THE UNIVERSITY OF BRITISH COLUMBIA

ENGR 544, Life Cycle Assessment and Management

School of Engineering, Faculty of Applied Science

The University of British Columbia (Okanagan)

Chapter 14, Use of Input–Output Analysis in LCA

Learning Objectives

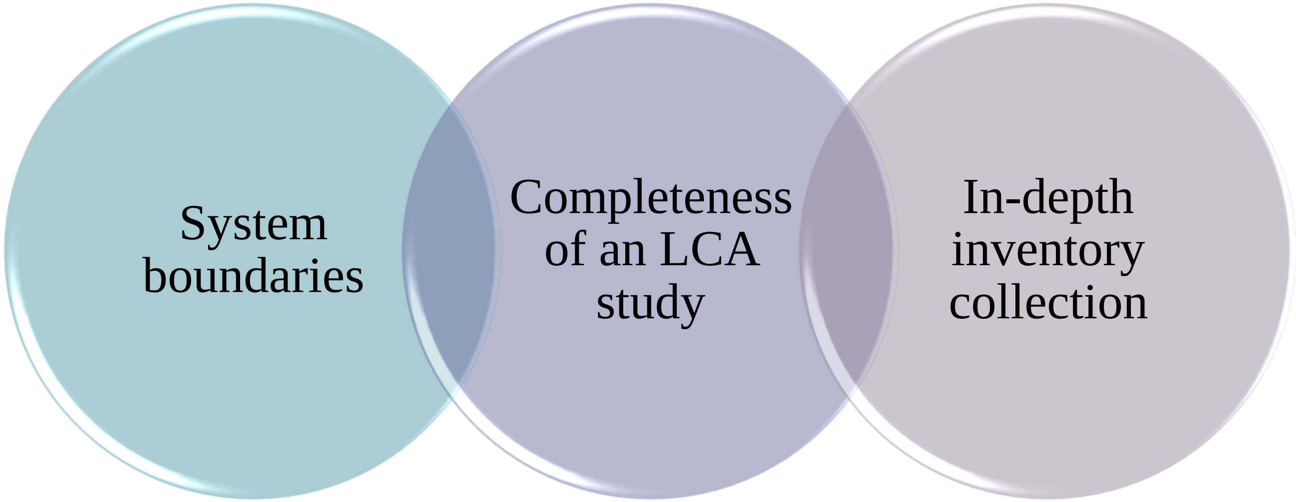
- Understand the historical background of **input–output analysis** and how it relates to LCA.
- Understand the basic equations of input–output analysis.
- Use input–output datasets to **find background information** on product systems and processes.
- Use hybrid input–output analysis to **identify hotspots** and the effect of **cut-off in process-LCA**.
- Use input–output analysis to **improve process-LCA dataset**.

1. Introduction

Introduction

- The **main applications** of **input–output analysis (IO)** is:

- To ensure consistent system boundaries,
- To evaluate the completeness of an LCA study,
- To form a basis for in-depth inventory collection.



Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (2018). Life cycle assessment (Vol. 2018). Springer International Publishing.

Introduction

- **IO** was initially developed for **macroeconomic** systems analysis and planning.
- The recent trend is to combine the IO into **environmentally** extended input–output analysis (EEIO), and develop hybrid IO-LCA and comprehensive sustainability assessment.
- The **application of IO** together with **LCA** shares the **same structure** as **attributional LCA**, linking **environmental impacts** to **demand** through a product system.
- An important problem in conventional process-based LCA is cut-off, or the omission of certain parts of the product system.
- **LCA** attempts to model every **environmental**, **social** and **economic** impact caused by a product throughout its life cycle from "cradle to grave", integrated over time and space.
- In practice, this is impossible, and certain s**implification** for the **system boundaries** have to be introduced. Everything outside those system boundaries is considered to be "cut-off" from the analysis.

