Design of Sustainable Products Systems and Supply Chains – Some Concepts, Cases, and Lessons from an Engineering Perspective

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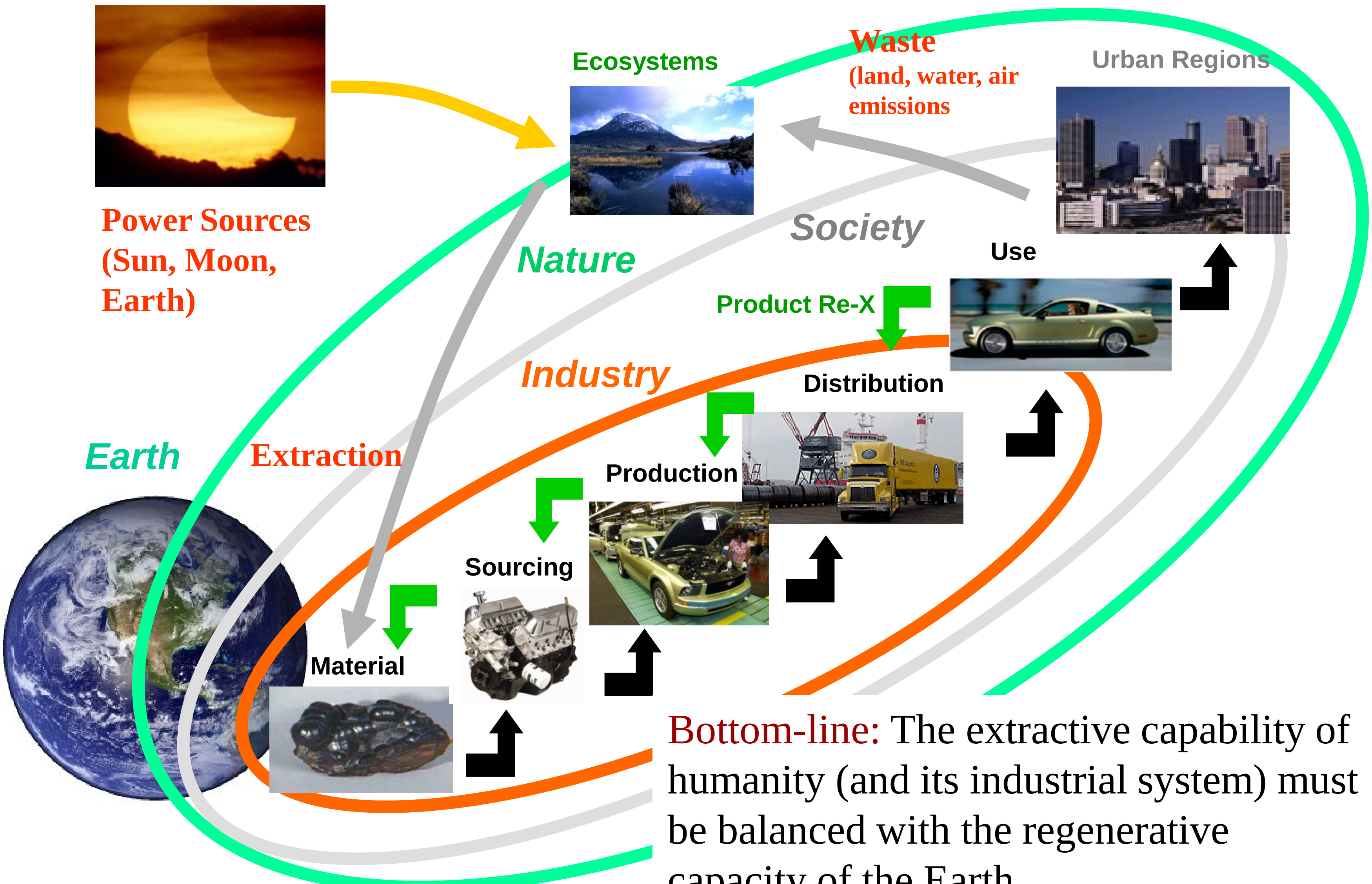
Sustainability: Common Definition

"development that meets the needs of the present generation without compromising the needs of future generations."

United Nations' World Commission on Environment and Development in their report "Our Common Future", 1987

Sustainability: Physical and Biological Limits



Bottom-line: The extractive capability of humanity (and its industrial system) must be balanced with the regenerative capacity of the Earth.

Key variables: Time & Location

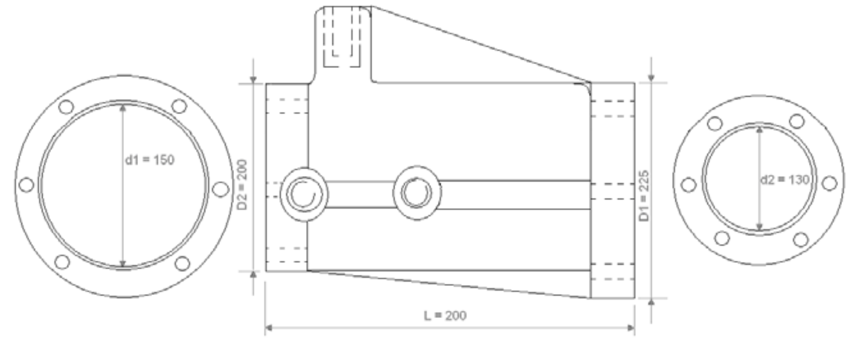
Need for a Systems Approach

Observations from 2001 National Science Foundation sponsored global study on Environmentally Benign Manufacturing:

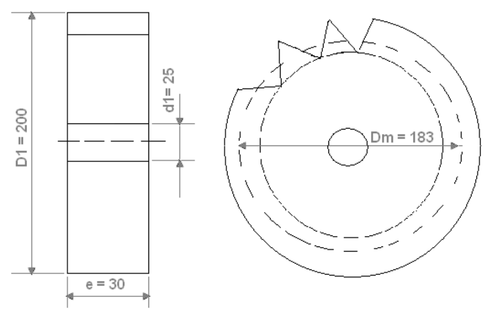
- There was no evidence that the environmental problems from our production systems are solvable by a "silver bullet" technology.
- There is a need for **systems-based solutions**
  - which requires a comprehensive systems approach
  - where scientists, engineers, managers, economists, entrepreneurs, policy-makers, and other stakeholders all work together to
    - address environmental issues in product realization and
    - achieve economic growth while protecting the environment.

- **Final Report**: *Environmentally Benign Manufacturing*. WTEC Panel Report, Baltimore, MD, Loyola College, 2001.
- **Online**: http://itri.loyola.edu/ebm/ebm.pdf

Example - Two Automotive Parts



Aluminum transfer case



Steel pinion gear

- Simple question: What is better?
  - Virgin manufacturing & disposal
  - Recycling
  - Remanufacturing

