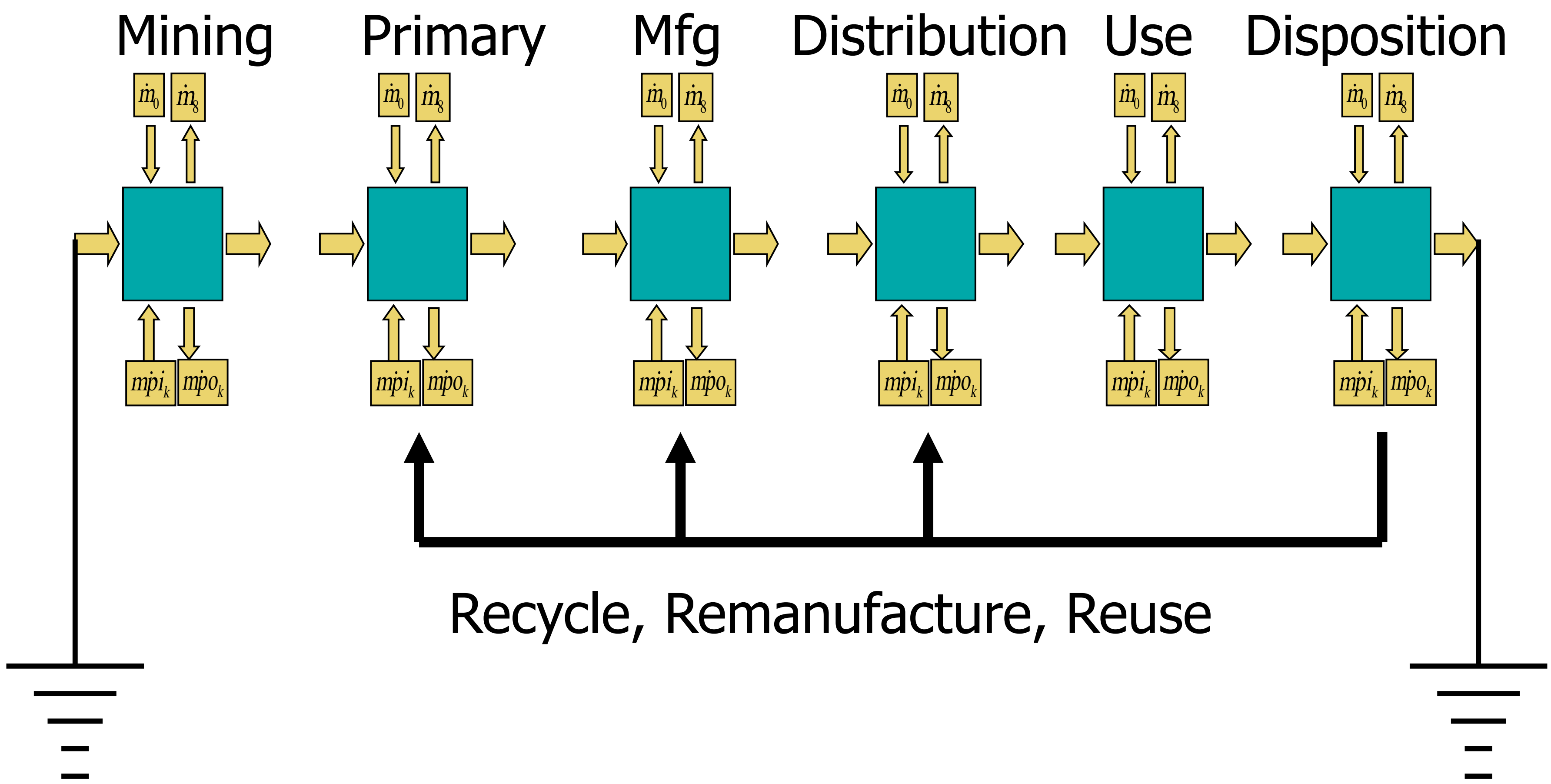
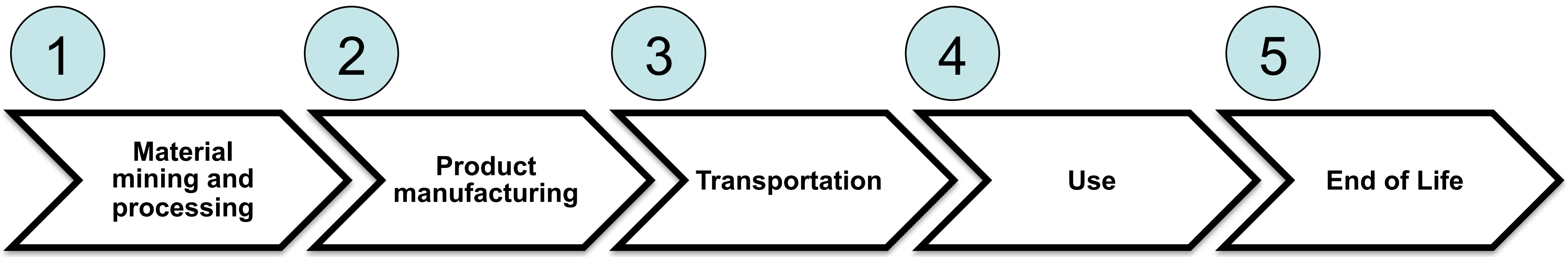
Intro to Life Cycle Analysis
2.83/2.813

Life Cycle Assessment

LCA is a methodology to account for and assess the environmental impacts from all phases / stages of a product life cycle



LCA Exercise



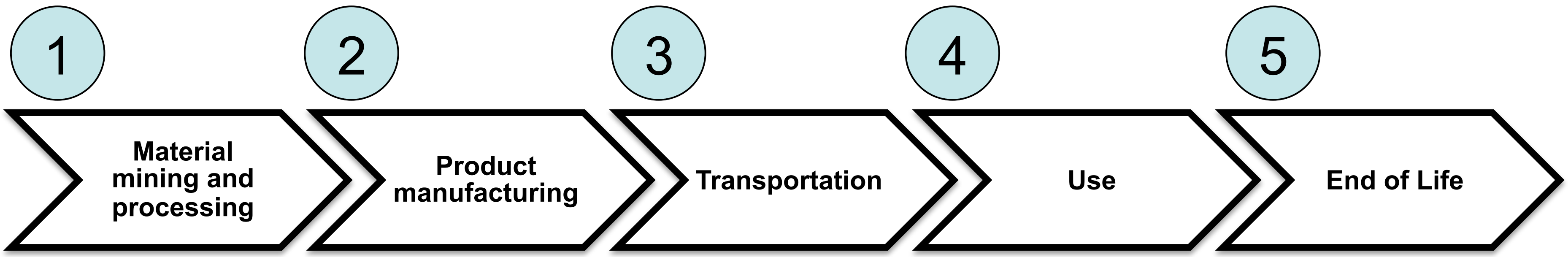
Cooling? Landfill?

Energy Consumption: 1 > 3 > 4 > 2 > 5

Distance dependent?

Environ. Res. Lett. 4 (2009) 014009, http://iopscience.iop.org/1748-9326/4/1/014009

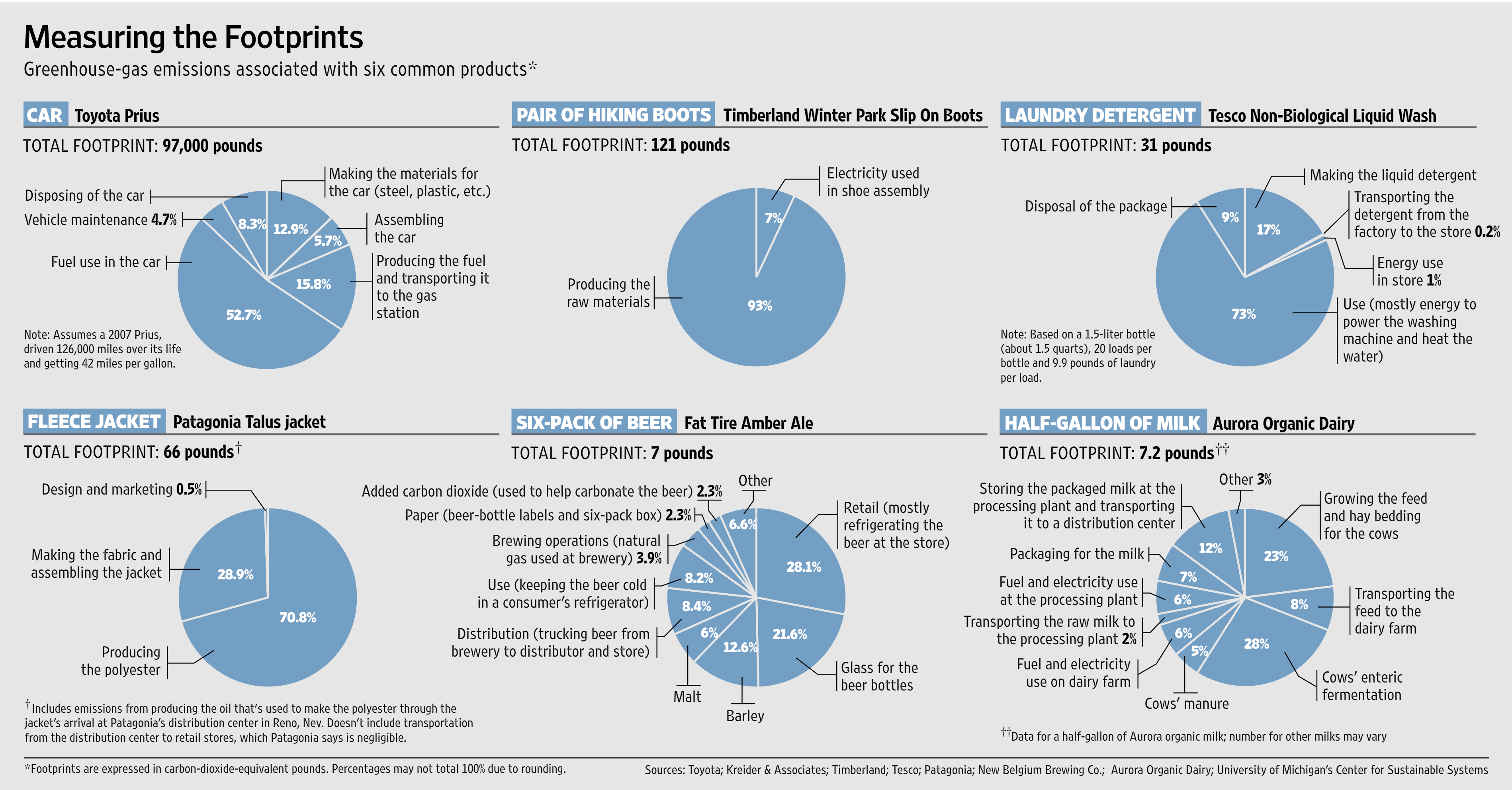
Results: Yours



Product	Descending Order of Energy Consumption
Car	4>2 >1 >5 >3
Shoes	1>3 >2 >5 >4
Laundry Detergent	4>1 >2 >3 >5
Fleece Jacket	1>2 >4 >3 >5
Beer	1>2 >4 >3 >5
Milk	3>2 >4 >1 >5

Six Products, Six Carbon Footprints, WSJ, 2009

Results: WSJ



Six Products, Six Carbon Footprints, WSJ, 2009

Introduction to Product Analysis

<u>What is the impact of a product?</u>

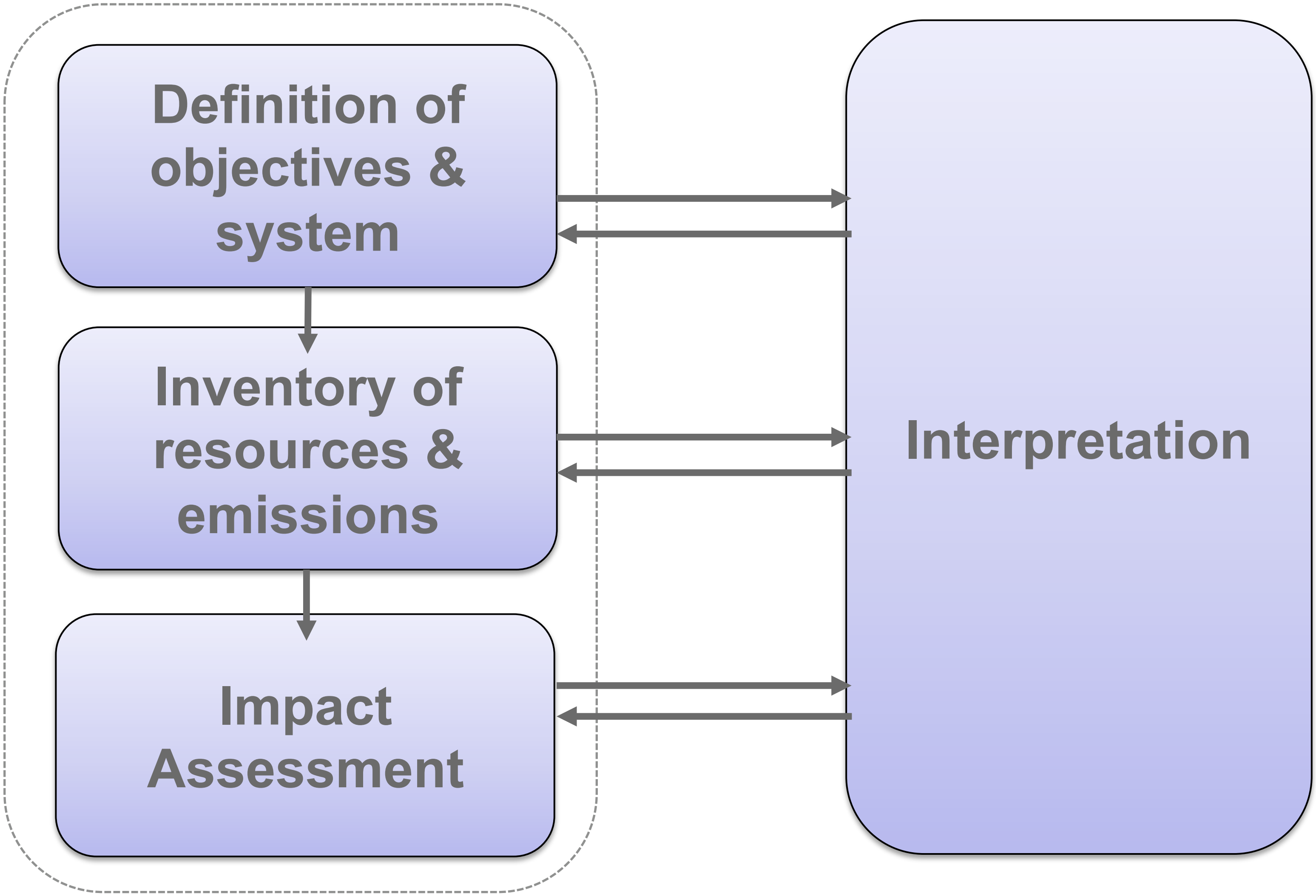
- What impact are we interested in?
- What unit of service is provided?

1. What is it made of?
2. How is it made?
3. Is it transported a long distance?
4. How is it used?
5. How is it disposed of?