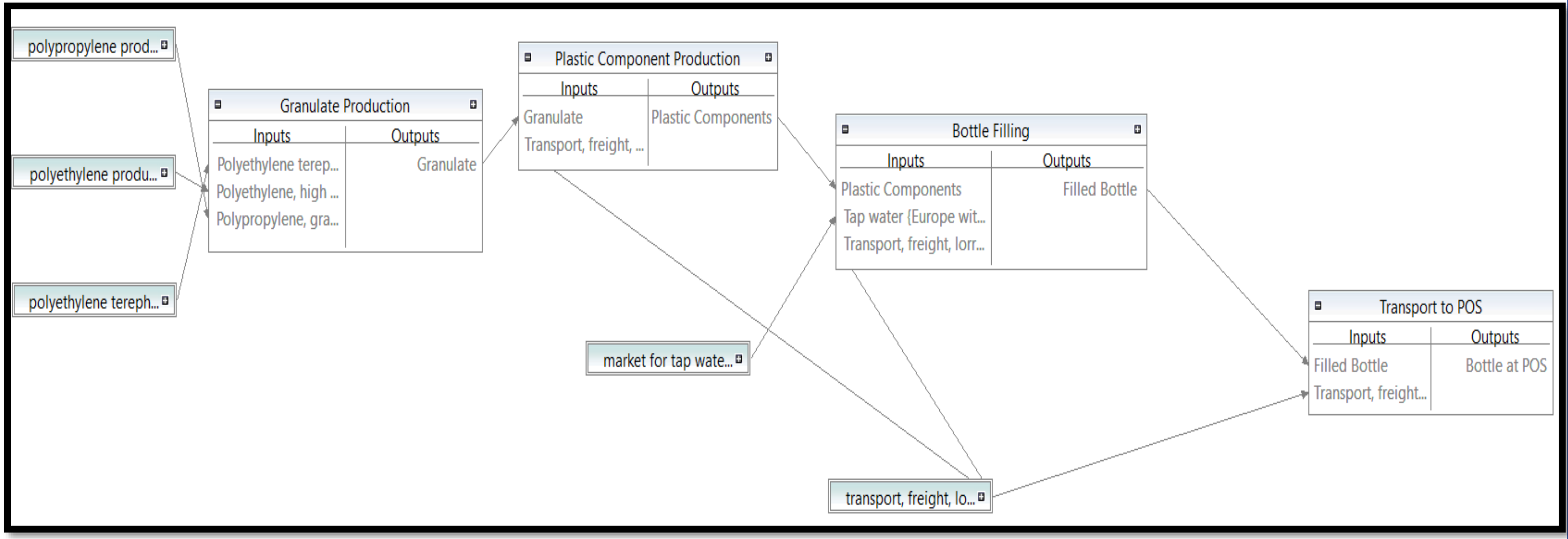
Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (2018). Life cycle assessment (Vol. 2018). Springer International Publishing.

Introduction

- The product system of an LCA can be thought of as a branching tree. It starts from the functional unit and branches out to the first tier of inputs needed to supply the functionality.

- In a typical study, **primary data** is collected for the **foreground processes**, which are closest to the final user.

- The **remaining inputs** are connected to **LCA databases**, which include product systems from previous studies. This forms the background system.



Input–Output Analysis in LCA

How much environmental impacts should be **allocated** to the **product system**?

- In the IO-based sustainability assessment, **inventory data** is collected at the **whole economy level**. Then, the **total environmental**, **social** and **economic** results are allocated to **specific industries**.
- A key assumption in IO is that the relationship between production and impacts is **linear**.
- This assumption is shared by attributional LCA but not by consequential LCA.
  - What fraction of airplane emissions is attributed to an air-freight package?
- Consequential LCA estimates the consequences of changing a part of the economy.
  - How much do global emissions change in response to one additional package?
  - What if airfreight increases tenfold?

Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (2018). Life cycle assessment (Vol. 2018). Springer International Publishing.

2. Environmentally Extended Input–Output Analysis (EEIO)

Environmentally Extended Input–Output Analysis (EEIO)

- Assume that a farmer needs to supply **1,000 kg of grain**. Each **1,000 kg** of grain requires **30 kg** of **grain as seed**. How much total grain has been produced to supply 1,000 kg to a consumer?

