Intro to Life Cycle Analysis
2.83/2.813

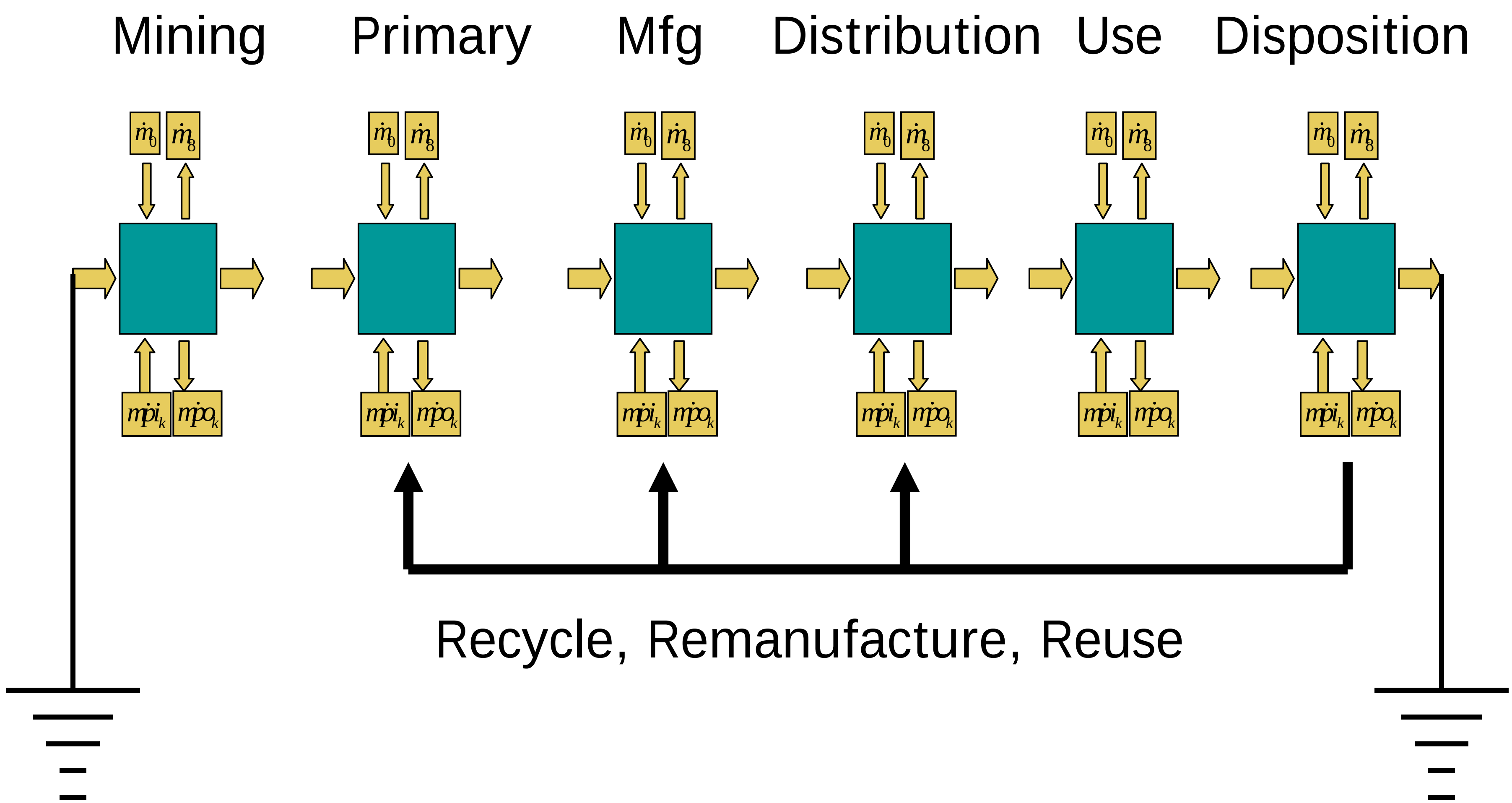
References

1. Allen and Shonnard, Ch 13 *"Life Cycle Concepts…"*
2. Hendrickson, Lave and Matthews, Chapters (1), 2, and 5, 6 & App. I
3. **Leontief**, Input/Output Economics, pp19 – 24 (handout)
4. **CMU I/O Website**: Environmental Input-Output LCA: http://www.eiolca.net/
5. **Sullivan et al** LCI of Family Sedan

Outline

1. Streamlined Life Cycle Analysis
2. Process Level LCA
3. Input/Output LCA
4. Case Study: Automobiles
5. Other Examples (critique)

Life Cycle Analysis



Life Cycle Inventory

- LCA = LCI + Impact Analysis
- i.e. counting the mercury emissions, and then accounting for their impact…
- Issues:
  - transport, exposure, sensitivity
  - aggregating impacts
  - weighting impacts

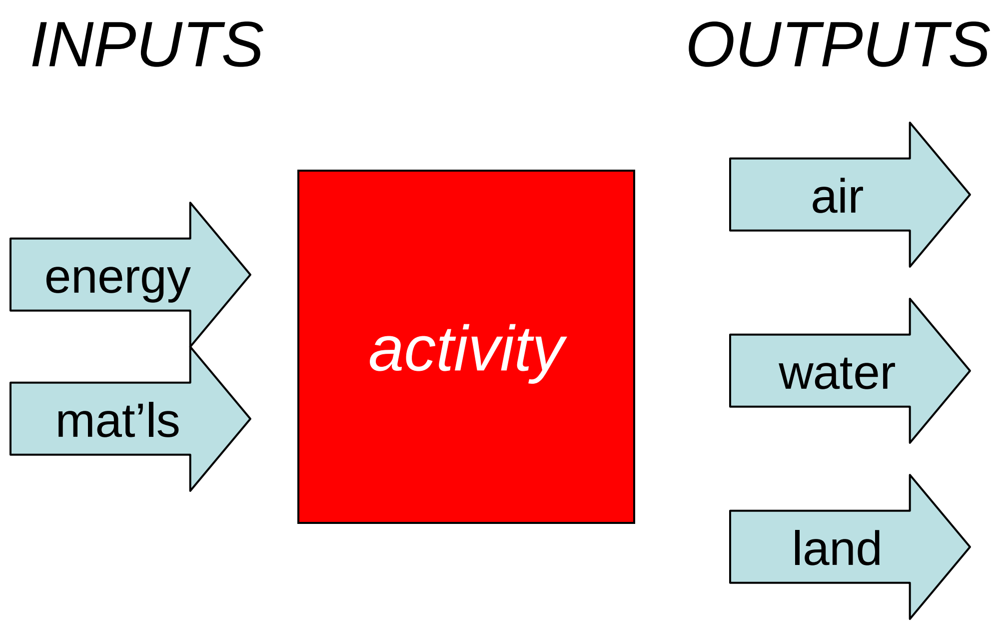
Life Cycle Perspective

- 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

Streamlined Life Cycle Assessment

- qualitative assessment
- value judgments by experts
- for each stage of the life cycle
- in broad categories of impact
- “first cut” at the problem
- See SLCA by T. Graedel 1998

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

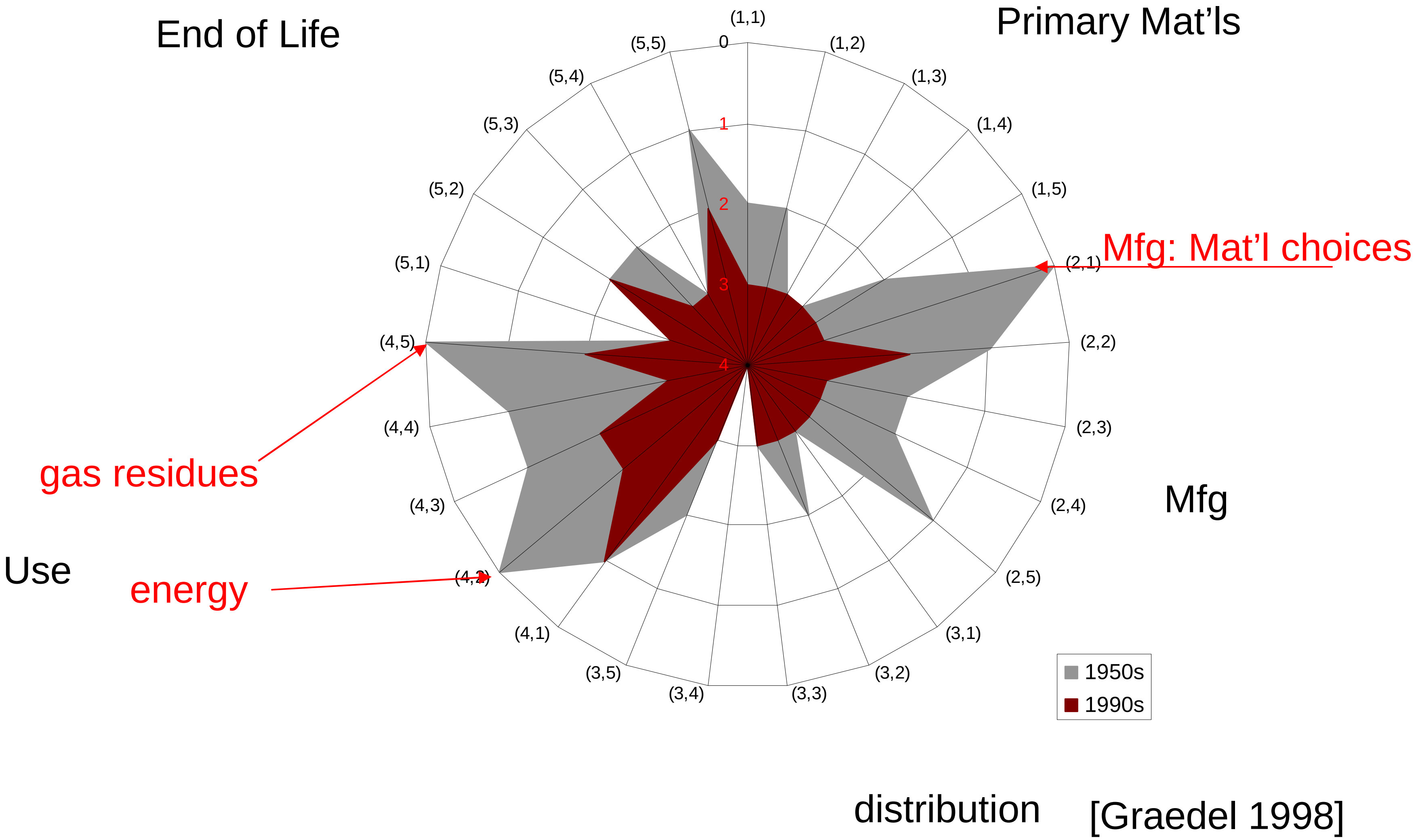
Product Assessment Matrix for the Generic 1950s Automobile [Graedel 1998]

