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

Cost-Benefit Analysis, Material Flow Analysis

March 7, 2022

SEE 1003 class overview

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, Material Flow Analysis, Life Cycle Assessment		
Week 9			
Week 10	**MODULE VI** Advances in Environmental and Energy Engineering	**Project deliverable 1.4**	**Project deliverable 1.3; Quiz3**
Week 11	**MODULE VII** Waste management and Waste-to-Energy		
Week 12	**MODULE VIII** Economics and Policy of Energy and Environment	**Project deliverable 1.5**	**Quiz4** **Project deliverable 1.4**
Week 13	**Individual Presentations (5-mins)**		**Final Project Report**

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 (19th century), to regional (20th century) and to global and longer term (latter 20th 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

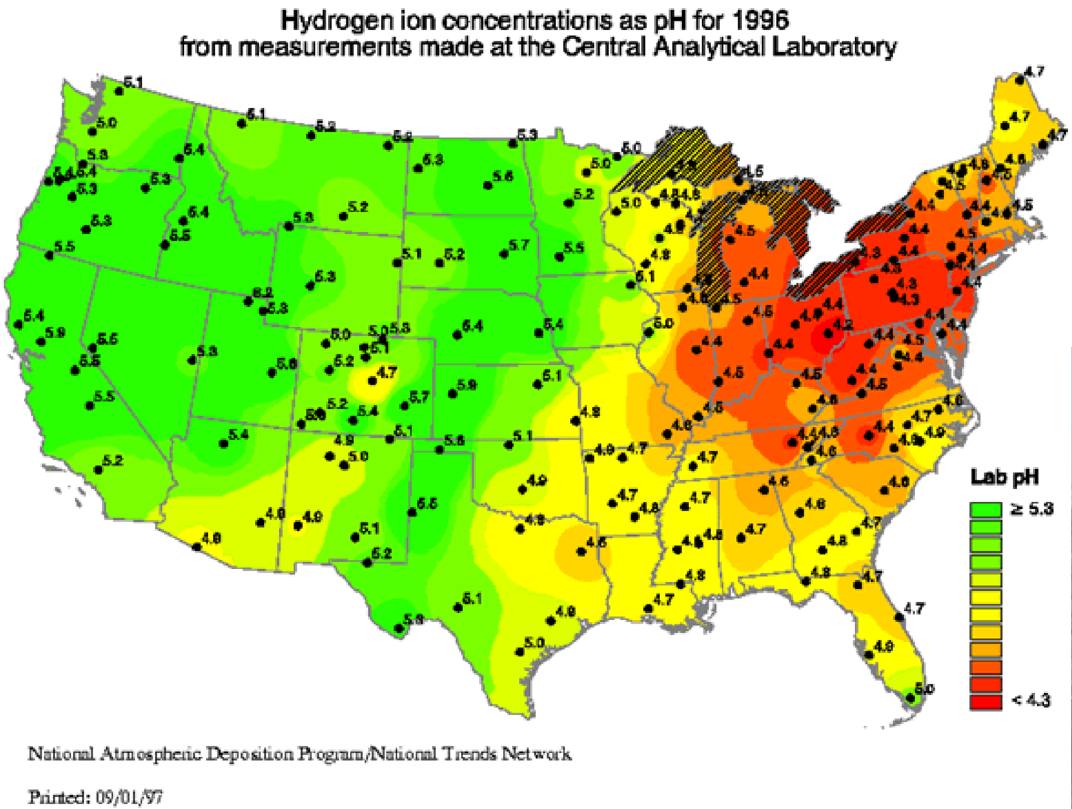
Fine particulate impacts: respiratory problems, lowered visibility, aesthetic enjoyment

Donora, PA 1948—50 Deaths

US Steel zinc smelter, Donora PA
*www.eoearth.org/article/**Donora**,_Pennsylvania*

Noon Oct. 29, 1948, in Donora, PA
(Source: NOAA)

Acid rainfall



pH of rainfall, US 1997

www.nature.nps.gov/.../images/precip1996.gif

Forest impacted by acidic rainfall, Czech Republic

www.solcomhouse.com/acidrain.htm

Solutions to Acid Rain (a "Tame Problem")

Require most power plants (except old ones) to reduce emissions of SO_2 and NO_x

- control devices (flue-gas desulfurization)
- low-sulfur coal

Figure 17a: Annual Mean Ambient Sulfur Dioxide Concentration, 1989–1991*

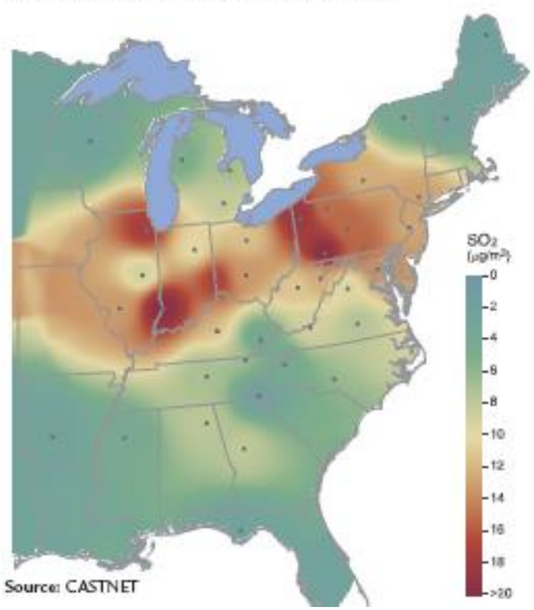
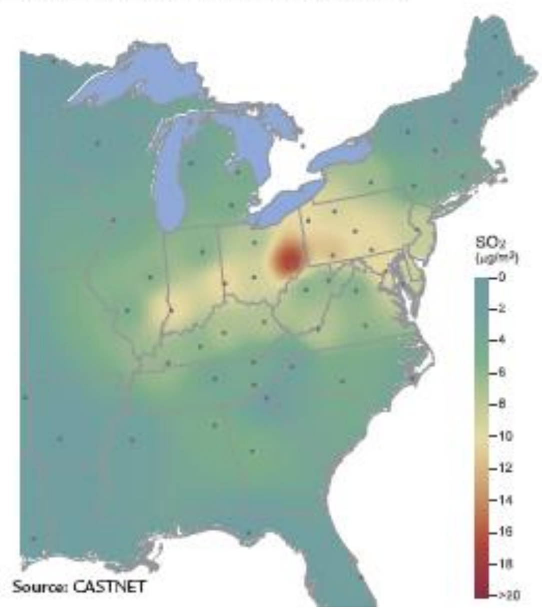


