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ENV 501 / GR A3 30

Material Flow Analysis and resource management

Prof. Dr. Claudia R. Binder claudia.binder@epfl.ch
Dr. Maria A. Hecher maria.hecher@epfl.ch
Dr. Francisco Xavier Felix Martin Del Campo francisco.felixmartindelcampo@epfl.ch
Exercices Teacher Assistant Jaïr Campfens jair.campfens@epfl.ch
Student Assistant Alicia Pérez Domouso alicia.perezdomouso@epfl.ch

Fall 2024

- Laboratory on Human-Environment Relations in Urban Systems

Last week

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- EW-MFA recap and adaptability to other boundaries
- Example of Swiss Cantons
- Validation of methodology and insights
- Insights from Urban MFA’s and policies

Course outline

Block	Week	8:15 - 9:00 and 9:15 - 10:00		13:15 - 14:00	14:15 - 15:00
Block I: EW-MFA global / national	W1 - Sep 12	Introduction to the course and general concepts	All	Exercise	Project
	W2 - Sep 19	EW – MFA and EW – MFA in different countries	FMC	Exercise	Project
	W3 – Sep 26	EW – MFA in the Swiss context, Urban Metabolism	External Guest – Florian Kohler	Exercise	Project
	W4 - Oct 03	EW – MFA in the Swiss context: Cantons and Circular Economy	FMC	Exercise	Project
Block II: MFA regional / urban	W5 - Oct 10	The Service-Stock-Flows Nexus	FMC	Exercise	Project
	W6 - Oct 17	Dynamic MFA	External Guest – Stefan Pauliuk	Exercise	Project
	Oct 24	Autumn break			
	W7 - Oct 31	Spatial MFA	FMC	Exercise	Project
	W8 - Nov 07	Input-Output Analysis and Material Flow Cost Accounting	External Guest – Vincent Moreau	Exercise	Project
	W9 - Nov 14	MFA and Uncertainty	External guest – Stefan Pauliuk	Exercise	Project
	W10 - Nov 21	Case studies: Waste management in Indonesia / Critical Raw Materials in the Swiss context	GF & FMC	Exercise	Project
Block III: Social sciences and public policy	W11 - Nov 28	Social Metabolism	CRB	Exercise	Project
	W12 - Dec 05	Agent-based model	CRB, FMC, MAH, SLC	Past exam	Project
	W13 - Dec 12	Group Project Presentation	CRB, FMC, MAH	Project	Project
	W14 - Dec 19	Group Project Presentation	CRB, FMC, MAH	Project	Project

Content of lecture

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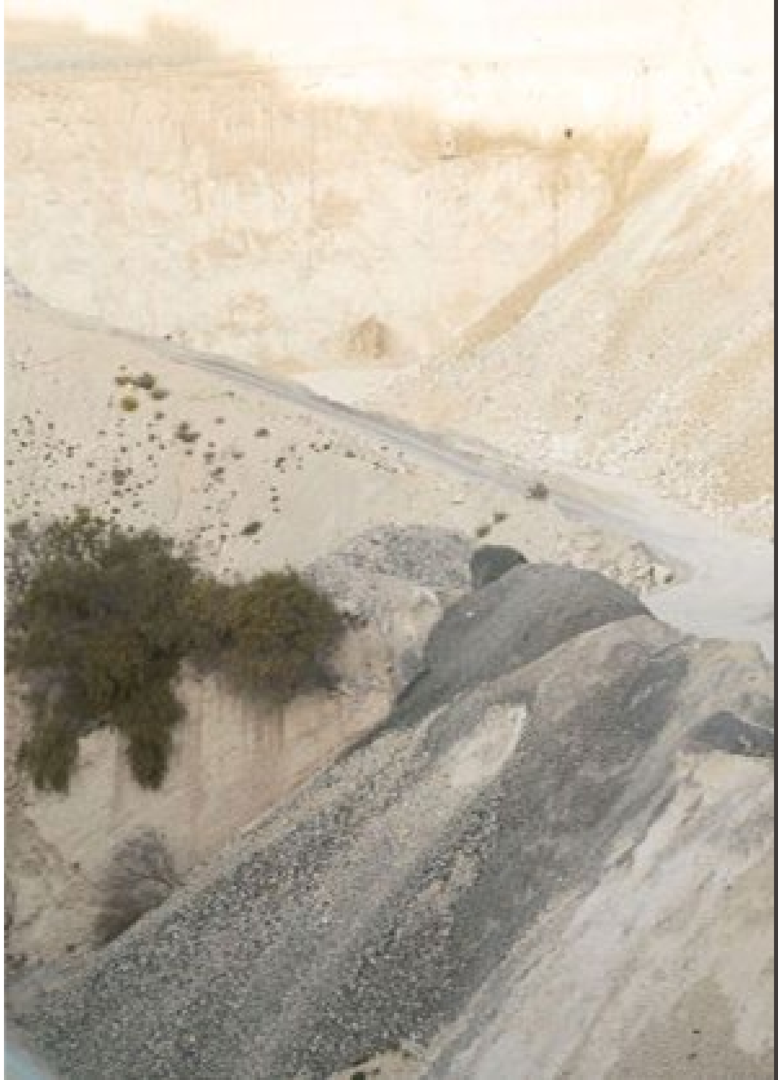
- Recap on the importance of resource dynamics and MFA
- Main components of MFA systems
- The Stock-Flow-Service Nexus: Definitions and relevance
- System’s linkages in society’s metabolism
- MFA and mathematical system definition



Resource dynamics and MFA

The importance of resource dynamics

- Resource Use and Environmental Pressure
- Human Well-Being and Societal Development
- Linking Resource Use to Global Challenges
- Balancing Socio-Economic Goals and Environmental Limits
- Stewardship and Sustainable Resource Management

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Material Flow Analysis (MFA) – Definition (recap)

- Material Flow Analysis (MFA) is the systematic study of **physical flows of natural resources and materials** <u>into</u>, <u>through</u> and <u>out</u> of a given system (usually the economy).
- It is based on accounts in **physical units,** and uses the **principle of mass balancing** to analyze the **relationships between material flows** (including energy), **human activities** (including economic and trade developments) and **environmental changes.**
- The system is defined in **space** and **time**.
- **Connects** the sources, pathways and sinks of a **material**.

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MFA in practice – Applications (recap)

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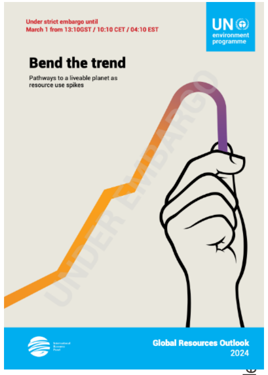
- **Early detection** of harmful/useful material accumulation or depletion in anthropogenic/natural subsystems.
- **Prediction of future** quantities in anthropogenic/natural subsystems.
- **Identification** of the need for action in the areas of environmental, resource, waste and policy management.
- **Evaluation** of the effectiveness of current/planned measures.
- **Design** of ecologically-optimized products, processes and systems (e.g. green design, eco-design, circularity).

Resources vs Materials (recap)



***Biomass**: crops for food, energy and bio-based materials, wood for energy and industrial uses*

***Fossil fuels**: covering coal, gas and oil*

***Metals**: such as iron, aluminum, copper, energy transition minerals*

***Non-metallic minerals:** sand, gravel, limestone and minerals used for industrial applications*

Air, Land

Oceans, Freshwater

Materials: *Everything extracted from the Earth* (Biomass, Fossil fuels, Metals, Non-metallic minerals)

Includes biodiversity (Air, Land, Oceans, Freshwater)

Resources: *Materials +Air, Land, Oceans and Freshwater*

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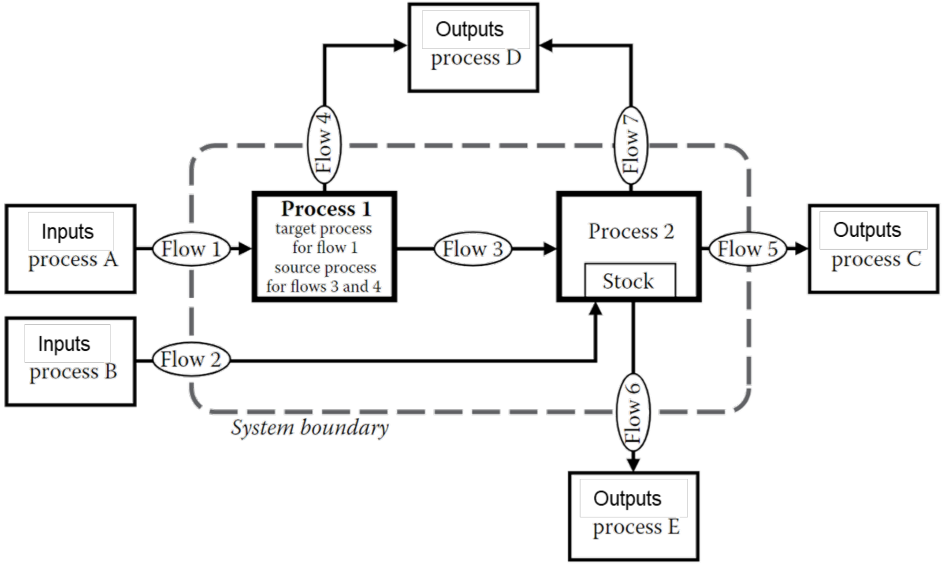
Global Resources Outlook 2024, International Resource Panel, UNEP, 2024

Main components of MFA systems



MFA system

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- **MFA system:** comprises a set of material **flows**, **stocks**, and **processes** within a defined **boundary**.
- **System boundary** is defined in space and time.
- **Temporal boundary:** time period over which the material balance is calculated (e.g. 1 hour for waste incineration process, 1000 years for landfills, 1 year for a city).
- **Spatial boundary:** geographical area (e.g. municipality, region, city) or virtual limits (e.g. private households, company).

MFA system

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What is a **process**?

- A **process** is any **transformation**, **operation**, or **activity** within a system where materials or energy are **converted**, **stored**, or **utilized** to produce **goods**, **services**, or **emissions**.
- Processes interact with flows by receiving inputs, transforming these into products or services, and generating outputs like emissions or waste.
- Analyzing processes is crucial for identifying material efficiencies, optimizing resource use, and evaluating the impacts and sustainability of the entire system.

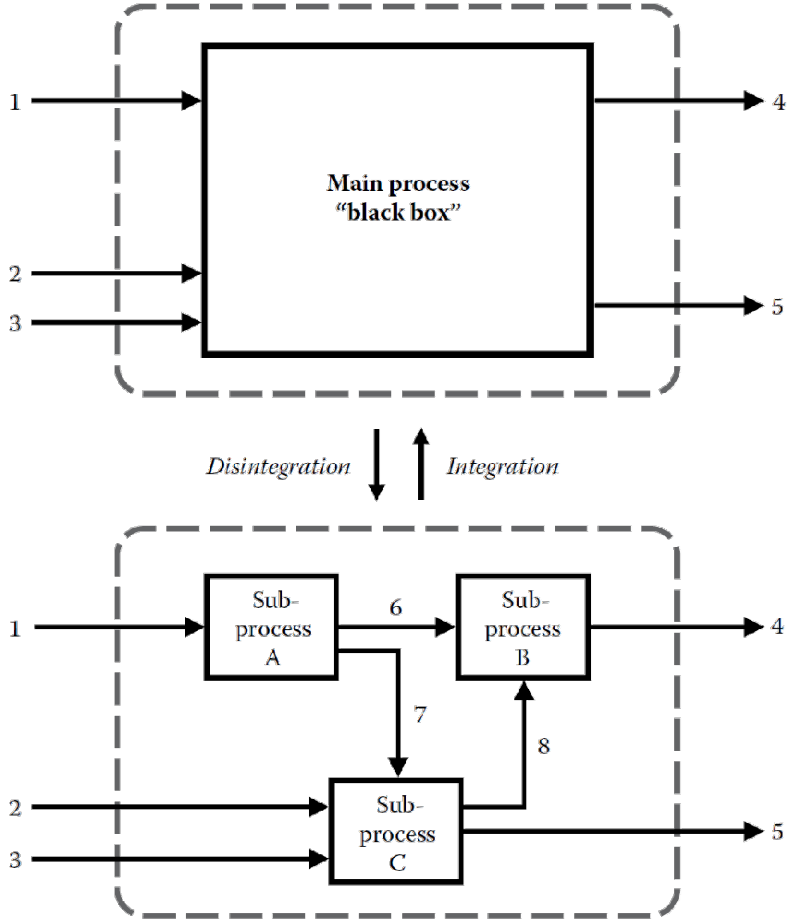
MFA system

Process

System understanding

Opening the "black box"

- Waste incineration process
- Wastewater treatment plant
- Energy production
- Recycling
- Landfill
- Gas tank farm



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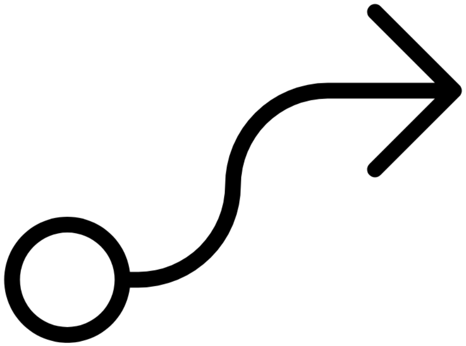
MFA system



What is a **flow**?

- A **flow** refers to the **movement** or **transfer** of materials, resources, or energy **through a system** over a specific period of **time**.
- Flows are typically categorized into **inflows** (inputs), **throughputs** (processing or transformation within the system), and **outflows** (outputs such as emissions, waste, or products).
- Tracking flows is essential to understanding resource efficiency, consumption patterns, and environmental impacts associated with production and use.