Challenges

- Boundary and Scope
  - What does each phase mean?
  - What is actually included?
- Geo-temporal
- Uncertainty
- Functional Unit
- Data Quality
- Methodological Choices

Life Cycle Assessment: Framework (ISO)

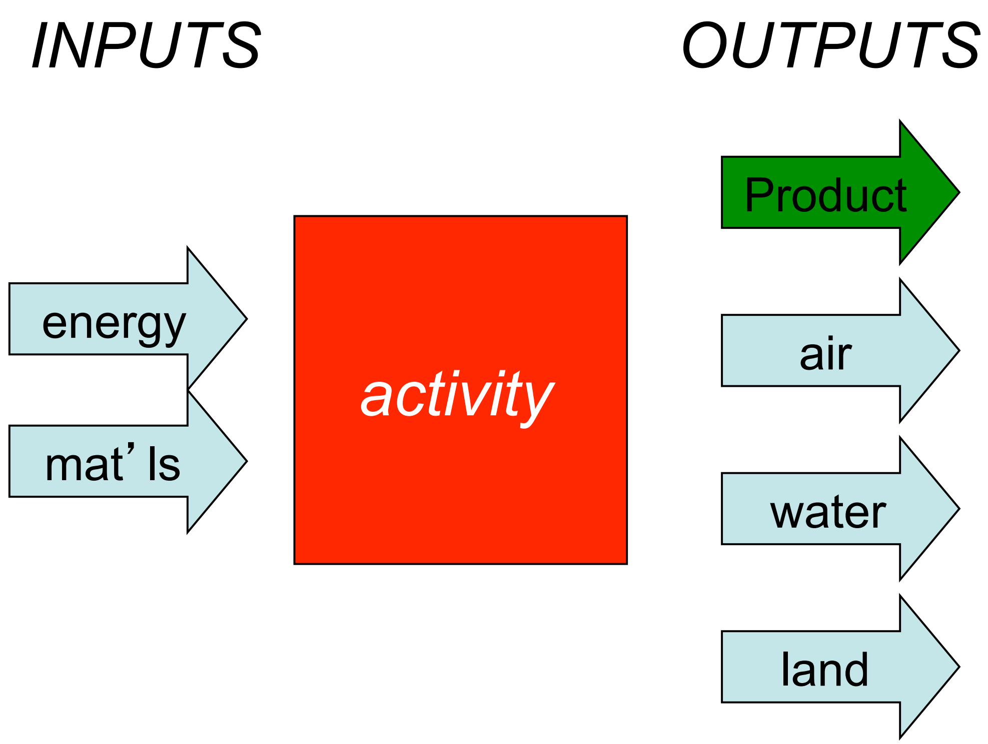


ISO 14044 and other 14000

Life Cycle Inventory

- LCI collected data on material inputs and outputs
- LCA = LCI + Impact Analysis
- Impact Analysis Issues:
  - Converting LCI to ‘comprehensible’ impacts
    - Human Health
    - Ecotoxicity
    - Natural Resources
    - Others

Life Cycle Inventory



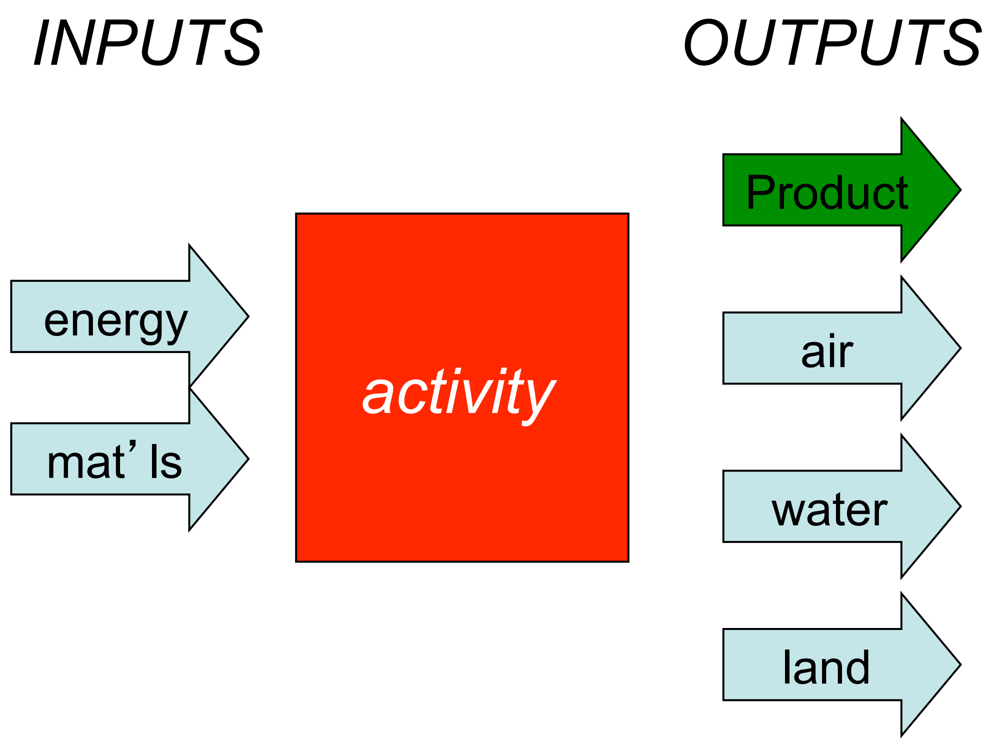
Life Cycle Perspective

- In theory boundaries start from earth as the source, and return to earth as the sink
- Evaluation is often focused on a product or service
- Tracking is of materials
- Time stands still

Estimations Methods

- Streamlined Life-cycle Assessment (SLCA)
  - Eco-Audit (Ashby)
- Process Models (LCA)
- Input / Output Models (EIOLCA)
- Hybrid Models

Streamlined LCA



Issues: *1. qualitative Vs quantitative*
2. aggregation

Evaluation Matrix for SLCA, M_{ij}♪

Life Cycle Stages	Materials Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues
Extraction and♪ Refining♪	11	12	13	14	15
Manufacturing♪	21	22	23	24	25
Product Delivery♪	31	32	33	34	35
Product Use♪	41	42	43	44	45
Refurbishment, Recycling, Disposal♪	51	52	53	54	55

Graedel

Scoring M_{21} (mat'ls used in mfg)

- M_{21} = 0 when product mfg requires relatively large amounts of restricted mat'ls (limited supply, toxic, radioactive) and alternatives are available.

- M_{21} =4 when mat'ls used in mfg are completely closed loop and minimum inputs are required.

Automobile Example; Manufacturing Ratings 0-4 (best)♪

Element Designation♪		*Element Value & Explanation: 1950s Auto*♪		*Element Value & Explanation: 1990s Auto*♪	
Matls. choice♪	**21**	0	Chlorinated solvents, cyanide	3	Good materials choices, except for lead solder waste
Energy use♪	**22**	1	Energy use during manufacture is high	2	Energy use during manufacture is fairly high
Solid residue♪	**23**	2	Lots of metal scrap and packaging scrap produced	3	Some metal scrap and packaging scrap produced
Liq. Residue♪	**24**	2	Substantial liquid residues from cleaning and painting	3	Some liquid residues from cleaning and painting
Gas residue♪	**25**	1	Volatile hydrocarbons emitted from paint shop	3	Small amounts of volatile hydrocarbons emitted

taken from Graedel 1998

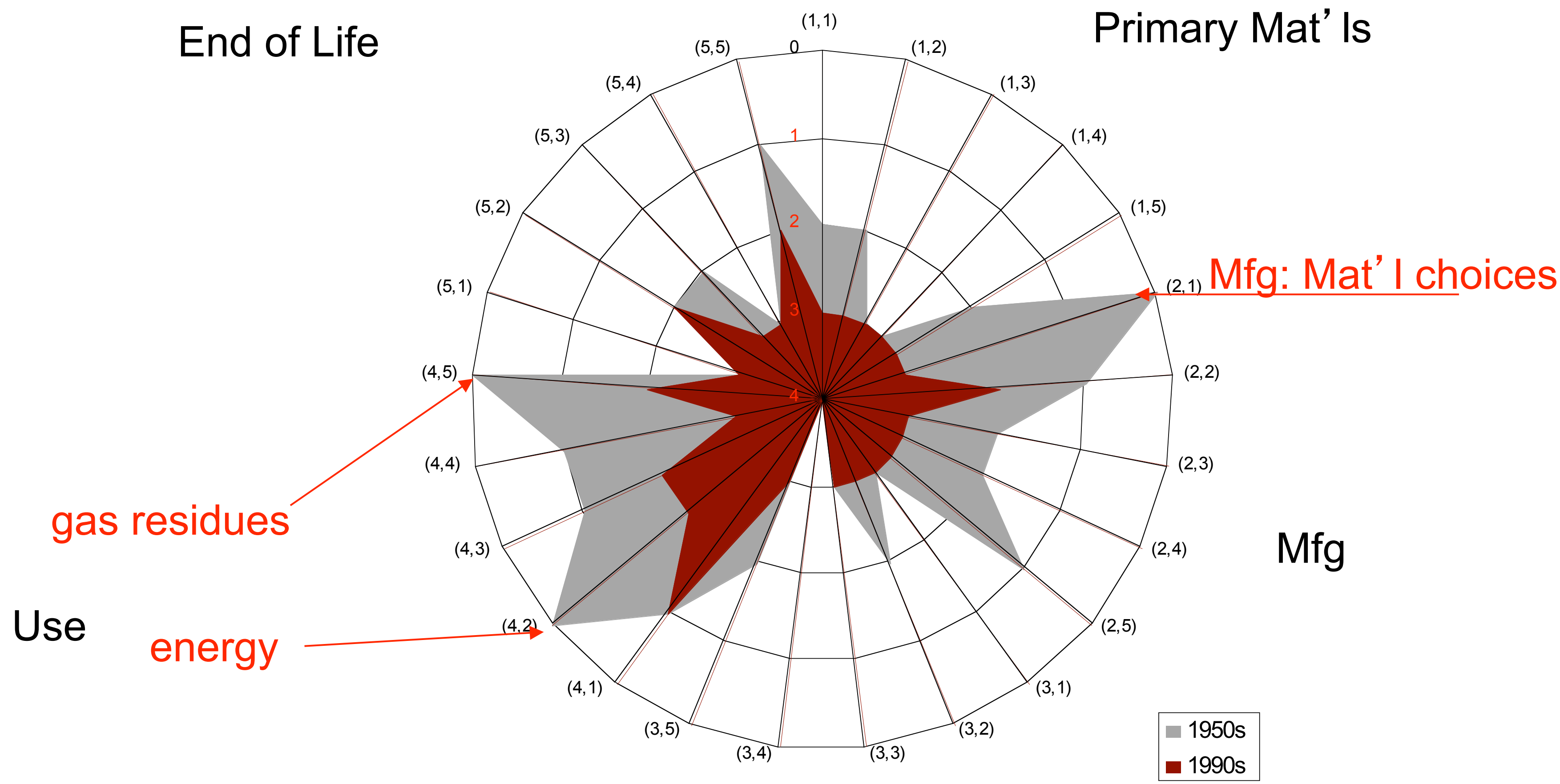
Product Assessment Matrix for the Generic 1950s Automobile [Graedel 1998]♪

	Environmental Stressor					
Life Cycle Stage	**Materials Choice**	**Energy Use**	**Solid Residues**	**Liquid Residues**	**Gaseous Residues**	**Total**
Premanufacture	2	2	3	3	2	12/20
Product Manufacture	0	1	2	2	1	6/20
Product Delivery	3	2	3	4	2	14/20
Product Use	1	0	1	1	0	3/20
Refurbishment, Recycling, Disposal	3	2	2	3	1	11/20
Total	9/20	7/20	11/20	13/20	6/20	46/100

Product Assessment Matrix for the Generic 1990s Automobile [Graedel 1998]♪

	Environmental Stressor					
Life Cycle Stage	**Materials Choice**	**Energy Use**	**Solid Residues**	**Liquid Residues**	**Gaseous Residues**	**Total**
Premanufacture	3	3	3	3	3	15/20
Product Manufacture	3	2	3	3	3	14/20
Product Delivery	3	3	3	4	3	16/20
Product Use	1	2	2	3	2	10/20
Refurbishment, Recycling, Disposal	3	2	3	3	2	13/20
Total	13/20	12/20	14/20	16/20	13/20	68/100

Target plot of the estimated SLCA impacts for generic automobiles for the 1950s and 1990s♪



distribution [Graedel 1998]

Eco-Audit for Energy

1. Materials Production
2. Manufacturing
3. Transport
4. Use Phase
5. End of Life

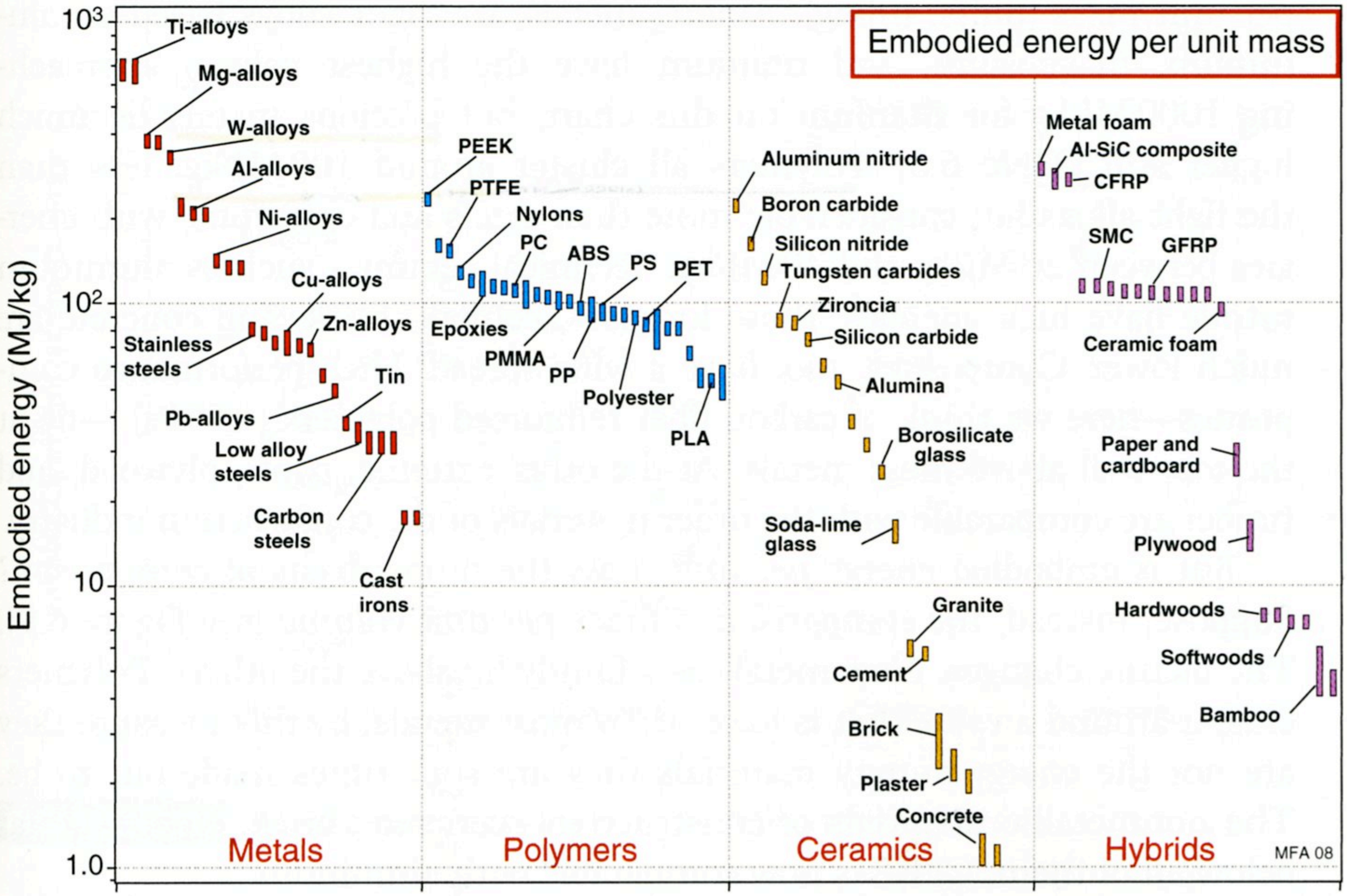


FIGURE 6.8 *A bar chart of the embodied energies of materials per unit mass.*

Ashby 2009

Estimate Manufacturing Methods

TABLE 1. EMPERICAL MANUFACTURING ENERGY STUDIES

Manufacturing Process	Energy Requirement Range (MJ/kg processed)			Source
Coventional Manufacturing				
Machining	5.3	-	7.5	[4]
Milling	1.3	-	2.6	
Grinding		8.8		[5]
Iron Casting	19	-	29	[3]
Sand casting	11.6	-	15.4	[6]
die casting		14.9		[7]
Forging		16.3		[8]
Finish Machining		24		[9]
Advanced Manufacturing				
Waterjet (Nylon)	150	-	214	[10]
Waterjet (Steel)	167	-	238	
Waterjet (Al)	195	-	1670	

[1]

Table 2

Manufacturing methods	Energy intensity (MJ/kg)
Autoclave molding	21.9[a]
Spray up	14.9[b]
Resin transfer molding (RTM)	12.8[b]
Vacuum assisted resin infusion (VARI)	10.2[b]
Cold press	11.8[b]
Preform matched die	10.1[b]
Sheet molding compound (SMC)	3.5[b]
Filament winding	2.7[b]
Pultrusion	3.1[b]
Prepreg production	40.0[b]
Injection molding (hydraulic)	19.0[c]
Glass fabric manufacturing	2.6[d]
Iron casting (Cupola)	13.6[e]

Table 1: N. Duque Ciceri, T. G. Gutowski, M. Garetti, 2010, and

Table 2: Young S. Song, Jae R. Youn, Timothy G. Gutowski,

Transported?