Figure 17b: Annual Mean Ambient Sulfur Dioxide Concentration, 2003–2005

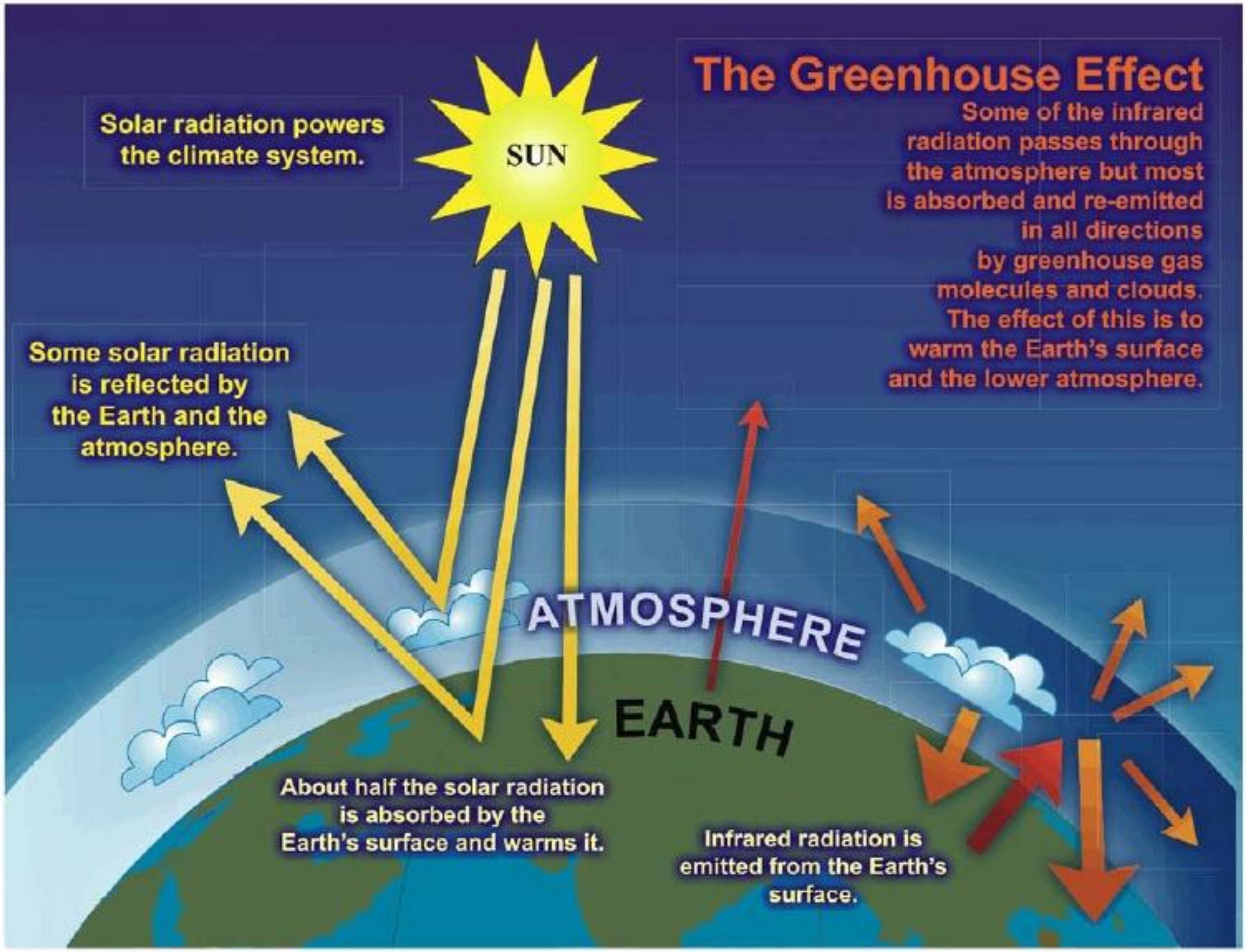


Example of "Wicked" problems: Global Climate Change

A collection of impacts induced by the warming of the earth's surface and atmosphere through the heat trapping capacity of several anthropogenically generated gases

http://climate.nasa.gov/key_indicators

The Greenhouse Effect



Greenhouse gases

There are six major anthropogenic greenhouse gases that contribute to global warming (in order of their contribution):

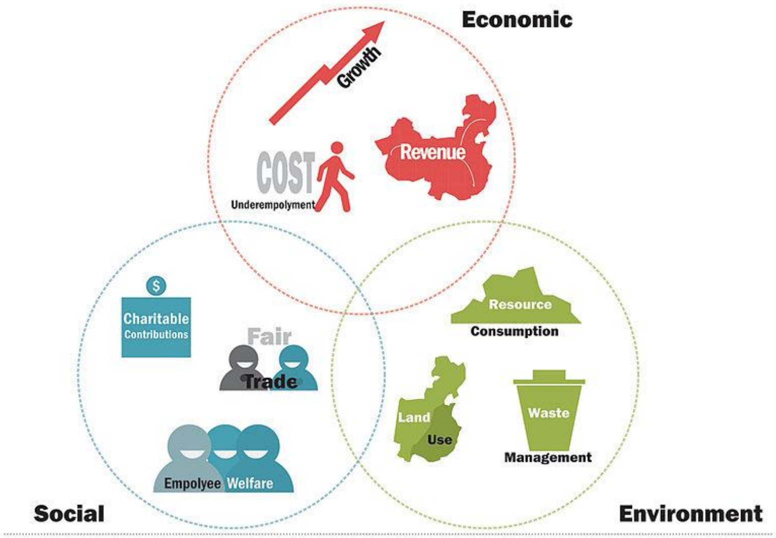
- ***Carbon dioxide*** **(major source: combustion of fossil carbon, deforestation)**
- ***Met*** **mat**
- ***Nitr*** **es)**
- And
  hyd **e:**
  industrial chemicals and by-products)
- And water vapor…?

Solution to this "Wicked" problem needs an interdisciplinary approach that integrates <u>Technological, Social, and Economic</u> aspects

Sustainable Development

"Development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Bruntland Report for the World Commission on Environment and Development (1992)

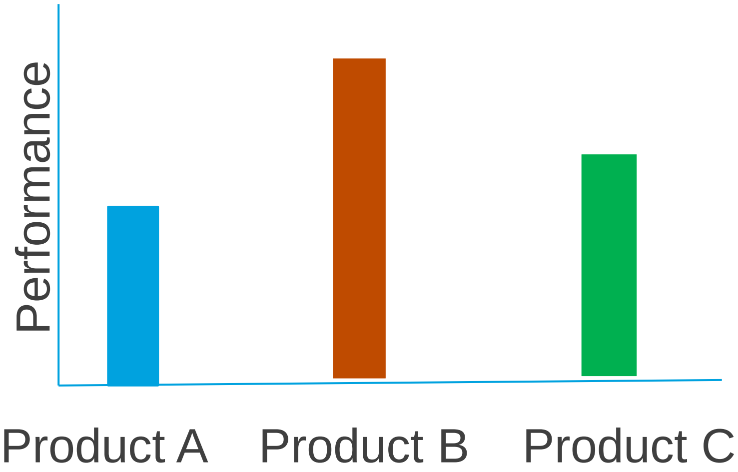


Triple Bottom Line Approach

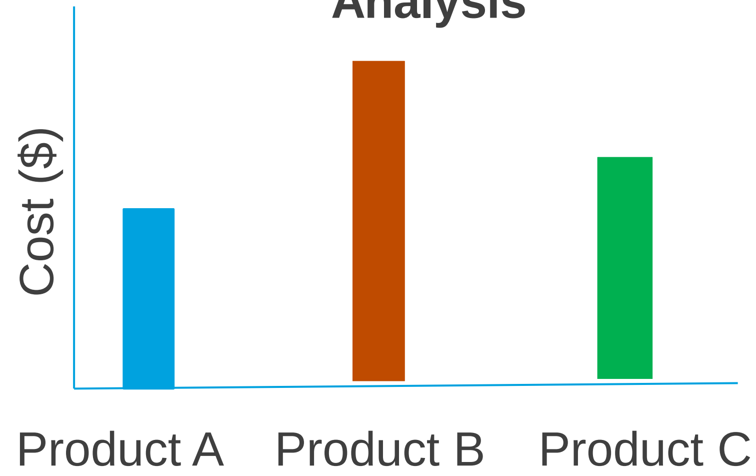
Energy and Environmental Engineering

How do Engineers make Decisions?

