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ENV 501 / GR A3 30

Material and Energy Flow Analysis for resource management

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Lecture content

- Understand the use and content of Input-Output Tables (IOT)
- Compare process MFA and Input-Output Analysis (IOA)
- Learn how to apply IOA
- Understand Material Flow Cost Accounting (MFCA)

Input Output Analysis (IOA)

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Rationale for Input Output Analysis (IOA)

- Understand the inter-linkages between economic activities
- Conduct MFA from a macro perspective
- Evaluate material and energy flows of the service sector
- Perform screening MFA at low granularity
- Identify hotspots, target activities and resource impacts
- Compare production and consumption perspectives
- Bridge data gaps in process MFA/LCA

Historical background

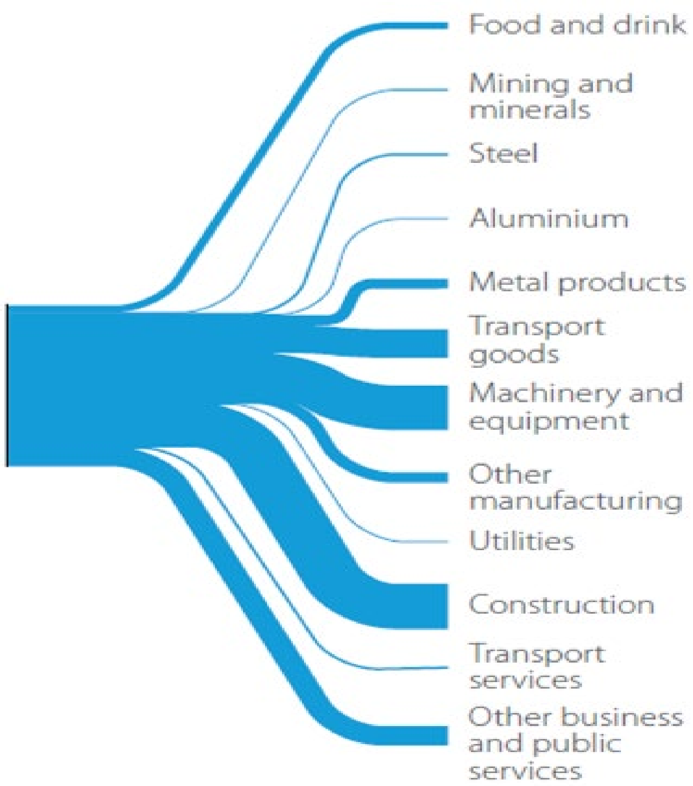
Wassily Leontief (1905 - 1999), *Die Wirtschaft als Kreislauf*

Walter Isard (1919 - 2010), Regional Science

What is the impact on one economic activity or sector resulting from changes in another activity or sector?

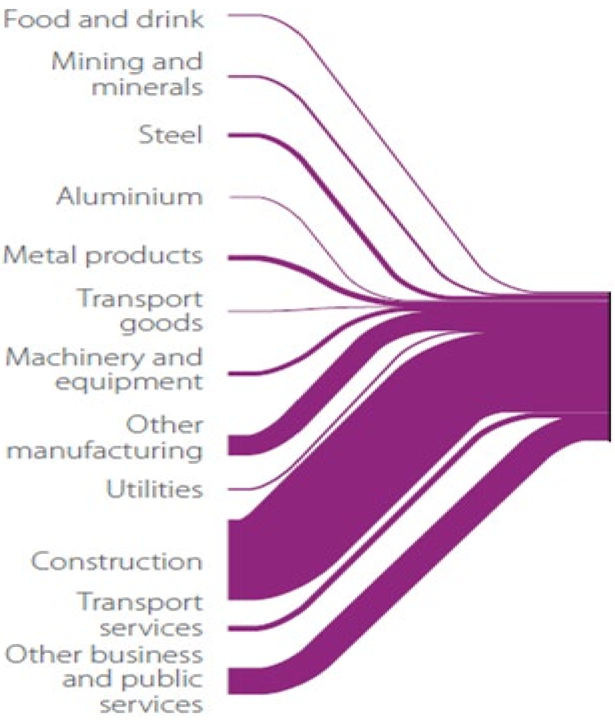
- Input-Output Tables (IOTs)
  Supply Use Tables (SUTs)
  Social Accounting Matrices (SAMs)

Which sectors purchase steel?



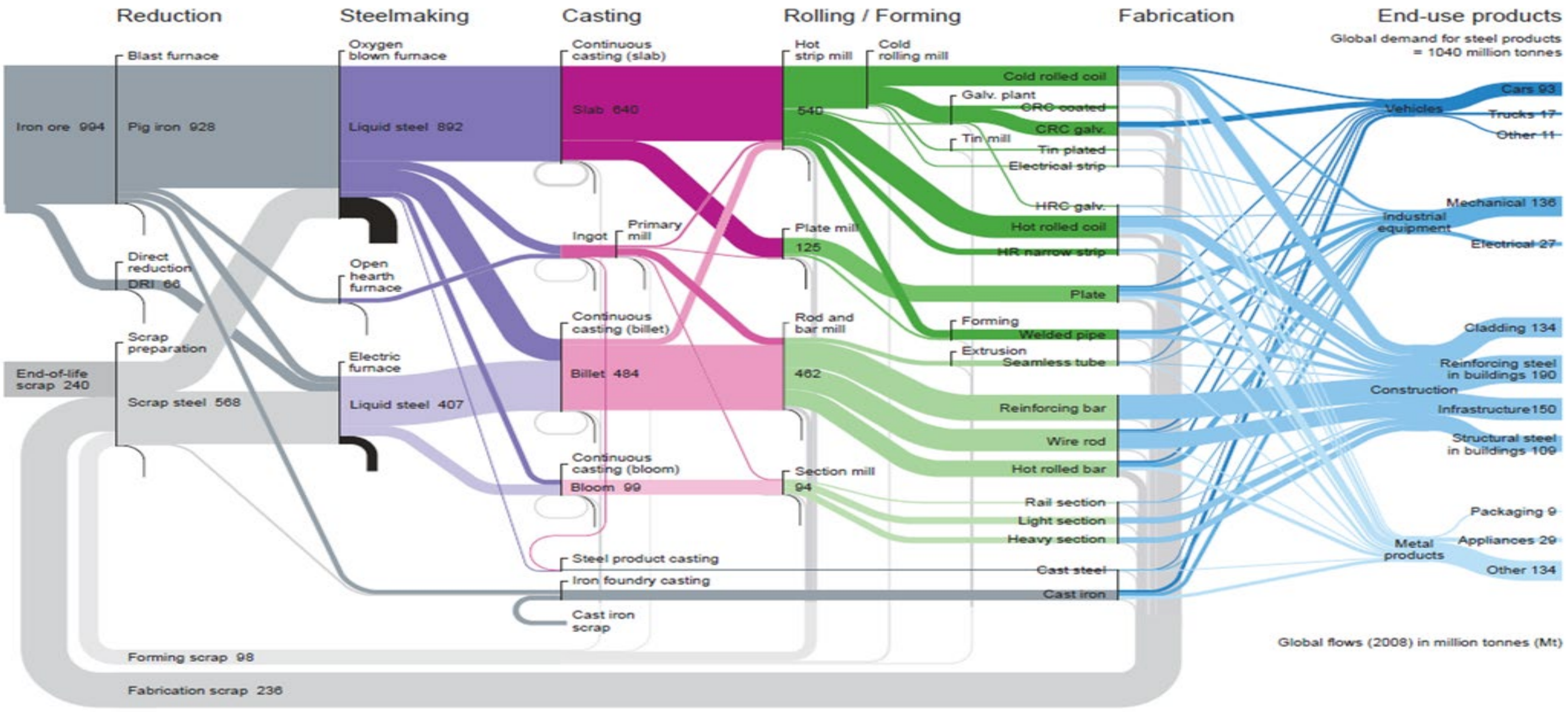
Source: Sustainable materials with both eyes open

How are construction expenditures allocated?



Source: Sustainable materials with both eyes open

Steel Flow Analysis



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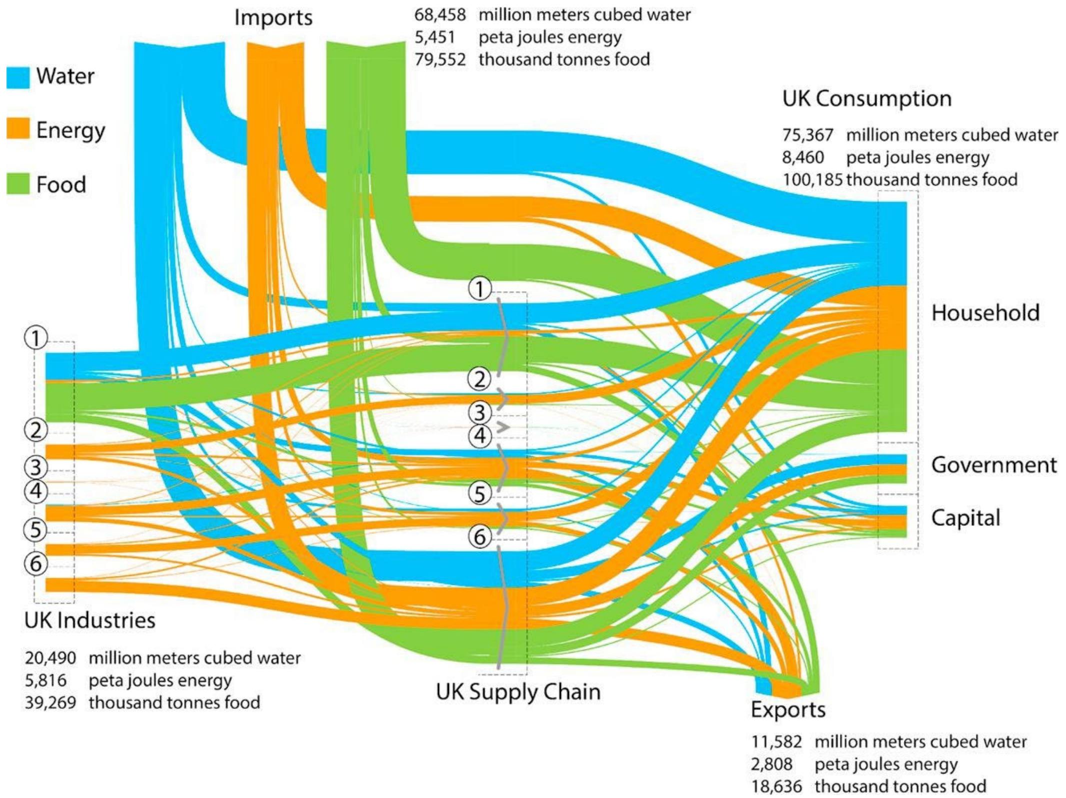
Source: Sustainable materials with both eyes open