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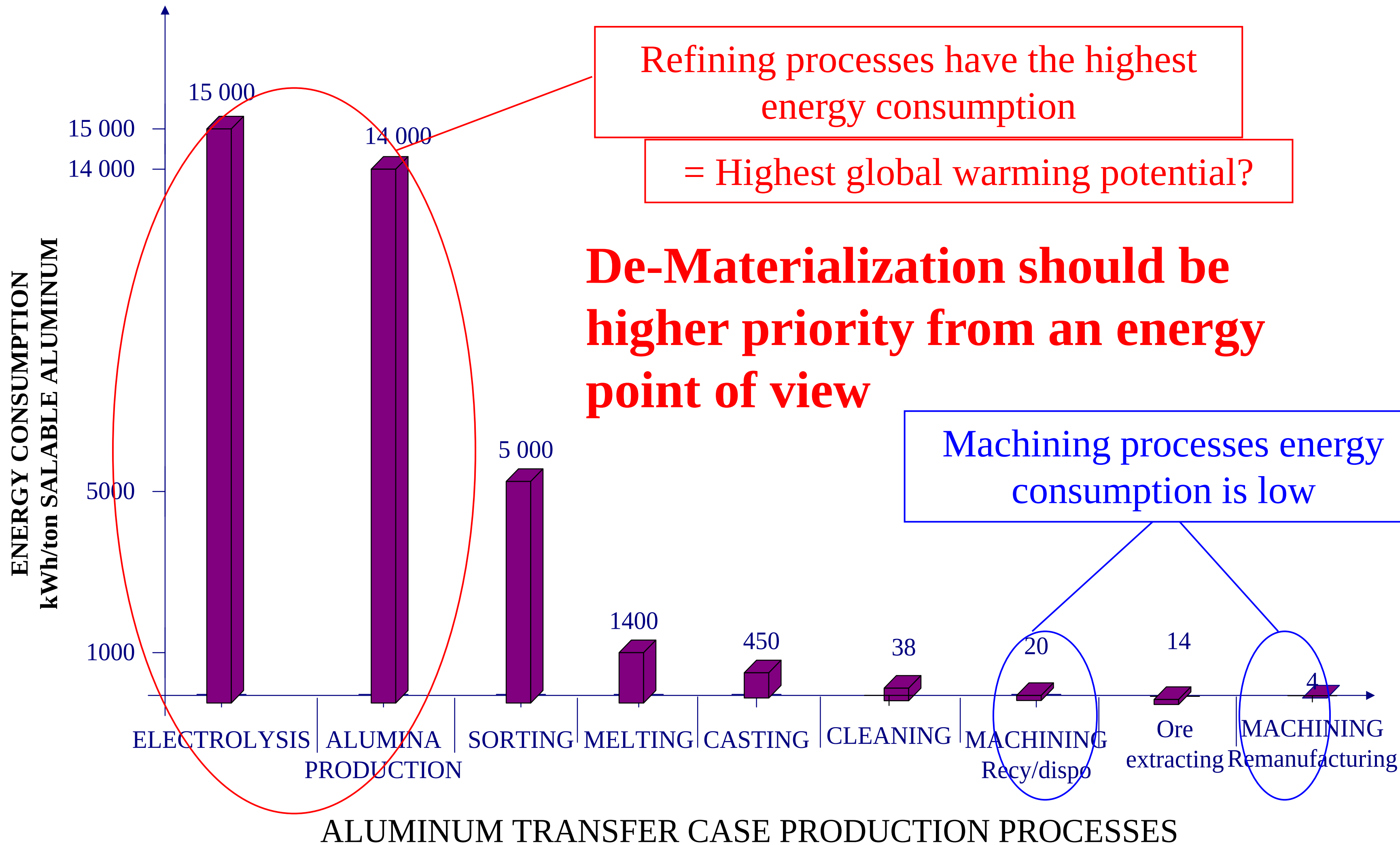
Life-Cycle Perspective is Crucial



Bras, B., "Sustainability and Product Life Cycle Management – Issues and Challenges", International Journal of Product Life-Cycle Management, Vol. 4, No 1-3, pp. 23-48, 2010

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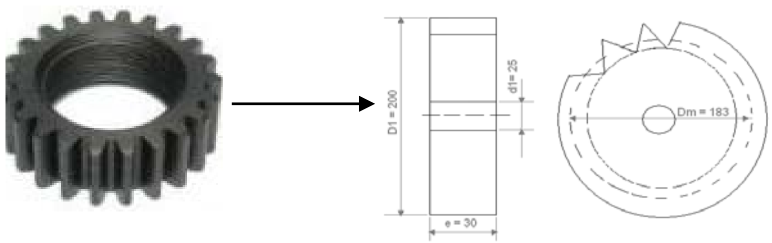
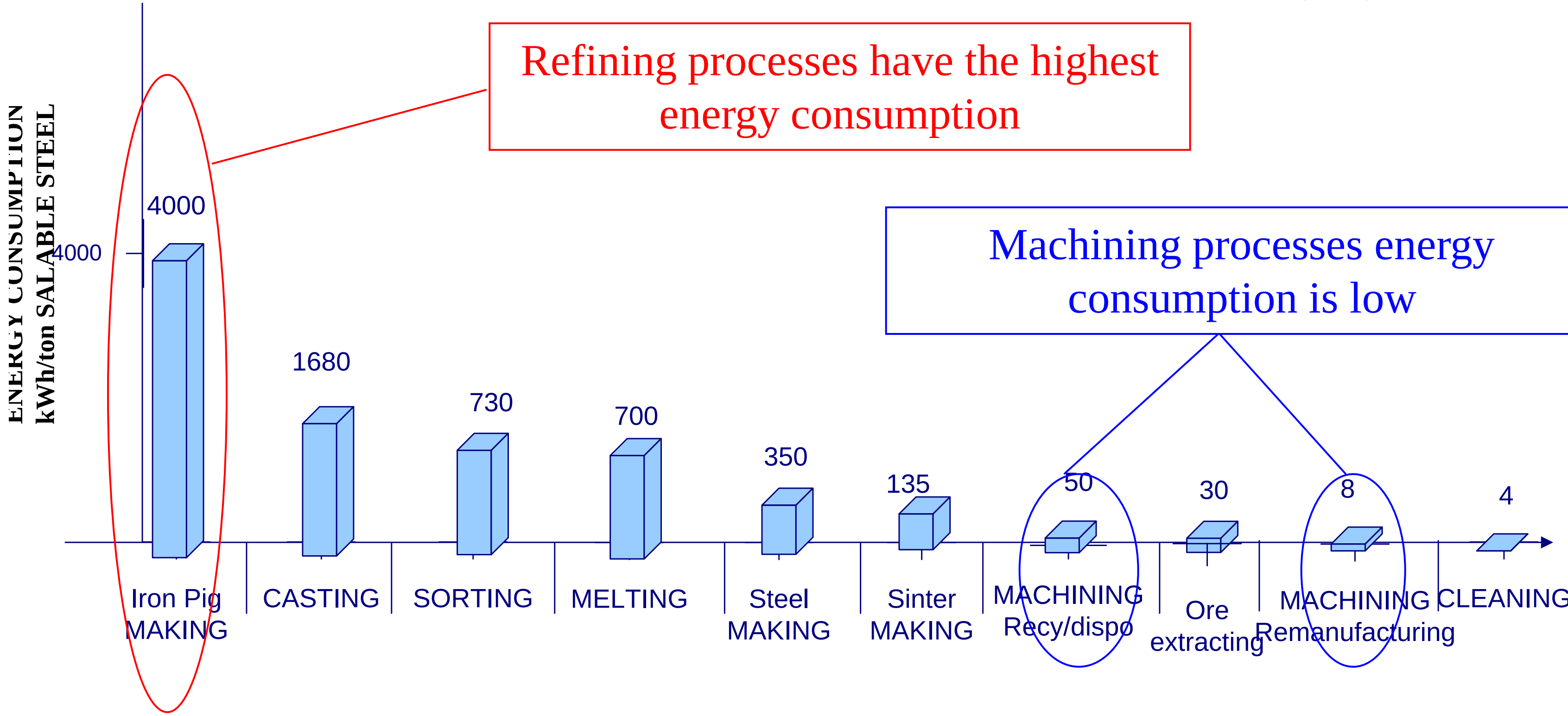
Steel Processing Energy Consumption

De-Materialization again will result in higher gains from an energy pint of view





STEEL PRODUCTION PROCESSES

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Energy Consumption in Manufacturing Sectors

- **Manufacturing process energy savings are small when majority is embodied in upfront material production/refining**