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MFA system

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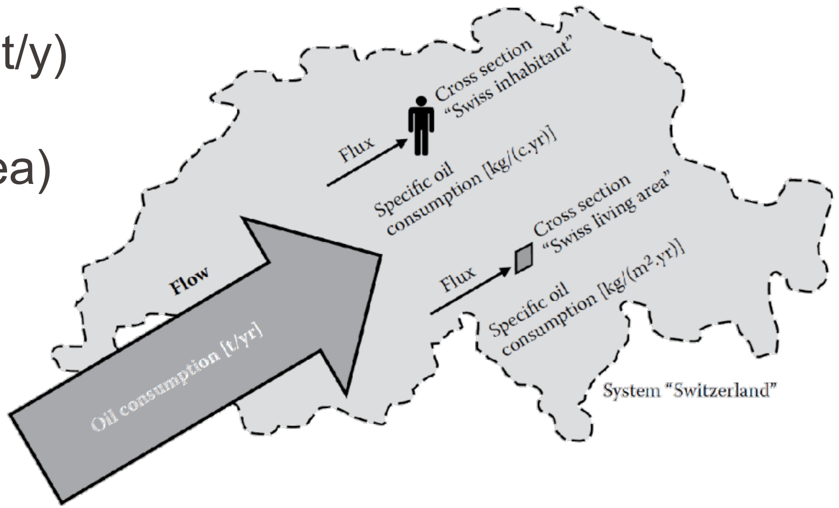
Flows

- Materials flowing from one process to another

- **Flows:** ratio of mass per time (e.g. t/y)
- **Fluxes:** flow per cross section (e.g. person, private household, area)
- Flows/fluxes entering a process: **inputs**
- Flows/fluxes exiting a process: **outputs**
- Flows/fluxes across system boundaries: **imports and exports**



Source: Brunner & Rechberger, 2016

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Importance of flows

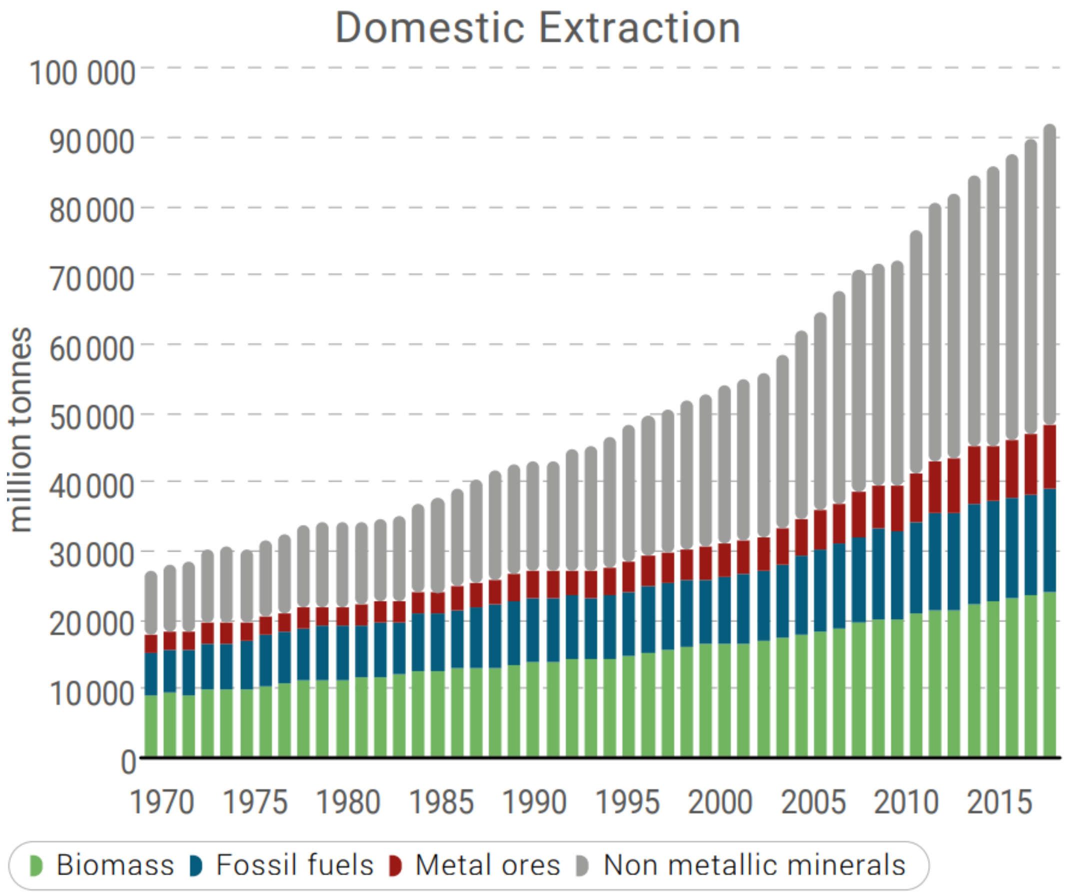
The growth in resource use has caused a sharp increase in global material extraction, particularly of non-renewable materials.

Extraction in **1970**: **+20** billion tonnes

Extraction in **2020**: **+100** billion tonnes

Projections by **2050**: **+180** billion tonnes

Recycling rates in **2020**: **8.6%**



Source: UNEP & IRP, 2018

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MFA system

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What is a **stock**?

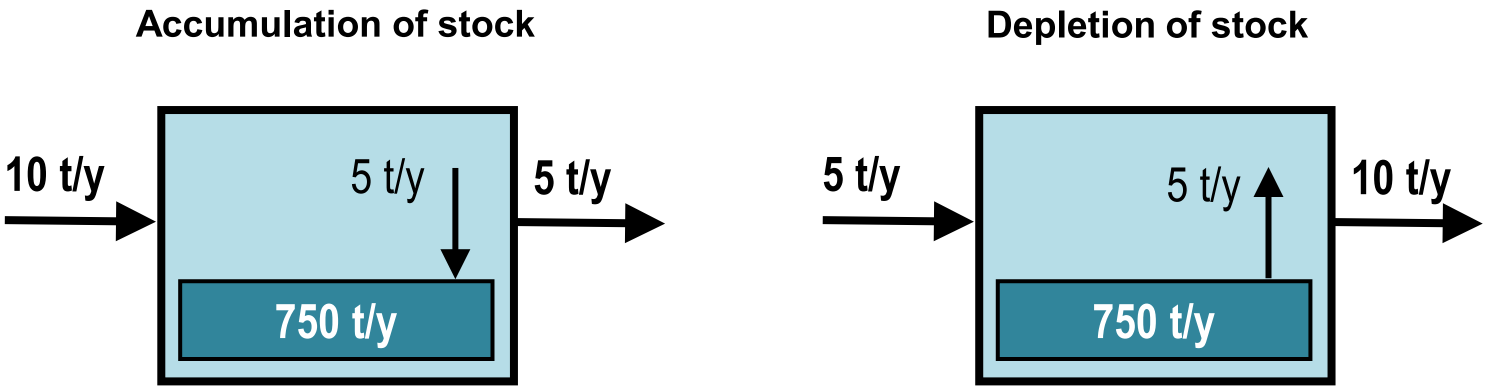
- A **stock** represents the **accumulated quantity** of a material, resource, or product present in a **defined system or boundary** at a given point in **time**.
- In industrial ecology, stocks can refer to physical assets such as buildings, infrastructure, machinery, or the amount of a resource stored within a particular environment (e.g., metal stock in urban buildings).
- Stocks are crucial because they influence how materials are used, maintained, and eventually released back into the environment.

MFA system

Stocks

- Material reservoirs or material quantity within a process

- Stocks can stay constant, increase or decrease in size
- Accumulation/depletion of stock: difference between process inputs and outputs between two time steps



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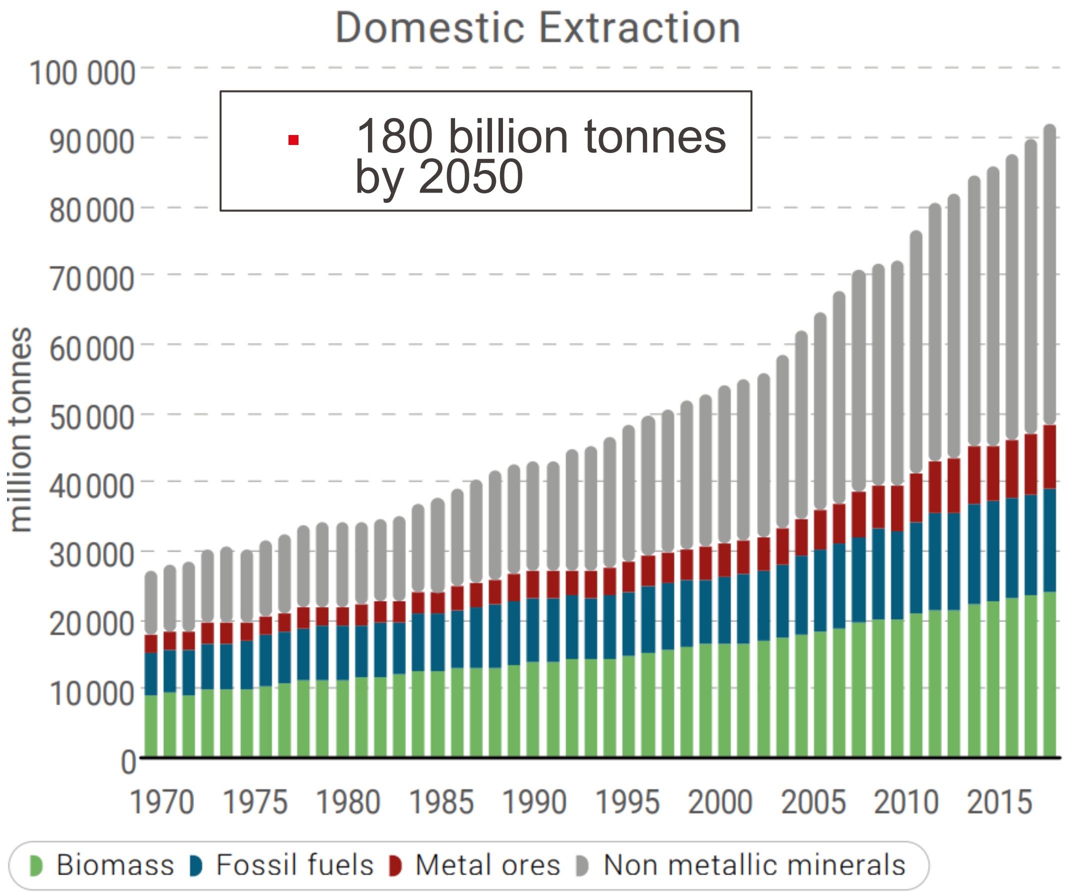
Importance of stocks

- In 2015**, 75%** of all **extracted materials** were linked to **material stocks**
  - Buildings
  - Infrastructures
  - Machinery, etc.

- Utilized for **building** and **maintaining** these, or for **operating** them and **providing services**



Source: UNEP & IRP, 2018; Krausmann et al., 2020

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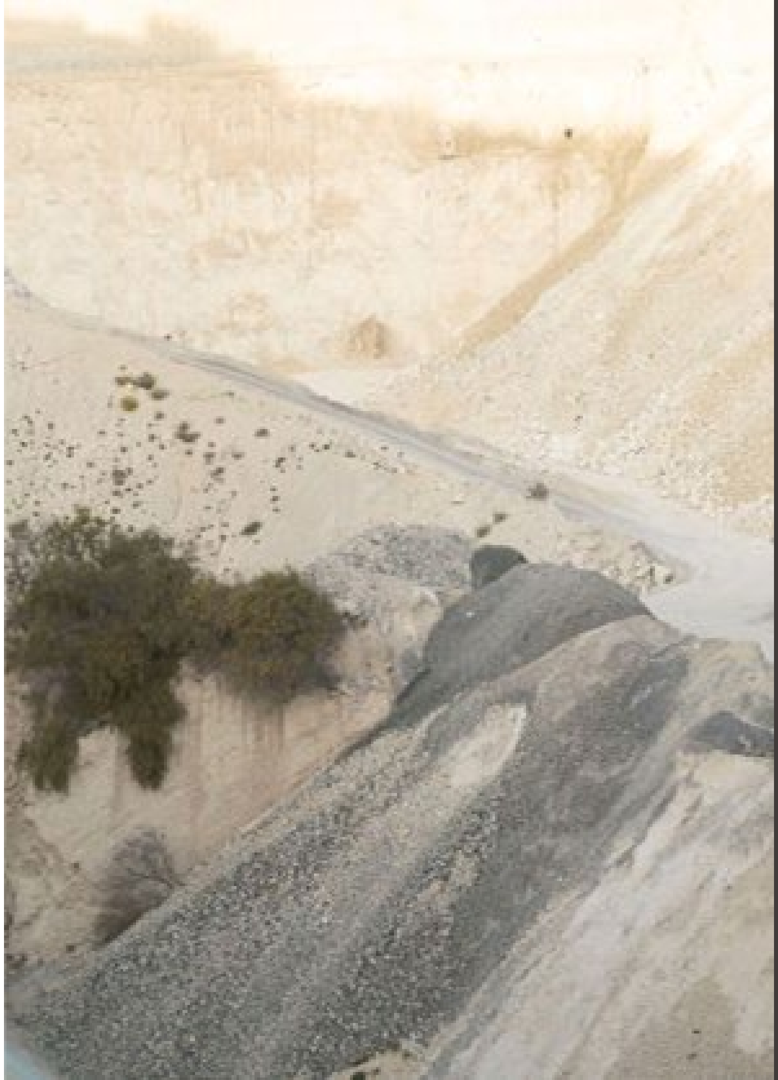

The Stocks-flows-service nexus

Definitions and relevance

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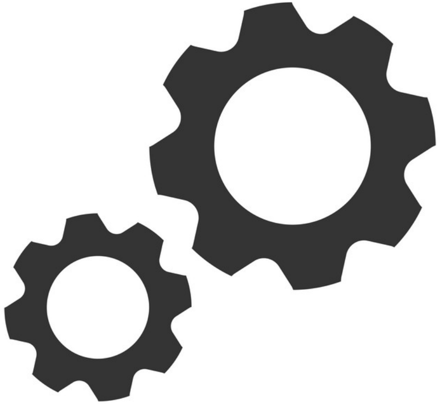
The Stock-Flows-Service Nexus



What is a **service**?

- A **service** is the **functional output or utility** derived from the **use** of materials or products **within a system**.
- It represents the benefits and functions provided by a stock to society, such as shelter provided by housing stock, mobility from transportation infrastructure, or energy supplied by power systems.
- Services are a core concept in understanding how resource use translates into societal well-being and economic activities

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The Stock-Flows-Service Nexus

- Recreation
- Transportation
- Housing
- Health
- Information
- Culture
- Employment
- Etc.

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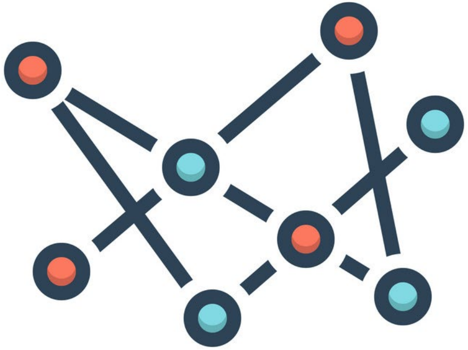
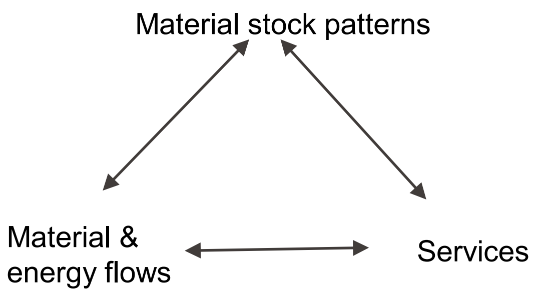
The Stock-Flows-Service Nexus



What is a **nexus**?

- A **nexus** refers to a **connection**, **link**, or series of **interconnected** elements between **multiple components** or **systems**.
- It describes a point of convergence where different elements come together and interact, often highlighting the interdependencies and relationships between them.
- The term can be applied in various contexts, such as social, economic, or environmental systems, to emphasize how changes in one part can influence others.