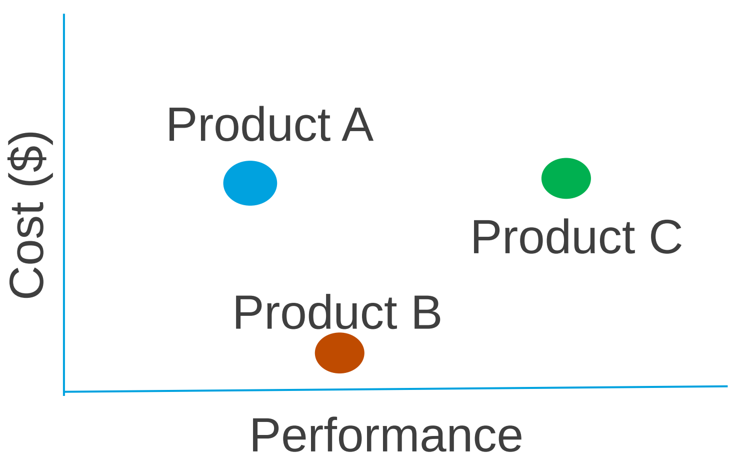
Decisions based on Technical Analysis



Decisions based on Cost-effectiveness Analysis

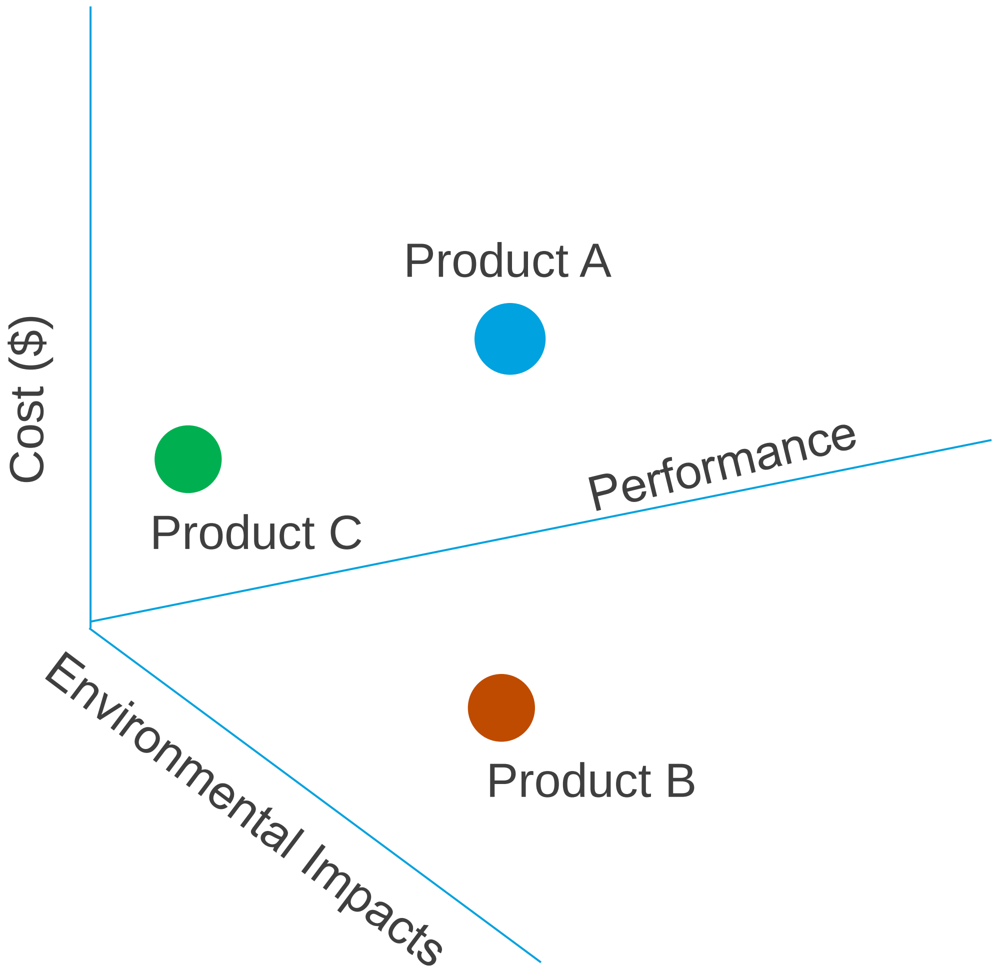


Decisions based on Cost-Benefit Analysis

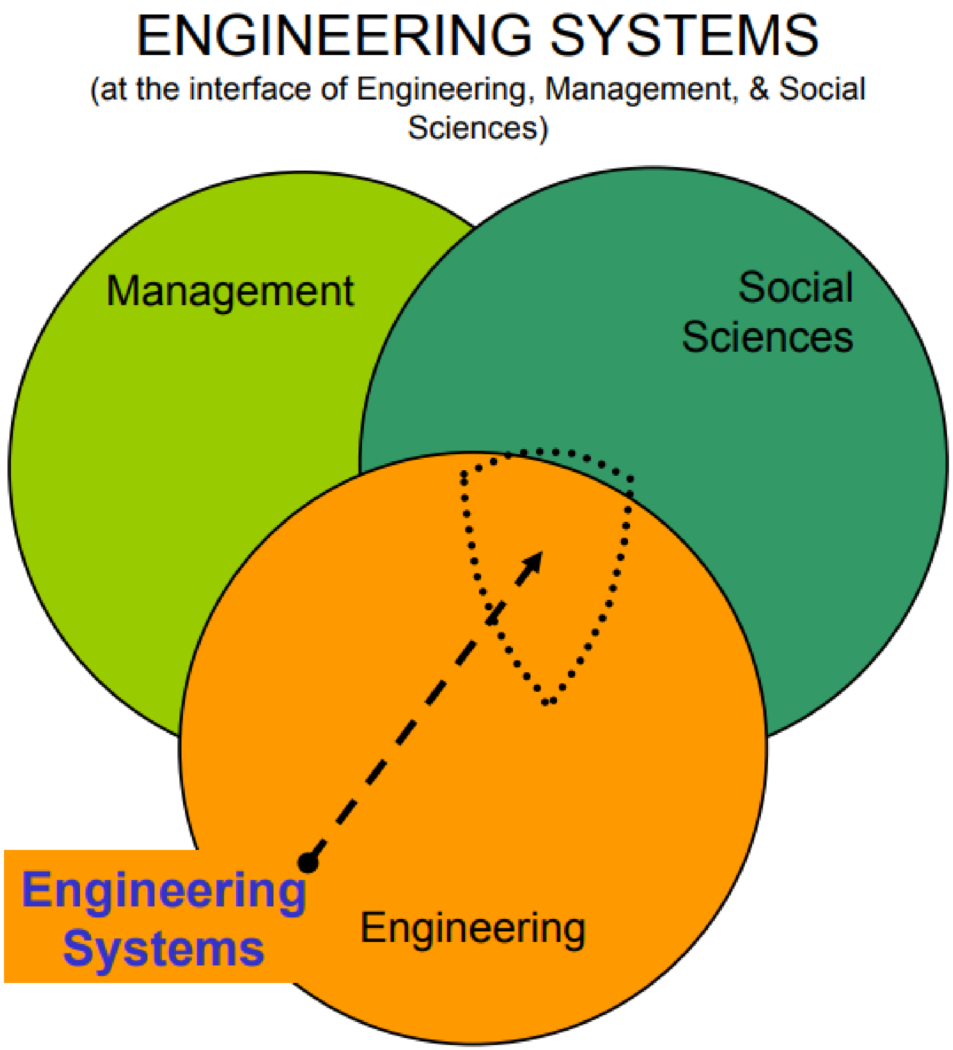


How do Sustainability Engineers make Decisions?

