Introduction to Life Cycle Assessment (LCA)

T. G. Gutowski

Department of Mechanical Engineering

Massachusetts Institute of Technology

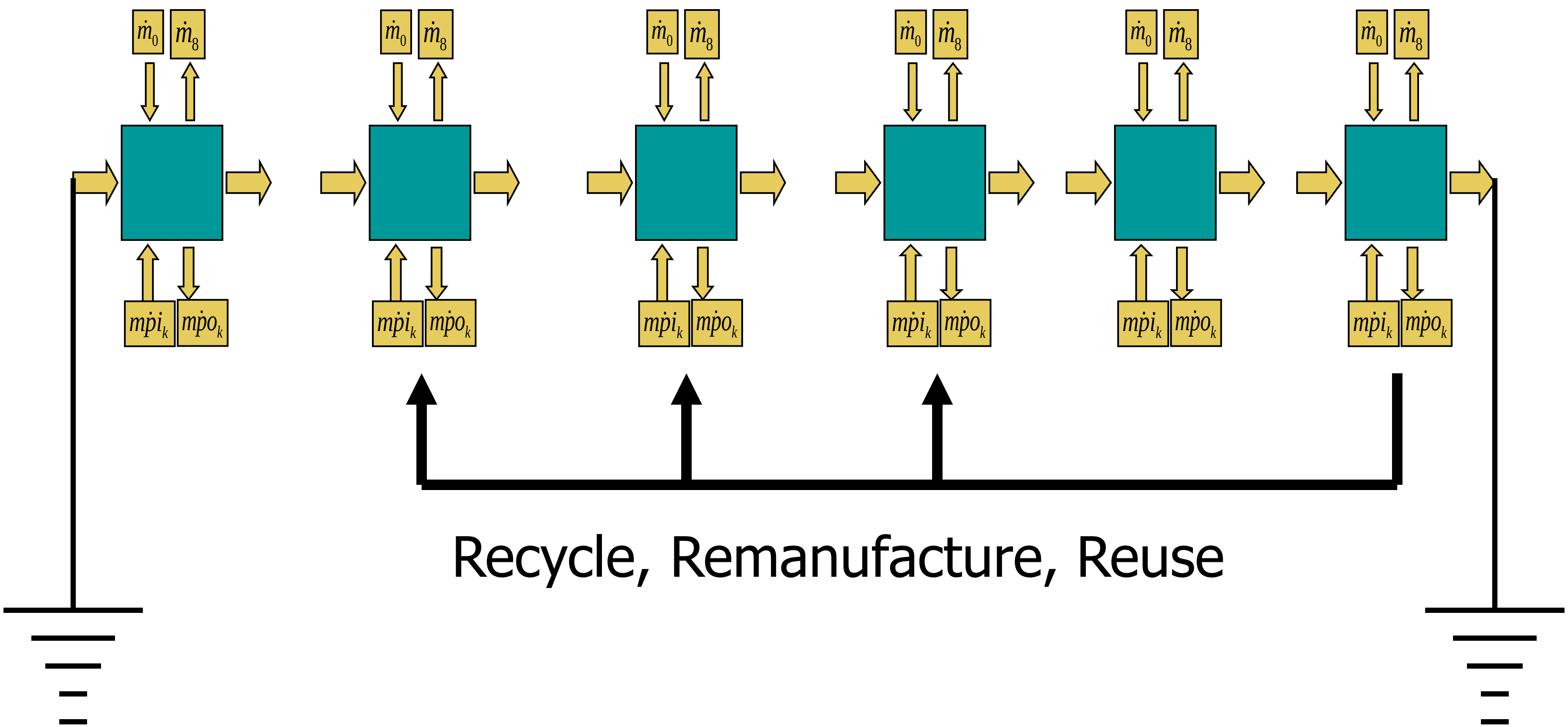
Outline

1. The general idea of LCA
2. Eco-Audit - quantitative method focused on energy and CO_2
3. Process model LCA - small boundaries
4. Input/output LCA -economy wide
5. Next Steps - regional & world

The General Idea…

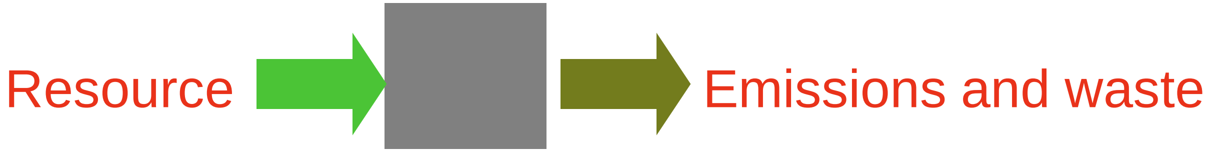
Life Cycle Stages (or Phases)

Mining Primary Mfg Distribution Use Disposition



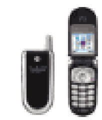
Two Steps

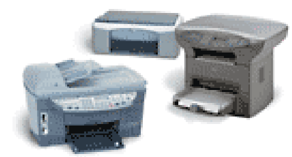
- Life Cycle Inventory (LCI)



- Assessment and Improvement + LCI = LCA
  - Pathways, exposure, sensitivity
  - Aggregation, weightings
  - Comparisons

Introduction to Product Analysis





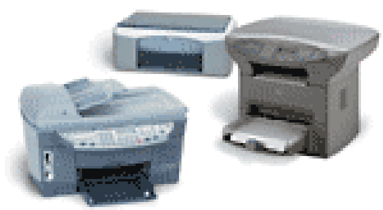
- What is the impact of a product?
  - What impact are we interested in?
  - What unit of service is provided?

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?

Functional Unit (service provided)

QuickTime™ and a decompressor are needed to see this picture.

QuickTime™ and a decompressor are needed to see this picture.



- e.g. vehicle-km or passenger-km, 100 pages of printed sheet paper, cubic meter of refrigerated space, 1 kg of aluminum, etc.

Not All Functional Units are Equal

"Eco-efficiency = service provided/impact"

Life Cycle Perspective

1. In theory boundaries start from earth as the source, and return to earth as the sink
2. Focus is on a product or service
3. Impact is evaluated at the receiver
4. Tracking is of materials
5. Time stands still
6. But this is hard to do, so…

Life Cycle Perspective

1. Boundaries start from earth as the source, and stop at emissions
2. Focus is on a product or service
3. Impact potentials are aggregated (e.g.CO_2e)
4. Tracking is of materials
5. Time stands still
6. We call this Life Cycle Inventory or LCI

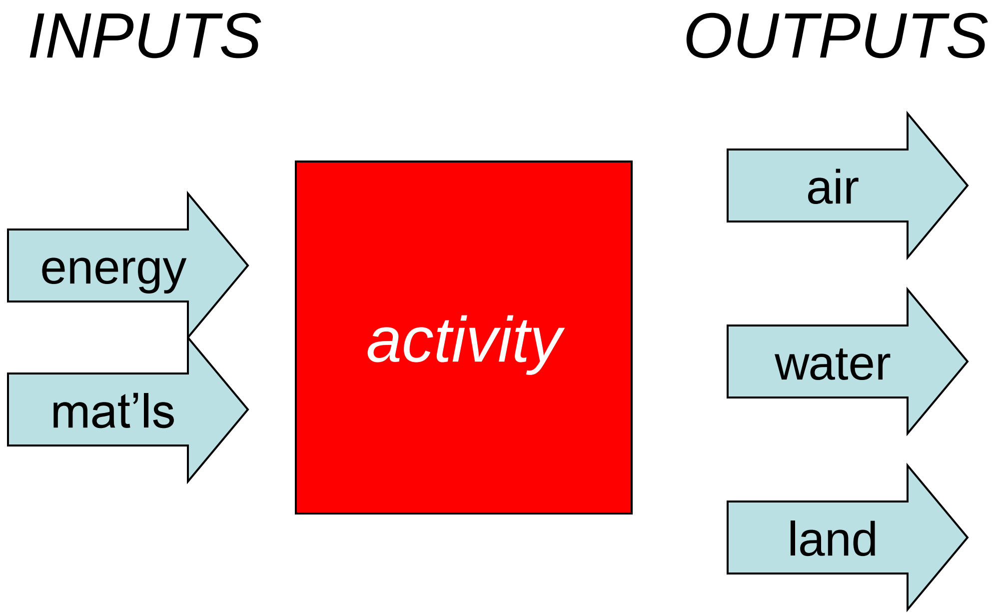
Life Cycle Perspective

1. This can be followed by an evaluation of the product and/or service and a redesign for improvement
2. Typically we evaluate alternatives for comparison
3. Some of the most challenging parts include
   - Identifying boundaries (what is included)
   - Functional unit to represent product or service
   - Allocation of impacts…who is responsible?

