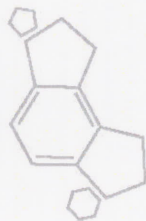


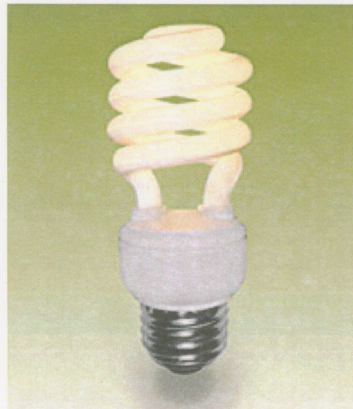
# Life Cycle Assessment (LCA) Methods for Design and Manufacturing of Sustainable Composites



Michael D. Lepech  
Assistant Professor  
Stanford University  
*[mlepech@stanford.edu](mailto:mlepech@stanford.edu)*



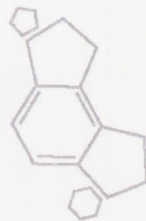
# Lots of “Green” ...





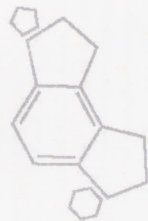
## Outline

- Life Cycle Assessment
  - ISO and Process-based LCA
- LCA Results
  - Case Studies
- Implementing Results
  - Marketing
  - R&D Focus – Green Product Design
  - Strategy
- Conclusions



# Green Motivation

- Year 2050
  - 1.8 to 2.2 Earth-size planets to meet our needs
  - Space
  - Energy
  - Food
  - Water
  - Materials





# One Framework

- The “IPAT” Equation

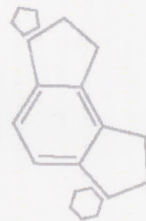
$$\mathbf{I} = \mathbf{P} \times \mathbf{A} \times \mathbf{T}$$

I = impact of population

P = population size

A = affluence (per capita consumption)

T = environmental damage inflicted as a function of technology



# IPAT & LCA

$$I = P \times A \times T$$

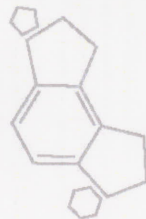
## Policy Instruments

Tax Policy  
Public Service Campaigns  
Financing Instruments  
Family Planning (India & China)  
Consumer Preference Marketing  
Mass Transit Funding  
LEED

## Technology Instruments

Fuel Efficient Vehicles  
Cellulosic Ethanol  
Green Composites  
Energy Star Appliances

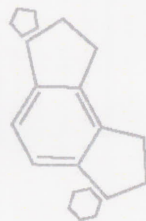
Life Cycle Analysis is the tool we use to evaluate the full impacts of current and proposed policies and technologies.



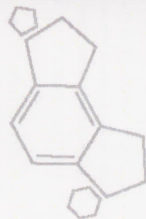
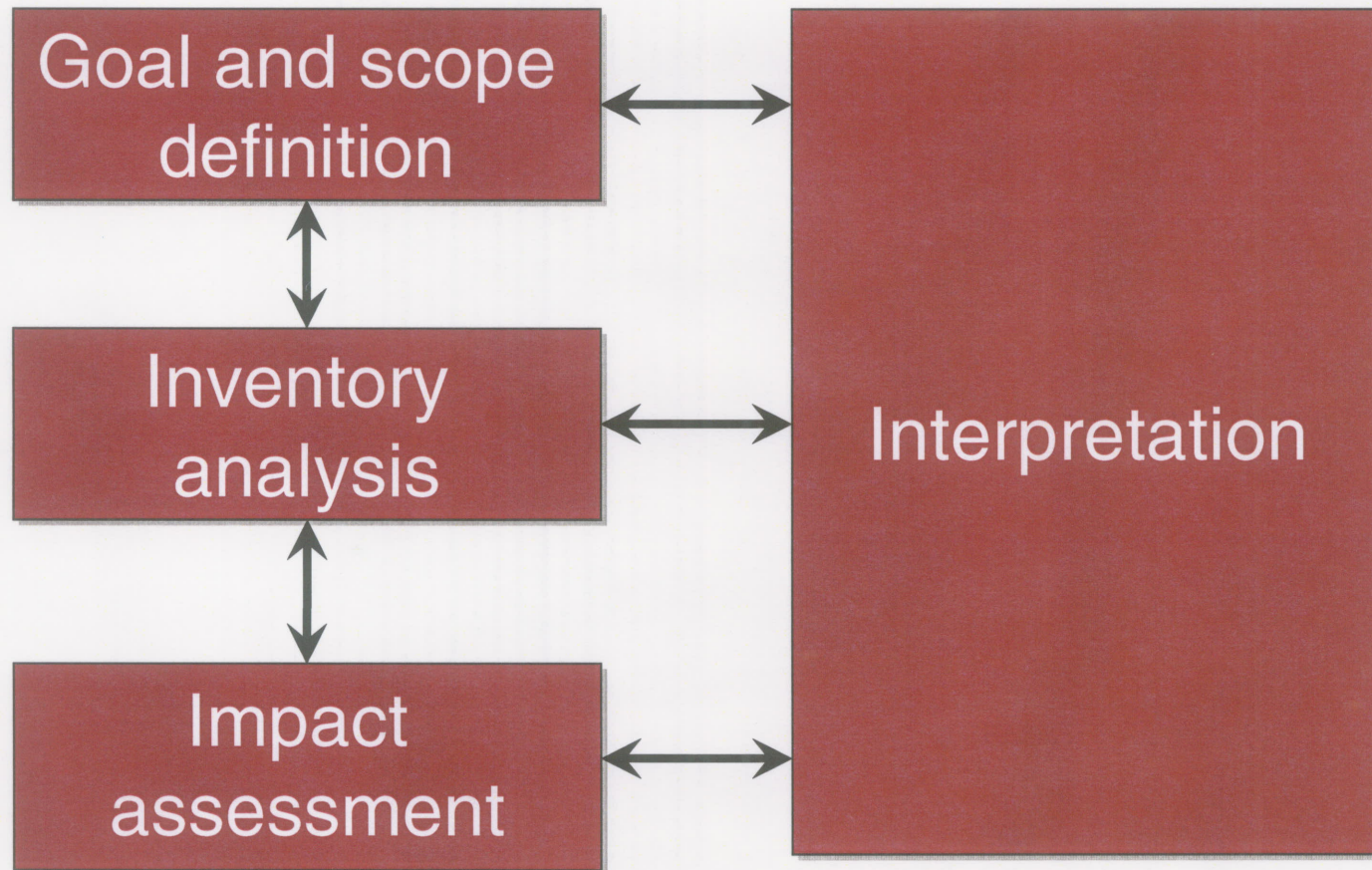


# LCA Standards

- ISO: International Organization for Standardization
- LCA standards are voluntary
- Part of 14000 Environmental Management Series
- LCA Standards:
  - 14040 Principles and Framework
  - 14041 Goal and Scope Definition and Inventory Analysis
  - 14042 Impact Assessment
  - 14043 Interpretation
- 14020 series: Environmental Labeling



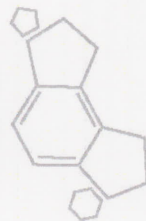
# LCA Requirements





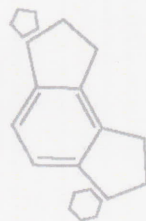
# Goal and Scope

- Goal of the study
  - State the intended application
  - Identify the intended audience
- Scope of the study
  - Function and functional unit
  - System boundaries
  - Data requirements/assumptions/limitations
  - Critical review and report format



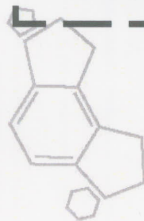
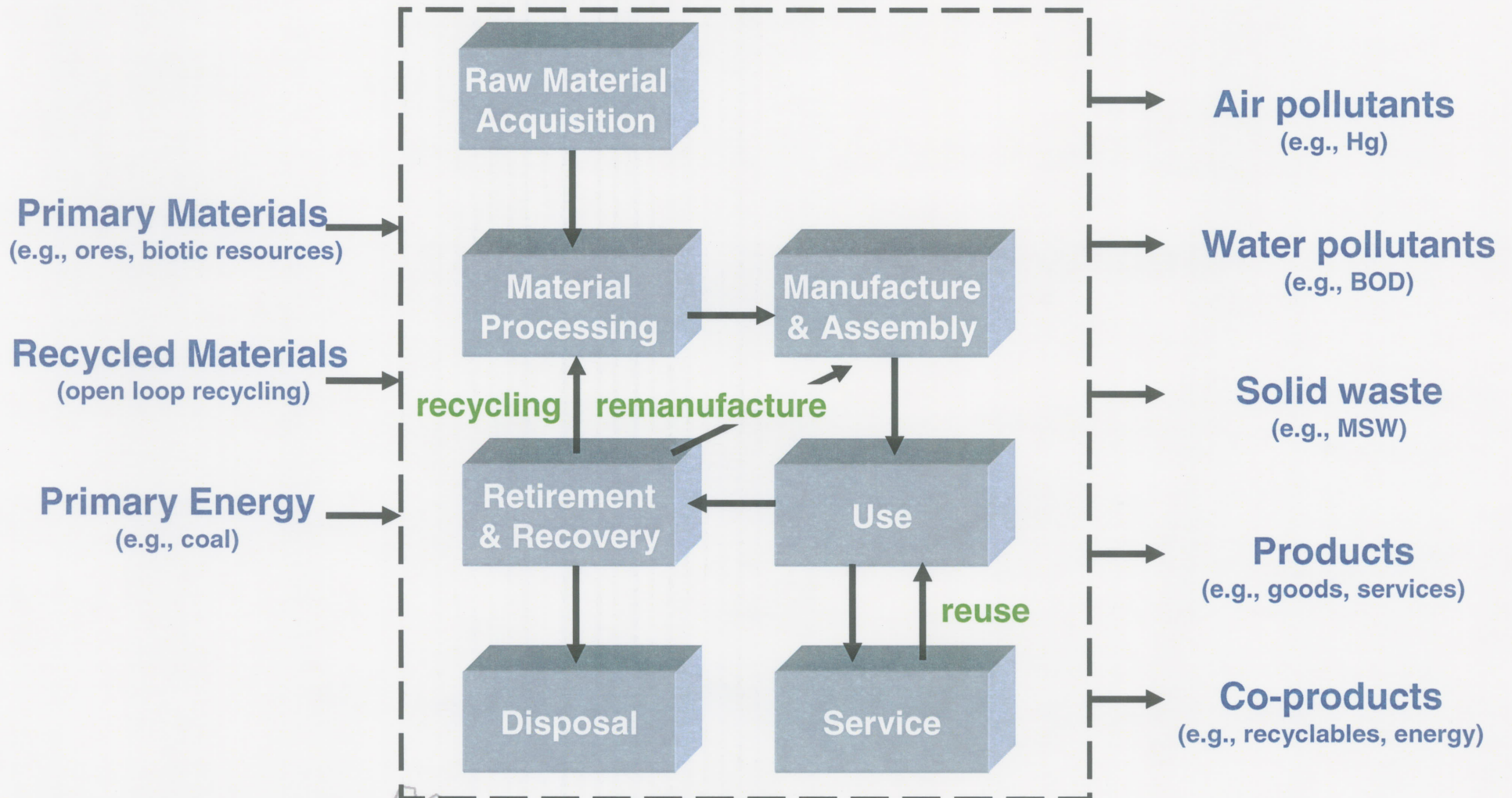
# Functional Unit

- Function
  - Service provided by system; performance characteristics of the product
- Functional unit
  - Means for quantifying the product function
  - Basis for an LCA
  - Reference for normalization of input and output data



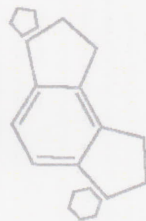


# Process-based LCA



# Lifecycle Inventory (LCI)

- The identification and quantification of relevant inputs and outputs for a given system throughout its life cycle
  - Franklin and Associates
  - Ecolnvent
  - BEES
  - APME
  - NREL
  - ELCD
  - Others...