Use Phase

End of Life (EOL)

- Recycle
- Remanufacture
- Reuse
- Landfill
- Incinerate

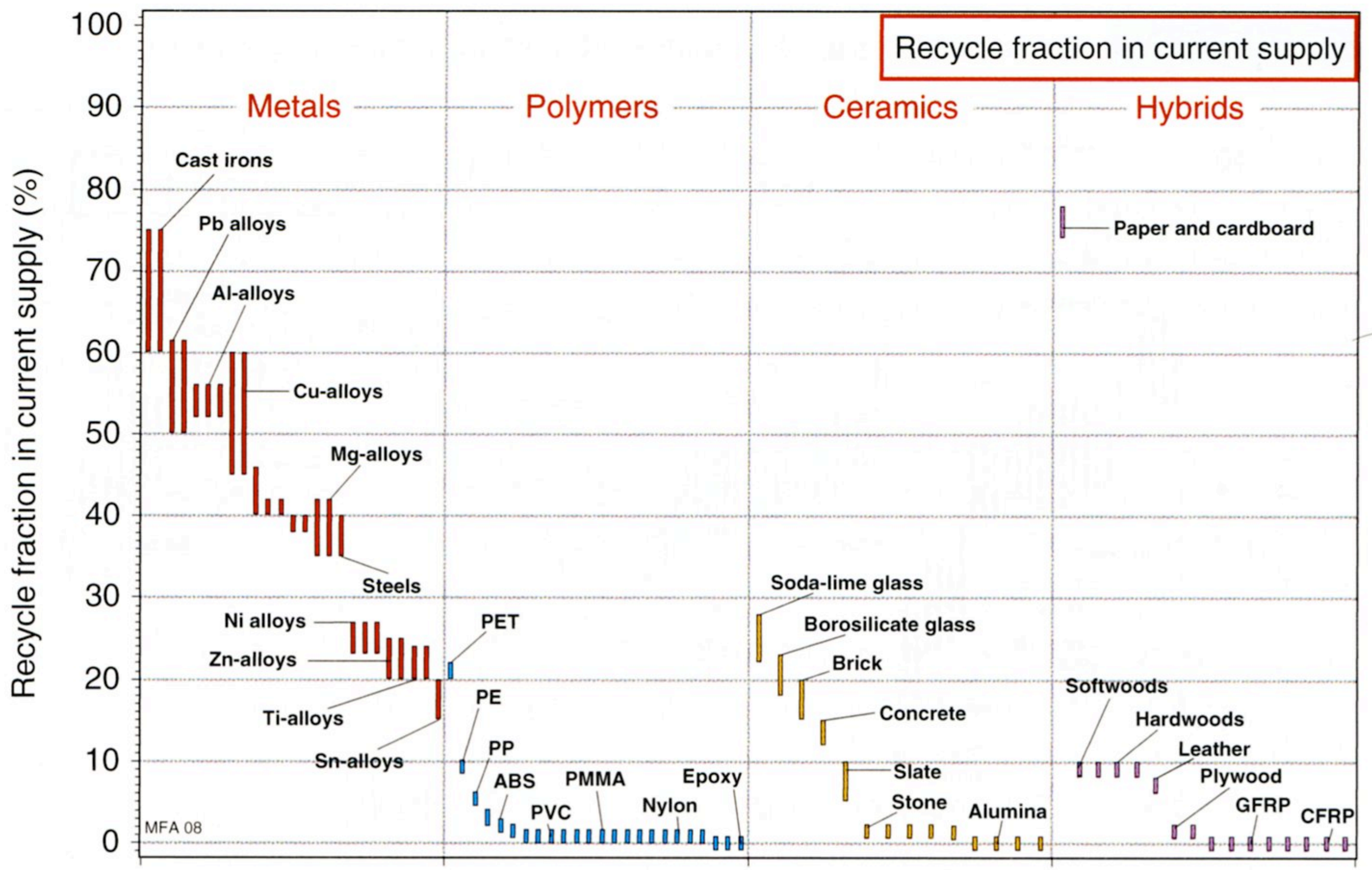


FIGURE 6.13 *Recycle fraction bar chart.*

Ashby 2009

Table 7.3 Recycle energy and CO_2 for PET

Component	Material	Mass m kg	Recycle energy H_{rc} MJ/kg*	Recycle CO_2 kg/kg*	$m.H_{tot}$ MJ	$m.(CO_2)_{tot}$ kg
Bottle, 100 units	PET	4	35	0.98	–188	–5.6

*From the data sheets of Chapter 12.

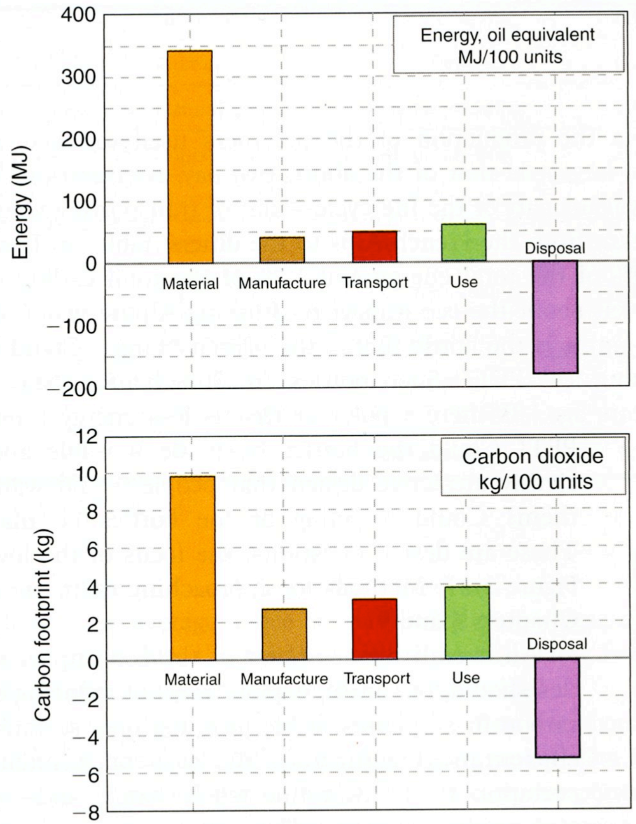
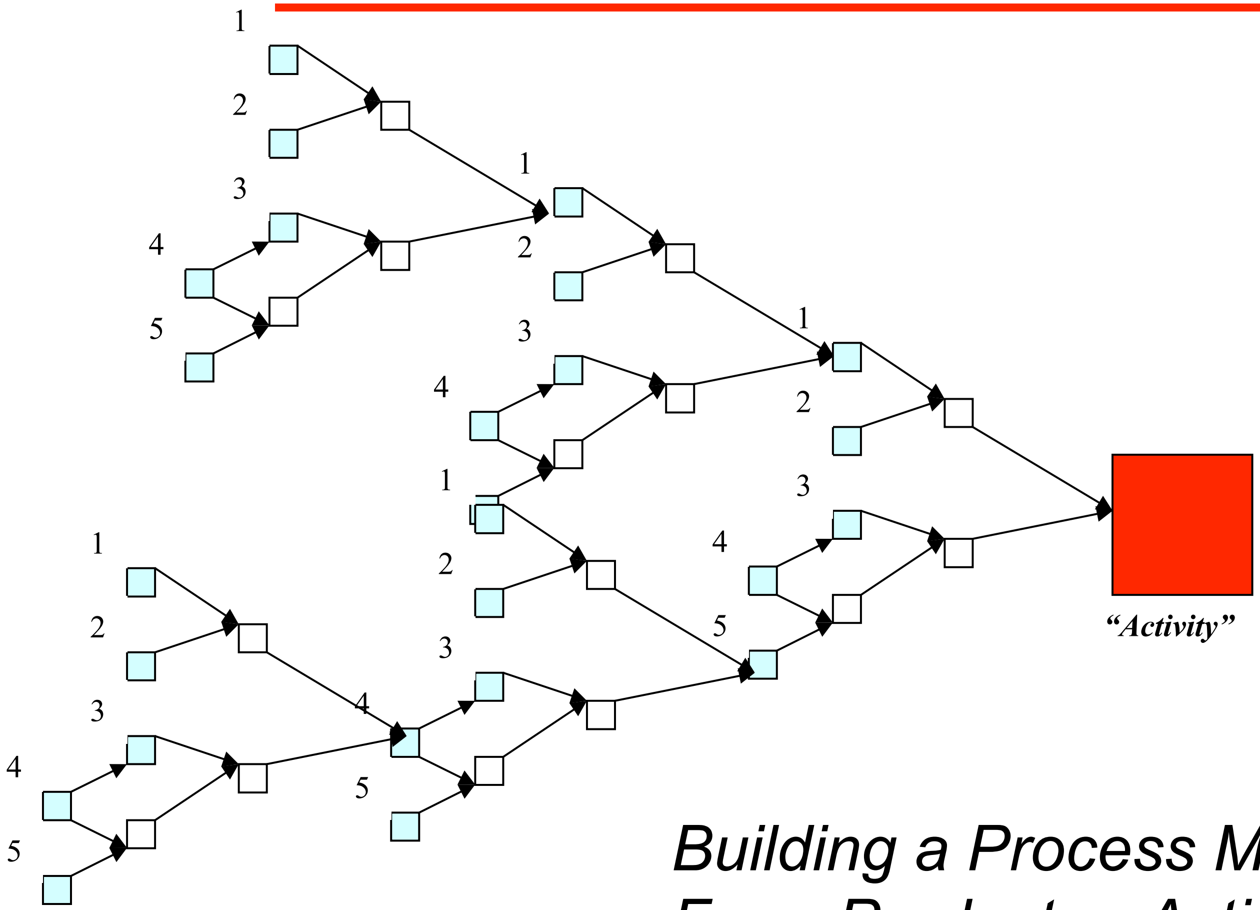


FIGURE 7.3 *The energy and the carbon footprint bar charts for bottled water per 100 units.*

See Ashby Ch. 7 for basic assumptions and Ch 9 for a comparison between various beverage container options

Process Model LCA♪



Building a Process Model
For a Product or Activity
Takes time, but you know what
Is in it!

Process Model for "U.S. Family Sedan"♪

- Estimated from 644 parts
- 73 different materials
- 120,000 miles life time
- 23 mpg
- total mass 1532 kg
- solvent based paints with controls

Plastics	9.3%
Ferrous	64%
Non-ferrous	9%
Fluids	4.8%
Other	13%
Total	100%

Sullivan et al SAE 1998♪

System Boundaries

1. Extraction of materials from earth and materials processing
2. Sub assembly manufacture
3. Auto assembly
4. Use, maintenance & repair
5. Recovery, recycling and disposal

Inputs

Table 7: LCI of the Generic Vehicle (Raw Materials Use)

	Units	Generic Vehicle	Material Production	Manufacturing	Operation	Maintenance & Repair	End Of Life
Inflow							
(r) Bauxite (Al2O3, ore)	Kg	32	32	0.0026	0	0.021	0
(r) Bauxite Rich Soil	Kg	222	222	0	0	0	0
(r) Chromium (Cr, in ground)	Kg	0.91	0.91	0	0	0	0
(r) Coal (in ground)	Kg	2,509	1,033	618	748	100	11
(r) Copper (Cu, in ground)	Kg	23	23	0	0	0	0
(r) Ilmenite (FeO.TiO2, in ground)	Kg	0.97	0.32	0.65	0	9.9 E-05	0
(r) Iron (Fe, in ground)	Kg	1,443	1,440	0.38	0	3.0	0.045
(r) Lead (Pb, in ground)	Kg	33	13	0.26	0	20	0
(r) Limestone (CaCO3, in ground)	Kg	458	199	95	142	21	2.
(r) Manganese (Mn, in ground)	Kg	24	23	0	0	0.76	0
(r) Natural Gas (in ground)	Kg	1,810	491	216	1,027	73	2.2
(r) Oil (in ground)	Kg	16,486	631	87	15,562	171	35
(r) Olivine (in ground)	Kg	8.3	8.3	0	0	0.0032	0
(r) Perlite (SiO2, in ground)	Kg	2.4	2.3	0.056	0	0	0
(r) Platinum (Pt, in ground)	Kg	0.0015	0.0015	0	0	0	0
(r) Pyrite (FeS2, in ground)	Kg	13	13	0	0	4.3 E-05	0
(r) Rhodium (Rh, in ground)	Kg	2.9 E-04	2.9 E-04	0	0	0	0
(r) Sand (in ground)	Kg	179	140	0	0	12	27
(r) Sulfur (S)	Kg	0.1	0.08	0.022	0	4.0 E-05	0
(r) Tin (Sn, in ground)	Kg	0.48	0.067	0.41	0	0	0
(r) Tungsten (W, in ground)	Kg	0.012	0.011	0	0	6.8 E-04	0
(r) Uranium (U, in ground)[a]	Kg	0.039	0.01	0.0089	0.018	0.0019	2.5 E-04
(r) Zinc (Zn, in ground)	Kg	22	22	0	0	4.3 E-04	0
Cullet (from stock)	Kg	0.013	0	0.013	0	0	0
Iron Scrap	Kg	243	200	0.05	0	43	0
Natural Rubber	Kg	25	8.8	0	0	16	0
Raw Materials (alloying additives)	Kg	4.0	4.0	0	0	0	0
Raw Materials (Iron Casting Alloys)	Kg	12	12	0	0	0	0
Raw Materials (unspecified)	Kg	17	7.4	9.2	0	0.32	0
Steel Scrap	Kg	474	428	0	0	46	0
Water Used (total)	Liter	76,959	59,672	9,818	2,007	5,459	4.0

[a] From electricity production

Output and Energy Use

Table 8: LCI of the Generic Vehicle (Outflows and Energy Use)