- **Closed loop supply chains that save material through recovery, reprocessing, recycling, remanufacturing, etc. (re-X) is an important aspect to be pursued**

		MECS Survey Years	
NAICS	**Subsector and Industry**	**1998**	**2002**
311	**Food**	**1,044**	**1,123**
312	Beverage and Tobacco Products	108	105
313	Textile Mills	256	207
314	Textile Product Mills	50	60
315	Apparel	48	30
316	Leather and Allied Products	8	7
321	Wood Products	509	377
322	**Paper**	**2,747**	**2,363**
323	Printing and Related Support	98	98
324	**Petroleum and Coal Products**	**7,320**	**6,799**
325	**Chemicals**	**6,064**	**6,465**
326	Plastics and Rubber Products	328	351
327	Nonmetallic Mineral Products	979	1,059
331	**Primary Metals**	**2,560**	**2,120**
332	Fabricated Metal Products	445	388
333	Machinery	217	177
334	Computer and Electronic Products	205	201
335	Electrical Equip., Appliances, and Components	143	172
336	Transportation Equipment	492	429
337	Furniture and Related Products	88	64
339	Miscellaneous	89	71
	Manufacturing	23,796	22,666

Consumption of Energy (Site Energy) for All Purposes (First Use) for Selected Industries, 1998 and 2002 (Trillion Btu)

Source: Energy Information Administration, Form EIA-846, Manufacturing Energy Consumption Surveys, 1998 and 2002, http://www.eia.doe.gov/emeu/efficiency/mecs_trend_9802/mecs9802_table1a.html

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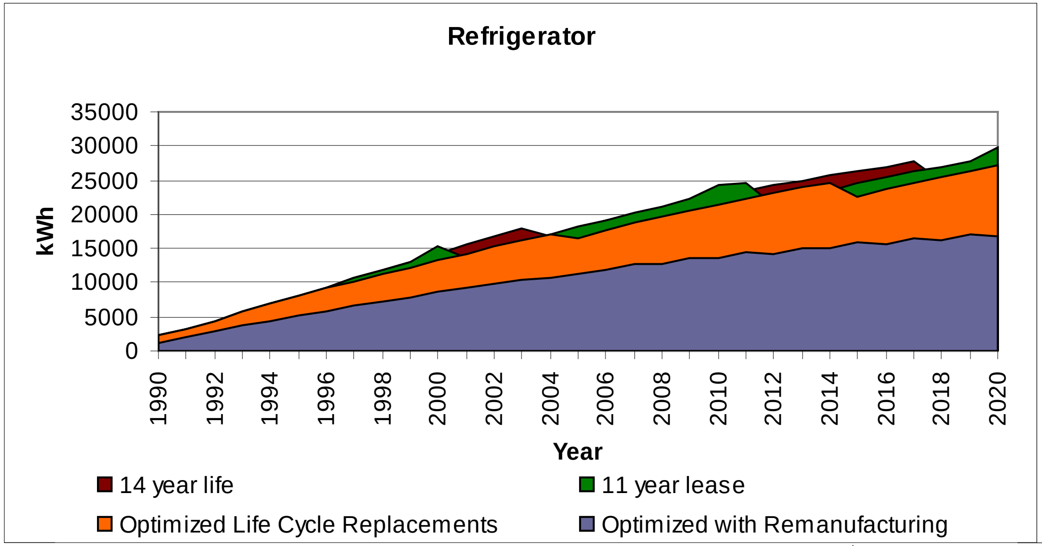
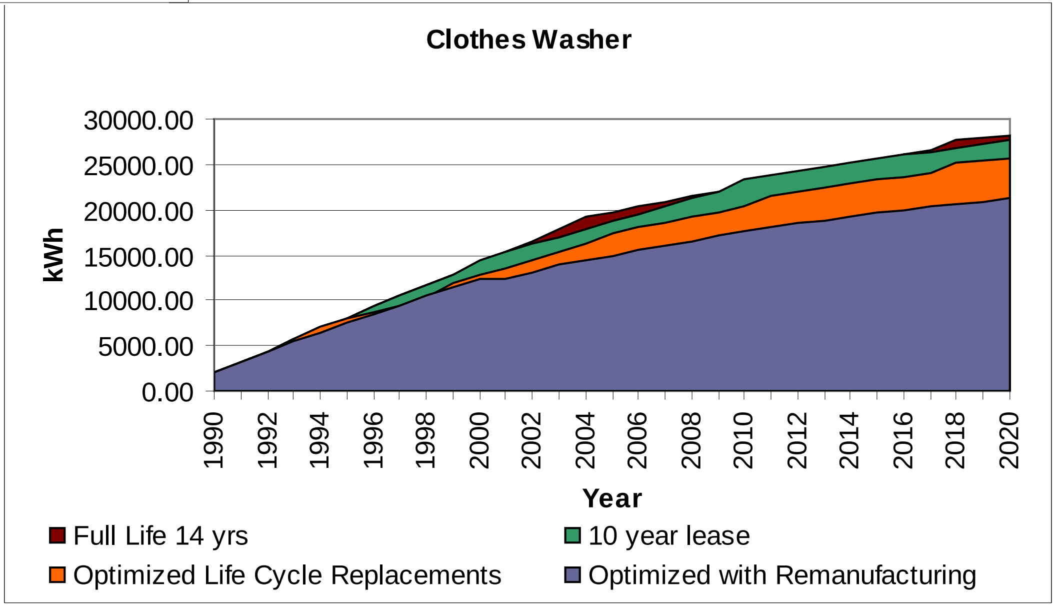
Re-X: Energy Savings through Remanufacturing



- Replacing products more frequently with more energy efficient technology helps
- But bigger gains can be made by including **remanufacturing**

Need:

- **Understanding of user behavior**
- **Understanding and modeling of impact of different options**
- **New enabling technologies**
  - Additive Manufacturing
  - Non-destructive testing



