能源及環境學院
SCHOOL OF ENERGY AND ENVIRONMENT

香港城市大學
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SEE 1003
Introduction to Sustainable Energy and Environmental Engineering

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Module 5 – Tools: Systems Analysis for Sustainability

Material Flow Analysis, Life Cycle Assessment

March 21, 2022

Week	Topics	Assignment issued	Key dates
Week 1	Course introduction; Climate Change and the Engineering approach		**Quiz 1**
Week 2	**MODULE I** Introduction to Sustainability Energy, Natural Resources and pollution, Electromagnetic energy; Electrical energy – Lighting, Light pollution, Policy	**Semester-long Project**	
Week 3		**Project deliverable 1.1**	
Week 4	**MODULE II** Energy and Environmental Implications– Transportation Human-Environment Impacts		
Week 5		**Project deliverable 1.2**	**Project deliverable 1.1**
Week 6	**MODULE III** Noise Pollution in Urban Environment	**Project deliverable 1.3**	**Quiz2**
Week 7	**MODULE IV** Urban Sustainability and Resilience		**Project deliverable 1.2**
Week 8	**MODULE V** Tools: Systems Analysis for Sustainability Cost-Benefit Analysis		
Week 9			
Week 10	Material Flow Analysis, Life Cycle Assessment		**Project deliverable 1.3; Quiz3**
Week 11	**MODULE VI** Advances in Environmental and Energy Engineering **MODULE VII** Waste management and Waste-to-Energy	**Project deliverable 1.4**	
Week 12	**MODULE VIII** Economics and Policy of Energy and Environment	**Project deliverable 1.5 (Now this is extra credit- BONUS!)**	**Quiz4**
Week 13	**Individual Presentations (5-mins)**		**Final Project Report (merged with Project deliverable 1.4)**

Evolution of Complex Environmental Problems

Societal need	Solution leading to…	Today's problem
Inexpensive, easily generated energy	Mining fossil fuels	Global climate change, mercury emissions
Nontoxic, nonflammable refrigerants	Chlorofluorocarbons	Ozone depletion
Octane booster (to allow higher performance IC engines)	Tetraethyl lead	Lead in soil, air, and human tissues
Protection of metal parts	Coatings and electroplating	Heavy metal toxicity
Need for lightweight, moldable materials	Plastics	Toxic organic emissions, nondegradable containers
Control of malaria	DDT and other biocides	Adverse effects on birds and mammals
Food production (calories and protein)	Artificial fertilizer (N and P)	Eutrophication, hypoxia, and climate change
Cleaner air (power plants)	Taller stacks	Acidification
Cleaner air (automobiles)	Oxygenate additive (MTBE)	Groundwater pollution
Energy independence	Biofuels	Higher food prices
Living spaces	High-rise apartments	Urban congestion

The Rise of the Sustainability Paradigm

Trend: Appearance of environmental problems at periodic intervals that force the evolution of environmental policy

Observation: The problems proceed from local and relatively simple and short term (19^{th} century), to regional (20^{th} century) and to global and longer term (latter 20^{th} century), each time becoming more complex technically, economically, and socially, i.e. from “tame” problems to “wicked” problems

Tame vs. Wicked Problems

Characteristic	How it appears in tame problems	How it appears in wicked problems
Problem formulation	Can be clearly written down. The problem can be stated as a gap between what is and what 'ought' to be.	Difficult to define. Many possible explanations may exist.
Testability	Potential solutions can be tested as either correct or false	There is no single set of criteria for whether a solution is right or wrong, they can only be more or less acceptable relative to each other
Finality	Problems have a clear solution and ending point	There is always room for more improvement and potential consequences may continue indefinitely
Level of analysis	It is possible to bound the problem and identify its root cause. There is no need to argue about the level at which to intervene	Every problem can be considered a symptom of another problem. It has no identifiable root cause and one is not sure of the appropriate level at which to intervene
Replicability	It may repeat itself many times	Every problem is essentially unique
Reproducibility	Solutions can be trialed and excluded until the correct solution is found	Each problem is a one-shot operation. Once a solution is attempted, you cannot undo what you have already done

Acid Rain/Fine Particulates

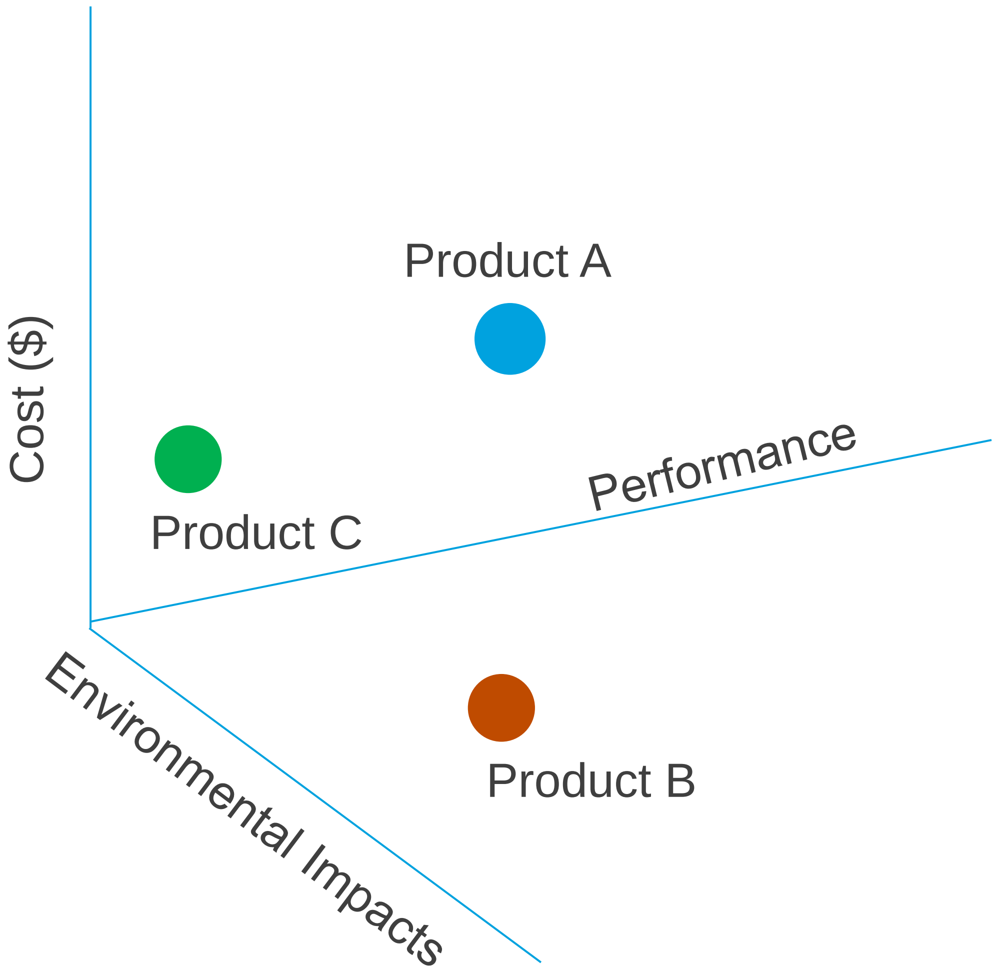
Caused by the emission of “acidic” gases (SO_2, NO, NO_2) from coal power plants, which form sulfuric and nitric acid when in contact with rainwater, and which are precursors to the formation of fine (~2.5 µm) particulates

Acidity impacts: Impairment of fisheries, loss of biodiversity, decay of buildings and monuments, damage to automotive coatings, aesthetic enjoyment

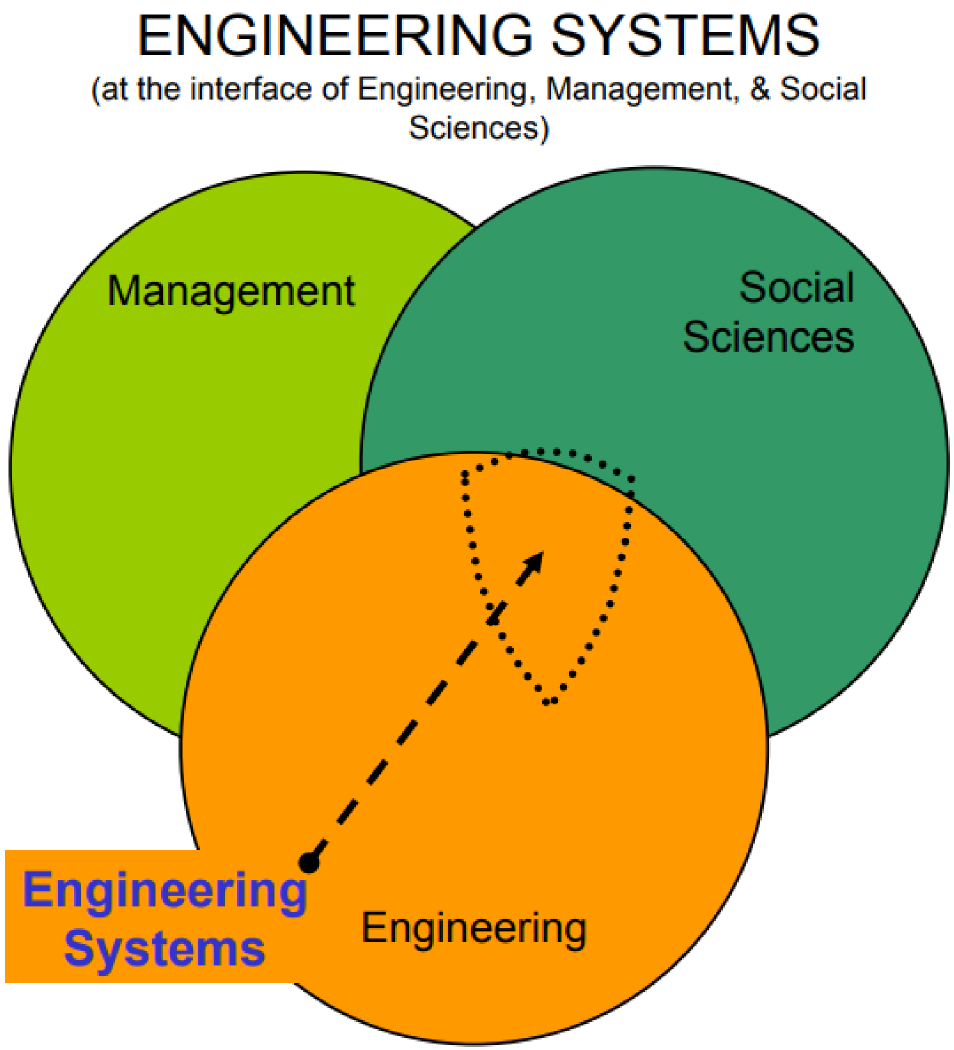
Fine particulate impacts: respiratory problems, lowered visibility, aesthetic enjoyment

How do Sustainability Engineers make Decisions?