Supply chain analysis

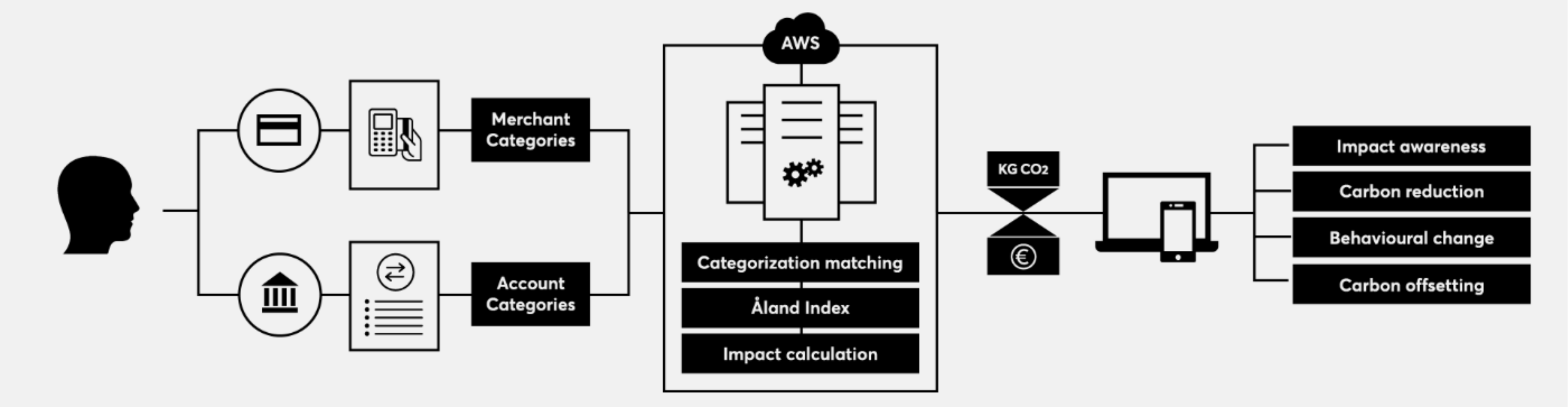
Energy water and food nexus in the UK

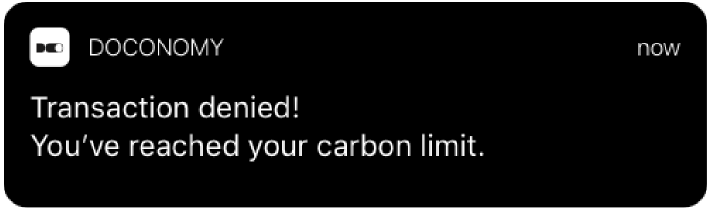


Owen et al. 2018

Impact screening

What are the impacts of my consumption choices?





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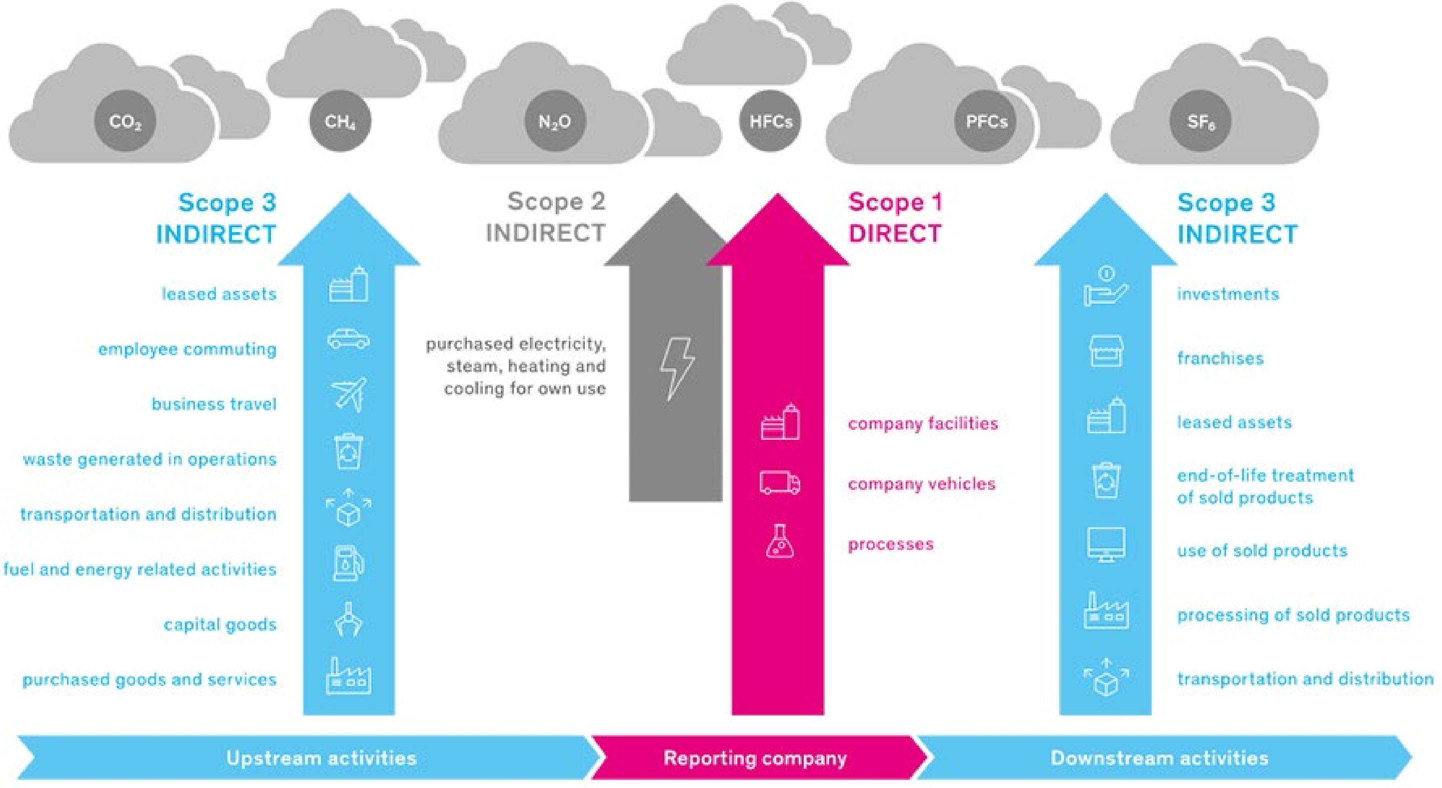
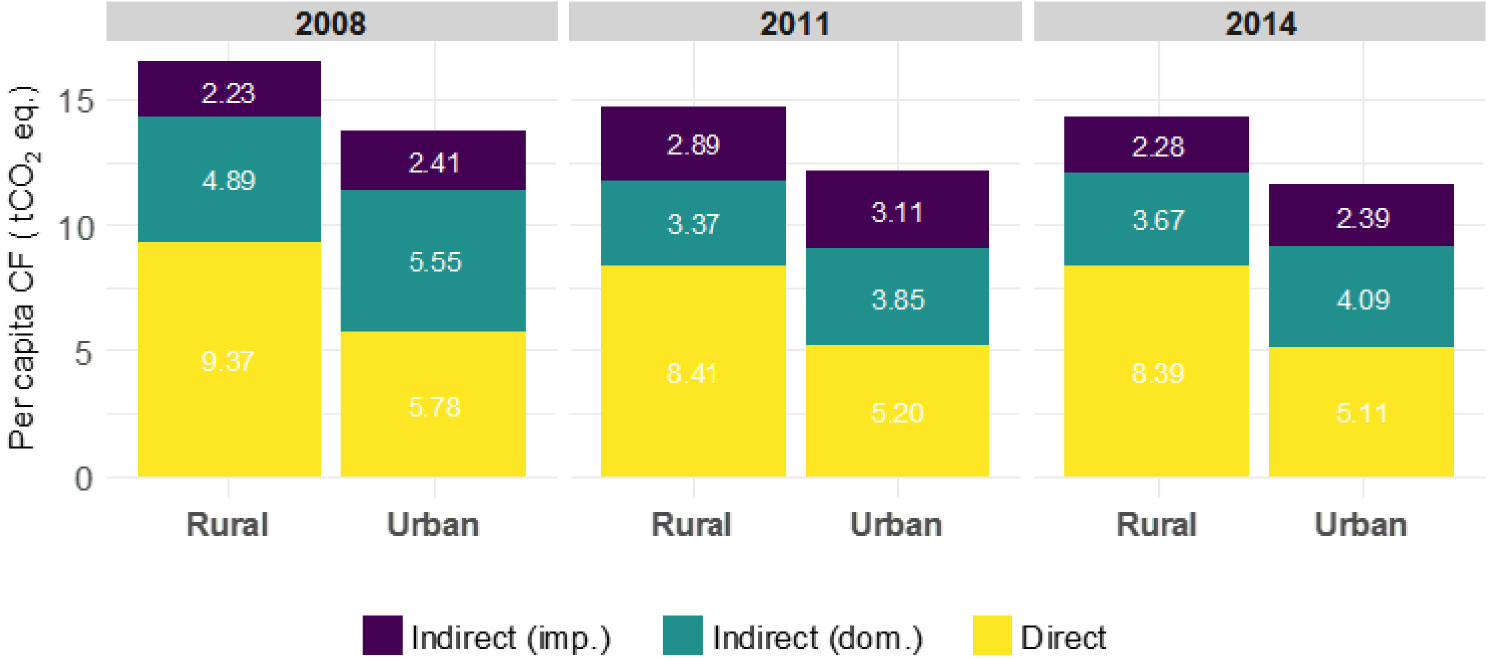
Doconomy, Alang Index

Corporate reporting



myclimate

Policy relevance [1]