	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]

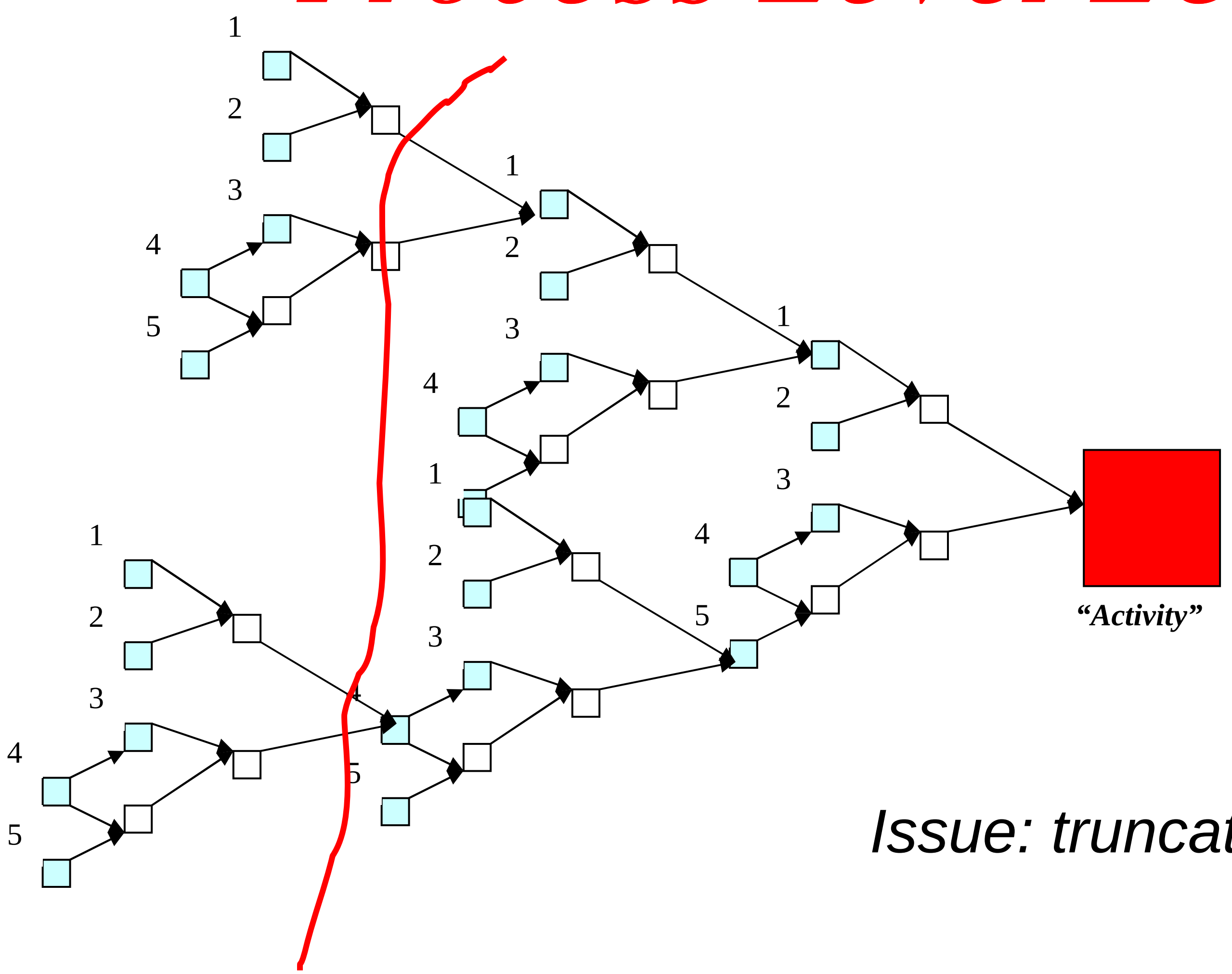
	Environmental Stressor					
Life Cycle Stage	**Materials Choice**	**Energy Use**	**Solid Residues**	**Liquid Residues**	**Gaseous Residues**	**Total**
Premanufacture	3	3	3	3	3	15/20
Product Manufacture	3	2	3	3	3	14/20
Product Delivery	3	3	3	4	3	16/20
Product Use	1	2	2	3	2	10/20
Refurbishment, Recycling,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



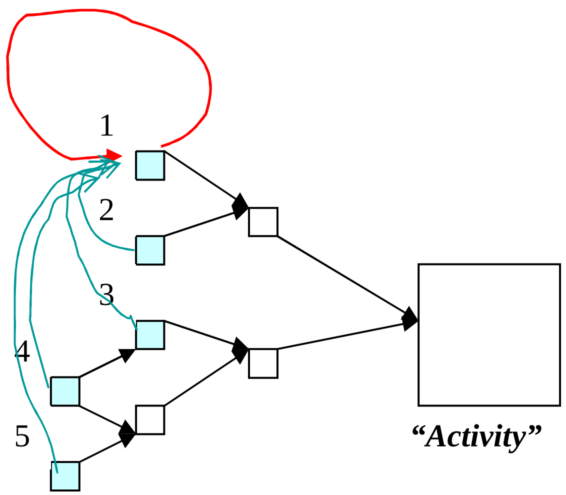
[Graedel 1998]

Process Level LCA

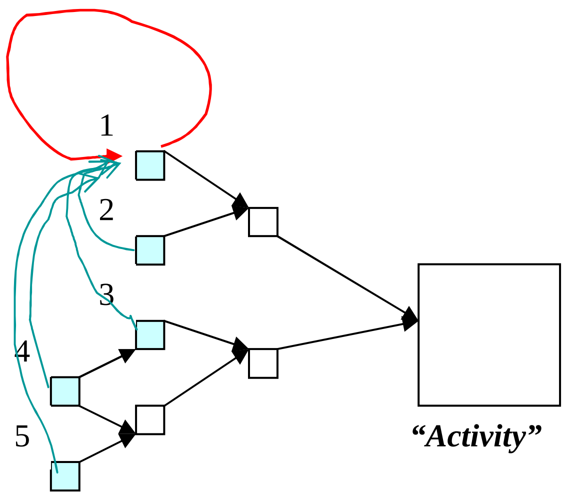


Issue: truncation error

Demand Vs Production



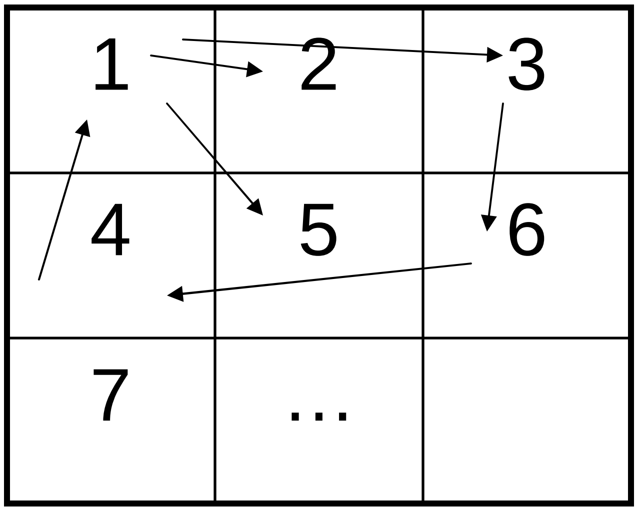
Demand Vs Production



- 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

Rewrite as table in 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 $$[I - a]\ \{x\} = \{f\}$$