	Units	Generic Vehicle	Material Production	Manufacturing	Operation	Maintenance & Repair	End Of Life
Outflow							
(a) Carbon Dioxide (CO2, fossil)	gm	59,092,200	4,439,850	2,562,160	51,331,400	615,481	143,273
(a) Carbon Monoxide (CO)	gm	1,942,230	63,813	5,914	1,832,728	39,088	683
(a) Hydrocarbons (except methane)	gm	256,640	12,627	7,349	234,520	1,974	170
(a) Hydrogen Chloride (HCl)	gm	725	278	10	402	29	5.7
(a) Hydrogen Fluoride (HF)	gm	113	59	1.1	50	2.0	0.71
(a) Lead (Pb)	gm	115	50	1.2	1.1	63	0.015
(a) Methane (CH4)	gm	65,806	11,773	5,534	44,500	3,854	144
(a) Nitrogen Oxides (NOx as NO2)	gm	254,193	12,871	8,295	229,465	2,755	806
(a) Particulates (unspecified)	gm	53,526	26,470	8,235	16,525	2,050	247
(a) Sulfur Oxides (SOx as SO2)	gm	133,326	30,491	14,917	83,180	4,424	315
(w) Ammonia (NH4+, NH3, as N)	gm	2,354	116	17	2,208	12	1.9
(w) Dissolved Matter (unspecified)	gm	7,686	4,527	1,118	982	1,041	17
(w) Heavy Metals (total)	gm	39	29	7.5	0	3.1	0.0013
(w) Oils (unspecified)	gm	7,611	130	516	6,918	39	7.4
(w) Other Organics (unspecified)	gm	80	77	0.43	0	2.5	2.2 E-04
(w) Phosphates (as P)	gm	15	7.2	7.8	0	0.42	1.6 E-05
(w) Suspended Matter (unspecified)	gm	74,321	2,779	2,450	68,522	512	58
Waste (municipal and industrial)	Kg	415	22	56	8.0 E-05	41	296
Waste (total)	Kg	4,213	2,440	386	783	277	326
Energy Reminder							
E (HHV) Feedstock Energy	MJ	28,016	18,574	953	308	8,182	0
E (HHV) Fossil Energy	MJ	967,367	90,741	38,414	819,791	16,274	2,147
E (HHV) Non-Fossil Energy	MJ	6,053	3,719	803	1,142	373	16
E (HHV) Process Energy	MJ	934,369	74,531	36,691	814,014	8,389	746
E (HHV) Total Energy	MJ	973,418	94,460	39,217	820,933	16,645	2,164
E (HHV) Transportation Energy	MJ	11,033	1,355	1,574	6,612	74	1,418
Electricity	MJ	10,577	2,468	6,769	0	1,203	136

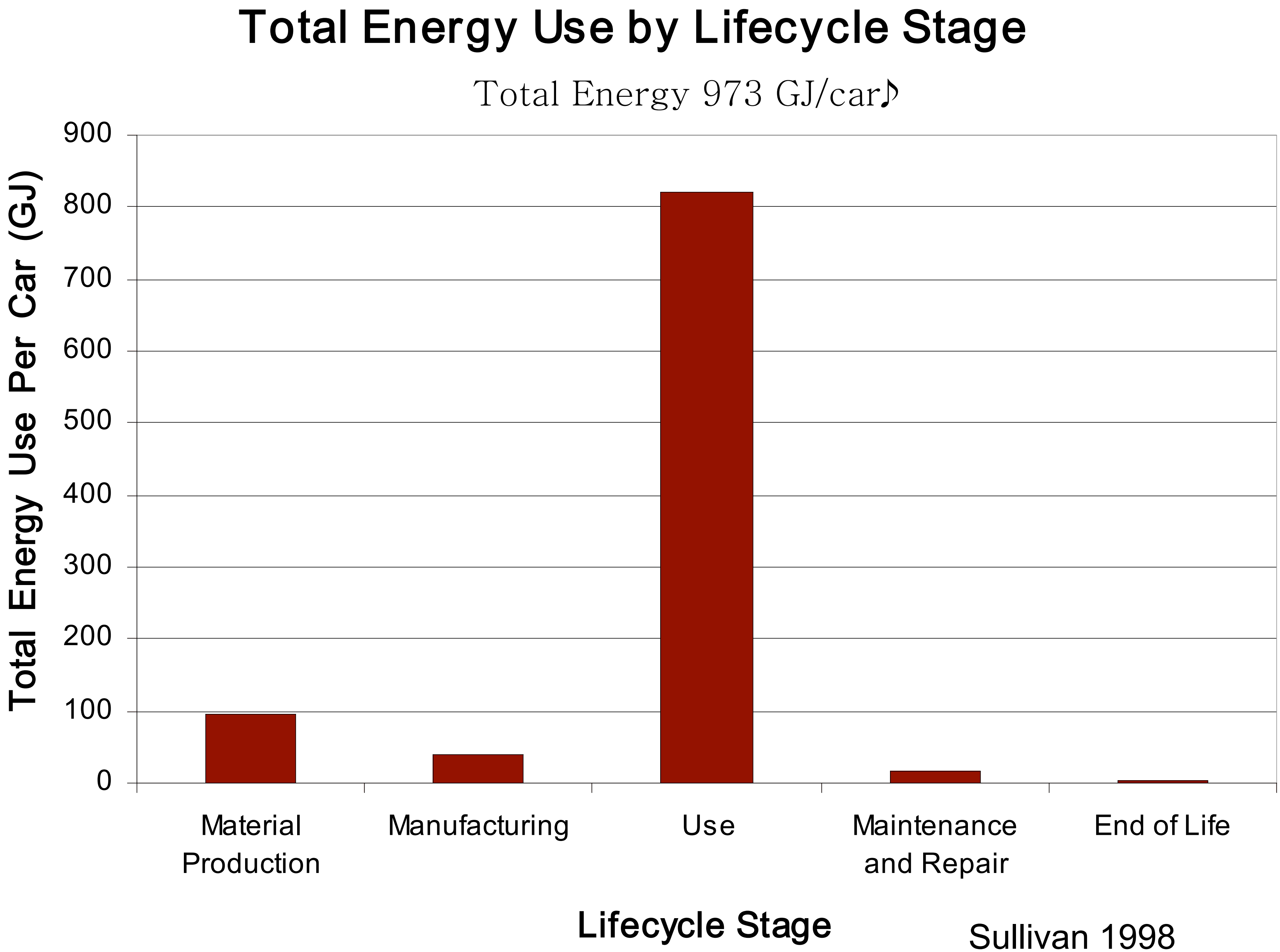

Total Energy Use by Lifecycle Stage
Total Energy 973 GJ/car♪
Total Energy Use Per Car (GJ)
900
800
700
600
500
400
300
200
100
0
Material Production
Manufacturing
Use
Maintenance and Repair
End of Life
Lifecycle Stage
Sullivan 1998

Table 1
Eco-Audit for Sullivan's Automobile (Primarily using energy values from Smil)

Bill of Materials (BOM)	**Mass (kg)**	**MJ/kg**	**Energy (MJ)**
Plastics (PUR, PVC, Nylon, ABS…)	143kg	100 MJ/kg	14,300
Non-Ferrous			
Alu	93kg	200	18,600
Cu	18	100	1,800
Brass (Copper ~ 65%, zinc ~ 35%)	8.5	90	765
Lead	13	50	650
Other (Zn, Cr…)	5.5	30	165
Iron	156.5 kg	25	3,913
Steel	828.5 kg	50	41,425
Fluids (gasoline, oil,….)	74	10	740
Rubber (not tire)	60	100	6,000
Glass	42	20	820
Tires	45	100	4,500
Other (textiles, carpet…)	45	20	900
TOTAL			**94,578**

Sullivan result: 94,460!

Tables from Smil, 2008

Table A.11 Efficiencies of Common Energy Conversions

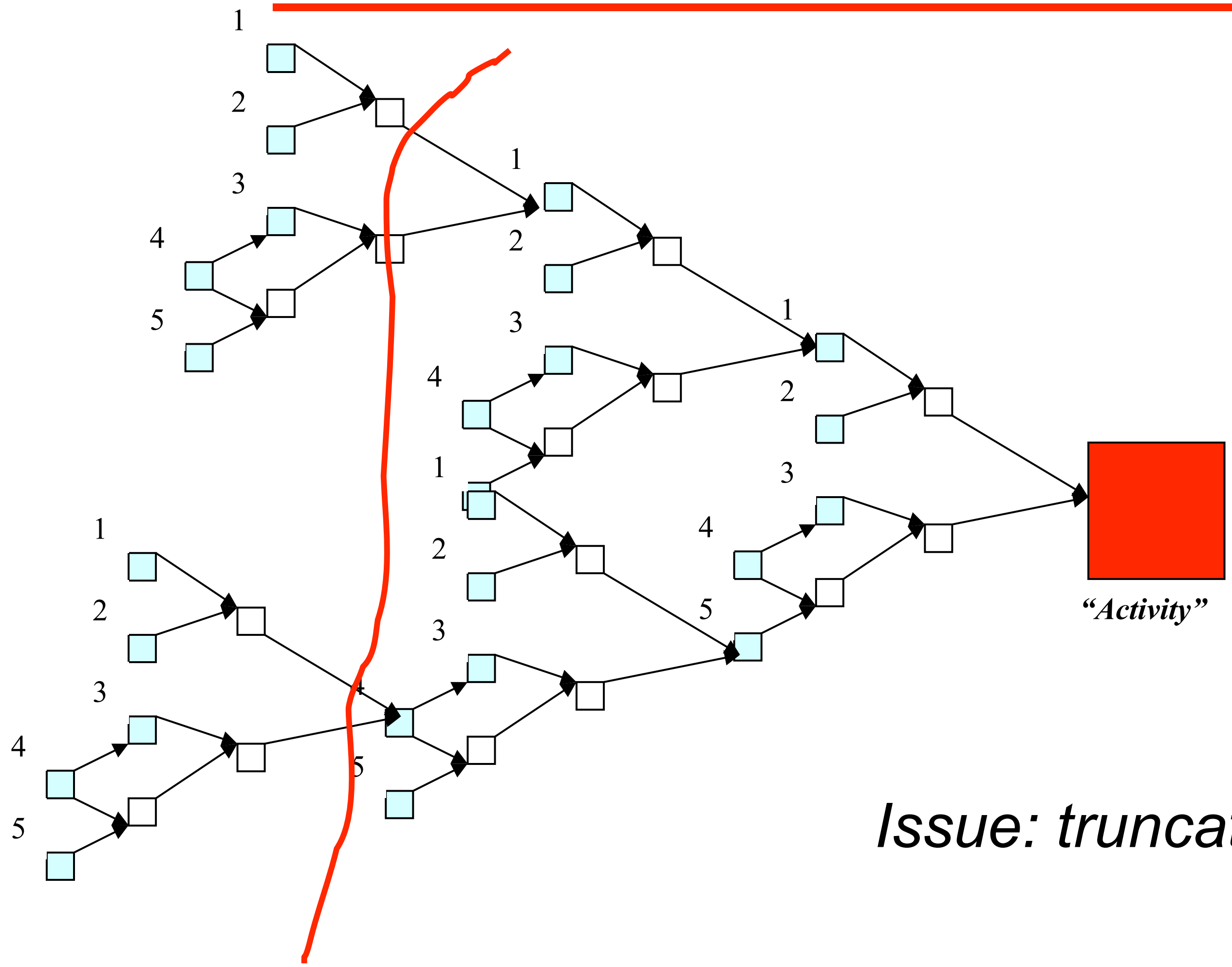
Converter	Conversion	Efficiency (%)
Large electricity generator	m ⇒ e	98–99
Large power plant boiler	c ⇒ t	90–98
Large electric motor	e ⇒ m	90–97
Best household natural gas furnace	c ⇒ t	90–97
Dry-cell battery	c ⇒ e	85–95
Human lactation	c ⇒ c	75–85
Overshot waterwheel	m ⇒ m	60–85
Small electric motor	e ⇒ m	65–80
Most efficient bacterial growth	c ⇒ c	50–65
Glycolysis maxima	c ⇒ c	50–60
Large steam turbine	t ⇒ m	40–45
Improved wood stove	c ⇒ t	25–45
Large gas turbine	c ⇒ m	35–40
Diesel engine	c ⇒ m	30–35
Mammalian postnatal growth	c ⇒ c	30–35
Best PV cell	r ⇒ e	20–30
Best large steam engine	c ⇒ m	20–25
Internal combustion engine	c ⇒ m	15–25
High-pressure sodium lamp	e ⇒ r	15–20
Mammalian muscles	c ⇒ m	15–20
Milk production	c ⇒ c	15–20
Pregnancy	c ⇒ c	10–20
Broiler production	c ⇒ c	10–15
Traditional stove	c ⇒ t	10–15
Fluorescent light	e ⇒ r	10–12
Beef production	c ⇒ c	5–10
Steam locomotive	c ⇒ m	3–6
Peak photosynthetic rate	r ⇒ c	4–5
Incandescent light bulb	e ⇒ r	2–5
Paraffin candle	c ⇒ r	1–2
Most productive ecosystem	r ⇒ c	1–2
Global photosynthetic mean	r ⇒ c	0.3

c = chemical energy; e = electrical energy; m = mechanical (kinetic) energy; r = radiant (electromagnetic) energy; and t = thermal energy.

Table A.12 Typical Energy Cost of Common Materials

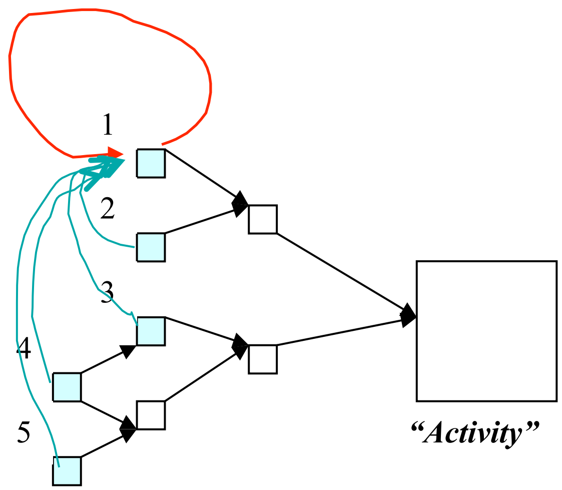
Material	Energy Cost (MJ/kg)	Source
Aluminum	190–230	Bauxite
Aluminum	10–40	Recycled metal
Bricks	2–5	Fired clay
Cement	5–9	Raw materials
Ceramics	3–7	Raw materials
Concrete	1–3	Cement and aggregate
Copper	60–150	Ore
Explosives	10–70	Raw materials
Glass	15–30	Raw materials
Gravel	<0.1	Quarries, rivers
Hydrogen	192–252	Electrolysis of water
Iron	20–25	Ore
Lead	30–50	Ore
Lime	10–12	Limestone
Newsprint	8–10	Wood pulp
Oxygen	6–14	Air
Nitrogen	1.5–1.9	Air
Paints	90–100	Raw materials
Paper, packaging	10–15	Kraft process
Paper, high quality	25–35	Wood pulp
Polyethylene	75–115	Crude oil
Polyvinylchloride	75–100	Crude oil
Sand	<0.1	Excavated
Silicon	1400–4100	Single crystal from silica
Steel, ordinary	20–25	Pig iron
Steel, specialty alloy	30–60	Raw materials
Stone	<1	Quarried
Sulfuric acid	2–3	Sulfur
Timber	1–3	Standing wood
Titanium	900–1000	Ore concentrate
Water	<0.01	Streams, reservoirs

Process Model LCA♪



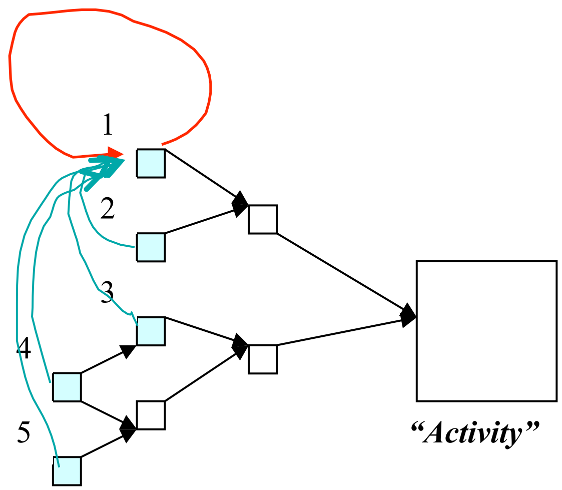
Issue: truncation error

Demand Vs Production♪



Each sector may have to produce "extra" to satisfy not only the identified "activity" but also to provide for all of the inputs

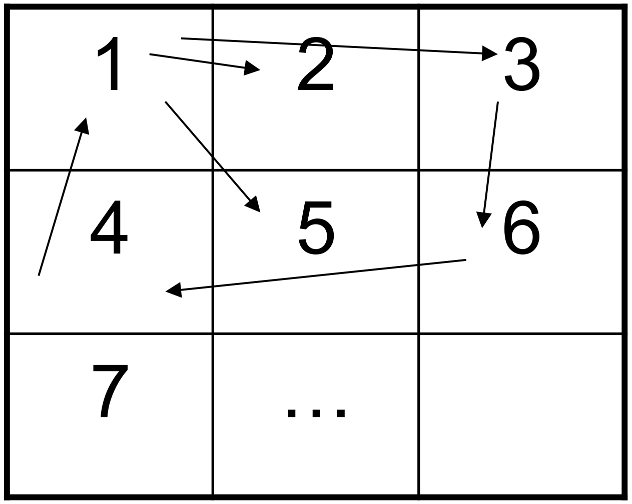
Demand Vs Production♪



- f = "demand for 1" by the "Activity"
- x = quantity of 1 produced to meet the demand
- $x - \alpha x = f$
- $x = f/(1-\alpha)$