LCA Methods

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

Streamlined LCA



Ref: Thomas Graedel, Streamlined LCA

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

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

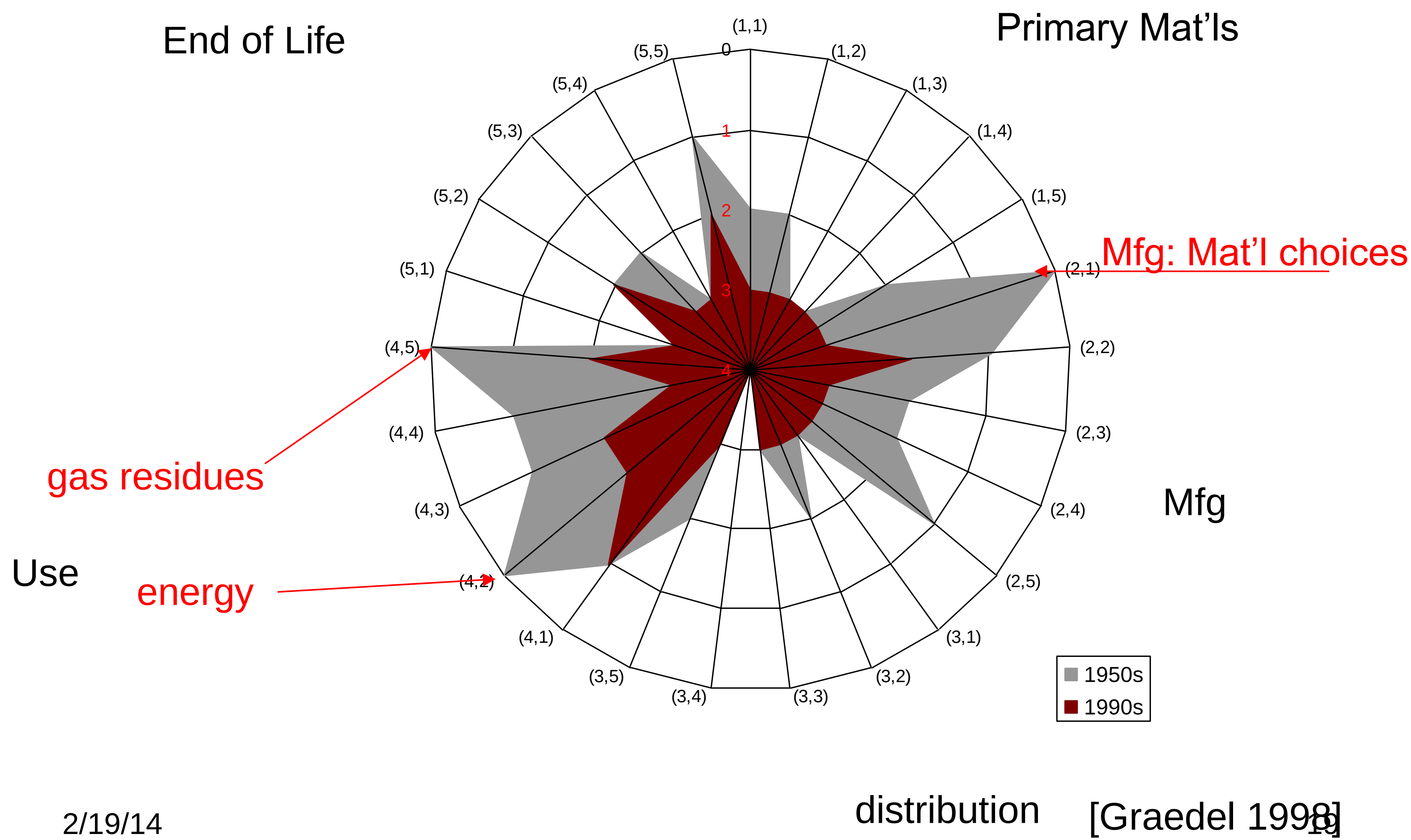
Product Assessment Matrix for the Generic 1950s Automobile [Graedel 1998]

	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]

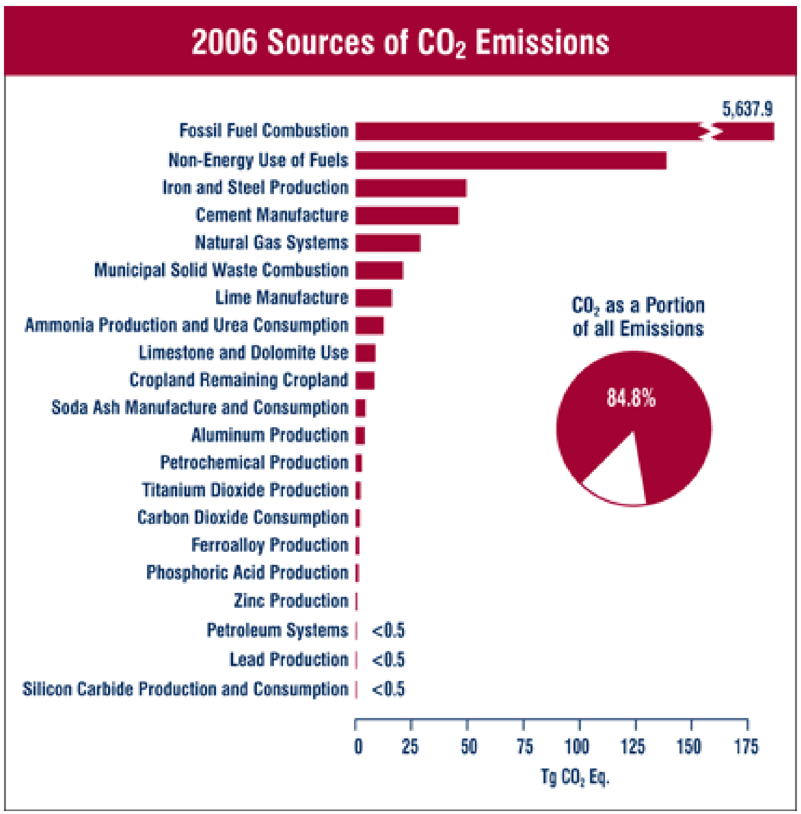
How to deal with the complexity-

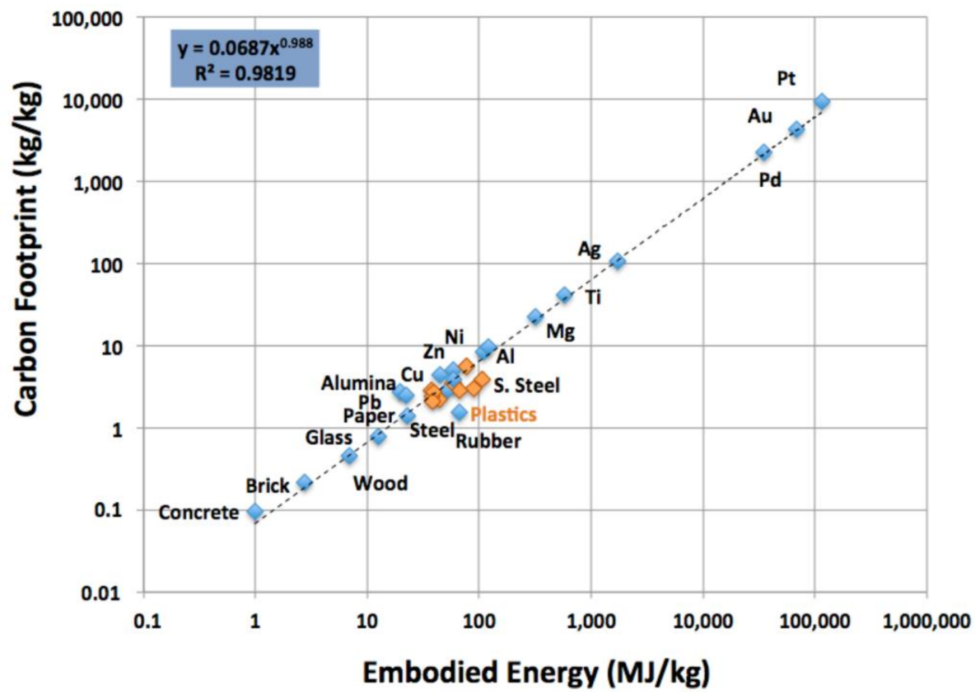
- LCA software and data bases
  - Hundreds of inputs and outputs
  - Uniformity
  - Can be non-transparent and dated
- Simplifications
  - Streamlined LCA
  - Fossil fuel energy and carbon

Impacts from fossil fuels

- GWP - CO_2, CH_4
- PM - especially from coal
- NO_x - nitrogen cycle, acid rain, ground level ozone
- SO_2 - acid rain
- Hazardous chemicals- CO, VOCs, Hg, and heavy metals

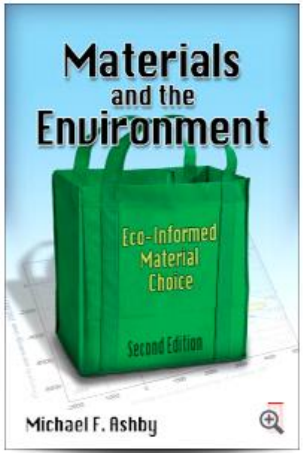
CO2 and Energy





Example: Eco-Audit for Energy

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



Ashby p 176
1 liter water
40g PET
1g PP
550km

Materials

QuickTime™ and a
decompressor
are needed to see this picture.

