data on internal processes
- Collection of data from suppliers and customers
- Modelling the processes (need some knowledge on processes, physics, chemistry..)

Software(s):

- Spreadsheet software (Excel, openoffice..) are usually enough for simple MFA
- Commercial software can help when dealing with more complex studies and improve clarity (diagrams)
  - Umberto (https://www.ifu.com/en/umberto)
  - Stan (https://www.stan2web.net)
- Sankezy diagram software: eSankey (commercial - https://www.ifu.com/en/e-sankey/), http://sankeymatic.com/ (free)

Miscellaneous:

- travel expenses
- access to online databases, scientific papers, etc.

3. How can MFA results be used?

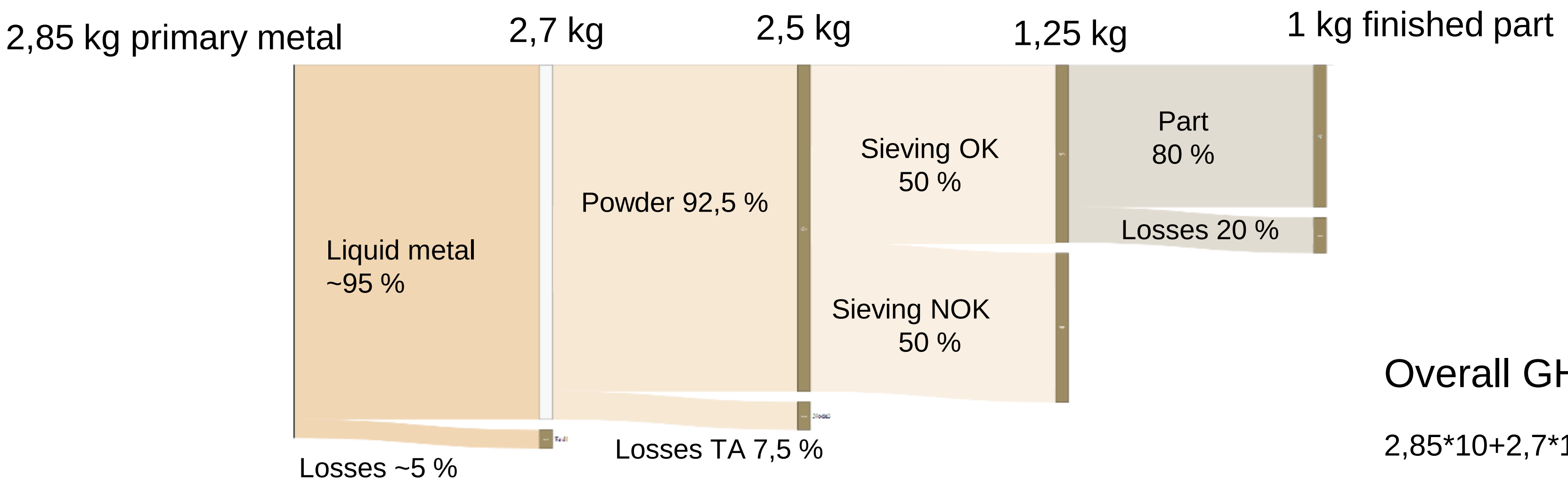
PRODUCE

Direct links with LCA (Life Cycle Assessment) for environmental impact assessment can be interesting

In case of single/few substance(s) MFA, the system can be directly implemented in a LCA software or each unit process step can be linked with its specific environmental impacts in order to:

- Assess the overall impacts of the system
- Identify the flows associated to significant impacts

Example on additive manufacturing process with metallic powder:



Overall GHG emissions of the process:

2,85*10+2,7*15+2,5*0,05+1,25*1 = 70,3 kgCO2e/ kg part

Specific greenhouse gas emissions at each step

10 kgCO2e/kg Ti liquid

15 kgCO2e/kg powder

0,05 kgCO2e/kg powder ok

1 kgCO2e/kg part

Direct links with LCA (Life Cycle Assessment) for environmental impact assessment can be interesting

In case of MFA studies for small systems, which cover all inputs/outputs, the results can be used to perform Life Cycle Inventories (LCI) of the systems or their sub-systems (see LCA guideline). These LCI can afterward be implemented in LCA software for more global LCA.

Link with Cost Benefit Analysis (CBA)

The concept of Cost Benefit Analysis is quite old (>150 years) and was initially developed to assess the costs and the benefits associated to building bridges.

CBA is a decision-making tool which can be used to assess quantitatively the strengths and weaknesses of different solutions.

It consists in quantifying all benefits and costs (economic and environmental) of a project as currency units ($, €..).