The Stock-Flows-Service Nexus



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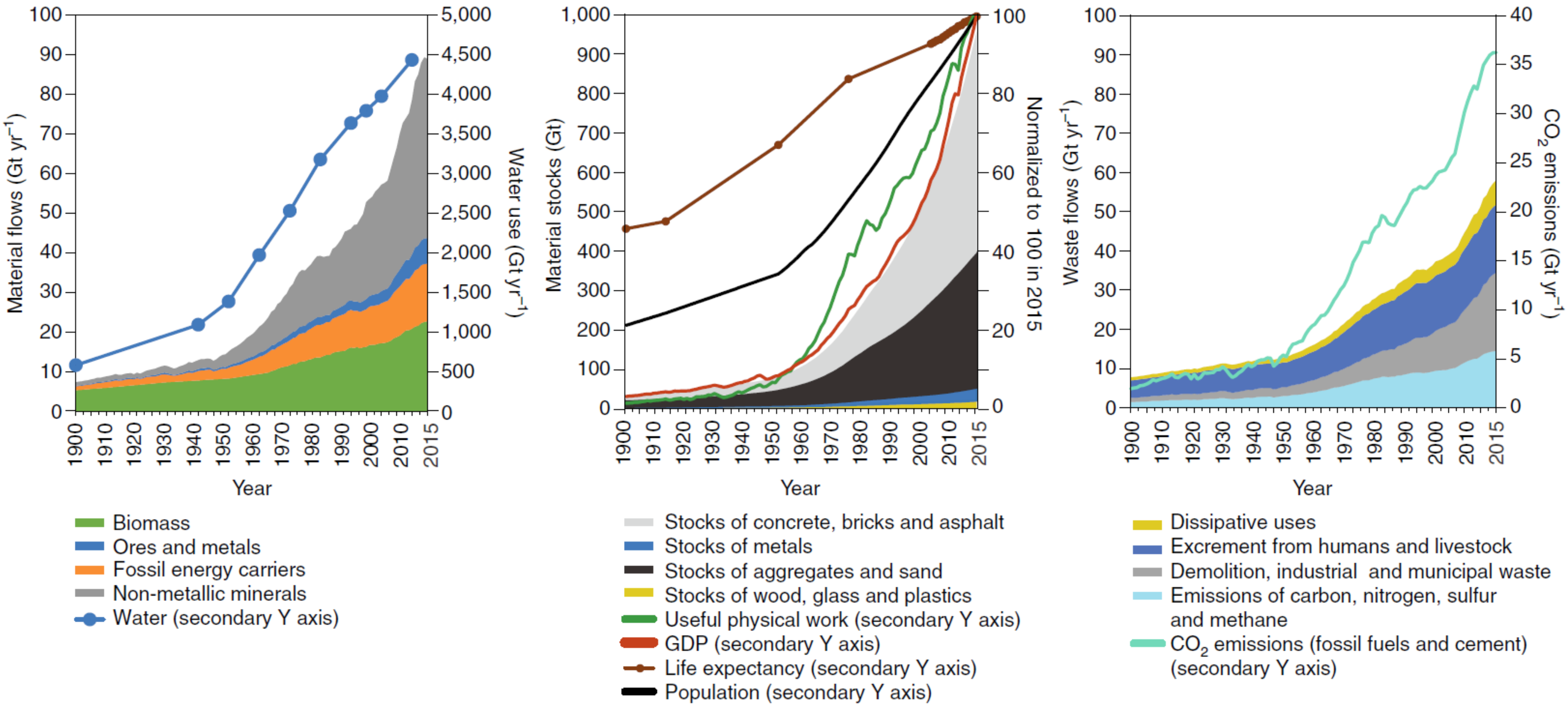
What is the **stocks-flows-service nexus**?

- The **Stock-flows-service nexus** refers to the **interconnection** and **interdependence** between **stocks**, **flows**, and **services** within a **system**.
- It highlights the dynamic relationships and feedback loops that influence material and energy use, service provision, and the resulting environmental, social, and economic outcomes.
- The Stock-Flow-Service Nexus helps to analyze and optimize these interconnections, aiming for sustainable resource management and minimizing trade-offs among different sustainability goals.

Source: Haberl et al. 2017

Links between stocks and flows



Source: Haberl et al. 2019

The Stock-Flows-Service Nexus

Relevance in Industrial Ecology and Sustainability

- The **Stock-flows-service nexus (SNSF)** helps bridge the gap between material and energy inputs (flows), accumulated resources (stocks), and the services they provide to society.
- It aids in understanding **how changes** in one part of the system (e.g., reducing input flows) **can influence resource dynamics** and **service provision**, guiding sustainable transitions at different scales—from products to cities to national economies.

Links between resources and SDGs

Direct and indirect relationship of natural resources to the three dimensions of sustainability in relation to the Sustainable Development Goals (SDGs)

Adapted from: IRP (2019)

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The role of flows, stocks and services in resource-dynamics

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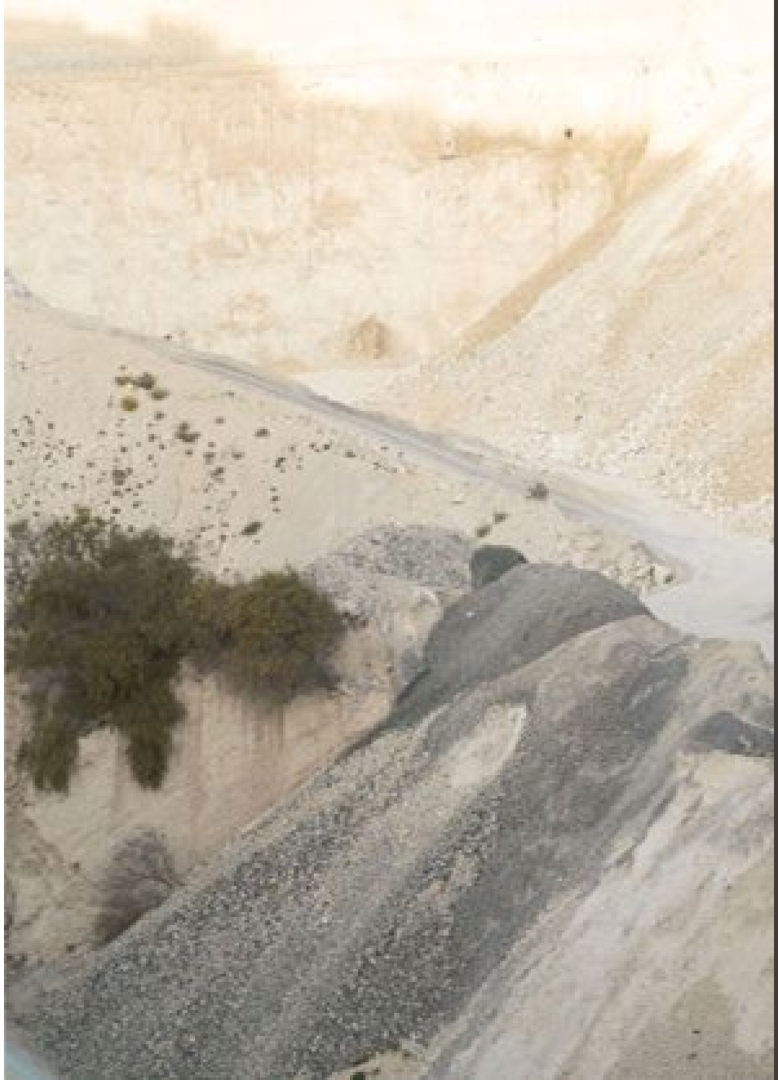
- **In-Use Stocks as Biophysical Structures of Society**
  - Physical “backbone” of societal functions. Integral to understanding material accumulation and resource efficiency
- **Service Provision as a Driver of Stock Accumulation**
  - Living space, transportation, etc. drives growth in material stocks. Services dictate the size and composition of stocks
- **Shift from Substance-Specific to Broader Analysis**
  - Single substance vs all commodities. Stock-flow relationships
- **Integration of Stock and Flow Dynamics**
  - Insights into resource efficiency, circularity, drivers

The role of flows, stocks and services in resource-dynamics

- **Material Stocks are Key to Providing Services**:
  - Societal services rely on material stocks and resource flows.
- **Rethinking Well-Being**:
  - Traditional indicators (like GDP) alone don’t capture societal well-being. A service-based approach offers a more nuanced understanding of how material use supports societal needs.
- **Investments in Stocks Shape Future Options**:
  - Long-lived stocks create lasting legacies that can either support or limit future resource options.



System's linkages in society's metabolism

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The Stock-Flows-Service Nexus: The challenge

- **Material stocks** (e.g. infrastructures, buildings, dams) **enable certain modes of production and living**
- But **determine further resource use** (e.g. energy)
- And **restrict alternative pathways** => **lock-in** effects
- Trends are a **major obstacle for sustainable resource use** levels

- How to **identify alternative pathways?**

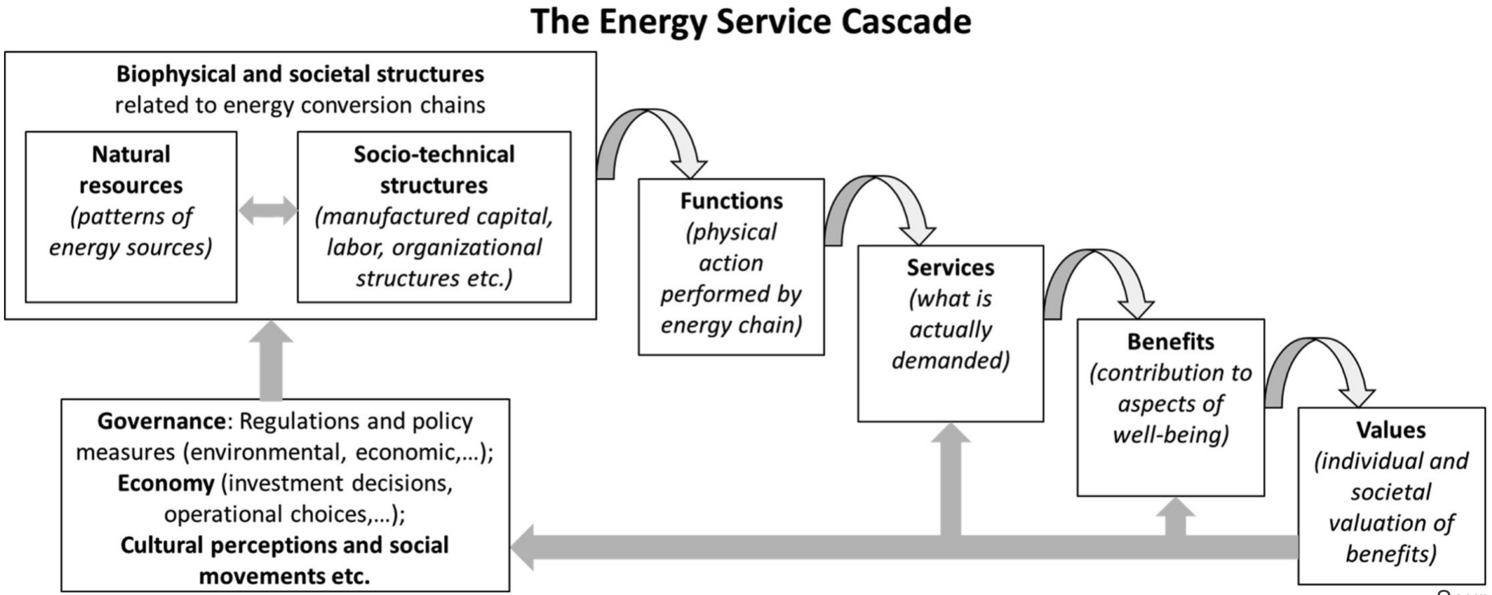
The Stock-Flows-Service Nexus: The challenge

- **Reducing** resource **use** by determining **alternative** options for **service** provisioning
  - Clarity about services
  - Identify and measure the links between flows and stocks

- Questions:
  - **How** to determine alternatives?
  - What possible **alternatives** exist?
  - What could be **potential obstacles** for **implementing** these alternatives?

The "cascade" approach

- A "cascade" approach: used to understand the **multi-step process** through which **benefits** and finally their **values** are **derived** from **biophysical structures and processes**, which in turn **influences** the **functioning** of (eco)systems and their **services**



Source: Kalt et al. 2019

The Stock-Flows-Service Nexus and the material and energy service cascade

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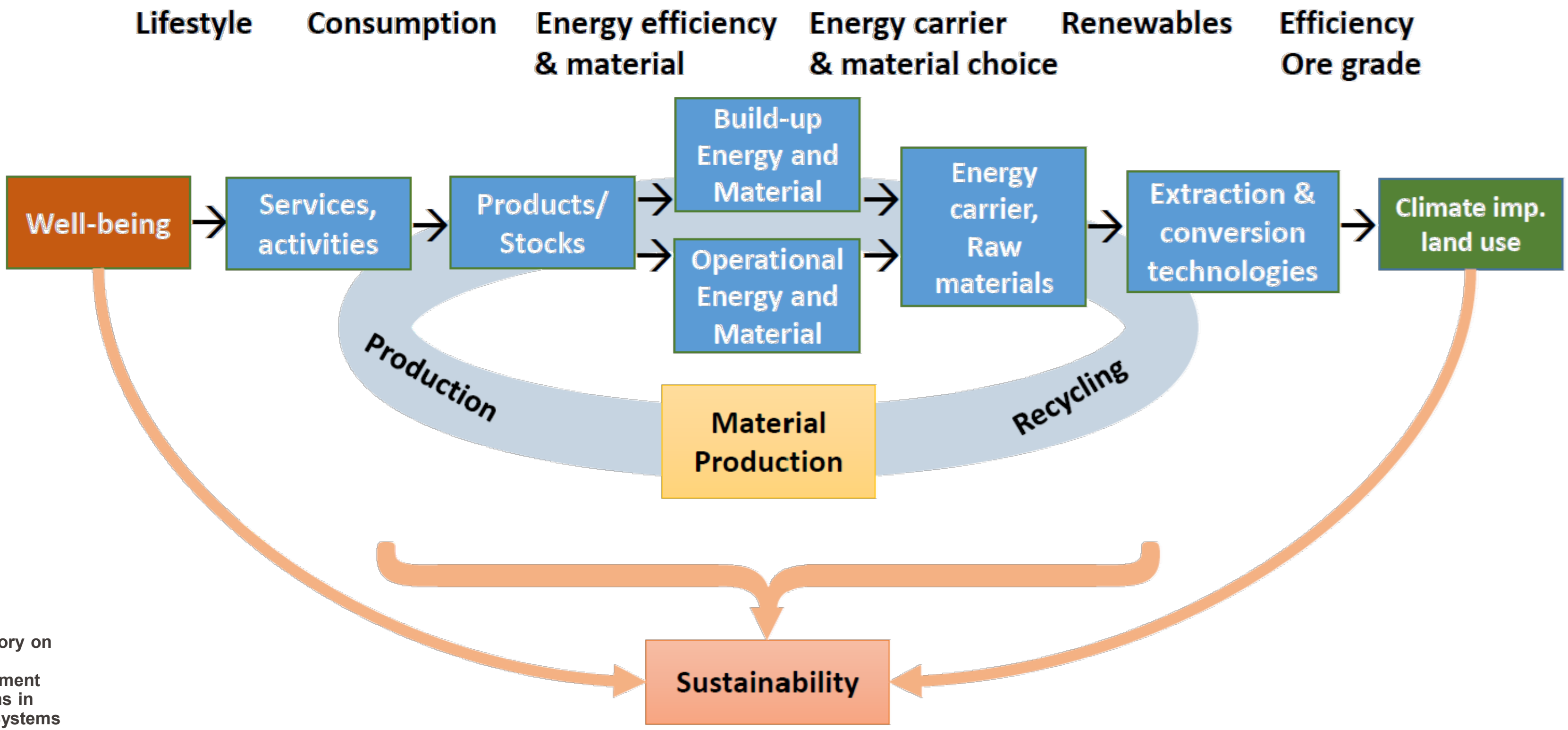

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Source: Bergsdal et al. (2007),; Kalt et al. (2019), ; Haberl et al. (2017)