Ashby 2009

Manufacturing

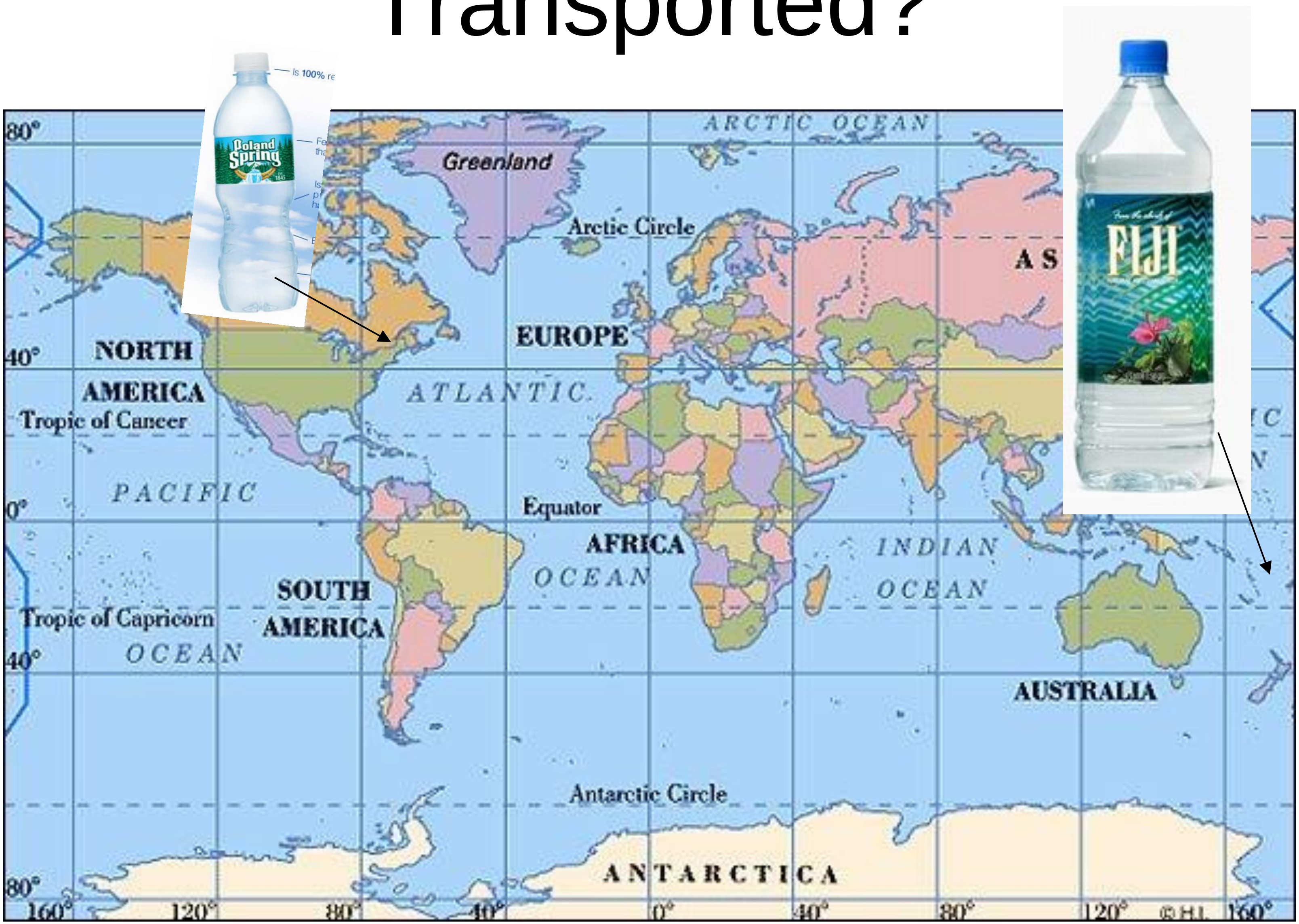
Gutowski
“Ch 6” TDR

Injection molding:
3MJ/kg x 2 x 3 =
~ 18 to 20 MJ/kg
Includes
- Extrusion
- Grid Losses
- Runners and startup losses

QuickTime™ and a
decompressor
are needed to see this picture.

or Ashby
p 133-135, 154

Transported?



Transportation

Table 6.9 The approximate energy and carbon footprint of transportation*

Transportation type and fuel	Energy (MJ/metric ton · km⁺)	Carbon footprint (kg CO_2/metric ton · km⁺)
Ocean shipping—Diesel	0.16	0.015
Coastal shipping—Diesel	0.27	0.019
Barge—Diesel	0.36	0.028
Rail—Diesel	0.25	0.019
Articulated HGV (up to 55 metric tons)—Diesel	0.71	0.05
40 metric ton truck—Diesel	0.82	0.06
32 metric ton truck—Diesel	0.94	0.067
14 metric ton truck—Diesel	1.5	0.11
Light goods vehicle—Diesel	2.5	0.18
Family car—Diesel	1.4–2.0	0.1–0.14
Family car—Gasoline	2.2–3.0	0.14–0.19
Family car—LPG	3.9	0.18
Family car—Hybrid gasoline-electric	1.55	0.10
Super sports car and SUV—Gasoline	4.8	0.31
Long haul aircraft—Kerosene	6.5	0.45
Short haul aircraft—Kerosene	11–15	0.76
Helicopter (Eurocopter AS 350)—Kerosene	55	3.30

*Data sources are listed under Further reading.

⁺1 ton · mile = 1.46 metric ton · km

Ashby 2013 p142

Use Phase

Estimated energy
for cooling:

A-Rated Appliances-

0.12 kW/m3 (at 4ºC)

and

0.15 kW/m3 (at -5° C)

Ashby p 180

End of Life (EOL)

- Recycle
- Remanufacture
- Reuse
- Landfill
- Incinerate

Recycling rates as fraction of supply

QuickTime™ and a
decompressor
are needed to see this picture.

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.*

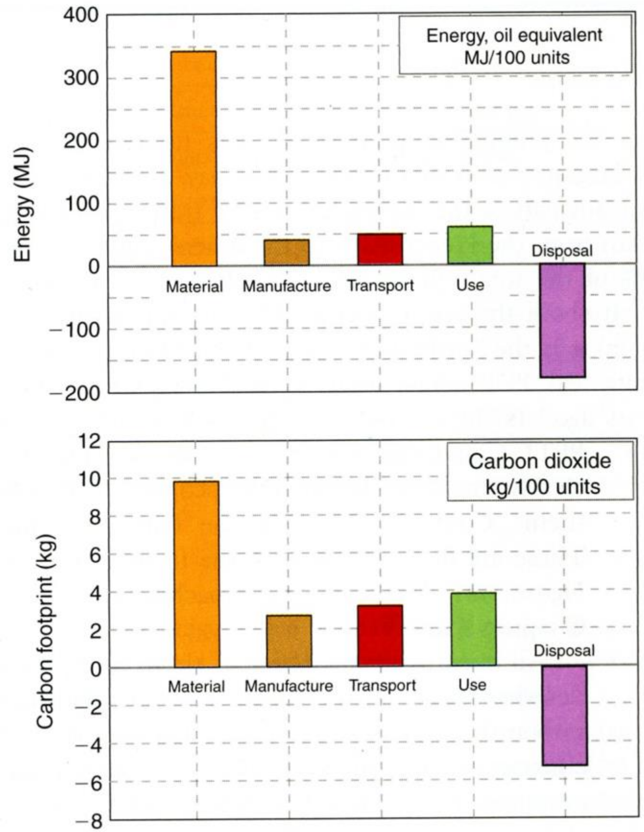


FIGURE 7.3 *The energy and the carbon footprint bar charts for bottled water per 100 units.*

Eco-Audit Result per 100 bottles: Materials dominate potential for recycle Credit, Ashby 1st ed

