Lecture:
Advanced Environmental Assessments

Input-Output and hybrid LCA
November 28, 2013

What we will learn today

• Basic structure of Input-Output tables
• Similarities and Differences of LCA and Input-Output analysis

Content

• Some basics of Input-Output tables
• Computational structures
  – life cycle inventory analysis
  – Input Output analysis
  – hybrid analysis
• Comparison with Product LCA
• Synthesis and outlook

Economic Input-Output tables

• Input-Output tables describe sectoral interrelations within an economy
• Reflect national energy, environmental and social policy
  - fuel prices
  - subsidies
  - environmental legislation
• Used in applied economic research and policy analysis
  - economic impact assessment of policy measures
  - impacts of economic activities on employment, energy use, environmental impacts
Economic Input-Output tables (II)

- Input-Output tables are defined on a macroeconomic level.
- National economy is structured into economic sectors.
- Interrelations within these sectors are quantified in economic terms:
  - how much one sector purchases from other sectors
  - how much one sector supplies to other sectors
- Final consumption, imports and exports are quantified as well.
- Some additional, nasty things like value added, taxes, subsidies, capital formation.

Structure of symmetric input/output table

<table>
<thead>
<tr>
<th>Products</th>
<th>Final demand</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intermediates</td>
<td>Commodity consumption</td>
<td>Total</td>
</tr>
<tr>
<td>Private consumption</td>
<td>Public consumption</td>
<td>Total</td>
</tr>
<tr>
<td>Gross capital formation</td>
<td>Exports</td>
<td>Total use of commodities</td>
</tr>
</tbody>
</table>

Nathani et al. 2006

Basic concept of Input-Output analysis

**Swiss economy**

Exports

Imports

Sector 1

Sector 2

Sector n

Processed Food Products

Impacts from intermediate inputs

Impacts of the Sector

(Suh 2011)
Examples of sectors

- 01-05: Agriculture and hunting; forestry and logging; fishing and fish farming
- 15 & 16: manufacture of food products and beverages; and of tobacco products
- 21: manufacture of pulp, paper and paper products
- 22: publishing, printing and reproduction of recorded media
- 33: manufacture of medical, precision and optical instruments, watches and clocks
- 51, 52: wholesale trade and commission trade
- 55: hotels and restaurants
- 62-64: transport via pipeline, air, water, and land

How to add additional attributes to IO tables

Swiss economy - employment - energy use - emissions

Satellite matrix: per CHF spent in sector i:
- person months of employment
- MJ primary energy required
- kg CO₂ emitted
- ...

CO₂-intensities of economic sectors in selected countries [kg CO₂/US-$]

<table>
<thead>
<tr>
<th>Sector</th>
<th>ISIC CODE</th>
<th>Switzerland (Exports)</th>
<th>Switzerland (Imports)</th>
<th>France</th>
<th>Germany</th>
<th>Italy</th>
<th>Japan</th>
<th>Sweden</th>
<th>UK</th>
<th>USA</th>
<th>China</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mining, extraction, refining</td>
<td>10-14, 23</td>
<td>0.18</td>
<td>1.07</td>
<td>1.1</td>
<td>1.1</td>
<td>0.6</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>1.9</td>
<td>1.8</td>
</tr>
<tr>
<td>Food, beverages, tobacco</td>
<td>15-16</td>
<td>0.19</td>
<td>0.56</td>
<td>0.5</td>
<td>0.5</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Textiles, leather, footwear</td>
<td>17-19</td>
<td>0.83</td>
<td>0.83</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Wood &amp; products of wood &amp; cork</td>
<td>20-21</td>
<td>0.00</td>
<td>0.00</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Pulp, paper, printing &amp; publishing</td>
<td>22-23</td>
<td>0.19</td>
<td>0.56</td>
<td>0.5</td>
<td>0.5</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Chemicals</td>
<td>24-25</td>
<td>0.19</td>
<td>0.56</td>
<td>0.5</td>
<td>0.5</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Other metal products, machinery eqpt</td>
<td>26-27</td>
<td>0.00</td>
<td>0.00</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Average | 0.16 | 0.50 |