Because of interactions, "1" has to produce more "x" than "f" furthermore, 2, 3, 4, … have to produce to support "1"

Input/Output Analysis♪



- f_1 = "demand for 1" by the "Activity 1"
- x_i = quantity of "i" produced to meet the demand for "1"

Physically we can think of subdividing the economy in sectors that interact with each other. The sectors include all activities so there are no truncation errors, however to be manageable we can only handle a few hundred sectors, therefore each sector will actually include a lot of different activities. "Aggregation errors"

Simplified input-output table for a three-sector economy

Table 2.1 from Leontief, Oxford Press ' 86

From:	**to**	**Sector 1: :Agriculture**	**Sector 2: Manufacture**	**Sector 3: House-Holds**	**Total Output**
Sector 1: Agriculture		25	20	55	100 bushels of wheat
Sector 2: Manufacture		14	6	30	50 yards of cloth
Sector 3: Households		80	180	40	300 man-years of labor

Physical Units

From:	to	Sector 1: :Agriculture	Sector 2: Manufacture	Sector 3: House-Holds	Total Output
Sector 1: Agriculture		25	20	55	100 bushels of wheat
Sector 2: Manufacture		14	6	30	50 yards of cloth
Sector 3: Households		80	180	40	300 man-years of labor

Dollars

	Ag	Mfg.	House (demand)	Total (pro-duction)
Ag	x_{11}	x_{12}	f_1	x_1
Mfg	x_{21}	x_{22}	f_2	x_2

In matrix form♪

$$(x_1 - x_{11}) - x_{12} = f_1$$♪

$$-x_{21} + (x_2 - x_{22}) = f_2$$

or using coefficients $a_{ij} = x_{ij}/x_j$ ♪

$$(1 - a_{11})x_1 - a_{12}x_2 = f_1$$♪

$$-a_{21}x_1 + (1 - a_{22})x_2 = f_2$$♪

♪

or $$[I - a]\ \{x\} = \{f\}$$

$$[I - a]\{x\} = \{f\}$$♪

♪

$$\{x\} = [I - a]^{-1}\{f\}$$♪

♪

$$\{e\} = [R]\{x\}$$♪

♪

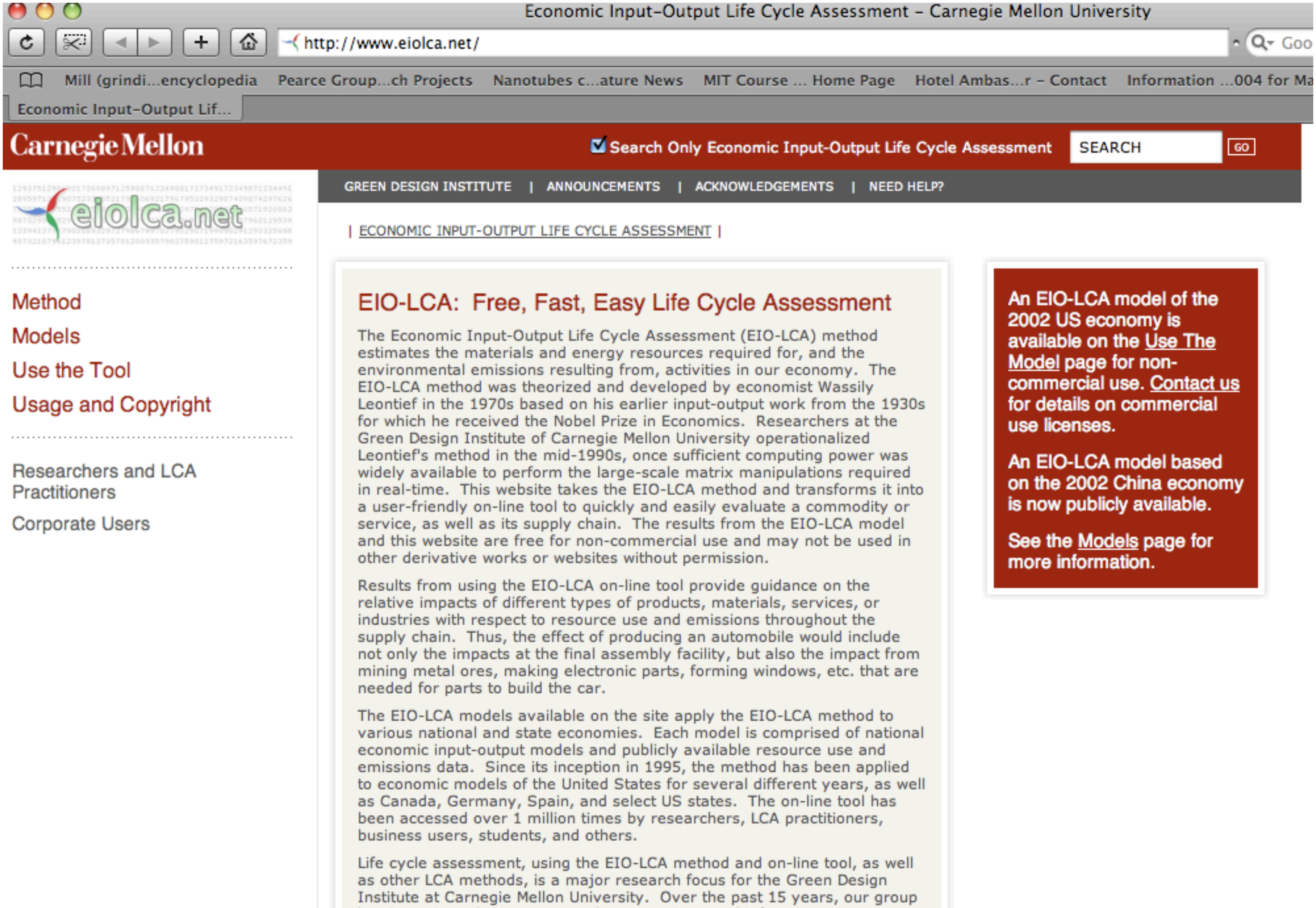
$$\{e\} = [R][I - a]^{-1}\{f\}$$♪

where [R] is a matrix with diagonal elements (impact/dollar) and {e} = environmental impacts♪

CMU I/O website

http://www.eiolca.net/

Read HLM Ch 1, 2, 5, 6



Economic Input-Output Life Cycle Assessment - Carnegie Mellon University

http://www.eiolca.net/

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Economic Input-Output Lif...

Carnegie Mellon

Search Only Economic Input-Output Life Cycle Assessment | SEARCH | GO

GREEN DESIGN INSTITUTE | ANNOUNCEMENTS | ACKNOWLEDGEMENTS | NEED HELP?

eiolca.net

Method

Models

Use the Tool

Usage and Copyright

Researchers and LCA Practitioners

Corporate Users

| ECONOMIC INPUT-OUTPUT LIFE CYCLE ASSESSMENT |

EIO-LCA: Free, Fast, Easy Life Cycle Assessment

The Economic Input-Output Life Cycle Assessment (EIO-LCA) method estimates the materials and energy resources required for, and the environmental emissions resulting from, activities in our economy. The EIO-LCA method was theorized and developed by economist Wassily Leontief in the 1970s based on his earlier input-output work from the 1930s for which he received the Nobel Prize in Economics. Researchers at the Green Design Institute of Carnegie Mellon University operationalized Leontief's method in the mid-1990s, once sufficient computing power was widely available to perform the large-scale matrix manipulations required in real-time. This website takes the EIO-LCA method and transforms it into a user-friendly on-line tool to quickly and easily evaluate a commodity or service, as well as its supply chain. The results from the EIO-LCA model and this website are free for non-commercial use and may not be used in other derivative works or websites without permission.

Results from using the EIO-LCA on-line tool provide guidance on the relative impacts of different types of products, materials, services, or industries with respect to resource use and emissions throughout the supply chain. Thus, the effect of producing an automobile would include not only the impacts at the final assembly facility, but also the impact from mining metal ores, making electronic parts, forming windows, etc. that are needed for parts to build the car.

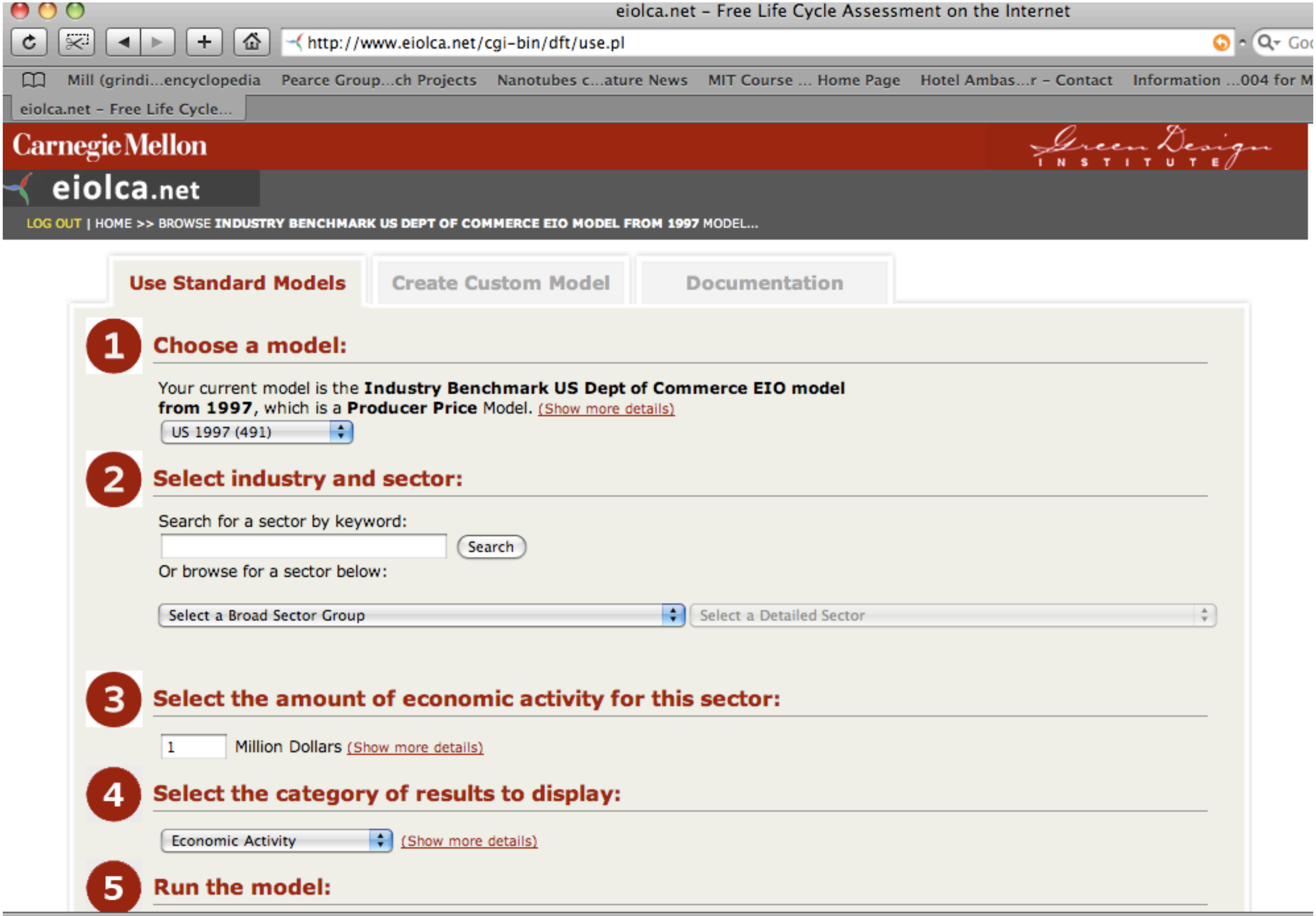
The EIO-LCA models available on the site apply the EIO-LCA method to various national and state economies. Each model is comprised of national economic input-output models and publicly available resource use and emissions data. Since its inception in 1995, the method has been applied to economic models of the United States for several different years, as well as Canada, Germany, Spain, and select US states. The on-line tool has been accessed over 1 million times by researchers, LCA practitioners, business users, students, and others.

Life cycle assessment, using the EIO-LCA method and on-line tool, as well as other LCA methods, is a major research focus for the Green Design Institute at Carnegie Mellon University. Over the past 15 years, our group

An EIO-LCA model of the 2002 US economy is available on the Use The Model page for non-commercial use. Contact us for details on commercial use licenses.

An EIO-LCA model based on the 2002 China economy is now publicly available.

See the Models page for more information.


eiolca.net – Free Life Cycle Assessment on the Internet
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Carnegie Mellon
Green Design INSTITUTE
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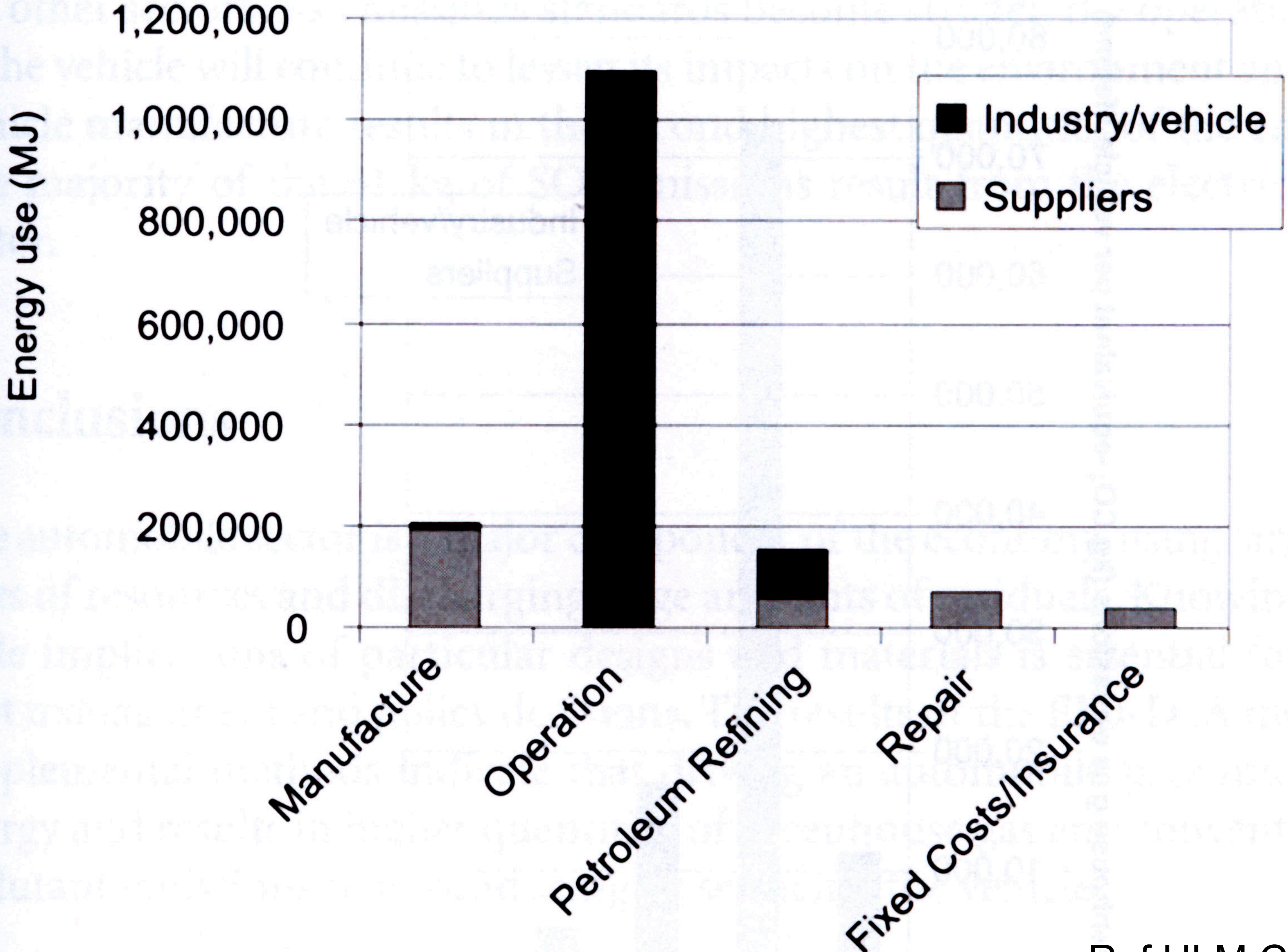
LOG OUT | HOME >> BROWSE INDUSTRY BENCHMARK US DEPT OF COMMERCE EIO MODEL FROM 1997 MODEL...
Use Standard Models
Create Custom Model
Documentation
1
Choose a model:
Your current model is the Industry Benchmark US Dept of Commerce EIO model from 1997, which is a Producer Price Model. (Show more details)
US 1997 (491)
2
Select industry and sector:
Search for a sector by keyword:
Search
Or browse for a sector below:
Select a Broad Sector Group
Select a Detailed Sector
3
Select the amount of economic activity for this sector:
1
Million Dollars (Show more details)
4
Select the category of results to display:
Economic Activity
(Show more details)
5
Run the model:

I/O Example: Automobile

see Ch 6 of HLM

- Sector #336110: Automobile and light truck manufacturing
- 7.57 TJ/M$ = 7.57 MJ/$
- 7.57 MJ/$ X $16,000 = 121 GJ
- 193,800 miles/23.6 mpg = 8212 gal
- Smil (p 392) ~45 MJ/kg, 2.8 kg/gal
- 8212 X 2.8 x 45 = 1035 GJ



Ref HLM Ch 6

FIGURE 6-3. Energy Use in the Automobile Life Cycle

Comparisons between Models

Summary for Different Modeling Approaches
Late 1990's – early 2000's family auto (~1500 kg)

Model	**Materials (GJ)**	**Mfg (GJ)**	**Total (GJ)**
Sullivan	94.5	39	133.5
HLM (Ch 6 see text p 73)			138
EIOLCA 1997 ($16,009 –HLM deflator, producer price)			121
EIOLCA 1997 ($15,276 –cpi deflator, producer price)			116
EIOLCA 2002 ($17,126 producer price)			143
Eco-Audit (above)	94.6	30.6 (est 20MJ/kg)	125
Mean Value (n=6)			***129.4***
Standard Deviation			***9.5 (about 7%)***

Hybrid Models and Supply Chains

- See A) Ch 2 of HLM and, B) Matthews, H.S., Hendrickson, C.T., and Weber, C.L., The Importance of Carbon Footprint Estimation Boundaries *Environ. Sci. Technol.* 2008, vol. 42, pp 5839 – 5842.

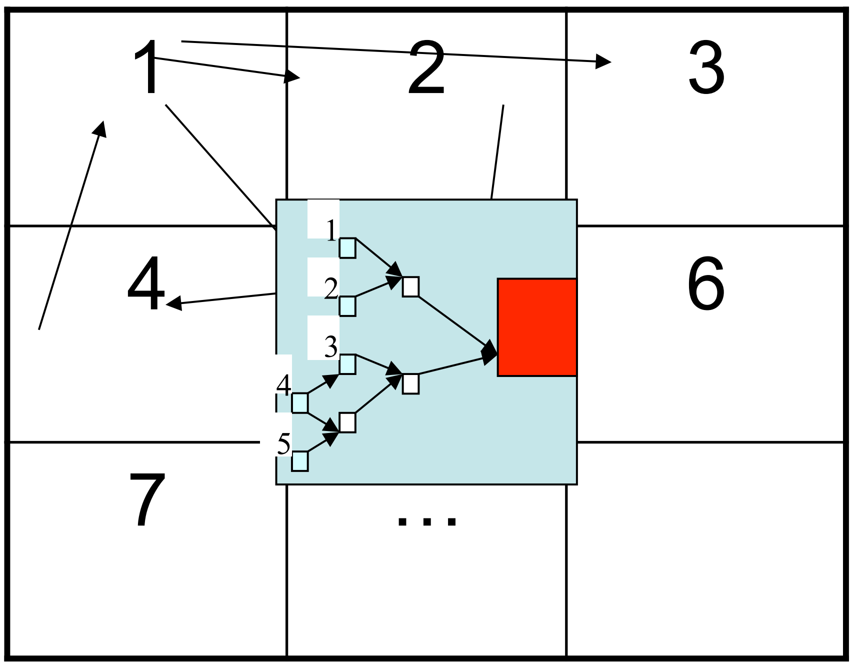


TABLE 1. Summary of Carbon Footprint Estimates for Protocol Tier and Total Emissions

	tier 1 (% of total)	tier 2 (% of total)	tier 1 + 2 (% of total)
book publishers	5	1	6
power generation	92	1	93
average sector	14	12	26

LCA software

http://www.life-cycle.org/LCA_soft.htm

- Boustead Consulting Database and Software
- ECO-it: Eco-Indicator Tool for environmentally friendly design - PRé Consultants
- EDIP - Environmental design of industrial products - Danish EPA
- EIOLCA - Economic Input-Output LCA at Carnegie Mellon University
- GaBi 4 - (Ganzheitlichen Bilanzierung - holistic balancing) - Five Winds International/University of Stuttgart (IKP)/PE Product Engineering
- IDEMAT - Delft University Clean Technology Institute Interduct Environmental Product Development
- KCL-ECO 3.0 - KCL LCA software
- LCAiT - CIT EkoLogik (Chalmers Industriteknik)
- SimaPro 6 for Windows - PRé Consultants
- TEAM(TM) (Tools for Environmental Analysis and Management) - Ecobalance, Inc.
- Umberto - An advanced software tool for Life Cycle Assessment - Institut für Umweltinformatik

SIMAPRO 6.0

What is it?

SIMAPRO is a compilation of LCI libraries together with LCA evaluation tools such as the Eco-indicator 99. Some of its libraries include:

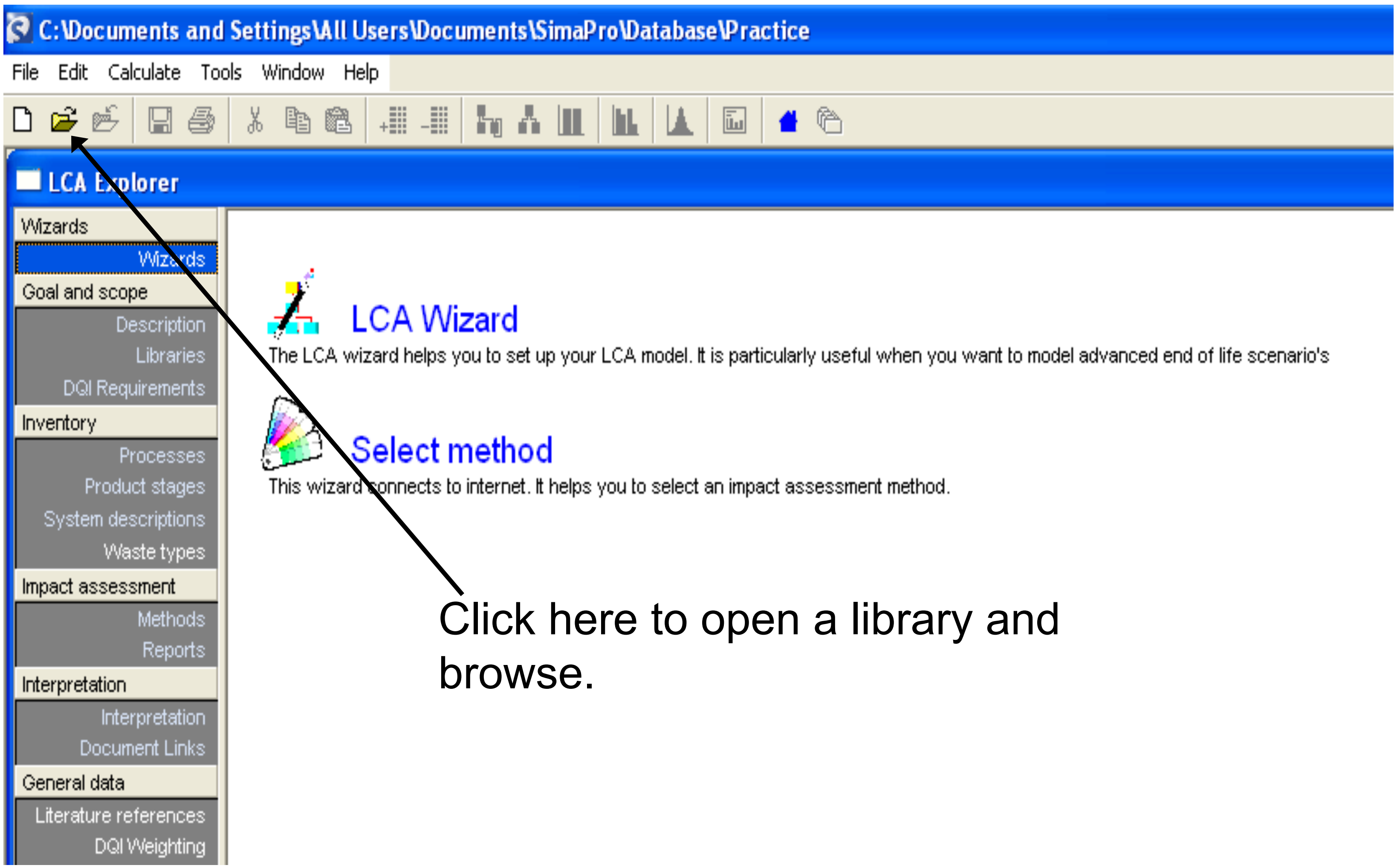
- Buwal 250 (Swiss - EMPA)
- IDEMAT 2001 (Netherlands – Delft University of Technology)
- ETH-ESU (Swiss)
- USA Input Output Database 1998

Download and play with the demo
http://www.pre.nl/content/simapro-demo

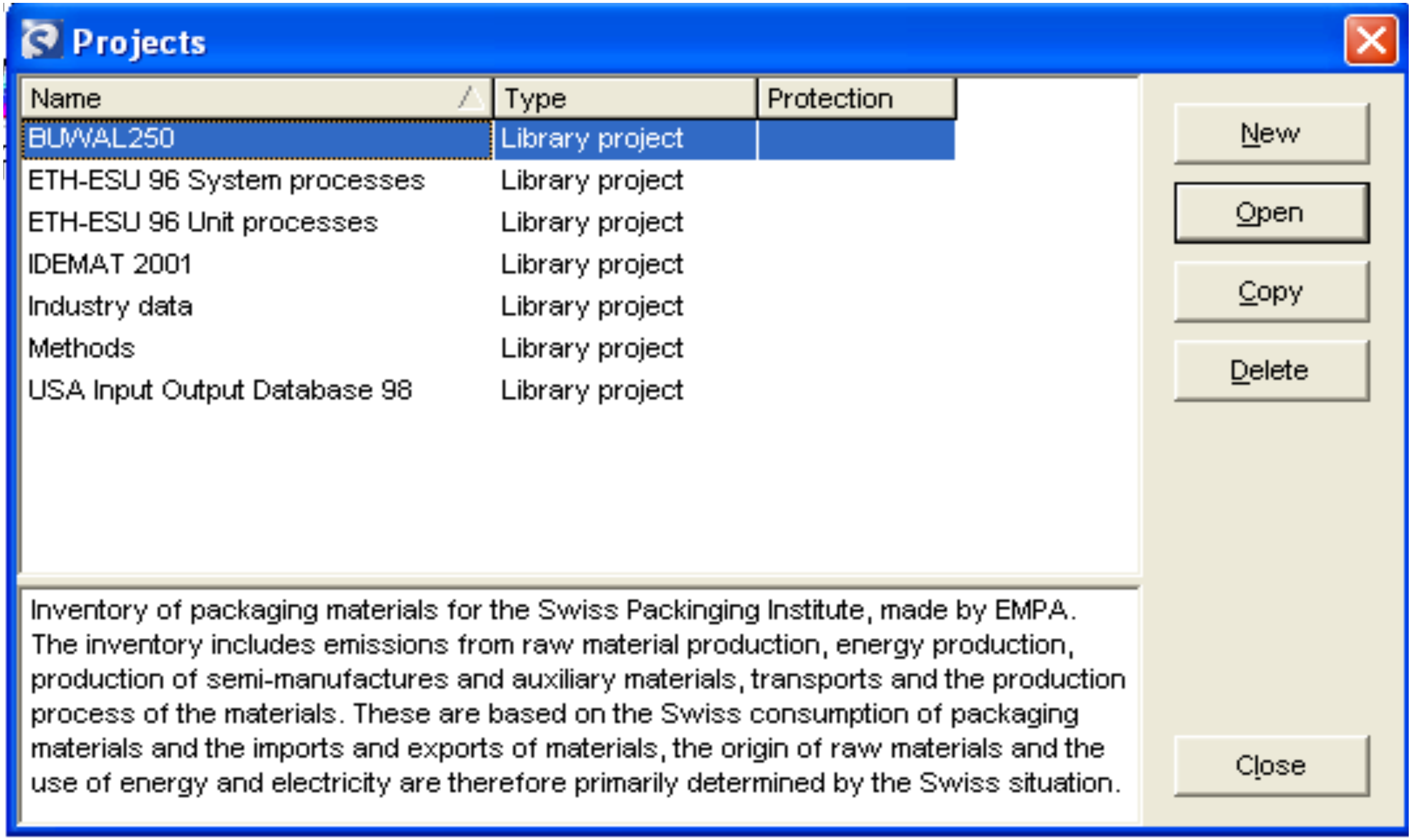
The Focus of this presentation is on Navigation. Please refer to the "Wood Example" tutorial online for instructions on creating a full LCA.