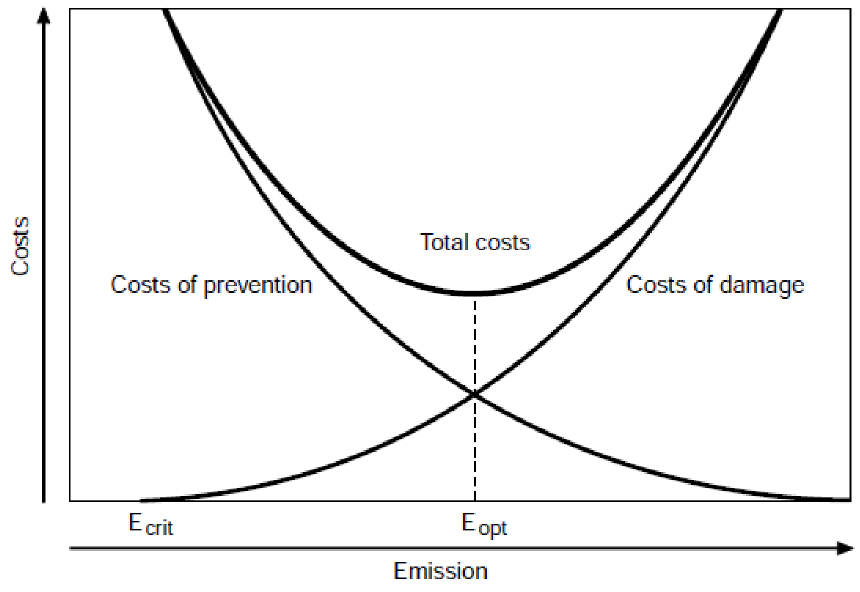
Interest: Assist in understanding the pros and cons as everyone is familiar with costs

Main issue with CBA: some effects are difficult to translate into currency units

Link with Cost Benefit Analysis (CBA)

Can be broken down into 8 main steps:

1. Definition of the project
2. Identification of the impacts of the project
    - Resources required (material, human)
    - Effects on local employment
    - Effects on the prices of local properties
    - Emissions…
3. Evaluate which impacts should be taken into account
4. Assess costs and benefits flows (quantification) for the project and identify when they will occur
5. Translation of physical flows into currency units (including future prices, with potential evolutions and assessment of non-already existing prices)
6. Conversion of all costs in today's currencies
7. Comparison of overall costs (C) and benefits(B). If B > C, the project is interesting or it theoretically improves social well-being.
8. Performing a sensitivity analysis to assess the significance of the uncertainties



PRODUCE

MFA for industrial symbiosis

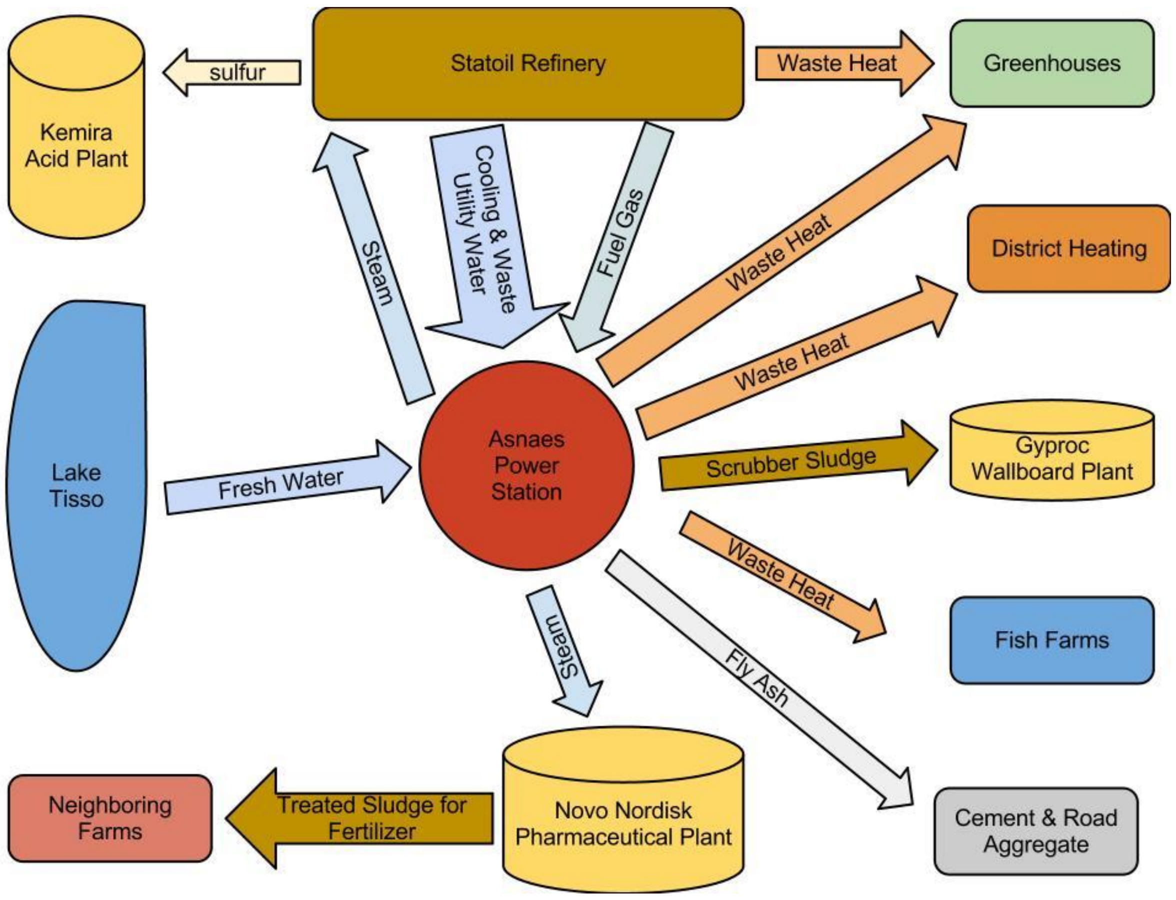
MFA over industrial zones or whole regions can help monitor the different routes of material utilisation and wastes, as well as industrial processes.