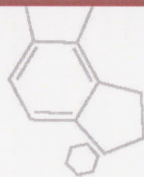




# US Electricity Life Cycle Inventory

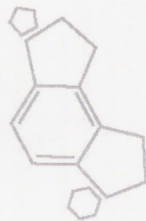
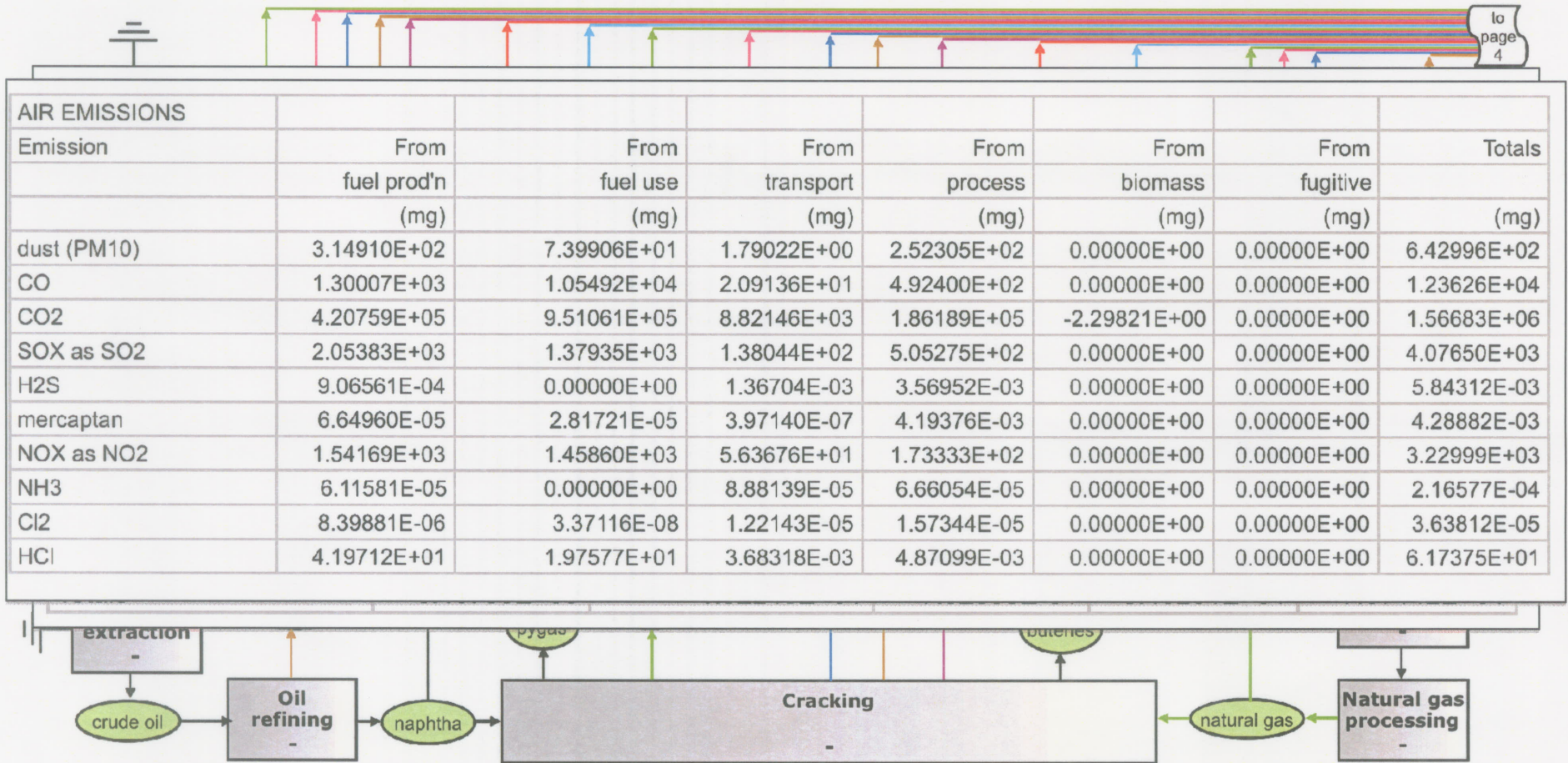
Appendix B: Environmental burdens associated with generating 1 MJe electricity in the United States in 2000 [based on generation] (cont'd)

			SPP	WSCP
Butadiene		US average	1.32E-07	4.31E-08
Butane			4.63E-04	4.64E-04
Cadmium			6.30E-06	2.84E-06
Calcium			6.29E-08	2.84E-08
Carbon dioxide (biomass)			9.33E-05	1.17E-03
Carbon dioxide (fossil)			2.60E+02	1.35E+02
Carbon disulfide	Butadiene	g	6.08E-08	2.98E-06
Carbon monoxide	Butane	g	3.18E-04	4.76E-02
Chlorides			1.54E-05	1.96E-05
Chlorine			2.14E-09	1.67E-09
Chlorobenzene			3.92E-07	1.60E-07
Chloroform	Cadmium	g	4.31E-06	5.04E-07
Chromium (Cr III, Cr VI)			3.30E-06	1.35E-06
Chrysene	Calcium	g	1.25E-07	6.90E-05
Cobalt			7.20E-09	3.09E-09
Copper	Carbon dioxide (biomass)	g	2.97E-04	2.66E-06
Cumene			2.87E-07	3.07E-07
Cyanide	Carbon dioxide (fossil)	g	1.83E+02	1.21E-07
Di(2-ethylhexyl)phthalate			1.40E-04	5.73E-05
Dibenzo(a,h)anthracene	Carbon disulfide	g	4.46E-06	4.09E-06
Dichlorobenzene			2.24E-09	9.14E-10
Dimethyl benzantracene	Carbon monoxide	g	5.10E-02	2.64E-07
Dimethyl sulfate			3.51E-09	3.53E-09
Dinitrotoluene	Chlorides	g	8.78E-05	2.69E-06
Dioxins (unspecified)	Chlorine	g	1.23E-09	1.57E-08
Diphenyl			1.09E-09	6.42E-09
Ethane			9.51E-08	3.90E-08
Ethyl benzene			6.83E-04	6.85E-04
Ethyl chloride			5.27E-06	2.16E-06
Ethylene dibromide			2.35E-06	9.60E-07
Ethylene dichloride			6.73E-08	2.75E-08
Fluoranthene			2.25E-06	9.14E-07
Fluorene			6.61E-08	2.53E-08
			1.50E-07	5.37E-08





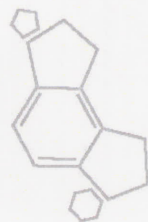
# APME LCI Database





# Life Cycle Impact Assessment

- Evaluation of the magnitude and significance of the potential environmental impacts of a product system
  - using inventory analysis results



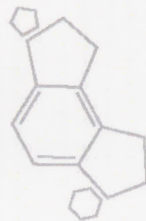
# Life Cycle Impact Categories

- Input related categories
  - abiotic resource extraction
  - biotic resource extraction
  - land use
- Output related categories
  - global change (climate, ecosystem, etc.)
  - stratospheric ozone depletion
  - human toxicity
  - ecotoxicity
  - photo-oxidant formation
  - acidification
  - nutrification



# Life Cycle Interpretation

- Draw conclusions and recommendations from inventory analysis and/or impact assessment
  - identify major burdens and impacts
  - select among alternative designs or materials



## Outline

- Life Cycle Assessment
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  - Strategy
- Conclusions



# Case Study – Office Furniture

- Spitzley, D., B. Deitz, G.A. Keoleian (2006) “Life Cycle Assessment of Office Furniture Products” Center for Sustainable Systems, University of Michigan (CSS06-11)