1) Open Simapro

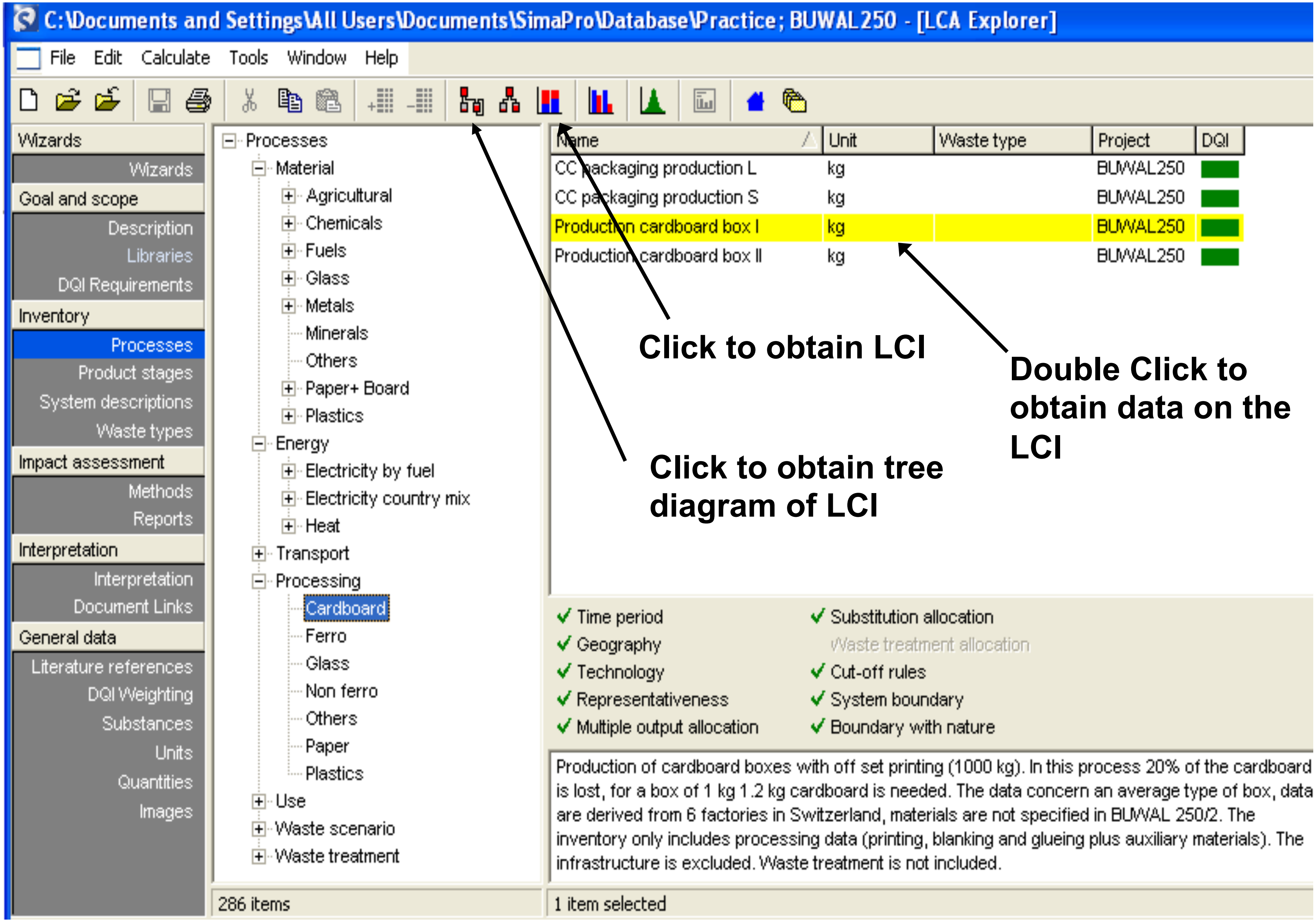
2) This is the first screen you see:



Open a database



Imagine we are interested in the LCI of a cardboard box



Data on the LCI – Input/Ouput Tab

C:\Documents and Settings\All Users\Documents\SimaPro\Database\Practice; BUWAL250 - [Edit processing process 'Production cardboard box I']

File Edit Calculate Tools Window Help

Documentation | Input/output | System description

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Category	Comment
Production cardboard box I	1000	kg	Mass	100 %	Cardboard	
(Insert line here)						

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Ink		18.3	kg	Uniform		7.8	34.5	not traced ba average
Glue		5.2	kg	Uniform		0.9	10.6	not traced ba
Oil		0.2	kg	Undefined				not traced ba
Additives		7	kg	Undefined				not traced ba
Water, unspecified natural origin/kg	in water	2.5	kg	Undefined				
(Insert line here)								

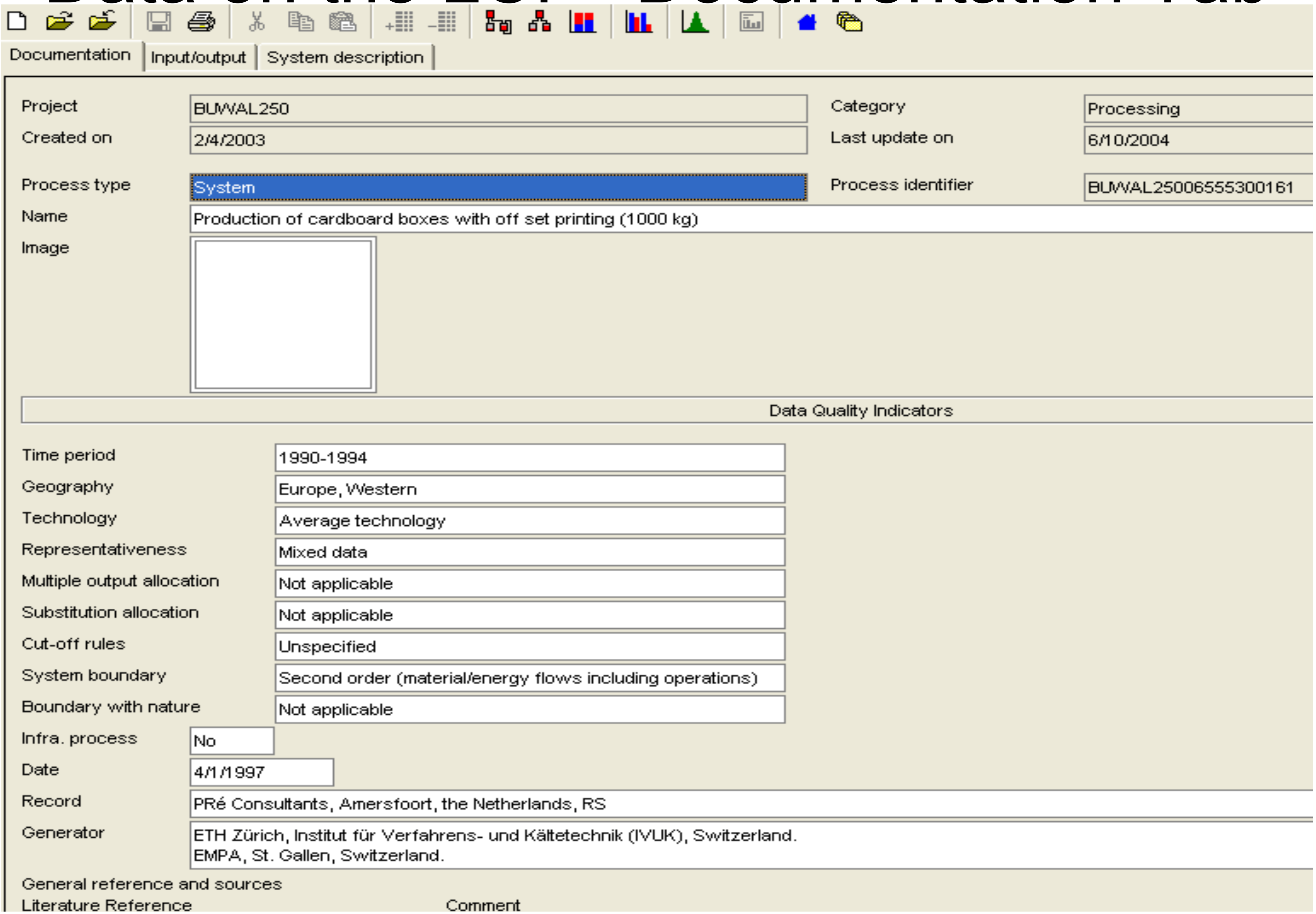
Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Paper wood-free C B250	52	kg	Undefined				average amount , paper type not s in the inventory
LDPE B250	8.5	kg	Undefined				listed as unspecified plastics.
(Insert line here)							

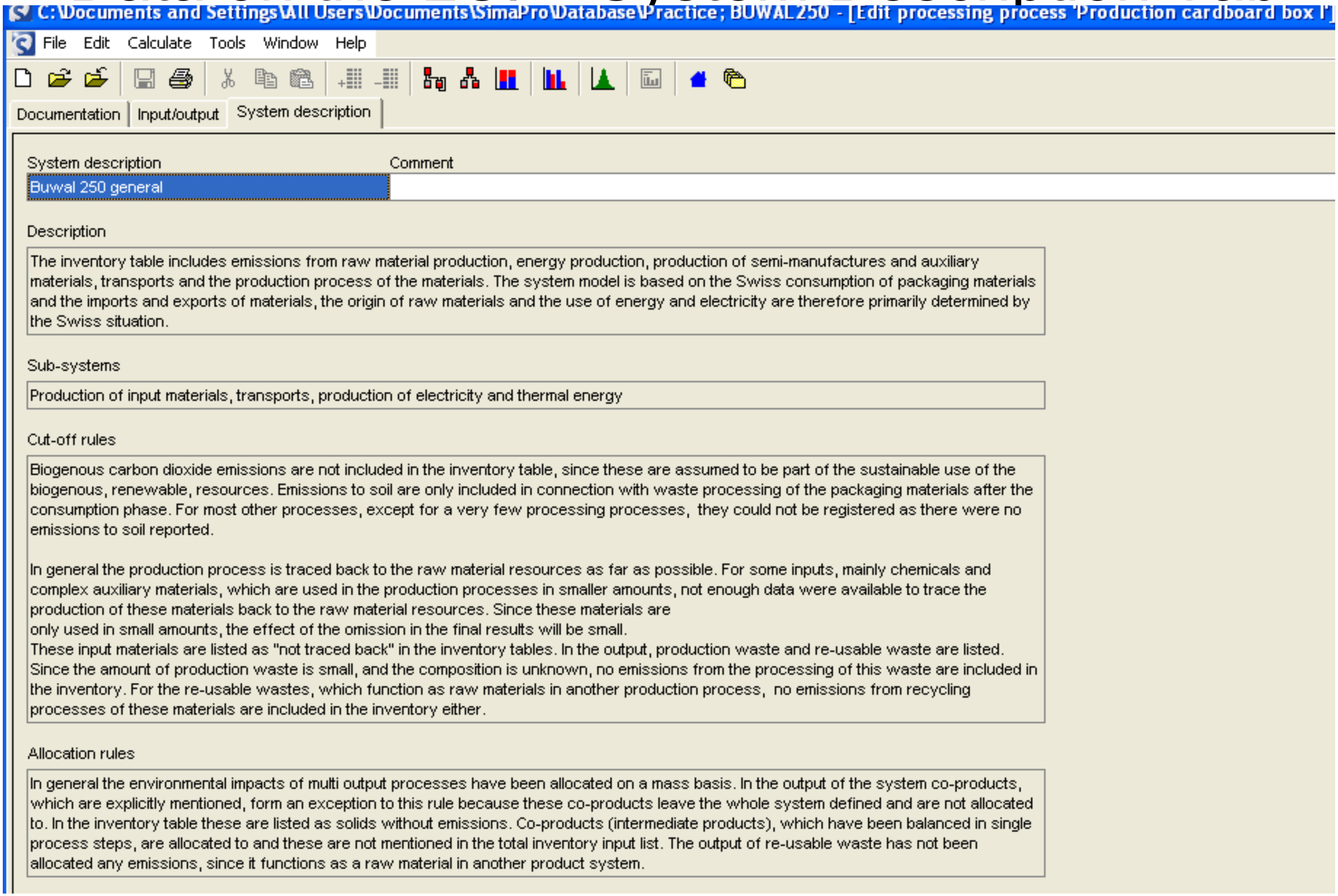
Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Heat diesel B250	90.8	MJ	Undefined				(2 kg, 45.4 MJ/kg)
Heat gas B250	5.03	MJ	Undefined				0.1 kg propane, 50.3 MJ/kg, avera
Electricity Swiss B250	325	kWh	Uniform		86	807	average