Ashby 2009

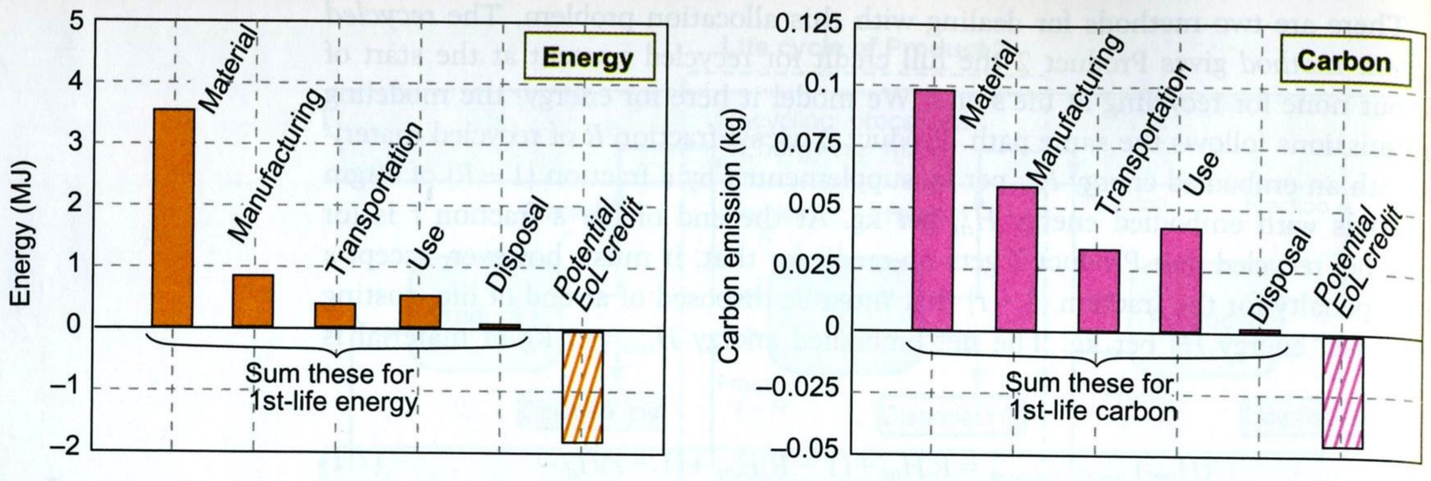
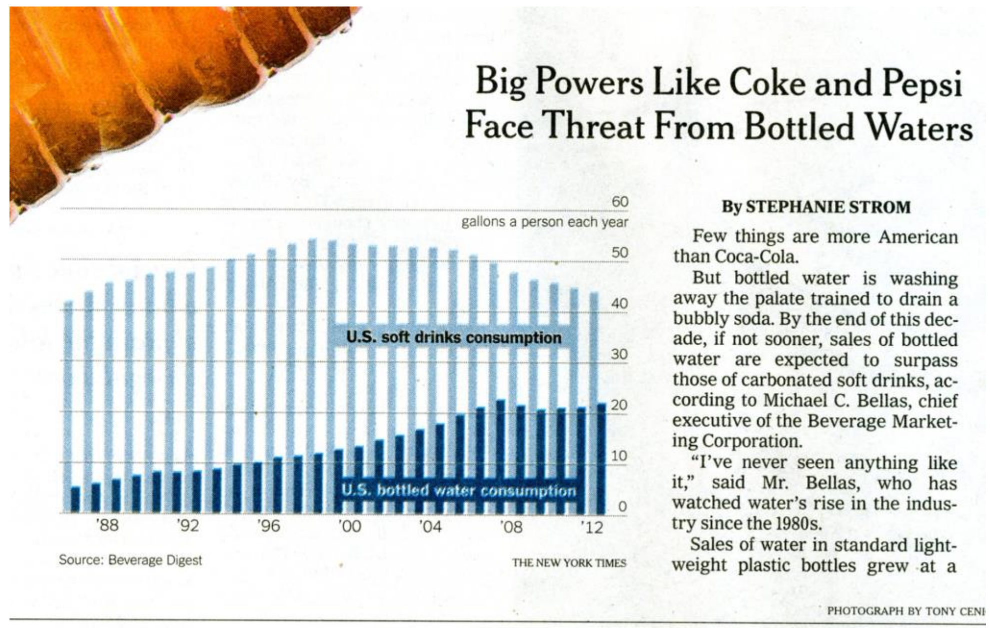


FIGURE 7.4 *The way of displaying end-of-life (EoL) data for energy and carbon for the PET bottle based on the "recycle fraction" method*

Ashby 2nd ed. (Here for only one botttle)
Shows disposal and potential EOL credit
based on reusing the material. If the product is burned for energy the energy credit would still accrue, but not the CO2 credit. And this accounting would not indicate other potential emissions.

Is bottled water good for the planet?

- Plastic waste
- Transportation waste
- Ground water depletion….



Big Powers Like Coke and Pepsi Face Threat From Bottled Waters

By STEPHANIE STROM

Few things are more American than Coca-Cola.

But bottled water is washing away the palate trained to drain a bubbly soda. By the end of this decade, if not sooner, sales of bottled water are expected to surpass those of carbonated soft drinks, according to Michael C. Bellas, chief executive of the Beverage Marketing Corporation.

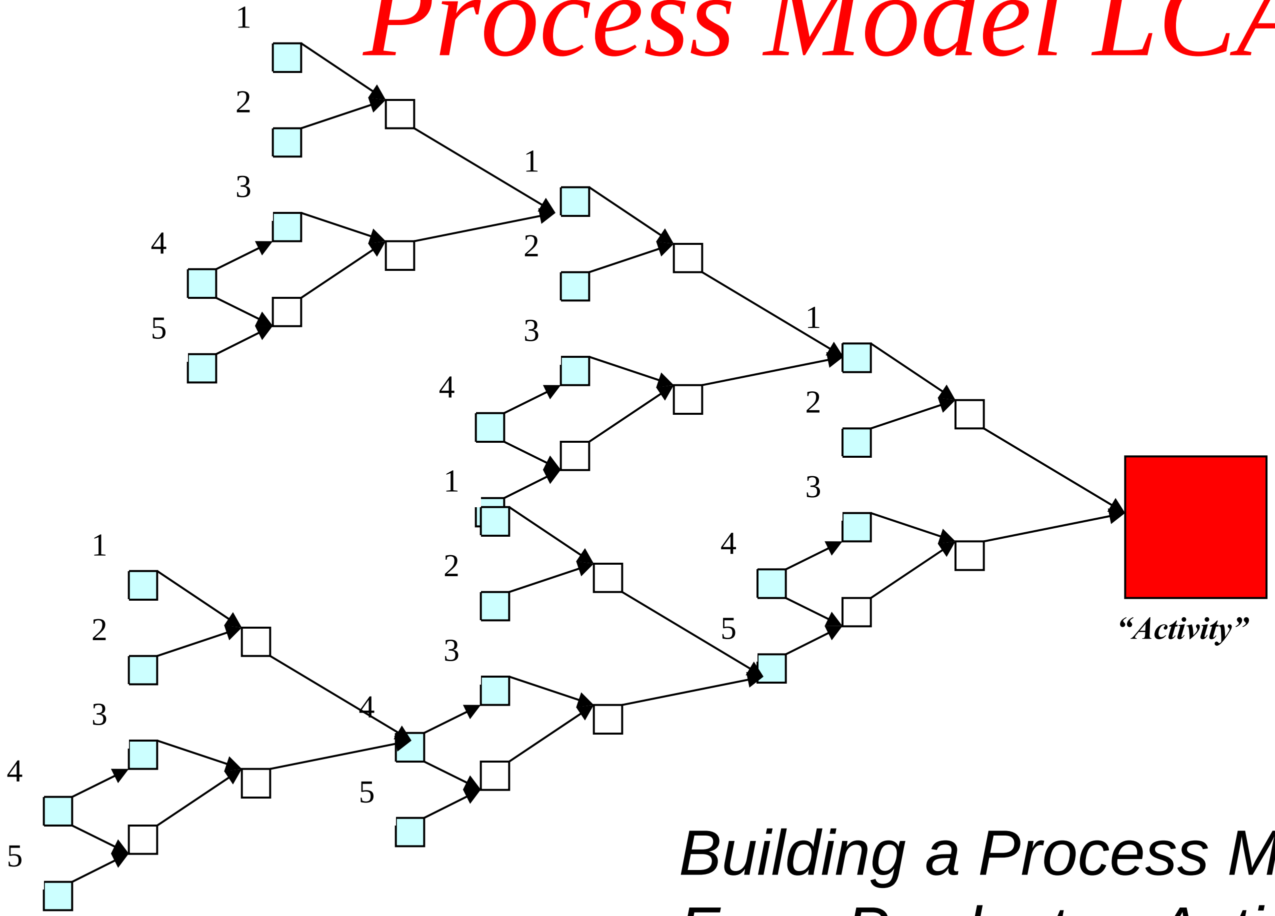
"I've never seen anything like it," said Mr. Bellas, who has watched water's rise in the industry since the 1980s.