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

$$\{x\} = [I-a]^{-1}\{f\}$$

$$\{e\} = [R]\{x\}$$

$$\{e\} = [R][I-a]^{-1}\{f\}$$

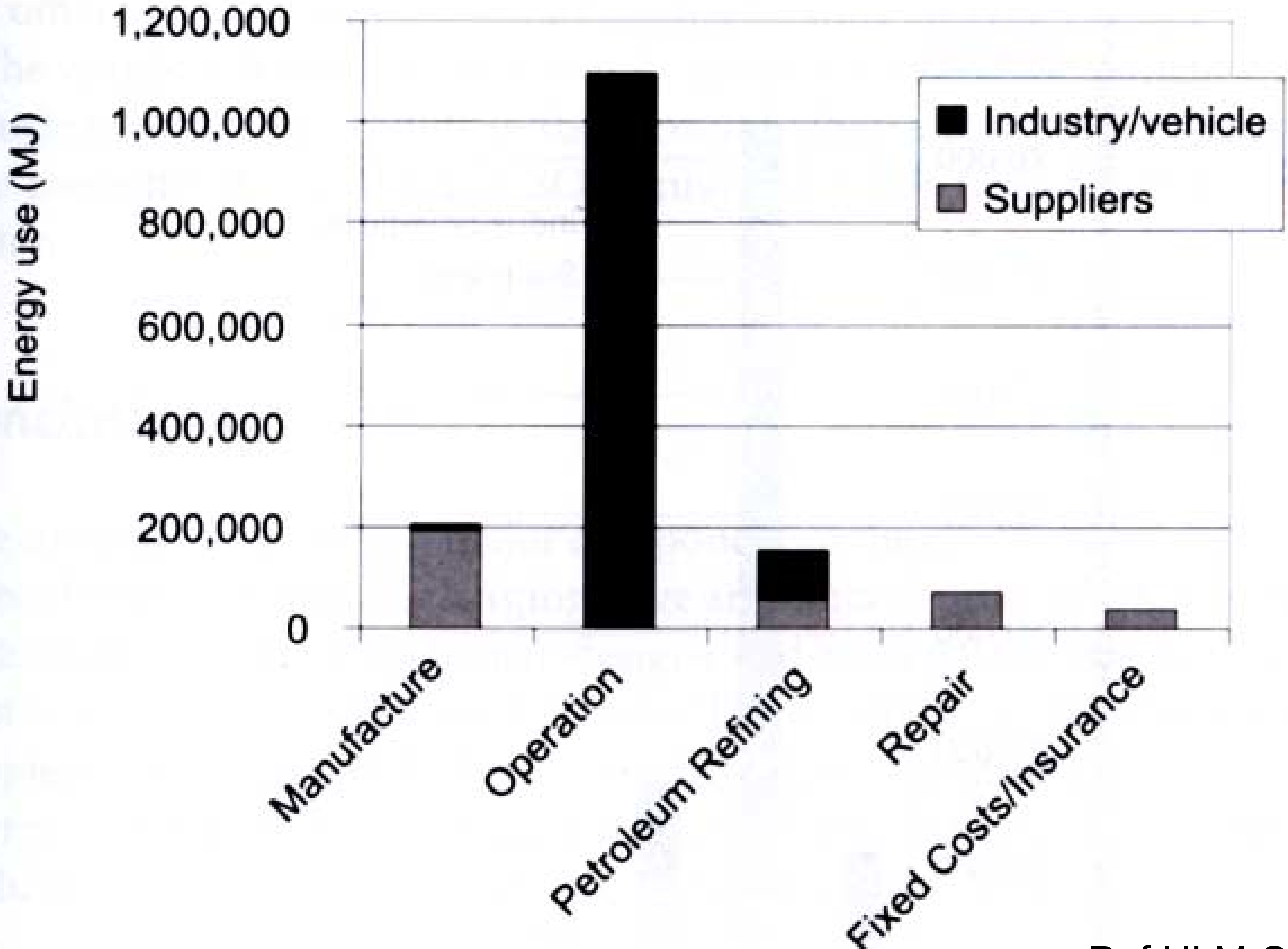
where [R] is a matrix with diagonal elements (impact/dollar) and {e} = environmental impacts

CMU I/O website

http://www.eiolca.net/

Auto example (Ch 6 of HLM)

- Sector #336110: Automobile and light truck manufacturing
- 7.57 TJ/G$ = 7.57 MJ/$
- 7.57 MJ/$ X $16,000 = 121 GJ
- 193,800 miles/23.6 mpg = 8212 gal
- Smil (p 16) 45 MJ/kg, 2.57 kg/gal
- 8212 X 2.57 x 25 = 950 MJ



Ref HLM Ch 6

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

Sullivan et al 1998

- “family sedan”
- 120,000 miles life time
- estimate from 644 parts
- 23 mpg
- total mass 1532 kg
- solvent based paints with controls

1. Material Production
2. Manufacturing
3. Use
4. Maintenance & Repair
5. End of Life

Inputs

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

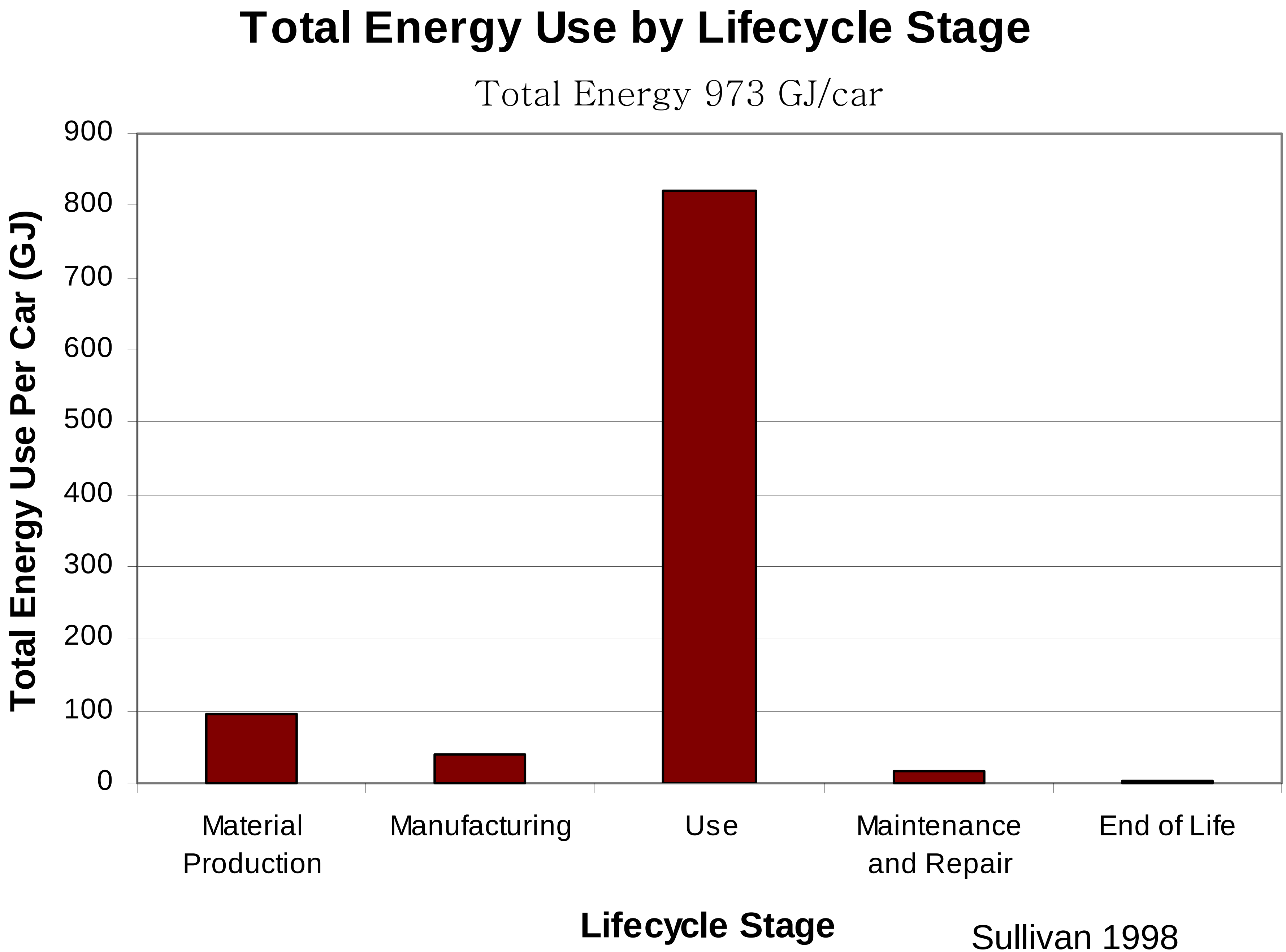
	Units	Generic Vehicle	Material Production	Manufacturing	Operation	Maintenance & Repair	End Of Life
Inflow							
(r) Bauxite (Al2O3, ore)	Kg	32	32	0.0026	0	0.021	0
(r) Bauxite Rich Soil	Kg	222	222	0	0	0	0
(r) Chromium (Cr, in ground)	Kg	0.91	0.91	0	0	0	0
(r) Coal (in ground)	Kg	2,509	1,033	618	748	100	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)*	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

* From electricity production

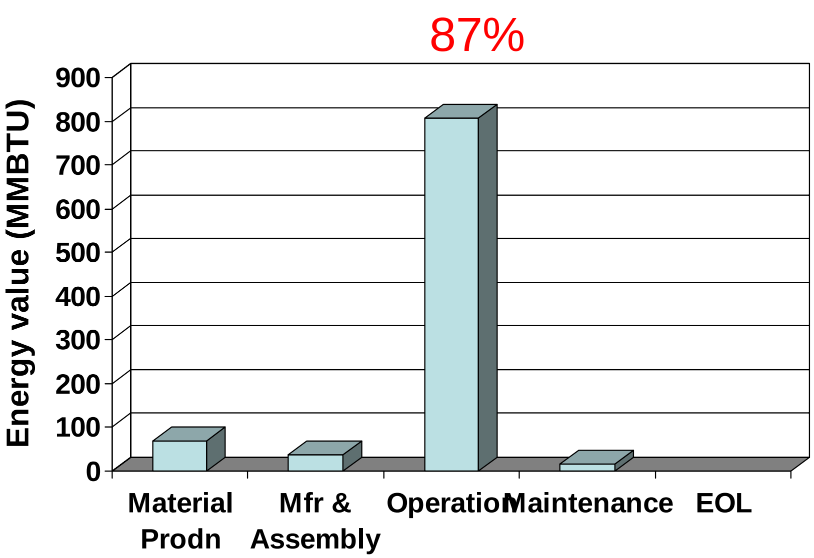
Output and Energy Use

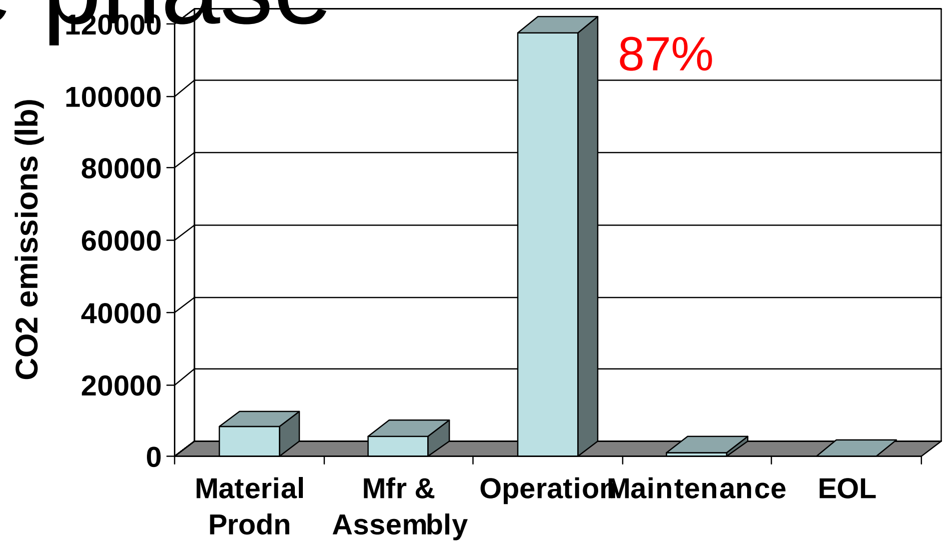
Table 8: LCI of the Generic Vehicle (Outflows and Energy Use)