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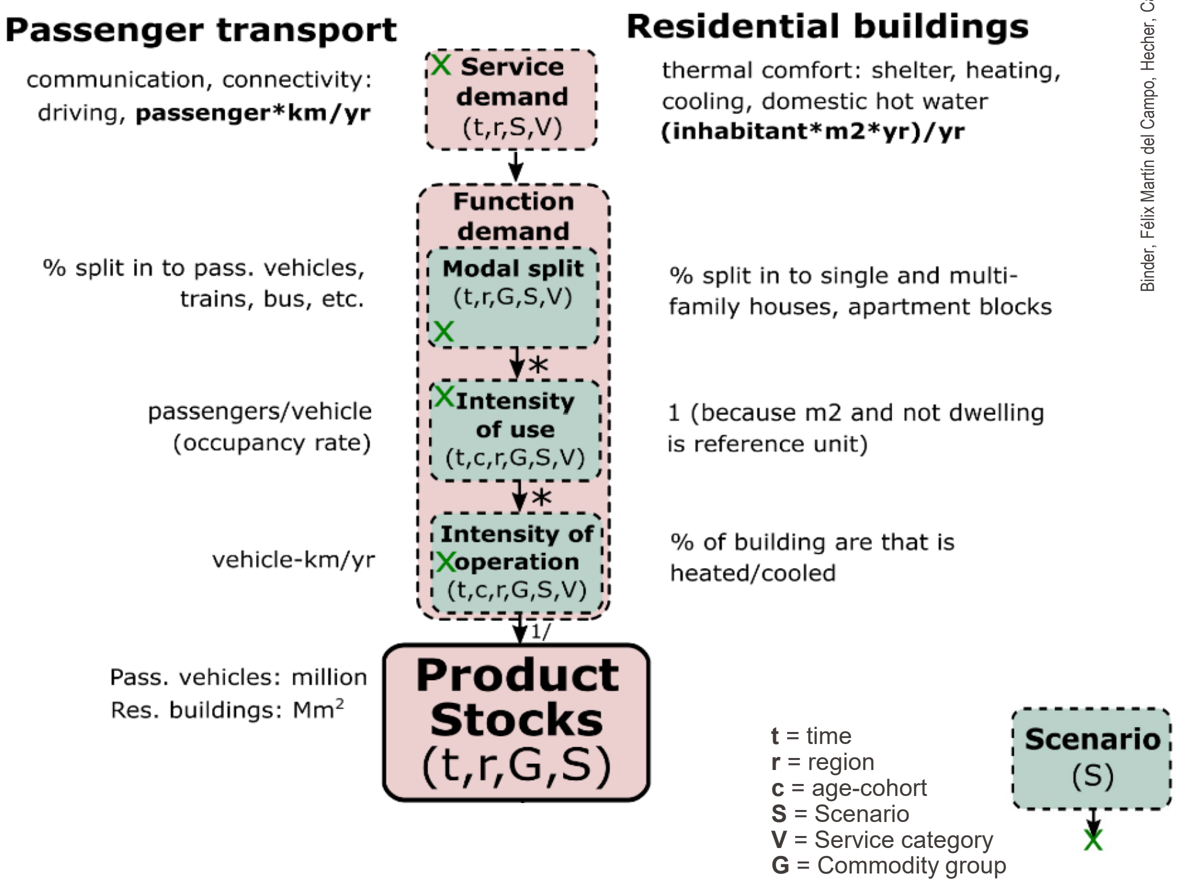
Final remarks

- Materials are needed to build up and maintain stocks
- Stocks provide services
- Services are linked to wellbeing



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Final remarks

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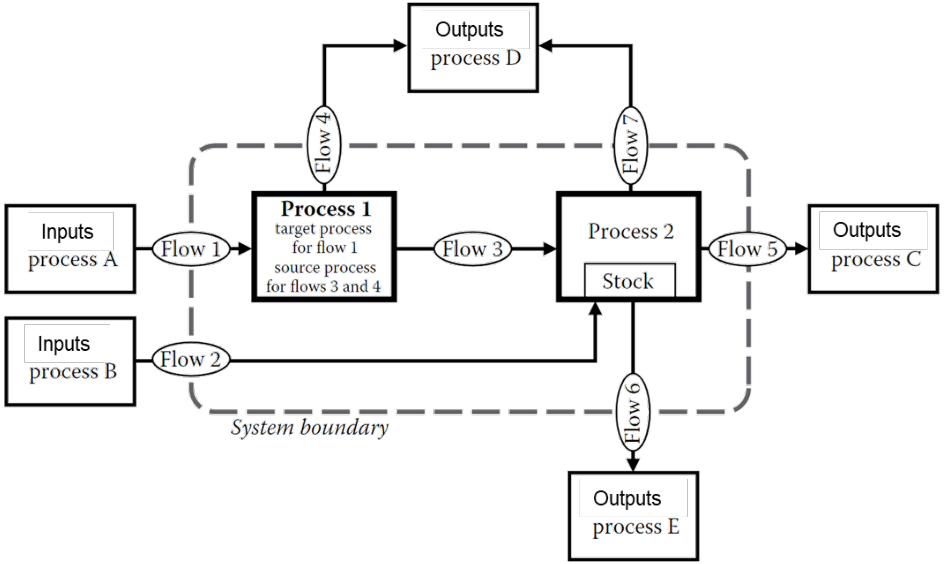
- MFA (flows and stocks) are beneficial to **understand** past **trajectories** and current and future **patterns** of society-nature **interactions**
- **Need** to distinguish flows and stocks **services!**
- Future research on this will likely be able to underpin strategies for:
  - **Decoupling** between societal well-being and resource demand
  - **Contingencies and lock-ins** resulting from past build-up of material stocks,
  - Possible **leverage points** to foster sustainability transformations



Material Flow Analysis

MFA notation, transfer coefficients and the time aspect in MFA

Symbols used in MFA diagrams

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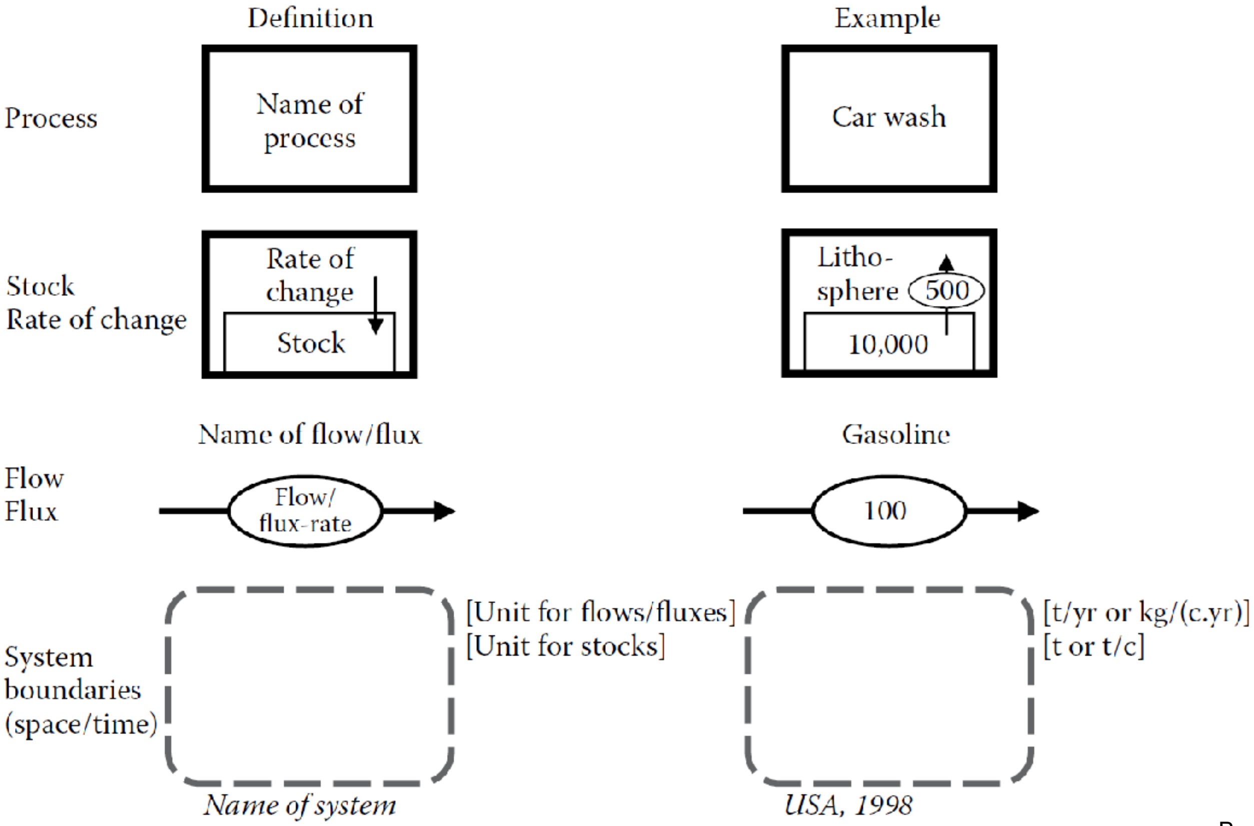

Brunner & Rechberger, 2016

MFA notation

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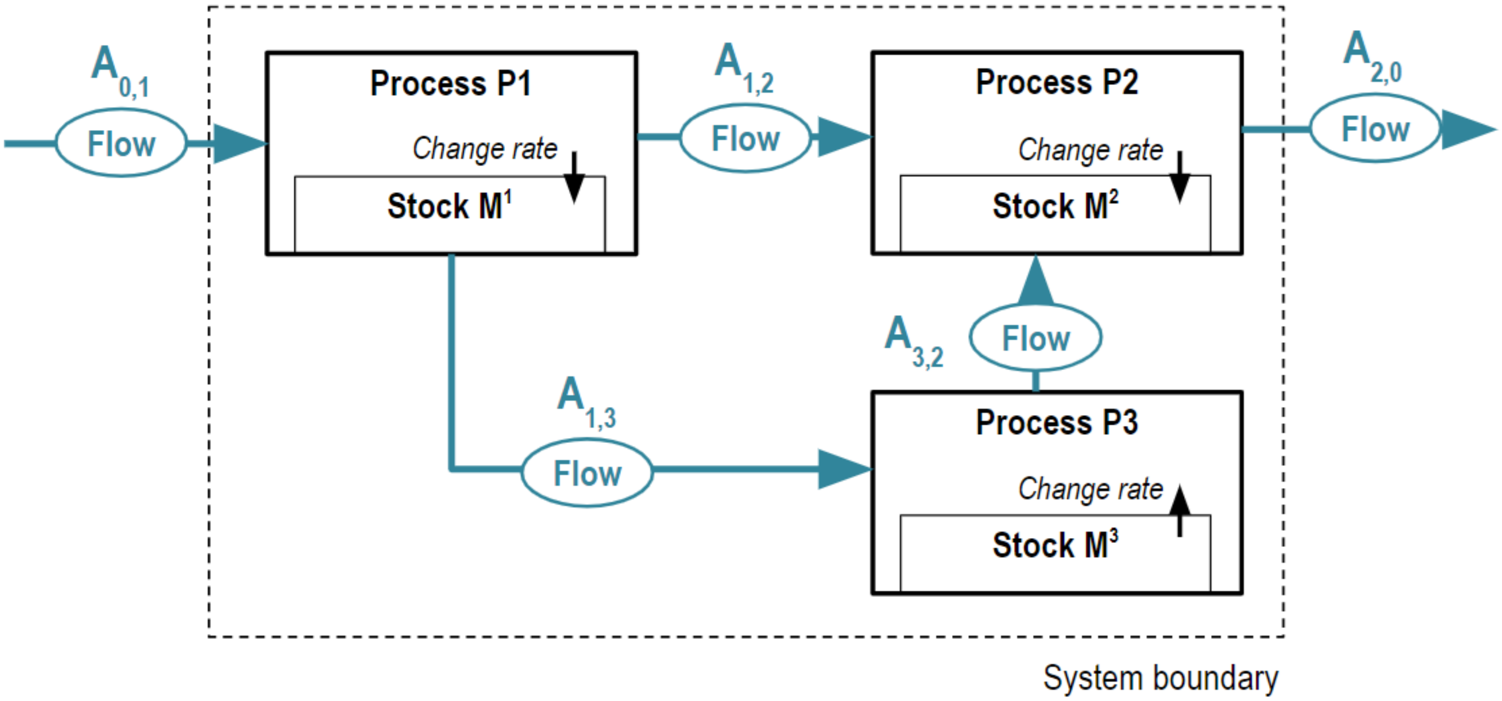

Brunner & Rechberger, 2016

MFA notation

- **Mass** [t] $\mathbf{M}_{\text{salt, stock}}$
- Material **flow** [t/yr] $\mathbf{A}_{\text{salt, flow}}$
- **Substance** flow [kg/yr] $\mathbf{A}_{\text{Cl, salt, flow}}$
- Substance **concentration** [kg/t] $\mathbf{C}_{\text{Cl, salt}}$

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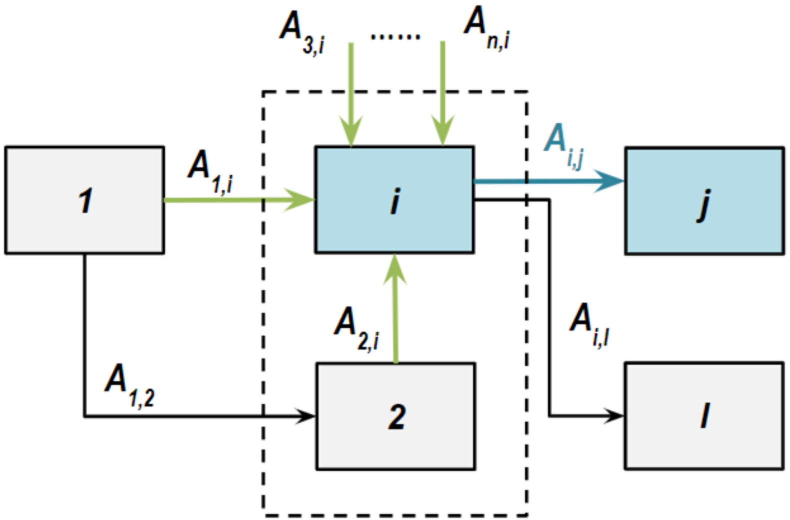
Transfer coefficients

Transfer coefficients describe the **division** of a **material/substance leaving a process** (output) for a single input or the sum of all inputs.

Transfer coefficient ($k_{i,j}$) indicates the relative proportion of the total input to process *i* that flows into process *j*.



$$k_{i,j} = \frac{A_{i,j}}{\sum_n A_{n,i}}$$

$$k_{i,j} + k_{i,l} = 1$$

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Transfer coefficients

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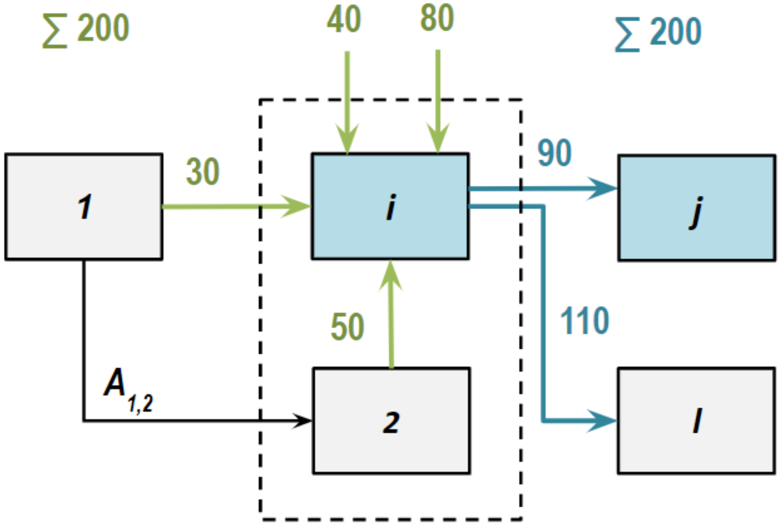

$k_{i,j}$ = 90 / (50+30+40+80) = 0.45

$k_{i,l}$ = 110 / (50+30+40+80) = 0.55

$k_{i,j} + k_{i,l}$ = 0.45 + 0.55 = 1

Transfer coefficients

Transfer coefficients describe the **division** of a **material/substance leaving a process** (output) for a single input or the sum of all inputs.