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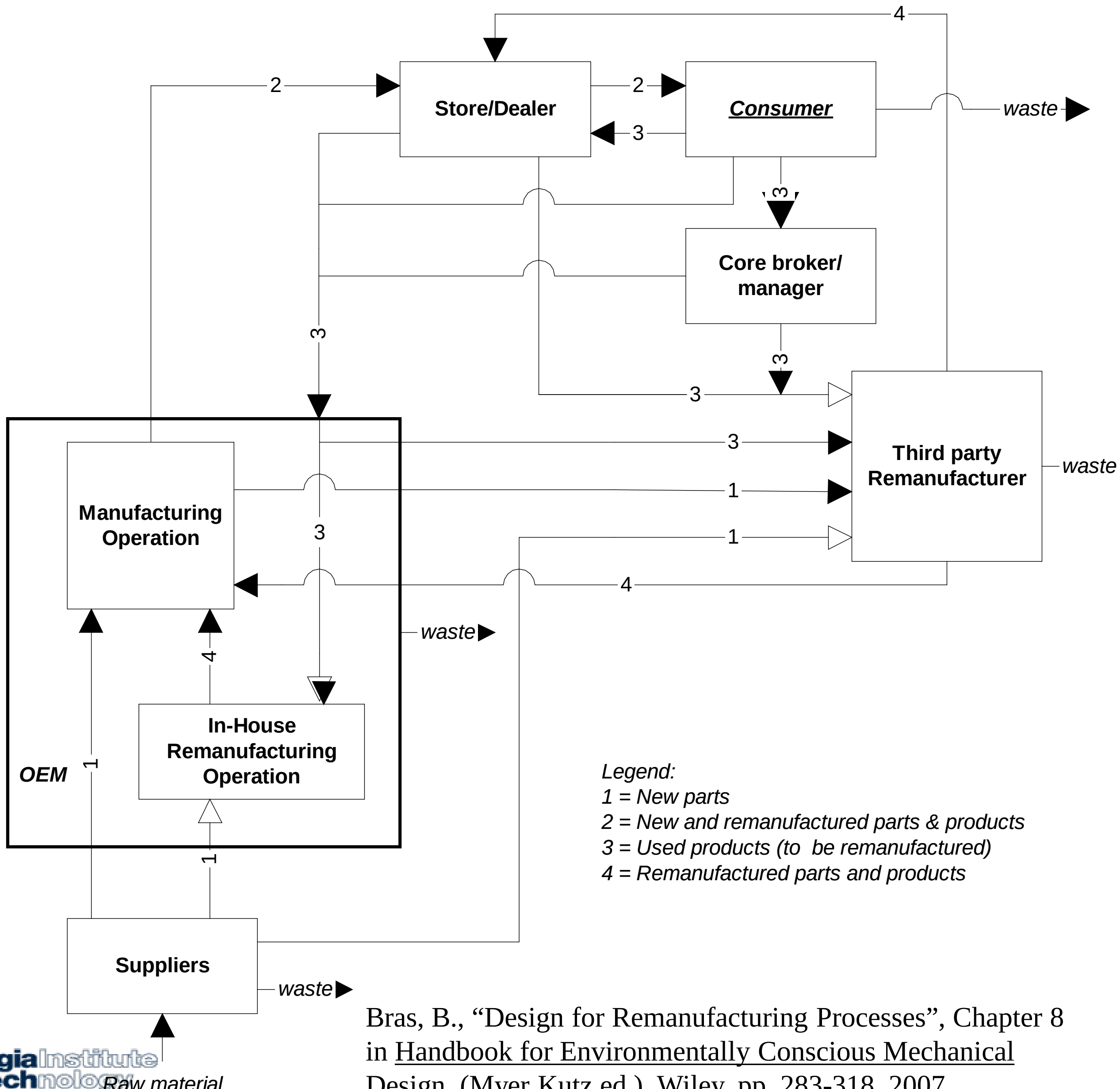
Intlekofer, K., Bras, B., and Ferguson, M., “Energy Implications of Product Leasing” Environmental Science and Technology, Vol. 44, No. 12, pp. 4409-4415, 2010

NSF Grant # 0620763

Remanufacturing Supply Chain -- Messy



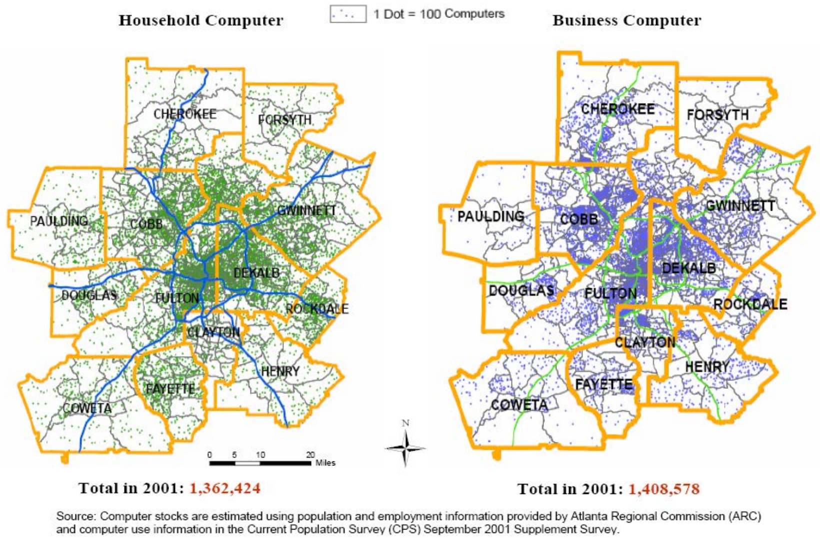
Bras, B., "Design for Remanufacturing Processes", Chapter 8 in <u>Handbook for Environmentally Conscious Mechanical Design</u>, (Myer Kutz ed.), Wiley, pp. 283-318, 2007

Social consequences – Re-X in China

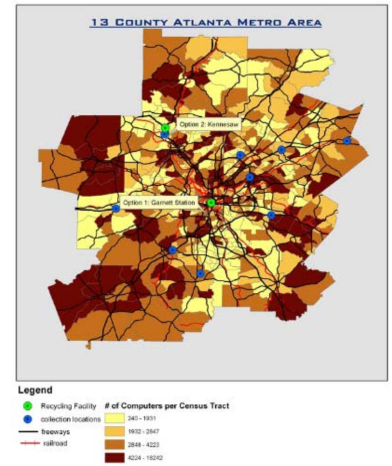
Mining Material from Cities (Urban Mining) – Local Socio-Economic Implications?

Urban Region (Atlanta)

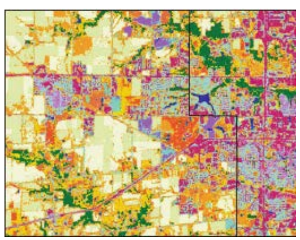
Product



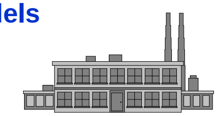
Recycling facility locations



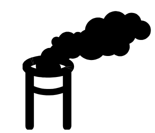
Product Inventory Estimate (PIE) models



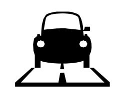
GIS, Demographic, and Consumer Behavior Models



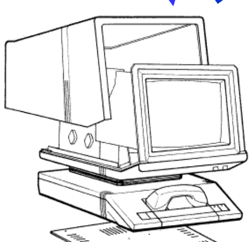
Facility/Process models



Environmental impact models



Transportation models



Product Bill of Material (BOM) & Sales data

Integrate urban datasets & GIS with engineering & industrial process models to quantify the socioeconomic and environmental impacts of locations for recycling centers and collection strategies
(Sustainable Industrial Systems for Urban Regions – SISFUR)

Social Accounting Matrices

- Production Activities
- Value Added by Sectors and Components
- Factor Incomes Wages, Profits, Rents, Interest
- Income Distribution
- Institutions: Households, Business, Government
- Consumption Patterns

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Another "Simple" Question…

- *What is better for the environment*: Digital pictures or conventional pictures?

  - Digital camera avoids chemicals in film developing.
  - However, digital cameras require electronics and computers that need energy and contribute to greenhouse gasses.

- Typical (correct) answer: *"It depends…"*

- In truth, the question has become irrelevant because the market has already spoken…

Again, it gets more complicated…

- **Consumer has many different options**
- **What is the environmental performance of product <u>systems</u>?**

Imaging Scenarios	ABBR	Capture	Processing	Output
Film Capture to Retail Print	FC/R	Film	Retail	Retail
Film Capture to Wholesale Print	FC/W	Film	Wholesale	Wholesale
Digital Capture to CRT Retail Print	DC/CR	Digital	PC/CRT	Retail
Digital Capture to LCD Retail Print	DC/LR	Digital	PC/LCD	Retail
Digital Capture to CRT Wholesale Print	DC/CW	Digital	PC/CRT	Wholesale
Digital Capture to LCD Wholesale Print	DC/LW	Digital	PC/LCD	Wholesale
Digital Capture to CRT Inkjet Print	DC/CI	Digital	PC/CRT	PC / CRT Inkjet
Digital Capture to LCD Inkjet Print	DC/LI	Digital	PC/LCD	PC / LCD Inkjet
Digital Capture to Display CRT	DC/CD	Digital	PC/CRT	PC / CRT Display
Digital Capture to Display LCD	DC/LD	Digital	PC/LCD	PC / LCD Display

Companies make strategic product and processes technology decisions and need to know the environmental issues associated with *different product systems, strategies, and use scenarios.*