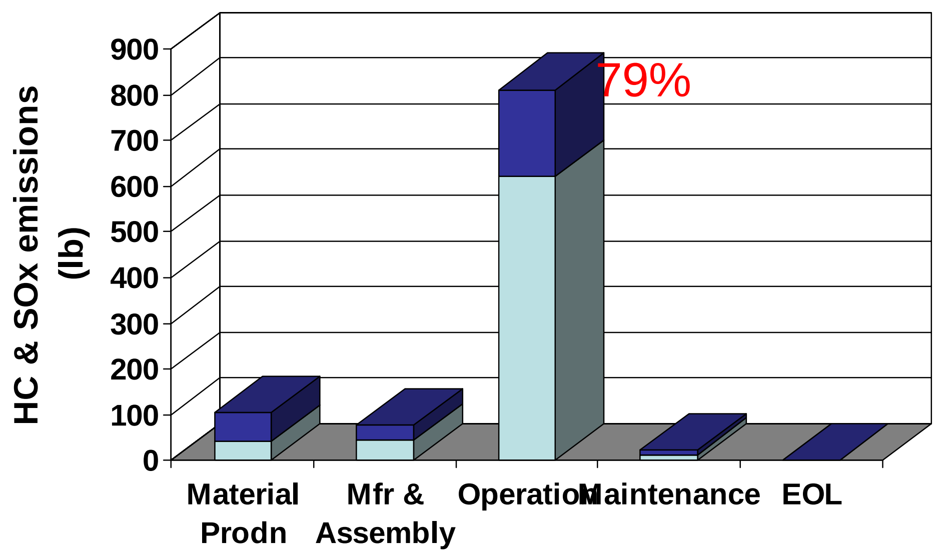
	Units	Generic Vehicle	Material Production	Manufacturing	Operation	Maintenance & Repair	End Of Life
Outflow							
(a) Carbon Dioxide (CO2, fossil)	gm	59,092,200	4,439,850	2,562,160	51,331,400	615,481	143,273
(a) Carbon Monoxide (CO)	gm	1,942,230	63,813	5,914	1,832,728	39,088	683
(a) Hydrocarbons (except 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

A majority of the environmental burden of an auto occurs during the use phase







Source: Sullivan & Cobas-Flores (2001),
Full Vehicle LCAs: A Review, SAE 2001-01-3725

CMU Input/Output Model Vs. Sullivan's Process Model

emissions (gms) per vehicle	**CMU I/O** (1992 data)	**Sullivan et al** (1995 ref. vehicle)	**% Difference from CMU**
CO_2	7,536,196	7,002,010	-7%
CH_4	69,483	17,307	-75%
SO_2	32,484	45,408	40%
CO	51,079	69,727	37%
NO_2	31,937	21,166	-34%
VOC	12,008		
Lead	28	51	86%
PM10	5,582	34,705	522%

Results for all activities up to and including manufacturing

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:

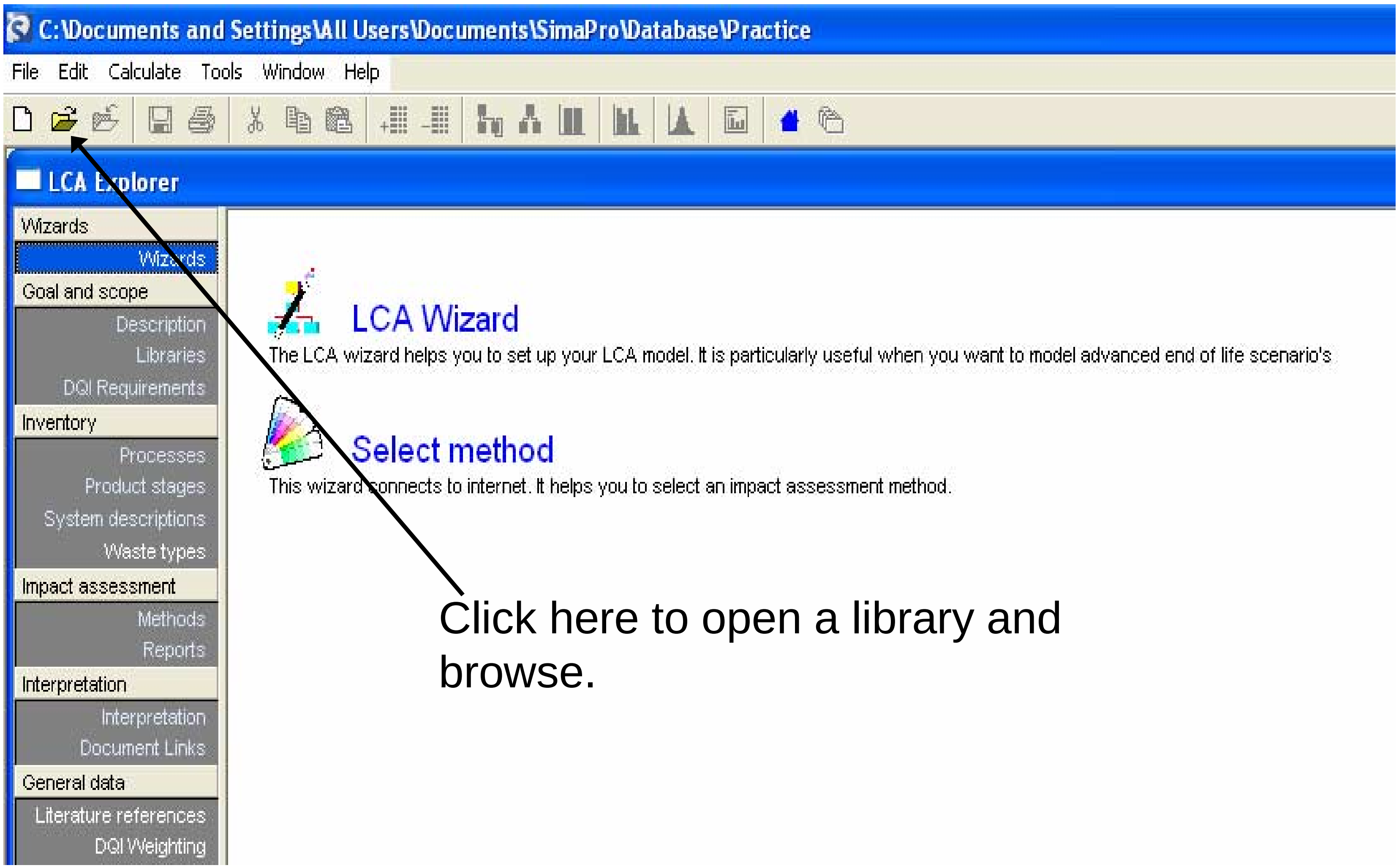
- Buwal 250 (Swiss - EMPA)
- IDEMAT 2001 (Netherlands – Delft University of Technology)
- ETH-ESU (Swiss)
- USA Input Output Database 1998

Aside from the latter one, all the other libraries contain process LCI's (the traditional bean counting way)