Benefits

- Quantifying Resource Allocation and Efficiency
- Tracing Material Flows and Pathways
- Supporting System Optimization
- Enabling Modeling and Predictive Analysis
- Understanding Environmental and Economic Trade-Offs

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The time aspect in MFA

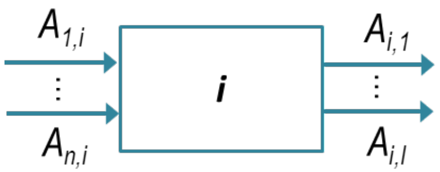
- **Steady state:** constant flows and stocks
- **Quasi-stationary:** constant flows and linear (de)growth of stocks
- **Dynamic:** system state at "*t*" is a function of the state a "*t-1*"
- **Time dependent:** parameters external to the model are function of time (e.g. extraction or disposal costs)

Steady state

- Material and energy are conserved for each individual process and for the overall system.
- **Steady state of a process *i*:**

$$\frac{\partial A}{\partial t} = 0$$

$$\frac{\partial M^i}{\partial t} = A_{1,i} + A_{2,i} + \ldots + A_{n,i} - (A_{i,1} + A_{i2} + \ldots + A_{i,l}) = \sum_n A_{n,i} - \sum_l A_{i,l} = 0$$



- **Steady state of the overall system *j*:**

$$\frac{\partial M^{tot}}{\partial t} = A_{in} - A_{out} = 0$$

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Quasi-stationary

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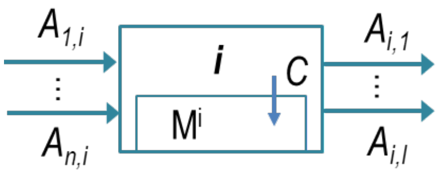
- **Quasi-stationary case of a process *i*:**

$$\frac{\partial A}{\partial t} = 0$$

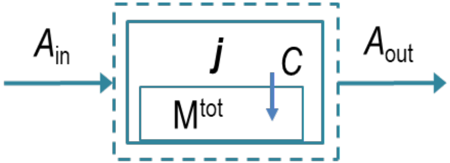
$$\frac{\partial M^i}{\partial t} = A_{1,i} + A_{2,i} + \ldots + A_{n,i} - (A_{i,1} + A_{i2} + \ldots + A_{i,l}) = \sum_n A_{n,i} - \sum_l A_{i,l} = C$$

$$\frac{\partial C}{\partial t} = 0$$



- **Quasi-stationary case of the overall system *j*:**

$$\frac{\partial M^{tot}}{\partial t} = A_{in} - A_{out} = C$$



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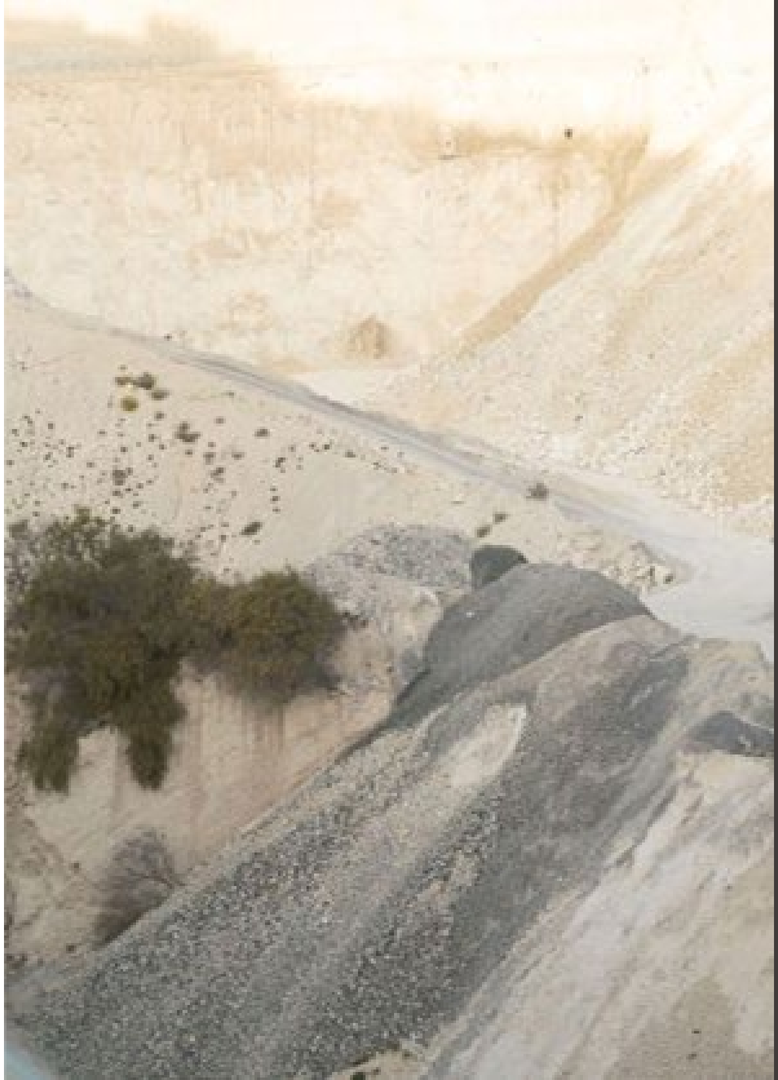

Example of MFA and mathematical system definition

Steps of MFA

Step I: System definition
Problem definition, definition of system boundaries, selection of processes and flows of materials/substances (qualitative model)

Step II: Measurement
Data collection of flows and stocks of materials/substances and characterization of uncertainties (measurements, literature data, estimations)

Step III: Calculation
Calculation of unknown quantities by balancing of materials based on the principle of mass conservation (MFA software)

Step IV: Illustration and interpretation
Sources, stocks, flows and sinks

Step V: Recommendations
How can the system be optimized?

System definition

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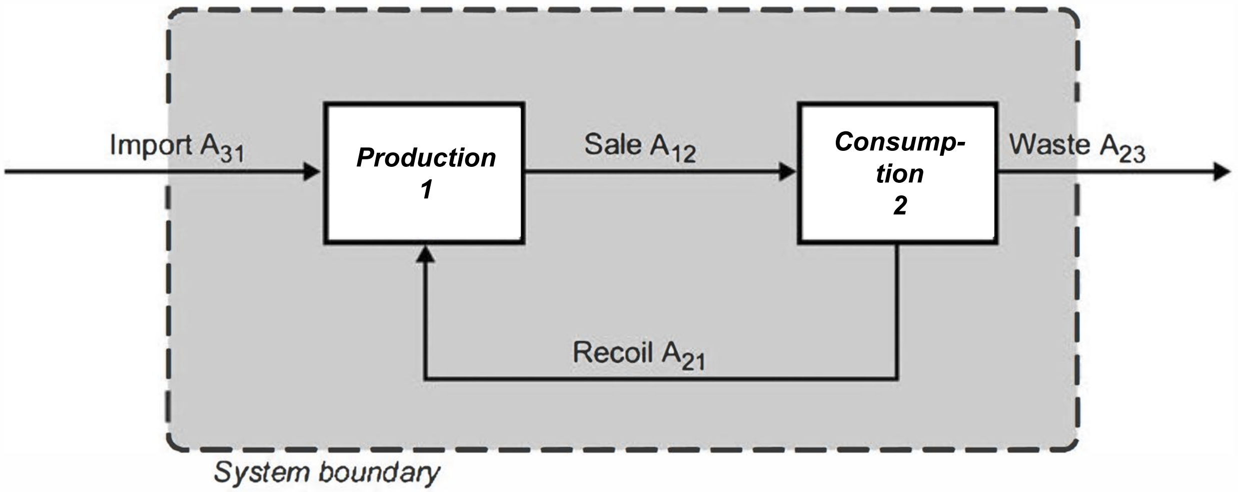
- **Research question for glass bottle management in CH:**

  How does glass recycling change the system?
  a. How much glass needs to be imported?
  b. How much energy can be saved?
- **System boundary:** Switzerland, 1 year
- **Unit for flows:** kg/c,yr
- **Unit for stocks:** kg/c
- **Processes:** glass production, glass consumption
- **Material flows:** glass, waste glass
- **Indicators:** glass import rate, energy use

System definition

Simplified material system for glass bottle management in Switzerland

Material flow: glass, waste glass



Baccini & Brunner, 2012

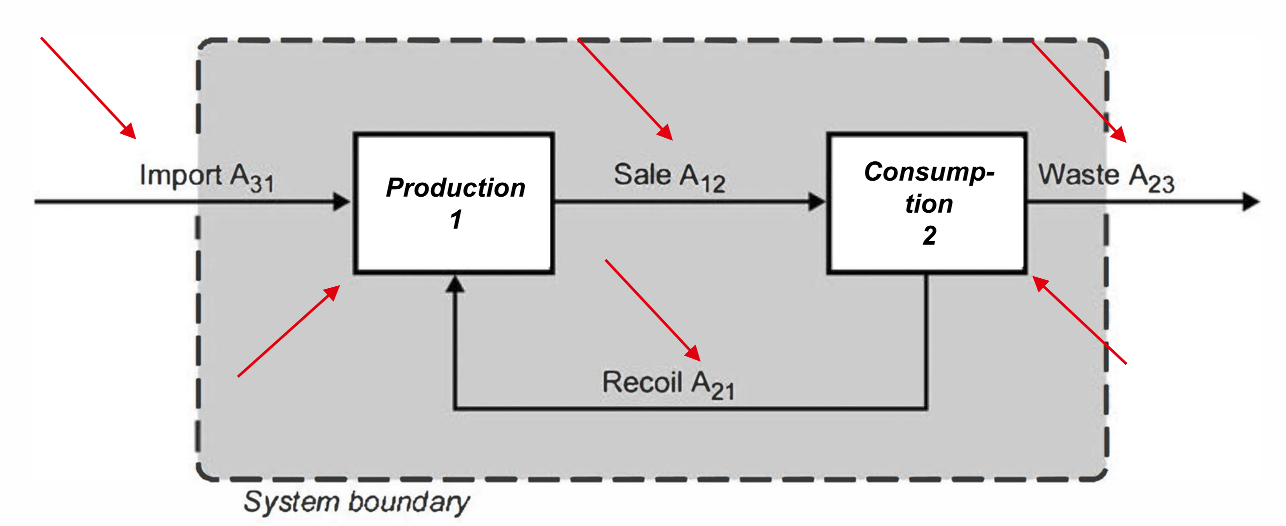
System definition

Procedure for mathematical system definition:

- Define the system unknowns
- Setup the system of equations
- Complete the system of equations with specific relationships
- Solve the system of equations
- Analyze the results and check for errors

System unknowns (steady state)

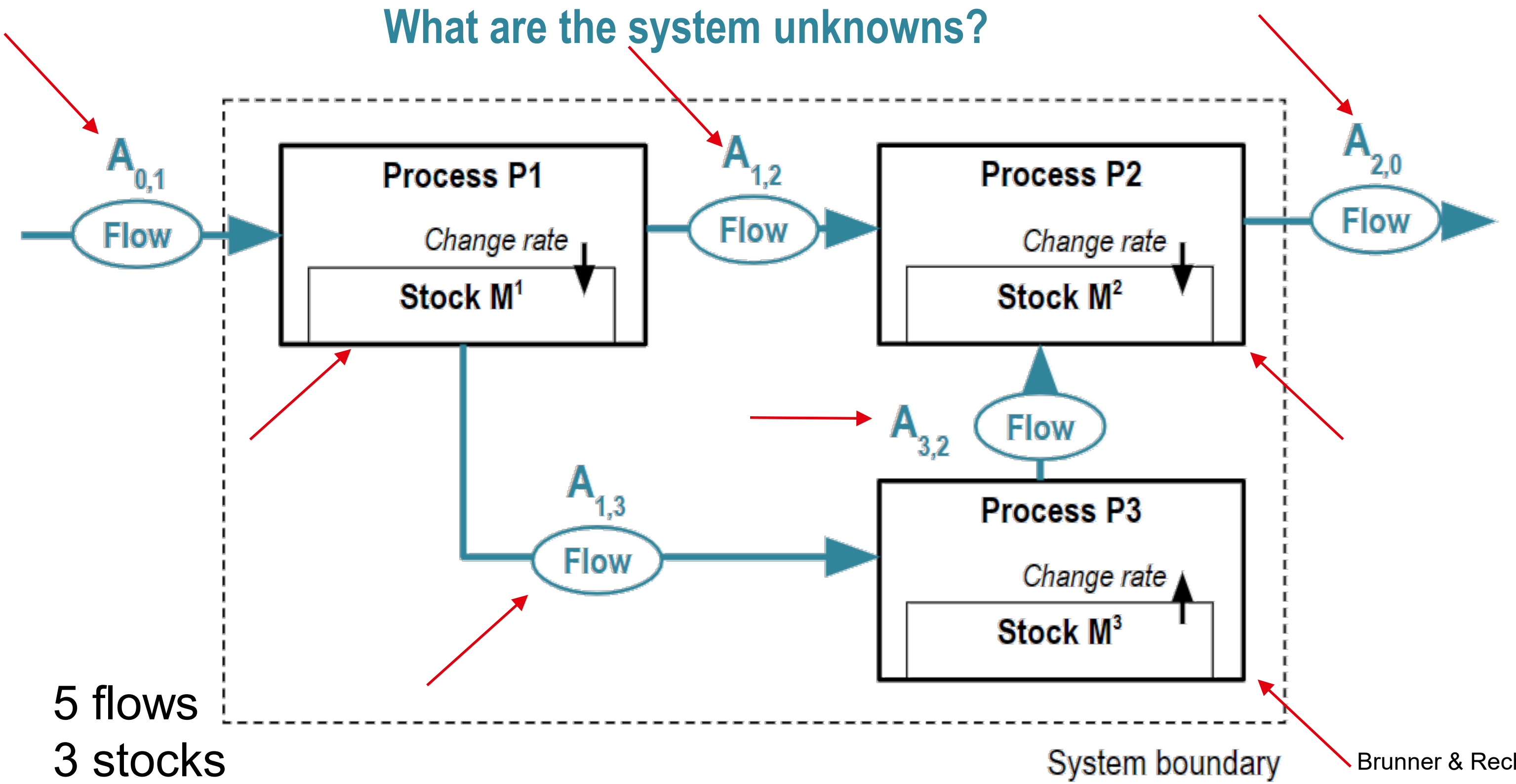
What are the system unknowns?