Decisions based on assessing trade-offs between Cost, Technical and Environmental Factors

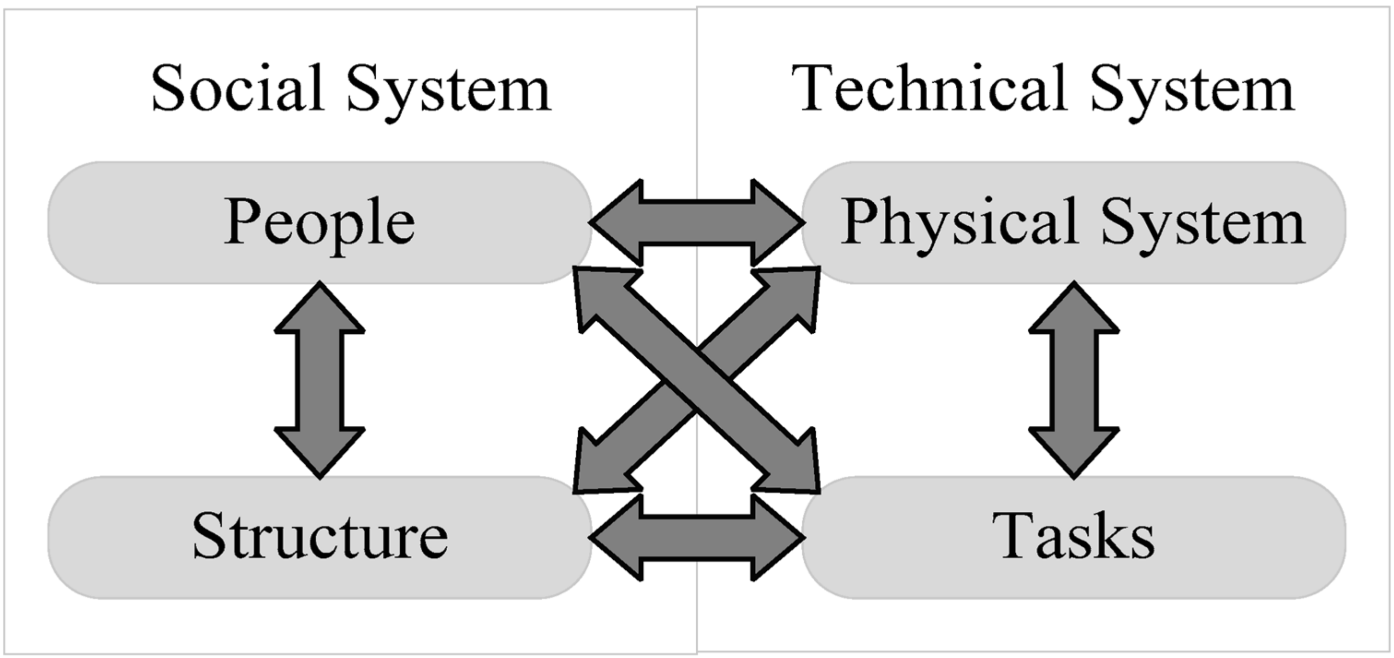


Sustainability of Engineered Systems



Definition: Socio-Technical System

- Socio-Technical System
  - an intellectual **tool** to help us recognize patterns in the way **technology is used and produced for sustainability**



Simplest Form:

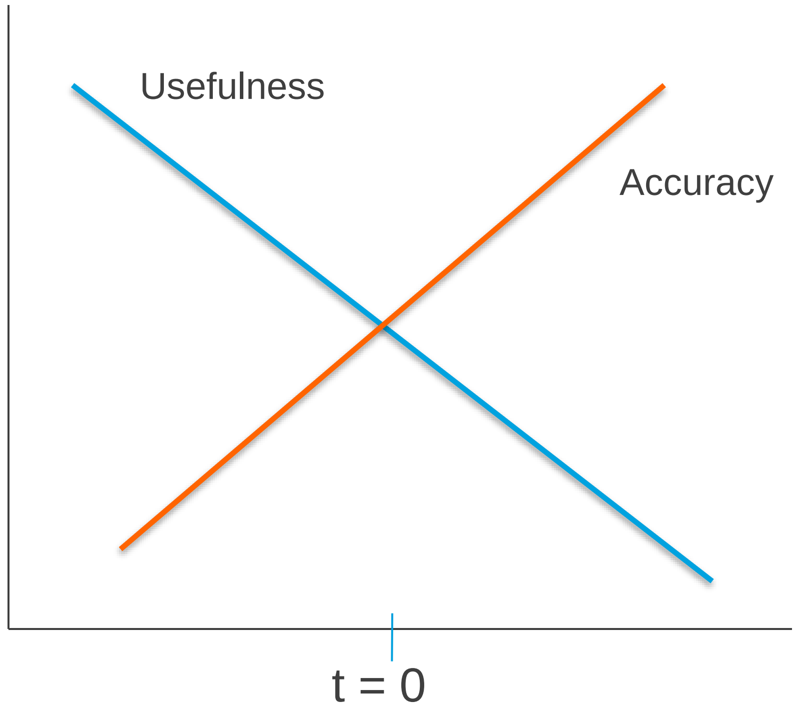
	Benefits
-	Costs
	Net Benefit

Are net benefits positive (NB > 0) ?

Frustrating Correlation

Accuracy (*ex post*) ≥ Accuracy (*in medias res*) ≥ Accuracy (*ex ante*)

Usefulness (*ex post*) ≤ Usefulness (*in medias res*) ≤ Usefulness (*ex ante*)



Alternative Domination

- Choose among these 3 cars

Car 1	Car 2	Car 3
$25,000	$16,000	$26,000
47 mpg	33 mpg	45 mpg
High performance	Medium Performance	Medium Performance
Medium comfort	Medium comfort	Low comfort

- Why would I ever choose car 3?
  – It is “dominated” by Car 1: on every metric, Car 1 is better

Who uses it?

- **Everyone!**
  - Government
  - Individuals
  - Consultants
  - Industries
  - NGOs
  - Citizen groups

- Done under different labels, or even subconsciously

What are its limitations?

- Information gathering costs/burden
  - Benefits are difficult to quantify
  - Costs are difficult to quantify
  - Difficulty in monetizing benefits and costs
  - Costs and benefits may not be spread across the same groups
  - Predicting future behavior is not easy

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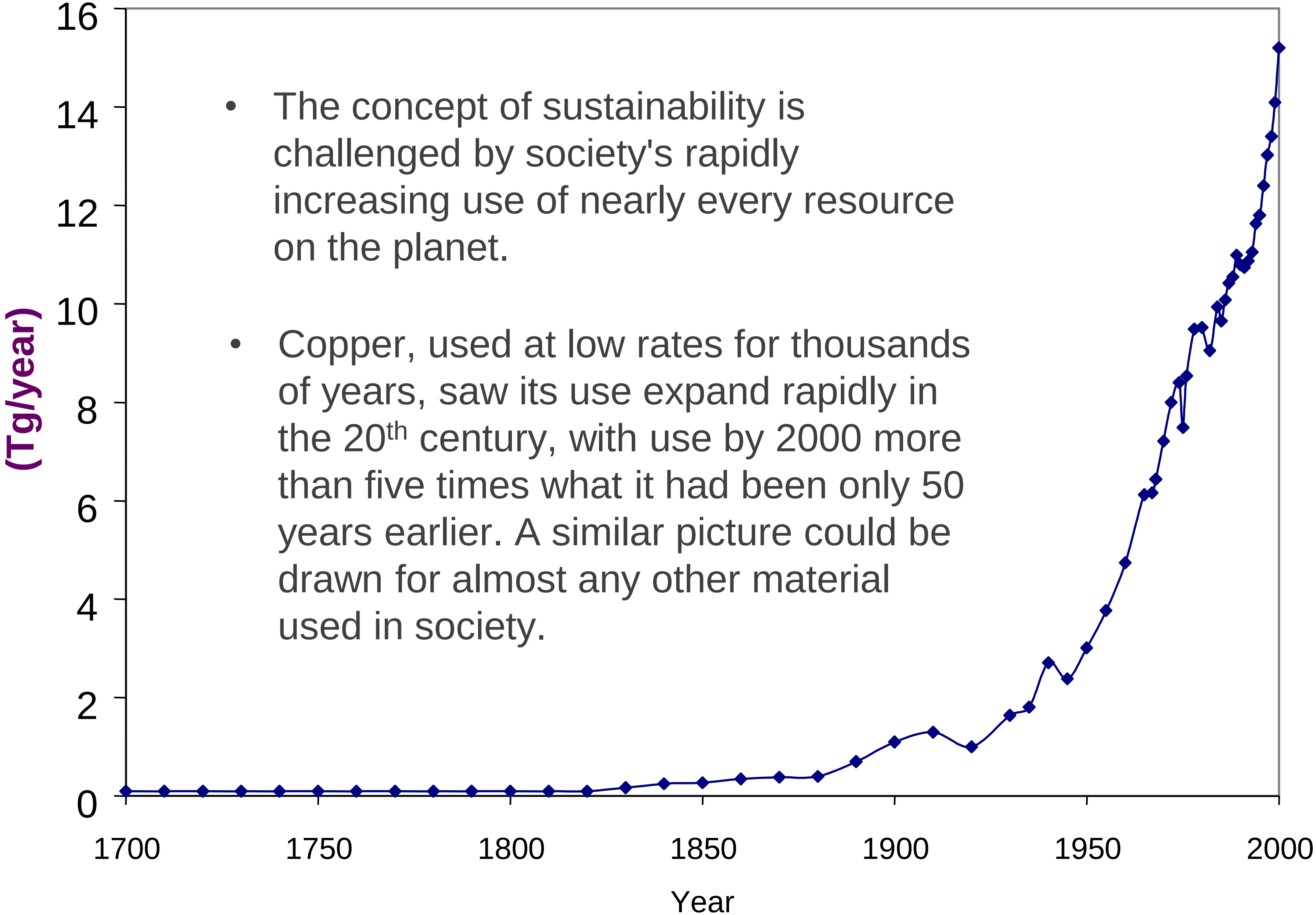
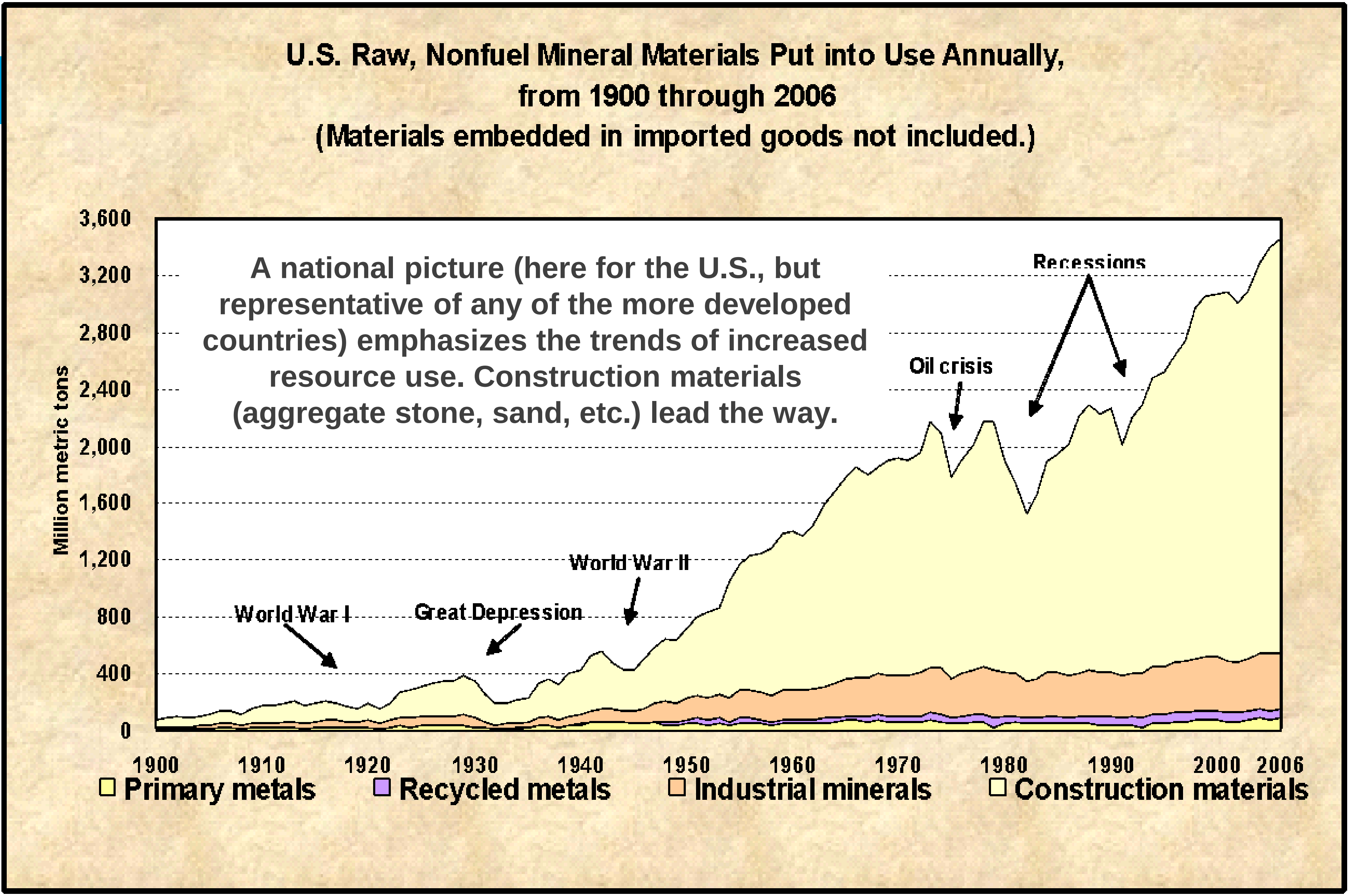
Material Flow Analysis (MFA)