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

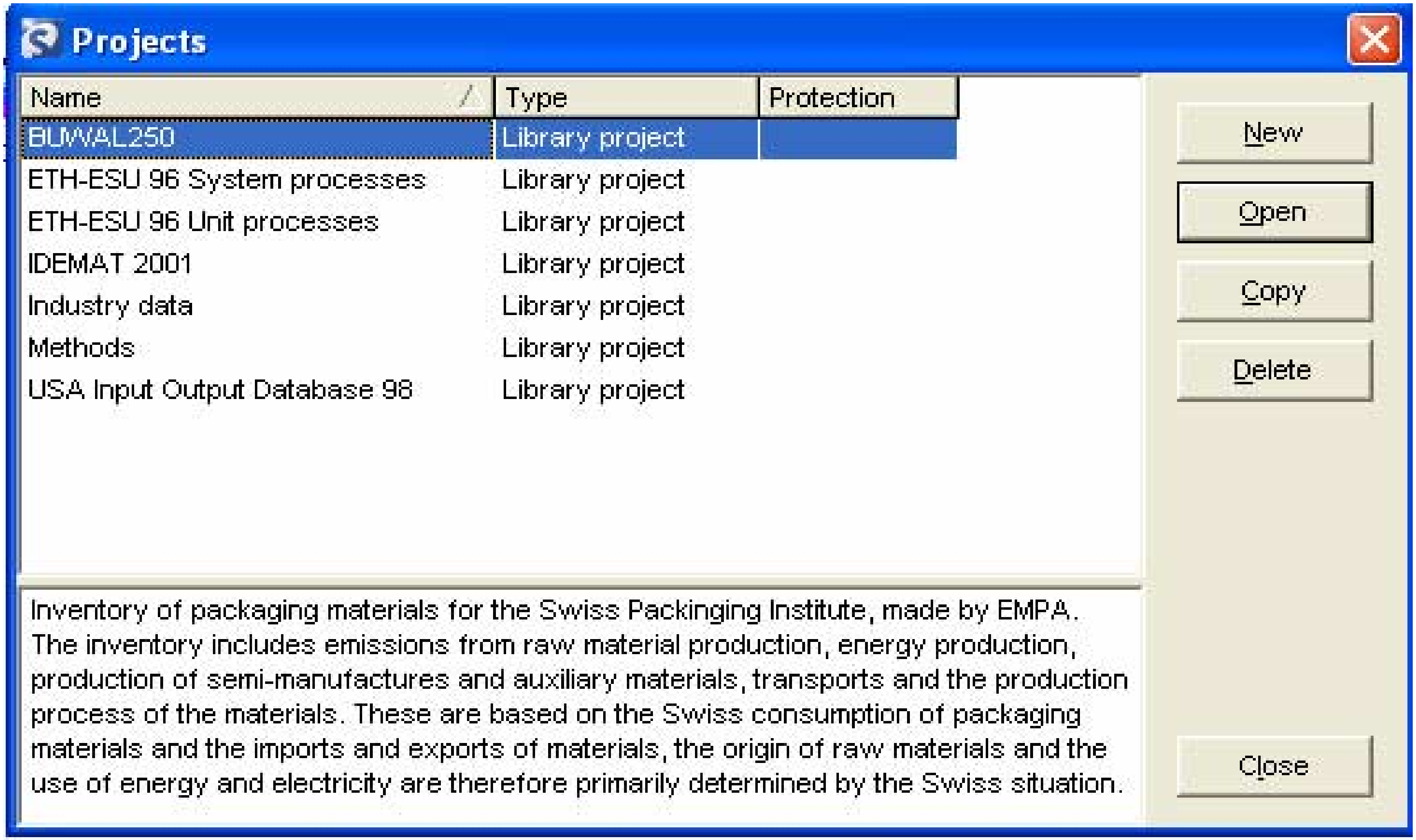
1) Open Simapro

2) This is the first screen you see:

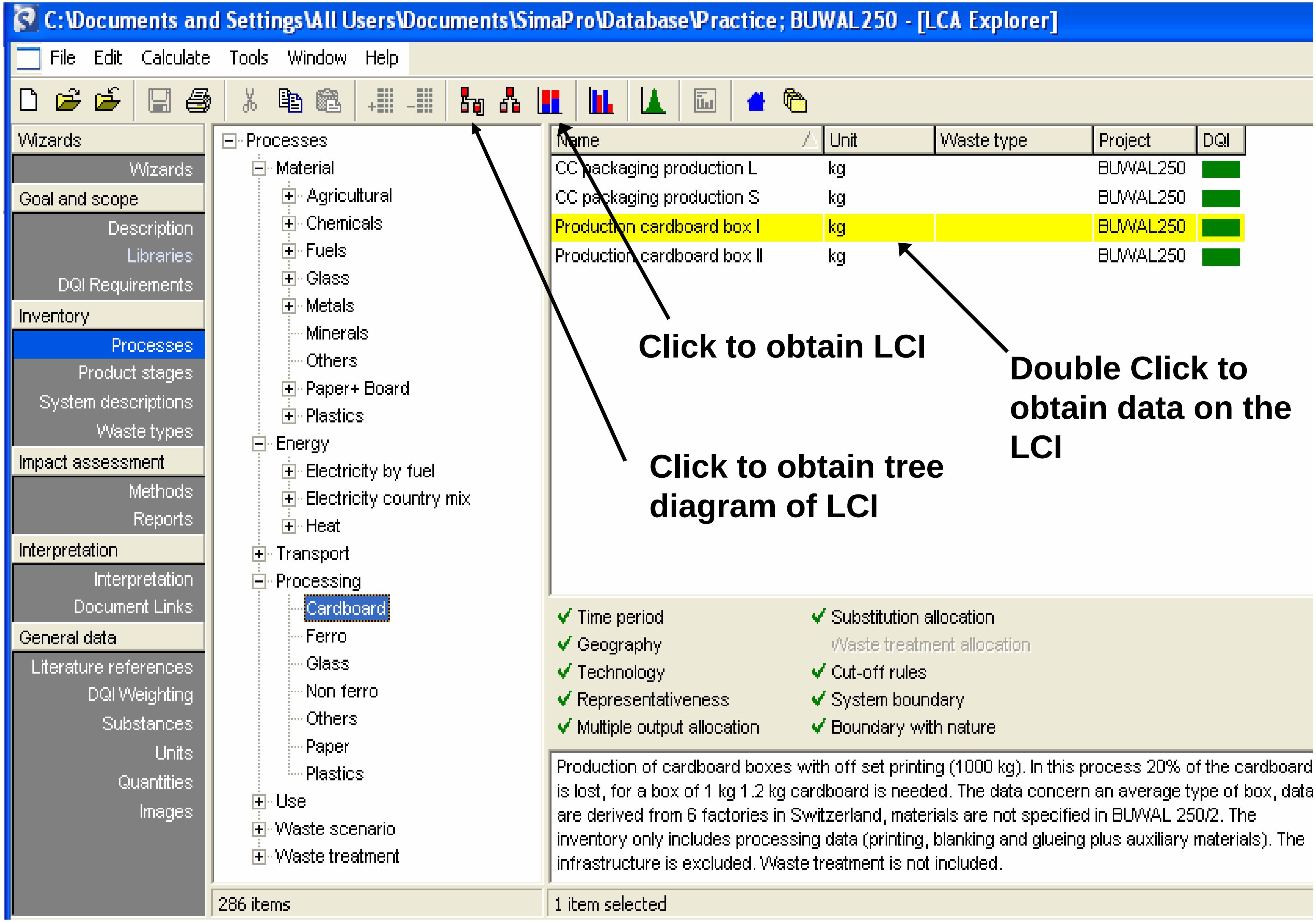


Click here to open a library and browse.

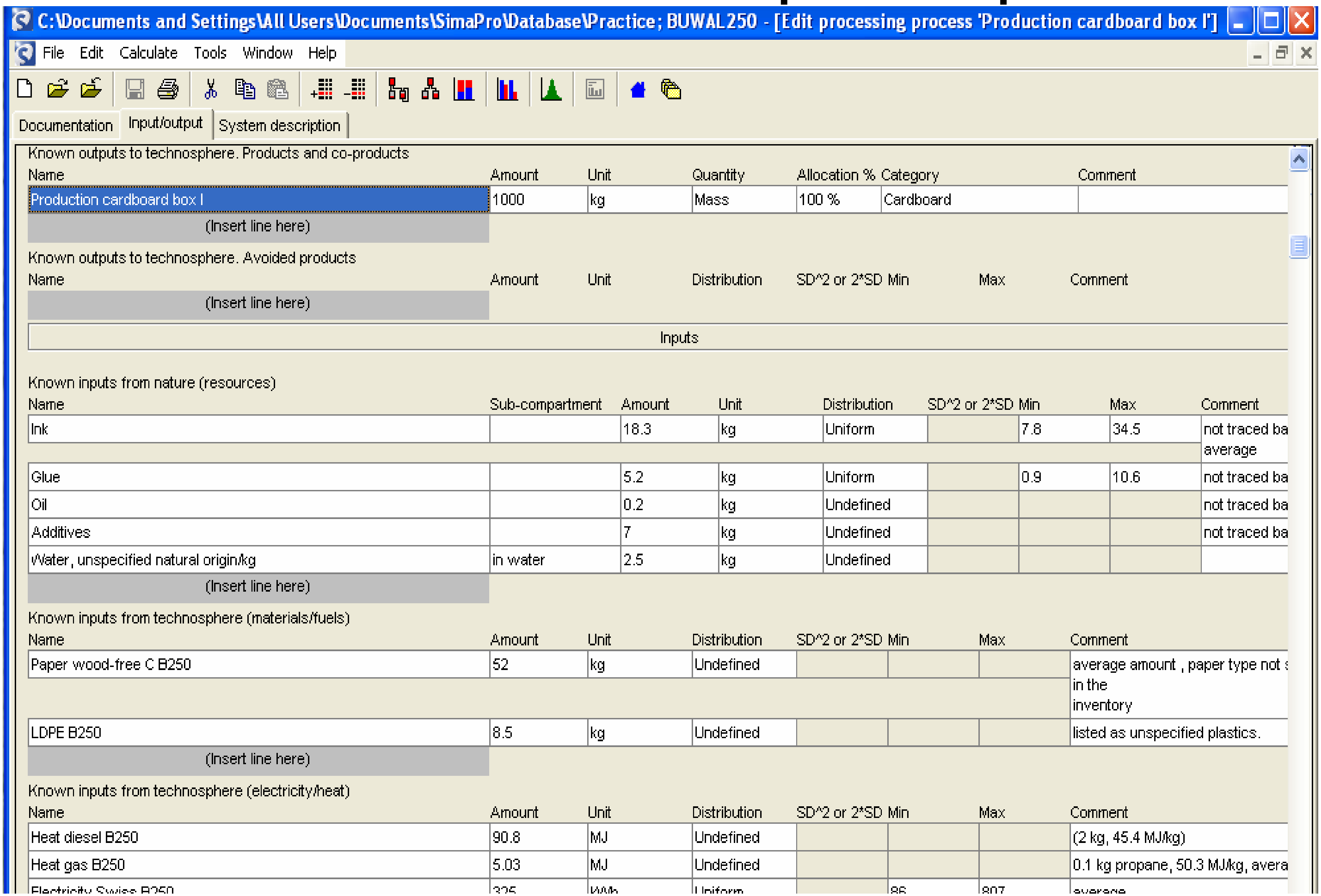
Open a database



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)								