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LCA Results

Scenario	ABBR	Greenhouse Emission kg CO_2 eq. / kg CO_2 eq.	Water Use m^3 / m^3	Waste Generation kg / kg	Energy Use MJ / MJ
Film Capture to Retail Print	FC/R	**1**	0.0075	0.0992	0.9801
Film Capture to Wholesale Print	FC/W	0.6127	**0.0064**	**0.0714**	0.6508
Digital Capture to CRT Retail Print	DC/CR	0.6770	0.2053	0.2512	0.7945
Digital Capture to LCD Retail Print	DC/LR	0.6409	0.0595	0.2281	0.6786
Digital Capture to CRT Wholesale Print	DC/CW	0.4673	0.2053	0.2494	0.6193
Digital Capture to LCD Wholesale Print	DC/LW	**0.2085**	0.0547	0.2034	**0.2235**
Digital Capture to CRT Inkjet Print	DC/CI	0.3122	0.1976	**1**	0.4606
Digital Capture to LCD Inkjet Print	DC/LI	0.2798	0.0670	0.9794	0.3567
Digital Capture to Display CRT	DC/CD	0.5145	**1**	0.3388	**1**
Digital Capture to Display LCD	DC/LD	0.3337	0.2709	0.1724	0.4203

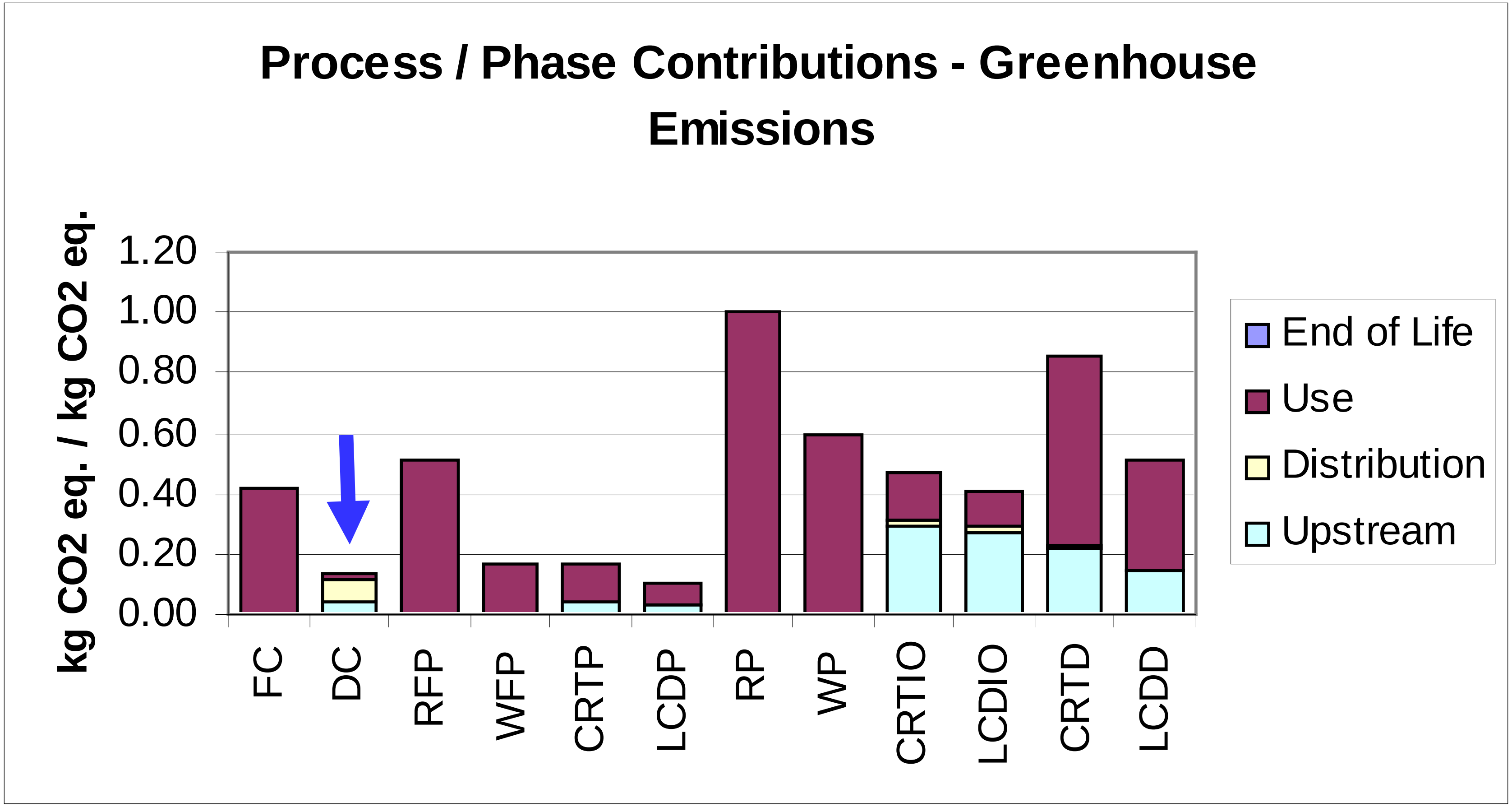
Best and worst are indicated in each column

Outcome/Impact:

- No clear winning or high risk scenario
- Supported business decision to go "digital"
- Digital technologies offer more choice and flexibility, resulting in a much wider range of potential impact
- Influence of consumer during use phase can significantly influence environmental burden
- ***Providing services (wholesale printing, Ofoto) instead of products (PC printers) is better (in this case)***

Muir, M., Bras, B., and Matthewson, J., "Life Cycle Assessment of Film and Digital Imaging Product System Scenarios", Journal of Sustainable Manufacturing, Vol. 1, No. 3, pp. 286-301, 2009

GHG Emissions – Logistics are irrelevant



- GHG emissions for various options by process
- Distribution has only real impact in DC (Digital Camera). ***Any ideas why?***

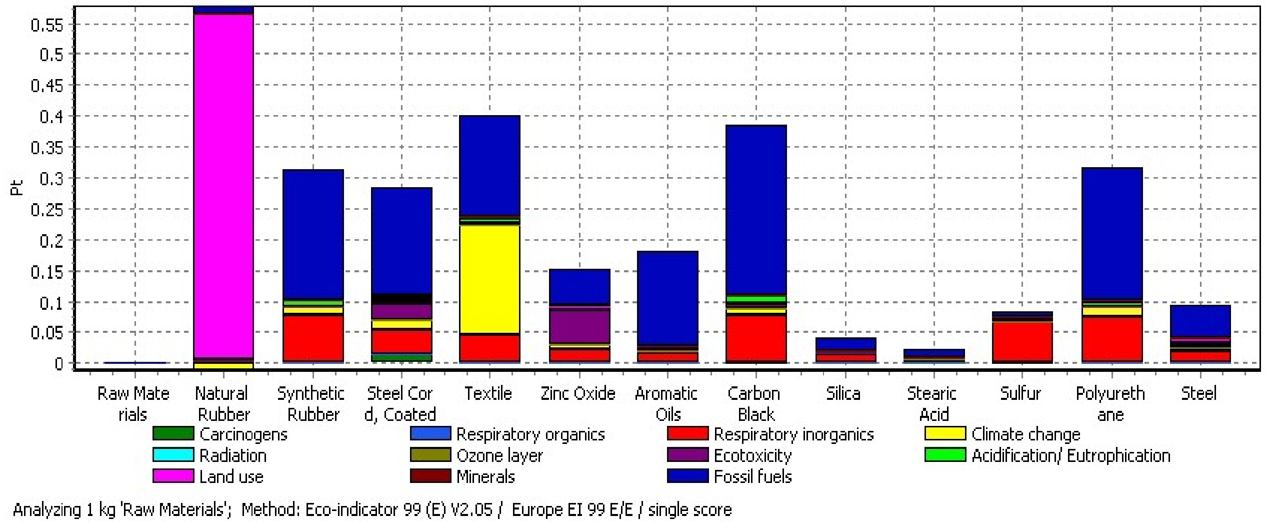
Natural vs Synthetic Rubber – Typical Dilemma