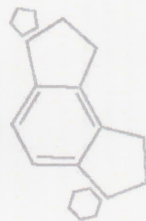
**Adjustable Table**



**Wood Casegood**

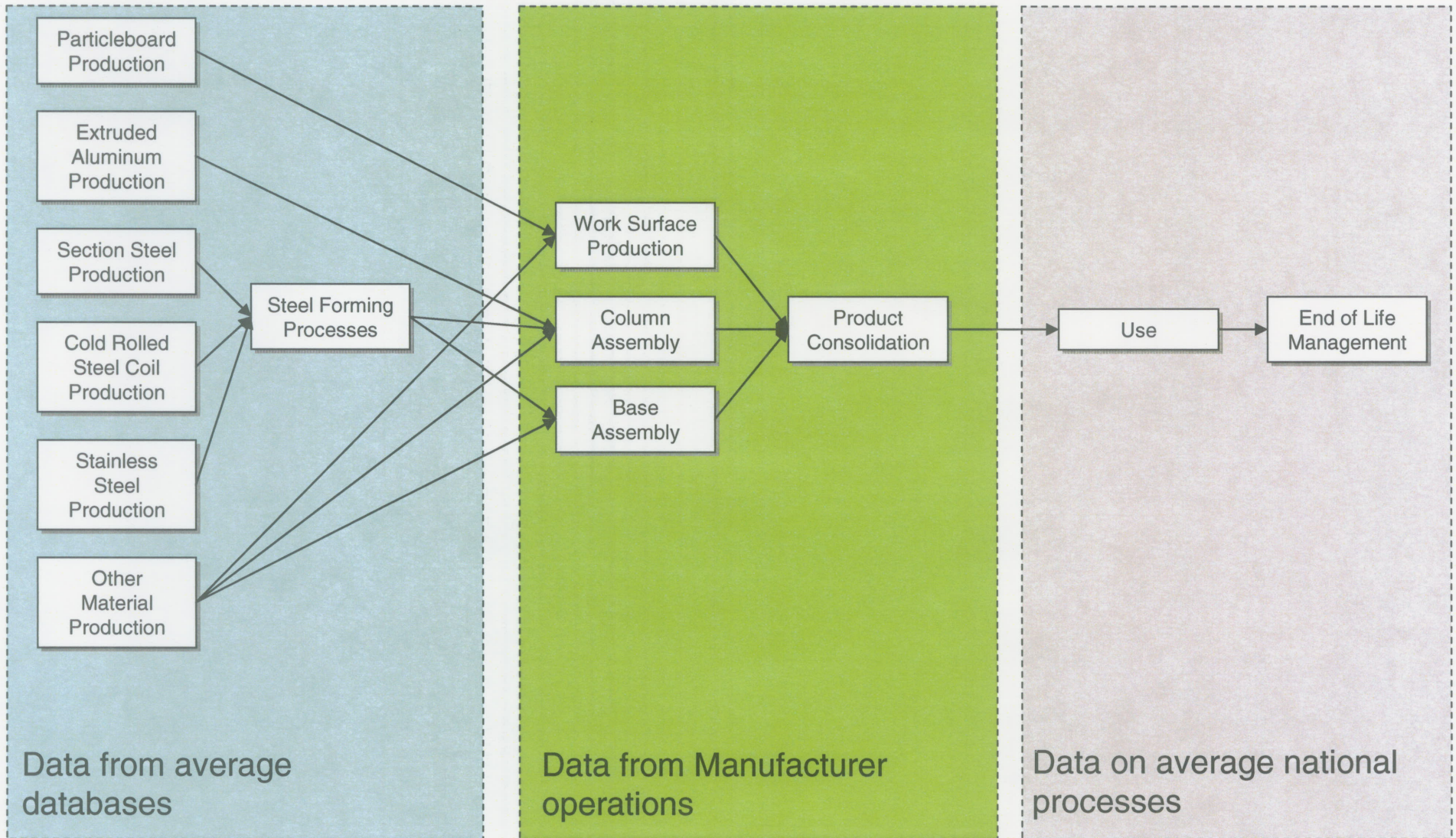


**Executive Chair**





# Product Life Cycle



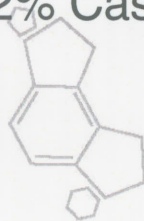


# Product Composition

- **Total product weight = 116 lbs**

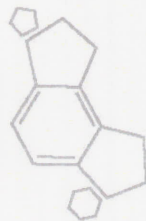
- **Work Surface = 37.2 lbs**
  - 89% Particleboard
  - 8% Laminate
  - 2% PVC
  - 1% Adhesive
- **Column = 45.2 lbs**
  - 56% Wrought Aluminum (inc. extruded and rolled)
  - 27% Sheet Steel
  - 13% Other Steels (inc. stainless)
  - 3% Cast Aluminum
  - 1% Polymers
- **Base = 33.1 lbs**
  - 71% Section Steel
  - 27% Sheet Steel
  - 2% Cast Aluminum

*Material modeling  
accounted for 99%  
of total product  
mass*



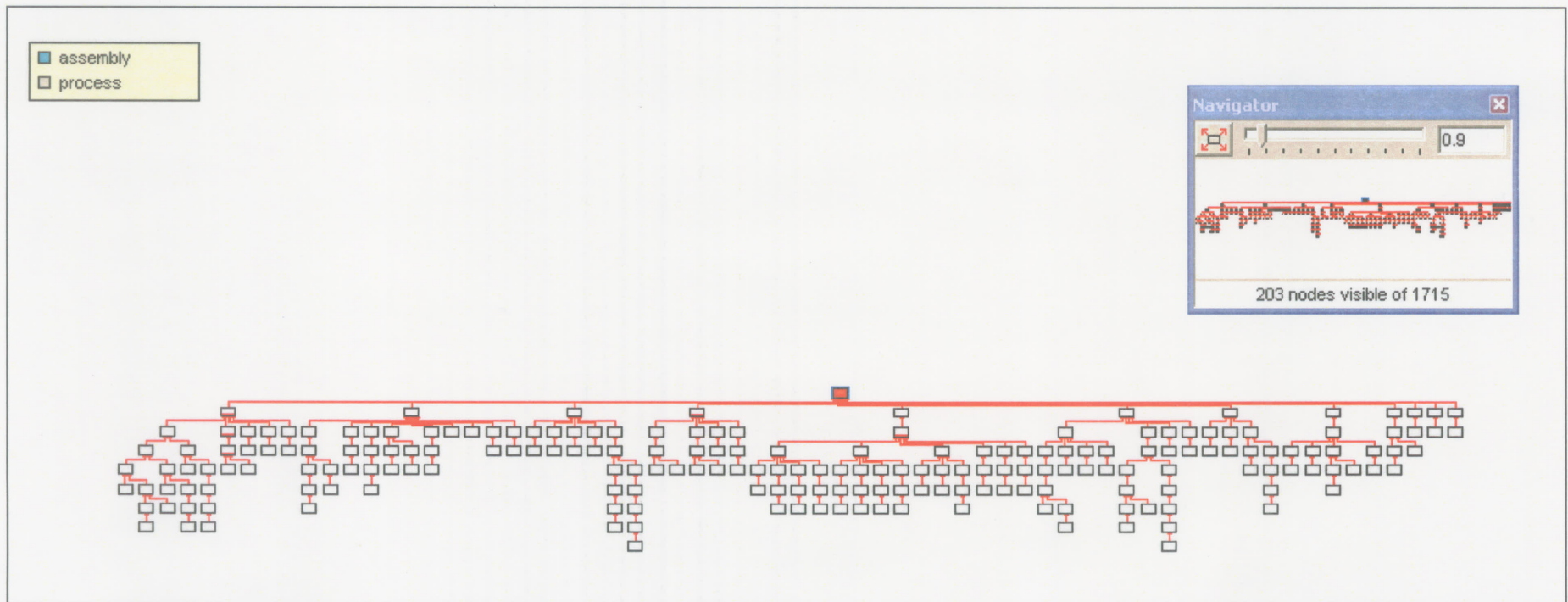
# Manufacturer Operations

- **Example data:**
  - Manufacturing equipment data
    - MIG welder (720 inch/hr)
      - 56.88 kWh/hr
      - 684 cf comp. air/hr
      - 360 gal water/hr
    - Pneumatic screwdriver (data from Stanley Assembly Tech.)
      - 1463 cf comp. air/hr
    - Steel machining (average US data)
      - 98 kWh/hr
      - 8.9 kg scrap/hr
  - Base assembly (approx. data)
    - 24" MIG weld (2 min)
    - Drill/Tap (5 min)
    - Pneumatic Screwdriver (1 min)
- **Overhead is not included in manufacturing data**



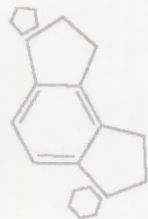
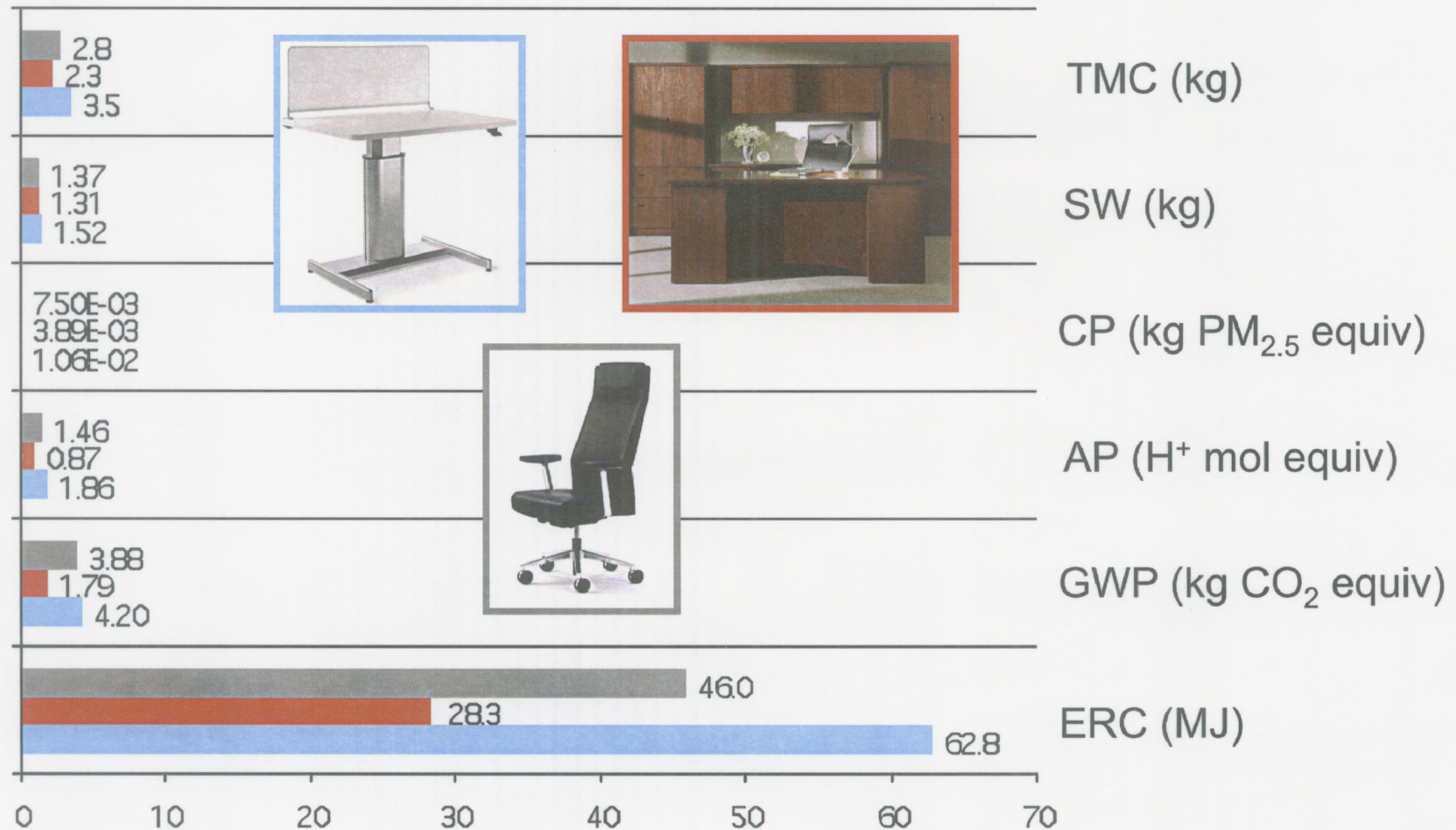