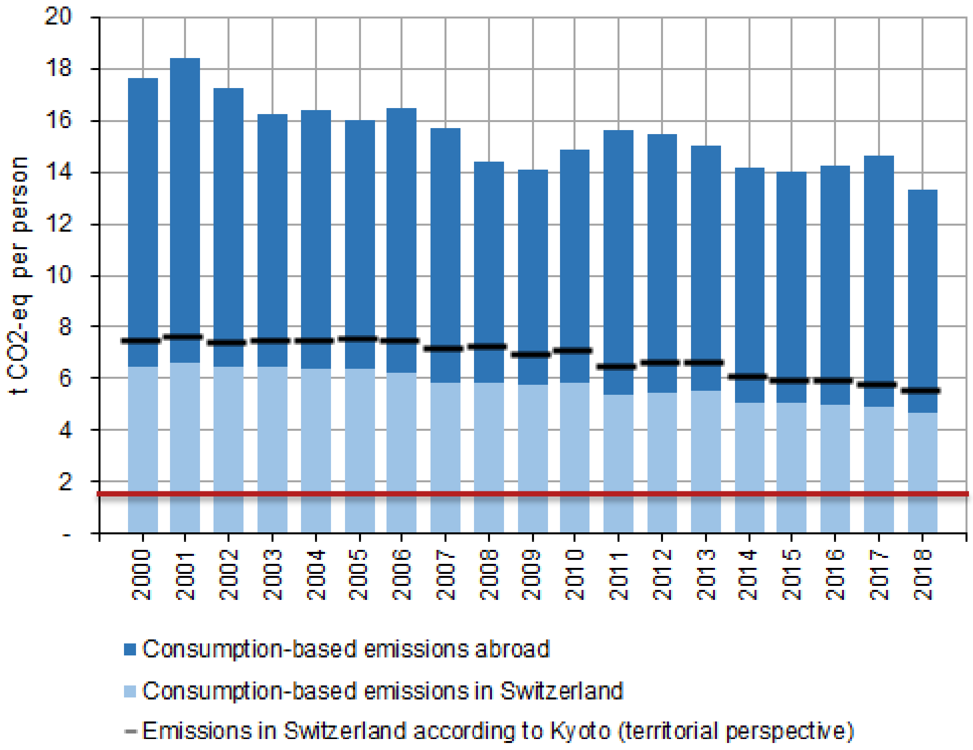


Direct: consumption of fuels and heating

Indirect: induced by households final consumption of goods and services

Pang et al. 2019

Policy relevance [2]

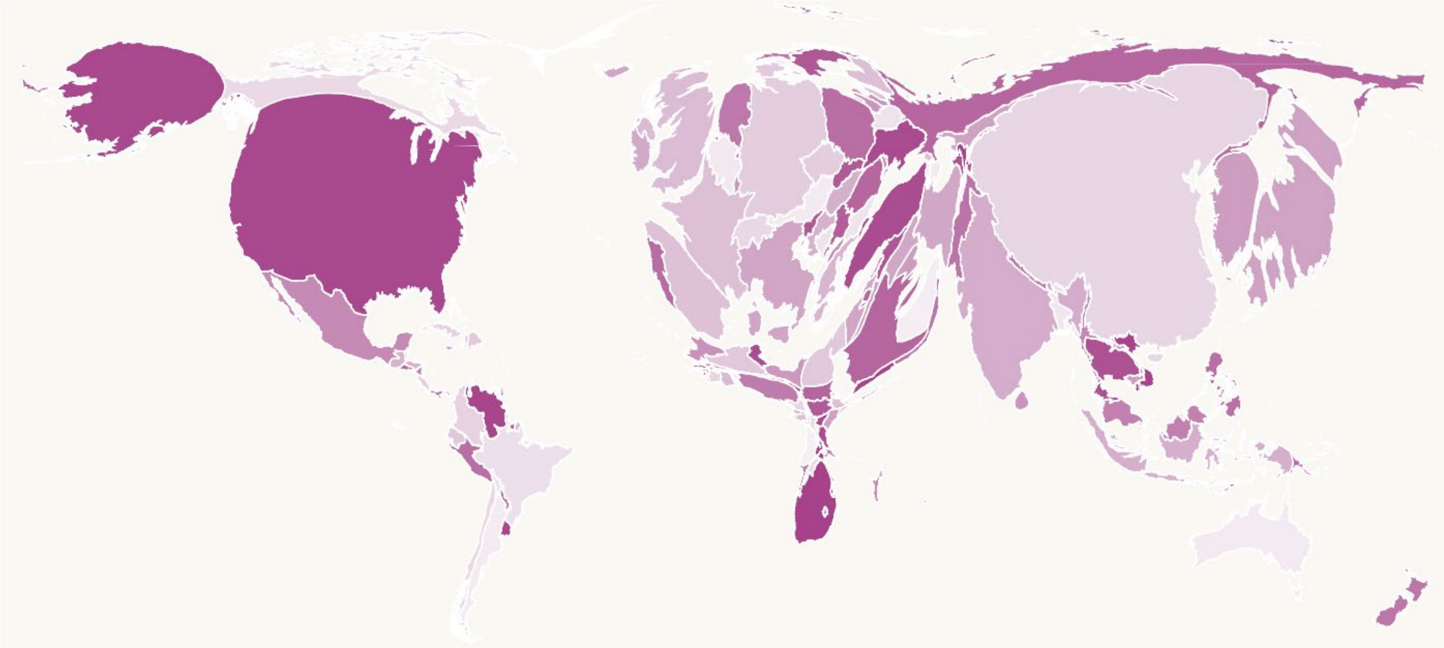


1.5 t CO_2-eq per person by 2050

Swiss Federal Office for the Environment, 2018

Policy relevance [3]

Global resource footprint 2007



CREEA, Tukker et al. 2014

Process MFA vs. IOA

- Processes vs. economic activities
- System boundaries, spatial and temporal
- Bottom up vs. top down
- Physical units vs. monetary
- Production vs. consumption perspectives

Σ input = Σ output + net additions to stocks

Σ revenues = Σ expenditures - savings

Resource and monetary flows move in opposite directions

Input-Output Model: Accounting equation

Domestic inputs + imports = intermediate consumption

+ final consumption (HH + Gov't)

+ capital formation (investment)

+ exports

= **Total output**

Hypotheses

Steady state (over an accounting period)

The multiple uses of given products have the same share of imports

A given product's availability is proportional to the market share of its producer

Input-Output Tables

Combination of supply (V) and use (U) tables

V is an activity by product matrix of which element vij shows the amount of product j produced by activity i

U is a product by activity matrix of which element uij shows the amount of product i used by activity j

Matrix (A) of n x n economic activities

Diagonal shows net production of each activity in monetary unit worth of gross economic output, and off-diagonal elements aij

Shows the amount of output from activity i used by activity j per unit worth of its output (matrix of transaction coefficients)

Input-Output Tables

Balanced MSUT	Activities	Import	Final use	Export	Valation	Total
Products	V'	N			Valuation	q
Total	g					
Products	U		y	E		q
Primary production factors	Labour costs					
	Net taxes					
	Net operating costs					
	Rent					
Total	g					

V': Production by industry and by product
N: Imports by products
U: Intermediate consumption by product and by industry
y: Final use of products
g: Vector of production by industry
q: Vector of total domestic production by product
E: Exports by products

Environmentally extended IO Tables

Satellite accounts (intervention matrices)

Interventions by economic activity matrix, of which elements bij shows the physical amount of ith environmental intervention caused by a unit output of the jth activity (matrix of coefficients)

Examples of satellite accounts/multipliers

Production factors (e.g. capital costs, employment) (F)
Resources (e.g. energy, land, water) (R)
Emissions (e.g. CO_2, NO_x, etc.) (B)
Wastes (W)

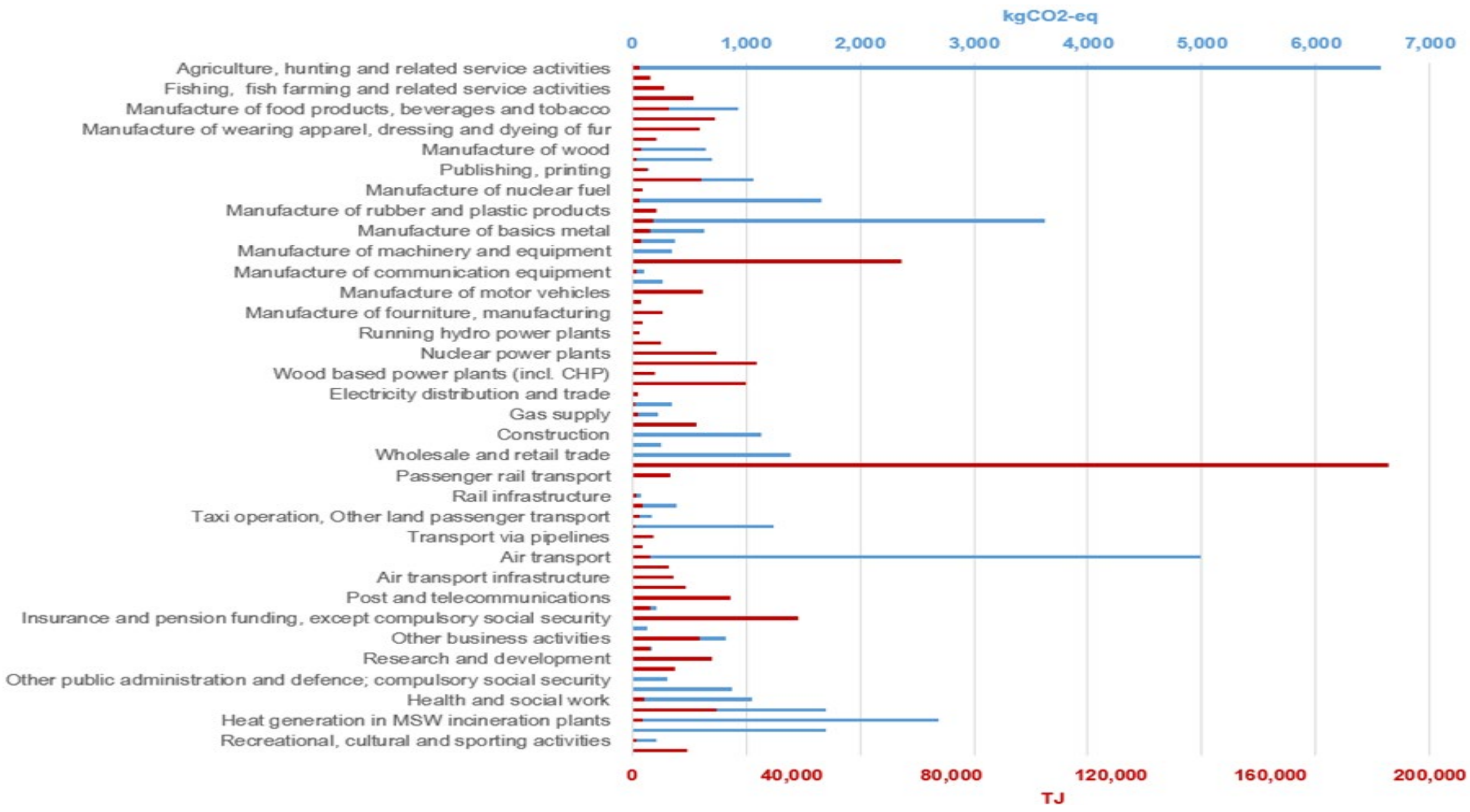
Input-Output Tables and satellite accounts

Balanced PSUT	Activities	Import	Final use	Export	Total
Products	V'	N			q
Total	g				
Products	U		y	E	q
Net additions to stocks	$-\Delta S$				
Supply of wastes	$-W_V$				
Use of wastes	W_U				
Resources	R				
Emissions	-B				
Total	g				