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

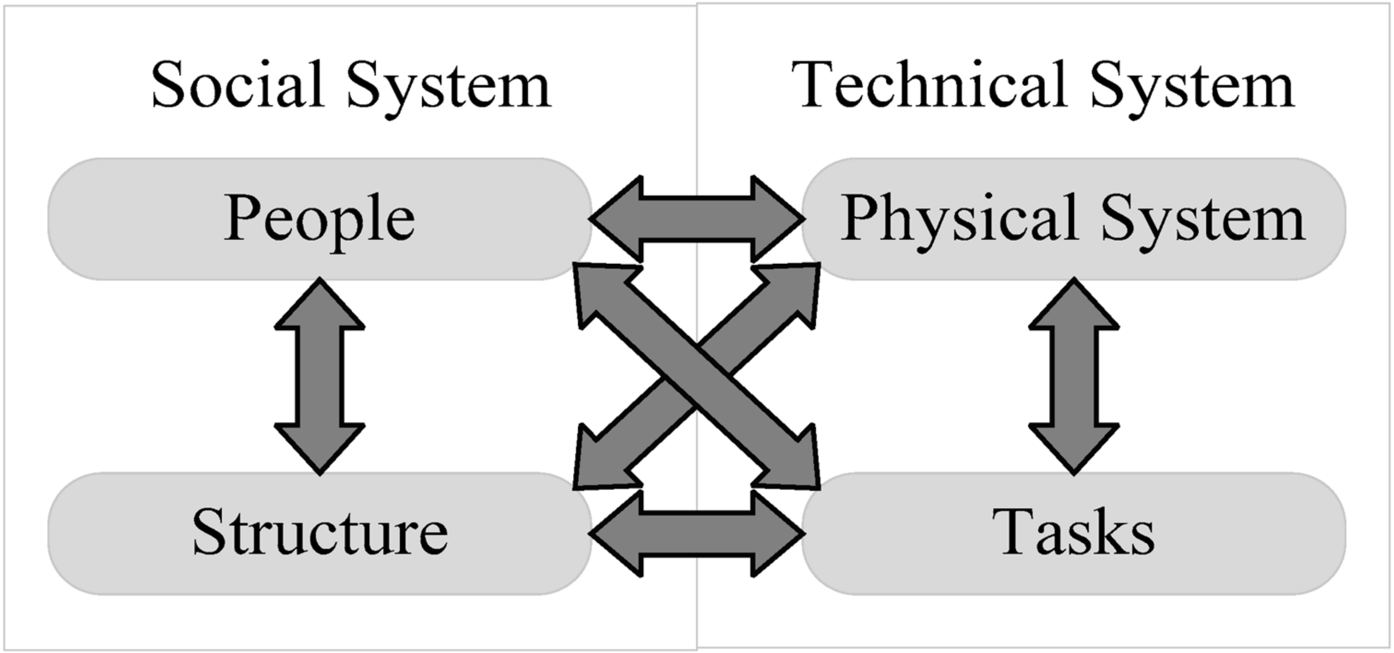


Sustainability of Engineered Systems



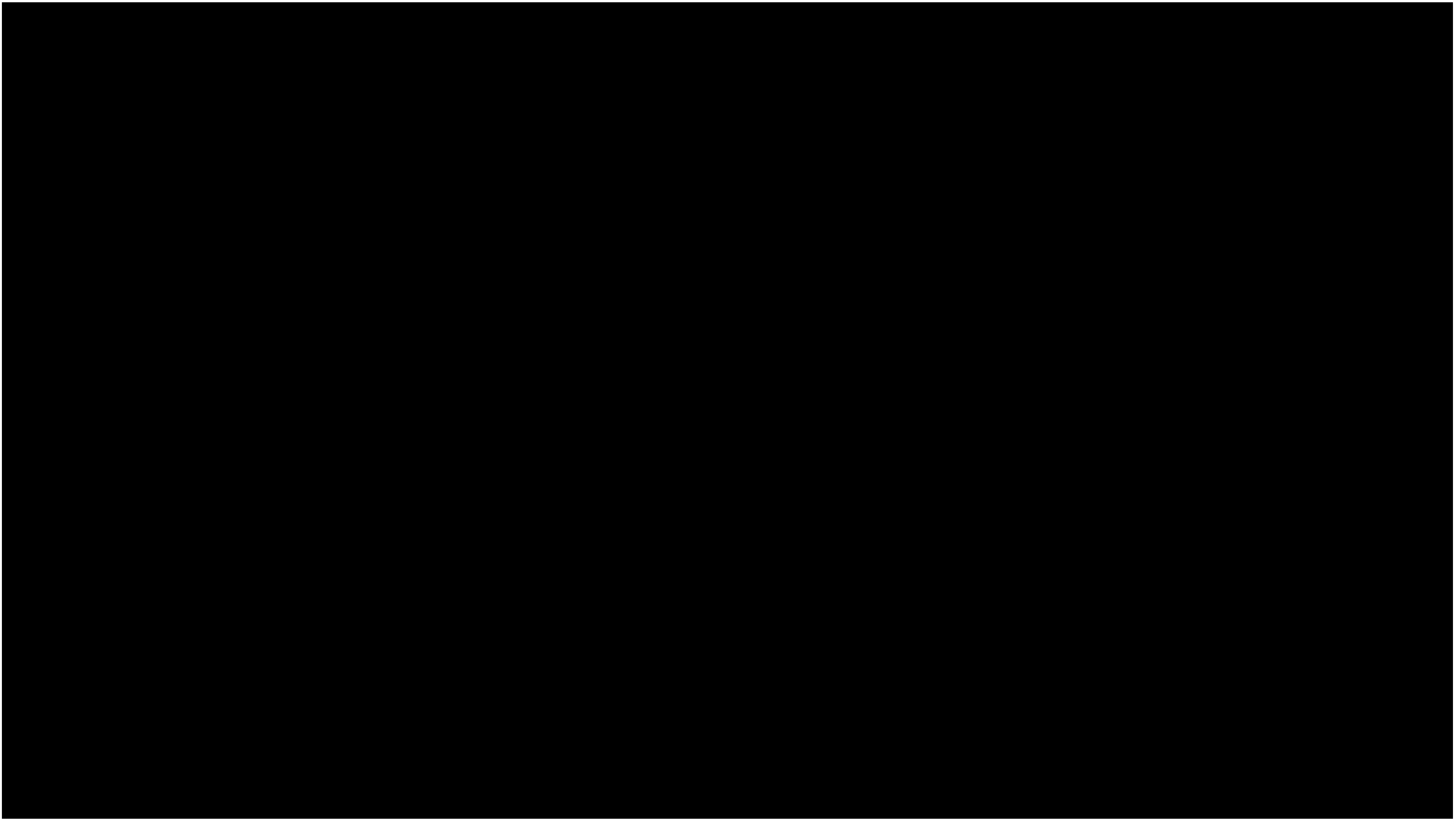
Definition: Socio-Technical System

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



Socio-technical Systems: Summary

https://www.youtube.com/watch?v=qP7EZojC440



STS as a Tool

- **Qualitative as well as quantitative** factors
  - Necessary step if systems thinking is to be applied to social and political systems
- Not searching for a **system optimum**
  - Focuses instead on the tradeoffs and uncertainties that are more characteristic of the political process
- Explicitly includes the **policy world** as a part of the system
  - Recognizes changes to existing policy structures as possible and sometimes necessary
- Clear, comprehensive and **structured process** for moving from analysis to implementation within a single system framework
  - Yet, allows flexibility in the use of a range of tools and processes to carry out the actual analysis

Definition of Cost-benefit Analysis

- Directly from Boardman:

  "…systematic cataloguing of impacts as benefits and costs, valuing in dollars, and then determining net benefits of the proposal relative to the status quo"

Simplest Form:

	Benefits
-	Costs
	Net Benefit

Are net benefits positive (NB > 0) ?

Day-to-day CBA

- Who did a CBA today?

Personal vs. Social CBA

- Personal CBA is relatively simple
  - Listing of options and the pros and cons may get longer as the complexity of your problem goes up (lunch vs. a new car)
  - Valuation of costs and benefits is by definition uncontroversial

- Now add 1 more interested party
  - For the car, add someone like a significant other

Social CBA

- In a social CBA, it may be difficult to even generate a list of people who have “standing”, which may change under different alternatives

Cost Benefit Analysis

- What is it?
- How do we use it?
- Why do we use it?
- Who uses it?
- What are its limitations?
- When is it appropriate to use it?

What is CBA?

- Decision making tool for agents and societies
- Allocation of (scarce) resources
- Systematic analysis:
  - *ex ante (before the event)*

    High level of uncertainty, 1^{st} order approximation as to whether resources should be allocated to a project
  - *in medias res (in the middle of things)*

    Updating as information is gathered during project
  - *ex post (after the event)*

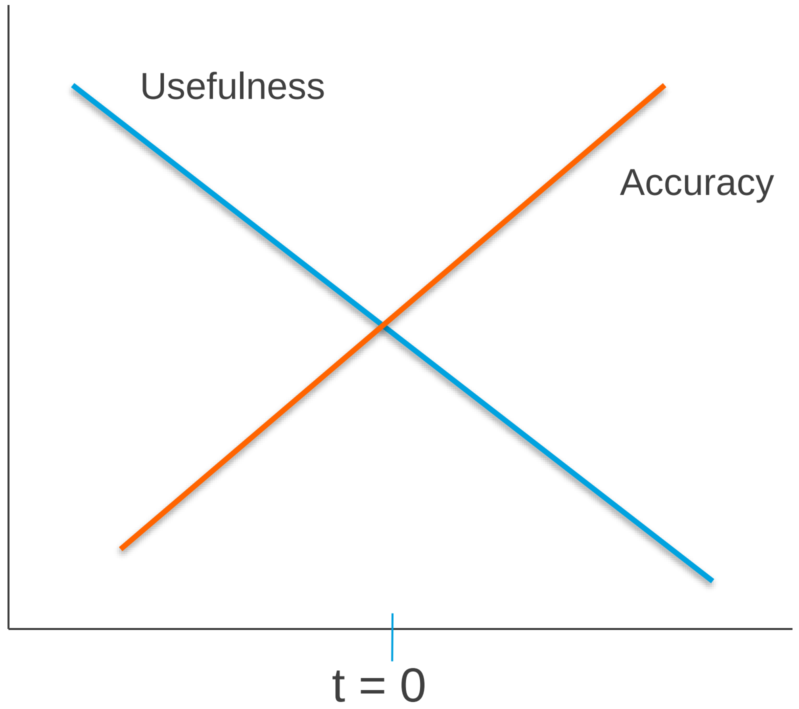
    Useful too, but after the fact

- Allows for updating
- Allows for comparisons of our various options

Frustrating Correlation

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

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



Cost Benefit Analysis

- Framework to systematically identify major benefits and costs associated with a particular investment or policy
- Often controversial, with different analysts coming to different conclusions or not agreeing on objectives
- CBA is a framework, not a recipe