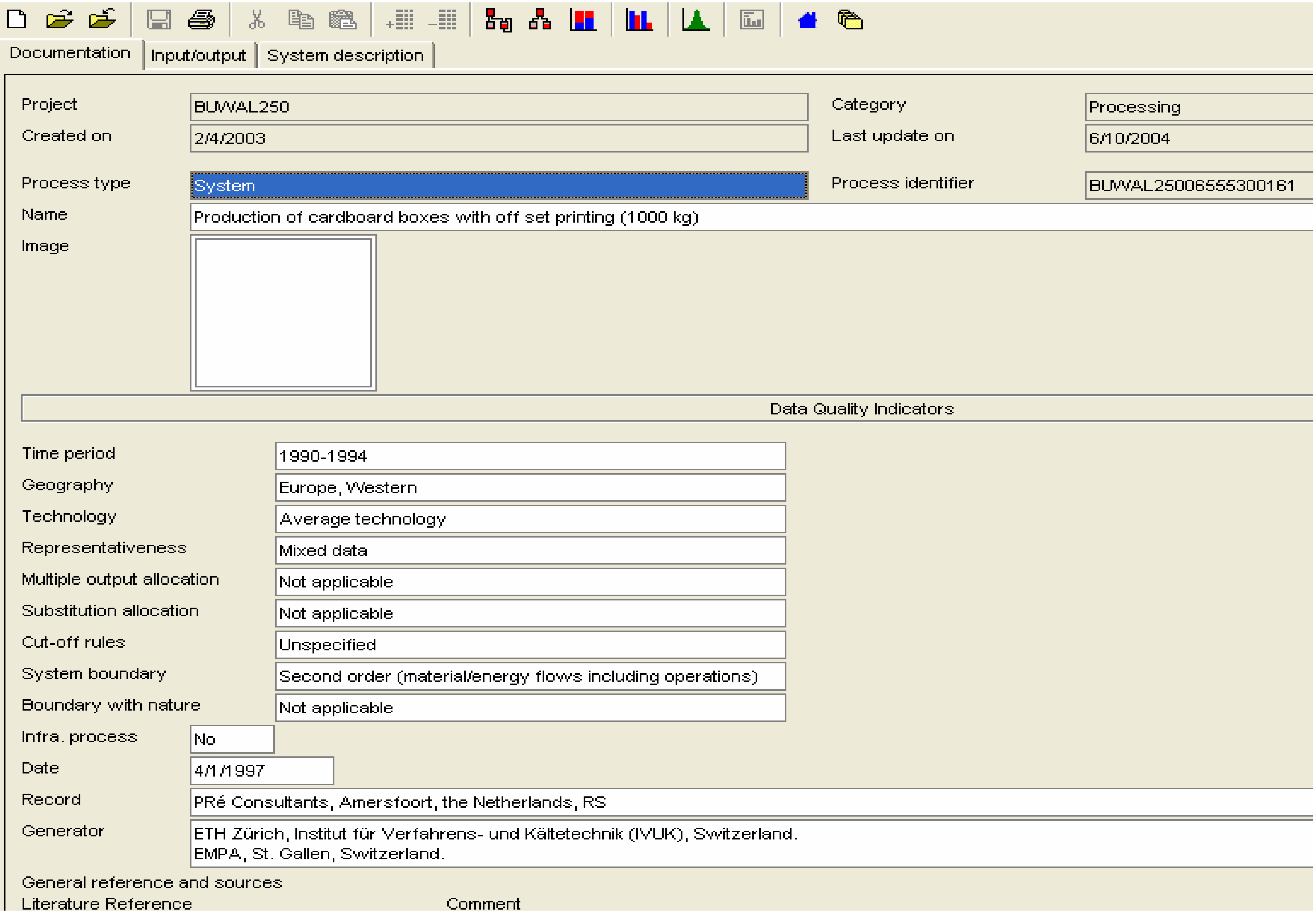
Known inputs from technosphere (materials/fuels)

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



Documentation | Input/output | System description

Project	BUWAL250	Category	Processing
Created on	2/4/2003	Last update on	6/10/2004
Process type	System	Process identifier	BUWAL25006555300161
Name	Production of cardboard boxes with off set printing (1000 kg)		
Image			

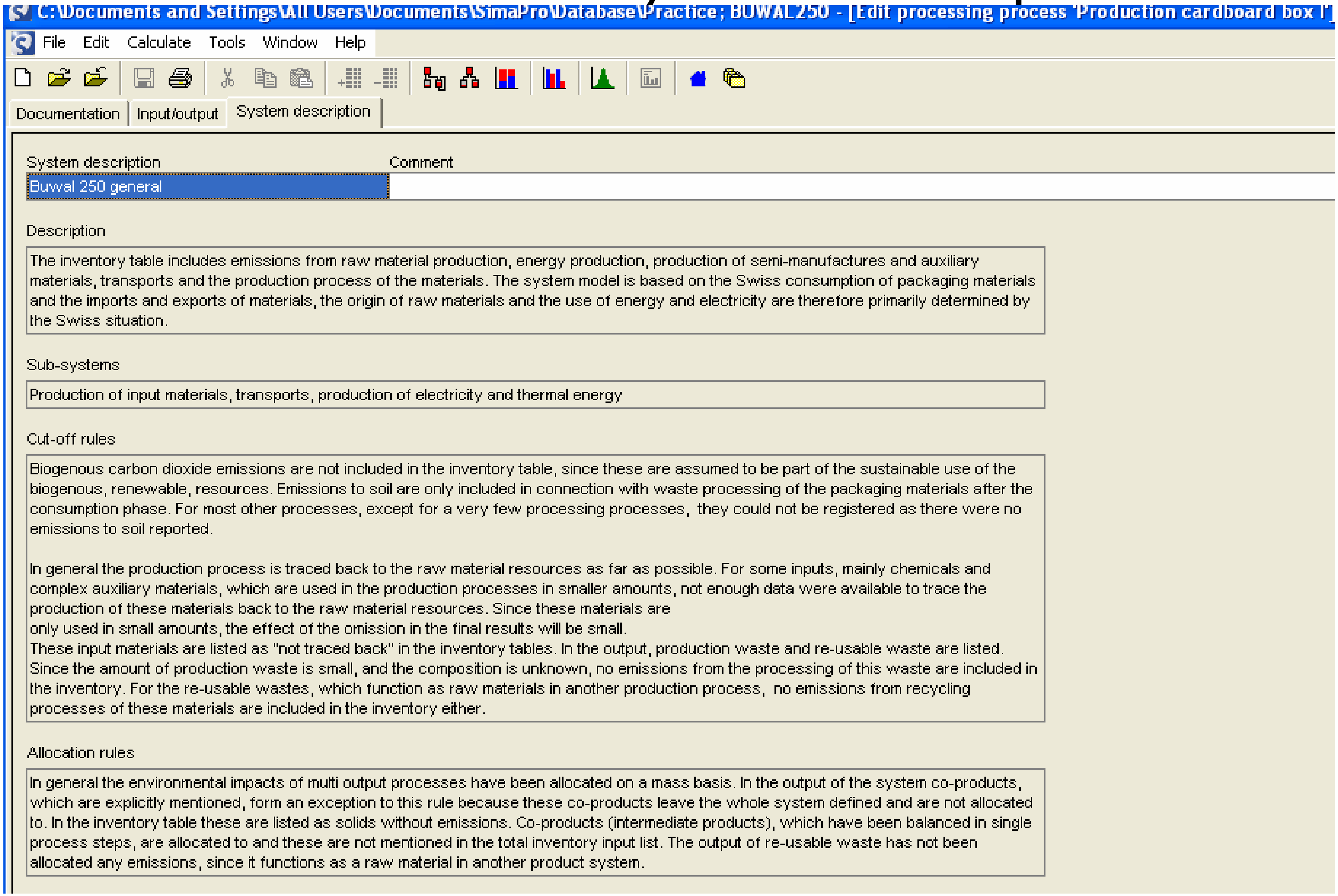
Data Quality Indicators

Time period	1990-1994
Geography	Europe, Western
Technology	Average technology
Representativeness	Mixed data
Multiple output allocation	Not applicable
Substitution allocation	Not applicable
Cut-off rules	Unspecified
System boundary	Second order (material/energy flows including operations)
Boundary with nature	Not applicable
Infra. process	No
Date	4/1/1997
Record	PRé Consultants, Amersfoort, the Netherlands, RS
Generator	ETH Zürich, Institut für Verfahrens- und Kältetechnik (IVUK), Switzerland. EMPA, St. Gallen, Switzerland.