4 flows
2 stocks

Baccini & Brunner, 2012

System unknowns (quasi-stationary state)



5 flows
3 stocks

Brunner & Rechberger, 2016

System unknowns

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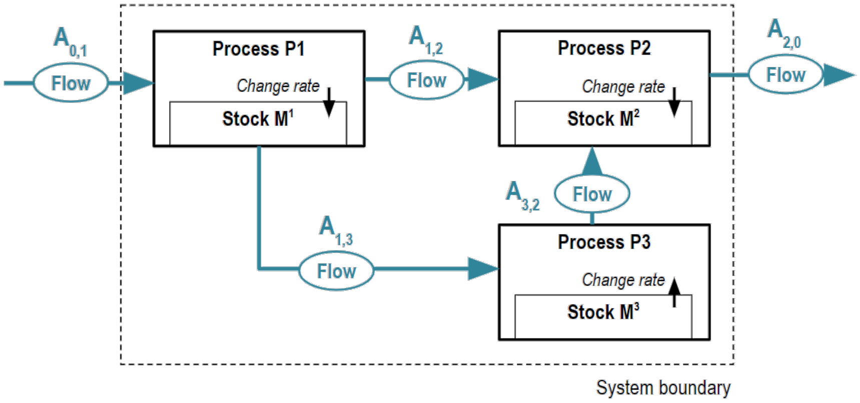
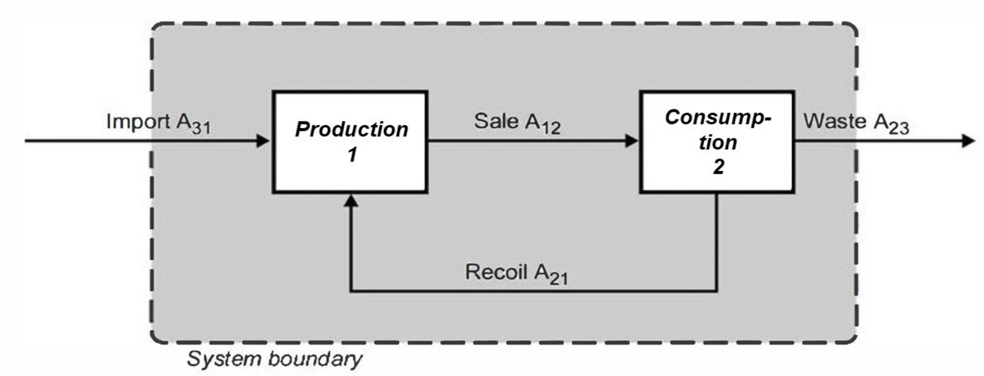
Steady state: 6 system unknowns (stocks, flows)

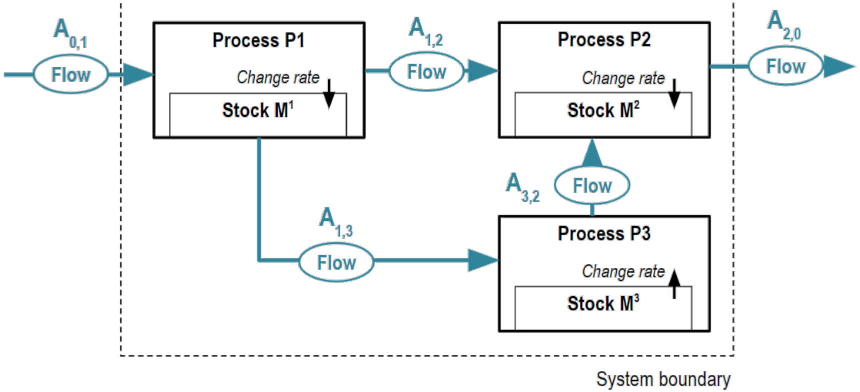
Quasi-stationary state: 8 system unknowns (stocks, stock changes, flows)

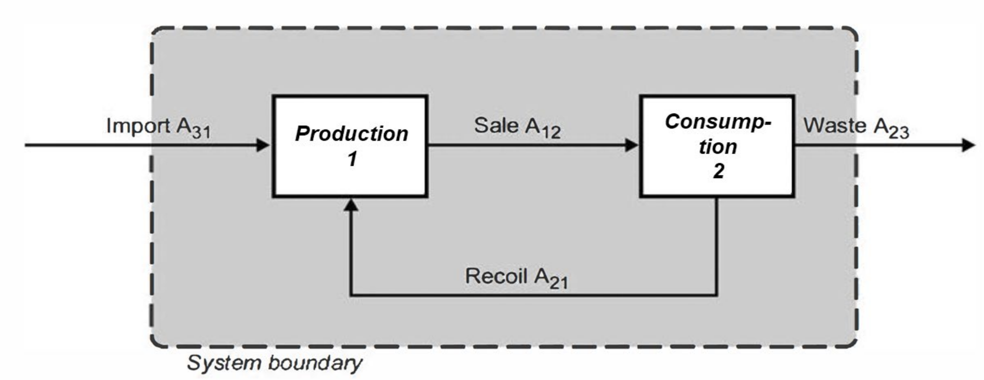




Baccini & Brunner, 2012

2 balance equations (whole system)





Quasi-stationary state

$$\frac{\partial M^{tot}}{\partial t} = A_{in} - A_{out} = C$$

$$\frac{dM^{(1)}}{dt} = A_{21} + A_{31} - A_{12}$$

$$\frac{dM^{(2)}}{dt} = A_{12} - A_{21} - A_{23}$$

Steady state

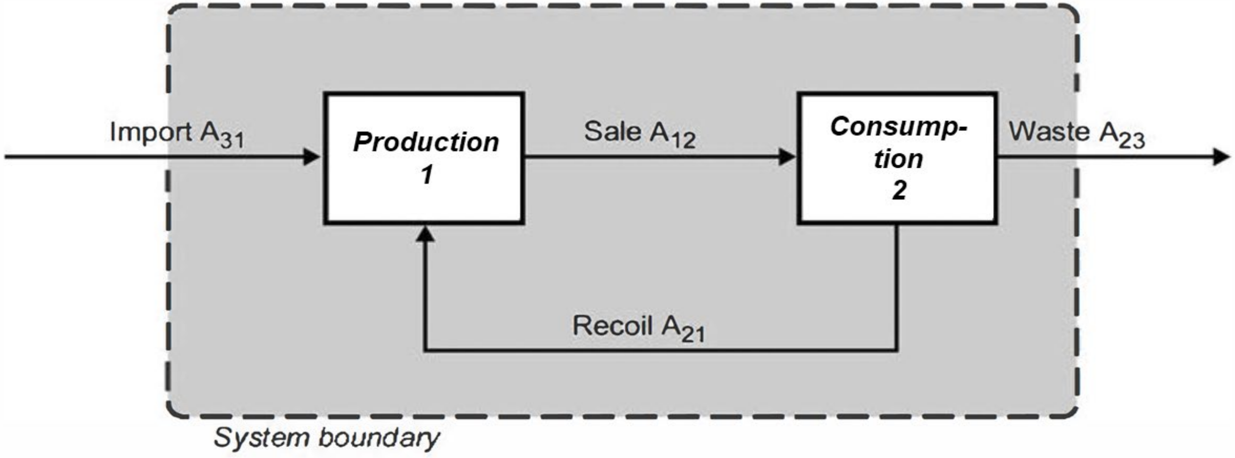
$$\frac{\partial M^{tot}}{\partial t} = A_{in} - A_{out} = 0$$

$$\frac{dM^{(1)}}{dt} = 0$$

$$\frac{dM^{(2)}}{dt} = 0$$

2 balance equations (steady state)

Binder, Félix Martín del Campo, Hecher, Campfens



$$M^{(1)} =$$

$$M^{(2)} =$$

$$A_{31} =$$

$$A_{12} =$$

$$A_{21} =$$

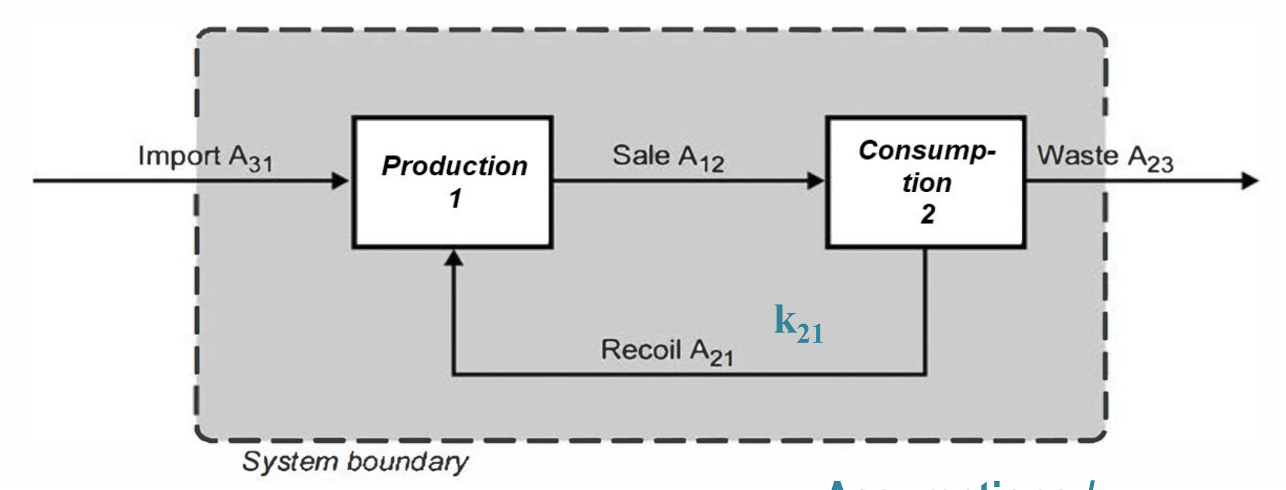
$$A_{23} =$$

$$\frac{dM^{(1)}}{dt} = 0$$

$$\frac{dM^{(2)}}{dt} = 0$$

6 parameter equations (steady state)

Binder, Félix Martín del Campo, Hecher, Campfens



$M^{(1)} = 0$

$M^{(2)} = 0$

$A_{31} =$ given input

$A_{12} =$

$A_{21} =$

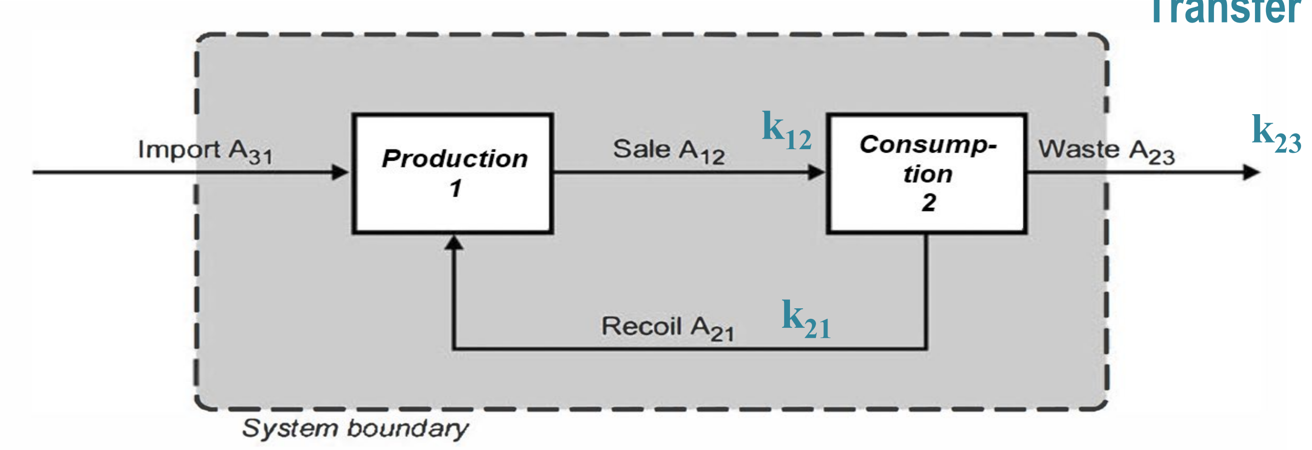
$A_{23} =$

Assumptions / available data

$A_{31} =$ given input
$k_{21} =$ given input

6 parameter equations

Transfer coefficients



$$k_{i,j} = \frac{A_{i,j}}{\sum_n A_{n,i}}$$

$$k_{i,j} + k_{i,l} = 1$$

$$M^{(1)} = 0$$

$$M^{(2)} = 0$$

$$A_{31} = \text{given input}$$

$$A_{12} = k_{12}(A_{21} + A_{31})$$

$$A_{21} = \underline{k_{21}}A_{12}$$

$$A_{23} = k_{23}A_{12}$$

Solving for each Flow A

$$k_{i,j} = \frac{A_{i,j}}{\sum_n A_{n,i}}$$

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6 parameter equations

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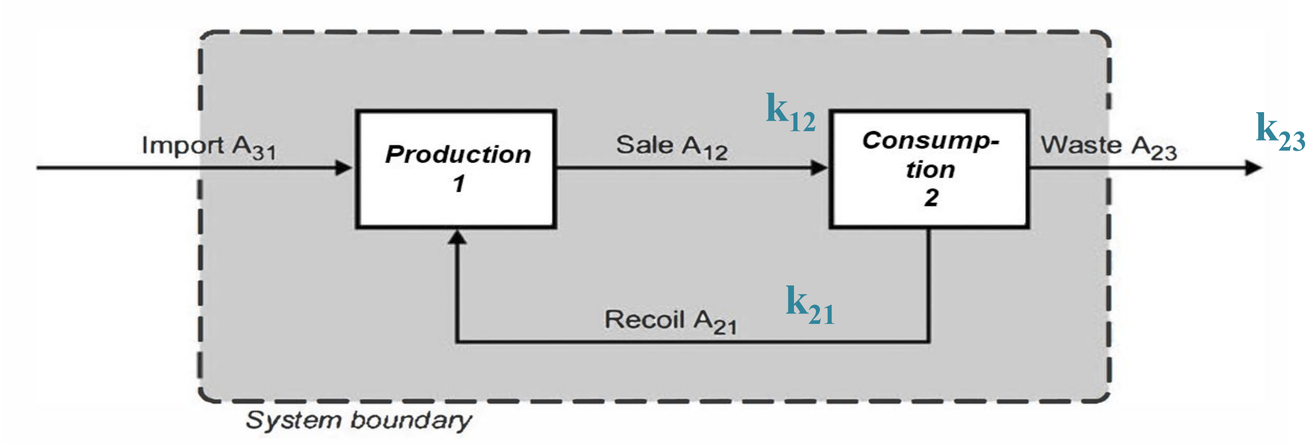


$$M^{(1)} = 0$$

$$M^{(2)} = 0$$

$$A_{31} = \text{ given input}$$

$$k_{21} = \text{given input}$$

$$A_{12} = \frac{A_{31}}{1 - k_{21}}$$

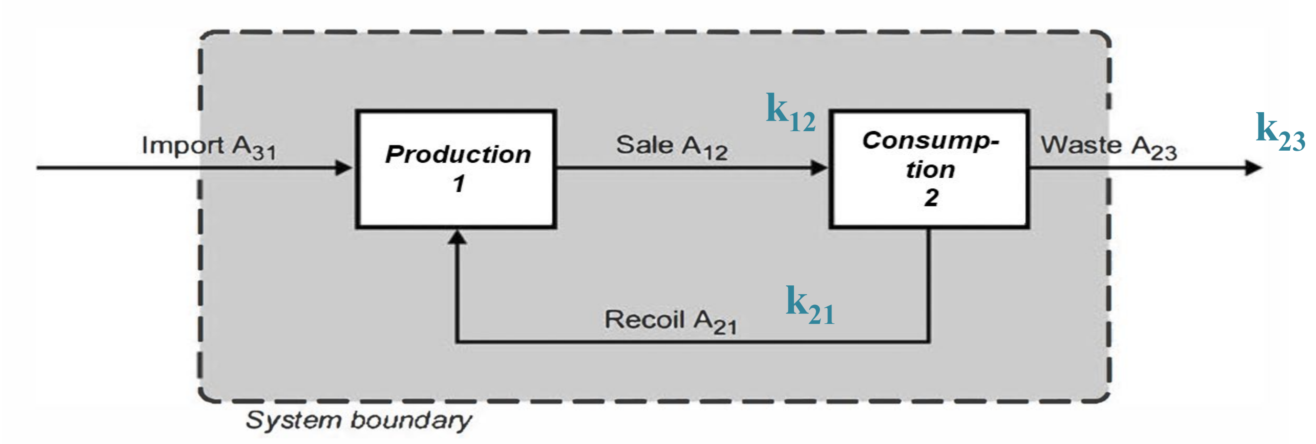
$$A_{21} = \frac{k_{21}\ A_{31}}{1 - k_{21}}$$