Application Areas

- Methods and techniques are general

- Emphasize environmental and civil system investment as examples
  - Ports, roadways, transit systems
  - Energy systems
  - Water and wastewater systems
  - Public, private and mixed investment/finance decisions (e.g. Stadium construction)

Simple Examples: 1-option CBA

Benefits/Pro

Benefit 1	$250
Benefit 2	$1100
Benefit 3	$430
Total Benefit	**$1780**

Costs/Con

Cost 1	$57
Cost 2	$780
Cost 3	$40
Cost 4	$400
Cost 5	$45
Total Cost	**$1322**

Since Benefits ($1780) > Costs ($1322), you should choose this option

Note on 1-option CBA

- This is really a 2-option CBA, where the 2nd option is the status quo, or “do nothing”
- Net benefits of the status quo assumed to be zero unless otherwise stated

Simple Examples: 2-option CBA

- Option 1 costs $10M, option 2 costs $1M

- But, option 1 has $11M in benefits, while option 2 has benefits of less than $500K

- So, despite its higher cost, we choose option 1 because $11M-10M > $1M – 500K

Status quo trick: when zero is the largest number

- Imagine a comparison of two public works projects, where the $NB < 0$ for both options
- Which should we choose? Well, if $NB_1 < NB_2$, then choose option 1 .
- Except that $0 > NB_{1 \text{ or } 2}$
- Thus, the status quo, with $NB=0$, is our “best” option

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

So, CBA is simple?

- Like most of the tools used for sustainable development, BCA seems simple but hides a lot of complexity
- Implied in these simple examples is the idea that there is a “right” answer
- The true right answer? “It depends”

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

Steps in a CBA: New infrastructure

1. **Determine standing**
   – Local vs. national vs. global

1. **Select portfolio of alternatives**
   – Status quo (use existing roads)
   – Toll road (pay for use)
   – Free road

1. **Catalogue potential impacts**
   (can be $, but don't have to be)
   – Positive: Time saved, reduced operating costs, fewer accidents, less congestion, toll revenues, new traffic revenues
   – Negative: Road/toll construction and maintenance

Steps in a CBA, cont.

4. **Select measurement indicators**
   - Lives saved per year, person-hours of travel, dollars

4. **Predict quantitative impacts of the life of the project**
   - Number of trips on old and new highways, safety

4. **Monetize - convert impact categories into dollars**
   - Leisure wages / Business wages / Values of lives

Steps, cont.

7. Time frame and money (present value)
   - Convert dollar values in future to present dollars

7. Sum NB = NPB - NPC > 0
   - For multiple projects, select one with highest NB

7. Sensitivity Analysis
   - Use varying ranges of the inputs to see if NB changes

7. Recommendation - highest NB

Simple exercise?

Project Parameters	Project 1	Project 2
Project Duration (Years)	3	2
Total Units to be Constructed	500	400
Units For Sale	400	350
Units For Rent	100	50
Rental Period of Units (Years)	20	15
Units For Sale after Rental Period	100	50
Construction Cost for Each Unit (USD)	100.000	90.000
Sales Office Cost (USD)	2.000.000	3.000.000
Sales Personnel Cost Per Year (USD)	300.000	250.000
Financing Cost Per Year (USD)	3.000.000	2.500.000
Sale Price of Each Unit (USD)	120.000	135.000
Sale Price of Each Unit After Rental Period(USD)	70.000	80.000
Rental Price of Each Unit Per Year (USD)	4.000	4.500

Calculate the costs and benefits for the two projects. Which is the better project?

- Any proposal will have winners and losers, even if we've maximized society's net benefit
- What are the possible issues with this?