Sales of water in standard lightweight plastic bottles grew at a

On the other hand…

NY Times, Nov 2013

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

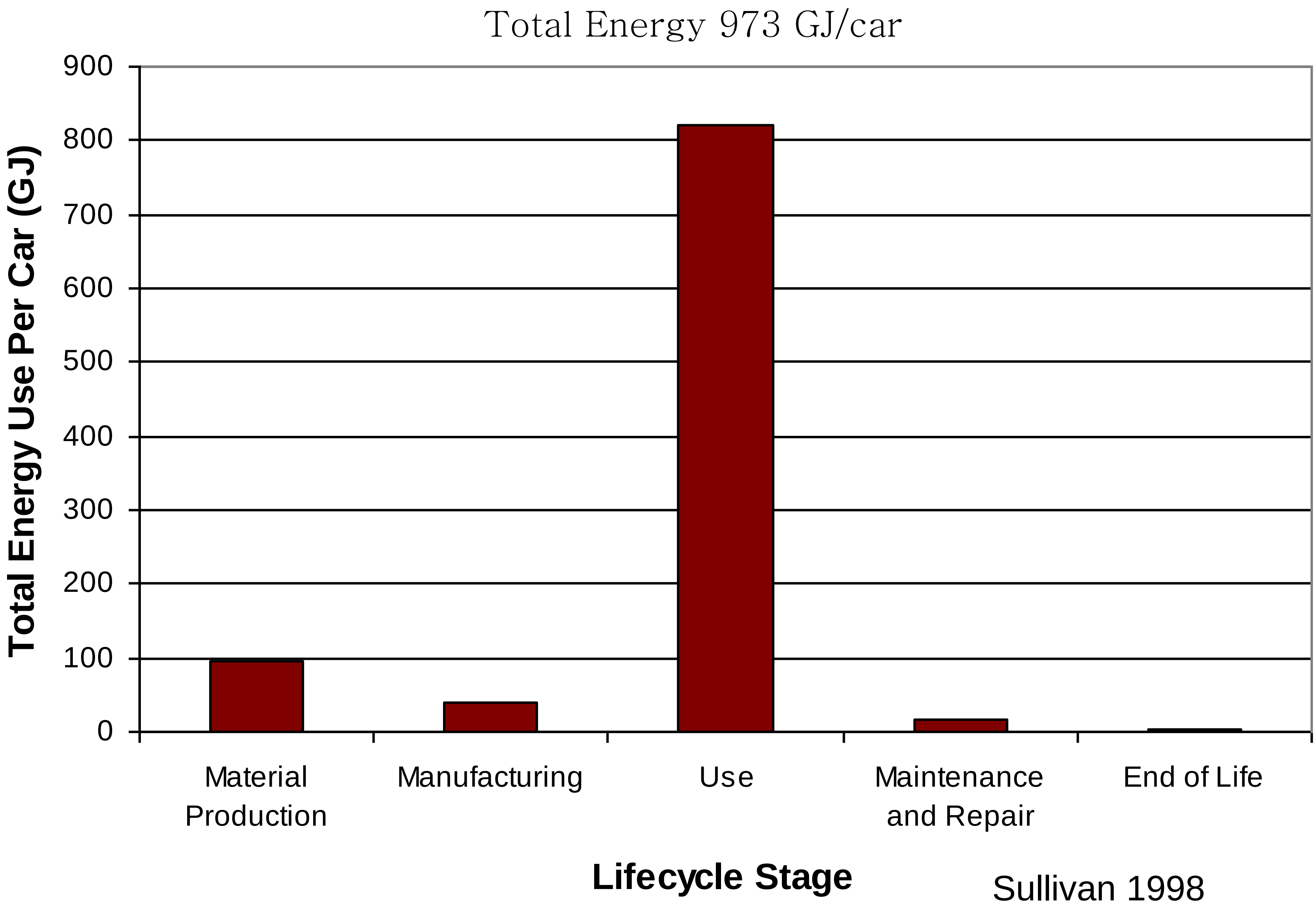
[a] From electricity production

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



Compare eco-audit and Sullivan

Table 1
Eco-Audit for SullivanÕs Automobile (Primarily using energy values from Smil)

Bill of Materials (BOM)	Mass (kg)	MJ/kg	Energy (MJ)
Plastics (PUR, PVC, Nylon, ABSÉ)	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, CrÉ)	5.5	30	165
Iron	156.5 kg	25	3,913
Steel	828.5 kg	50	41,425
Fluids (gasoline, oil,É .)	74	10	740
Rubber (not tire)	60	100	6,000
Glass	42	20	820
Tires	45	100	4,500
Other (textiles, carpetÉ)	45	20	900
TOTAL			**94,578**

Sullivan result: 94,460!

LCA software

- 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 - (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 - KCL LCA software
- LCAiT - CIT EkoLogik (Chalmers Industriteknik)
- SimaPro - PRé Consultants
- TEAM(TM) (Tools for Environmental Analysis and Management) - Ecobalance, Inc.
- Umberto - An advanced software tool for Life Cycle Assessment - Institut für Umweltinformatik

LCA software

- Input structuring and management
- Data bases
  - EcoInvent with SimaPro
  - GaBi data bases
- Data analysis and structuring

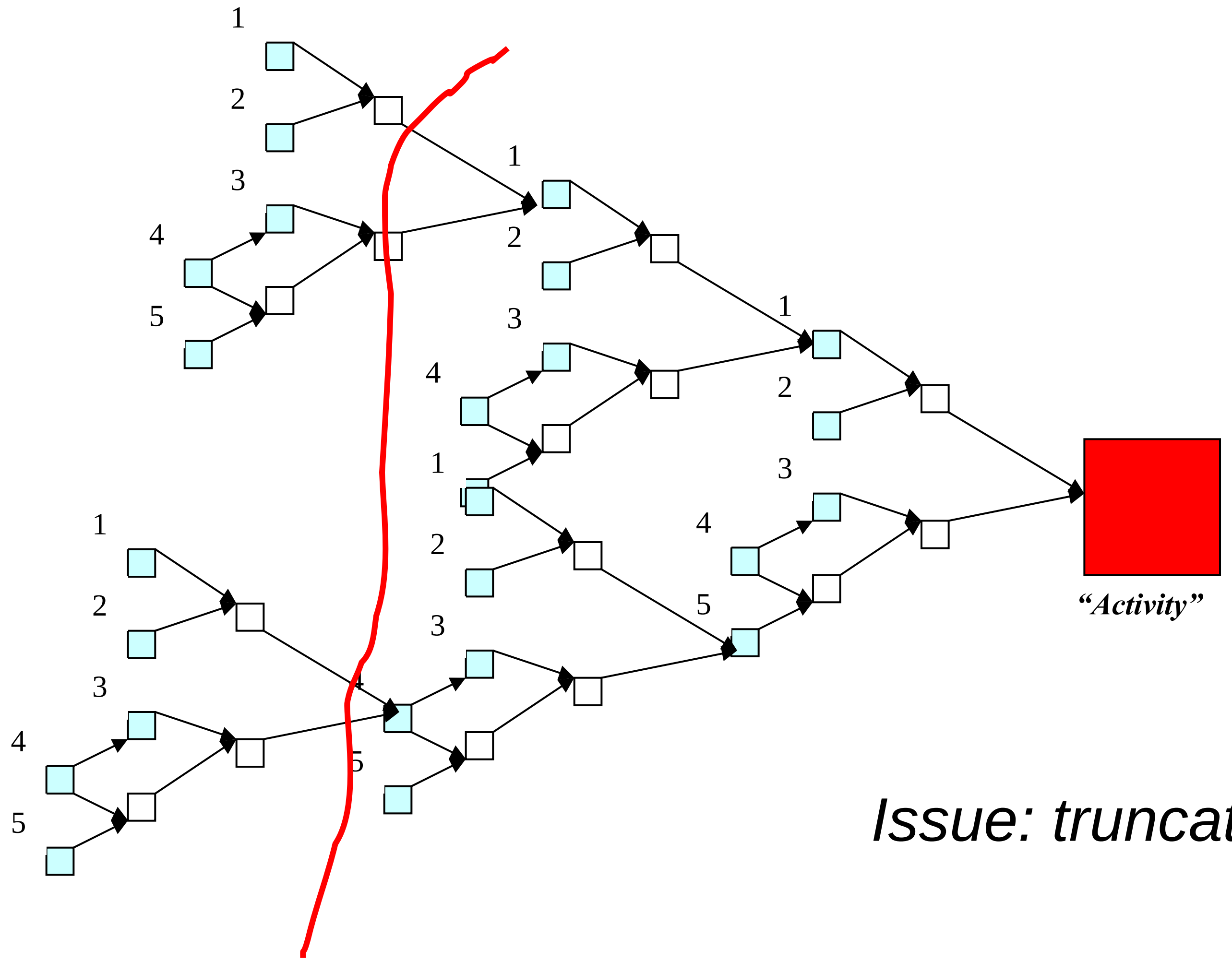
LCI - Inventory 1 kg of Cardboard Box

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 grou	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 barra	Raw	MJ	0.688	x	0.0567
11	Gas, natural, 35 MJ per m3, in g	Raw	m3	0.00247	x	x
12	Gas, natural, 36.6 MJ per m3, in	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 gro	Raw	kg	0.0202	x	0.00254
22	Oil, crude, feedstock, 41 MJ per	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 g	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