Annual Copper Usage



- The concept of sustainability is challenged by society's rapidly increasing use of nearly every resource on the planet.

- Copper, used at low rates for thousands of years, saw its use expand rapidly in the 20th century, with use by 2000 more than five times what it had been only 50 years earlier. A similar picture could be drawn for almost any other material used in society.

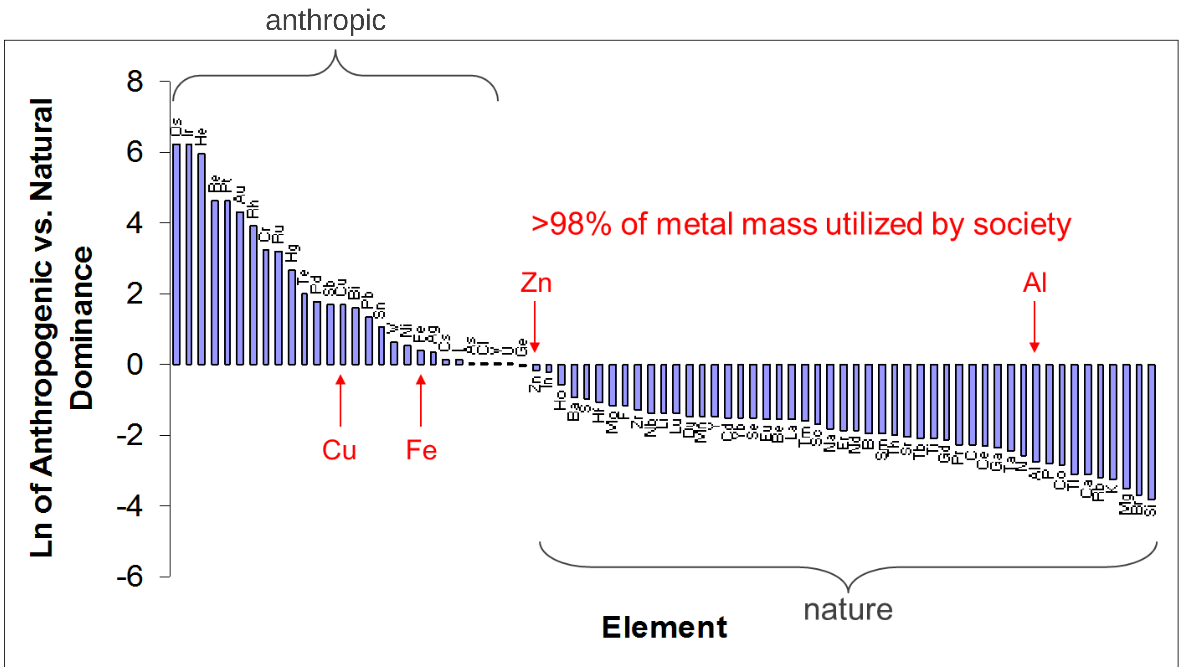


Courtesy of S. Sibley and G. Matos, U.S. Geological Survey

Humans as geomorphic agents (by element)

The ratio of the sum of anthropogenic flows (mining, fossil fuel combustion) to the sum of natural flows (erosion, air-blown dust).

The 4 metals that constitute over 98% of the mass of all metal utilized by society are across the spectrum (Cu anthro dominated, Al natural dominated, Fe & Zn about even).



Source:
Adapted from Klee, R. J. and T. E. Graedel (2004). "Elemental cycles: A status report on human or natural dominance." Annual Review of Environment and Resources **29**: 69-107.

Two stories are being told here: 1) total mass flows, and 2) the fact that humans dominate the global cycles of about a third of the elements of the periodic table.

Definition of Material Flow Analysis

- Material Flow Analysis (MFA) is the quantification and assessment of matter (water, food, excreta, wastewater...) and substances (nitrogen, phosphorus, carbon...) mass flows and processes, in a system (city, country, etc.) during a defined period.
- The method allows identifying problems and quantifying the impact of potential measures on resource recovery and environmental pollution.

Principle: Conservation of Mass

- MFA is based on the law of conservation of mass (and, when using MFA-type analyses to examine energy systems, the conservation of energy)
  - Material can be transformed but not lost
  - Boundary surrounding entire Earth
  - Overall quantity of material will not change over time
- Quite simply, an accounting of goods and substances through a system.

Tracking material flows at different organizational levels

- Single facility
- In a defined entity
- Across facilities
- In a city or region
- On an island
- Nationally
- Globally

In principle, material flow analysis can be conducted at any spatial or organizational level where a ***reservoir*** *and the associated* ***sources*** *and* ***sinks*** *can be identified and measured*

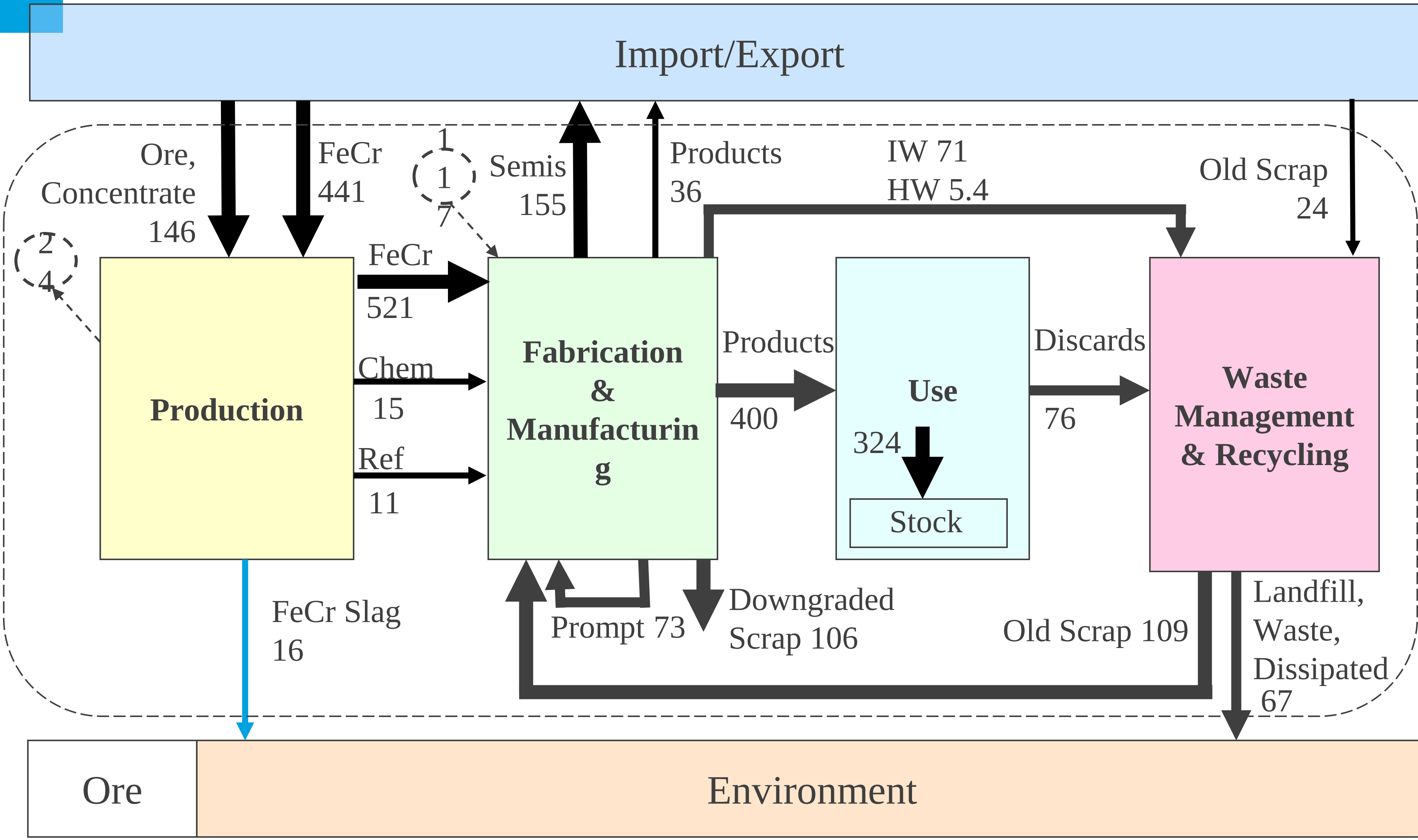
MFA contains the following main steps

1. **Identification** of the relevant material flows
2. **System analysis** (selection of the relevant matter, processes, indicator substances and system boundaries)
3. **Quantification** of mass flows of matter and indicator substances
4. **Identification** of weak points in the system
5. **Development and evaluation** of scenarios and schematic representation, **interpretation** of the results