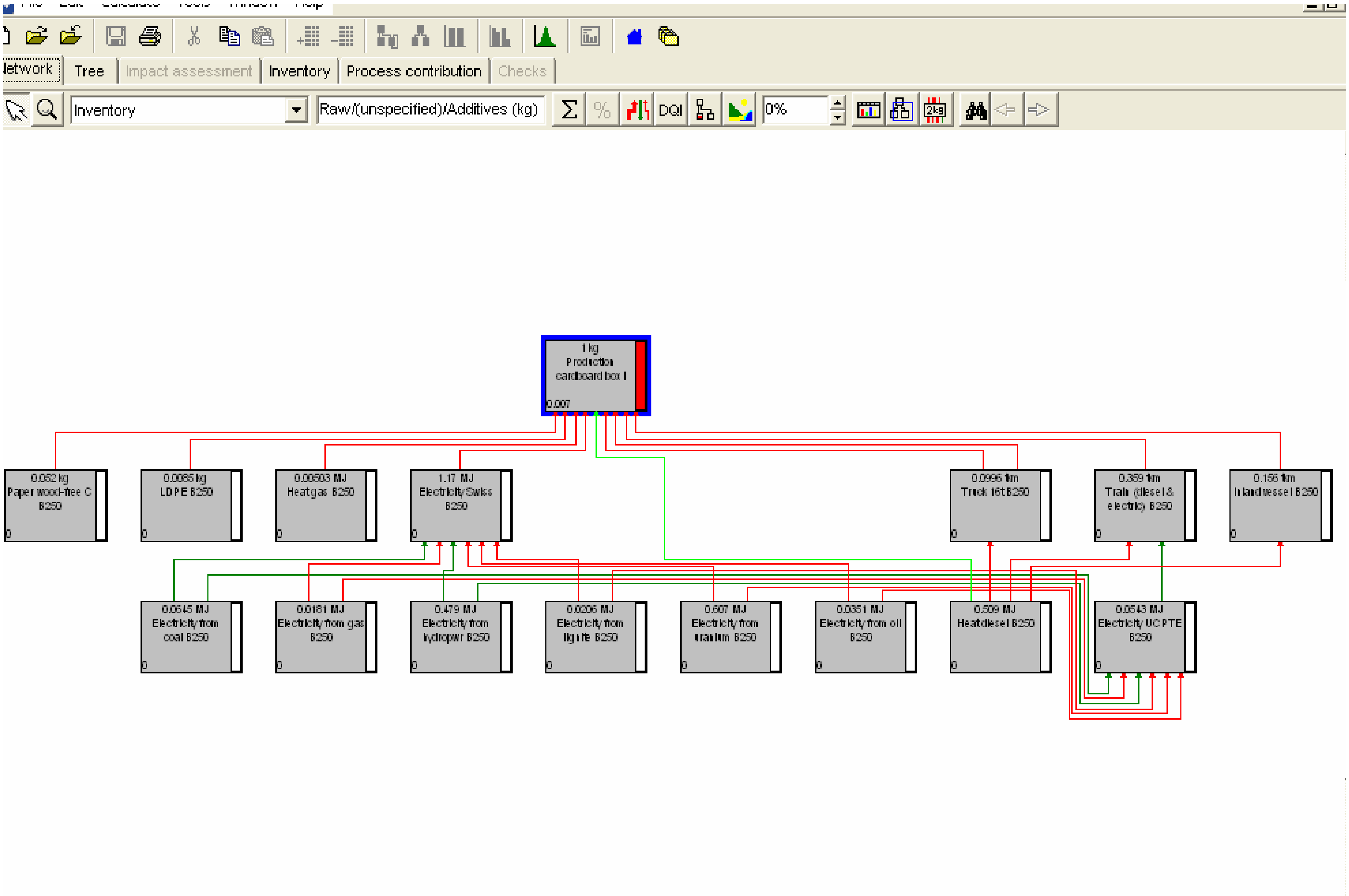
General reference and sources

Literature Reference | Comment

Data on the LCI – System Description Tab



LCI – Network Diagram



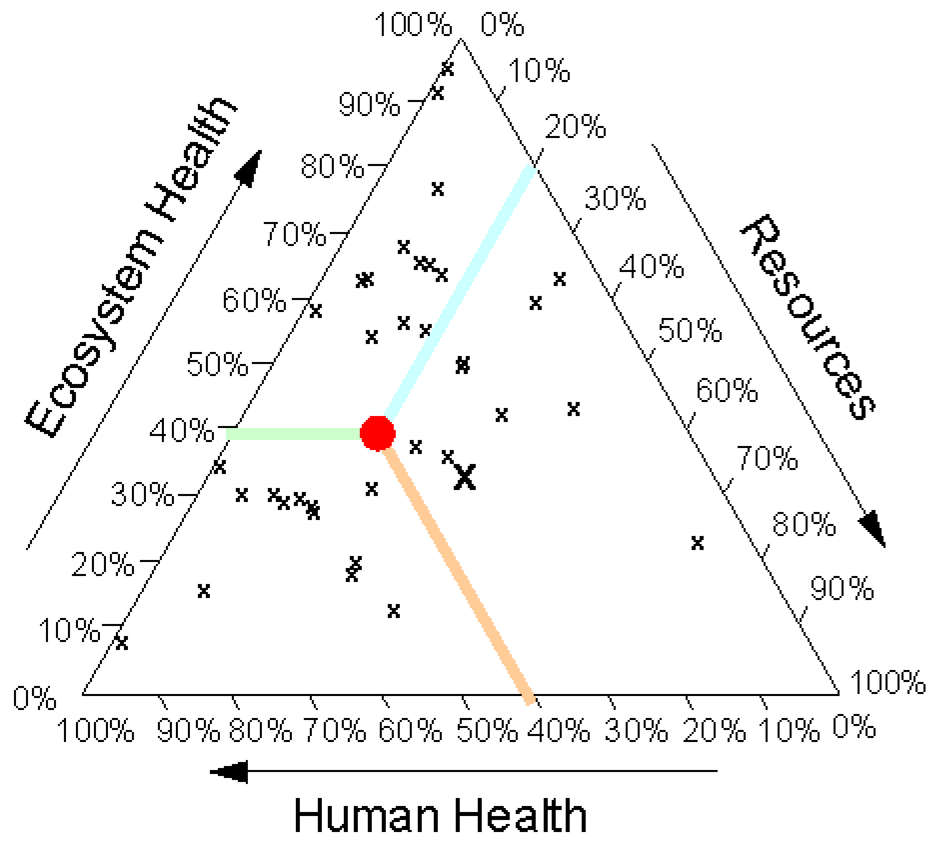
LCI - Inventory

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 gr	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 bar	Raw	MJ	0.688	x	0.0567
11	Gas, natural, 35 MJ per m3, in	Raw	m3	0.00247	x	x
12	Gas, natural, 36.6 MJ per m3,	Raw	m3	0.0154	x	0.0106
13	Gas, natural, feedstock, 35 MJ	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 g	Raw	kg	0.0202	x	0.00254
22	Oil, crude, feedstock, 41 MJ pe	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	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

Incorporating Values

- Self-interest
  - stakeholders
- Knowledge
  - mental models
- Power
  - if fish could vote….

Valuation: Eco-indicator 95



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

LCA applications and Limitations

- Improvements in products, OK
- Comparisons between products? dicey!
- Beware of “senseless substitutes”

Substitutes and Compliments

- Substitutes: replacement or elimination
- Compliments: stimulation or generation
- do emails substitute for letters (paper)?
- do telecommunications substitute for travel?
- What were the first words of Alexander Graham Bell over the telephone?
- “Mr Watson, come here; I want you”

ref Mokhtarian (2002) JIE, 6, 2, 43-57

Paper or Plastic?

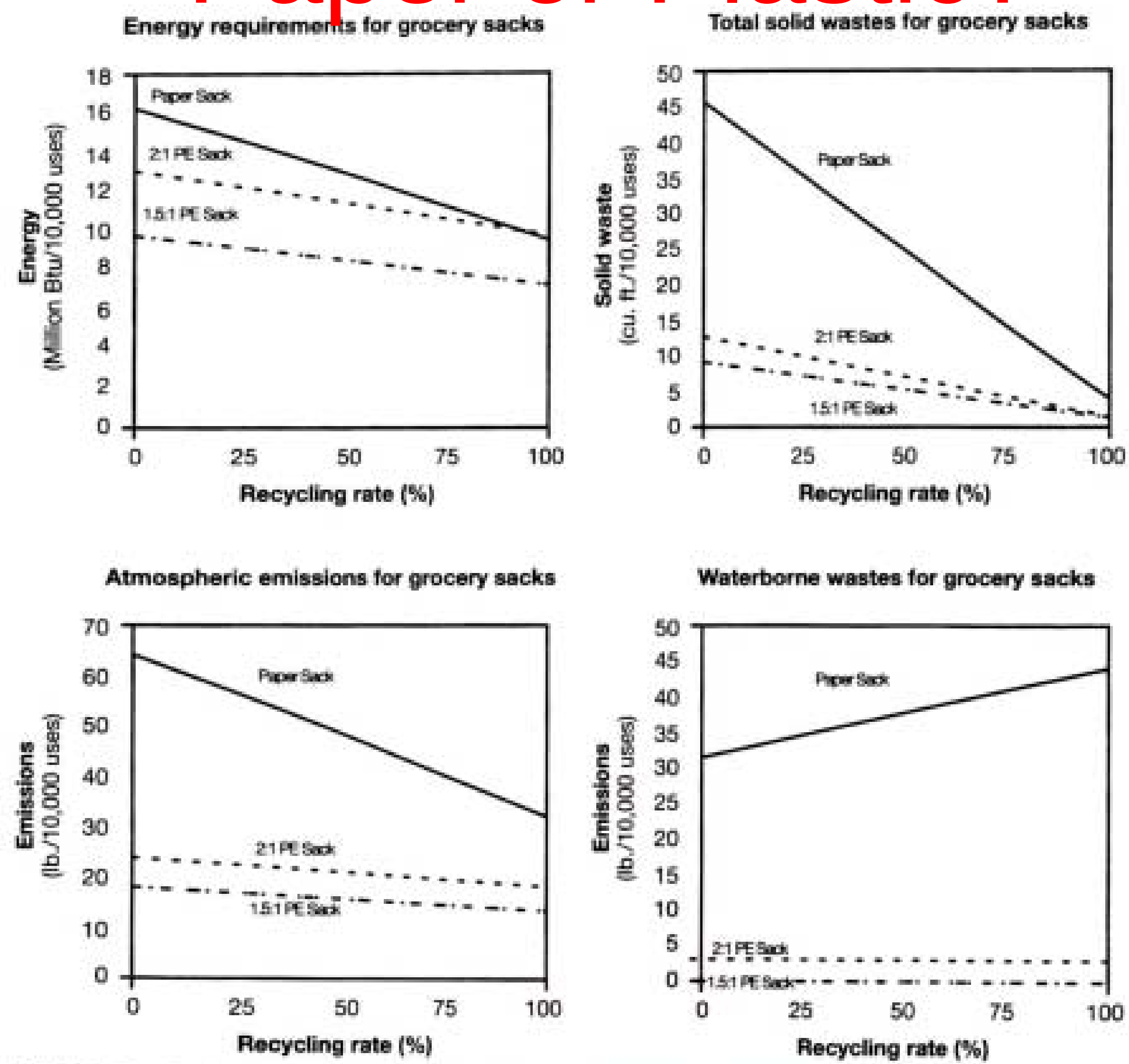


FIGURE 5.5 Environmental stresses attributable to polyethylene and paper grocery sacks. The units in each case are per 10,000 uses, and the analyses are performed for the cases in which 2.0 and 1.5 polyethylene sacks are used in place of each paper sack. (Adapted with permission from The Council for Solid Waste Solutions, Copyright 1993.)