From economic sectors to product groups

<table>
<thead>
<tr>
<th>Level</th>
<th>Group</th>
<th>Name and example</th>
<th>number of items</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Total of all imports and exports, resp.</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>Main group of goods: food and living animals</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>010.00</td>
<td>group of goods: meat and meat preparations</td>
<td>67</td>
</tr>
<tr>
<td>3</td>
<td>011.00</td>
<td>meat from beef, fresh, chilled or frozen</td>
<td>101</td>
</tr>
<tr>
<td>4</td>
<td>011.10</td>
<td>meat from beef, fresh or chilled</td>
<td>133</td>
</tr>
<tr>
<td>5</td>
<td>011.11</td>
<td>meat from beef, fresh or chilled, with bones</td>
<td>3882</td>
</tr>
<tr>
<td>6</td>
<td>001.11</td>
<td>additional classification regarding provenience</td>
<td>66500</td>
</tr>
</tbody>
</table>
### Structural similarity: IO table and product LCA

- product system is an excerpt of worlds economy
- each process belongs to an economic sector
- additional attributes are direct - emissions and - resource consumption

### Computational structure of life cycle inventory analysis (Heijungs & Suh 2002, slides 14-28)

- Two unit processes:
  - \( p_1 \): electricity production
  - \( p_2 \): fuel production

<table>
<thead>
<tr>
<th></th>
<th>( p_1 ) production of electricity</th>
<th>( p_2 ) production of fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>fuel (litre)</td>
<td>-2</td>
<td>100</td>
</tr>
<tr>
<td>electricity (kWh)</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>crude oil (litre)</td>
<td>0</td>
<td>-120</td>
</tr>
<tr>
<td>carbon dioxide (kg)</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>sulphur dioxide (kg)</td>
<td>0.1</td>
<td>2</td>
</tr>
</tbody>
</table>

\[
P = [A, B] = \begin{pmatrix} -2 & 100 \\ 10 & 0 \\ -120 & 10 \\ 1 & 2 \end{pmatrix}
\]

- final demand vector \( f \), with reference flow being the only non-zero element (e.g. 1'000 kWh electricity)

\[
f = \begin{pmatrix} 0 \\ 1'000 \end{pmatrix}
\]
Computational structure of life cycle inventory analysis: technology matrix

- Scaling vector
- balance equation for first economic flow, fuel
  \[ a_{11} \times s_1 + a_{12} \times s_2 = f_1 \]
  \[ -2 \times s_1 + 100 \times s_2 = 0 \]
- balance equation for second economic flow, electricity
  \[ a_{21} \times s_1 + a_{22} \times s_2 = f_2 \]
  \[ 10 \times s_1 + 0 \times s_2 = 1000 \]
- Matrix notation:
  \[
  \begin{pmatrix}
  a_{11} & a_{12} \\
  a_{21} & a_{22}
  \end{pmatrix}
  \begin{pmatrix}
  s_1 \\
  s_2
  \end{pmatrix}
  =
  \begin{pmatrix}
  f_1 \\
  f_2
  \end{pmatrix}
  \\
  A = \begin{pmatrix}
  -2 & 100 \\
  0 & 0
  \end{pmatrix}
  A^{-1} = \begin{pmatrix}
  0 & 0.1 \\
  0.01 & 0.002
  \end{pmatrix}
  \\
  As = f \\
  s = A^{-1} f
  \\
  \text{Solution: } s = \begin{pmatrix}
  s_1 \\
  s_2
  \end{pmatrix} = \begin{pmatrix}
  \frac{f_1}{a_{11}} \\
  \frac{f_2}{a_{22}}
  \end{pmatrix} = \begin{pmatrix}
  \frac{f_1}{a_{11}} \\
  \frac{f_2}{a_{22}}
  \end{pmatrix}
  \\
  f_1 = b_{11} \times s_1 + b_{12} \times s_2
  f_2 = b_{21} \times s_1 + b_{22} \times s_2
  \\
  \text{Matrix notation:}
  \begin{pmatrix}
  f_1 \\
  f_2
  \end{pmatrix} = B s
  \\
  B = \begin{pmatrix}
  0 & -120 \\
  1 & 10
  \end{pmatrix}
  g = Bs
  = \begin{pmatrix}
  0 & -120 \\
  1 & 10
  \end{pmatrix}
  \begin{pmatrix}
  f_1 \\
  f_2
  \end{pmatrix}
  = \begin{pmatrix}
  -240 & -120 \\
  -20 & 14
  \end{pmatrix}
  \text{g_1: crude oil} \\
  \text{g_2: CO}_2 \\
  \text{g_3: SO}_2

Computational structure of Input Output analysis

- Two «economic sectors»:
  - \( p_1 \): electricity production
  - \( p_2 \): fuel production