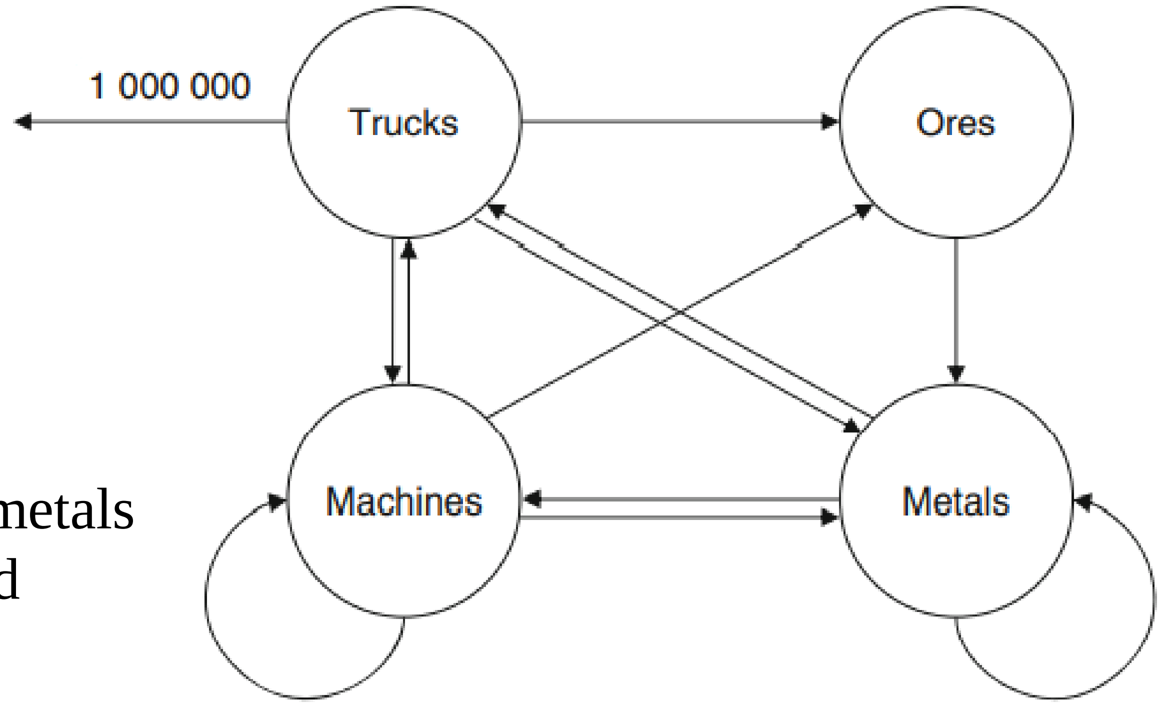
- Note: This problem presents **a loop**: the outputs of the process are used as its inputs. This results in an infinite series of tiers in the supply chain.

Environmentally Extended Input–Output Analysis (EEIO)

- For producing 1000 kg of grain, 30 kg of grain is needed for seed (1st tier), the production of 30 kg of grain requires 0.9 kg of seed (2nd tier), for which 0.027 kg of seed (3rd tier) was needed, etc.
- The solution can be found from the input–output relations.
  - If the production of 1000 kg requires 30 kg of seed, the input–output ratio is 30/1000 = 0.03. The net output per unit of production is then 1 − 0.03 = 0.97. The total amount of grain needed for a net output of 1000 kg is then (1/0.97) *1000 kg = 1030.928 kg.
- In more general terms, the total amount of production **$x = y/ (1- a)$,** where **x** is the total amount of production, **y** is the final demand and **a** is the input coefficient.
- These kinds of feedback loops are **simple**, when a process uses its **own outputs as inputs**.
- What if a process supplies outputs across the economy and uses inputs from several sources?

Environmentally Extended Input–Output Analysis (EEIO)

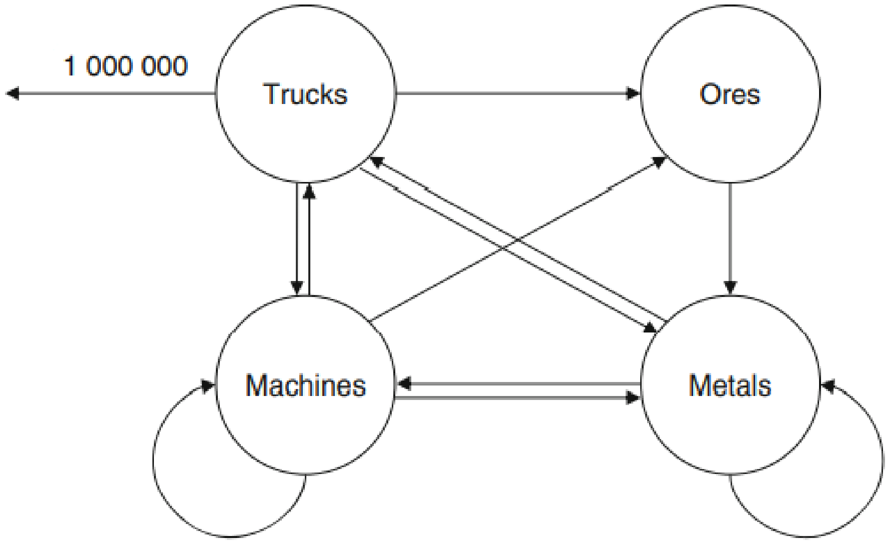
- The problem becomes more challenging, when a process **supplies** <u>outputs across the economy</u> and **uses** <u>inputs from several sources</u>.
- These delayed feedback loops are very common in complex supply chains (or more accurately supply networks), and make economic planning difficult.
- Assume that the **goal** is to build **1,000,000 trucks**, and that needs inputs from four economic sectors: **truck manufacture**, **metal manufacture**, **machine manufacture** and **ore mining**. The sectors are deeply interconnected.