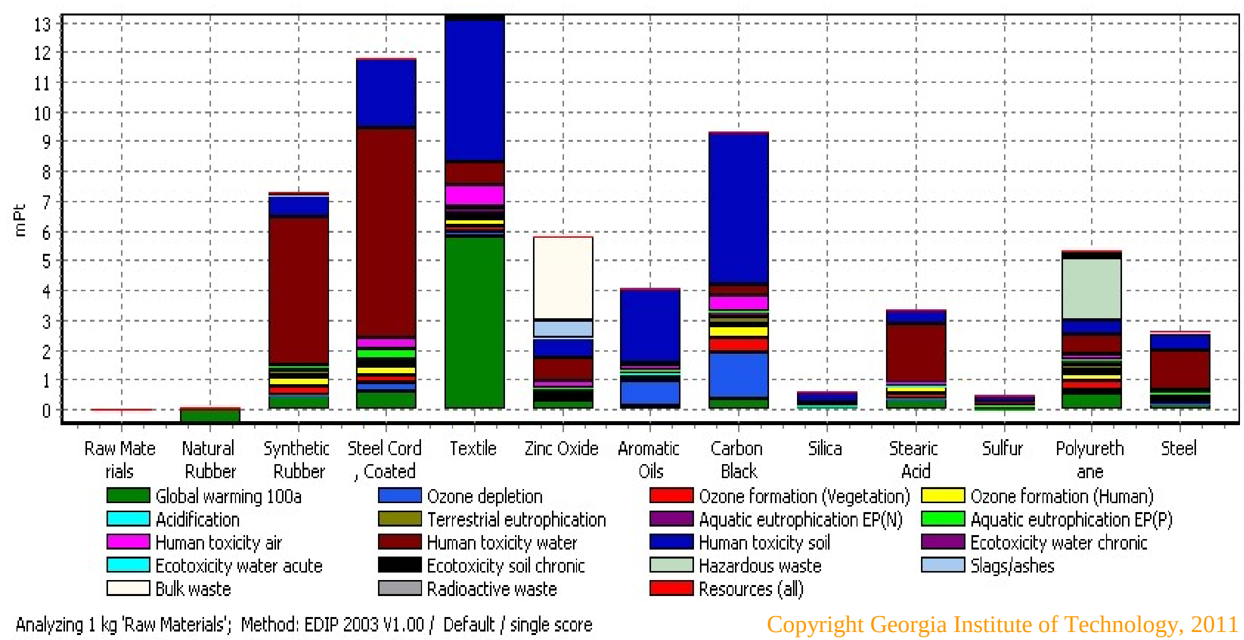
- Impact of production of 1 kg of raw material – EcoIndicator 99 versus EDIP 2003

- ***What now?***

- ***One solution: check whether it even matters…***

Bras, B. and Cobert, A., "Life-Cycle Environmental Impact of Michelin Tweel® Tire for Passenger Vehicle", SAE International Journal of Passenger Cars– Mechanical Systems, June, Vol. 4, No.1, pp. 32-43, 2011





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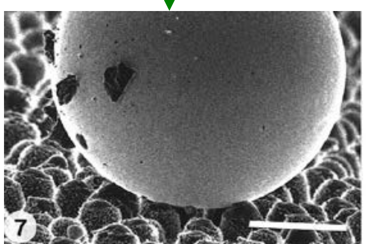
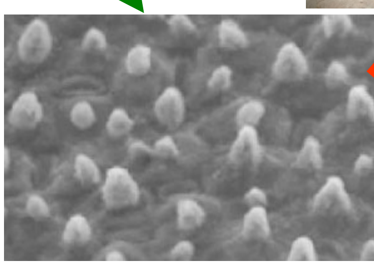
Direct Modeling and Simulation of Effects on Ecosystems – Great in theory, but hard in practice

Lotus effect (self-cleaning)





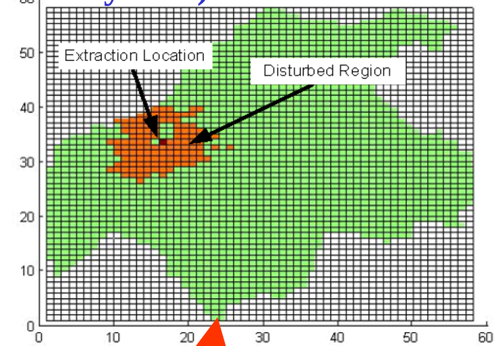
Surface nano-bumps

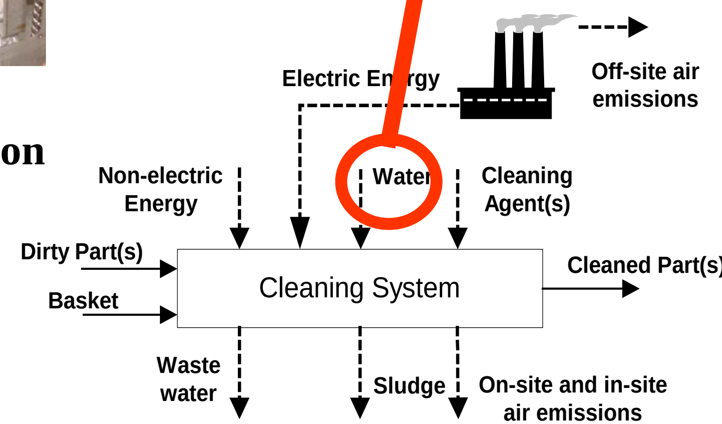
Process: aqueous cleaning machine

Ecosystem

Part: transmission casing

Spatial ecosystem landscape model (predicting effect on ecosystem)





Process model (predicting water use)

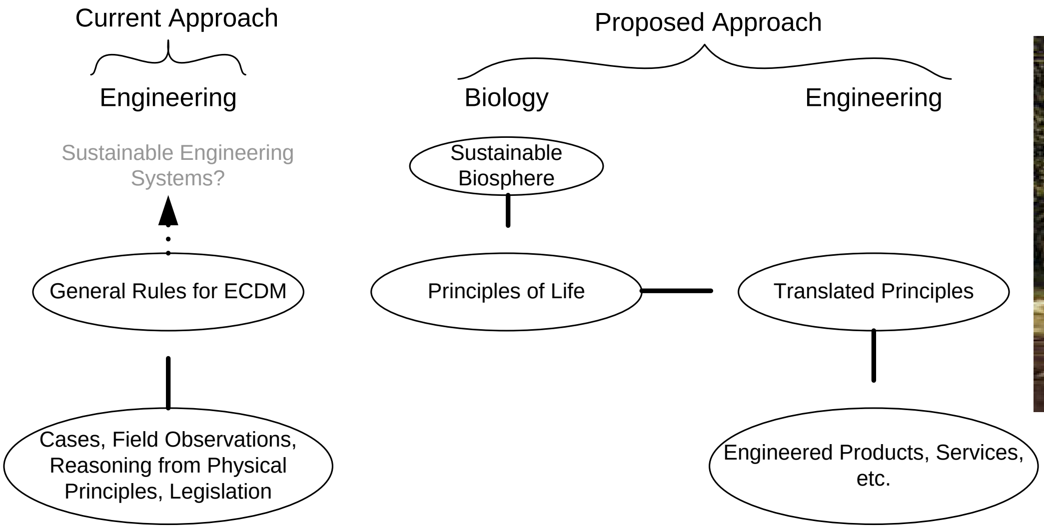
Idea: Reduce water consumption in remanufacturing through self-cleaning surface

Reap, J., Roman, F., Guldberg, T., and Bras, B., "Integrated Ecosystem Landscape and Industrial Modeling for Strategic Environmentally Conscious Process Technology Selection", 13th CIRP International Conference on Life-Cycle Engineering Conference, Leuven, Belgium, May 31-June 2, 2006

Bio-Inspired Metrics and Guidelines

Going beyond the metric conundrum:

- Nature has been sustainable for a long time.
- What can we learn from past & present biological systems?
  - Including extinct systems…
- Can we derive design guidelines from Nature that will result in inherently sustainable engineered systems?