<table>
<thead>
<tr>
<th></th>
<th>( p_1 ): production of electricity</th>
<th>( p_2 ): production of fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>fuel</td>
<td>Euro 2</td>
<td>Euro 10</td>
</tr>
<tr>
<td>electricity</td>
<td>Euro 4</td>
<td>Euro 2</td>
</tr>
<tr>
<td>crude oil</td>
<td>litre 0</td>
<td>-20</td>
</tr>
<tr>
<td>carbon dioxide</td>
<td>kg 0.8</td>
<td>3</td>
</tr>
<tr>
<td>sulphur dioxide</td>
<td>kg 0.07</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Example: sector 2 (electricity production) requires 10 Euro from sector 1 and 2 Euro from its own output

\[
Z = \begin{pmatrix}
  2 & 10 \\
  4 & 2
  \end{pmatrix}
\]
Input Output LCA

Computational structure of Input Output analysis

- Add households demand $y$:
  
  8 Euro electricity, 4 Euro fuel

- Calculate total demand $x$:

- Analyse consequences of changes in household demand

- Define matrix of technical coefficients by expressing each process’ inputs as a fraction of its outputs

\[
Z = \begin{pmatrix}
2/20 & 10/10 \\
4/20 & 2/10
\end{pmatrix} = \begin{pmatrix}
0.1 & 1 \\
0.2 & 0.2
\end{pmatrix}
\]

\[
\hat{z} = Z (\text{diag}(x))^{-1}
\]

Input Output LCA

Computational structure of Input Output analysis

- New total output vector $x'$ in function of new household demand $y'$

- Distinguish between total output and households demand vectors in existing ($x$ and $y$) and new ($x'$ and $y'$) situation

- Calculate change in demand $\Delta y = y' - y; \Delta x = x' - x$

\[
x' = (I - \hat{Z})^{-1} y' \quad I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}
\]

\[
\Delta x = (I - \hat{Z})^{-1} \Delta y
\]

\[
\Delta y = (17.69)
\]

Input Output LCA

Computational structure of hybrid analysis

- Two unit processes: $p_1$: electricity production
  $p_2$: fuel production

- Capital equipment: $p_1$: generator
  $p_2$: refinery

<table>
<thead>
<tr>
<th></th>
<th>$p_1$: production of electricity</th>
<th>$p_2$: production of fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>fuel</td>
<td>litre</td>
<td>kWh</td>
</tr>
<tr>
<td>electricity</td>
<td>kWh</td>
<td>generator Euro</td>
</tr>
<tr>
<td>generator</td>
<td>Euro</td>
<td>refinery Euro</td>
</tr>
<tr>
<td></td>
<td>-2</td>
<td>-0.1</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>-1</td>
<td>-1</td>
</tr>
</tbody>
</table>
Computational structure of hybrid analysis

• Environmental interventions combined

\[ g = b_{\text{IOA}} + b_{\text{LCA}} = B (I - \tilde{Z})^{-1} y + BA^{-1} f \]

• Matrix notation

\[
\begin{align*}
\begin{bmatrix}
\tilde{g} \\
\tilde{y}
\end{bmatrix} &= \begin{bmatrix}
B \\
0
\end{bmatrix} \begin{bmatrix}
(I - \tilde{Z})^{-1} \\
0
\end{bmatrix} \begin{bmatrix}
y \\
f
\end{bmatrix} \\
\begin{bmatrix}
\tilde{g} \\
\tilde{y}
\end{bmatrix} &= \begin{bmatrix}
B \\
0
\end{bmatrix} A^{-1} \begin{bmatrix}
y \\
f
\end{bmatrix}
\end{align*}
\]

Computational structure of hybrid analysis

• Establish Technology Matrix A and split it into LCA matrix and IO Matrix

\[ A = \begin{bmatrix}
A' & A'' \\
0 & 0
\end{bmatrix} \]

• (given) technical coefficients matrix

\[ \tilde{Z} = \begin{bmatrix}
0.1 & 0.5 \\
0.2 & 0.2
\end{bmatrix} \]

• Establish final demand, also split 1000 kWh electricity

\[
\begin{align*}
\begin{bmatrix}
\tilde{y} \\
\tilde{y}
\end{bmatrix} &= \begin{bmatrix}
0.9 & -0.5 \\
0.8 & 0.8
\end{bmatrix} \begin{bmatrix}
10 \ \\
10
\end{bmatrix} = \begin{bmatrix}
14.5 \\
16.1
\end{bmatrix} = x
\end{align*}
\]

x: total output vector

Analogous concepts in life cycle inventory and in Input-Output analysis (Heijungs & Suh 2002)