- Trucks need inputs from metals and machinery; metals need metals, machinery and ores; machinery need metals and machines; and ores need machinery.

Environmentally Extended Input–Output Analysis (EEIO)

- The economic system can be described by using an input **coefficient table (A). Each column represents a sector**.
- **A** shows the inputs needed to produce one unit of output from that sector. For example, it takes 0.1 units of ores to make one unit of metals in the truck example.
- The outputs from the economic system are accounted separately in a final demand vector (**y**).



$$A = \begin{array}{c} \\ \text{Trucks} \\ \text{Metals} \\ \text{Mechines} \\ \text{Ores} \end{array} \begin{array}{c} \begin{array}{cccc} \text{Trucks} & \text{Metals} & \text{Mechines} & \text{Ores} \end{array} \\ \begin{pmatrix} 0 & 0.02 & 0.02 & 0.05 \\ 0.15 & 0.2 & 0.2 & 0 \\ 0.2 & 0.1 & 0.2 & 0.4 \\ 0 & 0.1 & 0 & 0 \end{pmatrix} \end{array}$$

$$Y = \begin{array}{c} \text{Trucks} \\ \text{Metals} \\ \text{Mechines} \\ \text{Ores} \end{array} \begin{pmatrix} 1000000 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

Environmentally Extended Input–Output Analysis (EEIO)

- If there is only **a single sector**, we can apply the same solution as in the grain example: $x = y/(1 - a)$.
- When there are **several sectors**, the structure of the equation is the same but matrix inversion replaces scalar division.

$$\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{y}$$

- Where I is an identity matrix, which has ones on the diagonal and zeros elsewhere.
- $(\mathbf{I} - \mathbf{A})^{-1}$ is the inverse of $(\mathbf{I} - \mathbf{A})$

$$\underbrace{\begin{pmatrix} 1{,}012{,}608 \\ 264{,}734 \\ 299{,}480 \\ 26{,}473 \end{pmatrix}}_{\text{X}} = \underbrace{\begin{array}{l} \\ \text{Trucks} \\ \text{Metals} \\ \text{Mechines} \\ \text{Ores} \end{array} \begin{array}{c} \begin{array}{cccc} \text{Trucks} & \text{Metals} & \text{Mechines} & \text{Ores} \end{array} \\ \begin{pmatrix} 1.012608 & 0.037725 & 0.034746 & 0.064529 \\ 0.264734 & 1.317052 & 0.335881 & 0.147589 \\ 0.29948 & 0.239915 & 1.317466 & 0.54196 \\ 0.026473 & 0.131705 & 0.033588 & 1.014759 \end{pmatrix} \end{array}}_{\text{Inverse of (I - A)}} \quad \underbrace{\begin{array}{l} \text{Trucks} \\ \text{Metals} \\ \text{Mechines} \\ \text{Ores} \end{array} \begin{pmatrix} 1{,}000{,}000 \\ 0 \\ 0 \\ 0 \end{pmatrix}}_{\text{Y}}$$

Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (2018). Life cycle assessment (Vol. 2018). Springer International Publishing.

Environmentally Extended Input–Output Analysis (EEIO)

- The **environmental extension** describes how much emissions or resources are used for each unit of production on a sector.

$$\boldsymbol{g} = \boldsymbol{B}\boldsymbol{x} = \boldsymbol{B}(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{y} = \boldsymbol{C}\boldsymbol{y}$$

- where **g** is a vector of embodied environmental impacts associated with final demand **y**, and **B** is a matrix of direct environmental impact multipliers for each sector. **C** is a matrix of embodied environmental impact intensity.

Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (2018). Life cycle assessment (Vol. 2018). Springer International Publishing.

Environmentally Extended Input–Output Analysis (EEIO)

$$\boldsymbol{g} = \boldsymbol{B}\boldsymbol{x}$$

- ❑ If we were interested in **land use** and assume that the manufacturing sectors each require 0.01 m2 of land area and mining requires 1.0 m2 of land area.
- ❑ What is the total land area demand of the truck example?