# Detailed Process Flow



- Full life cycle model is comprehensive and detailed
  - 203 nodes visible of 1715

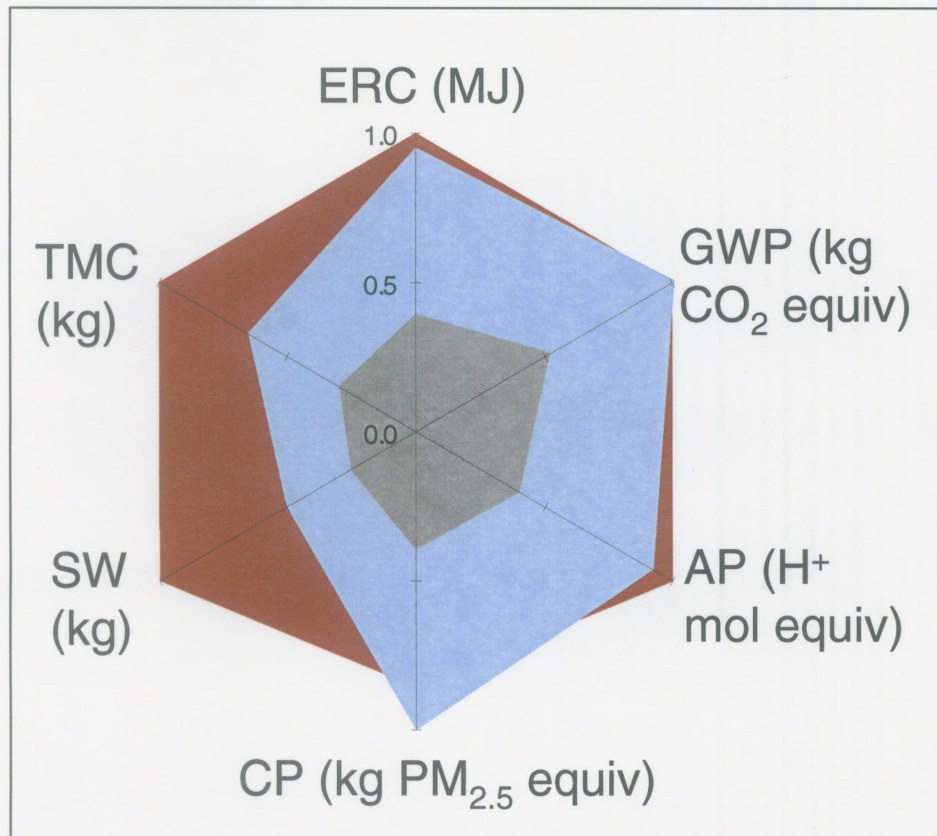
# Life Cycle Analysis Results



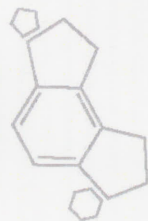
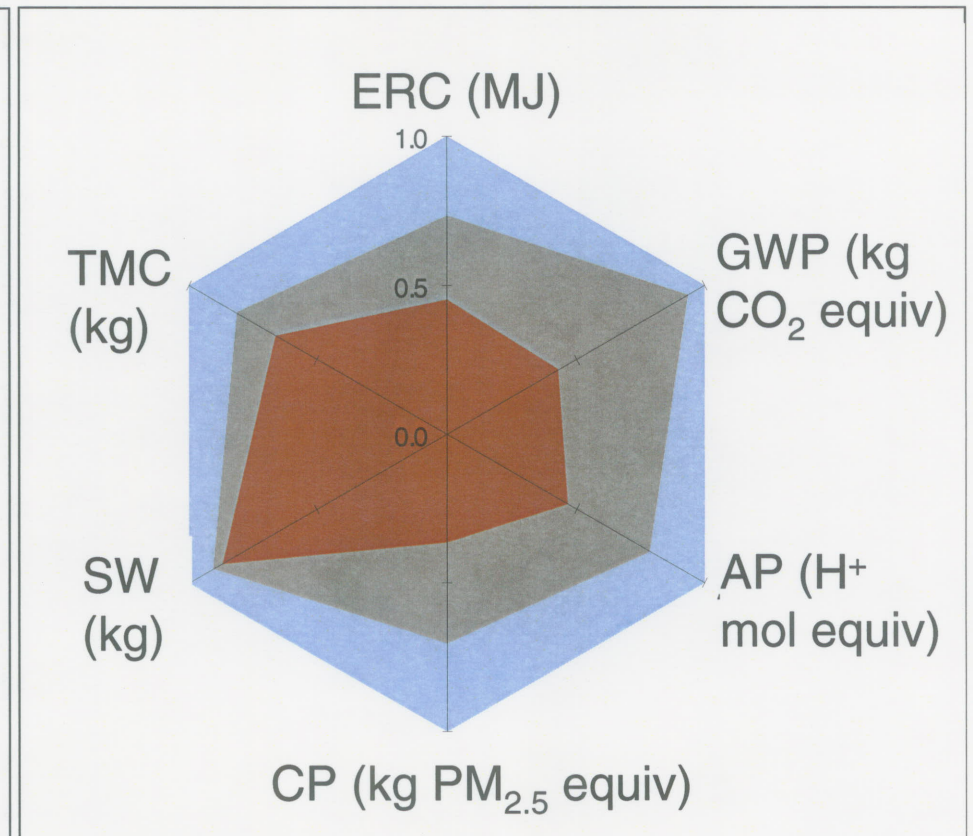