<table>
<thead>
<tr>
<th>life cycle inventory analysis</th>
<th>LCA</th>
<th>input-output analysis</th>
<th>IOA</th>
</tr>
</thead>
<tbody>
<tr>
<td>product, economic flow (unit process)</td>
<td>commodity</td>
<td>industry, sector, establishment</td>
<td></td>
</tr>
<tr>
<td>technology matrix</td>
<td>A</td>
<td>technical coefficients matrix</td>
<td>( \tilde{Z} )</td>
</tr>
<tr>
<td>final demand vector</td>
<td>f</td>
<td>households demand vector</td>
<td>y</td>
</tr>
<tr>
<td>scaling vector</td>
<td>s</td>
<td>total output vector</td>
<td>x</td>
</tr>
<tr>
<td>inverse of technology matrix</td>
<td>( A^{-1} )</td>
<td>Leontief inverse</td>
<td>(I-( \tilde{Z} ))^{-1}</td>
</tr>
<tr>
<td>intervention matrix</td>
<td>B</td>
<td>satellite matrix</td>
<td>( \tilde{B} )</td>
</tr>
<tr>
<td>environmental interventions of final demand</td>
<td>g</td>
<td>environmental interventions of household demand</td>
<td>g</td>
</tr>
<tr>
<td>equation for s</td>
<td>( s = A^{-1} f )</td>
<td>equation for x</td>
<td>x = (I-( \tilde{Z} ))^{-1} y</td>
</tr>
<tr>
<td>equation for g</td>
<td>( g = B s )</td>
<td>equation for g</td>
<td>g = ( B x )</td>
</tr>
</tbody>
</table>
**Input Output LCA**

**Inputs and uses of supply use tables and sector environmental data**

- Supply - Use/Input Output Table (IOT)
- Environmentally Extended Input Output (EEIO) table
- Process LCI database
- Hybrid approach
- EEIO analysis
- Sectoral environmental data

**UNEP-SETAC (2012): Shonan Guidance Principles**

**Synthesis (I)**

- IO tables report economic interrelations and emissions of economic sectors on a macro-economic level (nations, regions)
- Information on emissions per Euro spent in a sector can be added (in a satellite matrix)
- LCA matrices report physical interrelations of processes involved in the manufacture of a product (on a micro-economic level)
- LCA matrices include information on environmental impacts (emissions, resource consumption) per reference flow of a process

**Input Output LCA**

**Synthesis (II)**

- Product system is established based on economic input output tables, extended with environmental information
- Environmental impacts are averaged per sector (e.g., electricity, gas and water supply sector)
- Impacts of service sectors are included (system is virtually “all encompassing”)
- Impacts are often treated like domestic production
- Environmental IO-table of Switzerland established recently
- Transferability of IO tables of other nations like USA or DE?
  (influence of fuel prices, energy efficiency, agricultural practices, environmental legislation)

**Input Output LCA**

**Comparison of CO₂-intensity of different national IO tables**

- Comparing CO₂-emissions of USA and German IO table
- As USA table includes much more detailed economic sectors, several US sectors correspond to one DE sector
- Comparison on two levels:
  - Direct emissions (emissions occurring in the sector itself)
  - Cumulative emissions
- Graphs shown in logarithmic scale
**Observations**

- USA IO table shows higher direct emissions
- sectors with higher intensities show higher cumulative emissions in the USA IO table
- sectors with lower intensities show higher cumulative emissions in the German IO table
- Reasons are not known to me
- No comparison USA - CH tables available

**Hybrid LCA**

- combines precision of product LCA with completeness of IO LCA
- adds processes (economic sectors) to product LCA
  - printing works
  - wholesale trade
  - banking and insurances
- further detail economic sectors in IO tables with product LCA information
  - electricity production by technology
- challenges:
  - combine physical with monetary information (inflation rates, exchange rates)
  - availability of monetary information (expenses for printing works, legal services, working materials (chemicals))
Input Output LCA

Comparison of pLCA and IOLCA

- What is the share of impacts related to activities usually not taken into account in pLCA (like hairdresser, private dwellings)?
- How do results of pLCA and IOLCA compare?
- How feasible are foreign IO tables for CH?
- What are the synergies of combining pLCA and IOLCA?
- Study carried out by Yves Loerincik, EPFL