➢ B = [0.01, 0.01, 0.01, 1.0]

$$\underbrace{\begin{pmatrix} 1,012,608 \\ 264,734 \\ 299,480 \\ 26,473 \end{pmatrix}}_{\text{X}}$$

➢ The **total land area demand** of the truck example is:

g = 0.01 * 1,012,608 + 0.01 * 264,734 + 0.01 * 299,480 + 1.0 * 26,473 = **42,241 m2**.

3. Avoiding Cut-Off Through Comprehensive System Boundaries

Avoiding Cut-Off Through Comprehensive System Boundaries

- There are **two sources** of **cut-off**: the identified cut-off and the non-identified cut-off.
- The identified cut-off consists of flows that are identified during the process-LCA, but which have no LCI data available.
- The unidentified cut-off is flows which are omitted, since they are intangible (not related to energy or material flows) or simply overlooked.
- For example, ignoring **maintenance services** in a pulp and paper mill, although the maintenance services consume tools and specialty metals, with **considerable impacts** to **metal depletion**.
- Other classical examples would be **ignoring insurance**, **facility rent**, **retail trade**, **marketing** or **software development**. If these are omitted in all parts of the process-LCA product system, the complete omission will be significant.

Avoiding Cut-Off Through Comprehensive System Boundaries

- If economic or social indicators are considered, the omission will be even larger.

"In a case study of smartphone sustainability assessment, much of embodied child labour was in ***trade services*** *and* ***warehouse work*** *in developing countries in the parts of the supply chain that supplied parts for smartphone assembly. This came as a surprise both to the analysts and the social responsibility people of the smartphone manufacturers, wholesale trade had previously been ignored in the inventory for child labour".*

- Fortunately, IO can be used to estimate both identified and non-identified cut-off flows. The first case is termed missing inventories and the second is termed checking for completeness.

Estimating Missing Inventories from IO Data

- Process-**LCA** has **traditionally** focused on physical processes and products. Consequently, most LCA databases lack services.
- **Input–output** results can be applied to **complete** these **missing inventory items**.

- The analysis consists of four stages:
  - Convert physical flows to monetary flows using price data or import statistics, which report both mass and price flows.
  - Find an appropriate IO dataset (good geographical and year coverage).
  - Convert the monetary flow to the currency and year of the IO dataset using producer price indexes.
  - Multiply the monetary flows with the corresponding LCI results from the IO dataset.

Estimating Missing Inventories from IO Data

Example 14.2: **Estimate the carbon footprint** for a **wedding trip** planned to be from Denmark to San Francisco. The planned flight distance is 18,000 km, some estimated costs would be \$40 for public transportation, \$3000 for hotels and \$1000 for restaurants and \$100 for travel insurance.

Commodity	CPI 2014	CPI 2002	Purchase in 2014	In 2002 prices	Carbon intensity (kg CO_2-eq/ $\$_{2002}$)	Carbon footprint (kg CO_2-eq)
Taxi	297	184	\$40	\$25	1.870	46
Hotels	308	251	\$3000	\$2445	0.559	1367
Restaurants	155	113	\$1000	\$729	0.580	423
Insurance	318	211	\$100	\$66	0.117	8
Total			\$4440	\$3265		1844

- The **major contributor** is the stay at the hotel, contributing **1,367** kg CO2 -eq.
- In the case of hotels, the main contribution is from the power generation and supply sector, followed by direct emissions from hotel heating.