National MFA Example:

Chromium Cycle for Japan

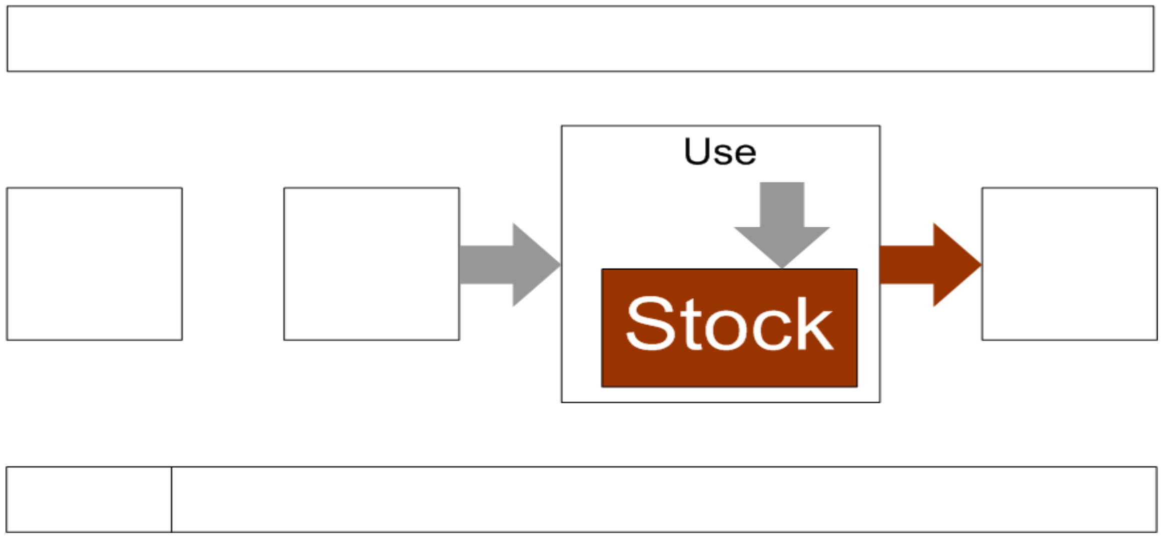
Japan Chromium Cycle: One Year Stocks and Flows, 2000



Gg Cr/yr

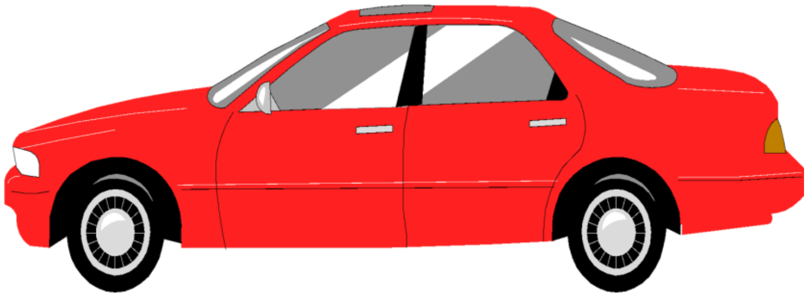
FeCr = ferrochromium; IW = industrial waste; HW = hazardous waste; Ref = refractories

How do we quantify stocks in use?



How we determine the stocks in use, their ages, and their probable in-use lifetimes?

Quantifying stock per capita Step 1: Determine content of major reservoirs



Typical auto – 21 kg Cu

Typical house – 200 kg Cu

Quantifying stock per capita
Step 2: Multiply by the number of units in the reservoirs

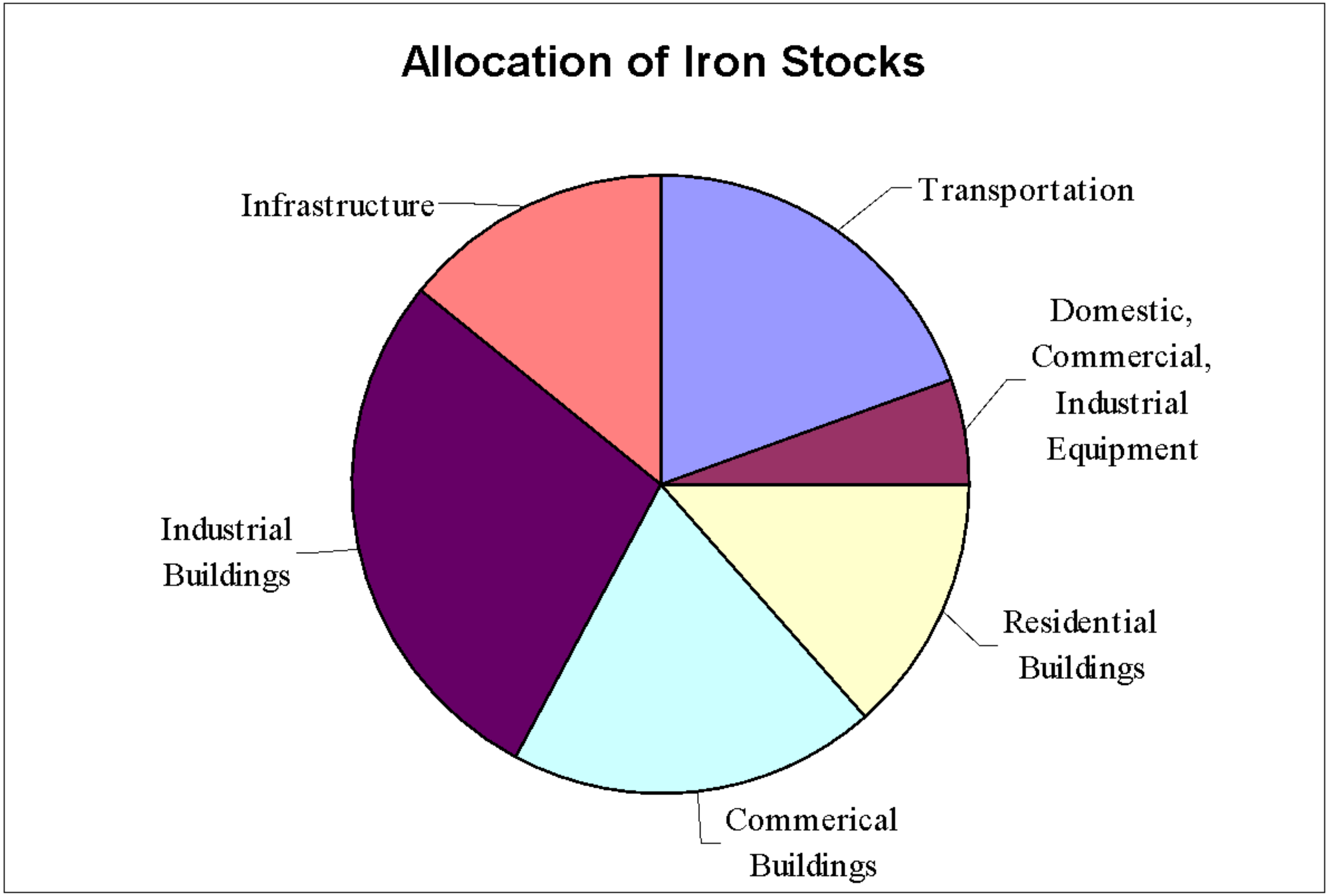
Municipal statistics furnish the number of registered vehicles, the number of homes, and other needed information.