Input Output LCA

CO₂-reduction when excluding services

<table>
<thead>
<tr>
<th>Sector</th>
<th>CO₂-reduction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semiconductor</td>
<td>60.00</td>
</tr>
<tr>
<td>Chemicals</td>
<td>30.00</td>
</tr>
<tr>
<td>Electricity</td>
<td>20.00</td>
</tr>
<tr>
<td>Primary non-ferrous metals</td>
<td>10.00</td>
</tr>
<tr>
<td>Plating and polishing</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Leerincik et al. 2006

Input Output LCA

Contribution of services and private sectors

<table>
<thead>
<tr>
<th>Sector</th>
<th>Cumulative CO₂ emissions [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semiconductor</td>
<td>100</td>
</tr>
<tr>
<td>Chemicals</td>
<td>100</td>
</tr>
<tr>
<td>Electricity</td>
<td>100</td>
</tr>
<tr>
<td>Primary non-ferrous metals</td>
<td>100</td>
</tr>
<tr>
<td>Plating and polishing</td>
<td>100</td>
</tr>
</tbody>
</table>

Leerincik et al. 2006
**Conclusions**

- Sectors that on purpose are excluded in pLCA contribute more than the service sectors.
- The percentage of service sector contributions is higher with sectors of lower CO\(_2\)-intensities.
- Mean value in CO\(_2\)-emission reduction is about 0.06-0.07 kg CO\(_2\)-eq / US$.
- Mean percentage in CO\(_2\)-emission reduction is less than 10%.

**Comparison of pLCA and IOLCA on a product level: pc-Si wafer**

- Electronics industry: production of 1 kg of poly-crystalline wafer.
- Grouping of pLCA processes according to economic sectors to better match with IOLCA.
- Two aspects to compare:
  - Contribution pattern
  - CO\(_2\) per kg
**Observations**

- IOLCA results in much higher emissions per kg wafer (factor 3-4)
- Contribution of semiconductor industry itself, of chemicals and of plating and polishing much higher in IOLCA
- Contributions in IOLCA not (explicitly) considered in pLCA (advertising, real estate management, repair and maintenance of construction, etc.) contribute about one third

**Reasons for deviations**

- Chemicals’ contribution seems underestimated in pLCA (industrial (low) grade chemicals’ pLCA used to model high purity chemicals inputs)
- Other potential reasons for deviations:
  - Wafer is not a typical product of the respective economic (IO) sector
  - Price of the product (wafer) substantially different
  - Amount of inputs substantially different
  - CO₂-intensity of inputs substantially different
- Difficult to identify the main and „real“ reasons
Comparison on a product level: US electricity

- energy supply industry:
  supply of 1kWh of USA electricity mix
- Two aspects to compare:
  - contribution pattern
  - CO₂ per kg
- contributions from other sectors much smaller as compared to the wafer example
- contribution pattern and cumulative CO₂ emissions match much better

Contribution analysis CO₂: USA electricity mix

Structure Comparison of pLCA and IOLCA
Mongelli, Suh & Huppes, 2005

- pLCA: LCI of energy systems, ETHZ 1996
- IOLCA: U.S. I/O Table 1996, MIET
- Characteristics of MIET:
  - classification in 91 economic sectors
  - includes capital equipment
  - based on U.S. information sources
- Characterisation of ETHZ:
  - about 600 process based LCI
  - Western European situation
  - covers energy supply, transports, waste manag., materials
  - includes capital equipment

Cumulative CO₂ emissions

- Significant differences in cumulative emissions
- No clear tendency
- rather high variation (in MIET)
Input Output LCA

Input structure comparison, principle

- Question:
  Which sectors contribute how much to the total emissions caused by all inputs?

- Comparing input structures of pLCA and IOLCA

Output structure comparison, principle

- Question:
  What is the contribution of Process 1 to the cumulative emissions of products grouped in sectors 1 to n?

- Comparing output structures of pLCA and IOLCA
Input Output LCA

Synthesis

• Several national IO tables including environmental impacts are available
• Updated environmental IO table of Switzerland is now available (reference year 2005)
• For LCA purposes, interlinked national IO tables are required (globalised production)
• IOLCA seems more complete, pLCA more precise

How to profit best from both approaches?

Input Output LCA

Perspectives

• Full scale integration of pLCA and IOLCA tables tricky and laborious
• Links from costs to physical units and vice versa
• IOLCA assessment provide valuable inputs with regard to the identification of environmentally important economic sectors neglected so far in pLCA
• Start classical product LCI work on those sectors
• Complement pLCI databases accordingly
• Information sources on environmental impacts used in pLCA and IO tables need to be harmonised