$$A_{23} = A_{31}$$

$$k_{i,j} = \frac{A_{i,j}}{\sum_n A_{n,i}}$$

$$k_{i,j} + k_{i,l} = 1$$

6 parameter equations



$$M^{(1)} = 0$$

$$M^{(2)} = 0$$

$$A_{31} = \text{given input}$$

$$k_{21} = \text{given input}$$

$$A_{12} = \frac{A_{31}}{1 - k_{21}}$$

$$A_{21} = \frac{k_{21} A_{31}}{1 - k_{21}}$$

$$A_{23} = A_{31}$$

Import

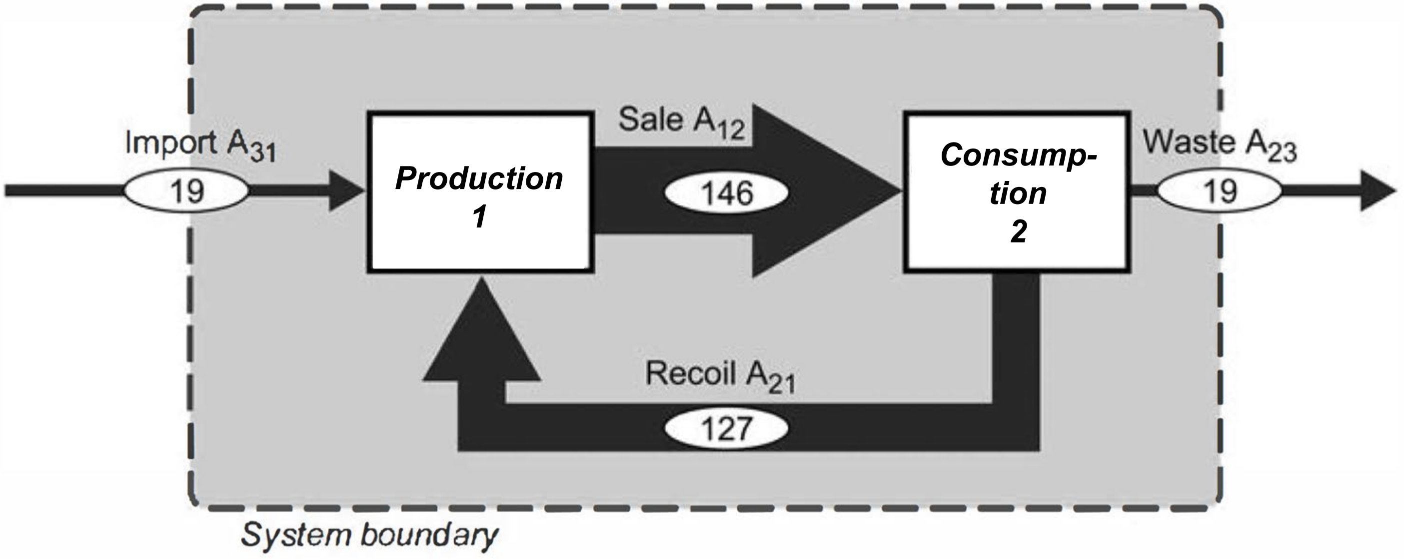
$$A_{31} = 19 \text{ kg}$$

Recycling rate

$$k_{21} = 0.87$$

Results

kg/c,yr



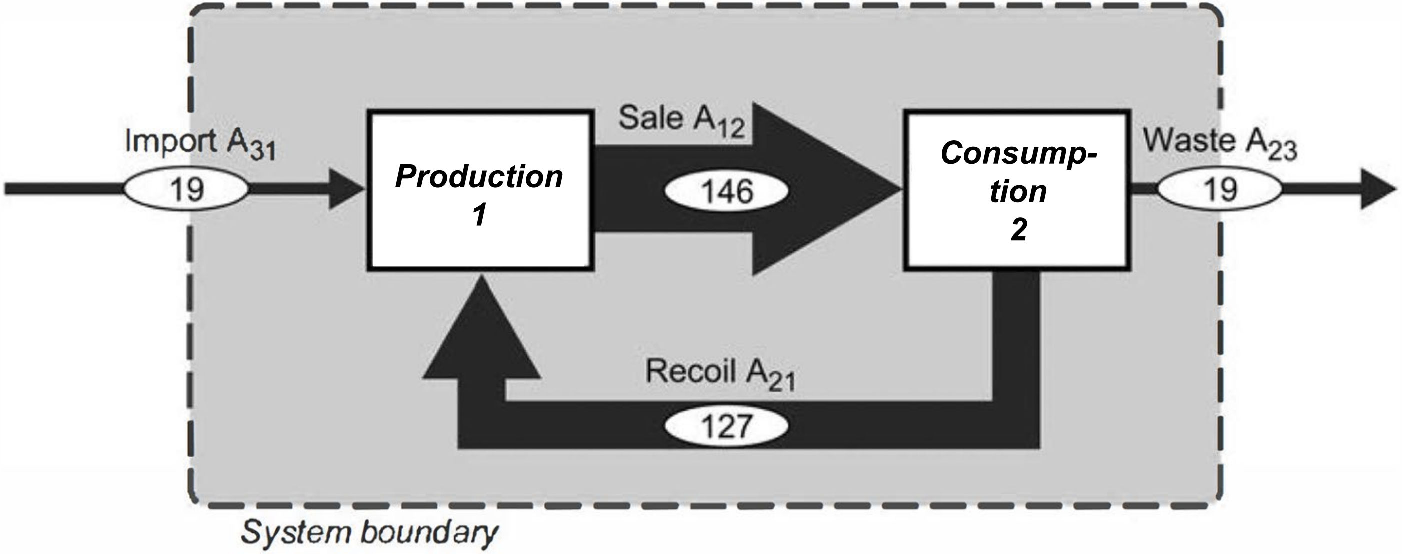
Baccini & Brunner, 2012

Results

What if recycling rate increases by 10%

assuming that glass imports and exports stay constant?

kg/c,yr



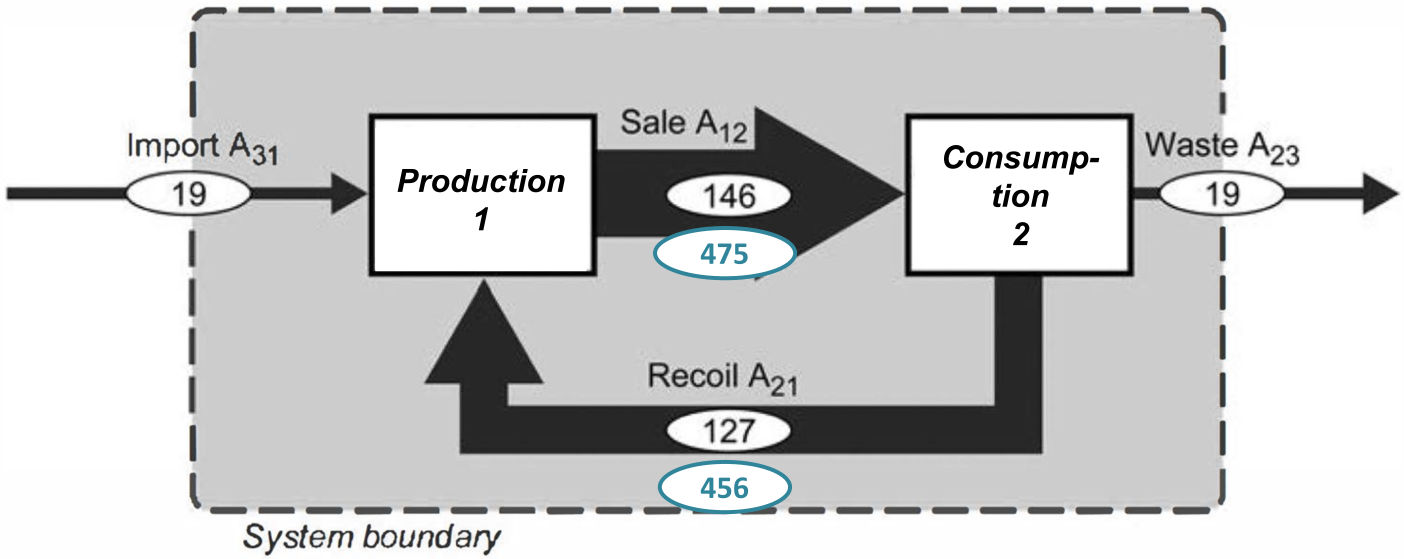
Baccini & Brunner, 2012

Results

What if recycling rate increases by 10%

assuming that glass imports and exports stay constant?

kg/c,yr



$$A_{12} = \frac{A_{31}}{1-k_{21}}$$

$$A_{21} = \frac{k_{21}\,A_{31}}{1-k_{21}}$$

$$A_{23} = A_{31}$$

Recycling rate

$k_{21} = 0.96$

Baccini & Brunner, 2012

Results

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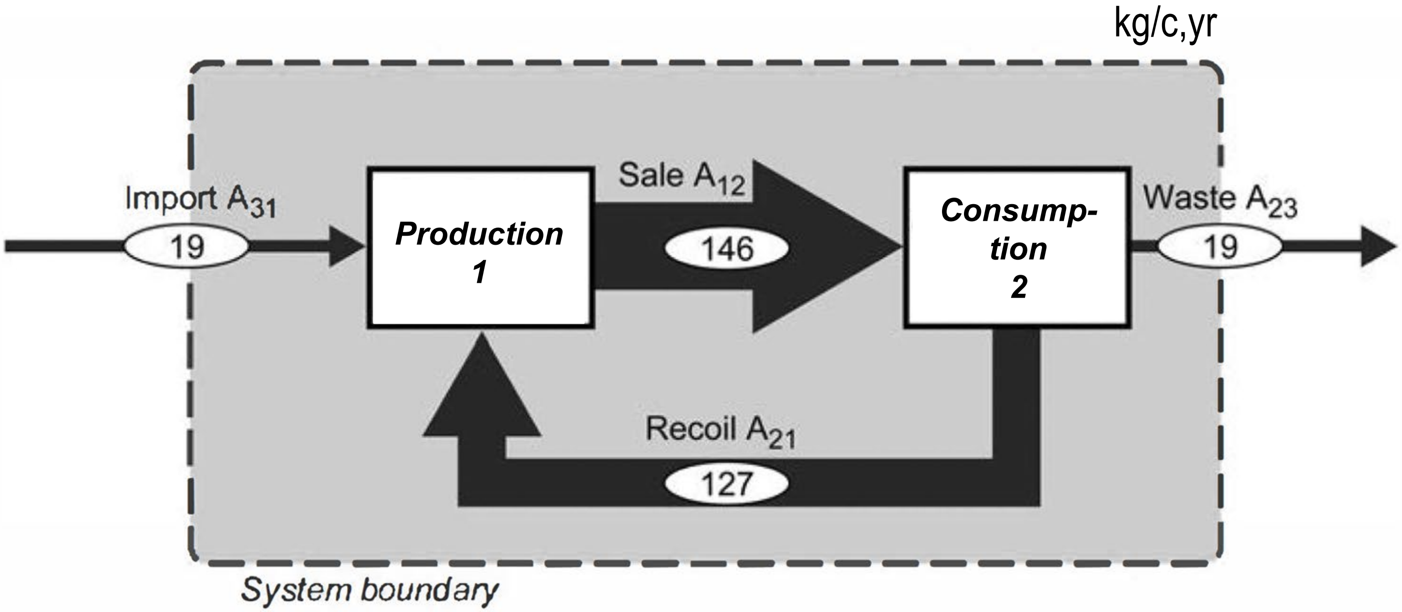
What if recycling rate increases by 10%
assuming that glass bottle sales stay constant?

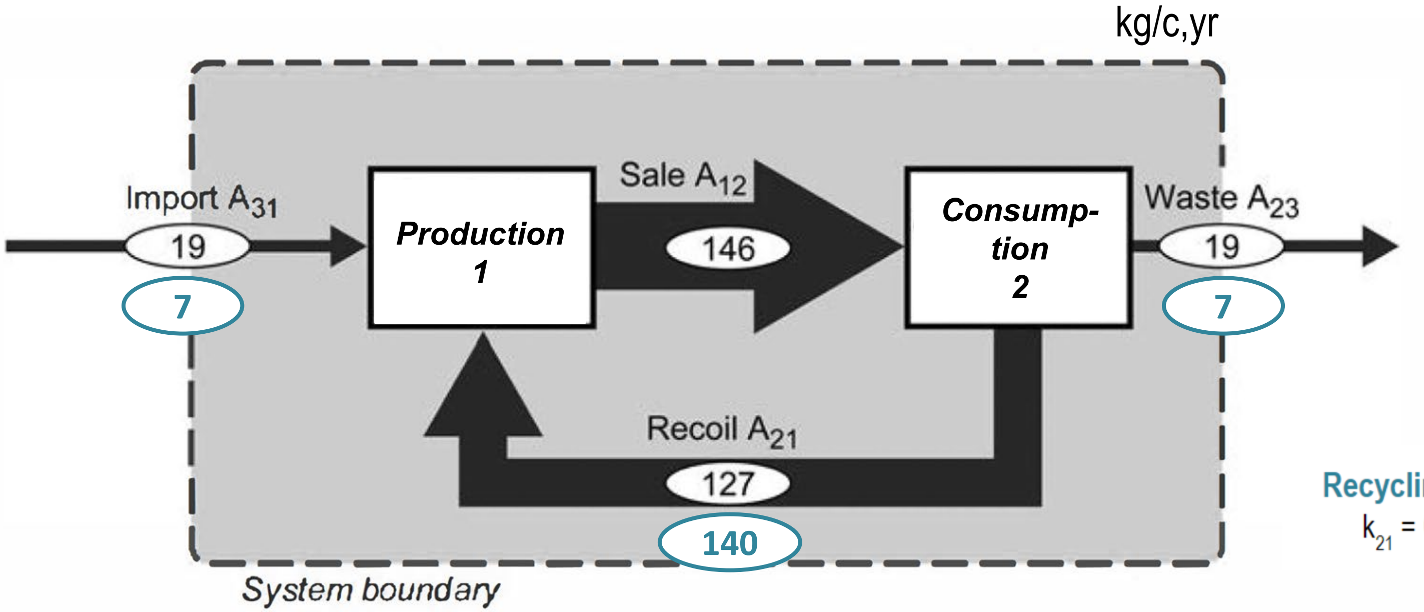


Baccini & Brunner, 2012

Results

What if recycling rate increases by 10%

assuming that glass bottle sales stay constant?