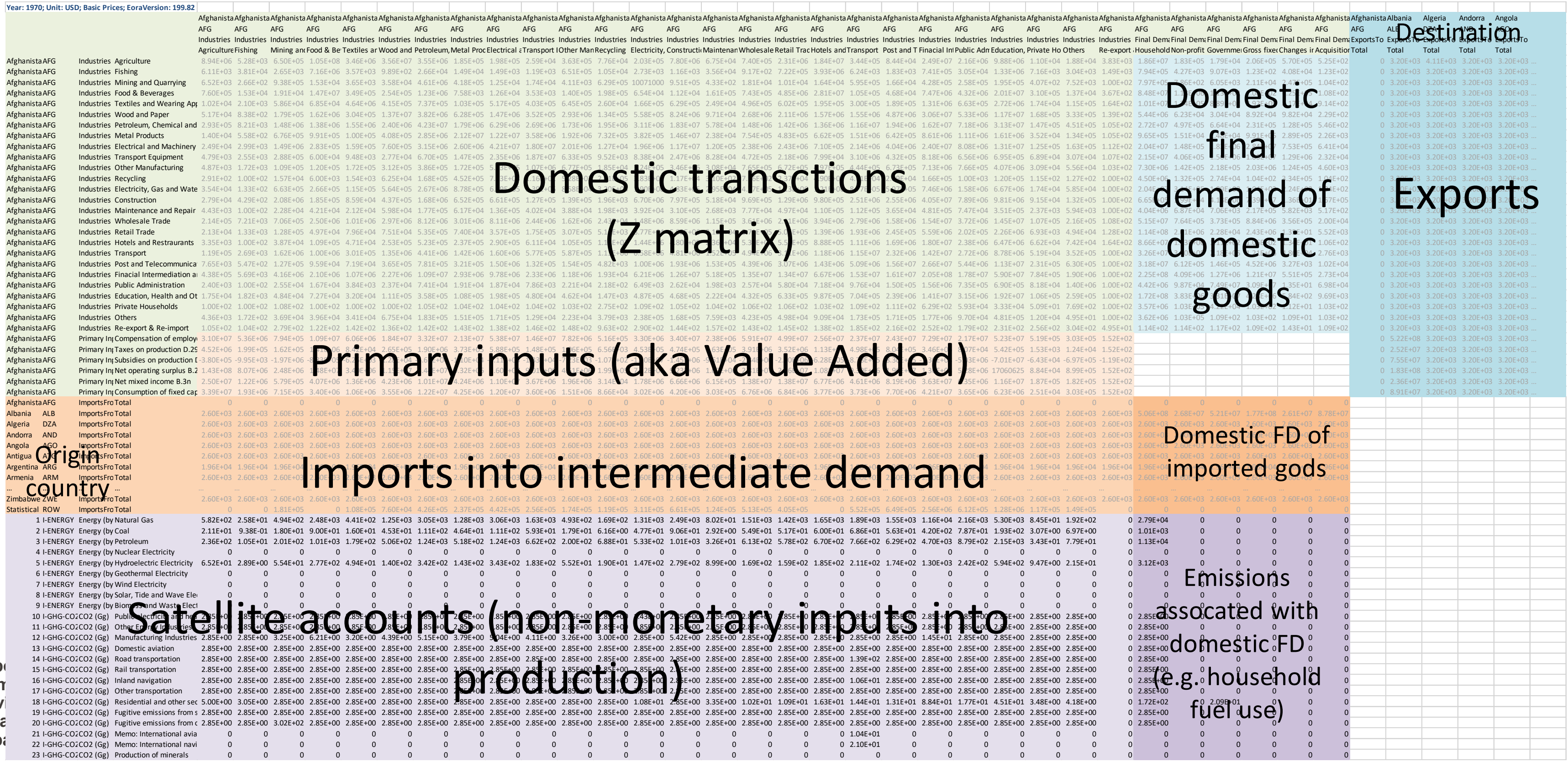
V’: Production by industry and by product
N: Imports by products
U: Intermediate consumption by product and by industry
y: Final use of products
g: Vector of production by industry
q: Vector of total domestic production by product
E: Exports by products

NAMEA: Air and Energy

National Accounting Matrix including Environmental Accounts (NAMEA)



Environmentally extended IO Tables



IO Model

Intermediate consumption + final consumption = Total output

$$AX + Y = X$$

$$a_{ij} = x_{ij}/X_j$$

$$\begin{cases} a_{11}x_1 + a_{12}x_2 + a_{13}x_3 + \cdots + a_{1n}x_n + y_1 = x_1 \\ a_{21}x_1 + a_{22}x_2 + a_{23}x_3 + \cdots + a_{2n}x_n + y_2 = x_2 \\ \vdots \\ a_{n1}x_1 + a_{n2}x_2 + a_{n3}x_3 + \cdots + a_{nn}x_n + y_n = x_n \end{cases}$$

Leontief inverse L

$$AX + Y = X$$

$$Y = X - AX$$

$$Y = IX - AX = (I - A)X$$

$$X = (I - A)^{-1}Y$$

$$X = LY$$

Leontief inverse

Note I = diag (1,1,...,1); $L = (I - A)^{-1}$

Input-Output model satellite accounts

Vector of resource flows b to satisfy final demand Y given matrix B of interventions per unit of output X:

$$b = BX = B(I - A)^{-1}Y$$

Vector of impacts d given matrix C of characterization factors (LCIA):

$$d = Cb = CB(I - A)^{-1}Y$$

Example [1]

Symmetric IO table of inter-industry transactions (mio CHF)

	Industry A	Industry B	Industry C	Final demand	Total output
Industry A	0	20	45	35	100
Industry B	30	0	30	140	200
Industry C	0	80	0	70	150
Value added	70	100	75		
Total input	100	200	150		

Example [2]

From satellite accounts

1. Direct energy use per unit of output X

x	mio CHF	F	MJ/CHF		TJ
A	100		5		500
B	200		7		1400
C	150		2		300

2. Energy use of suppliers per industry

	A	B	C	F	MJ/CHF		TJ
A	0	20	45		5		210
B	30	0	30		7		260
C	0	80	0		2		435

Example [3]

3. Matrix of transaction coefficients A

	A	B	C
A	0	0.1	0.3
B	0.3	0	0.2
C	0	0.4	0

Leontief inverse
$$L = (I - A)^{-1}$$

4. Total output X per industry to satisfy final demand Y

	A	B	C	Y	mio CHF	X	mio CHF
A	1.1	0.3	0.4		35		100
B	0.4	1.2	0.3		140		200
C	0.1	0.5	1.1		70		150

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Example [4]

5. Energy use per sector to satisfy final demand and total energy use

f	TJ		Total TJ
A	500		2200
B	1400		
C	300		

Energy used in direct operations

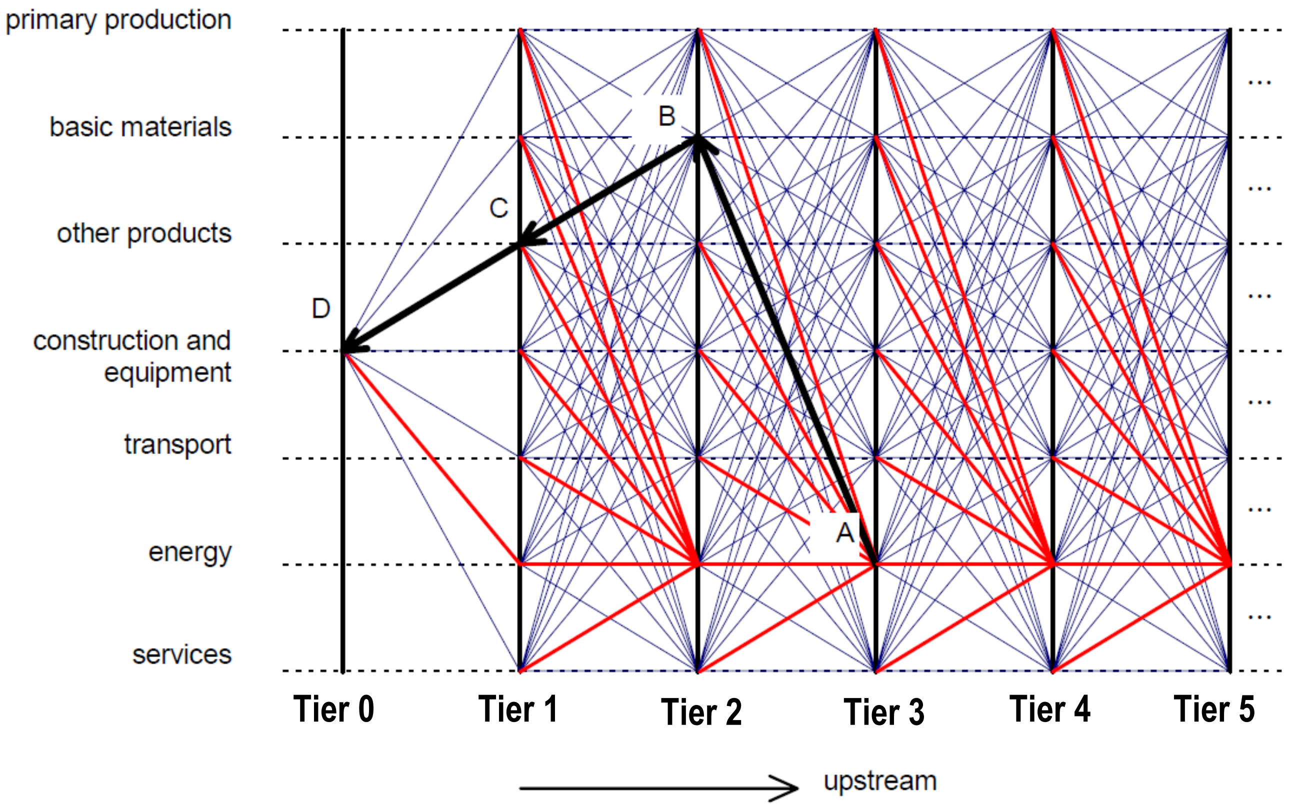
6. Comparison

Energy used by direct suppliers

Total energy used to satisfy demand

	Direct	Induced	Total
	TJ	TJ	TJ
A	500	210	500
B	1400	260	1400
C	300	435	300

Structural path analysis



IO Model

To satisfy final demand Y, the total output X is given by :

$$X = (I - A)^{-1} Y$$

With the Leontief inverse $L = (I - A)^{-1}$:

$$X = LY$$

The transaction coefficients a_{ij} of A are $0 < a_{ij} < 1$ so L can be expanded into a Taylor – Maclaurin series :

$$L = (I - A)^{-1} = I + A + A^2 + A^3 + \cdots$$

Path or tier analysis with IO

For a final demand Y, the output X is given by:

Tier 0	$X = IY$
Tier 1	$X = AY$
Tier 2	$X = A(AY) = A^2Y$
Tier 3	$X = A\big(A(AY)\big) = A^3Y$