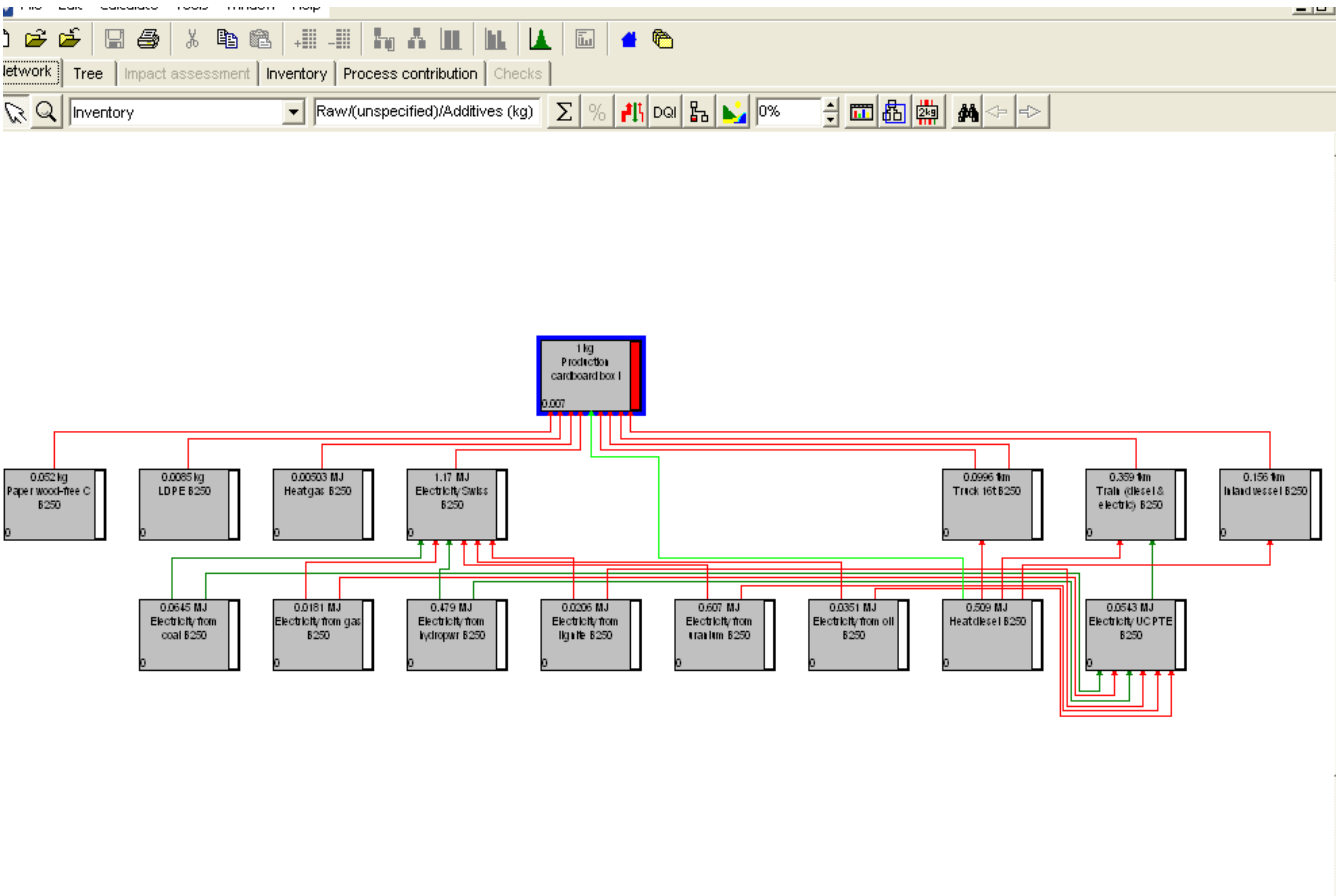
Data on the LCI – Documentation Tab



Data on the LCI – System Description Tab



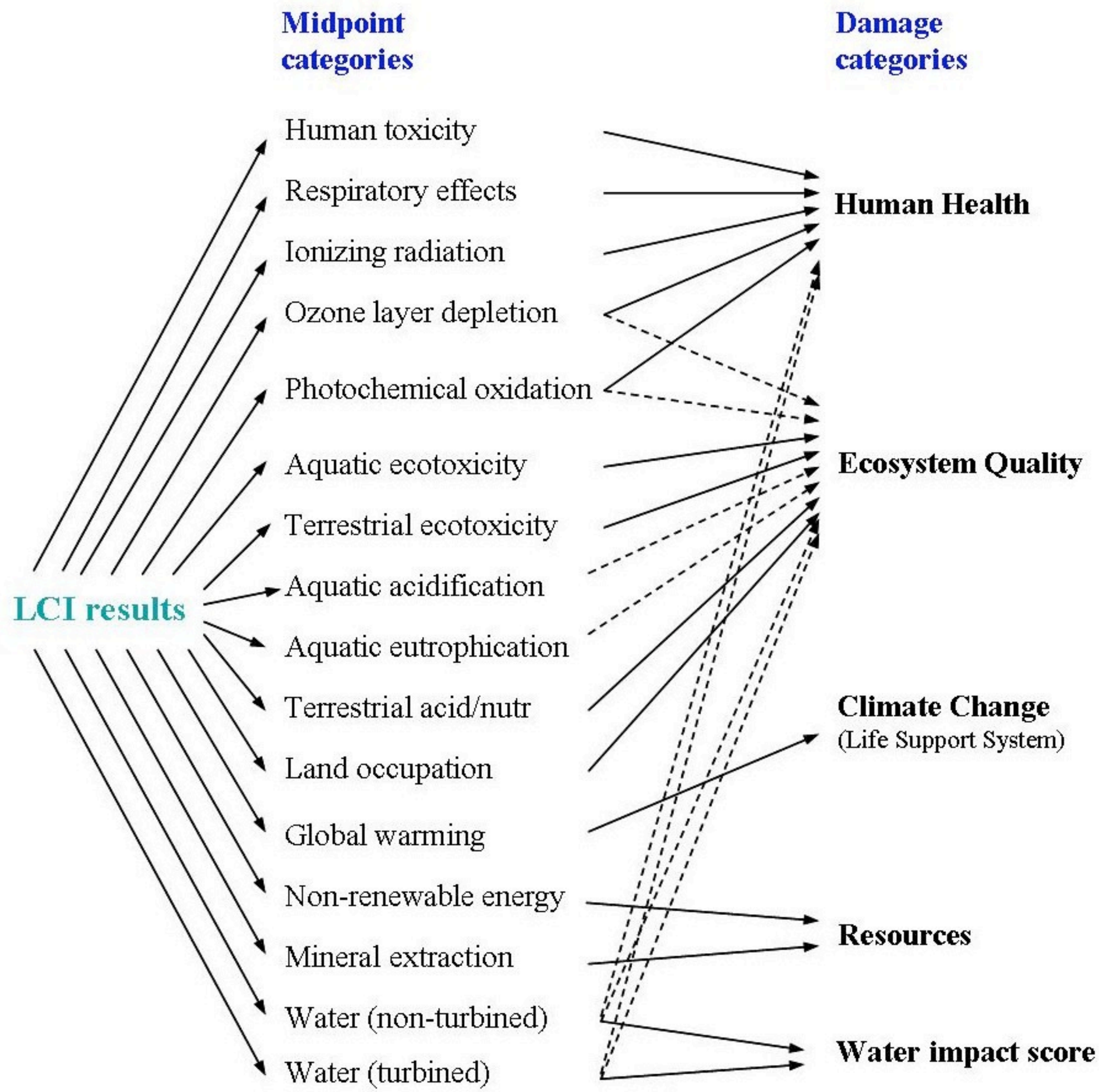
LCI – Network Diagram



LCI - Inventory 1 kg of Cardboard Box

No	Substance	Compartment	Unit	Total	Production cardboard box I	Paper wood-free C B250
1	Additives	Raw	kg	0.007	0.007	x
2	Artificial fertilizer	Raw	kg	0.0000473	x	0.0000473
3	Bauxite, in ground	Raw	kg	0.00000343	x	0.000000879
4	Biomass	Raw	kg	0.000629	x	0.000629
5	Clay, unspecified, in ground	Raw	kg	0.013	x	0.013
6	Coal, 18 MJ per kg, in ground	Raw	kg	0.0146	x	0.0021
7	Coal, brown, 8 MJ per kg, in groun	Raw	kg	0.0112	x	0.00135
8	Complexing agent	Raw	kg	0.00000417	x	0.00000417
9	Defoamer	Raw	kg	0.0000158	x	0.0000158
10	Energy, potential, stock, in barrage	Raw	MJ	0.688	x	0.0567
11	Gas, natural, 35 MJ per m3, in gro	Raw	m3	0.00247	x	x
12	Gas, natural, 36.6 MJ per m3, in g	Raw	m3	0.0154	x	0.0106
13	Gas, natural, feedstock, 35 MJ pe	Raw	m3	0.0051	x	x
14	Glue	Raw	kg	0.0052	0.0052	x
15	Ink	Raw	kg	0.0183	0.0183	x
16	Iron ore, in ground	Raw	kg	0.000002	x	0.000000302
17	Limestone, in ground	Raw	kg	0.0232	x	0.0232
18	Magnesium sulfate	Raw	kg	0.0000251	x	0.0000251
19	Manure	Raw	kg	0.00506	x	0.00506
20	Oil	Raw	kg	0.0002	0.0002	x
21	Oil, crude, 42.6 MJ per kg, in grou	Raw	kg	0.0202	x	0.00254
22	Oil, crude, feedstock, 41 MJ per k	Raw	kg	0.00561	x	0.0011
23	Pesticides	Raw	kg	0.00000407	x	0.00000407
24	Potatoes	Raw	kg	0.00105	x	0.00105
25	Sand and clay, unspecified, in gro	Raw	kg	0.00000017	x	x
26	Sand, unspecified, in ground	Raw	kg	0.000000135	x	0.000000135
27	Sodium chloride, in ground	Raw	kg	0.000817	x	0.000749

Impact Assessment



Impact Assessment

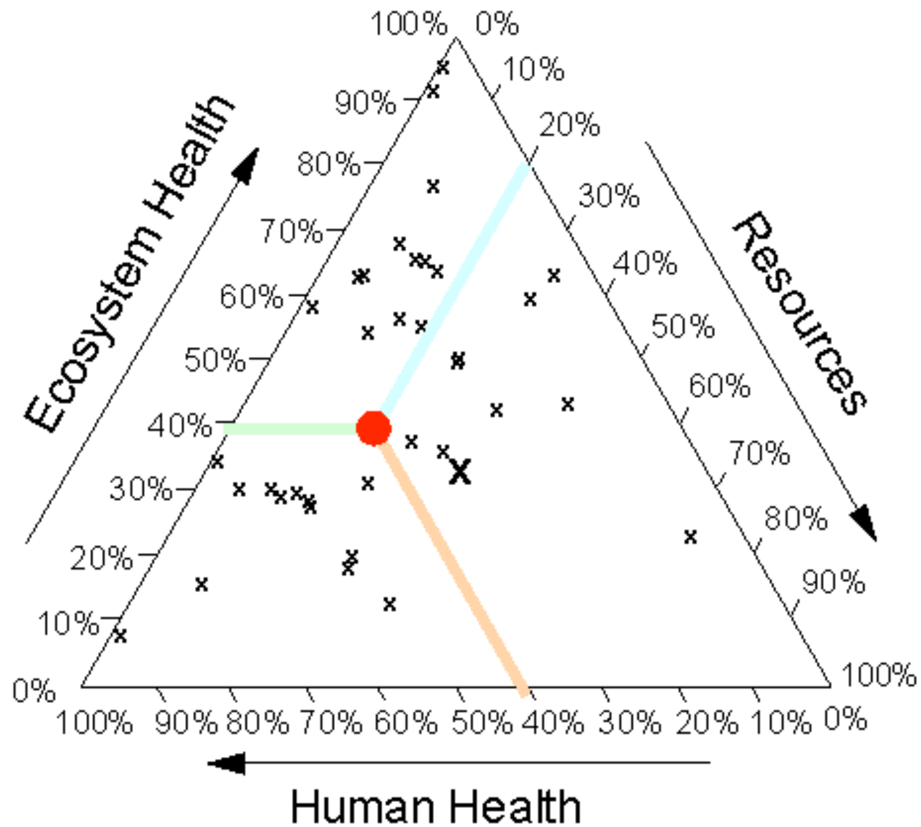
ReCiPe, Eco-indicator 99, USEtox, IPCC 2007, EPD, Impact 2002+, CML-IA, Traci 2, BEES, Ecological Footprint EDIP 2003, Ecological scarcity 2006, EPS 2000, Greenhouse Gas Protocol

All in SimaPro, http://www.pre.nl/content/databases

The difference between LCA and LCI♪

- LCA connects the flows to environmental impacts
- Usually focuses on one or a few effects, e.g.
- *GWP*: CO2, CH4, N2O, CFC, HCFC…
- *Acidification Potential*: SOx, NOx, HCL, NH3, …
- Possible to aggregate more by weighting but…

Valuation: Eco-indicator 95♪



Weighting of the damage categories by the panel •http://www.pre.nl/default.htm

LCI Software Results

- LCI gives a very large table of inputs and outputs, some can be aggregated to simplify e.g. GWP, acidification potential
- This result depends upon the boundaries
- This result depends upon the data set
- Therefore it is time and location dependent

Challenges

- Boundary and Scope
  - What does each phase mean?
  - What is actually included?
- Geo-temporal
- Uncertainty (usually at least ± 10%)
- Functional Unit
- Data Quality
- Methodological Choices

Accuracy and Aluminum

Ashby 2009

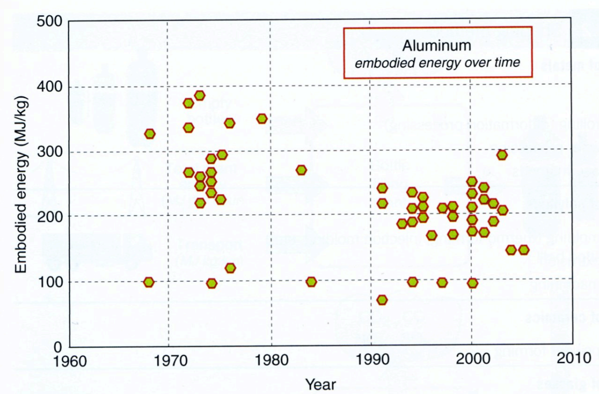


FIGURE 6.2 *Data for the embodied energy of aluminum. The mean is 204 MJ/kg, with a standarc deviation of 58 MJ/kg. Using the best-characterized data only gives a mean of 220 MJ/kg with a standarc deviation of 20 MJ/kg.*

McMillan & Keoleian 2009

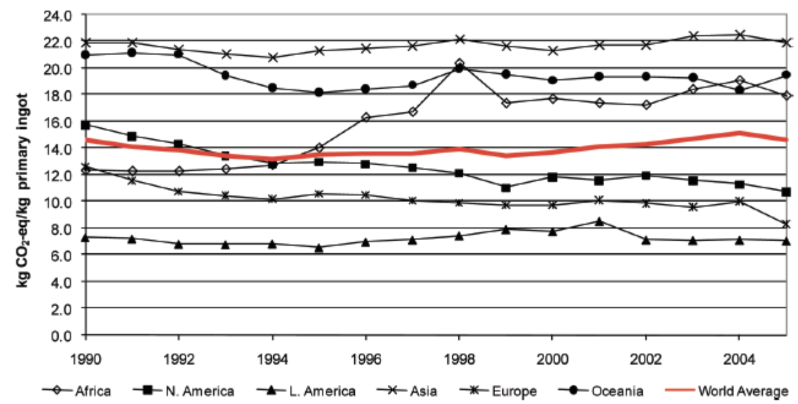


FIGURE 4. Production based GHG intensity of primary aluminum production by region.

1. Smil 2008:
   Aluminum from bauxite
   190 - 230 MJ/kg
2. Ashby 2009:
   200 - 240 MJ/kg
3. CMU EIO LCA:
   115 MJ/kg
4. Alcoa: 81 MJ/kg
5. International Aluminum Institute:
   84 MJ/kg

Ashby 2009:
11 - 14 kgCO2/kg

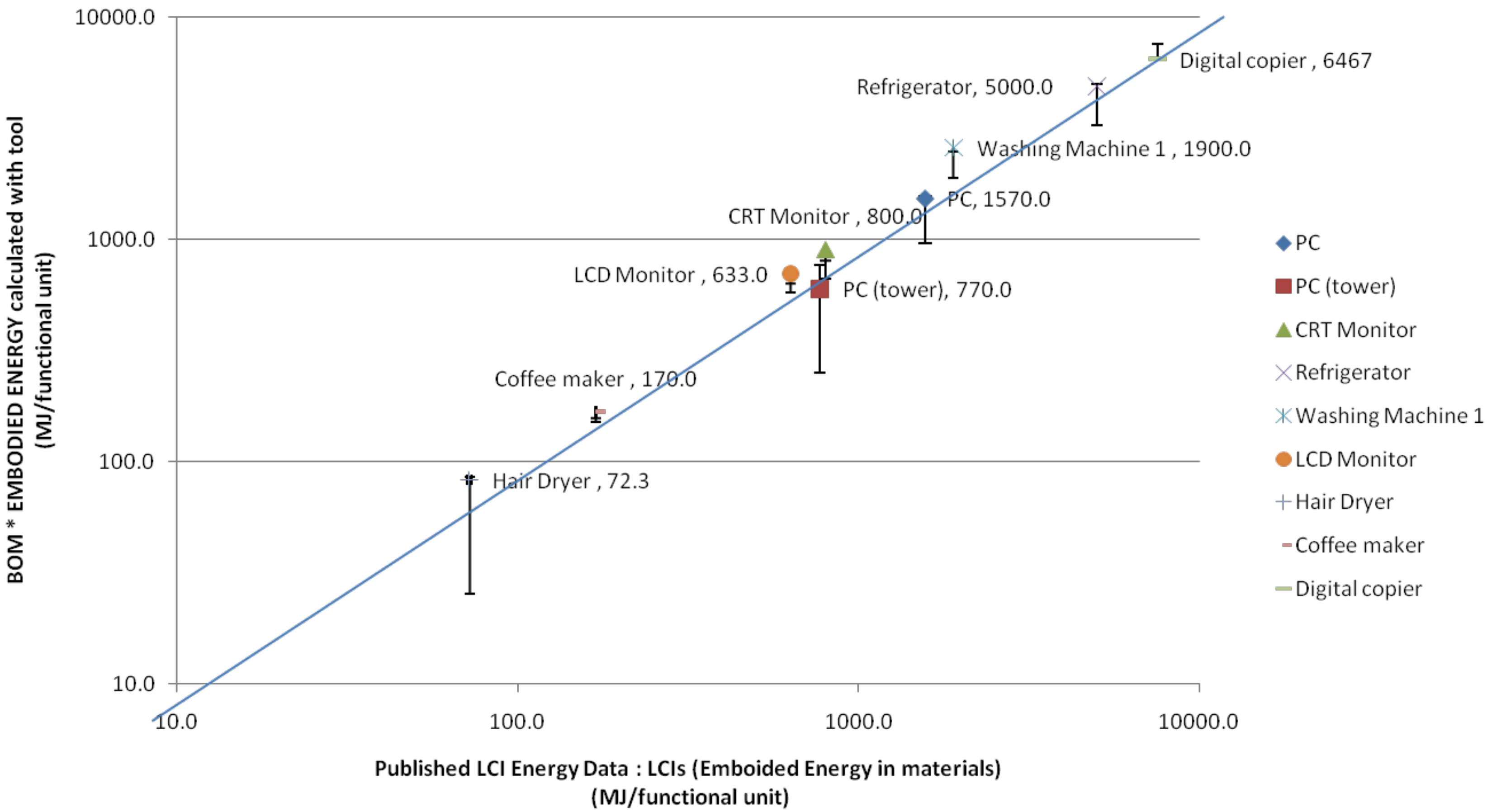
Also see debate on CNW's report on 'dust to dust' – Prius vs Hummer

Summary

- Powerful tool – All phases, various environmental impacts
  - Easy to pickup hard to master
  - Many applications
    - Sustainable design
    - Supplier / distributor selection
    - Performance measurement and tracking
    - CSR reporting

- Has challenges
  - Education
  - Data availability and qualification
  - Vague standards – ISO, WRI, PAS2050, EPD, PCR ..
  - Impact factors
  - Lack of regulation (Picking up in EU)

Comparison of PRODUCTS' MATERIAL EMBOIDED ENERGY DATA:
Calculated with BOM tool vs. LCIs Published



Natalia Duque Ciceri, 2009

Incorporating Values – the difference between LCA and LCI♪

- Value Laden
- Location dependent
- Depends on self interest
- Knowledge limitations
  - mental models
- Power advantages
  - if fish could vote….

Accuracy Limitations

- Functional unit limitations
- Boundaries need to be clearly stated
- Little Standardization
- Beware closer than ± 10%

Readings and References

a) Ashby Ch 3, also see Ch 7 and 12 (Refs)

b) Hendrickson, Lave and Matthews, Chapters 1, 2, and 5, 6, look at Appendix I.

c) Leontief, Input/Output Economics, pp19 – 24 (handout)

d) Sullivan, J., et al, "Life Cycle of US Sedan….." 1999, p 1-14. (handout)