11 Input-Output Models and Life-Cycle Assessment

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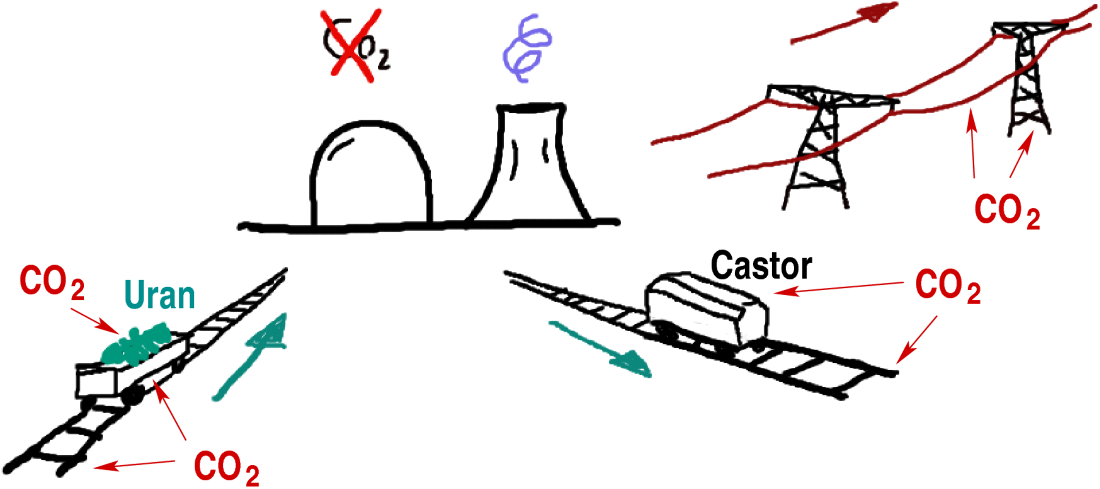
11.1. Input-Output Model (IOM) of Leontief: Motivation



- 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.

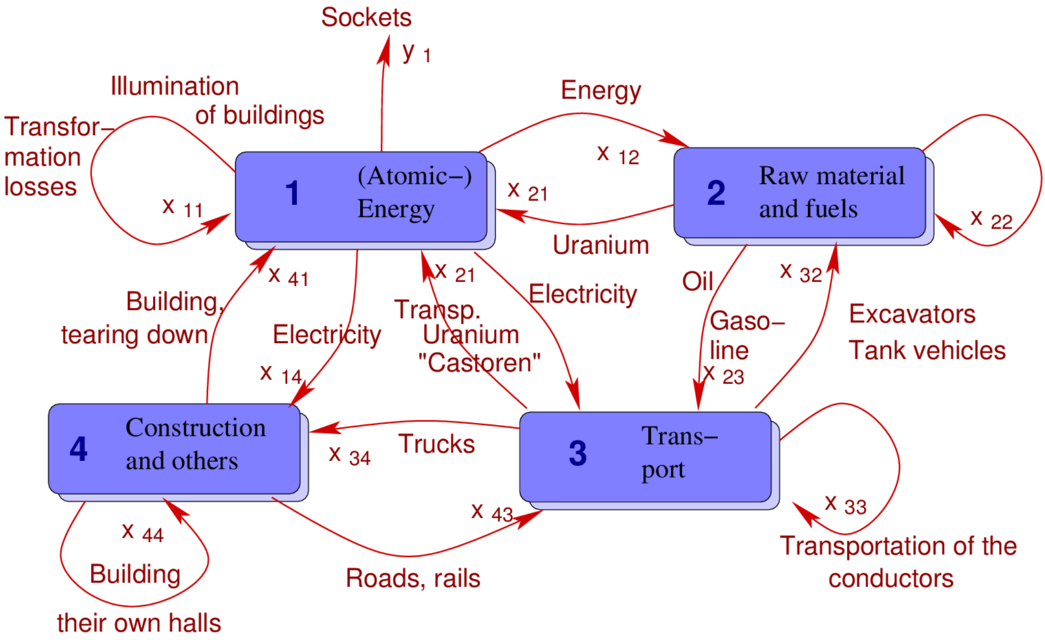
Specification of the IOM of Leontief

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:

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

- $\boldsymbol{x} = (x_1, x_2, \cdots, x_n)'$ **production vector**
- $\boldsymbol{y} = (y_1, y_2, \cdots, y_n)'$ **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:

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

Example: 1=transportation sector, 2=vehicle construction

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

- 1: Transportation of the passengers ("end consumers")
- A_{11}: The drivers, conductors, and the administrative staff of the transportation companies need transportation themselves
- A_{11}^2: The transport of employees of the transportation companies induces additional traffic, hence the need for additional employees to scale up the supply accordingly
- $A_{12}A_{21}$: To manage operations, the transport sector must offer aditional transportation for the commutes of the workers/employees of the vehicle making sector (A_{12}), so they can provide additional vehicles (A_{21}) needed by the transportation sector to maintain the steady state.
- $A_{11}A_{12}A_{21}$: Since also the employees of the transportation companies need transportation (A_{11}), even more transportation supply (A_{12}) must be offered to the employees of the vehicle making companies to get the additionally needed vehicles (A_{21})
- ...

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").

! In such an economy, sector i must deliver more units to operate itself ($A_{ii}x_i$) and the other sectors ($A_{ij}x_j$) than this sector produces in total (x_i).