Typical Major Product Categories

- Buildings
- Equipment
- Transportation
- Infrastructure

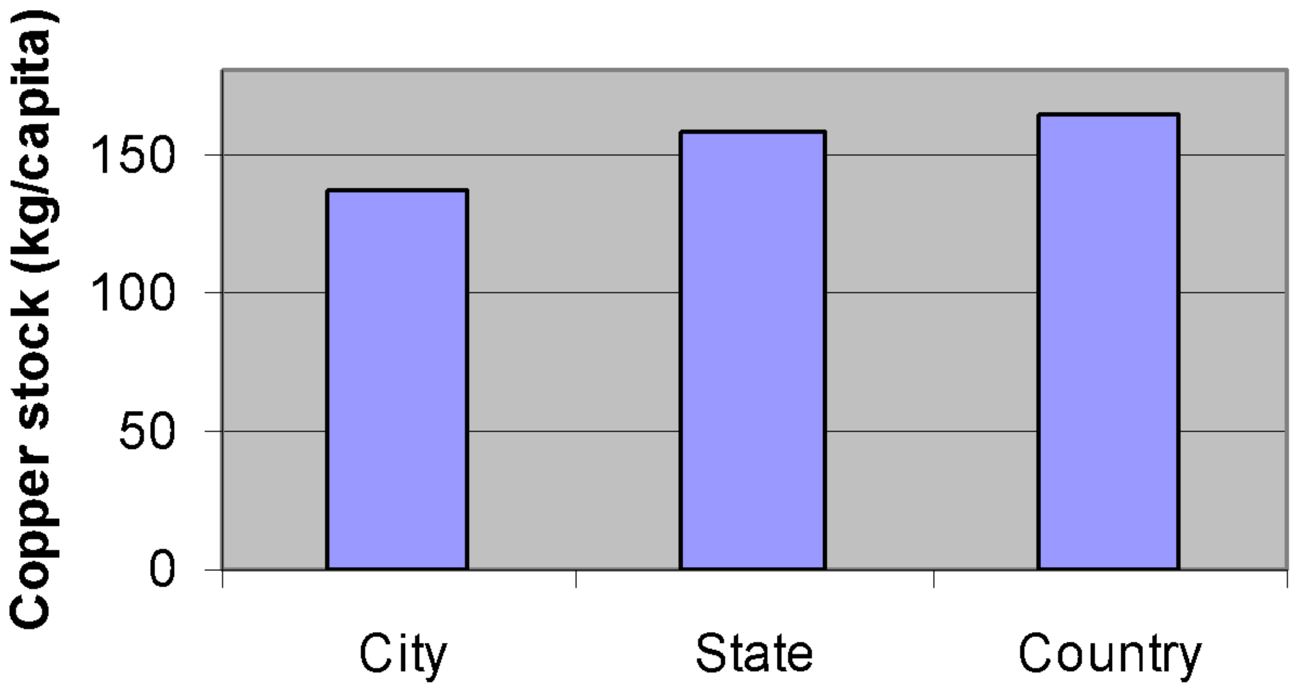
Results

9,300 kg Fe per capita



City: New Haven, State: Connecticut, Country: USA. Courtesy of T. Wang

Copper In-Use Stock Results at Different Spatial Levels

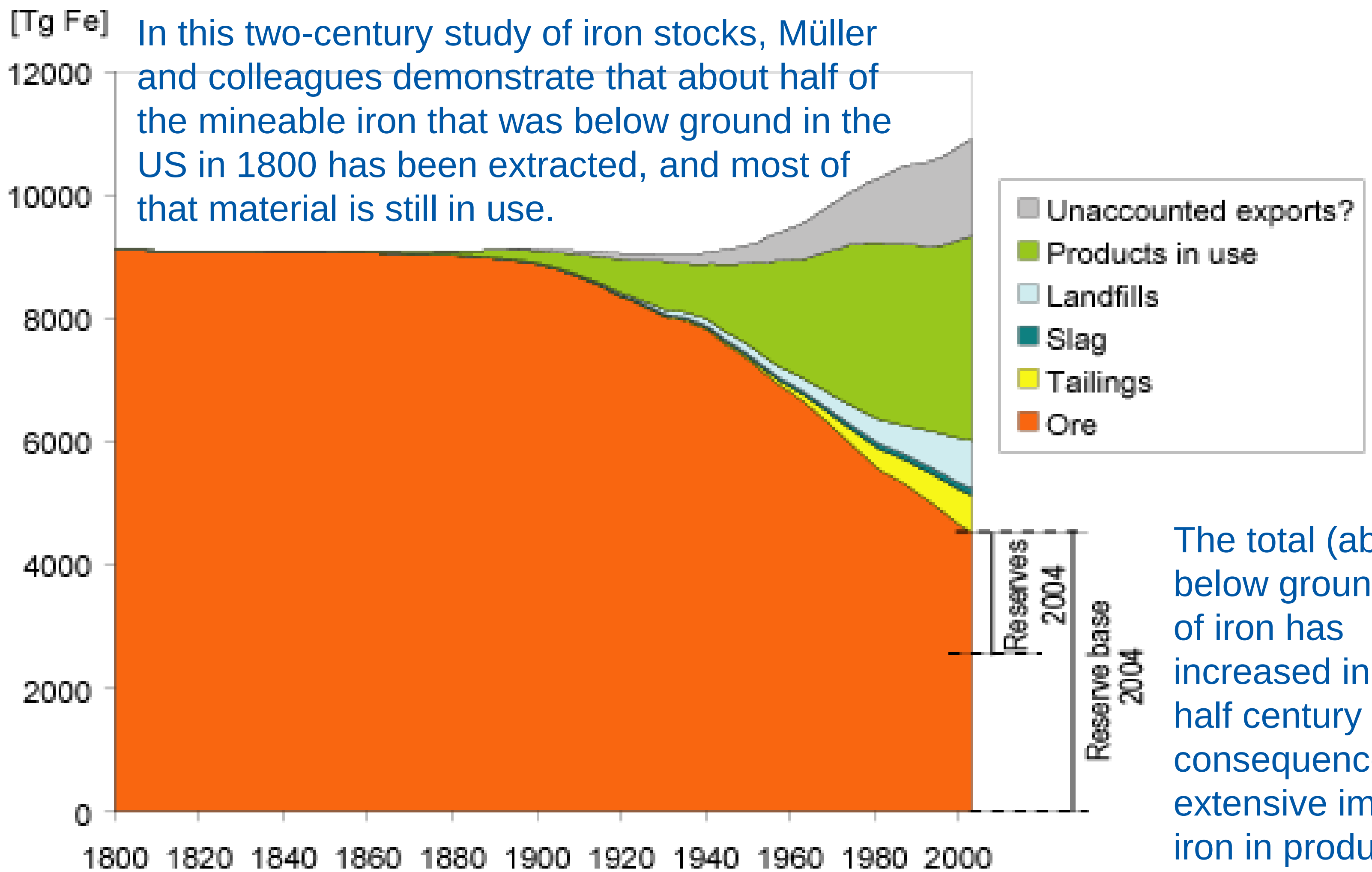


City: New Haven, State: Connecticut, Country: USA. Courtesy of T. Wang

Per capita in-use stock levels differ a bit at different spatial levels because some reservoirs (off-shore oil platforms, military and naval equipment, etc.) are not present at each level.

Distribution of iron stocks in the U.S.

In this two-century study of iron stocks, Müller and colleagues demonstrate that about half of the mineable iron that was below ground in the US in 1800 has been extracted, and most of that material is still in use.



The total (above and below ground) stock of iron has increased in the last half century as a consequence of extensive imports of iron in products.

Source: D. Müller et al., *Proc. Nat. Acad. Sci., 103*, 16111-16116, 2006

Conclusions - I

- Few anthropogenic element cycles have been adequately characterized, but humans appear to dominate most of those that have been studied
- Different features of cycles are revealed at different spatial levels
- The rate of use of metals is clearly a function of wealth

Conclusions - II

- Cycle analysis reveals the potential for the recovery and reuse of materials, but different materials require different strategies

- Characterizing anthropogenic materials cycles provides a wealth of useful information relating to resource availability, environmental impacts, and policy options

Types of Material Flow-Related Analysis

	Type 1 **Impacts per unit flow of**	**E.g. Life Cycle Assessment (next week)**
a	*b*	*c*
substances	materials	products
e.g. Cu, Fe, Pb, Zn, CO2	e.g., energy carriers, excavation, biomass, plastics	e.g., diapers, batteries, cars
	within certain firms, sectors, regions	
	Type 2 **Throughput of**	
a	*b*	*c*
firms	sectors	regions
e.g., single plants, medium and large companies	e.g., production sectors, chemical industry, construction	e.g., total throughput, mass flow balance, total material requirement
	associated with substances, materials, products	

Types of Material Flow-Related Analysis

Type 1 **Throughput of**		
a	*b*	*c*
firms	sectors	regions
e.g., single plants, medium and large companies	e.g., production sectors, chemical industry, construction	e.g., total throughput, mass flow balance, total material requirement
associated with substances, materials, products		

Type I

- Providing system's environmental performance data
- Derivation of sustainability indicators
- Development of material flow accounts for use in official statistics

Types of Material Flow-Related Analysis

	Type 2 Impacts per unit flow of	E.g. Life Cycle Assessment (LCA)
a	*b*	*c*
substances	materials	products
e.g. Cu, Fe, Pb, Zn, CO2	e.g., energy carriers, excavation, biomass, plastics	e.g., diapers, batteries, cars
	within certain firms, sectors, regions	

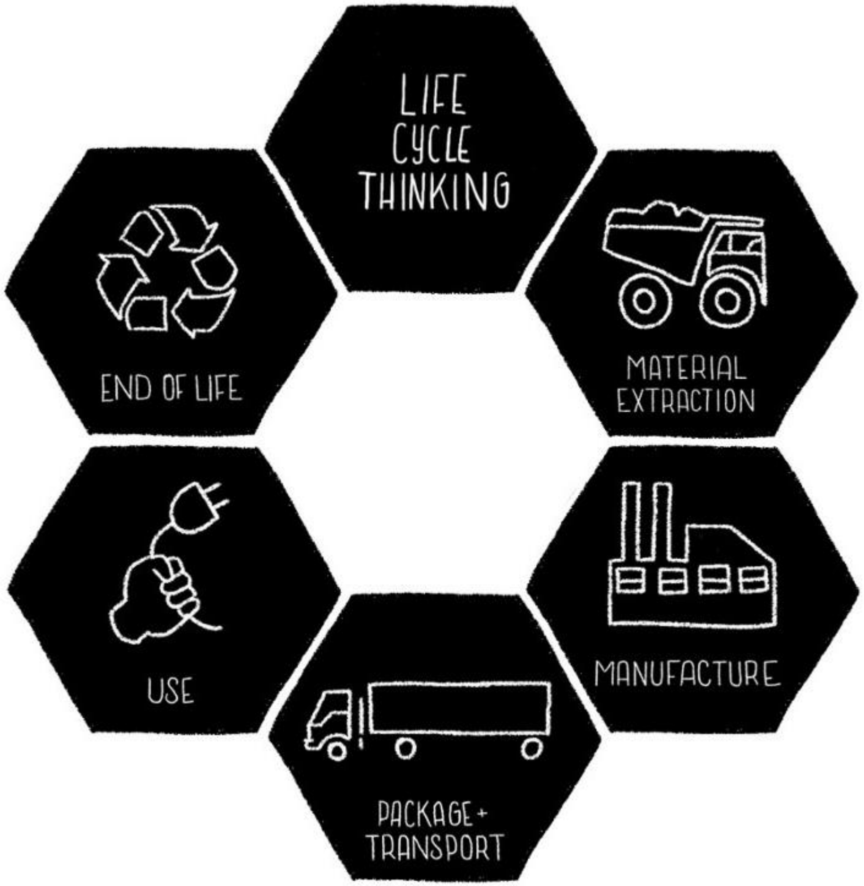
Type 2

- Development of environmental policy for hazardous substances
- Evaluation of product environmental impact

LCA: Life Cycle Assessment/ Life Cycle Analysis

- LCA is a tool to quantify the environmental impacts of a product or process throughout it's entire life cycle: from material and energy production and acquisition to product use and disposal
  - "A concept and methodology to evaluate the environmental effects of a product or activity holistically, by analyzing the whole life cycle of a particular product, process, or activity" (U.S. EPA, 1993)
- LCA is a tool that has been standardized by several organizations, including ANSI, ISO, and SETAC

MFA vs LCA



- MFA is a method to establish an inventory for an LCA
  - Hence, LCA can be an impact assessment of MFA results
- LCA strives for completeness
  - Include as many inputs and outputs as possible
- MFA strives for transparency and manageability
  - Restricted to limited number of substances (Li, Co, etc. in batteries)

Why Worry About Life Cycle Assessment (LCA)?

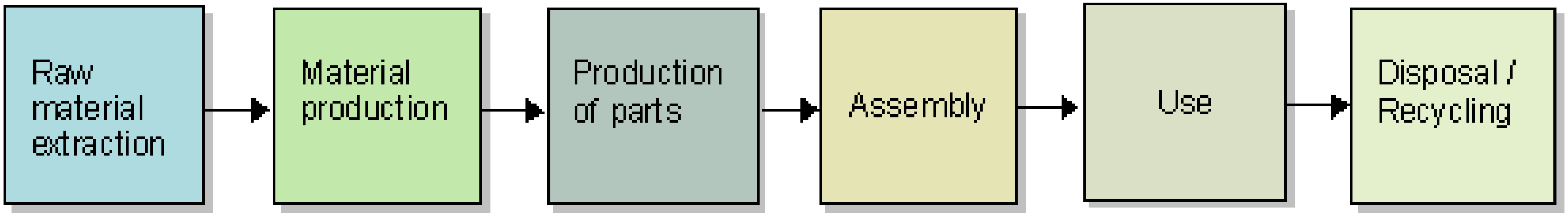
- Required in EU for new products
- Focuses engineers' and management's attention on major opportunities for improvement -- "bigger bang for a buck"
- Consistent with common "Extended Product Responsibility" (EPR) and "Supply Chain Management" (SCM) strategies
  - **EPR: Producers** are given a significant **responsibility** – financial and/or physical – for the **treatment or disposal of** post-consumer **products**
  - **SCM:** Management of the flow of goods and services and includes all processes that **transform raw materials into final products**
- Closely connected to "Carbon Footprinting" for indirect CO_2 emissions