Indeed, MFA results can give a clear view on industrial metabolism by providing reliable information (such as material nature, quantified flows, losses, etc.) on significant flows over the zone investigated.

MFA can also help assess the quantities of material consumed, produced (by-products as well as energy and material wastes) by a specific activity/production site into its surrounding ecosystem(s).

Coupled with the knowledge of the surrounding ecosystems (e.g. energy or material needs of close production sites) **this can provide important ground data for the implementation of possible industrial symbiosys.**

Example: Eco industrial park in Kalundbord (Denmark)



Project initiated when the refinery wanted to use surface water from a nearby lake instead of groundwater.
Industries around (powerplant station, greenhouses, gypsum producer…) then organised together to build an « industrial symbiosis ».

Globally, the symbiosis saves:
- 1,9 M m3 / year of groundwater
- 1,0 M m3 / year surface water
- 20 000 t / year of oil
- 200 000 t / year of gypsum

Eocnomics:
- Investment ~ 75 M$
- Savings: 15 M$ / year
- Savings between 1980 and 1998 : 160 M$
- Return on investment: 5 years

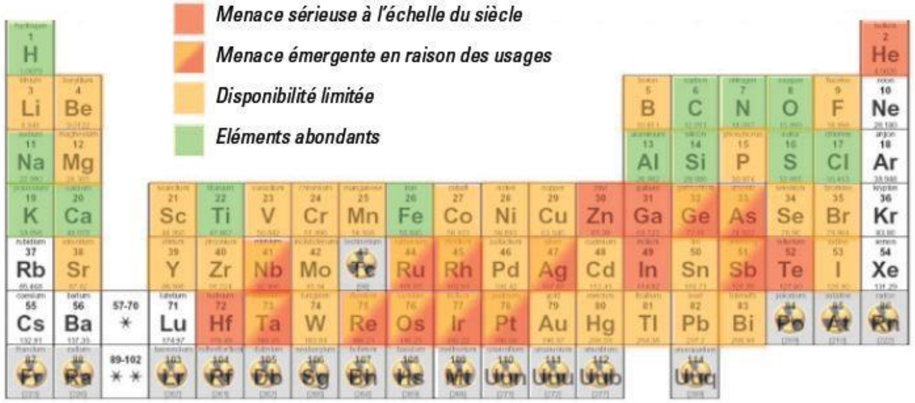
PRODUCE

Resource management

Resource management consists in analysing, planning and allocating resource exploitation (natural as well as anthropogenic).

MFA can model resource consumption and evolution of stocks within a system □ useful to anticipate future shortages or, on the contrary, over accumulation.

With the integration of dynamic aspects, MFA can inform on dynamic evolutions and on time remaining before the occurrence of critical states (shortages or accumulation).



Elements associated to shortage risks

For agricultural soils, MFA applied to crop fields can help anticipate the loss of nutrients or on contrary the accumulation of pollutant elements.

PRODUCE

Waste management

Waste management aims at planning the management of the wastes to protect human health and environment, save resources and if possible treat them to avoid landfilling.

Overall MFA can help identify the waste flows with the highest potential for improvement:

- either by reduction of their production by modifying the production process
- By determining better valorisation routes (reuse, recycling…)

Material balance based on an MFA and after the implementation of a specific waste management plan is useful to check/verify the efficiency of the plan/solutions set in place.