Pros and Cons of Methods

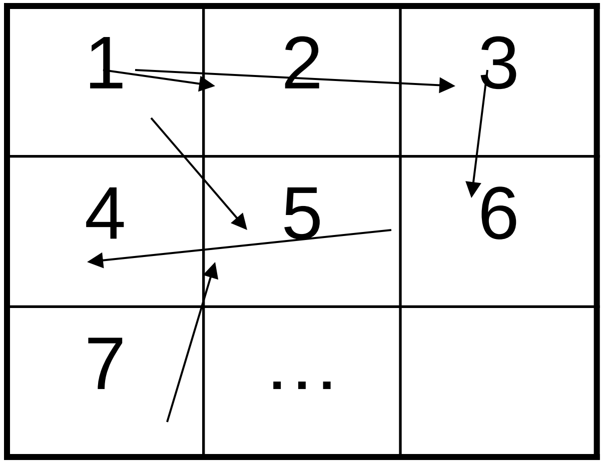
- Streamlined- there is a need for an early design evaluation tool - but this one maybe too subjective
- Eco-Audit - very hands on, often good enough, but limited in the number of impacts
- Software - does the heavy lifting, can be referenced, but depends on the data base

Limits to Process Model



Issue: truncation error

Input/Output Analysis



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

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

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

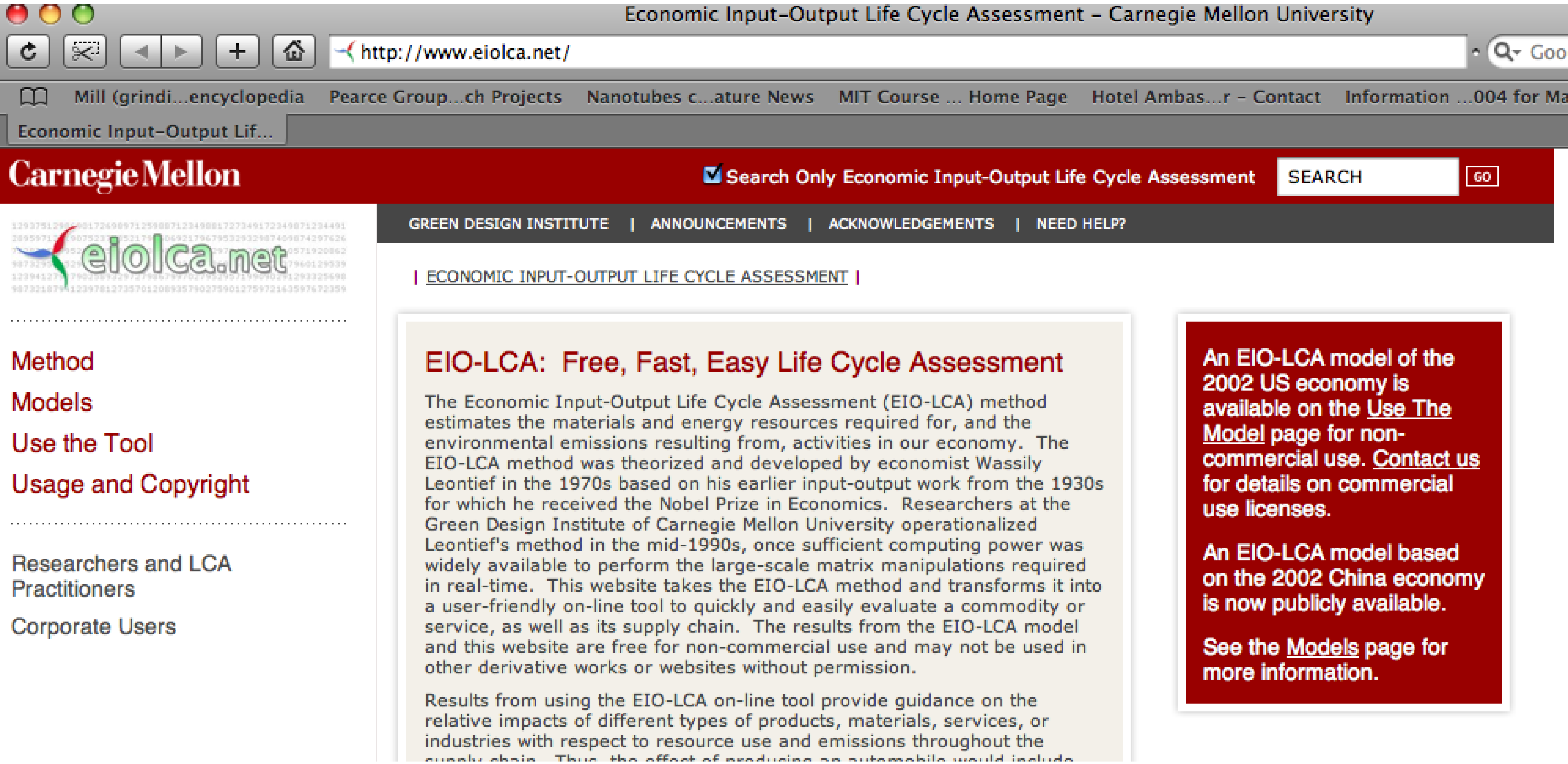
$$\{e\} = [R]\{x\}$$

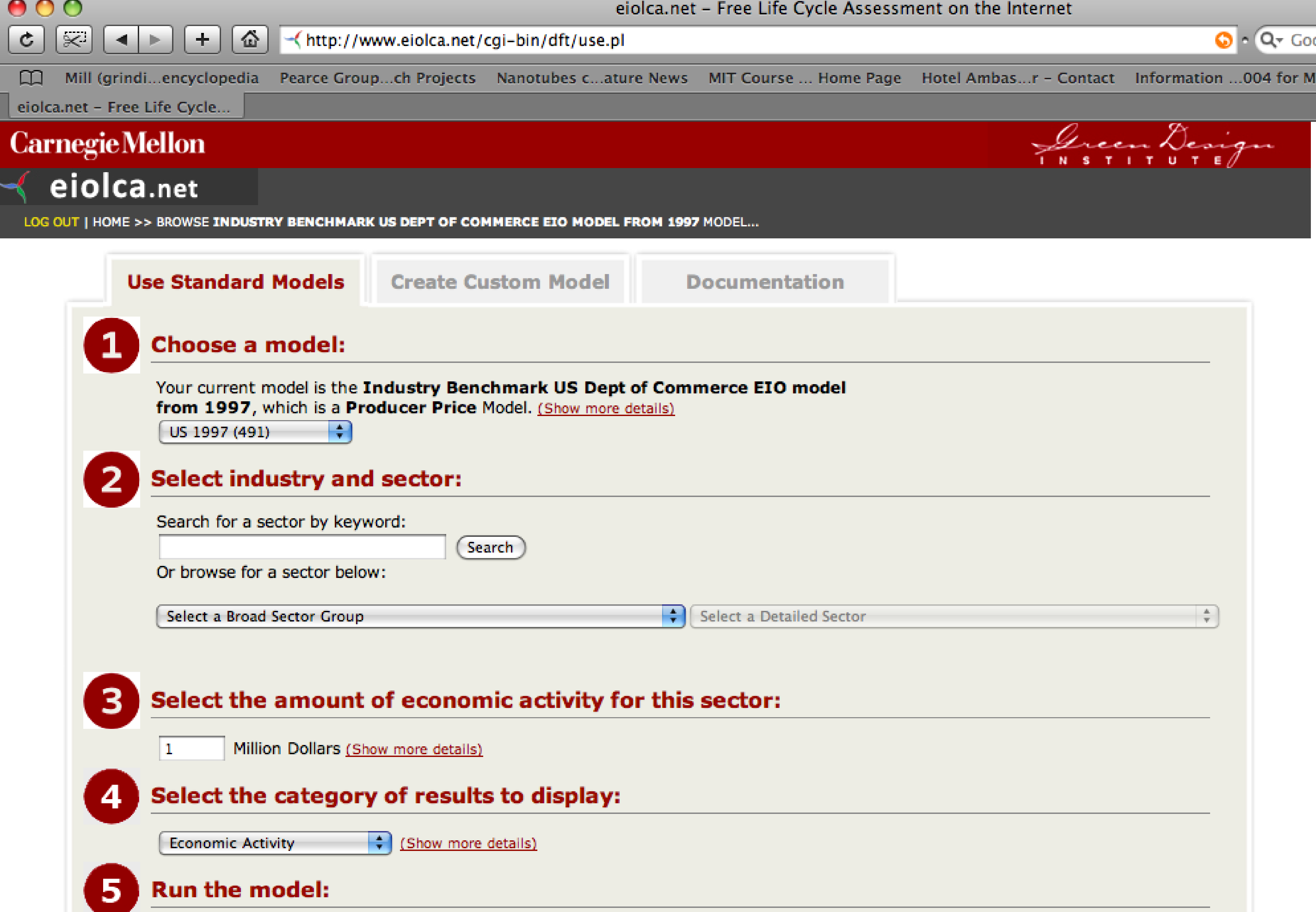
$$\{e\} = [R][I-a]^{-1}\{f\}$$

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

CMU website

http://www.eiolca.net/

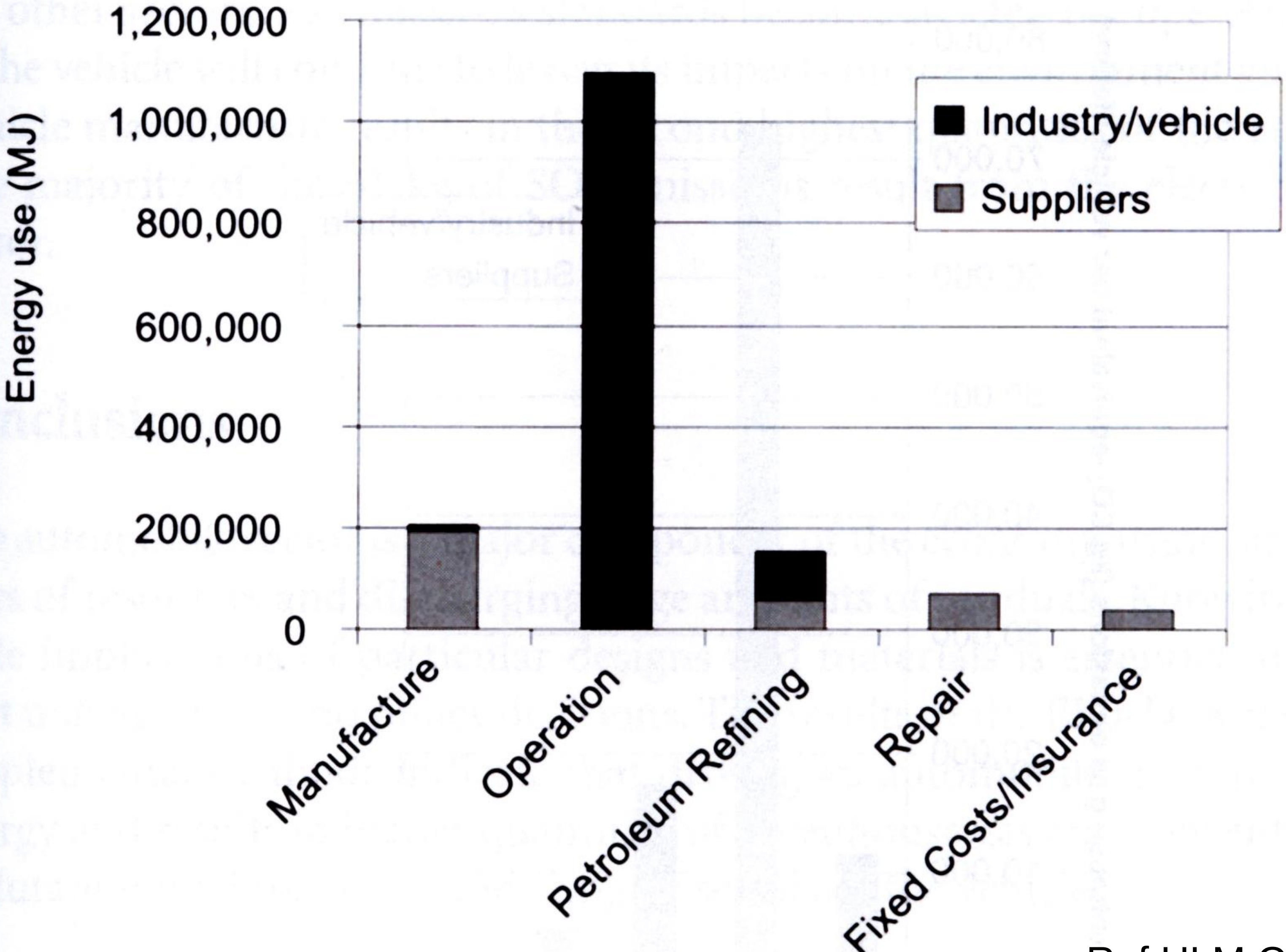