Carbon Footprint

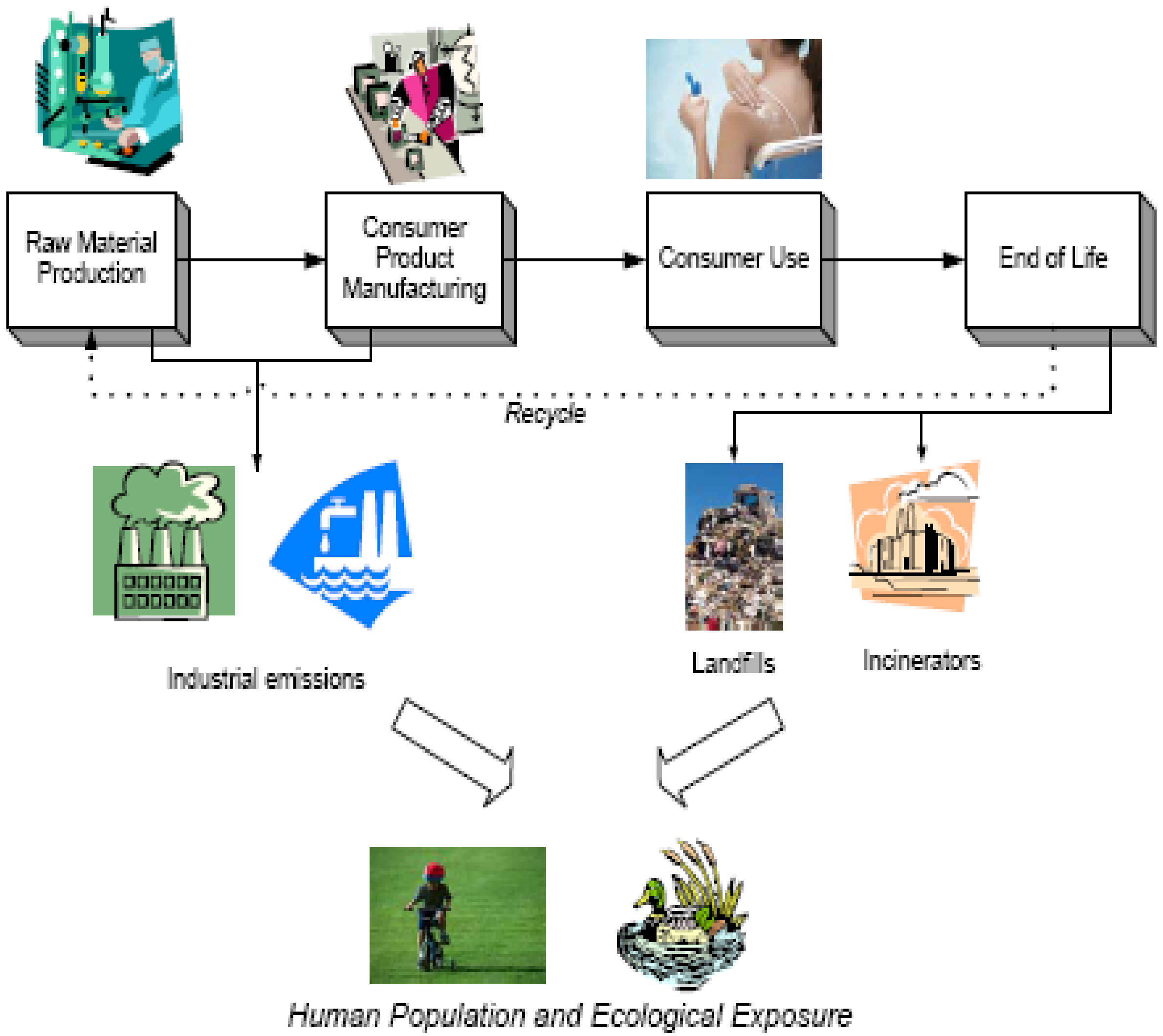
- **Carbon Footprint:** The total amount of greenhouse gases produced to directly and indirectly support human activities, usually expressed in equivalent tons of carbon dioxide (CO2).
  - **Your carbon footprint is the sum of all emissions of CO2 (carbon dioxide), which were induced by your activities in a given time frame.**
    - When you drive a car, the engine burns fuel which creates a certain amount of CO2, depending on its fuel consumption and the driving distance. (CO2 is the chemical symbol for carbon dioxide).
    - When you cool you heat your house with electricity, the generation of the electrical power emits a certain amount of CO2.
    - When you buy food and goods, the production of the food and goods also emitted some quantities of CO2.
- Carbon footprint is calculated per capita for a specific time period (day, week, year, etc.)
    - For instance, Carbon footprint associated with transportation may be calculated in terms of *per person per day*

Life Cycle Thinking

- Products pass through different stages in their life cycle



Life Cycle Concept



Why Life Cycle Assessment?

- A **systems methodology**--LCA is a good way to understand the totality of environmental impacts and benefits of new technologies (e.g. nanotechnology), material & energy supplies and flows, and where along the product chain these occur

- LCA allows for **comparisons with conventional products** that may be displaced in commerce by new products (nano-based), and helps to identify economic and environmental tradeoffs

- LCA facilitates **communication of risks and benefits** to stakeholders and consumers

- LCA can help to prevent **unnecessary regulation** and avoid **"unintended consequences"**

Motivation for LCA

- Two main reasons for performing an LCA:
  - Comparative (e.g. compare two products)
  - Improvement or ‘hot-spot’ identification
- LCA can aid in decision making:
  - What is environmentally friendly?
  - What is green?
  - What is sustainable?

What does an LCA tell you?

Examples

- **Comparative:** What would be a better alternative?

vs.

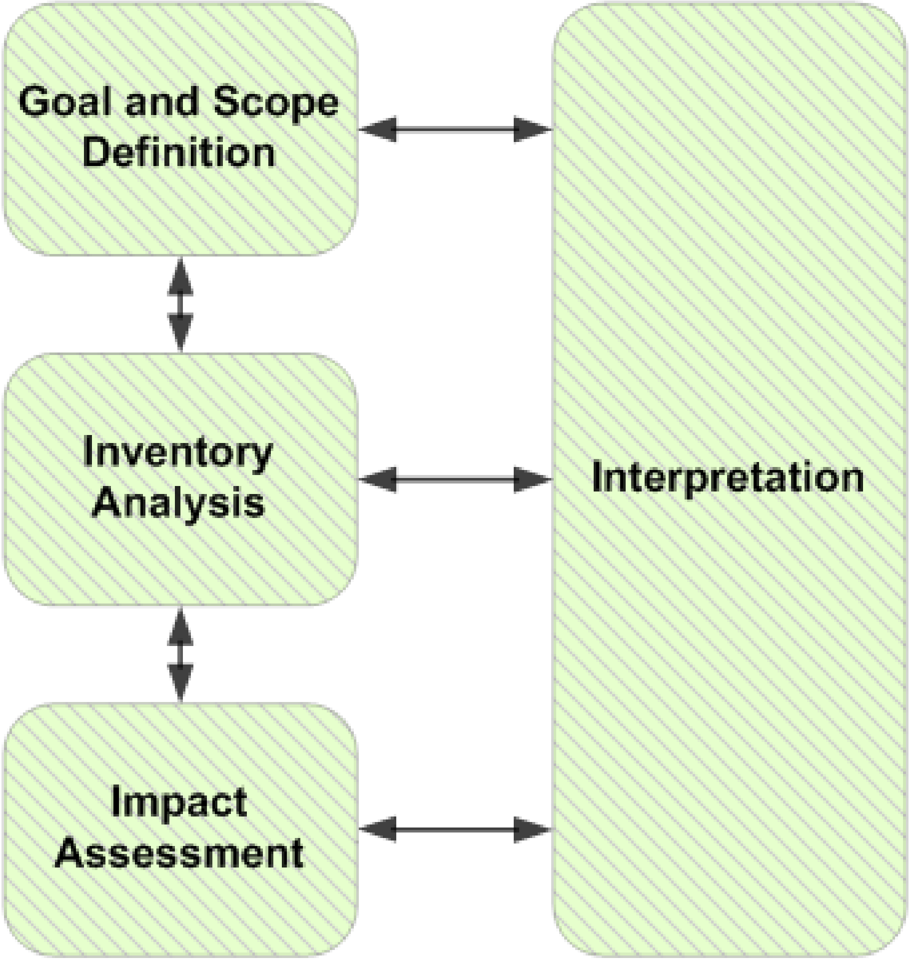
biofuels

petro-fuels

- **Improvement:** Where can I realize improvements within my current activity?

Improving production of fiber reinforced polymers with Bedford Plastics

Stages of Life Cycle Analysis



Functional Unit

- Primary purpose of the functional unit is to provide a reference to which the inputs and outputs are related and is necessary to ensure comparability of results
  - Example: Functional unit of a paper cup and a ceramic cup is 100 m

Vs.

- Functional Unit Exercise:
  - Define the functional unit for each
    - organic vs. conventional food
    - coal vs. natural gas for electricity production
    - concrete vs. asphalt pavement
    - natural gas bus vs. gasoline car transportation for people

Common LCA terminology

- Cradle-to-grave: Scope includes end-of-life disposition of the product/material
- Cradle-to-cradle: Scope includes the entire material cycle, including recylcing
- Cradle-to-gate: LCA boundaries include material acquisition, processing, transportation, and manufacturing (factory gate), but not product uses or disposition
- Gate-to-gate: Partial LCA looking at a single added process or material in the product chain
- Well-to-wheel: Application of fuel cycles to transportation vehicles