Estimating Completeness of the Process-LCA Dataset

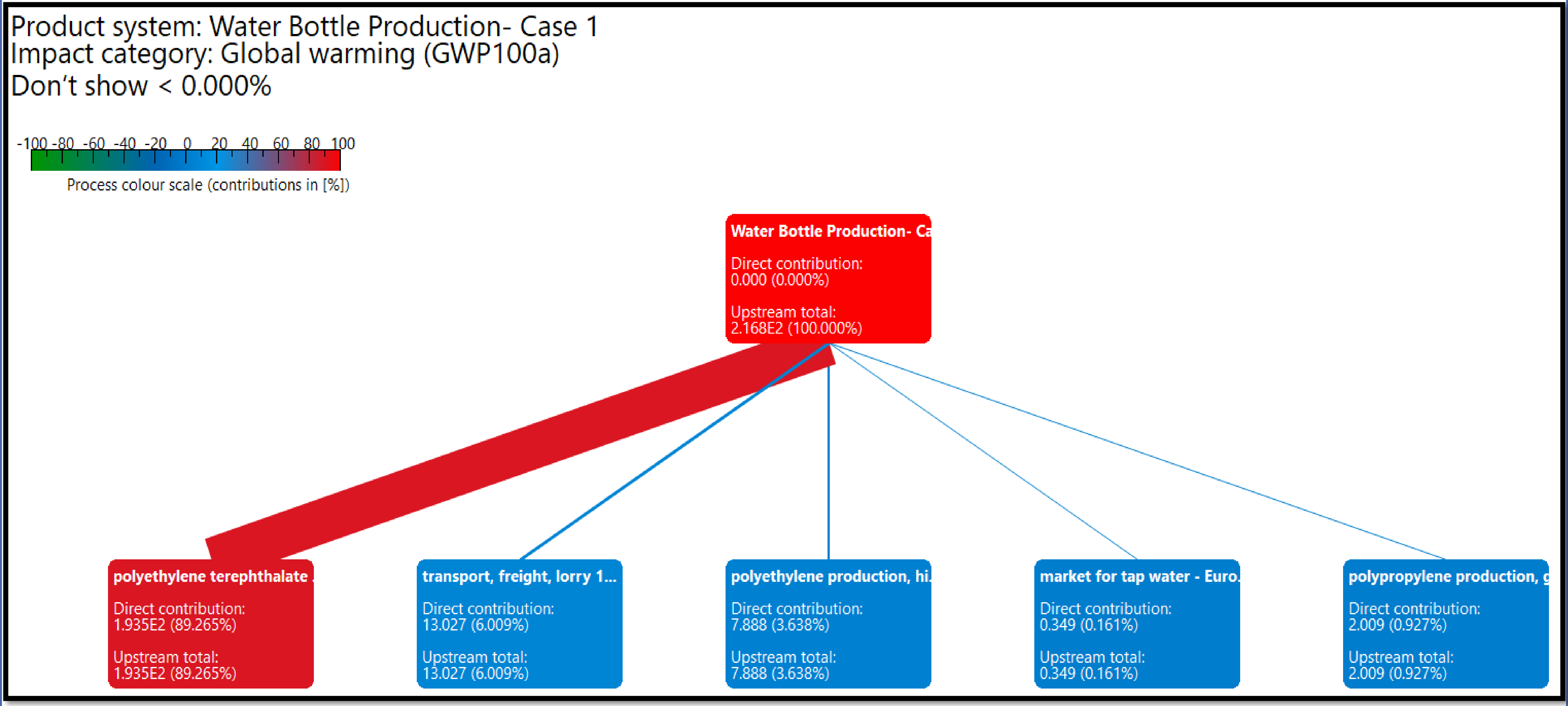
- **Input–output** can be useful for finding inventory data on flows that are commonly not found in process-LCA databases, such as insurance, financial services and hotels.
- **Input–output** can be used to analyze how complete the process-LCA dataset is. This is based on estimating the input coefficient and **value added** in the process-LCA dataset.

Using Input–Output Analysis as a Template for LCA

- In practice, **Accumulative Structural Path Analysis (ASPA)** is performed to show the **structure of the process system**.
- The ASPA is conceptually simple: one multiplies all the direct inputs (A matrix) with the corresponding embodied impact intensities (C matrix).
- Then top ranking inputs are screened to the next step based on either a specified cut-off level (e.g. more than 1% of total impact) or a specified inclusion limit (together the included inputs must cover >90% of total impact).
- This results in a **branching tree structure** of the process system, which can be visualised with a **Sankey diagram** or a flow chart.
- Then, the **most critical pathways are distinguished**.
- LCA software (such as SimaPro or OpenLCA) includes tools for drawing Sankey diagrams.

Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (2018). Life cycle assessment (Vol. 2018). Springer International Publishing.