? Give reasons why all A_{ij} and B_{ij} are ≥ 0 and $B_{ii} \geq 1$.

! Since sectors *need* products and services from other sectors.

? Assume that the external demand y_k for products/services of sector k suddenly increases by $r_k = 1\,\%$ (e.g., driven by politics). Give a general expression for the percentaged increase of the GDP in order to re-attain the steady state.

! The change of the demand vector is given by $\Delta\boldsymbol{y} = (0, .., r_k y_k, 0, ...)'$ and the change of the production vector components by $\Delta x_i = \sum_j B_{ij}y_j = r_k B_{ik} y_k$. Hence, the change of the total GDP is given by $\Delta x = \sum_i \Delta x_i = r_k \sum_i B_{ik} y_k$ and the old GDP itself by $x = \sum_i x_i = \sum_i \sum_j B_{ij} y_j$. Finally, the percentage increase of the total GDP is given by $\Delta x / x$

Questions (ctnd.)

? Give some additional elements and concepts needed to make the IOM dynamic

! After a sudden change of the demand, the demand vector $\boldsymbol{y}$ is no longer balanced against the available production $(\mathbf{1} - \mathsf{A})\boldsymbol{x}$ and the excess demand or supply is balanced by emptying or filling the stores. If the economy is **demand-driven (Keynes)**, this also induces ramping up/down the production. In the simplest case, the rate of change of the production is proportional to the excess demand,

$$\frac{\mathrm{d}x_i}{\mathrm{d}t} = \frac{1}{\tau_i}\left[y_i(t) - \left((\mathbf{1} - \mathsf{A})\boldsymbol{x}\right)_i\right]$$

where τ_i is the time the sector i needs to adapt to changing demands.

? Give some additional elements and concepts needed to introduce nonlinearity reflecting the economy of scale

! In an **economy of scale**, the IO coefficients become smaller with the number of produced units of the target sector which may be modelled, e.g., by

$$A_{ij}(x_j) = \frac{A_{ij}(0)}{1 + x_j/x_{j0}}$$

where x_{j0} is the production quantity where significal scale effects set in.

11.2. 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 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

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

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

$$\boldsymbol{C}_{\text{CO}_2} = (C_{1j}) = (4,\ 30,\ 2,\ 2,\ 20,\ 2.7\,\text{kg/l}).$$

The last emission factor $C_{16} = C_{16}^{\text{w2t}} + C_{16}^{\text{t2w}}$ 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: $C_{16}^{\text{w2t}} = 0.4\,\text{kg/l}$,
- **Tank-to-wheel (t2w)** emissions dictated by the chemistry during the actual combustion: $C_{16}^{\text{t2w}} = 2.3\,\text{kg/l}$ (it would be 2.7 kg/l for Diesel, i.e., the total w2w emissions of gasoline are about the t2w emissions when burning Diesel).

Example 2: 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:

$$\tilde{\boldsymbol{y}} = (800\,\mathrm{kg},\ 60\,\mathrm{kg},\ 60\,\mathrm{kg},\ 60\,\mathrm{kg},\ 600\,\mathrm{kg},\ 50\,000\,\mathrm{kWh})'.$$

- This leads to the new CO_2 emission factors vector

$$\boldsymbol{C}_{\mathrm{CO}_2} = (4,\ 30,\ 2,\ 2,\ 20,\ 0.45\,\mathrm{kg/kWh}).$$

  - 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*?

! Per 100 km, the BEV indirectly emits 20 kWh * 0.45 kg/kWh=9 kg. The ICV vehicle emits directly and indirectly 6 l * 2.7 kg/l=16.2 kg. So, the BEV "wins" when considering the direct and indirect emissions in the driving phase alone.

However, the BEV production emissions are significantly higher. Furthermore, less than ideal efficiencies when charging/discharging have not been considered.

? How would you proceed to calculate the *break-even* mileage beyond which a BEV is more environmentally friendly ("green") than the ICV?

! We saw that the *driving* emissions C' per kilometer x for the ICV are higher compared to the BEV. In contrast, it is the other way round for the *fixed* emissions C^0 due to production/disposal/recycling. So, just calculate the break-even kilometrage x_c by the equation

$$C^0_{\text{BEV}} + C'_{\text{BEV}} x_c = C^0_{\text{ICV}} + C'_{\text{ICVV}} x_c$$

Questions on LCA (ctnd.)

? Give the two most important factors influencing the total LCA emissions of battery-electric vehicles.

(i) The energy mix of the used electricity (this is tricky! particularly, you cannot save your soul by paying indulgences/ordering "green" electricity)
(ii) The production and disposal/recycling emissions of the battery and whether you need more than one battery during lifetime (to research this is even more trickky).

? 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.

(i) Get information about the usable lifetime τ,
(ii) Check the climate where you want to install your PV and determine the average power (in Germany, it is about 10 % of the installed power P_{max}) and calculate the total electric energy delivered, e.g., $W_{\text{el}} = 0.1\,\tau P_{\text{max}}$
(iii) Get the production and recycling emissions C of your PV including the connection to the electric grid and calculate the CO_2 footprint $e_{\text{PV}} = C/W_{\text{el}}$ [kg/kWh].

11.3. Econometric Input-Output LCA

See the German script, Chapter 5.3.