Total output

$$X = IY + AY + A^2Y + A^3Y + \cdots$$

$$X = (I + A + A^2 + A^3 + \cdots)Y$$

$$X = (I - A)^{-1}Y$$

Example [continued]

1. Total output per industry

	X [mio CHF]
A	100
B	200
C	150

2. Output X of suppliers per industry (Tier 1)

	A	B	C		Y [mio CHF]		X [mio CHF]
A	0	0.1	0.3		35		35
B	0.3	0	0.2	*	140	=	25
C	0	0.4	0		70		56

Example [continued]

3. Output X of suppliers of suppliers per industry (Tier 2)

	A	B	C		Y [mio CHF]		X [mio CHF]
A	0.03	0.12	0.02		35		19.25
B	0	0.11	0.09	*	140	=	21.7
C	0.12	0	0.08		70		9.8

4. Total output X per industry to satisfy final demand Y

	A	B	C		Y [mio CHF]		X [mio CHF]
A	1.1	0.4	0.1		35		100
B	0.3	1.2	0.5	*	140	=	200
C	0.4	0.3	1.1		70		150

Multi regional IOT

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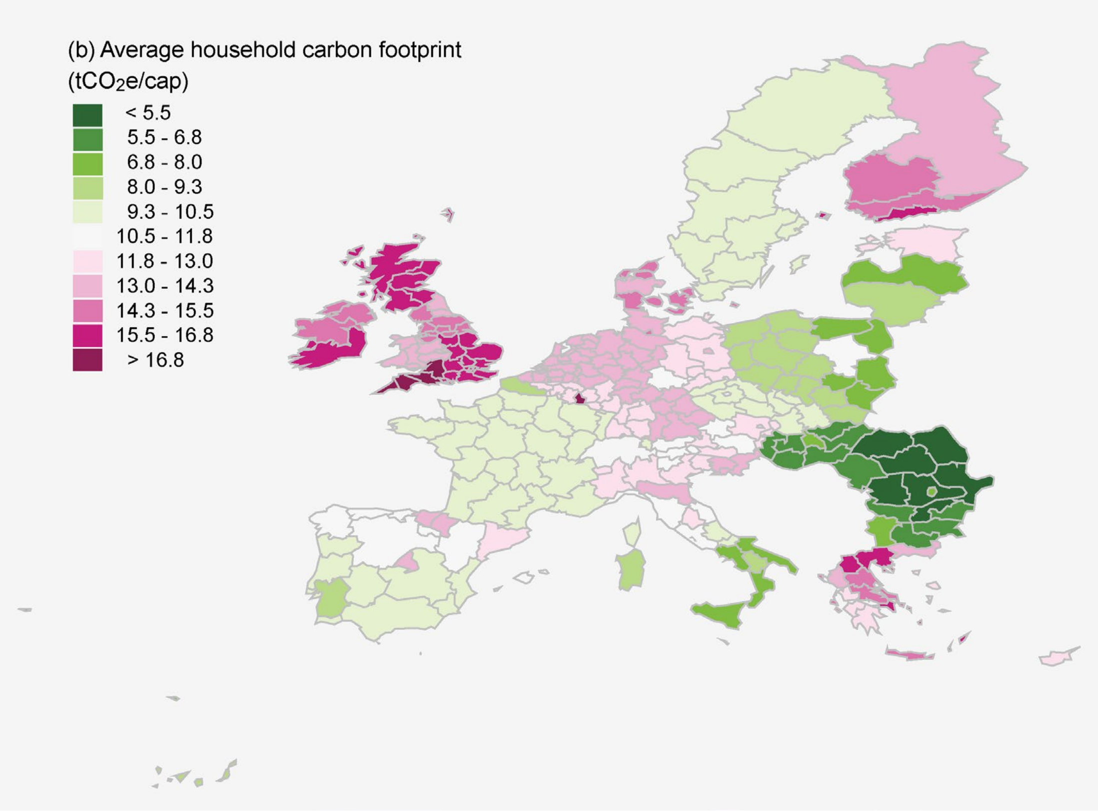
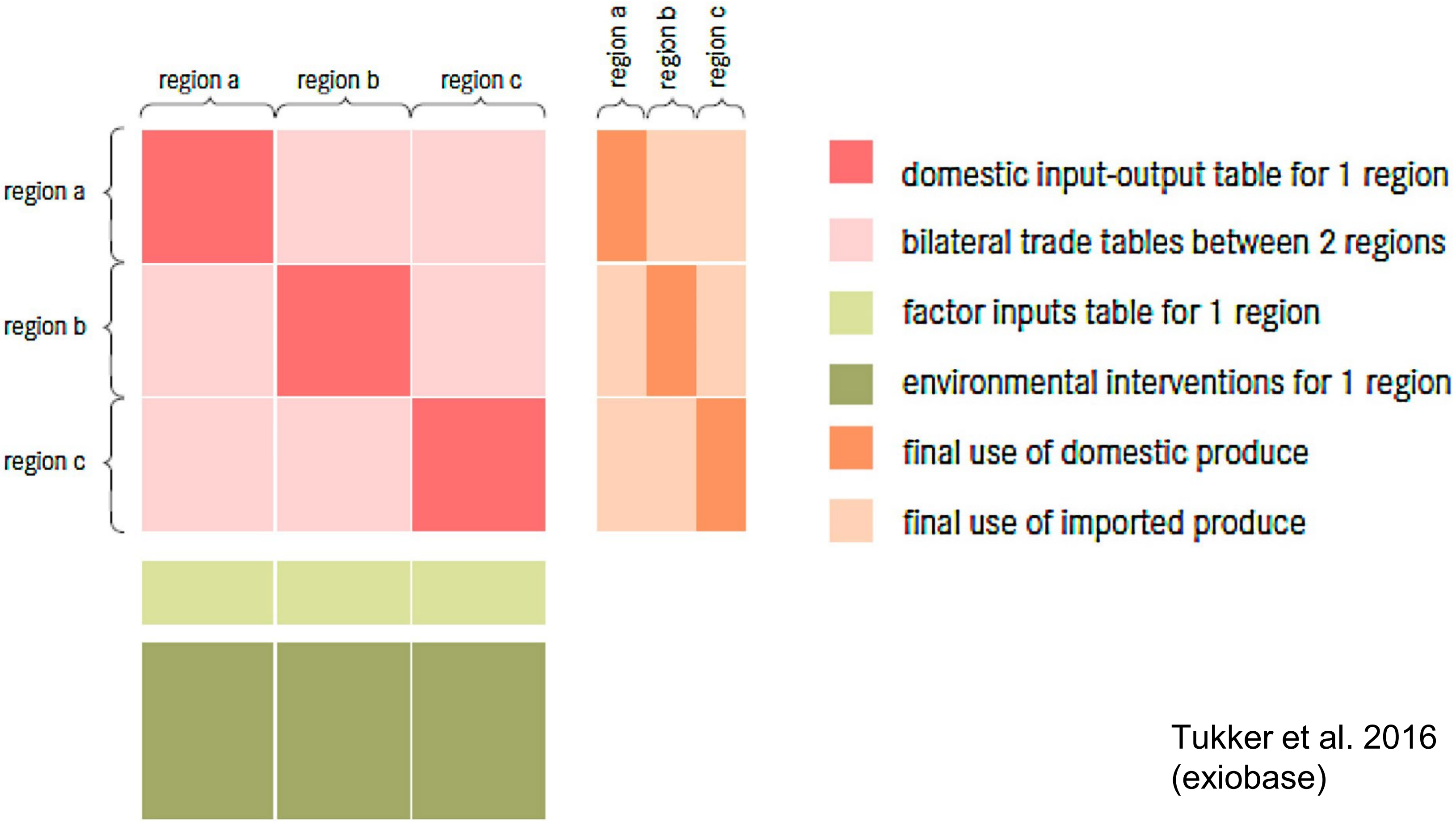
Regional level flows in Europe (NUTS2)



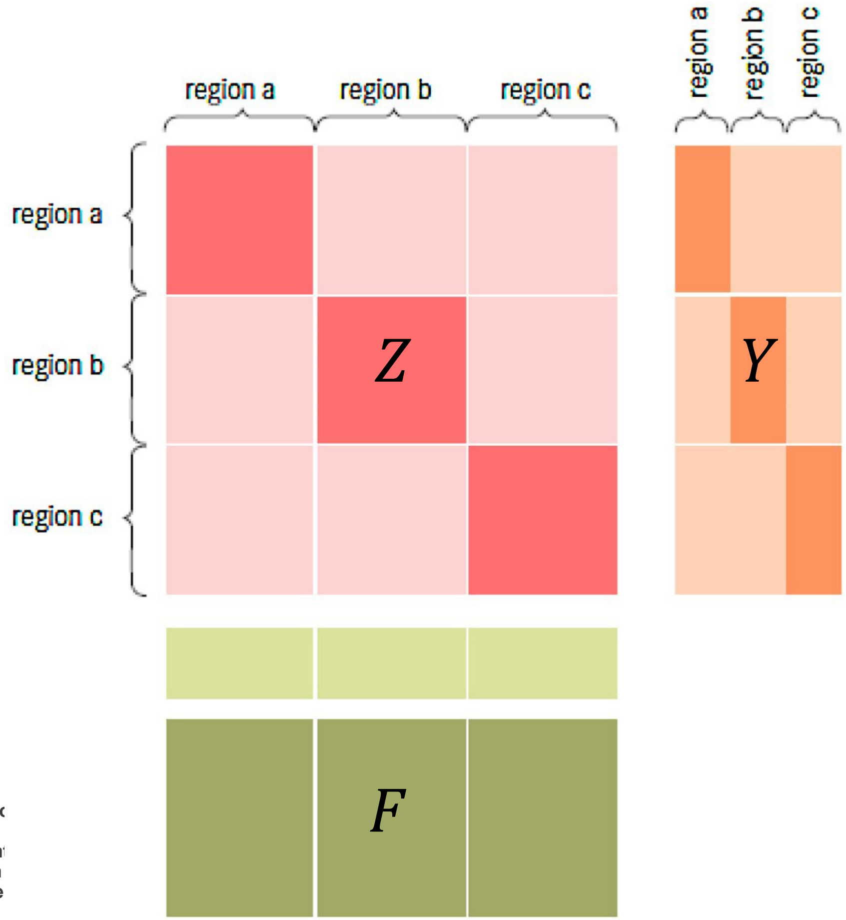
Ivanova et al. 2017

Multiregional IO tables (MRIOTs)



Tukker et al. 2016
(exiobase)

