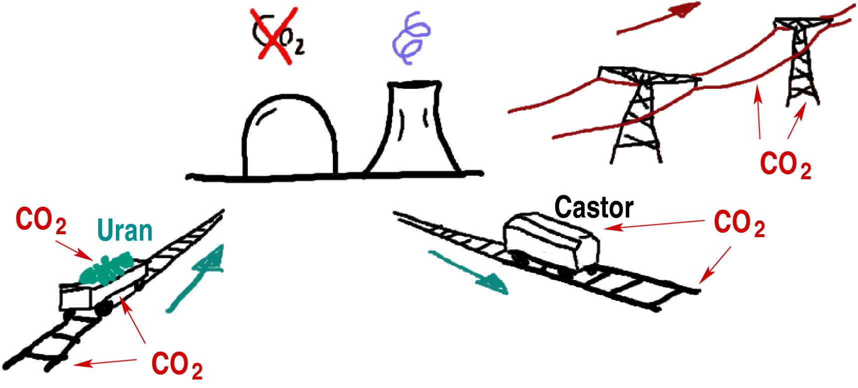
Chapter 5: Input-Output Models and Life-Cycle Assessment

- 5.1. Input-output model (IOM) of Leontief
- 5.2. Life-cycle assessment (LCA)
- 5.3. Combination: Econometric input-output LCA (EIO-LCA)

5.1. Input-output model (IOM) of Leontief: motivation



- Atomic power plants do not have any direct CO_2 emissions
- However, what are the *effective* emission considering all involved processes recursively?

Input-output model: problem statement

- In a modern economy, nearly everything is connected to "the rest" of the economy.
- *Wanted:* a quantitative description of the flows of material, services, and information between the different parts of an economy.
- The **input-output model (IOM) of Leontief** tackles this problem by making several assumptions:
  - Every material or service is associated with a certain **sector**.
  - To make all flows (kg, €, bytes, ...) commensurable, the common unit is a *monetary unit*, e.g., €.
  - The whole system is *linear* and *deterministic*: douple input means double output. Particularly, there is no economy of scale.
  - The whole system is in the **steady state**, e.g., there are no temporal changes (constant supply and demand); storage (if applicable) is neither built up nor depleted.

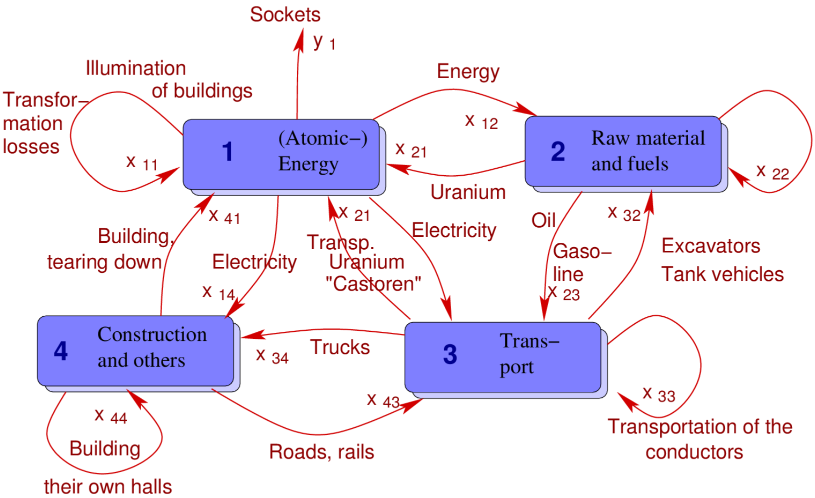
Specification of the IOM of Leontief

Linear, deterministic coupling of n sectors and an end consumer in the steady state:

$$x_i = y_i + \sum_{j=1}^{n} x_{ij} = y_i + \sum_{j=1}^{n} A_{ij} x_j.$$

- x_i: Total output of sector i in € or other monetary units per time unit.
- y_i: Flow of products/services of sector i to the end consumers (and to sectors that are not explicitely considered).
- x_{ij}: Flow from sector i to j: Sector j needs a supply x_{ij} from sector i to maintain the steady state and to ensure a constant supply y_j to the end consumer.
- $A_{ij} = x_{ij}/x_j$: IO coefficient reflecting linearity: In order to produce one unit, sector j needs A_{ij} units from all the other sectors i, including the own.