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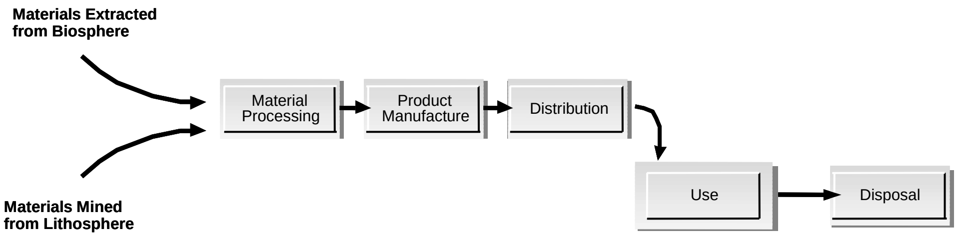
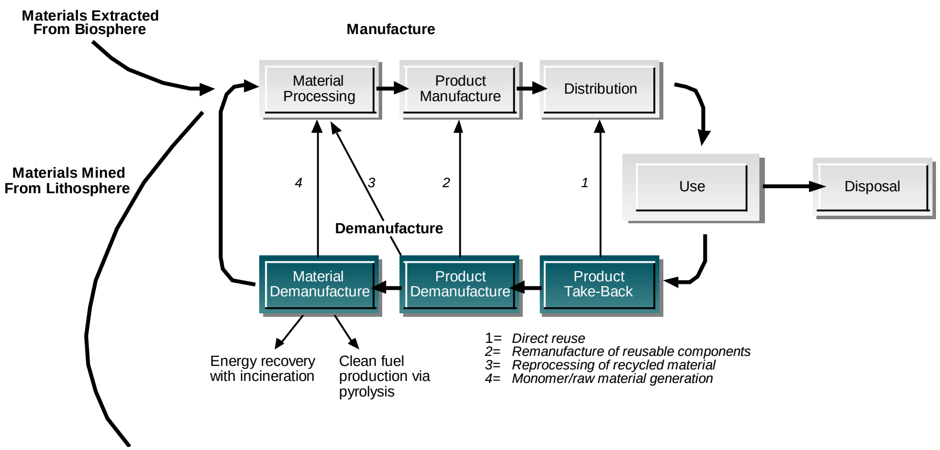
Different Production Systems



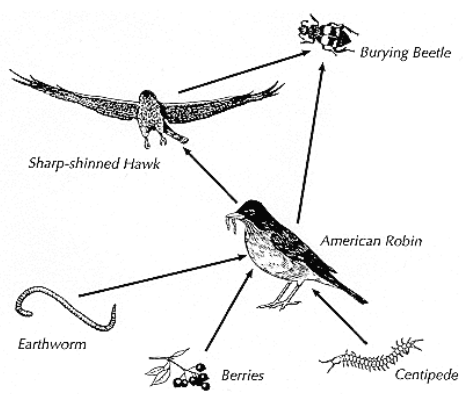
Linear Production:
“Take, make, waste”
(our current system)



Vs.

Closed Loop, Industrial
Symbiosis, etc.,
as promoted by
Industrial Ecologists

Vs.



An example of a food web.

Ecological Networks
(as in Nature)

How do they compare?

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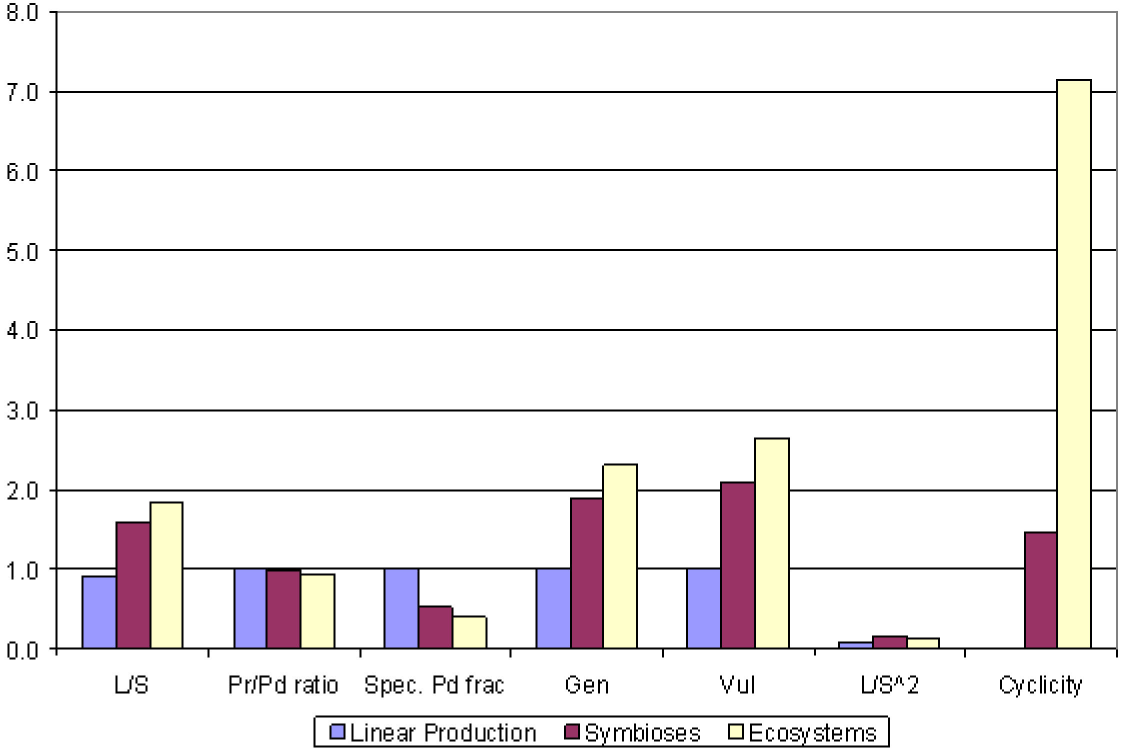
How industrial ecosystems rank



Average ecological structural metrics for a linear production chain, industrial symbioses (n=29) and ecosystems (n=40)

- Industrial symbioses have greater resource efficiency and less waste compared with linear counterparts
- Statistically, industrial symbiosis and food web structures cannot plausibly be grouped with food webs.
- Symbioses represent middle ground
- Worth exploring result of patterning closed industrial material flows after those found in nature