Multiregional IO tables (MRIOTs)



$$X = (I - A)^{-1} Y = LY$$

$$A = ZX^{-1}$$

$$S = FX^{-1}$$

$$M = SL$$

$$D = MY$$

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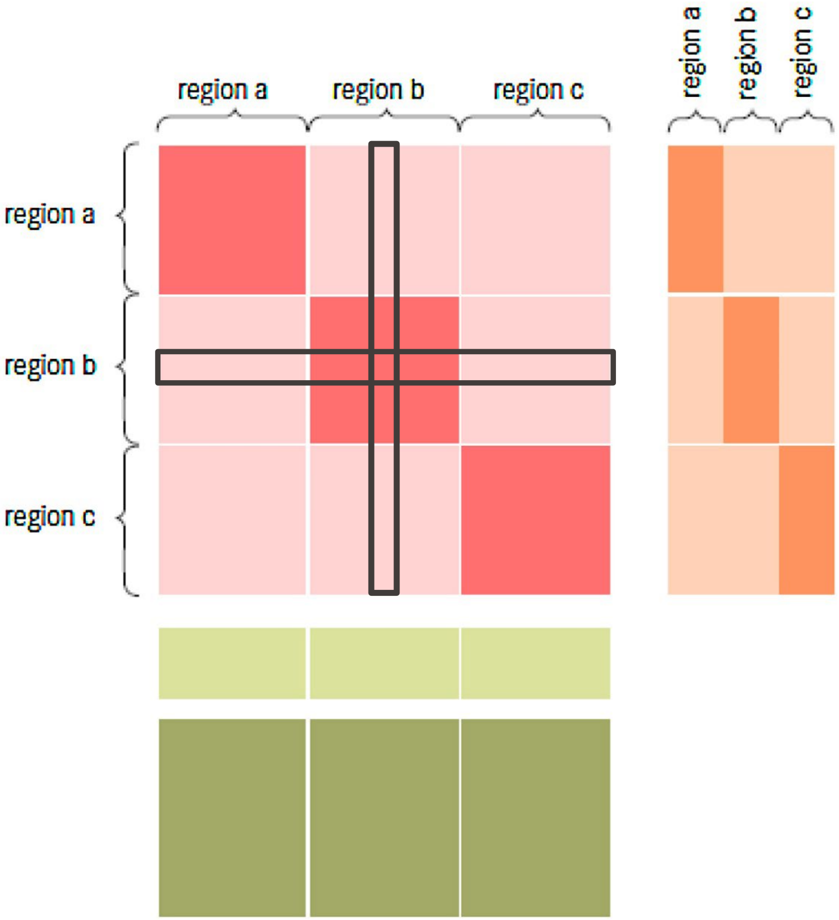
Multiregional IO tables (MRIOTs)



The sum of colums minus diagonal matrix, equals imports

The sum of rows minus diagonal matrix, equals exports

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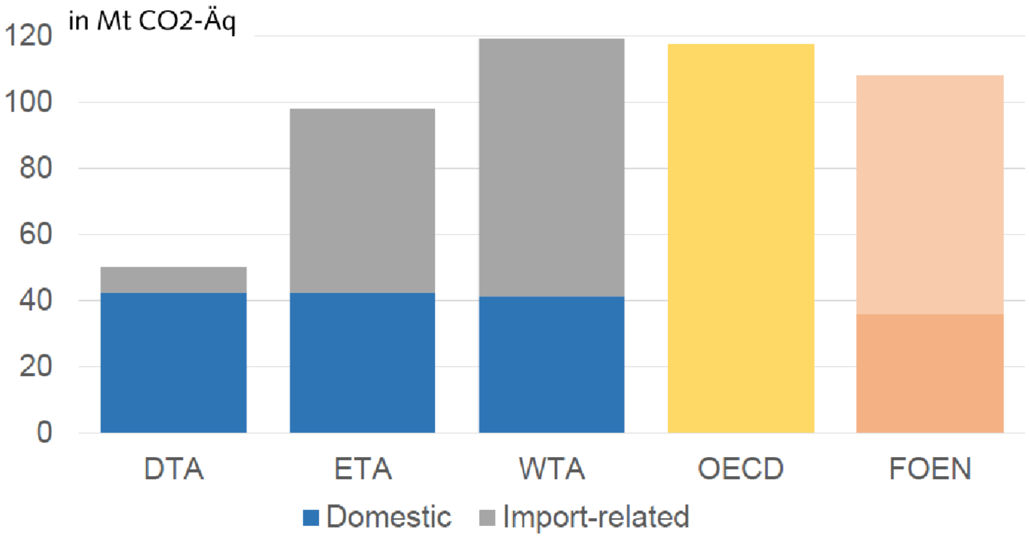
Consumption perspective on CH footprint



Domestic technology assumption (DTA), European technology assumption (ETA)
World technology assumption (WTA), Federal Office of the Environment (FOEN)

Federal Statistical Office

Summary

Input-Output analysis
Ideal for analysing service activities, the impacts of trade

Different methods address different problems
Top-down and bottom-up methods and data sources

Structural path analysis
Accounting for each stage/tier in the analysis
Time series of IO data make for more dynamic analysis

Extension of IO databases and satellite accounts
Approaching the vision of Leontief

Strengths and weaknesses

- Top down, screening analysis
- Large coverage, no thresholds
- Consistent with economic activities
- Interactions between economic activities

- Data intensive, yet low granularity
- Subject to inflation and price volatility
- Allocation of co-producing activities
- Steady state hypothesis

Recommended IO tables to work with…

- **EXIOBASE Multi-regional EEIO Database** (NAMEA)
  https://www.exiobase.eu/ https://zenodo.org/record/5589597
- **Swiss IOA projects** (energy, GHG)
  https://www.aramis.admin.ch/Grunddaten/?ProjectID=31264
  https://www.aramis.admin.ch/Grunddaten/?ProjectID=43188
- **Forwast project - Physical IO Tables** (EU)
  http://forwast.brgm.fr/results_deliver.asp

Where to find data?

Relevant databases [1]

Monetary IO Tables

- **EU IO Supply Use Tables** (EU27 + Norway, Macedonia, Turkey)
  https://ec.europa.eu/eurostat/web/esa-supply-use-input-tables
- **OECD STAN IO Tables** (extended with GHG)
  https://stats.oecd.org/Index.aspx?DataSetCode=IOTS
- **EORA Multi-regional IO Database** (global, extended)
  http://www.worldmrio.com/
- **World IO Database** (NAMEA)
  http://www.wiod.org/
- **GTAP IO Tables** (extended with GHG)
  https://www.gtap.agecon.purdue.edu/databases/default.asp

Relevant databases [2]

- **Carnagie Mellon's EEIO LCA** (US IO Tables)
  http://www.eiolca.net/
- **CEDA EEIO Database** (commodity based)
  https://watershed.com/solutions/ceda
- **EXIOBASE Multi-regional EEIO Database** (NAMEA)
  https://www.exiobase.eu/ https://zenodo.org/record/5589597
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Physical IO Table

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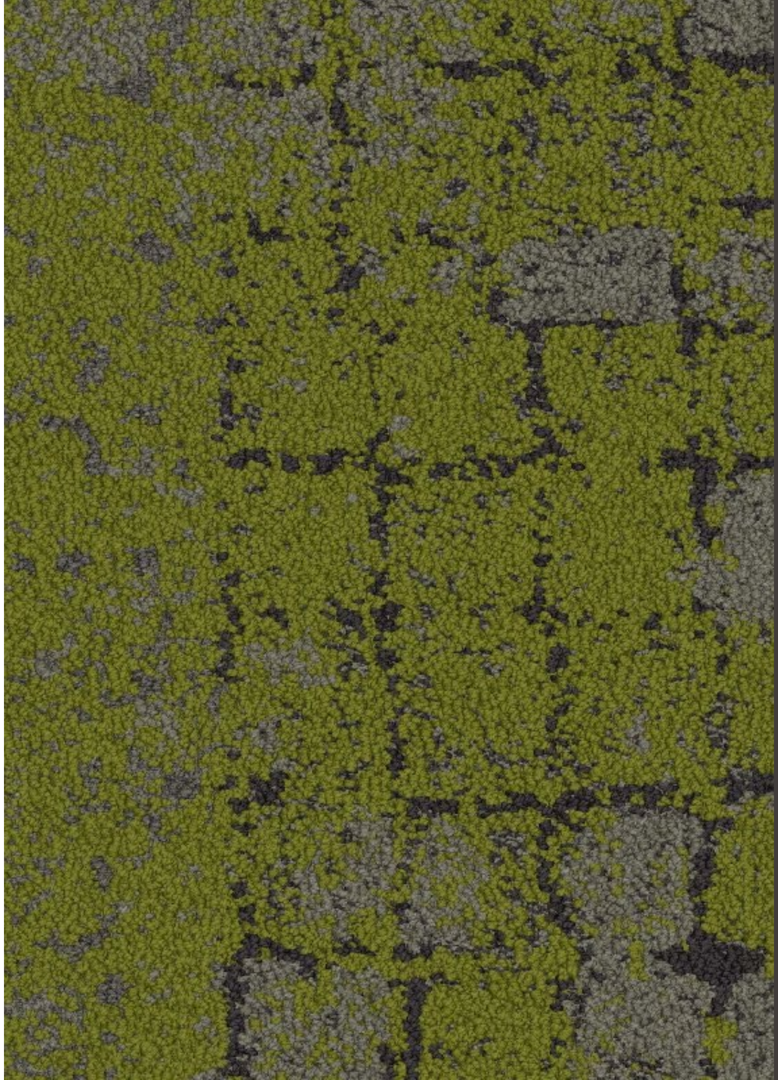

Material Flow Cost Accounting (MFCA)