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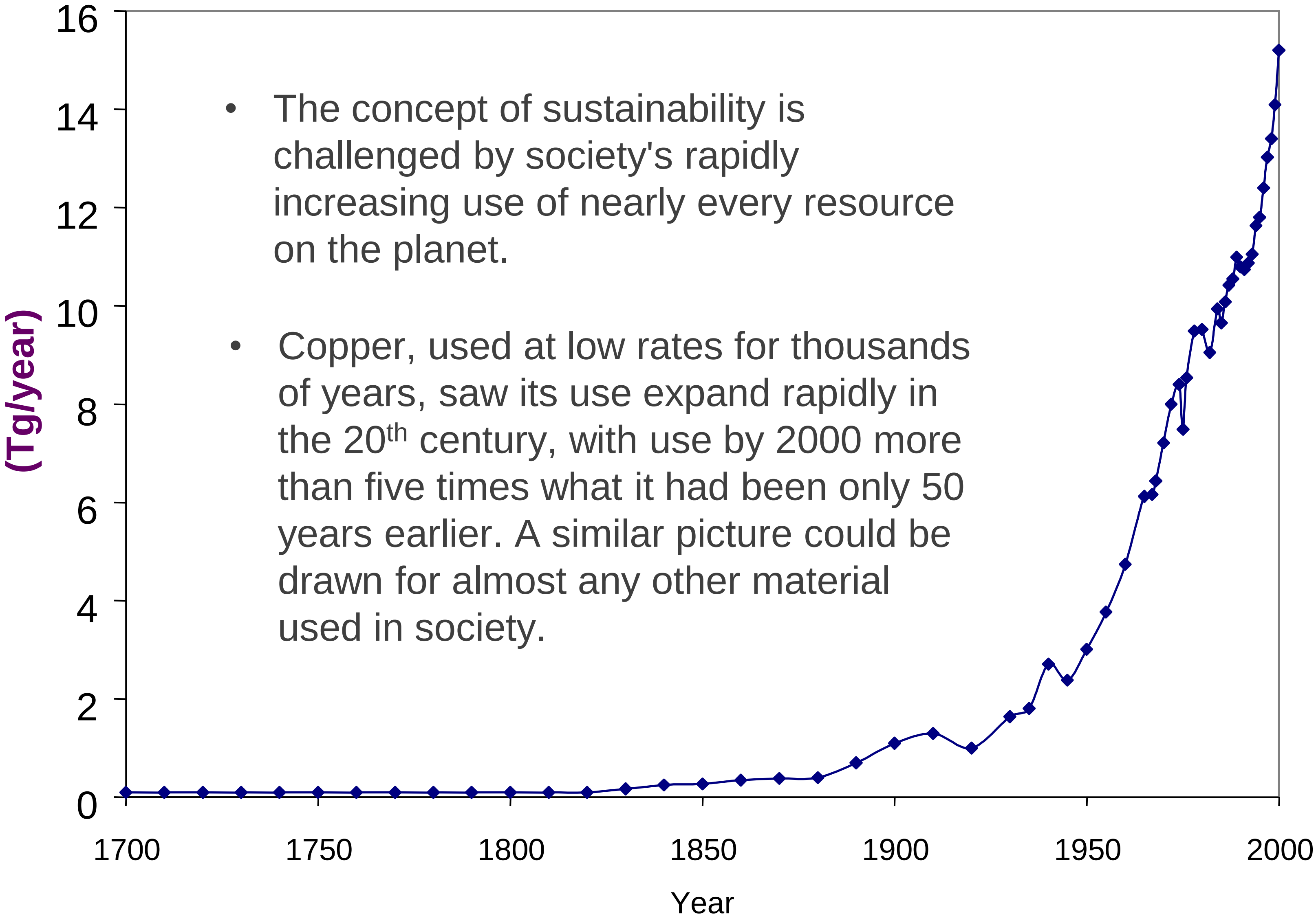
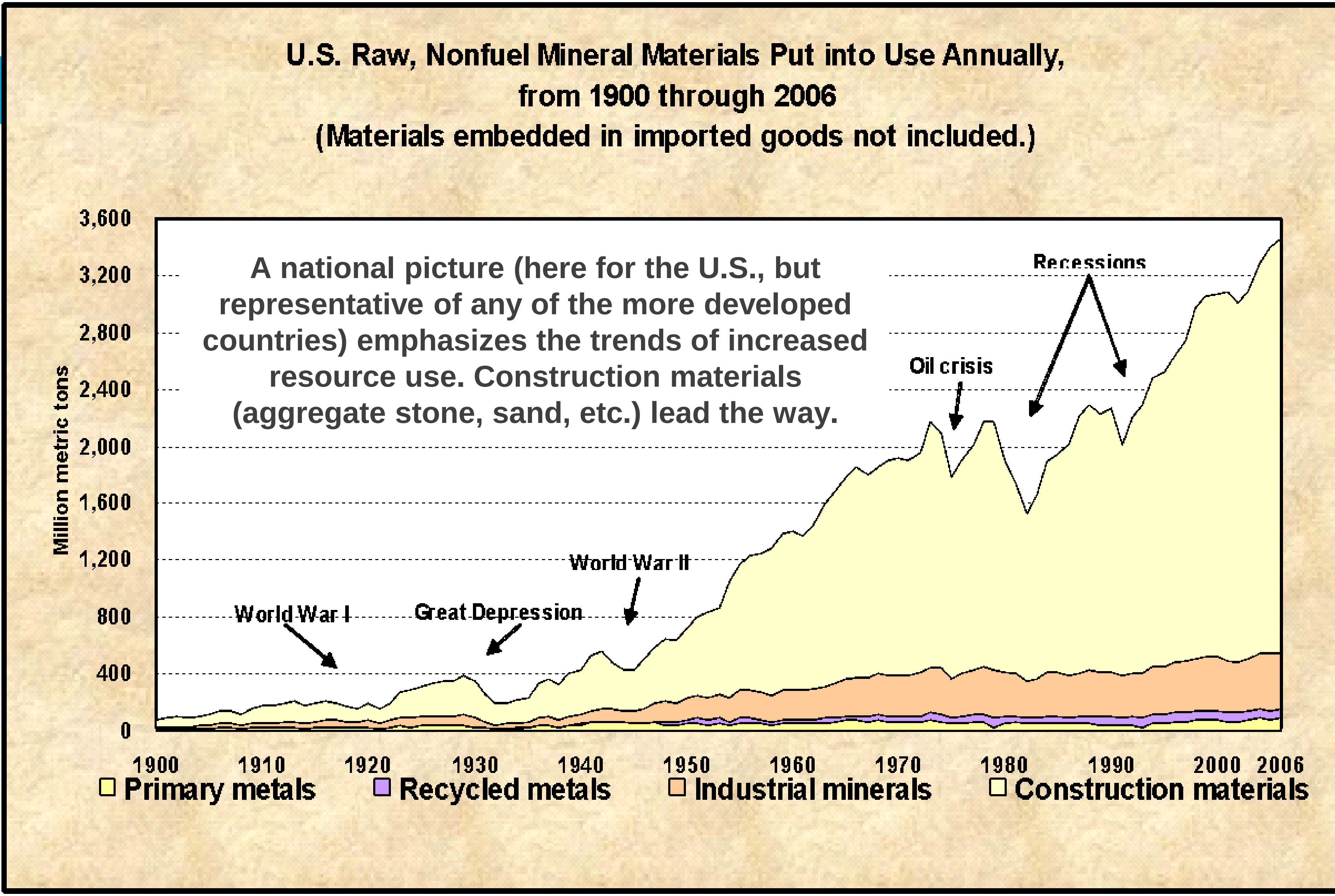
Material Flow Analysis (MFA)

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.





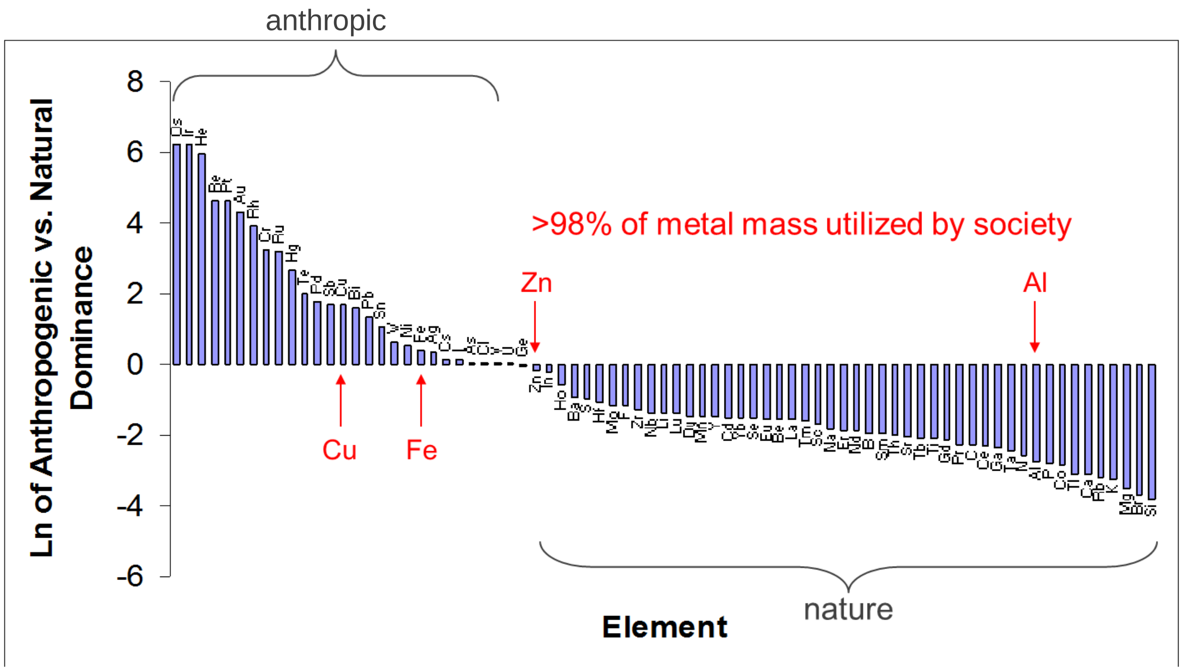
A national picture (here for the U.S., but representative of any of the more developed countries) emphasizes the trends of increased resource use. Construction materials (aggregate stone, sand, etc.) lead the way.