# Life Cycle Analysis Results

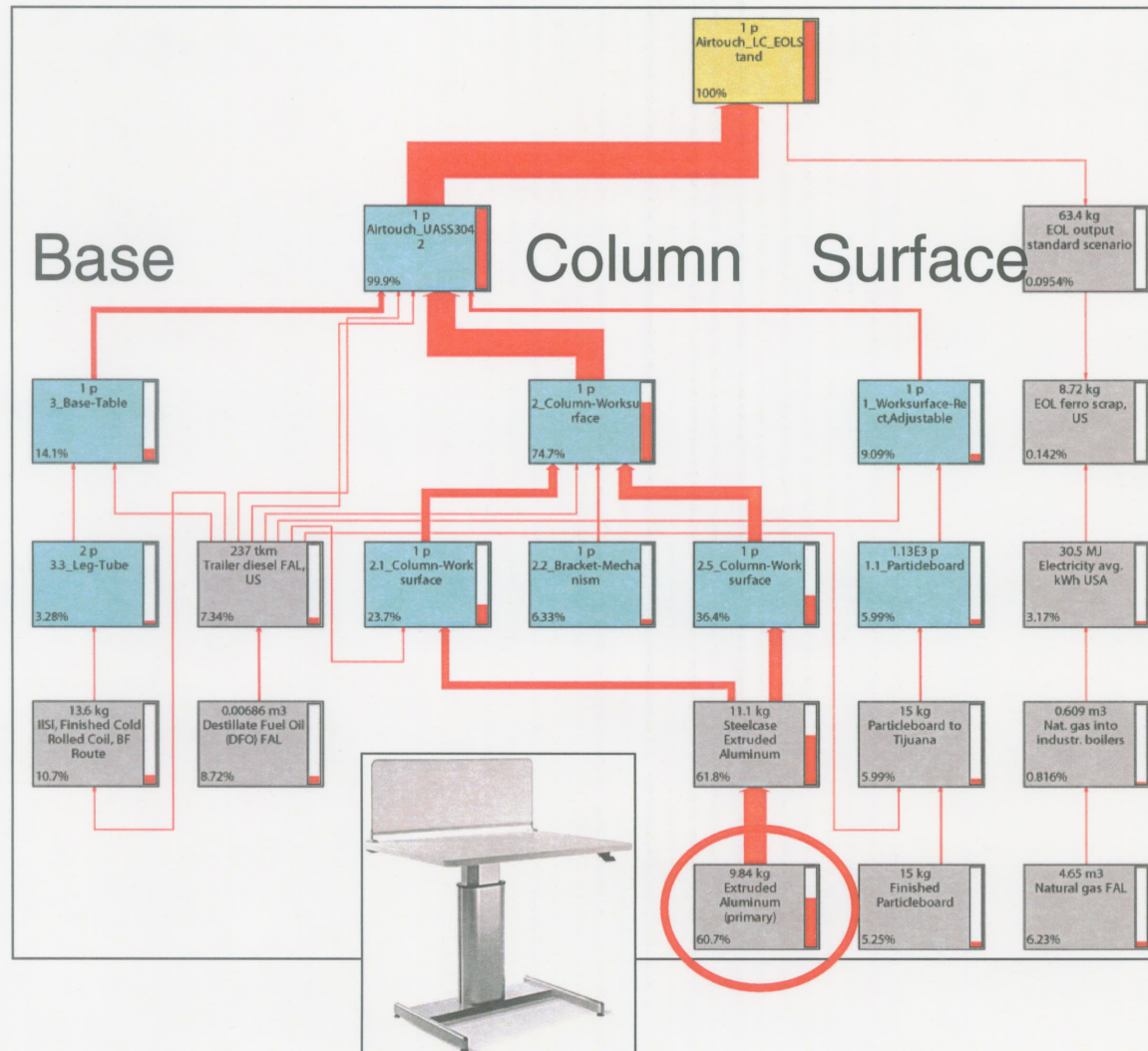
**Absolute Results**



**Intensity Results (per kg)**



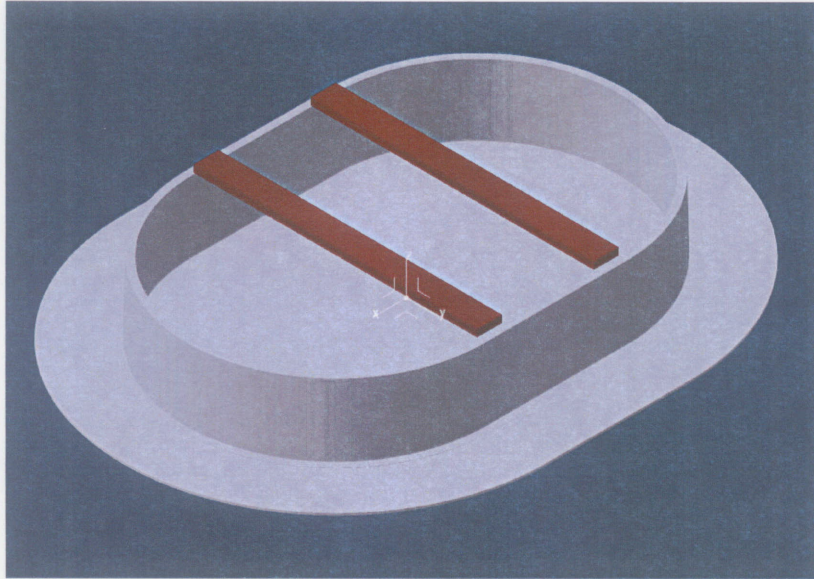
# Product Energy Flows



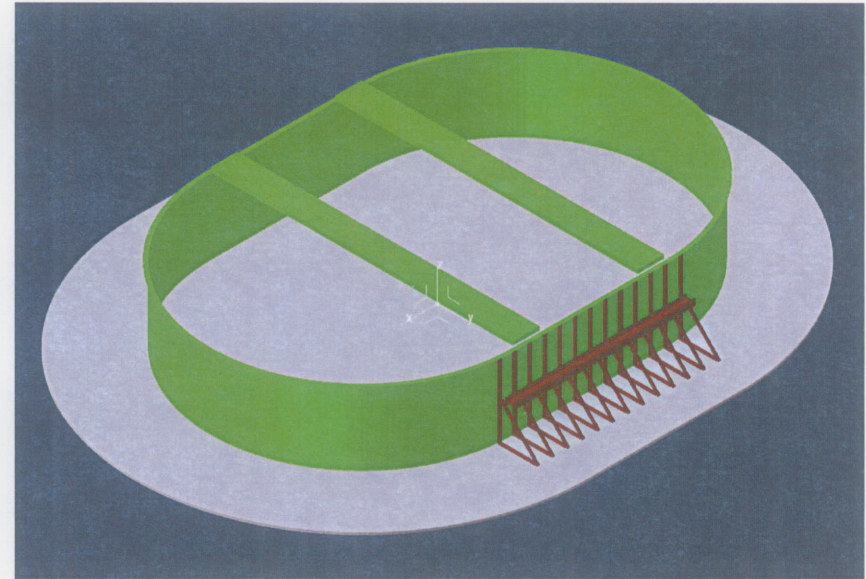
- Over 60% of life cycle energy consumed in aluminum extrusion process
- Baseline extruded aluminum uses 11% recycled content
- Increase of recycled content to maximum of 22% yields 6% reduction in ERC



# Case Study – FRP Tank

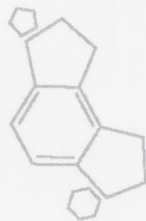


Shotcrete Tank



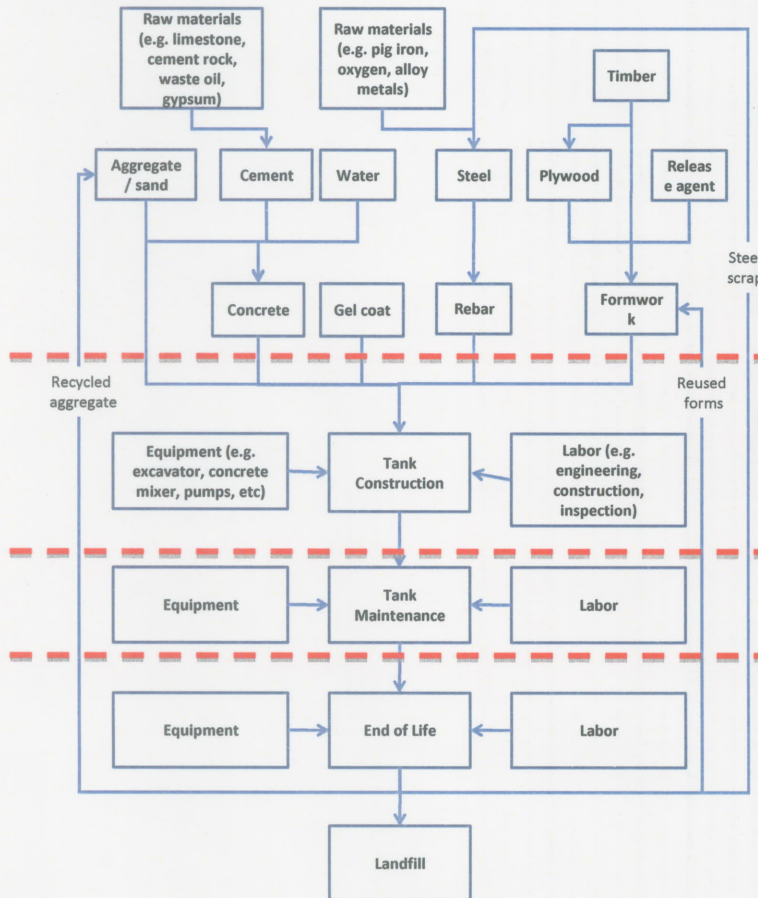
FRP Tank with Steel Ribs

- 20 year storage of aquatic ecosystem
- 20' x 40' x 10' freestanding saltwater tank (seismic resistant)

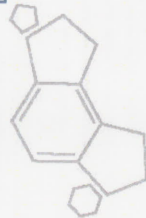
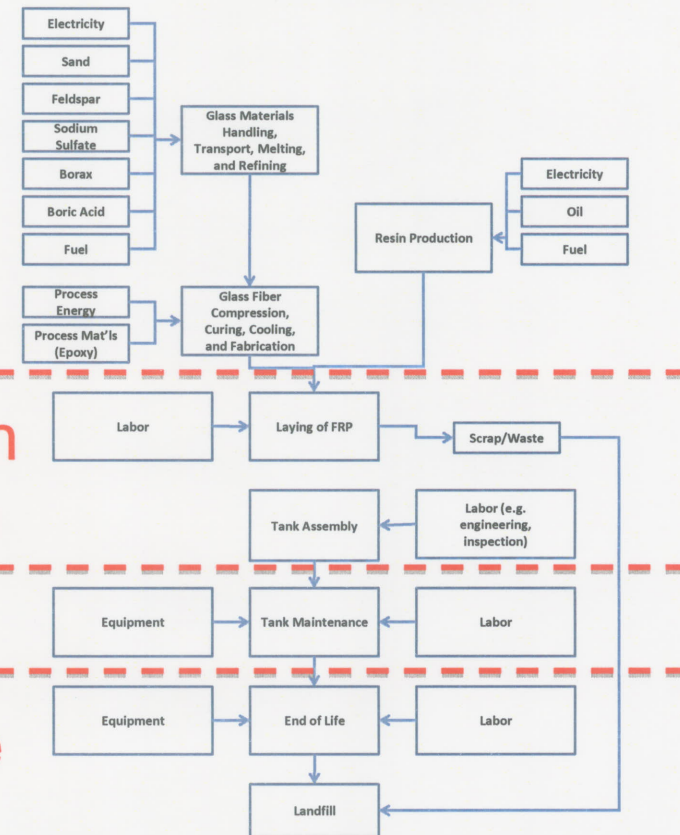