eiolca.net – Free Life Cycle Assessment on the Internet
http://www.eiolca.net/cgi-bin/dft/use.pl
Mill (grindi...encyclopedia
Pearce Group...ch Projects
Nanotubes c...ature News
MIT Course ... Home Page
Hotel Ambas...r – Contact
Information ...004 for M
eiolca.net – Free Life Cycle...
Carnegie Mellon
Green Design Institute
eiolca.net
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

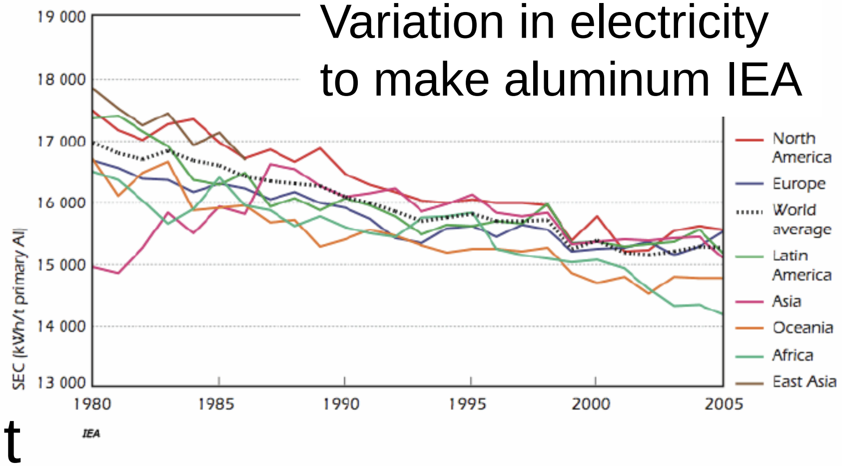
Late 1990Õs Ğearly 2000Õs family auto (~1500 kg)

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 ĞHLM deflator, producer price)			121
EIOLCA 1997 ($15,276 Ğcpi 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%)***

Issues with EIOLCA

- Builds on economic data
- Economy wide effects
- Highly aggregated
- Time delay
- Normalized by economic activity (e.g. MJ/$)
- Trouble with foreign trade
- Very powerful ("requires professional supervision")