Sankey Diagram of PET Bottle



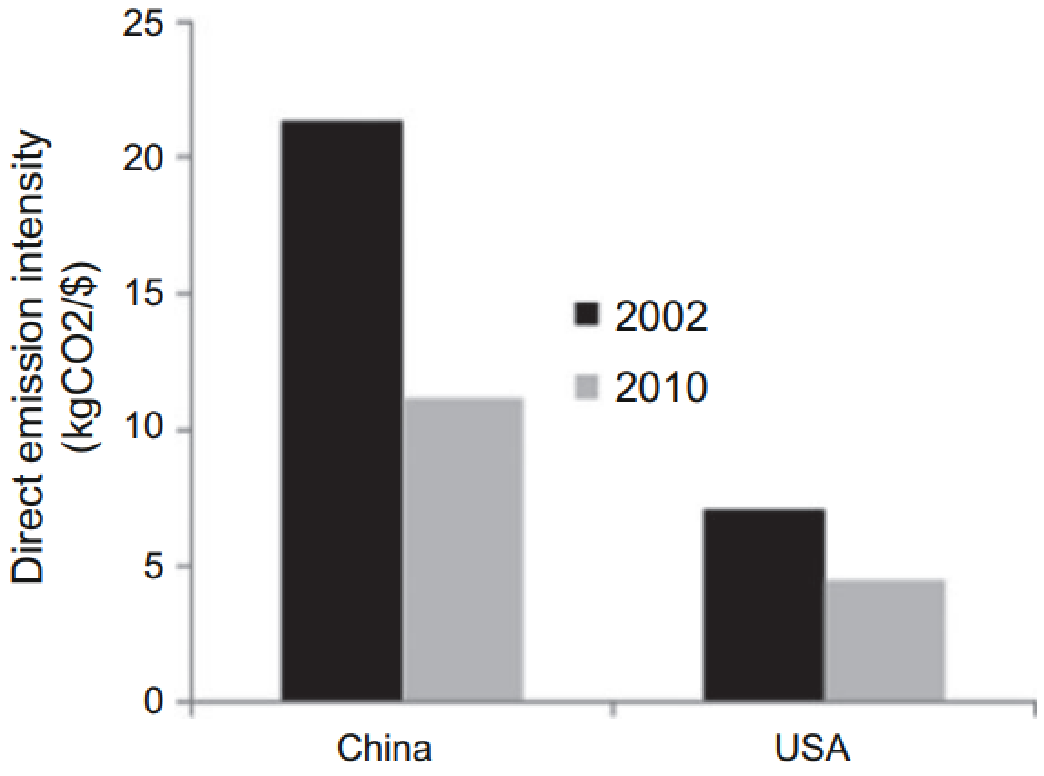
Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (2018). Life cycle assessment (Vol. 2018). Springer International Publishing.

4. Shortcomings of EEIO

Shortcomings of EEIO

- A major flaw in most **IO datasets** is that they do not cover the life cycle from cradle to grave. Quite often, the end-of-life stage is missing.
  - IO dataset includes data for a given year. But what if the infrastructure needed has been built a long time ago and is no longer maintained? Moreover, what about the eventual demolition and recycling of the infrastructure?

- Most **EEIO datasets** are based on a single year of production, while the emission intensities change over time.
  - For example, the carbon footprint of electricity production in China almost halved from 2002 to 2010 and the electricity production footprint in USA decreased by 37%.



Appendix

Inverse Matrix Calculator

$$I - A =$$

	A_1	A_2	A_3	A_4
1	1	-0.02	-0.02	-0.05
2	-0.15	0.8	-0.2	0
3	-0.2	-0.1	0.8	-0.4
4	0	-0.1	0	1

Write the augmented matrix

	A_1	A_2	A_3	A_4	B_1	B_2	B_3	B_4
1	1	-0.02	-0.02	-0.05	1	0	0	0
2	-0.15	0.8	-0.2	0	0	1	0	0
3	-0.2	-0.1	0.8	-0.4	0	0	1	0
4	0	-0.1	0	1	0	0	0	1

Find the pivot in the 1st column in the 1st row

	A_1	A_2	A_3	A_4	B_1	B_2	B_3	B_4
1	1	-0.02	-0.02	-0.05	1	0	0	0
2	-0.15	0.8	-0.2	0	0	1	0	0
3	-0.2	-0.1	0.8	-0.4	0	0	1	0
4	0	-0.1	0	1	0	0	0	1

Eliminate the 1st column

	A_1	A_2	A_3	A_4	B_1	B_2	B_3	B_4
1	1	-0.02	-0.02	-0.05	1	0	0	0
2	0	0.797	-0.203	-0.0075	0.15	1	0	0
3	0	-0.104	0.796	-0.41	0.2	0	1	0
4	0	-0.1	0	1	0	0	0	1

Make the pivot in the 2nd column by dividing the 2nd row by 0.797

	A_1	A_2	A_3	A_4	B_1	B_2	B_3	B_4
1	1	-0.02	-0.02	-0.05	1	0	0	0
2	0	1	-0.25470514429109159347	-0.009410288582183186951	0.18820577164366373902	1.2547051442910915934	0	0
3	0	-0.104	0.796	-0.41	0.2	0	1	0
4	0	-0.1	0	1	0	0	0	1