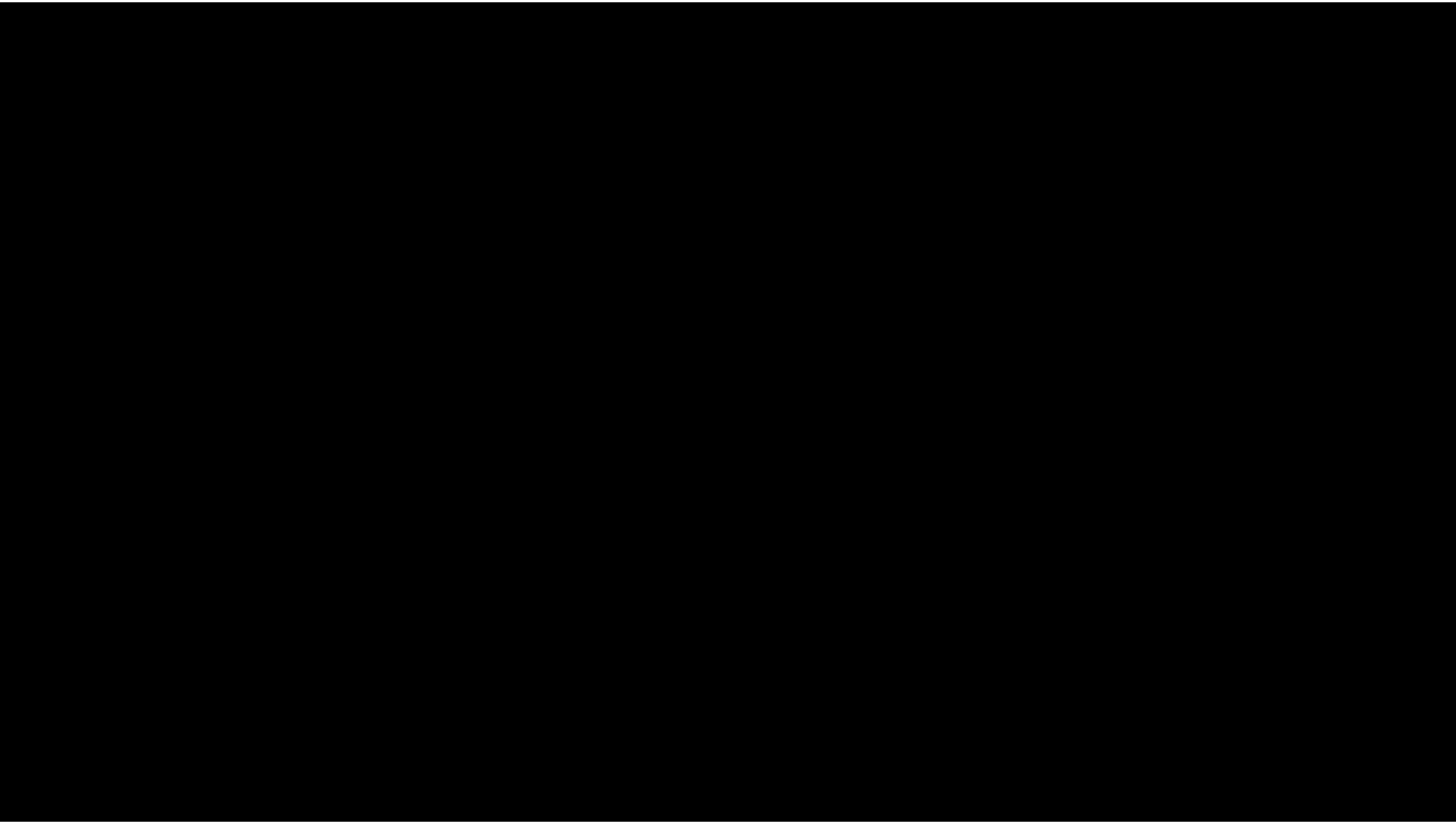
“Classical” Impact Categories

HH (cancer)	kg benzene eq/unit
HH (non cancer)	kg toluene eq/unit
Global Warming	kg CO_2 eq/unit
Eutrophication	kg N eq/unit
Ecotoxicity	kg 2,4 D eq/unit
Acidification	eq H^+/unit
Smog Formation	kg NO_x eq/unit
Ozone Depletion	kg CFC eq/unit

4 Steps to LCA

1. <u>Scoping: Goal and Scope Definition</u>
   - Defining your system & its boundaries
2. <u>Inventory Analysis (LCI)</u>
   - Quantifying material and energy flows throughout the system- sort of like a mass balance
3. <u>Impact Assessment (LCIA)</u>
   - Normalizing inventory data into meaningful impacts within the world (or your system)
4. <u>Interpretation</u>
   - Draw conclusions, make recommendations, improve upon product or process in your LCA

The life cycle of a t-shirt – Angel Chang



Let's go over the four steps again!

1. Goal and Scope Definition

   What is the goal?
   What is the scope?
   What should be the functional unit?

2. Inventory Analysis (LCI)

   What inputs will you consider in the manufacturing stage?

   What inputs will you consider in the use stage?

3. Impact Assessment (LCIA)

   Which impact categories are relevant to t-shirts?

4. Interpretation

   Which is the stage that is most polluting?

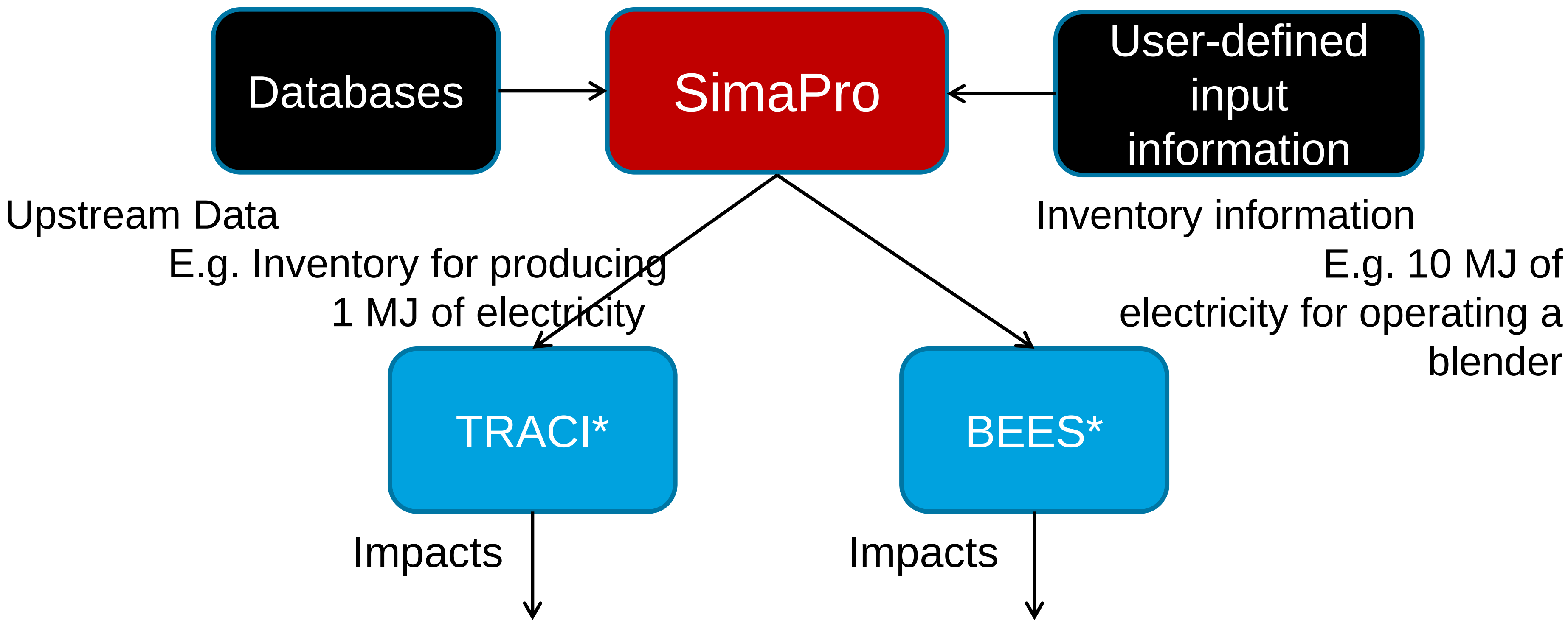
   Would you expect the results for a t-shirt made in USA, China and India to be the same?

Models of LCA

- “Conventional” LCA, developed by SETAC and U.S. EPA, based on process models
  - Create inventory of inputs (materials and energy resources) and the outputs (emissions and wastes to the environment) for a given step in producing a product
  - Even for a very simple product like a paper cup, the process-based LCA method can quickly spiral into an overwhelming number of inputs and outputs to include.

- Economic Input-Output analysis based LCA (EIO-LCA), developed by Carnegie Mellon’s Green Design Institute
  - Systems-based accounting framework that captures the totality of economic activity and associated waste emissions

LCA Process Model

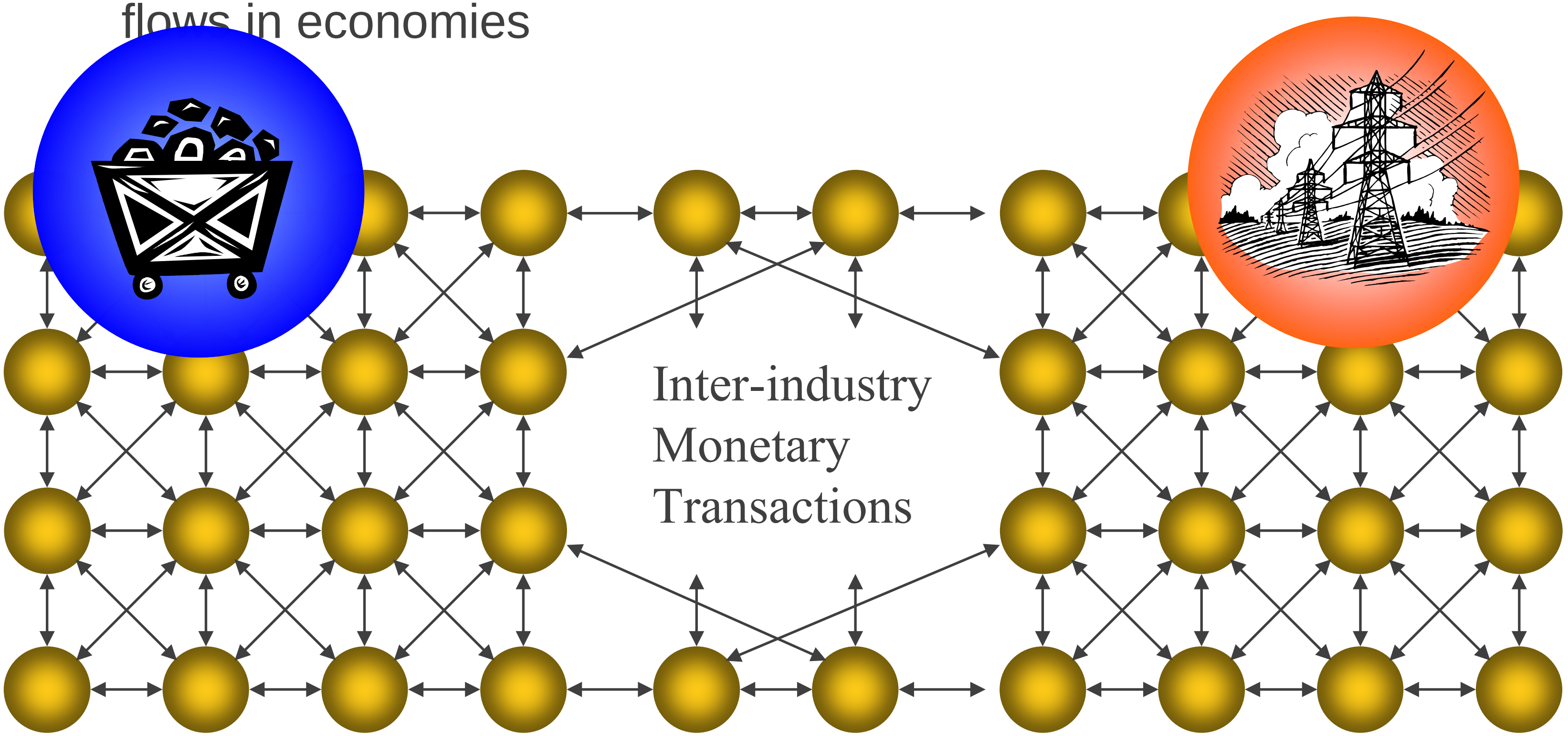


*Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (EPA)

*Building for Environmental and Economic Sustainability (NIST)

Economic Input-Output Model

- Input-Output model represents monetary transactions of a national/regional economy
  - Developed by Nobel Laureate Wassily Leontief
- Basic Idea of EIO-LCA
  - Material, Energy, and Emission flows are analogous to monetary flows in economies



Process vs EIO

	Process Models	EIO-LCA
Advantages	Detailed process-specific analysis	Economy-wide, comprehensive assessments
	Specific product comparisons	System-wide: Industries, products, services, wastes
	Able to do process/product improvements	Sensitivity analysis and scenario planning
	Future product development	Future product development
		Information on every commodity in the economy
		Fast and relatively inexpensive
Dis-advantages	System boundary settings can vary	Aggregated data; process assessments difficult
	Time and $$ intensive	Difficulty in linking dollar values to physical units
	Need for proprietary data/confidentiality issues	Econ and env data reflect past practices
		Imports treated as local products; difficulty applying to open economy (w/lots of imports)
		Non-US data problematic