Introduction

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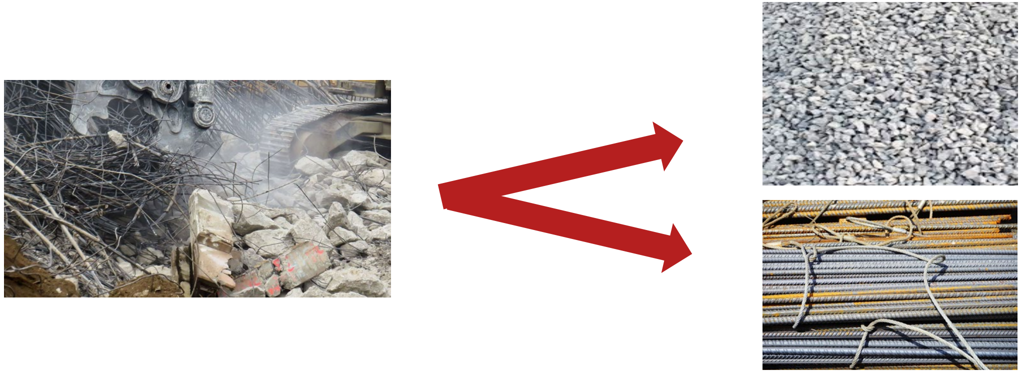
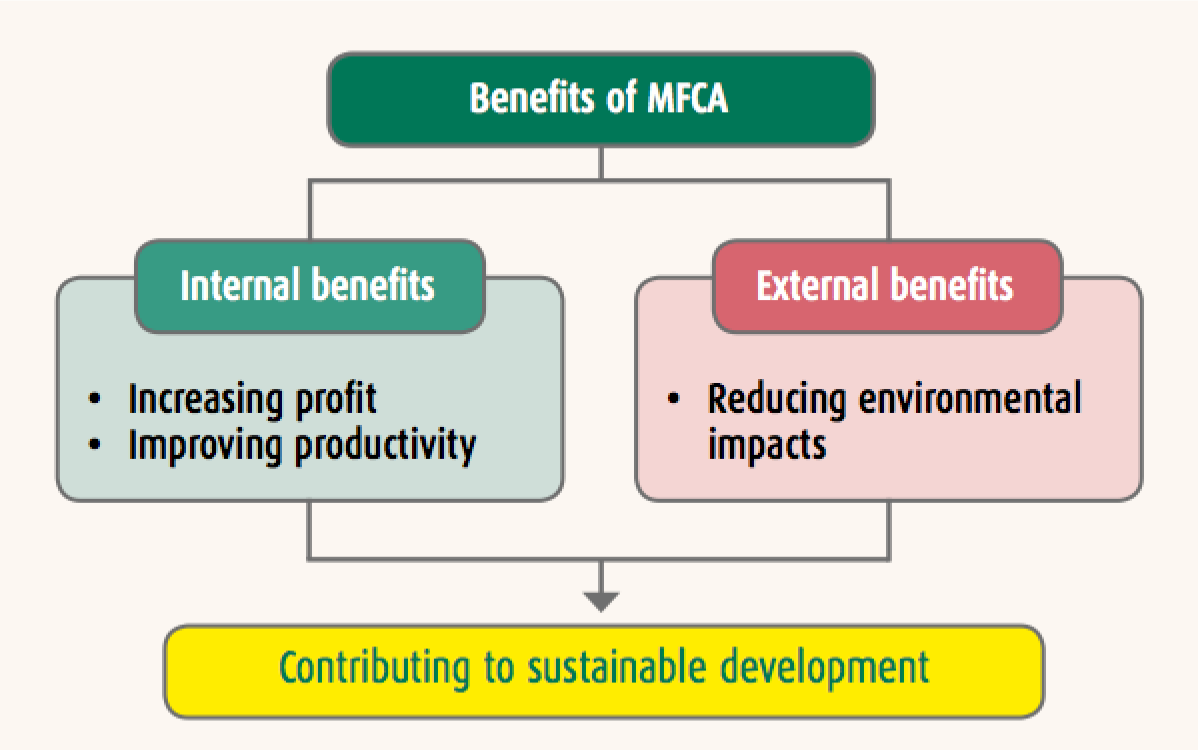
Material Flow Cost Accounting

Why account for the costs of materials in productive activities?

For example, to retain the value associated with wastes, energy or material losses.



Potential benefits of MFCA



Monetary and material statements

Income statement or balance sheet:
Details a company’s revenues and expenses over an accounting period

Focuses on the four key items:

- Revenue
- Expenses
- Gains
- Losses

Monetary statement

The cost of production factors

Cost of Goods Manufactured Statement		
Cost Element	**Decision(s)**	**Information Required**
Material	Supplier A, B, C, or D Order size, material X Number of orders, material X Order size, material Y Number of orders, material Y	List prices Quantity discounts Carrying cost Cost of placing an order
Direct labor (variable)	Number of factory workers Wage rate Budgeted production	Units of equipment Wage rate function Production budget
Manufacturing overhead	Type of finishing department equipment Order size of material Factory labor compensation	Capacity required Carrying cost of inventory Overhead rate Variable cost rates Salaries, supervisors

MFCA

"MFCA is a management tool that can assist organizations to ***better understand the potential environmental and financial consequences of their material and energy use practices****, and seek opportunities to achieve both environmental and financial improvements via changes in those practices."*
(ISO 14051, 2011)

ISO 14051 Environmental Management – Material flow cost accounting 2011

Standard available from the library

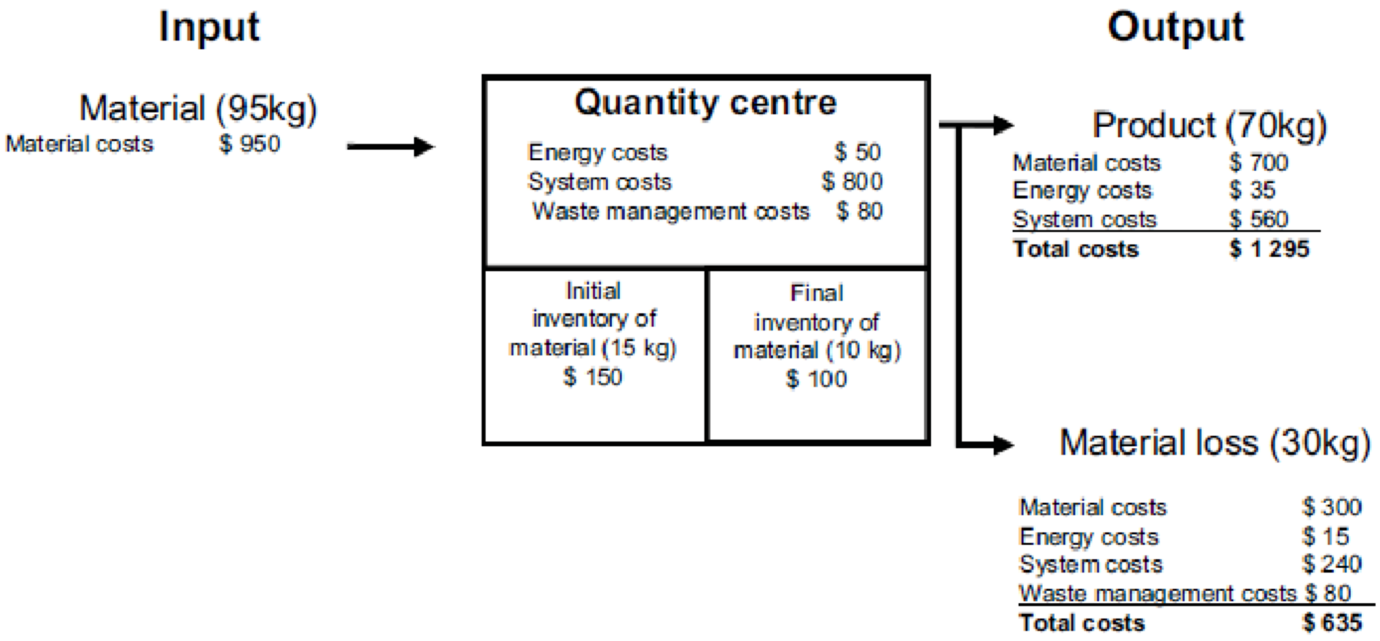
MFCA

Aim: Link resource costs and uses

- Provide a general framework for the analysis of material flows and their costs
- Promote transparency of resource consumption practices
- Quantify the real costs of material and other losses
- Standardized but not certified

MFCA standard

Material flow accounting



Material costs (1000$) = Input (950) + Initial inventory (150) - Final inventory (100)

MFCA standard: definitions

- **Cost:** Monetary value of resources used to perform activities
- **Cost allocation:** Indirect attribution of a cost between different objects, such as a product or process, by using an appropriate apportionment basis
- **Cost assignment:** Direct attribution of a cost to a specific object, such as a product or process

MFCA standard: definitions

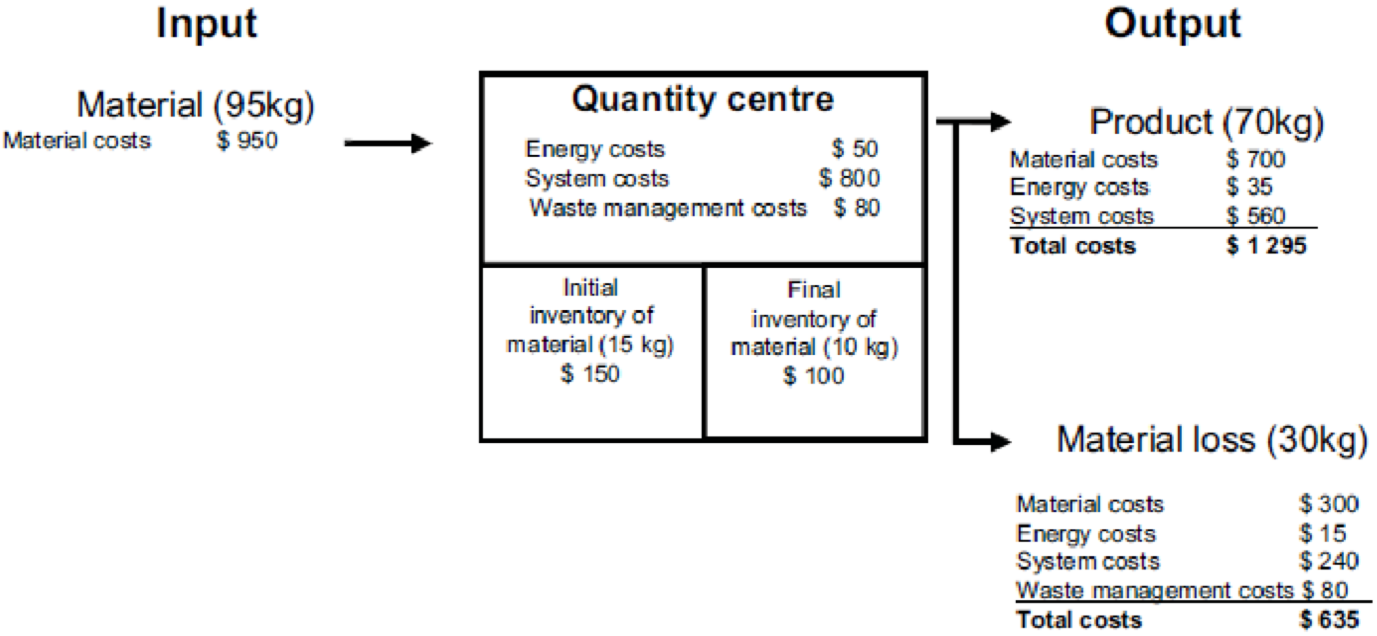
- **Quantity cost:** Selected part or parts of a process for which inputs and outputs are quantified in physical and monetary units (warehouses, production, inspection, shipping points, heating units) **= Process**

- **System cost:** Cost incurred in the course of in-house handling of the material flows, except for material cost, energy cost

- **Waste management cost:** cost of handling material losses generated in a quantity centre

MFCA standard: unit process

Material flow accounting



Material costs (1000$) = Input (950) + Initial inventory (150) - Final inventory (100)

MFCA standard: unit process

Material flow cost matrix for a quantity centre

	Mass kg	Material costs $	Energy costs $	System costs $	Waste management costs $	Total costs $
Total inputs	100	1 000	50	800	80	1 930
Product	70 (70 %)	700 (70 %)	35 (70 %)	560 (70 %)	0 (0 %)	1 295 (67 %)
Material loss	30 (30 %)	300 (30 %)	15 (30 %)	240 (30 %)	80 (100 %)	635 (33 %)
Total outputs	100	1 000	50	800	80	1 930

For simplicity, this table only includes physical data on materials, not energy.