Work in progress… NSF Grant # 0967536

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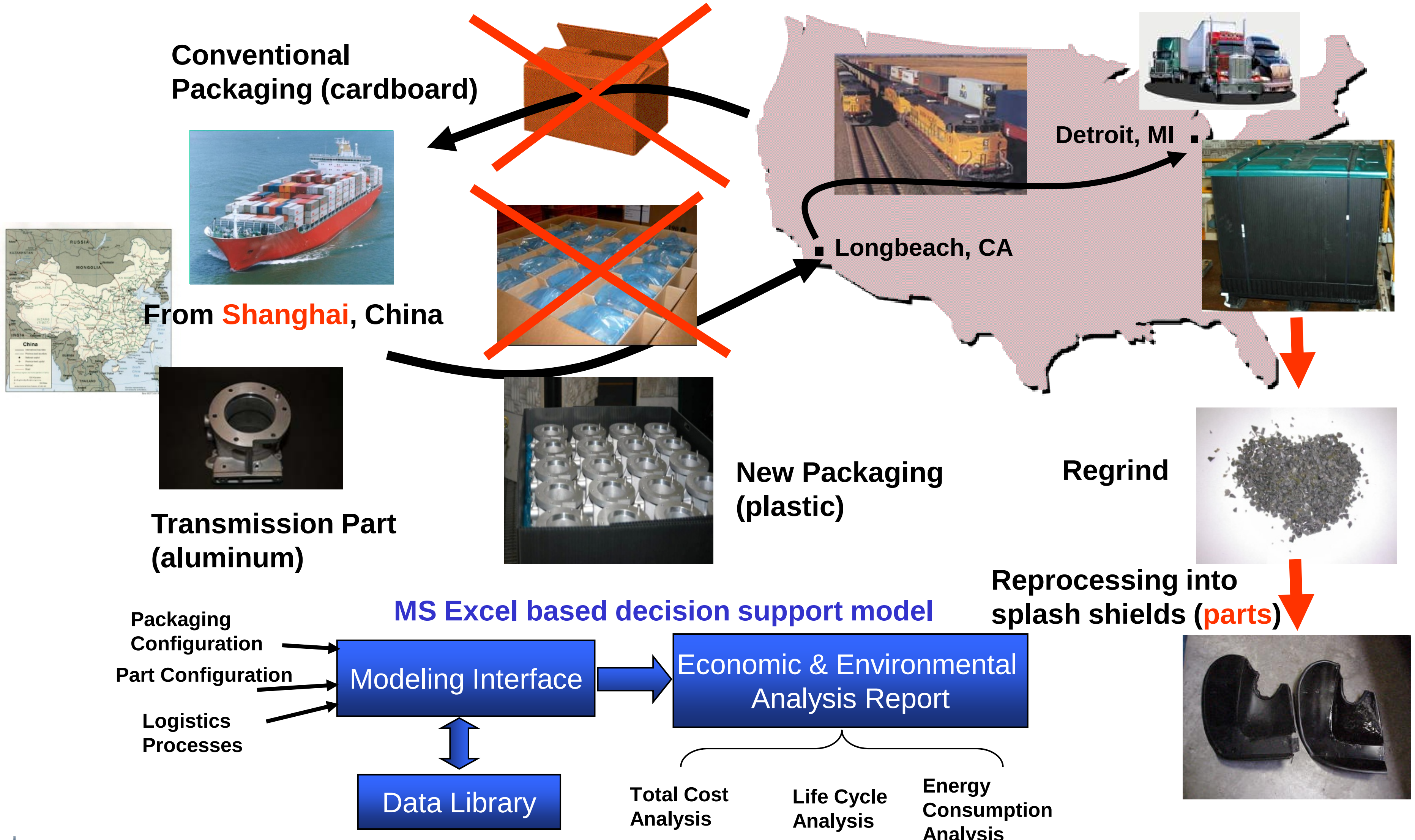
Importance of “Triple Bottom Line”

- Environmental assessments are not enough
- Financial is also needed
  - Total Cost Analysis
  - Life-Cycle Costing
  - Activity-Based Costing
- Social “quality of life” assessments also desirable
  - but harder for engineers
  - Example metrics: job creation, ergonomics, etc.
- Metrics are often not independent, but causally related

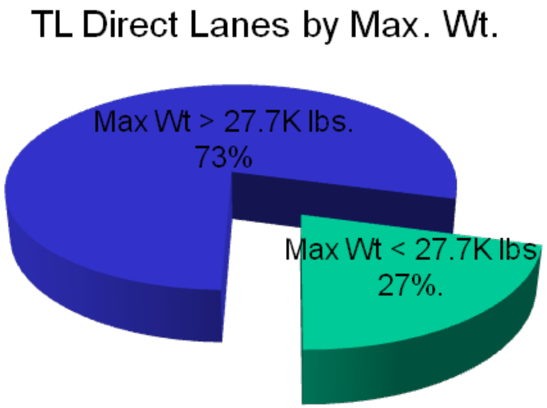
Triple Win Example – It can be done!
B2B Packaging



A key to success: Standard internal six sigma process format was used

Rethinking Delivery – Engaging External Parties with Sound Engineering

- Many systems are over-engineered
- Appropriate technology and sound engineering can go a long way towards sustainability
- Switching from Class 8 High Duty Diesel trucks to Ford F750 can provide significant savings.
- Ideas were triggered by quest for fuel savings.



	Ford F-450/550	Class 6 Ford F-650	Class 7 Ford F-750	Class 8 (Freightliner Day Cab)
MSRP (New)	$42,295/$45,240	$54,167	$55,448	$140,000
Price w/ Incentives	$33,750/$36,463	$43,334	$44,358	$87,000
Curb Wt.	17,950 – 19,000 lbs. (GVWR)	9,300 lbs.	9,300 lbs.	16,000 lbs.
Gross Combined Wt. Rating	24,000 – 33,000 lbs.	50,000 lbs.	50,000 lbs.	80,000+
Towing Wt.	24,800 lbs.	40,700 lbs.	40,700 lbs.	57,000 lbs.
Max Payload	16,800 lbs.	27,700 lbs.	27,700 lbs.	44,000 lbs.
Output	325-362 hp	325 hp	325 hp	410-550 hp

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Limits of Engineering

- **Be aware of "systems solutions" beyond engineering as well as "unintended consequences"**

For example:

- Localities matter in sustainability
  - Relocating a manufacturing facility to a locality with renewable power often has a larger carbon footprint effect than any process efficiency improvement

GA Power Plant Bowen (Cartersville):

- **CO_2 emission: 0.9 kg/kWh**
- **H_2O evaporation: 0.4 gallons/kWh**

South-East average (incl. Georgia):

- **CO_2 emission: 0.6 kg/kWh**

- Social behavior may have larger influence than engineering
  - Car pooling creates more fuel savings than all technologies combined
  - Rebound effect can kill any efficiency gains

Some Lessons Learned (over the years)…

- Assessment approach (top down, bottom up, accuracy level, etc.) and data requirements depend on the question to be answered
- Data is everywhere and nowhere, and never reconciled
- Legacy systems are a fact of life
- Location and time matter (where and when)
- System boundaries changes can fudge the numbers
- Expect the unexpected
- Verify! (prediction ≠ reality)
- Transparent modeling is crucial (for cont. improvement/use)
- Need for model base instead of database
- Start simple with best and/or worst case scenarios
- Best solutions invariably require change of system boundary
- The wheel is reinvented all the time – also in academia

In Summary…

- Key concepts:
  - Life Cycle Thinking
  - Closed Loop Thinking (Re-X)
  - Systems Thinking, Modeling & Simulation
  - Good science and engineering
- Some tools are available, but …
  - Not mainstream
  - Validity can be weak
  - Integration severely lacking
- Success is enhanced by using/extending/adapting known methods, techniques and tools
  - Six Sigma, Activity-Based Costing, etc.
- Evolution of thinking typically occurs - pushing the system boundaries
- Achieving sustainability solutions is a very complex, multi-scale problem requiring multi-disciplinary teams and approaches
  - which equates to slow going with high learning curves
  - Good Teams: Engineering + City/Regional Planning + Sciences (Earth & Atmospheric Science + Biology) + (Industrial) Practitioners + Management/Economics
- Need more dissemination, communication, and education