# Process Flows

## Concrete Tank

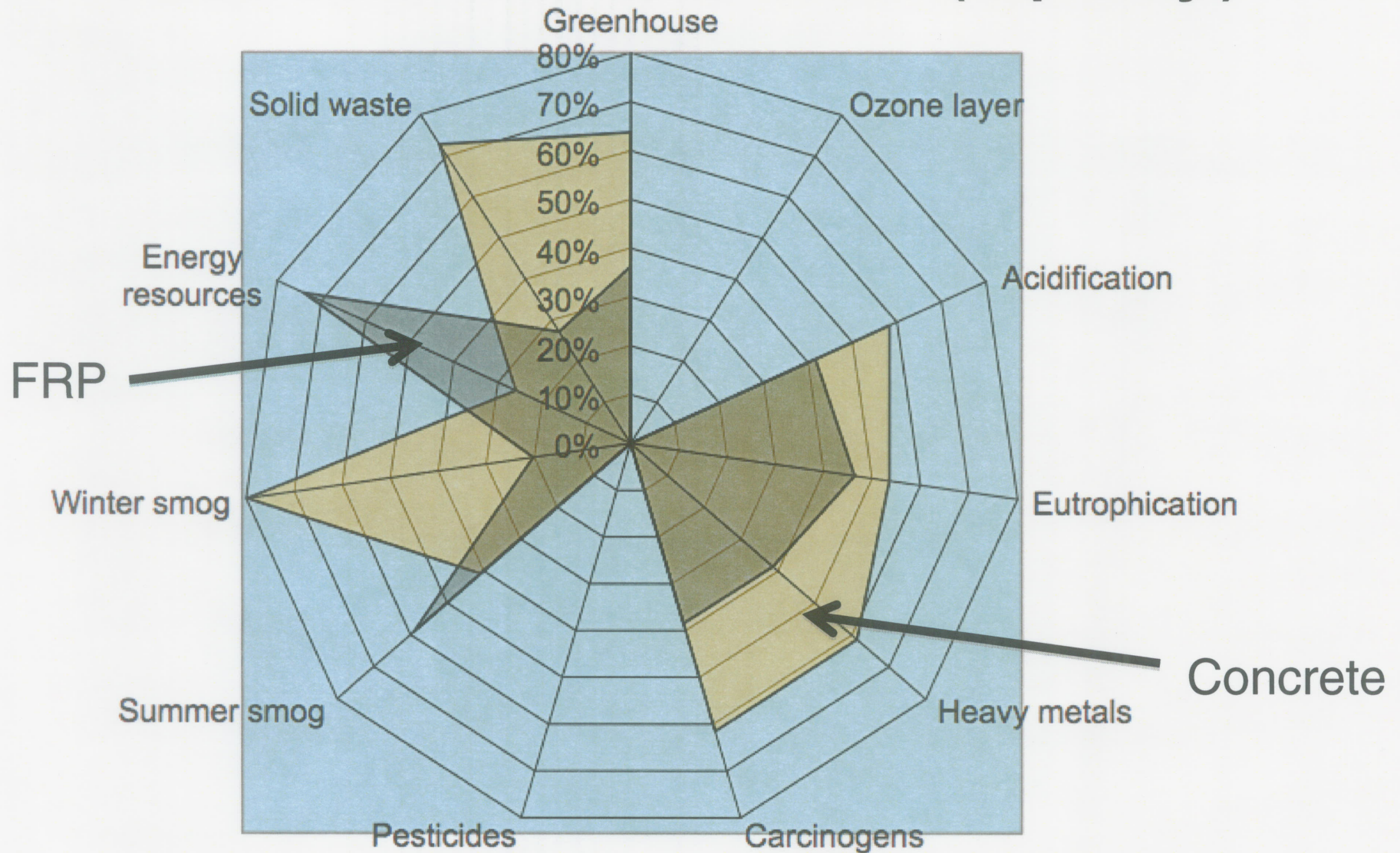


## FRP Tank



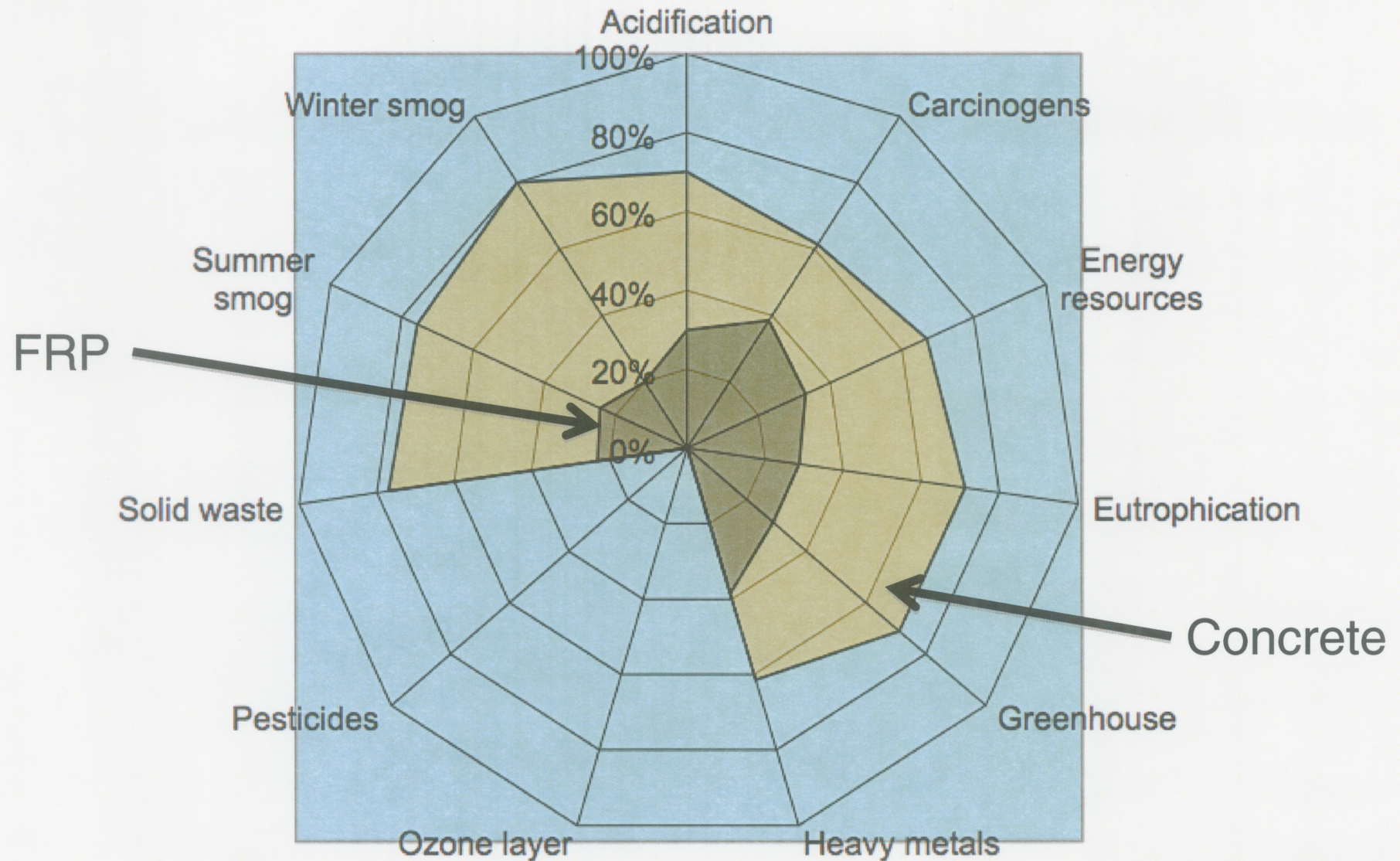


# Material Production (Epoxy)



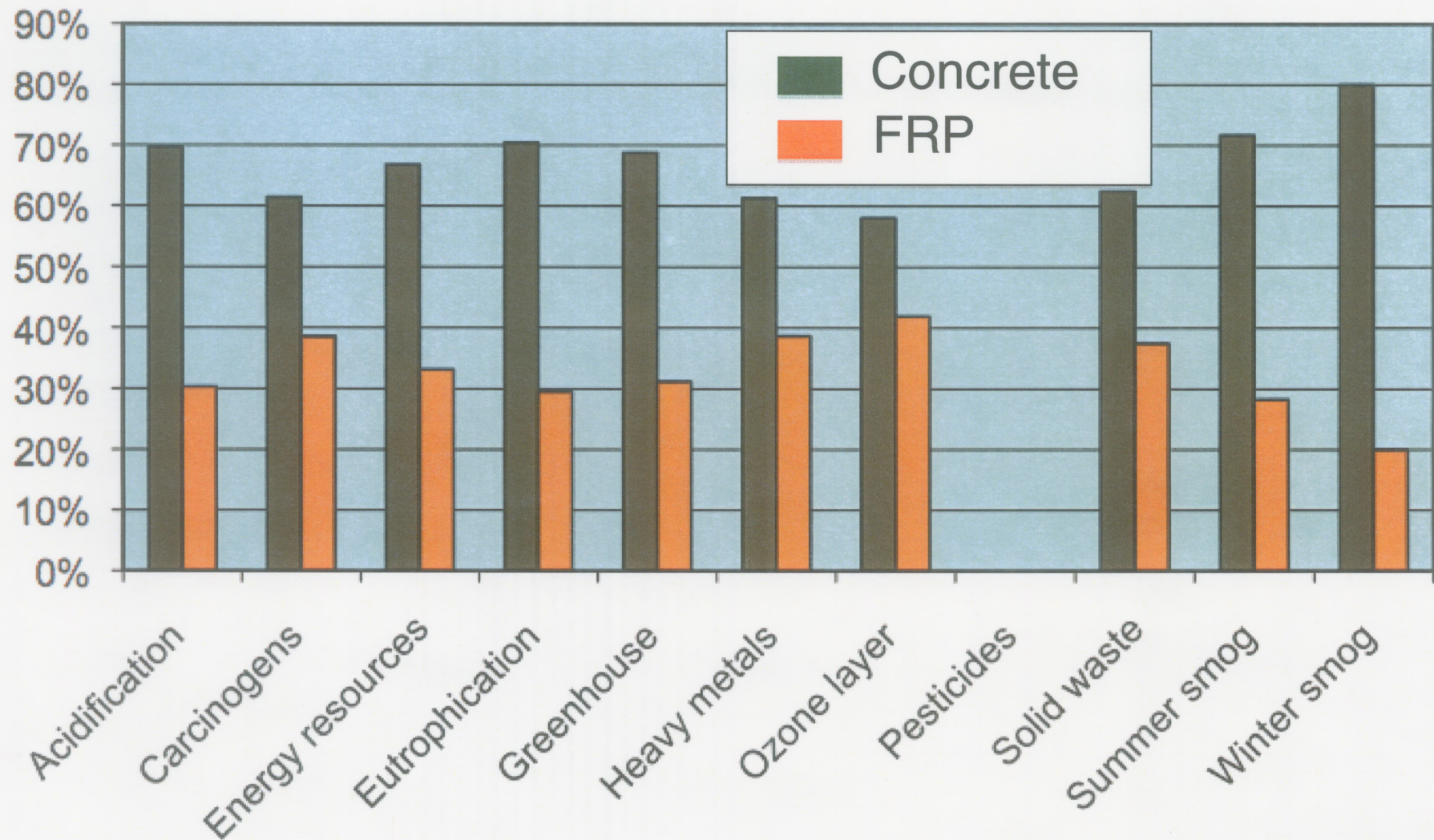


# Material Production (Polyester)



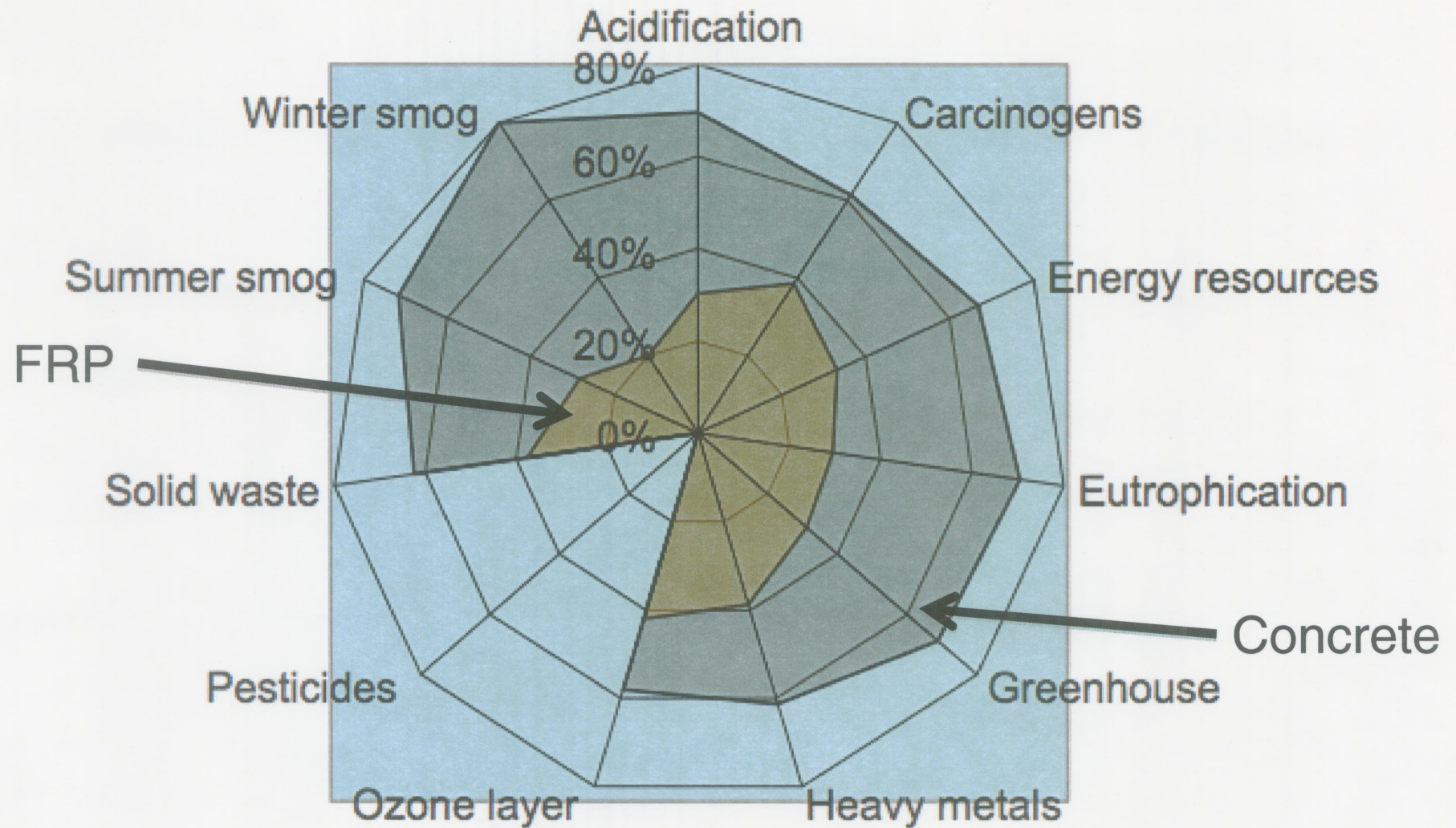


# LCA Results (Polyester)





# LCA Results (Polyester)



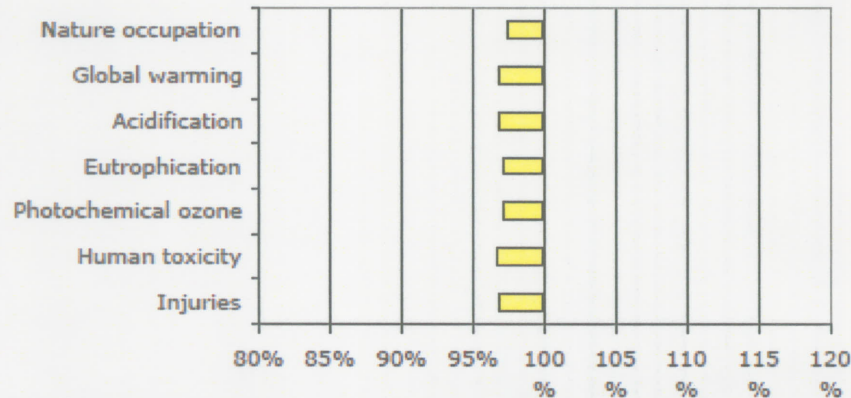


## Outline

- Life Cycle Assessment
  - ISO and Process-based LCA
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  - Marketing
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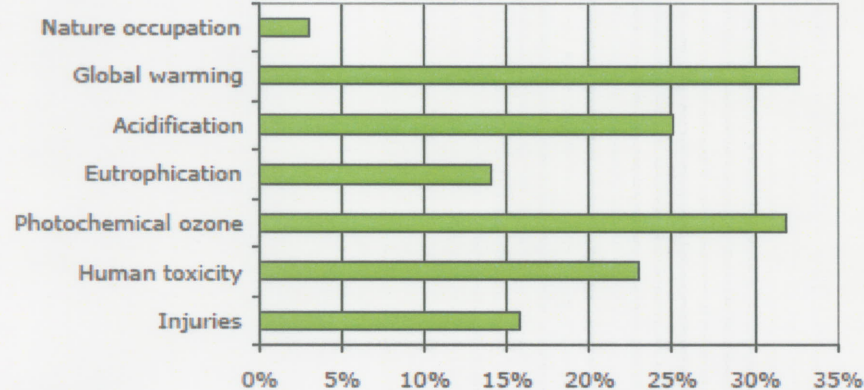
# Marketing & Eco-labeling

## Type III



**Life cycle impacts from the Fox® F5 Mobile Phone relative to the life cycle impacts of spending the same amount of money on "average mobile phones".