The total inputs and material costs include materials in inventory as in the previous slide:

Total material used (100 kg) = Input (95 kg) + Initial inventory (15 kg) - Final inventory (10 kg)

MFCA procedure

Two-step procedure:

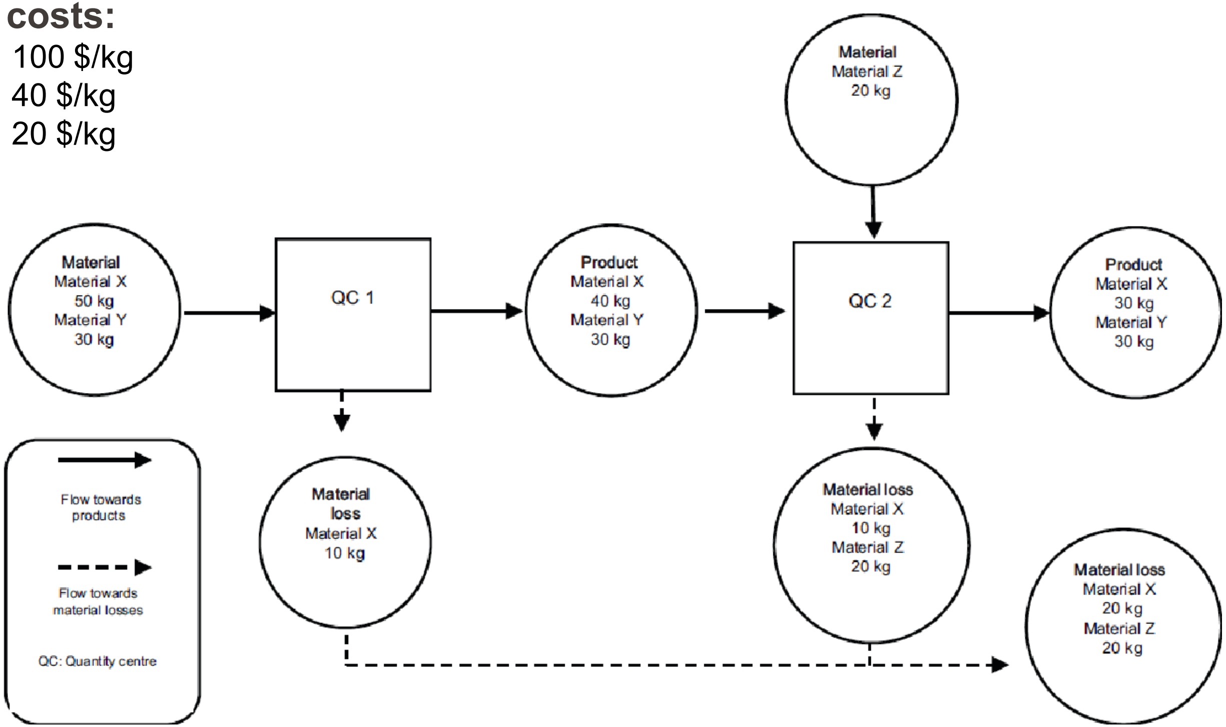
1. Spread costs across a process or production between different quantity centres
2. Allocate costs to the levels of qualifications between products and material losses

MFCA: simple example

Production system with 2 quantity centres (QC)

Material costs:

Material x: 100 $/kg
Material y: 40 $/kg
Material z: 20 $/kg



MFCA: simple example

Cost matrix for a production system with 2 QC

Composition of products and material losses	QC 1			QC 2			Result of production (mass)	Total
Products	Mass	Unit costs	Costs	Mass	Unit costs	Costs	60 kg	$ 4 200
Material X	40 kg	$ 100	$ 4 000	30 kg	$ 100	$ 3 000	30 kg	$ 3 000
Material Y	30 kg	$ 40	$ 1 200	30 kg	$ 40	$ 1 200	30 kg	$ 1 200
Material Z	—	$ 20	—	—	$ 20	—	—	$ 0
Materials losses	Mass	Unit costs	Costs	Mass	Unit costs	Costs	40 kg	$ 2 400
Material X	10 kg	$ 100	$ 1 000	10 kg	$ 100	$ 1 000	20 kg	$ 2 000
Material Y	—	$ 40	—	—	$ 40	—	—	$ 0
Material Z	—	$ 20	—	20 kg	$ 20	$ 400	20 kg	$ 400
Total material costs in this process								$ 6 600

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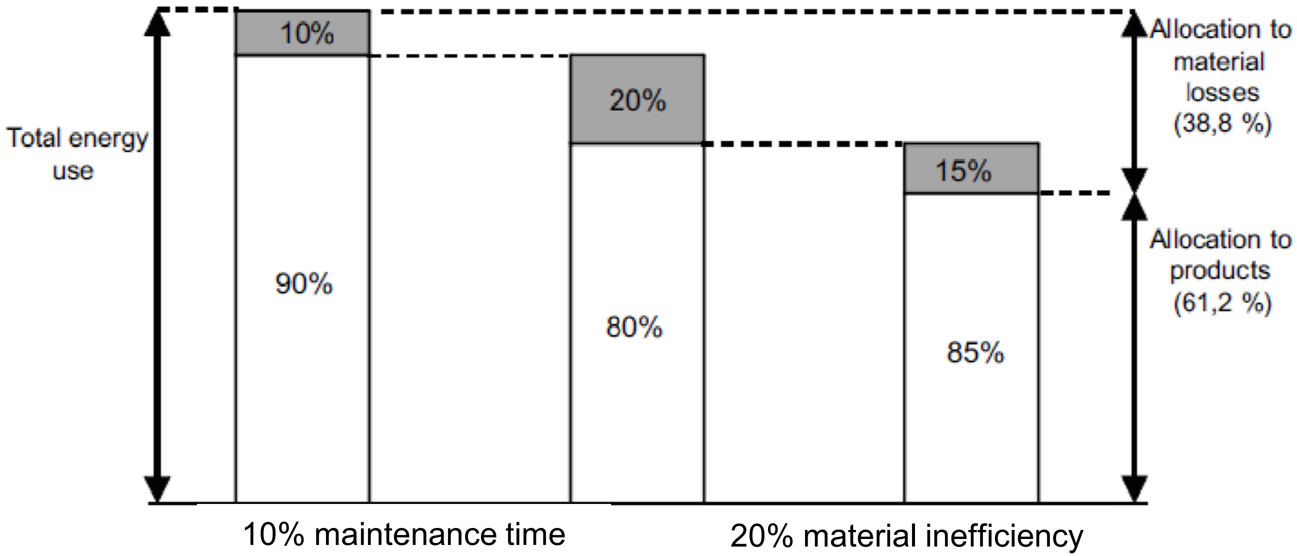
MFCA: simple example

Cost matrix for a production system with 2 QC

Composition of products and material losses	QC 1			QC 2			Result of production (mass)	Total
Products	Mass	Unit costs	Costs	Mass	Unit costs	Costs	60 kg	$ 4 200
Material X	40 kg	$ 100	$ 4 000	30 kg	$ 100	$ 3 000	30 kg	$ 3 000
Material Y	30 kg	$ 40	$ 1 200	30 kg	$ 40	$ 1 200	30 kg	$ 1 200
Material Z	—	$ 20	—	—	$ 20	—	—	$ 0
Materials losses	Mass	Unit costs	Costs	Mass	Unit costs	Costs	40 kg	$ 2 400
Material X	10 kg	$ 100	$ 1 000	10 kg	$ 100	$ 1 000	20 kg	$ 2 000
Material Y	—	$ 40	—	—	$ 40	—	—	$ 0
Material Z	—	$ 20	—	20 kg	$ 20	$ 400	20 kg	$ 400
Total material costs in this process								$ 6 600

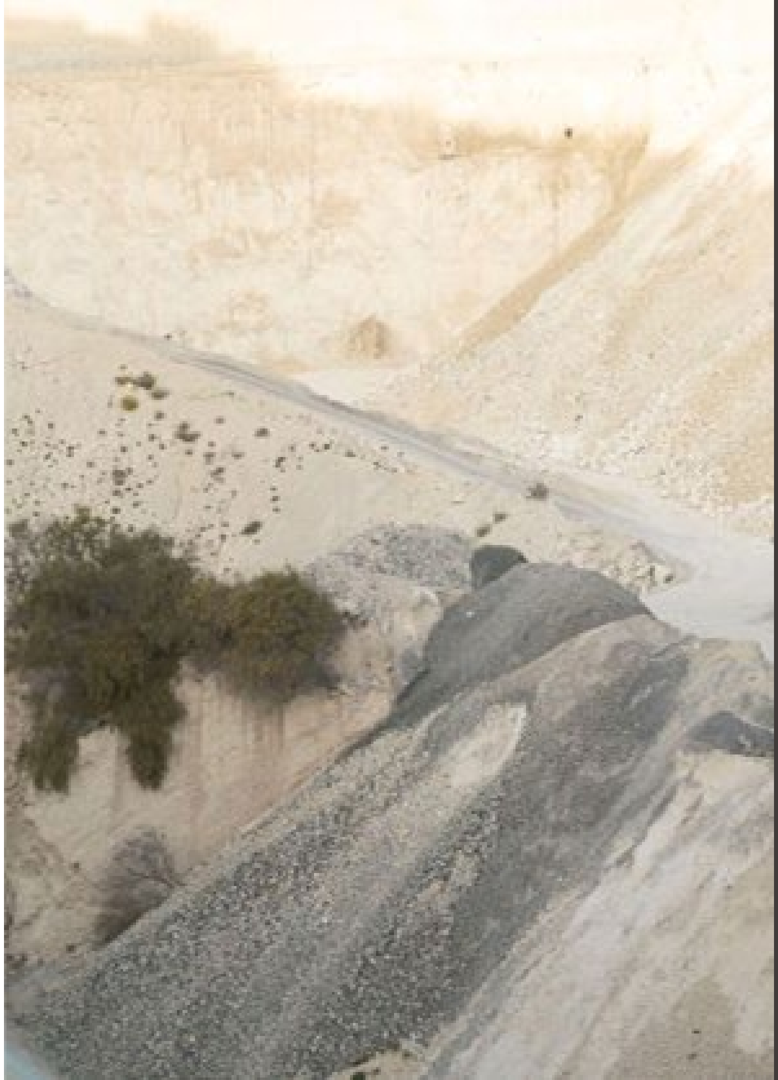
MFCA: simple example

More detailed criteria for distribution



Energy allocation to products: 90% * 80% * 85% = 61.2%
Energy allocation to material losses: 100% - 61.2% = 38.8%

Speaker



Thank you for your attention!

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