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*

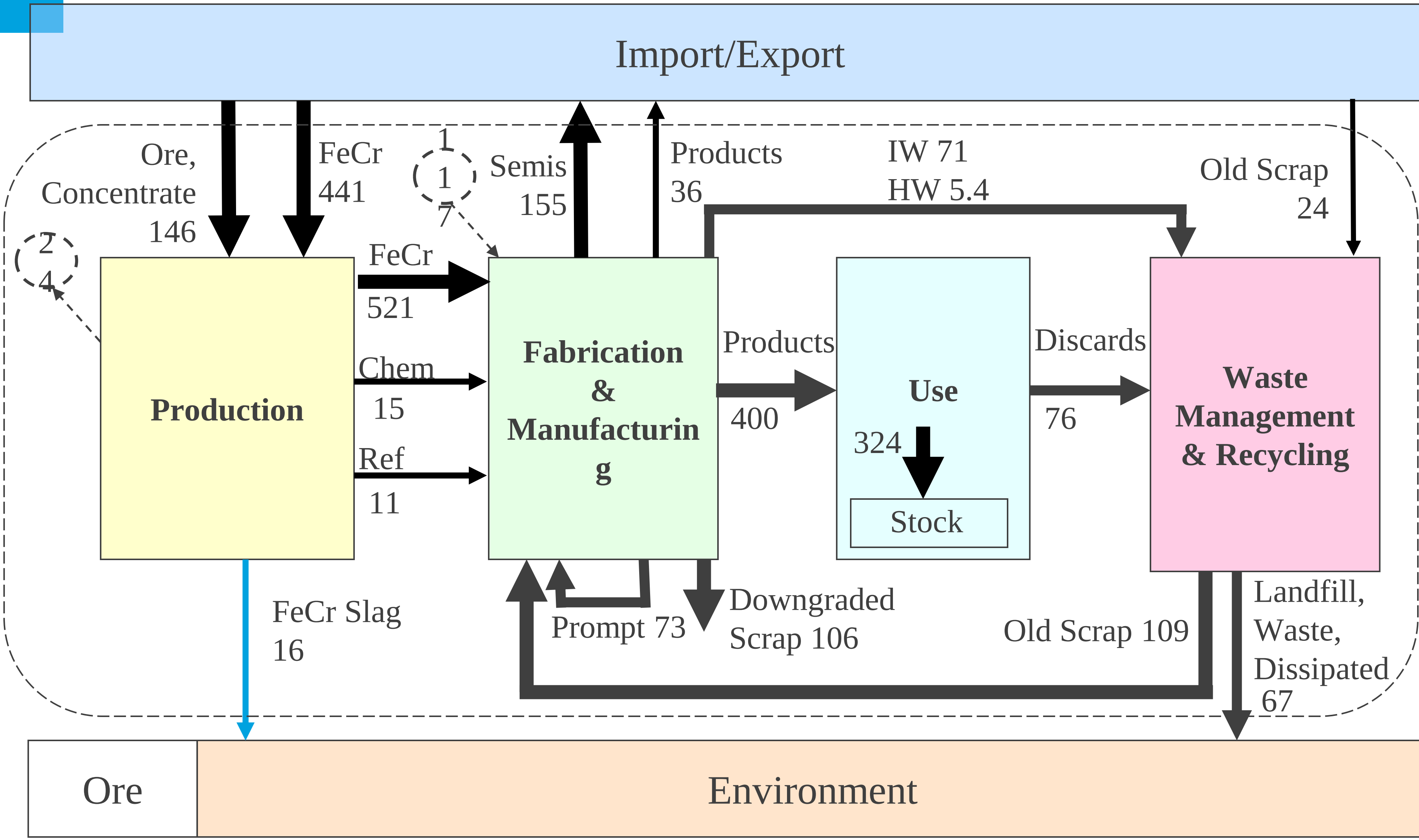
MFA contains the following main steps

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

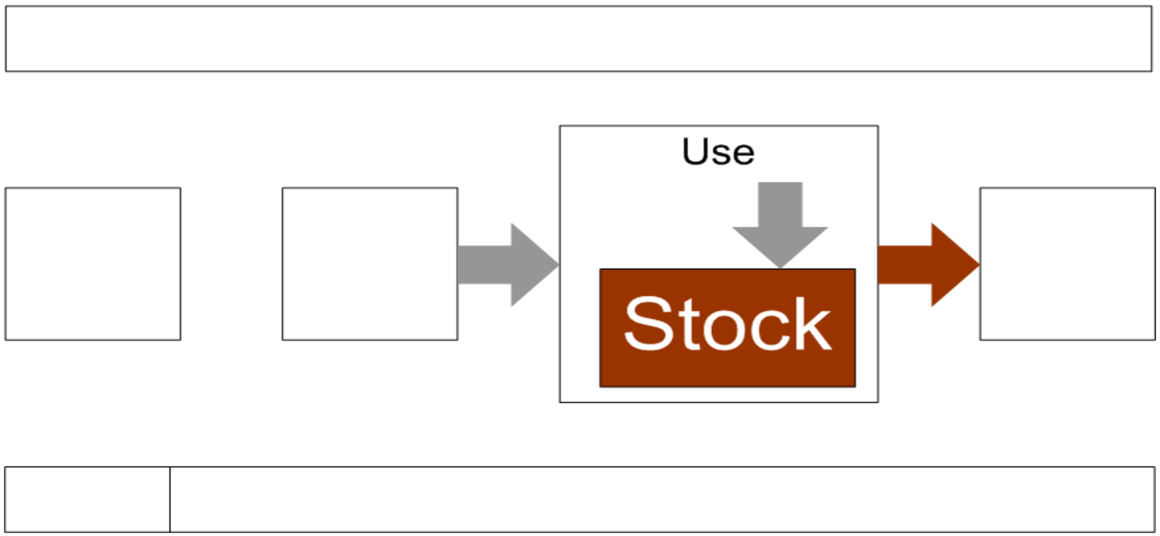
Japan Chromium Cycle: One Year Stocks and Flows, 2000



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

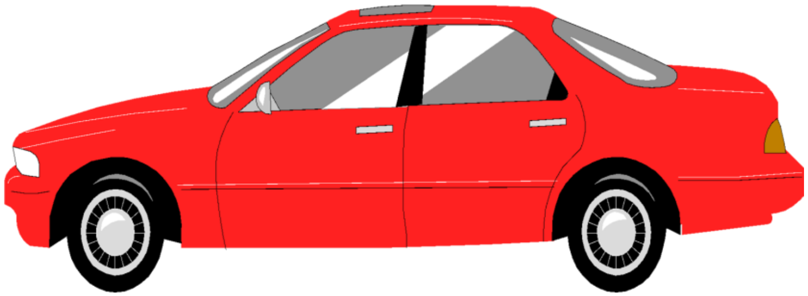
Gg Cr/yr

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

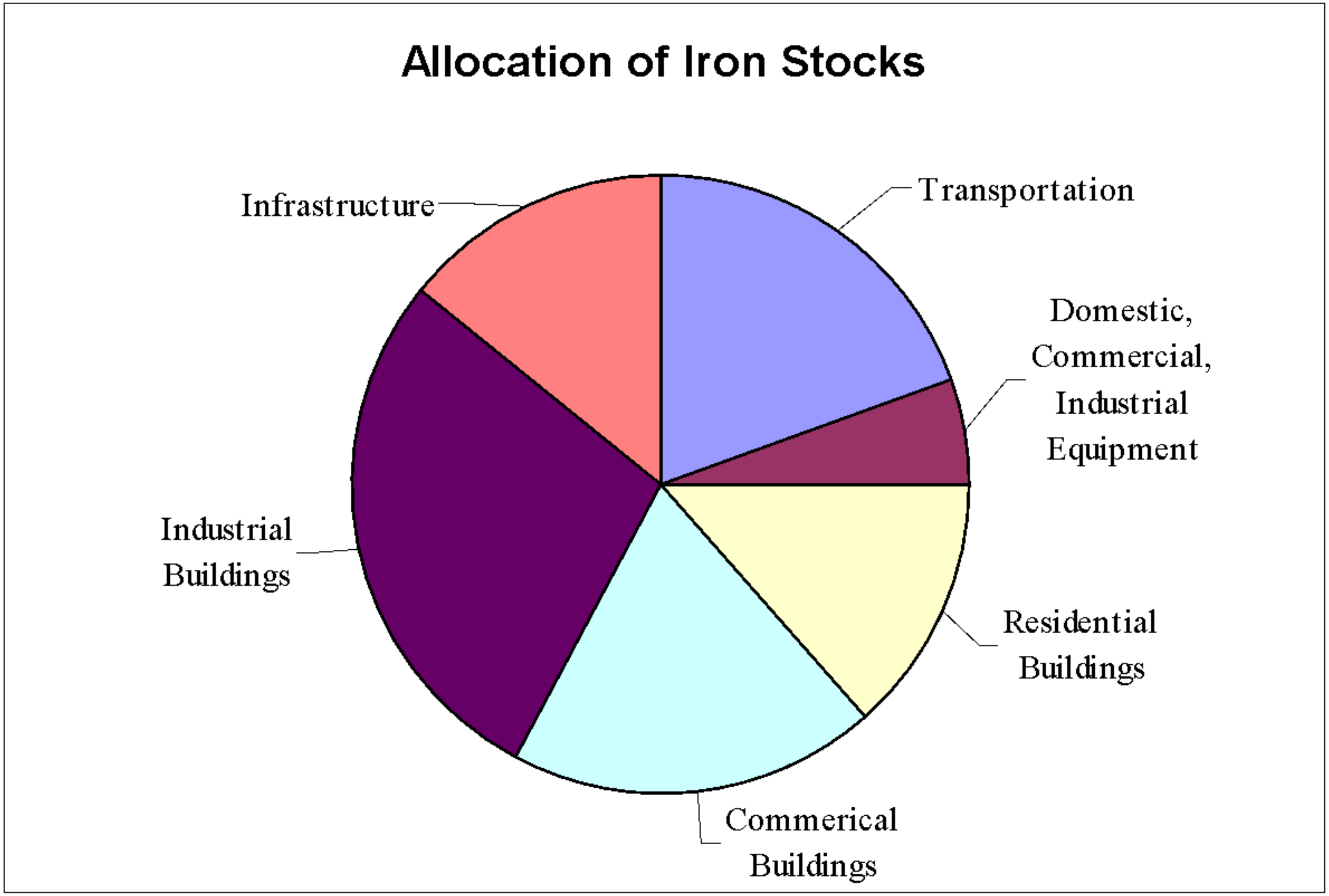
Municipal statistics furnish the number of registered vehicles, the number of homes, and other needed information.