Visualisation of the flows generated by atomic power plants



Total production for a given consumer's supply

IOM equation in vector-matrix notation:

$$\boldsymbol{x} = \mathbf{A} \cdot \boldsymbol{x} + \boldsymbol{y}$$

- $\boldsymbol{x} = (x_1, x_2, \cdots, x_n)^\mathsf{T}$ production vector
- $\boldsymbol{y} = (y_1, y_2, \cdots, y_n)^\mathsf{T}$ supply vector
- $\mathbf{A} = (A_{ij}), i, j = 1 \cdots n$ IOM coefficient matrix

Solving for $\boldsymbol{x}$ by writing $(\mathbf{1} - \mathbf{A})\boldsymbol{x} = \boldsymbol{y}$:

$$\boldsymbol{x} = (\mathbf{1} - \mathbf{A})^{-1} \boldsymbol{y} \equiv \mathbf{B} \boldsymbol{y}$$

- $\mathbf{B} = (\mathbf{1} - \mathbf{A})^{-1}$ coefficient matrix of the final demand

Meaning of the matrix of the final demand **B**

- B_{ij} denotes the needed total production from sector i in order to deliver one unit of j to the end consumer (or the not considered sectors) in the steady state
- **B** includes all indirect effect *in an infinite recursion* as can be seen from the Taylor expansion:

$$\mathbf{B} = (\mathbf{1} - \mathbf{A})^{-1} = \mathbf{1} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \dots = \sum_{j=0}^{\infty} \mathbf{A}^j$$

Example:

$$B_{11} = 1 + A_{11} + \sum_{k=1}^{2} A_{1k} A_{k1} + \sum_{k=1}^{2} \sum_{l=1}^{2} A_{1k} A_{kl} A_{l1} + \ \dots$$

Example: 1=transportation sector, 2=vehicle construction

- A_{11}: transport of bus/train/truck drivers to their workplace or driving vehicles to/from the depot or to/from services
- A_{12}: transport of vehicle construction workers to their workplace or of material needed to make the vehicles
- A_{21}: the continuous replacements of buses, trains and trucks needed to provide public or material transport of unchanged quality (steady state)
- A_{22}: the vehicle makers need vehicles themselves for their operations
- A_{11}^2: In order to transport bus/train/truck drivers to their workplace one needs drivers as well
- $A_{11}A_{12}$: The transport of the vehicle construction workers to their workplace (A_{12}) induces additional traffic, hence additional need for operators/drivers (A_{11})
- $A_{12}A_{21}$: To manage the additional traffic caused by transporting the vehicle construction workers (A_{12}), the transportation sector needs additional vehicles (A_{21}) to maintain the steady state
- ...

Questions

- ? Argue that a national economy with sectors i satisfying $\sum_j A_{ij}x_j > x_i$ would not be sustainable or needs external help ("GDR").
- ? Give reasons why all A_{ij} and B_{ij} are ≥ 0 and $B_{ii} \geq 1$.
- ? Assume that the external demand y_i for products/services of sector i suddenly increases by one percent (e.g., driven by politics). Give a general expression for the percentaged increase of the total production of all the sectors in order to re-attain the steady state. Show that the result is independent from the price of an unit.
- ? Give some additional elements and concepts needed to make the IOM (i) dynamic, (ii) nonlinear reflecting the economy of scale.

5.2. Life-Cycle Assessment (LCA): Motivation

- The IOM reflects a *snapshot* of *all products* of a national economy in the *steady state*
- Sometimes, it is more instructive or relevant to consider *the total lifetime* of *a single product* in a *time dependent way* by assessing production, operation, and destruction/recycling of this product.
- This is formalized by the methods of **Life-Cycle Assessment (LCA)** (German: **Ökobilanz**).
- However, LCA only considers first-order indirect effects, e.g., CO_2 emissions caused by electric vehicles through the CO_2 footprint of electricity production
- The class of **Econometric Input-Output (EIO) LCA models** combines both approaches.

The standard LCA procedure

1. Define the life phases of the product in question:
   - production
   - operation/usage
   - destruction/recycling.
2. For each life phase, calculate the amount of needed materials/energy resulting in the **life-cycle inventory** $\tilde{y}_j$ for product category j (the tilde denotes that the product is given in physical units such as kg or kWh rather than in €).
3. The total emissions e_i of pollutant i during the life time is obtained using the **emission factor matrix** $\mathbf{C}$:

$$e_i = \sum_j C_{ij} \tilde{y}_j$$

where the emission factor C_{ij} gives the units of pollutant i caused by one unit of product j (including the production chain).