**

*Note: The "use stage" is not included in this figure as it is the same for both the Fox® Phone and "average mobile phones."*



**Life cycle impacts from the Fox® F5 Mobile Phone relative to the life cycle impacts of spending the same amount of money on "average consumer goods".**

*Note: The "use stage" is included in this figure.*

**Explanation (applies for both figures)**

100% indicates same level.

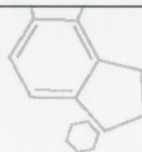
Impacts cannot be added across impact categories.

**Legend**

Green/medium grey: More than 10% less than the reference

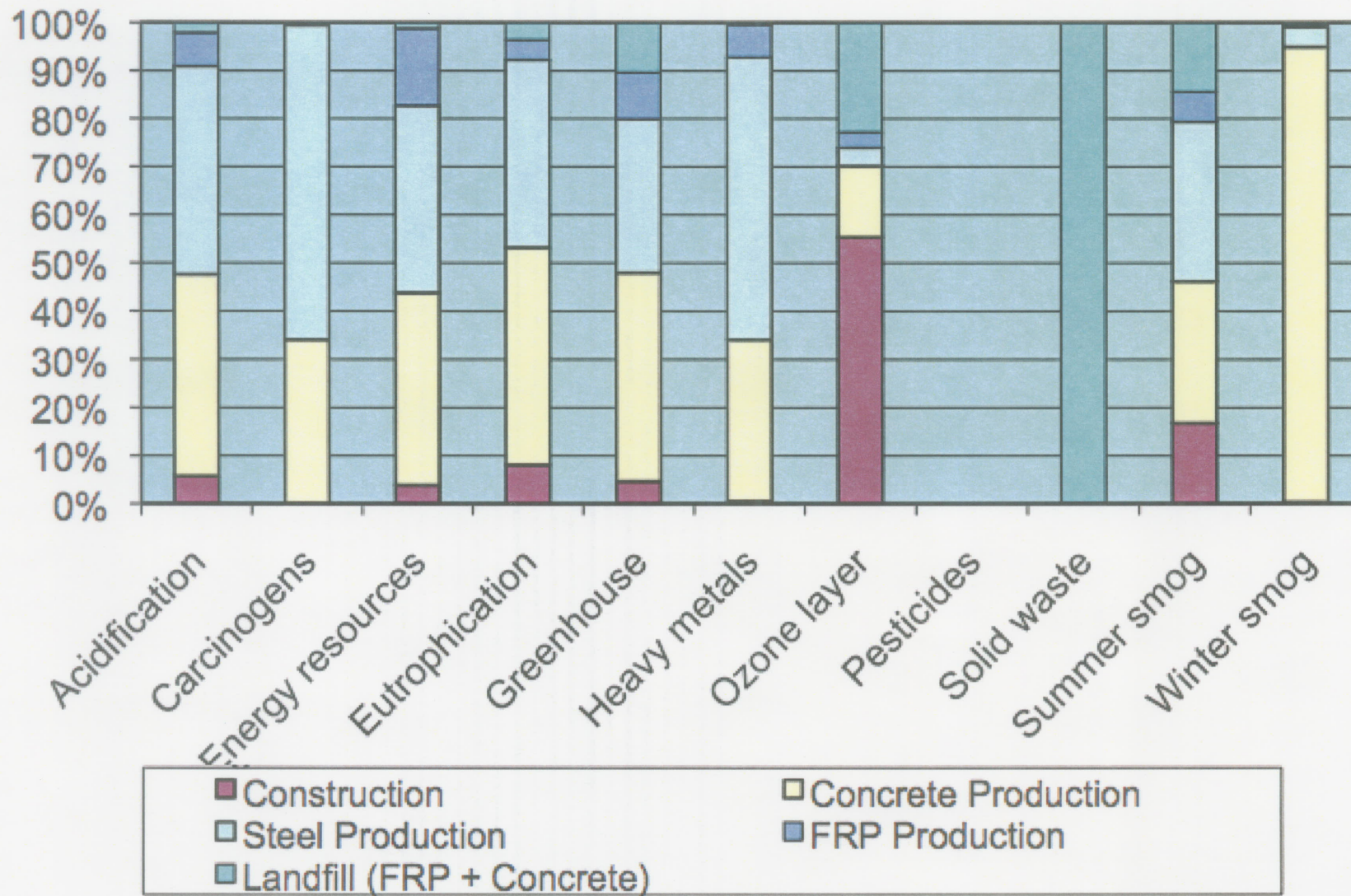
Yellow/light grey: Close to the reference