Typical Major Product Categories

- Buildings
- Equipment
- Transportation
- Infrastructure

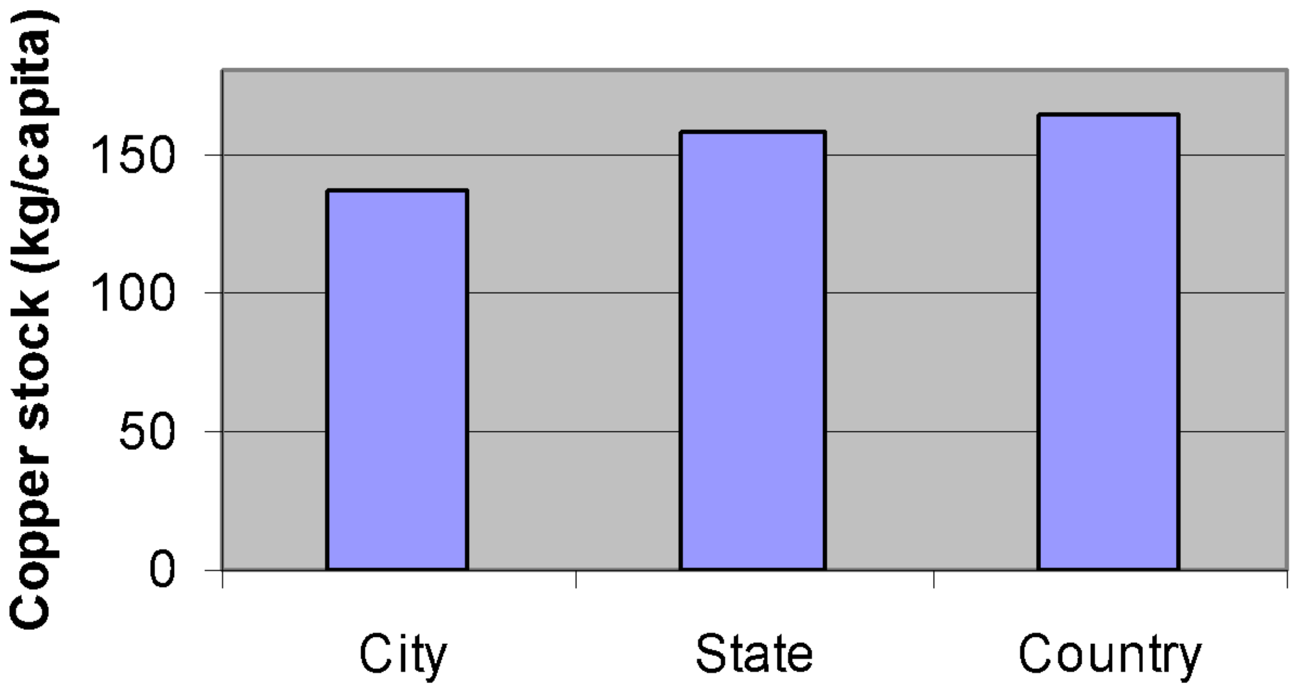
Results

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

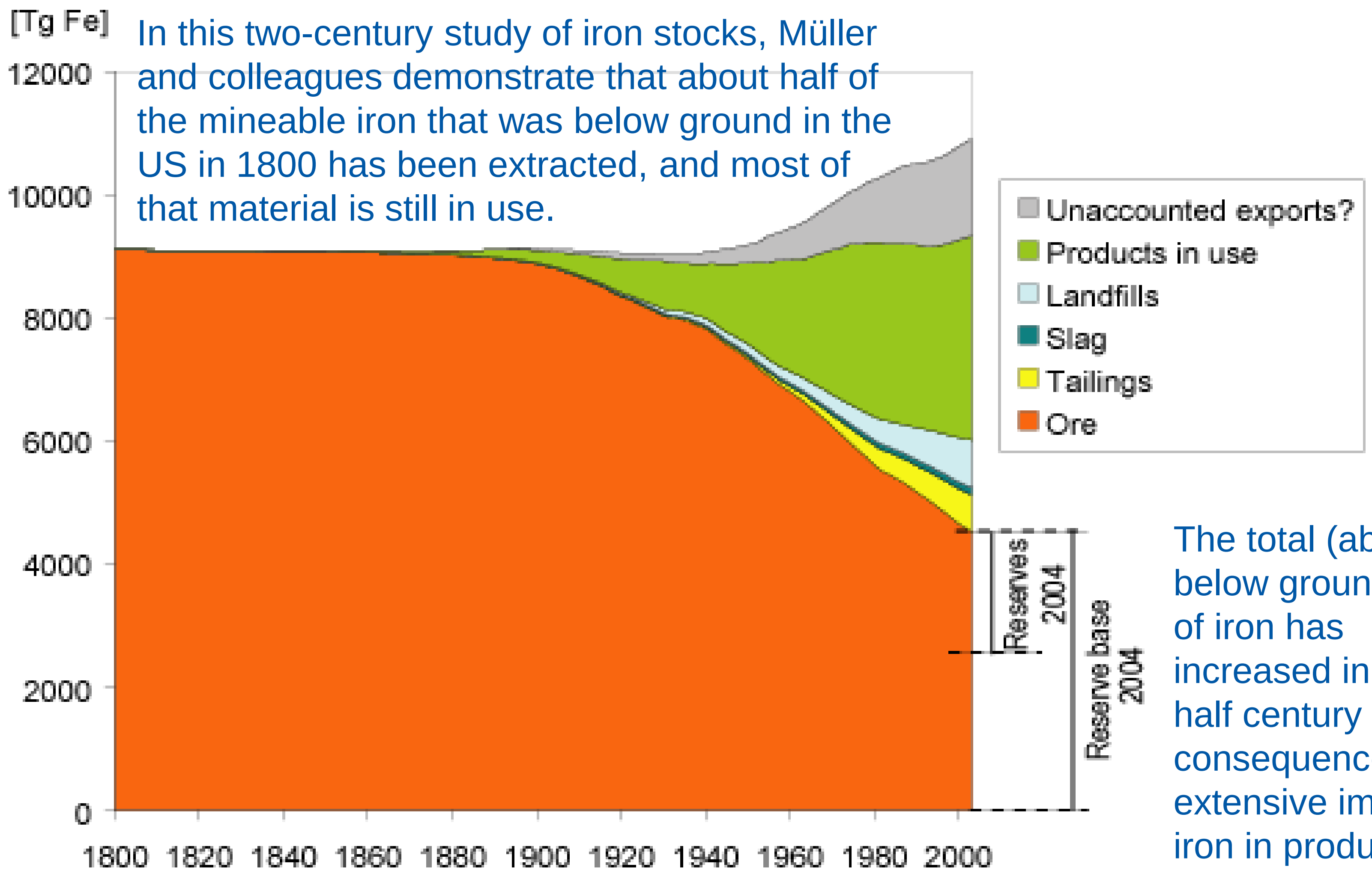


City: New Haven, State: Connecticut, Country: USA. Courtesy of T. Wang

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

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	

Uses of Material Flow Analyses

Type I

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

Type II

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

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