Example: Gasoline vehicle

Gasoline and Diesel vehicles are two examples of **internal combustion vehicles (ICV)**

1. Life-cycle inventory

- $\tilde{y}_1 = 800\,\mathrm{kg}$ steel (900 kg at production time, 80 kg spare parts during lifetime, 20 % emission-neutral recycling contribution),
- $\tilde{y}_2 = 60\,\mathrm{kg}$ aluminum (100 kg production, 40 % of it can be recycled without additional emissions)
- $\tilde{y}_3 = 100\,\mathrm{kg}$ plastic
- $\tilde{y}_4 = 50\,\mathrm{kg}$ rubber
- $\tilde{y}_5 = 36\,\mathrm{kg}$ lead (three starter batteries à 12 kg)
- $\tilde{y}_6 = 15\,000\,\mathrm{l}$ gazoline (250 000 km at 6 l/100 km during lifetime)

so we have

$$\tilde{\boldsymbol{y}} = (800\,\mathrm{kg},\ 60\,\mathrm{kg},\ 60\,\mathrm{kg},\ 60\,\mathrm{kg},\ 36\,\mathrm{kg},\ 15\,000\,\mathrm{l})^{\mathsf{T}}.$$

Example: Gasoline vehicle (ctnd)

2. Total CO_2 emissions

Defining e_1 to be the CO_2 emissions in kg (e_2 could be NO_x, e_3 PM and so on), we have

$$e_1 = \sum_{j=1}^{6} C_{1j} \tilde{y}_j$$

with the row vector

$$\boldsymbol{C}_{\mathrm{CO_2}} = (C_{1j}) = (4,\ 30,\ 2,\ 2, 20,\ 2.7\,\mathrm{kg/l}).$$

The last emission factor $C_{16} = C_{16}^{\mathrm{w2t}} + C_{16}^{\mathrm{t2w}}$ is the sum of two contributions:

- **Well-to-tank (w2t)** emissions of the production chain mining $\rightarrow$ transport to refinery $\rightarrow$ refining process $\rightarrow$ transport to the gas station: $C_{16}^{\mathrm{w2t}} = 0.4\,\mathrm{kg/l}$,
- **Tank-to-wheel (t2w)** emissions dictated by the chemistry during the actual combustion: $C_{16}^{\mathrm{t2w}} = 2.3\,\mathrm{kg/l}$ (gasoline) or $= 2.7\,\mathrm{kg/l}$ (Diesel)

Example: Battery-electric vehicle (BEV)

- The **Life-cycle inventory** of steel, aluminum, rubber, plastic etc is comparable to that of the ICVs.
- The starter batteries are replaced by the Lithium driving batteries (2× 300 kg) and the gasoline is replaced by the needed electrical energy, typically 20 kWh per 100 km:

$$\tilde{\boldsymbol{y}} = (800\,\text{kg},\ 60\,\text{kg},\ 60\,\text{kg},\ 60\,\text{kg},\ 600\,\text{kg},\ 50\,000\,\text{kWh})^{\mathsf{T}}.$$

- This leads to the new CO_2 emission factors vector

$$\boldsymbol{C}_{\mathsf{CO_2}} = (4,\ 30,\ 2,\ 2,\ 20,\ 0.45\,\text{kg/kWh}).$$

  - The Li driving batteries are expensive to produce and there is much controversy in extimating their overall emission factor C_{15}
  - The enery emission factor is based, e.g., on the present (2019) German energy mix emitting 450 g CO_2 per kWh of electrical energy at the socket

Questions on LCA

- ? Is it possible to check, at a glance, whether the example BEV emits less CO_2 per km than the example ICV *when considering the driving phase alone*?
- ? How would you proceed to calculate the *break-even* mileage beyond which a BEV is more environmentally friendly (“green”) than the ICV?
- ? Give the two most important factors influencing the total LCA emissions of battery-electric vehicles.
- ? A common saying states that *the Sun does not issue invoices* nor does the production of electric energy by photovoltaic (PV) elements entail any direct CO_2 emissions. Discuss why PV energy still has a nonzero CO_2 footprint and how to calculate the PV CO_2 emission factor. Use LCA arguments and assume a steady state.

5.3. Econometric Input-Output LCA

See the German script, Chapter 5.3.