Recycling rate

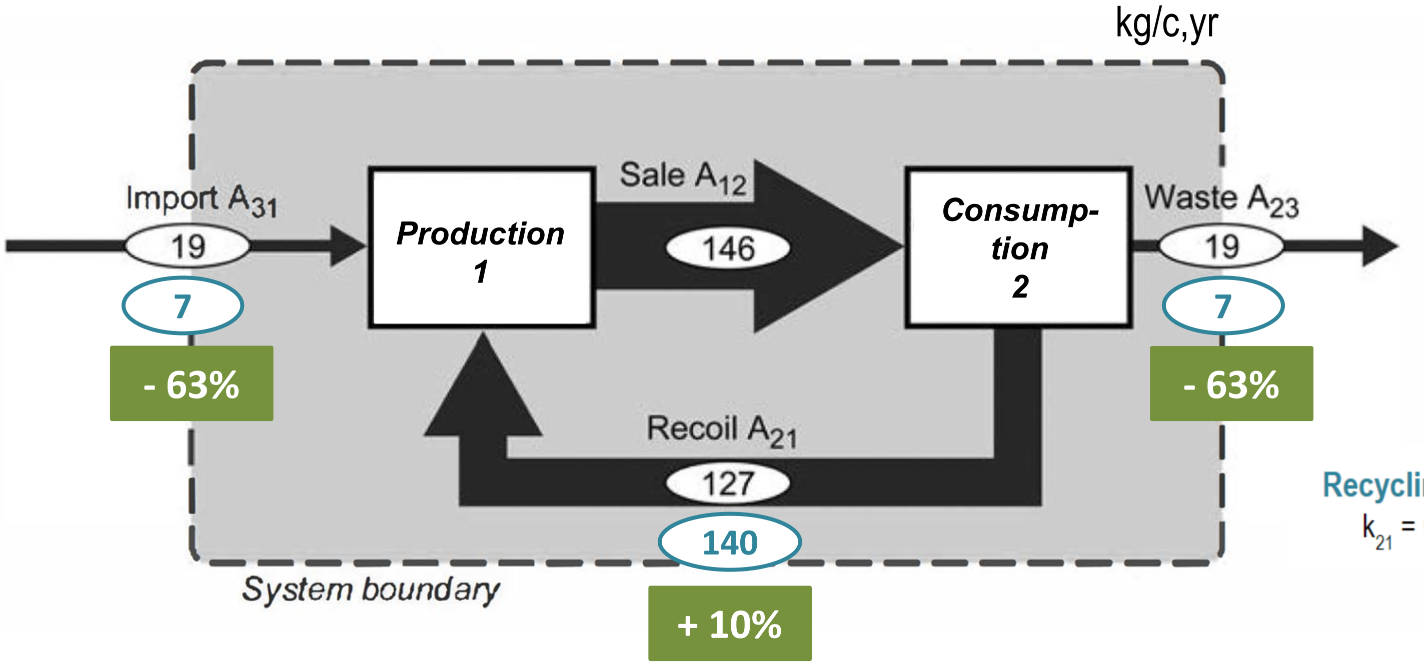
$k_{21} = 0.96$

Baccini & Brunner, 2012

Results

What if recycling rate increases by 10%

assuming that glass bottle sales stay constant?



Recycling rate

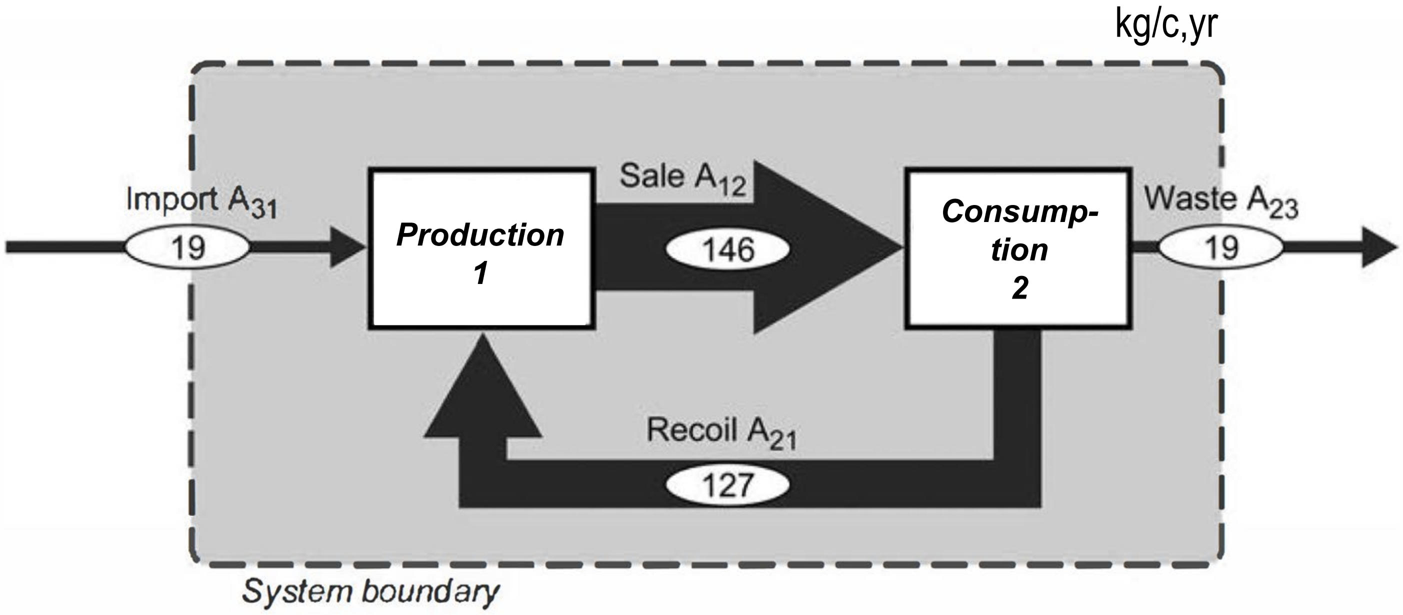
$k_{21} = 0.96$

Baccini & Brunner, 2012

Results

Binder, Félix Martín del Campo, Hecher, Campfens

How to check the results?



Results

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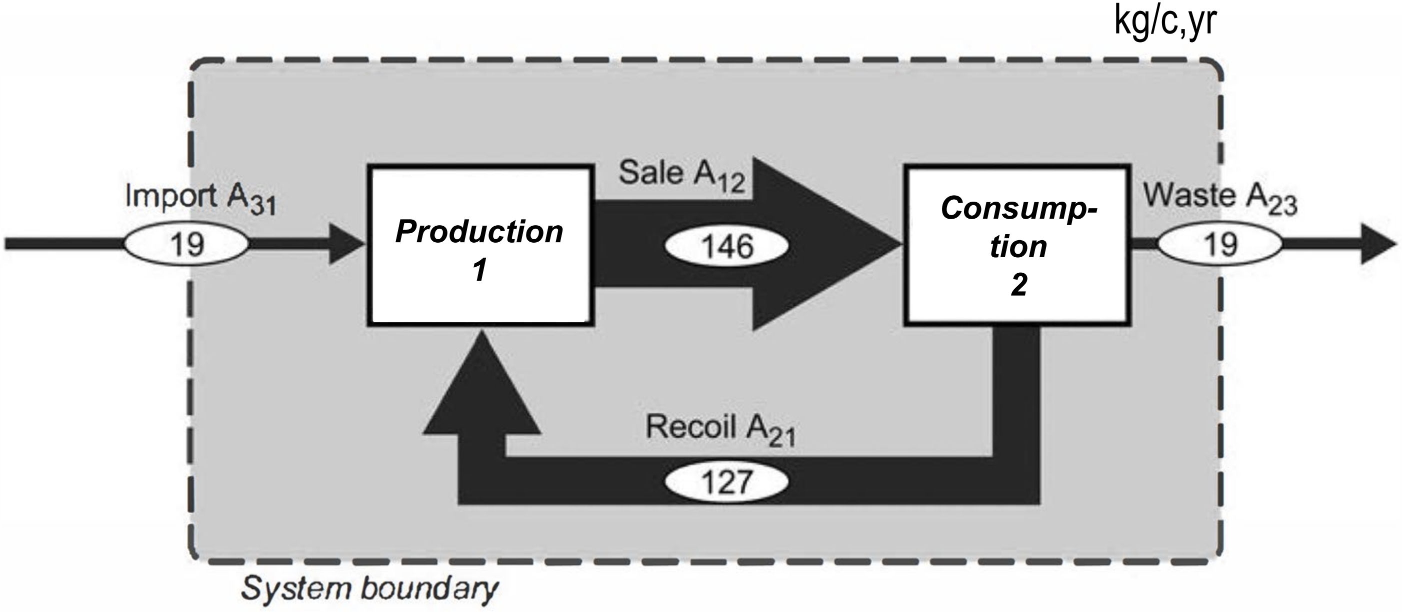
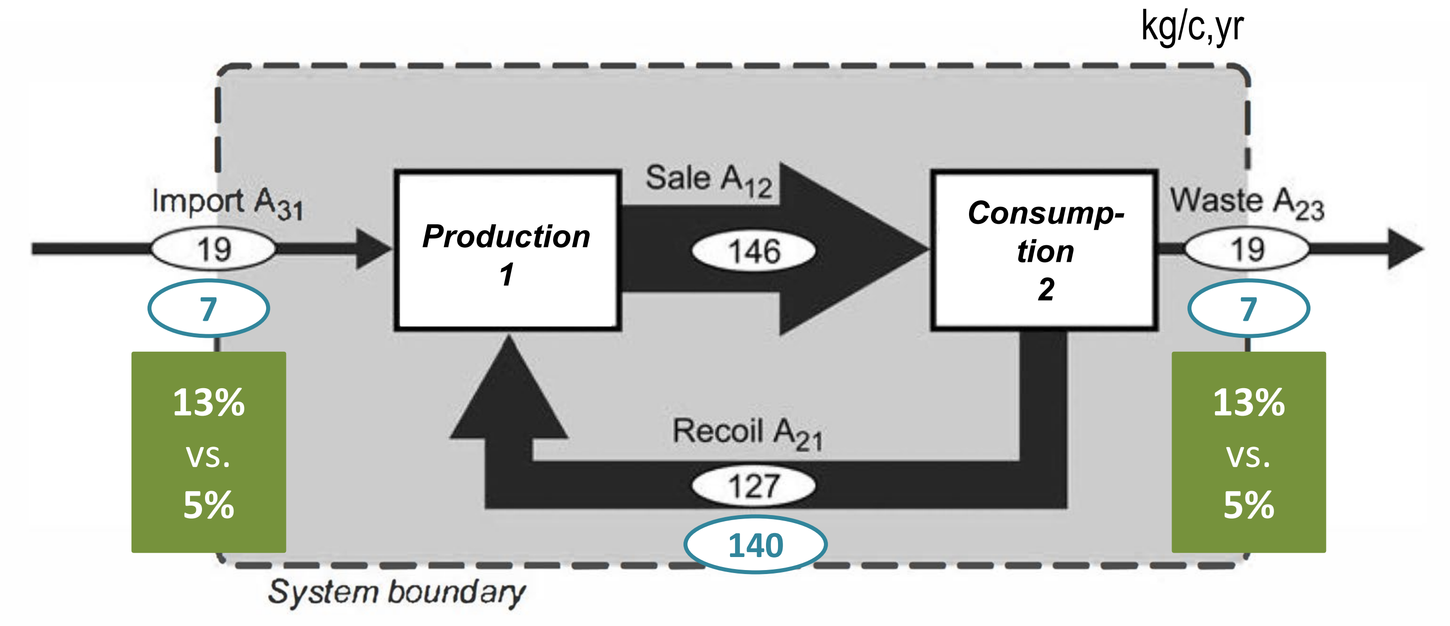
How to check the results?



a. Compare with statistical data
b. Compare with literature data
c. Get feedback from field experts

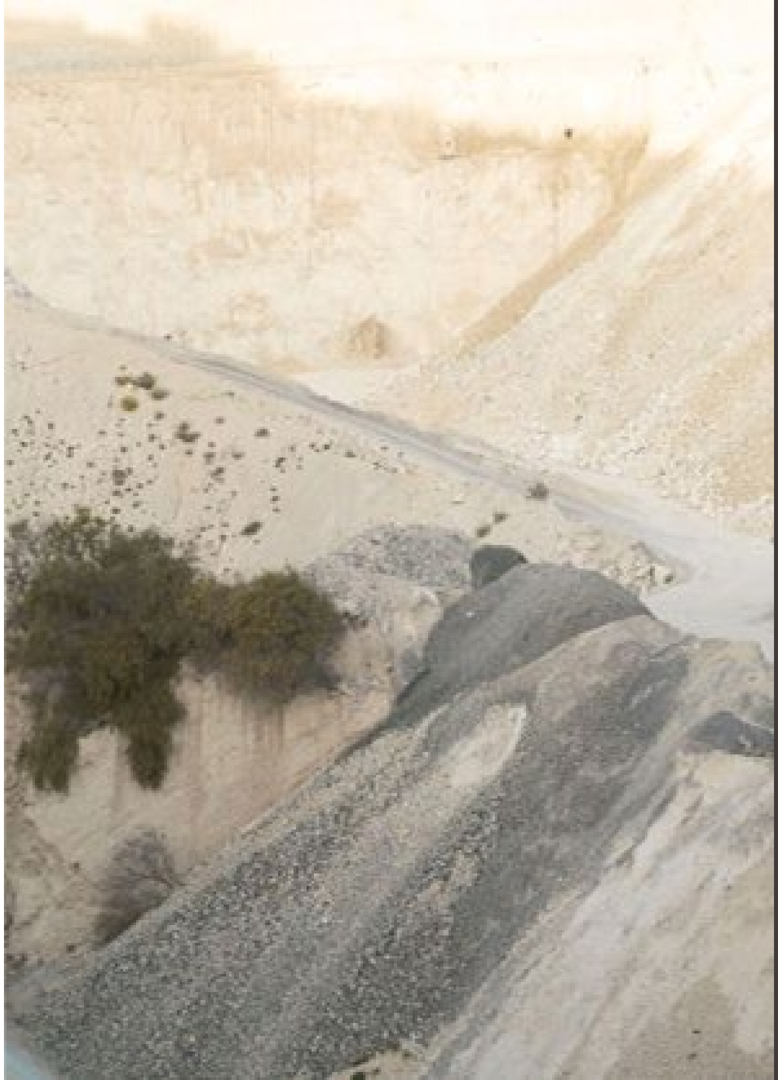
Indicators

How would you define indicators?



a. Import rate (sale/import)

Baccini & Brunner, 2012



Thank you for your attention!

EPFL

Guest lecturer: Dynamic MFA Prof. Stefan Pauliuk

Binder, Félix Martín del Campo, Hecher, Campfens

- **Position and Role:**
  - Professor of Sustainable Energy and Material Flow Management at the University of Freiburg, Germany, heading the Industrial Ecology Freiburg research group since 2021.
- **Research Focus:**
  - Specializes in **industrial ecology** and **socio-metabolic research**, including global supply chains, sustainable material cycles, environmental footprints, and circular economy strategies.
- **Methodological Expertise:**
  - Advanced methods such as **Material Flow Analysis** (MFA), **Life Cycle Assessment** (LCA), and **Multiregional Input-Output Analysis** (MRIO).
- **Professional Contributions:**
  - Led projects on resource efficiency and circular economy, contributed to policy development, and authored influential studies on sustainable material management.
- **Teaching and Community Engagement:**
  - Teaches various MSc-level courses, offers an online course in Industrial Ecology, and actively engages in scientific committees and international collaborations.

Course evaluation

- **Indicative Student Feedback on Teaching**
- This feedback system asks students to respond to a single question about the course (“*The running of the course enables my learning and an appropriate class climate*”)
- Opportunity for **students** to **provide comments**
- **Go to ISA and respond the Indicative Feedback**
- **Feedback is anonymous**