Input-Output Analysis and LCA

- Economic input-output data captures “life cycle” of entire economy in terms of monetary flow
- Compiled by most countries
  - Organisation for Economic Co-operation and Development (OECD)

https://stats.oecd.org/Index.aspx?DataSetCode=IOTSI4_2018)

- LCA also requires information about resource consumption and emissions

- Emissions and resource use data are available
  - US EPA Toxic release inventory (www.epa.gov/tri/)
  - Energy Information Agency, Dept. of Energy (www.eia.doe.gov)
  - US Geological Survey (www.usgs.gov)

- These data are combined in EIOLCA (www.eiolca.net)

www.eiolca.net

- EIOLCA is available on the internet (latest EIOLCA model is based on the year 2007 EIO model for the US economy)
- Approach
  - Select relevant industrial sector
  - Input change in economic activity (input year 2007 prices)
  - View results

Example:

- What is the life cycle impact of ordering new computers worth $10,000 for EENS?
- Industrial sector - “Electronic Computer Manufacturing”

Prices and EIOLCA

- Need to input prices for the year of the chosen model
  - if you found prices for computers for 2018 but wanted to use the 2007 U.S. Benchmark model, you would need to convert the prices.
- Two options

1. Obtain commodity prices for the year 2007
2. Or use current prices and adjust for the price change using consumer price index (CPI)
   - Use the Bureau of Labor Statistics Inflation Calculator (https://www.usinflationcalculator.com/)

Using www.eiolca.net

1. Choose a model
   - US
     - Producer vs. Purchaser
     - Year (1992 – 2007)
   - Germany
   - Spain
   - Canada
   - China
2. Select industry and sector
3. Amount of economic activity
4. Category of results

In-class Activity

Comparison of two products using EIO-LCA (http://www.eiolca.net/cgi-bin/dft/use.pl)

- Pick two different products that use electrical energy but from different sectors.

  Identify the respective broad and detailed EIO-LCA sectors for the two products. Mention the EIO-LCA model that you decided to use for this comparison and explain why.

  Provide the product specifications and the current prices (in HKD) of the chosen products.

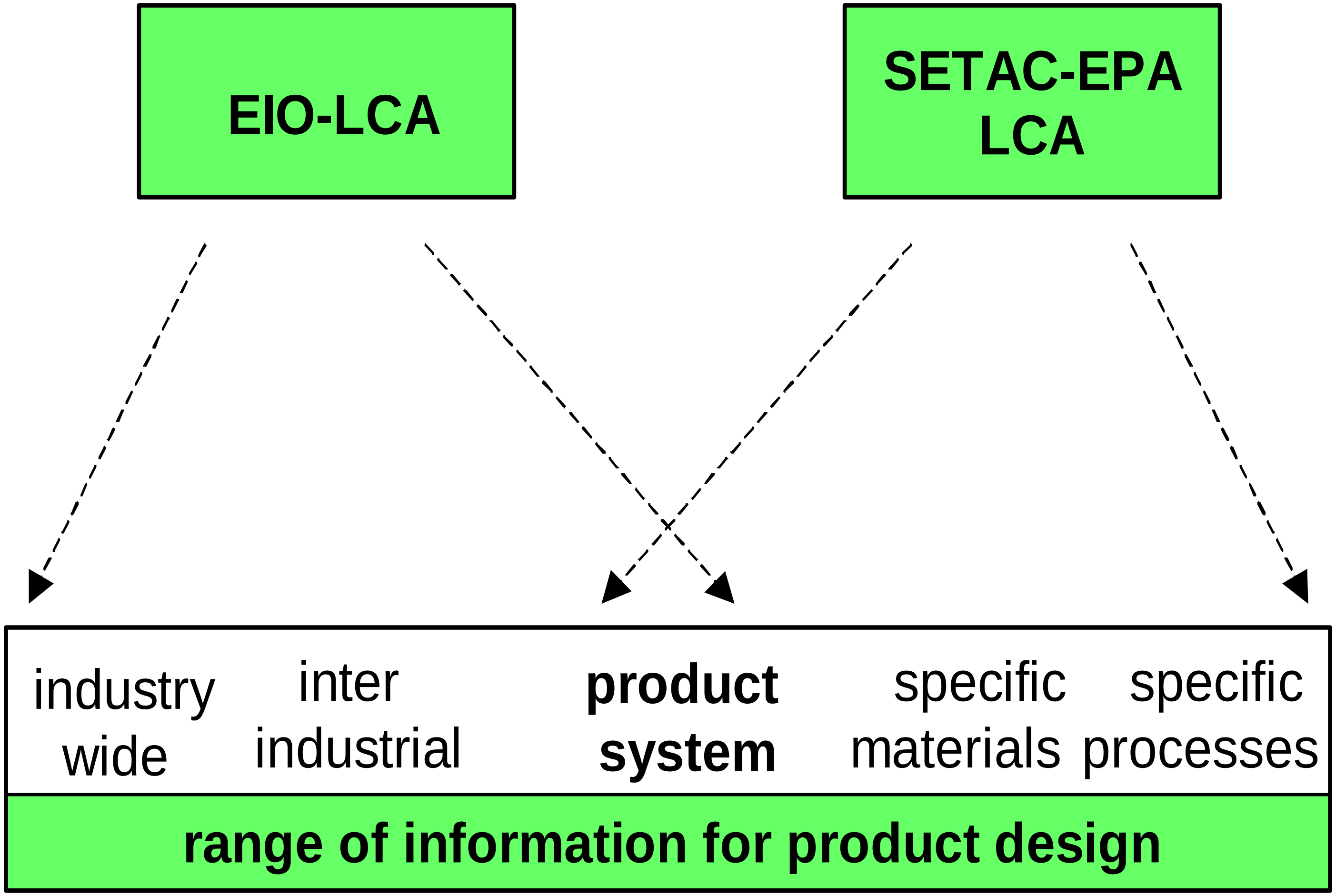
- Use the Bureau of Labor Statistics Inflation Calculator (https://www.usinflationcalculator.com/) to find out the corresponding price of products in the year of the chosen EIO-LCA model.

- Run the EIO-LCA model and find the impacts of chosen products on the environment based on two different impact categories (e.g. Energy, Land Use). Explain your choice of categories and provide a table of the top 10 sectors that contribute the highest environmental impacts. Make sure that your data table provides the total environmental impacts per product as well.

- Which product has a higher negative impact on environment and what are the possible reasons behind it?

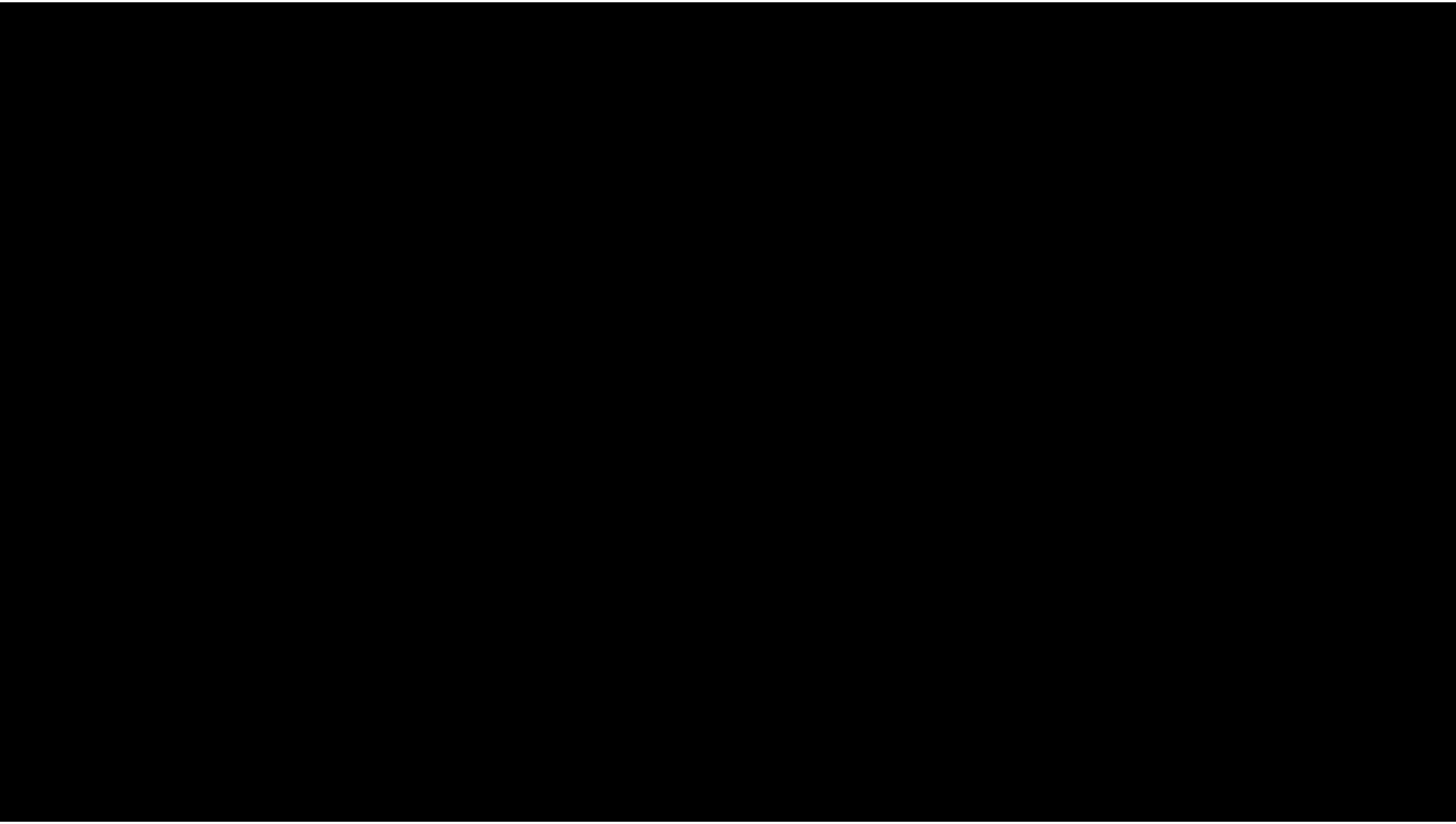
- Do you think EIO-LCA is a trustworthy tool and when is it acceptable to use it?

Utility of Two LCA Approaches



From HS Matthews, CMU

How about the end of life?



Environmental Impacts of End of life

- What inputs and outputs would you consider for the three different end-of-life pathways?
- Do you expect the three pathways to have high emissions for the same impact categories?
- How will you deal with the question about which impact category is more important?

In Summary,

- LCA is a valuable approach for informing decisions to improve environmental quality & sustainability
- While carbon footprints analyses are increasing in popularity, they lack standardization
  - C-footprints are a subset of LCA
- Sustainability is not just an adjective- but should be quantitatively assessed
  - Process-LCA and EIO-LCA