Eliminate the 2nd column

	A_1	A_2	A_3	A_4	B_1	B_2	B_3	B_4
1	1	0	-0.025094102885821831869	-0.050188205771643663739	1.0037641154328732747	0.025094102885821831868	0	0
2	0	1	-0.25470514429109159347	-0.009410288582183186951	0.18820577164366373902	1.2547051442910915934	0	0
3	0	0	0.76951066499372647428	-0.41097867001254705144	0.21957340025094102885	0.13048933500627352571	1	0
4	0	0	-0.025470514429109159347	0.99905897114178168130	0.018820577164366373902	0.12547051442910915934	0	1

Make the pivot in the 3rd column by dividing the 3rd row by 0.76951066499372647428

	A_1	A_2	A_3	A_4	B_1	B_2	B_3	B_4
1	1	0	-0.025094102885821831869	-0.050188205771643663739	1.0037641154328732747	0.025094102885821831868	0	0
2	0	1	-0.25470514429109159347	-0.009410288582183186951	0.18820577164366373902	1.2547051442910915934	0	0
3	0	0	1	-0.53407793901842491439	0.28534159465188325451	0.16957443339311919124	1.2995271482145768791	0
4	0	0	-0.025470514429109159347	0.9990589711417816813	0.018820577164366373902	0.12547051442910915934	0	1

Eliminate the 3rd column

	A_1	A_2	A_3	A_4	B_1	B_2	B_3	B_4
1	1	0	0	-0.063590412522419696722	1.0109245067666721016	0.029349421164193706177	0.032610467960215229085	0
2	0	1	0	-0.14544268710255992172	0.26088374368172183270	1.2978966248165661176	0.33099624979618457522	0
3	0	0	1	-0.53407793901842491439	0.28534159465188325451	0.16957443339311919124	1.2995271482145768791	0
4	0	0	0	0.98545573128974400782	0.026088374368172183270	0.12978966248165661176	0.033099624979618457522	1

Make the pivot in the 4th column by dividing the 4th row by 0.98545573128974400782

	A_1	A_2	A_3	A_4	B_1	B_2	B_3	B_4
1	1	0	0	-0.063590412522419696722	1.0109245067666721016	0.029349421164193706177	0.032610467960215229085	0
2	0	1	0	-0.14544268710255992172	0.2608837436817218327	1.2978966248165661176	0.33099624979618457522	0
3	0	0	1	-0.53407793901842491439	0.28534159465188325451	0.16957443339311919124	1.2995271482145768791	0
4	0	0	0	1	0.026473410768059829907	0.13170521857109765378	0.033588139911975909193	1.0147589265031933551

Eliminate the 4th column

	A_1	A_2	A_3	A_4	B_1	B_2	B_3	B_4
1	1	0	0	0	1.0126079618782884938	0.037724610344485257615	0.03474635163307852675	0.064528938747145835396
2	0	1	0	0	0.26473410768059829907	1.3170521857109765378	0.33588139911975909193	0.14758926503193355171
3	0	0	1	0	0.29948045931367682582	0.23991528508554220851	1.3174658327542274727	0.54196035606737483035
4	0	0	0	1	0.026473410768059829907	0.13170521857109765378	0.033588139911975909193	1.0147589265031933551

There is the inverse matrix on the right

	A_1	A_2	A_3	A_4	B_1	B_2	B_3	B_4
1	1	0	0	0	1.0126079618782884938	0.037724610344485257615	0.03474635163307852675	0.064528938747145835396
2	0	1	0	0	0.26473410768059829907	1.3170521857109765378	0.33588139911975909193	0.14758926503193355171
3	0	0	1	0	0.29948045931367682582	0.23991528508554220851	1.3174658327542274727	0.54196035606737483035
4	0	0	0	1	0.026473410768059829907	0.13170521857109765378	0.033588139911975909193	1.0147589265031933551

	B_1	B_2	B_3	B_4
1	1.0126079618782884938	0.037724610344485257615	0.03474635163307852675	0.064528938747145835396
2	0.26473410768059829907	1.3170521857109765378	0.33588139911975909193	0.14758926503193355171
3	0.29948045931367682582	0.23991528508554220851	1.3174658327542274727	0.54196035606737483035
4	0.026473410768059829907	0.13170521857109765378	0.033588139911975909193	1.0147589265031933551

https://matrix.reshish.com/inverse.php