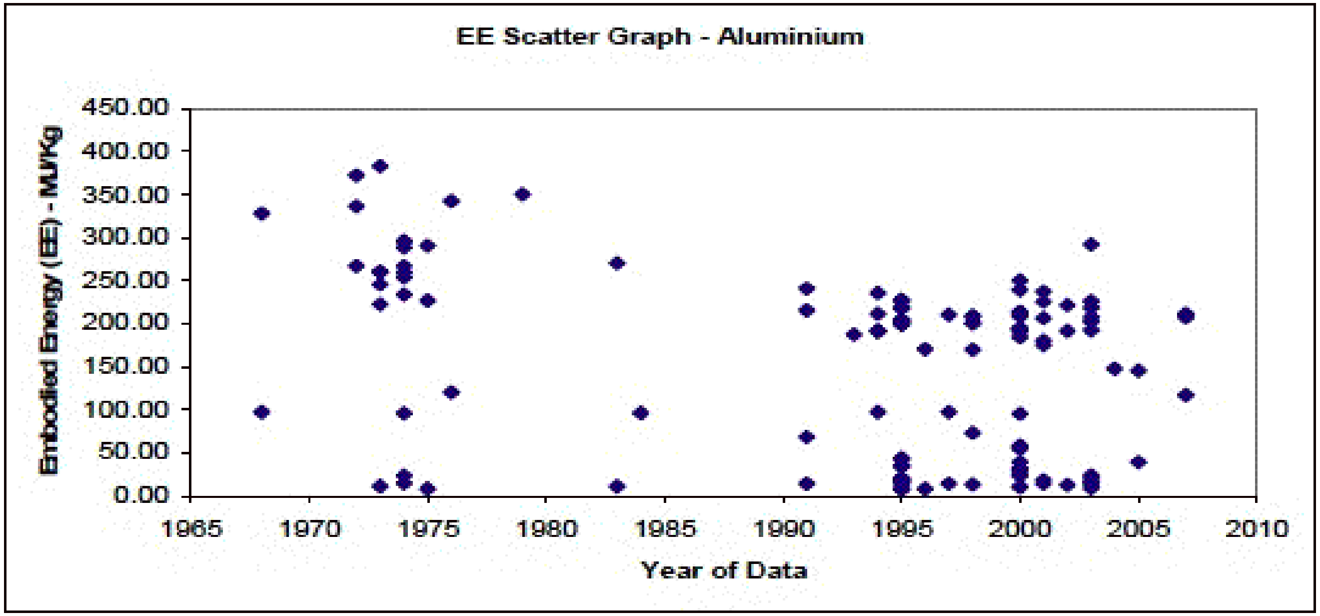
Issues with LCI



Variation in electricity to make aluminum IEA

- Accuracy
  - Time and location dependent
  - Possible variation not usually addressed
  - Monte Carlo simulations
  - Product competitions and claims
- Dynamic
  - “attributional” and,
  - “consequential” - how things might change

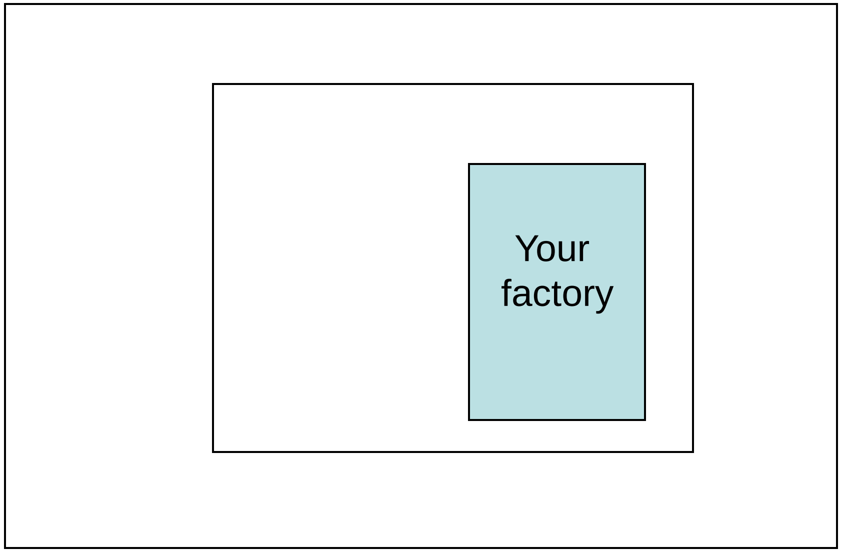
Accuracy:e.g. Aluminum



University of Bath, 2008

- Sources of errors: Boundaries;time, space, truncation, aggregation, unavailable data

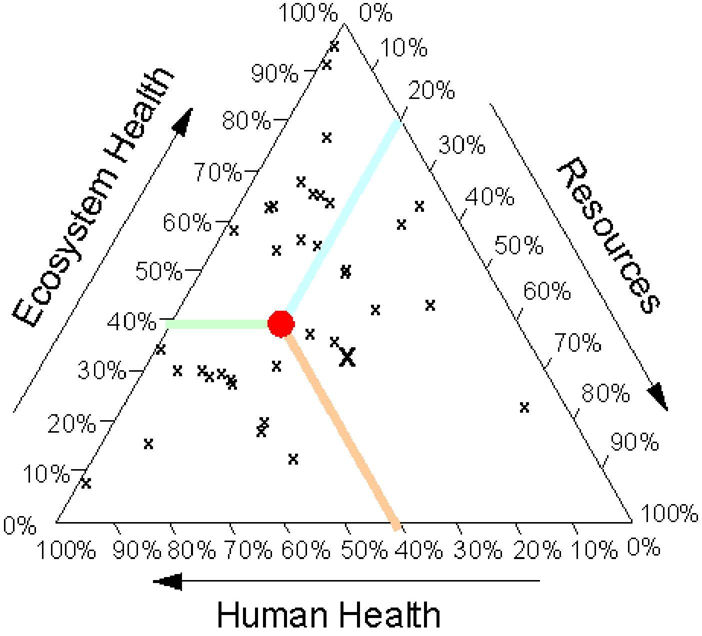
Defining the Boundaries

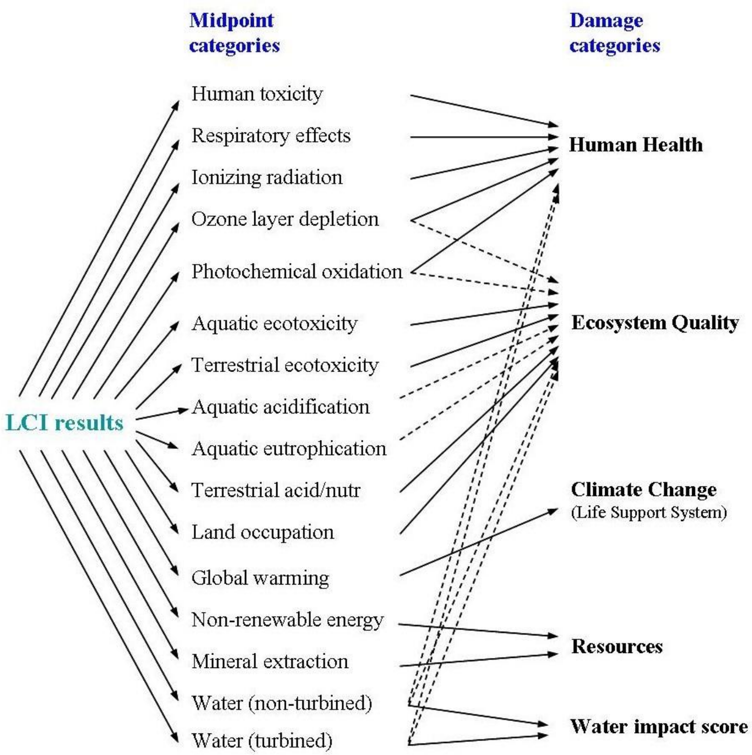


- Analysis generally goes outside your area of immediate data access

Issues with LCI

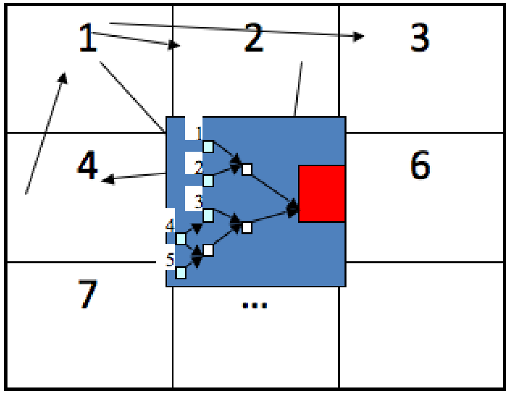
- Assessment LCI to LCA
  - Path ways, exposure, sensitivity
  - Aggregation of impacts
  - Weightings





New Developments

- Standards - ISO 14040series, SETAC, UNEP
- Boundaries
  - Custom and Hybrid EIOLCA (CMU site)
  - Cost of ownership models (Williams Ch 7 TDR)
  - Process + I/O = Hybrid (Williams…)
  - Eco-system services (Bakshi Ch 3 TDR)
  - Multiregional I/O models, e.g trading (Hertwich, Mueller…)



References

1) Thomas Graedel, Streamlined Life-Cycle Assessment, 1998
2) Michael F. Ashby "Materials and the Environment" 2nd ed. Butterworth - Heinemann, 2013
3) Sullivan, J., et al, "Life Cycle Inventory of a Generic US Family Sedan" Proceed Total Life Cycle Conf. SAE Internat'l, 1998
4) Chris T. Hendrickson, Lester B. Lave and H. Scott Matthews Environmental Life Cycle Assessment of Goods and Services – An Input-Output Approach RFF Press book, 2006 (Ch 1, 2, 5, 6)