Paper or Silicon?

Toffel, M.W., and A. Horvath. 2004. Environmental implications of wireless technologies: News delivery and business meetings. *Environmental Science & Technology* 38(June 1):2961-2970.

Reading the New York Times

- weighs about 236 kg/yr
- about 2.6 people read it
- paper production
- printing
- delivery
- half to land fill
- half to recycle
- PDA mfg?
- Uses Williams result 12MB/32MB
- energy usage
- telecommunications infrastructure

Newspaper Vs PDA

- New York Times
- 270 kg CO_2
- 8730 liters H_2O
- 0.9 kg NOx
- 1.4 kg SOx

- PDA
- 5 kg CO_2
- 232 liters H_2O
- 4 g NOx
- 4 g SOx

Travel Vs Cell phones

- Berkeley – Chicago
- auto, air, train
- average not marginal values
- lodging excluded
- mfg excluded

- mfg included I/O for $100 phone, 3 year life
- includes infrastructure
- 2 hour call

Travel Vs Cell phones

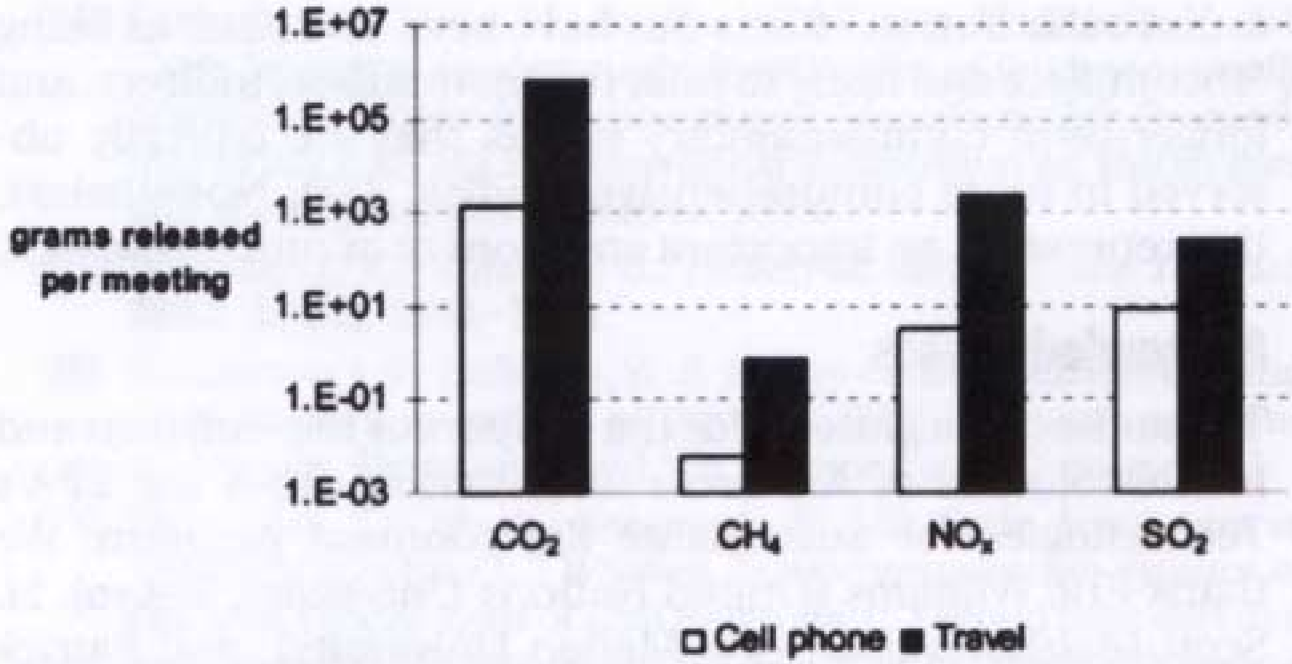
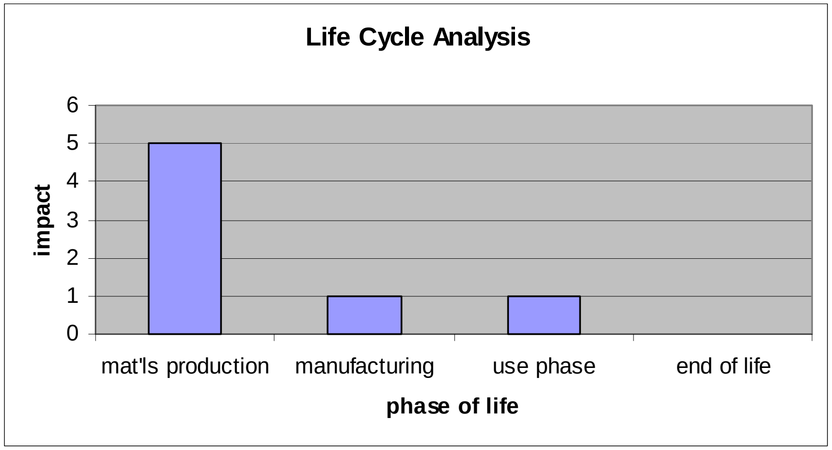
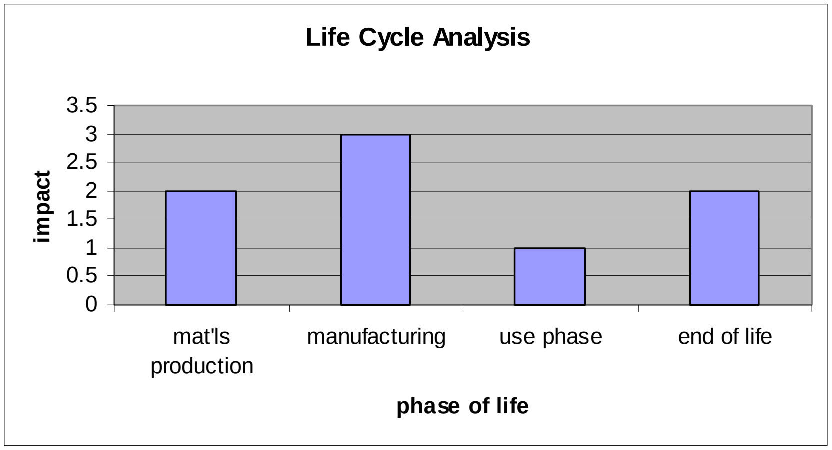
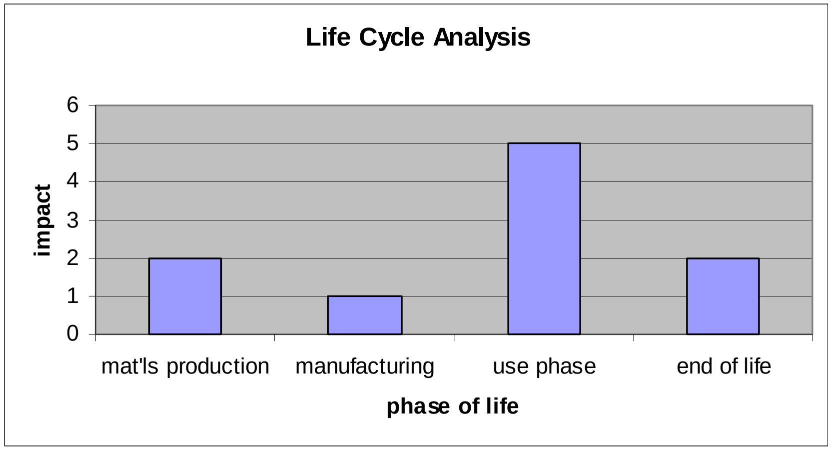


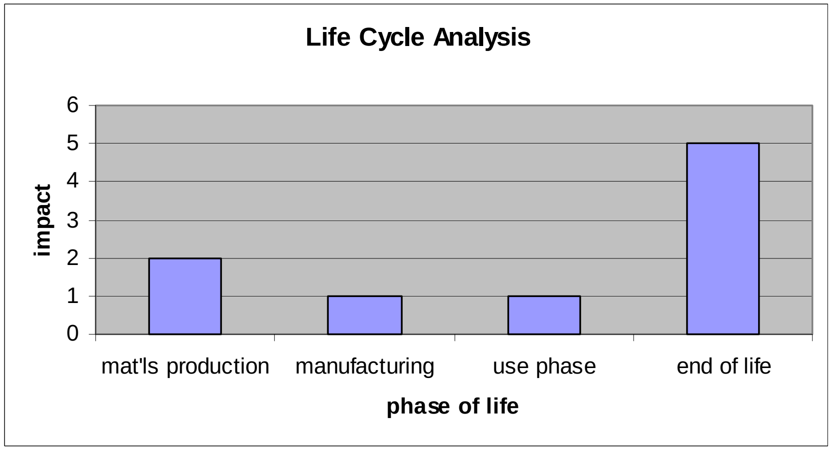
FIGURE 2. Environmental effects of travel versus wireless communication.

Where do major impacts occur?









LCI Summaries

Life Stage	Products with major impact in stage
Extraction and Refining	Paper Products: i.e. paper Vs plastics, paper Vs silicon…
Mfg	Microelectronics, Nano-technology
Use	Use fossil fuels, plug into grid
End of Life	Diapers, short life products

LCA/LCI critique

- Accuracy, looks like an engineering tool but it is not
- System boundaries may not be clear
- Inability to adequately address human behavior
- Gives a passing grade for business as usual
- BUT you have to start somewhere!