Red/dark grey: More than 10% higher than the reference

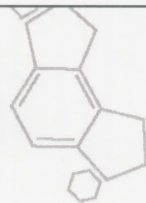
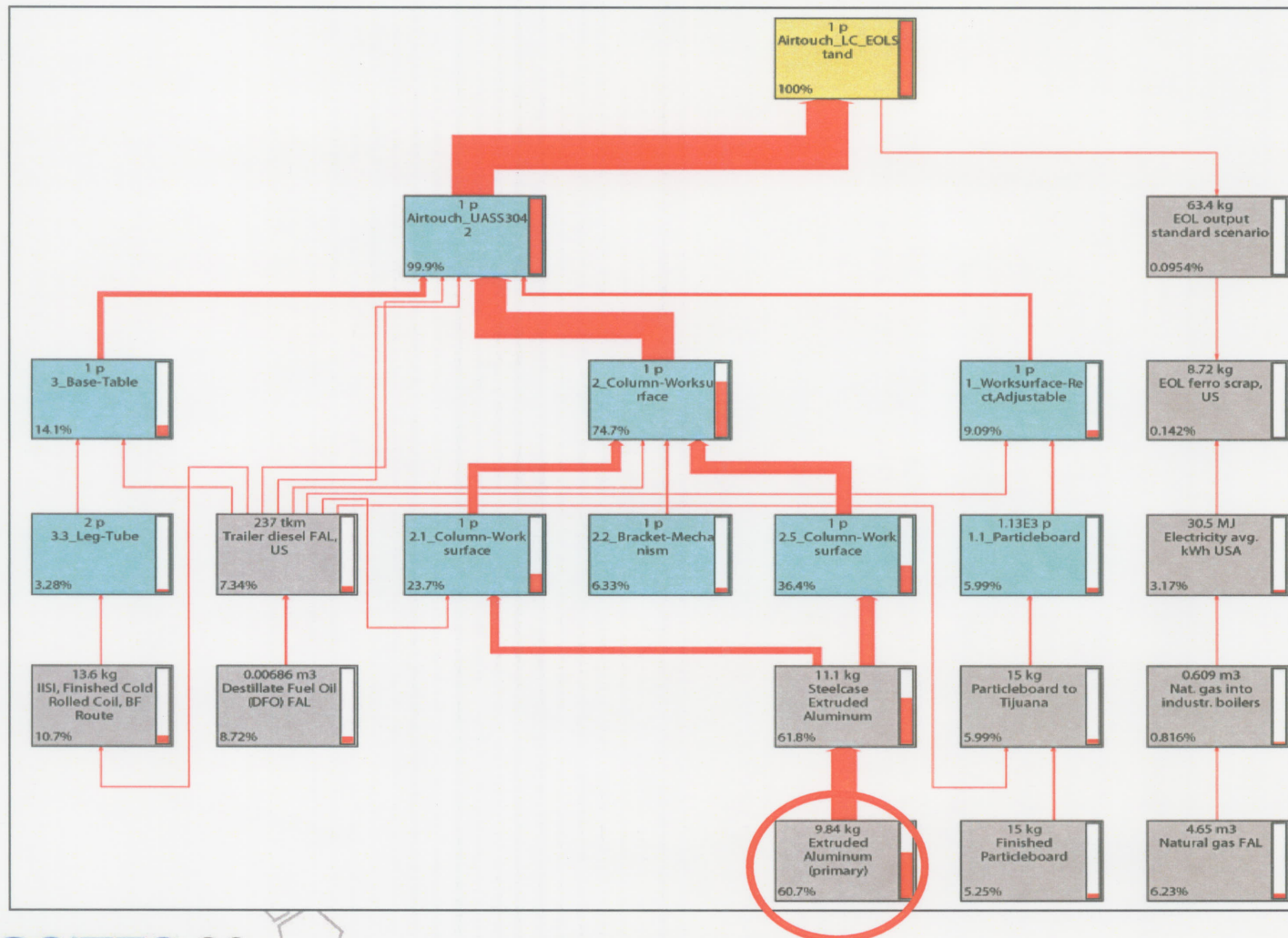




# LCA & Management

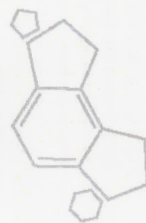
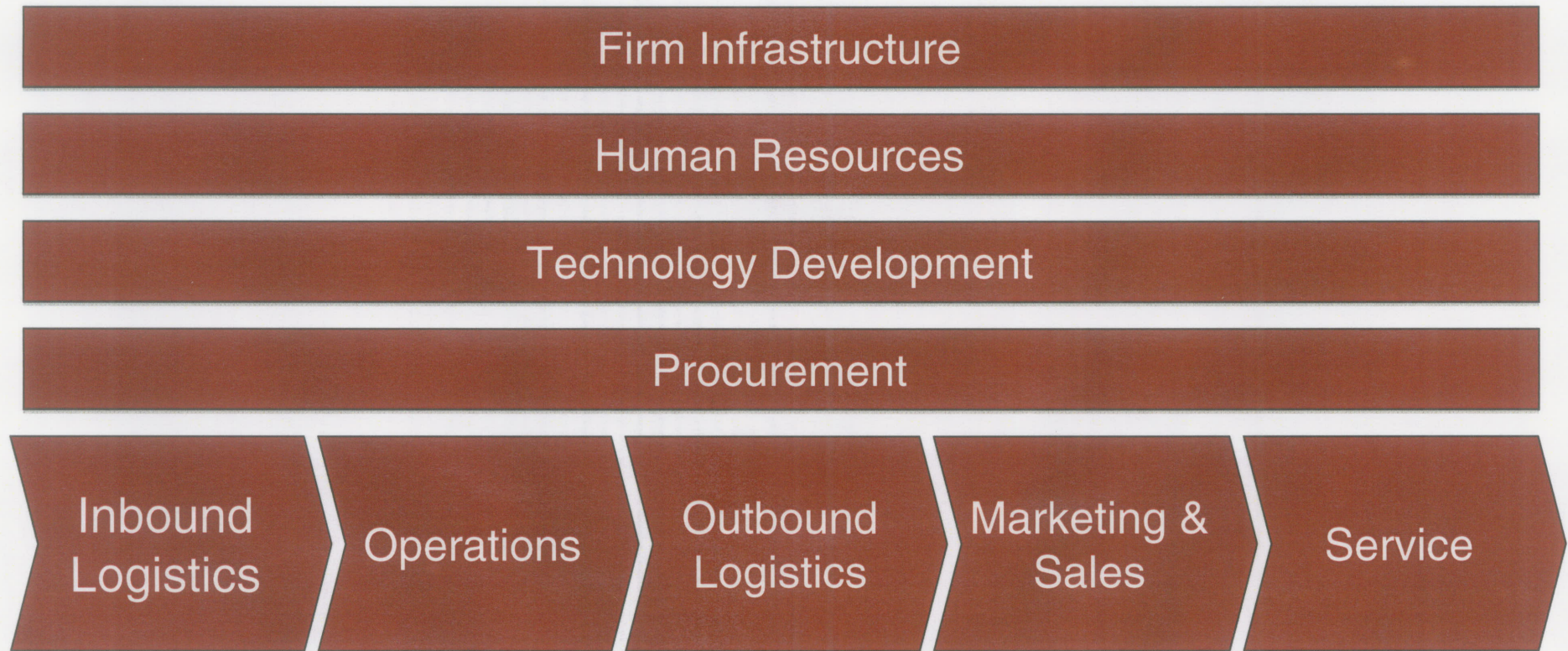


# LCA & Management





# LCA & Strategy (Value Chain Model)





# Opportunities



2002



2002:  
More than  
80 million  
square feet.

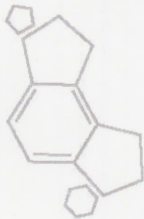
2003:  
More than  
141 million  
square feet.

2004:  
More than  
180 million  
square feet.

2005:  
500 million  
square feet.

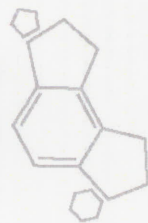
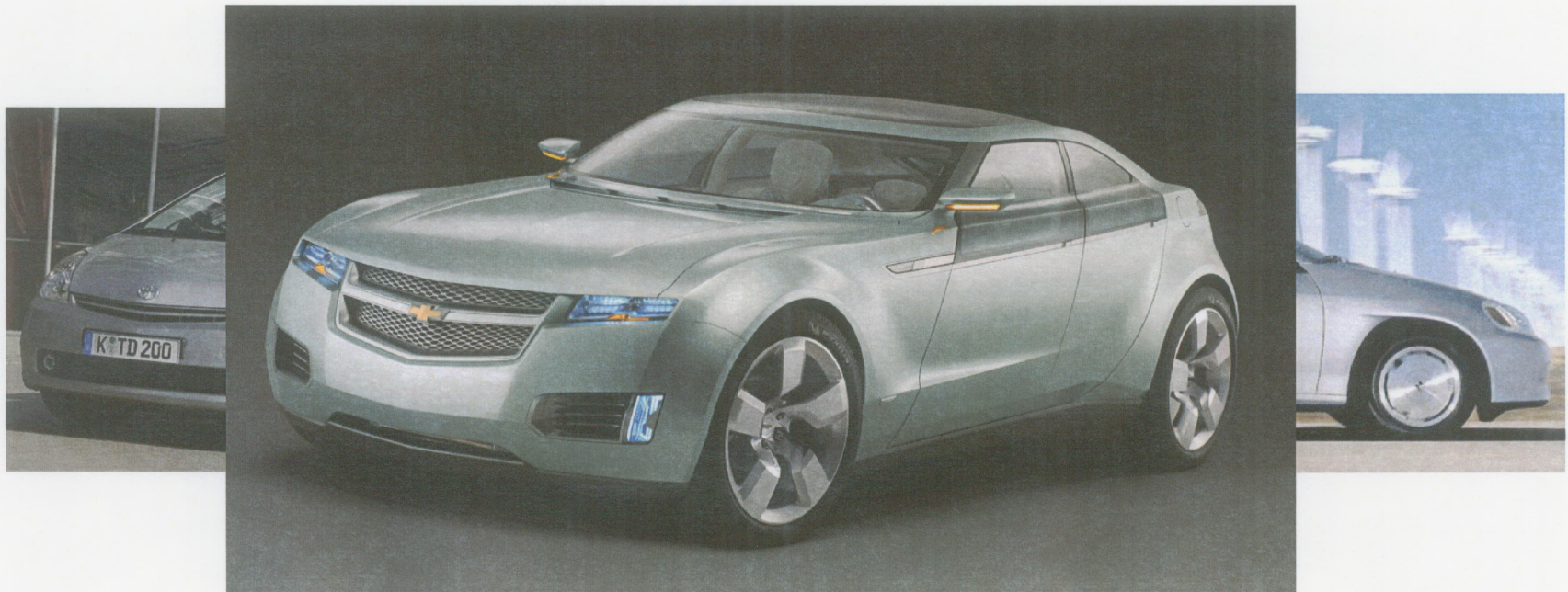
2006:  
519 million  
square feet.

2006



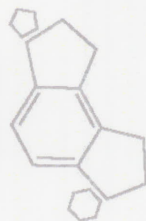


# Opportunities



## Outline

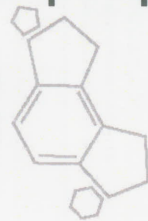
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# Conclusions

- Small pieces or processes → large impacts
- Creation of US life cycle inventory dataset for composites industry
  - Suppliers
  - Manufactures
- LCA can play a large role in firm activities
  - Marketing
  - R&D
  - Strategy
- Opportunities exist in green product markets...if approached properly



# Thank you for attending COMPOSITES & POLYCON 2009!

## Questions

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