Environmental Paradigms

Evaluation Context:
A Need to Understand Environmental Paradigms

- **Industrial ecology is identifying numerous options to improve environmental impact of society.**
- **In many cases, numerous technological options exist.**
- **How does one select the "best" option?**
- **Evaluation requires injection of values.**
- **Paradigms provide insight into how values vary.**

Environmental Paradigms

- **M E Colby**
  Environmental Management in Development: The Evolution of Paradigms
  - **Frontier Economics**
  - **Externality Control**
  - **Resource Management**
  - **Eco-development (industrial ecology)**
  - **Deep ecology**
- **M Thompson**
  Understanding Environmental Values: A Cultural Theory Approach
  - **Individualism**
  - **Hierarchy**
  - **Egalitarianism**
  - **Fatalism**

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Randolph Kirchain
Introduction: Slide 3

Frontier Economics

- **Earth provides limitless supply of**
  - **Physical resources**
  - **Sinks for by-products of consumption**
  - **Primary limitations imposed by availability of labor & capital**
- **Environmental problems as we know them are absent**
  - *Is this a fair statement?*
- **Sustainability is not a concern**
- **Policy strategy**
  - **Future is created through a price system based on free choice.**
  - **Free market -- Governments act only as necessary to deal with unavoidable market imperfections**
  - **Technological optimism -- Technology is good, progressive, and can cure any problem it creates**
  - **No pre-market assessments of technology –** *Why?*

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Look at the data. Life expectancy across the globe has shot up over the course of the last two centuries. People are better fed, better clothed, and better housed today than ever before. Inflation-adjusted **prices for virtually all resources** – renewable and nonrenewable – **are going down**, which points to growing abundance, not growing scarcity. Global forests have, on balance, expanded over the past 50 years. **Air and water pollution in the most industrialized nations of the world is a mere shadow of what it was decades ago**. Even Third World countries have found that, **once per capita income reaches a certain point, economic growth coincides with a cleaner environment**. And if current trends in productivity, population growth, and consumption continue, we'll be able to return a chunk of land the size of the Amazonian Basin back to nature by 2070. **The human footprint on the environment is indeed becoming lighter and softer**.

-- Jerry Taylor, Cato Institute

Externality Control / Environmental Protection

- Earth is an open system.
  - Waste and pollution can pose a problem
  - Waste and pollution are economic externalities.
  - Environmental problems are failures in the economic system.
- Sustainability is not a concern
  - Future can be protected by interventions in the market.
- Policy strategy
  - Technological optimism
  - Pollution reduction and control through laws and regulations.

Resource Management

- Earth is a closed economic system.
  - Exhaustion of resources is a matter of concern
  - Mismanagement of resources is an externality to be internalized.
- Sustainability (weak) means maintaining the combined stock of human and natural capital
  - Ecology poses a necessary constraint on growth
- Policy strategy
  - Technological optimism/clean technology
  - Economize ecology
  - Correct market incentives / Get the price right..
  - Incorporate all types of capital & resources into calculations for investment planning

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Industrial Ecology / Eco-development

- Earth is a closed ecological system.
  - scale / type of development ≠ long-term survival
- Human society and natural ecosystems have co-evolved.
  - Nature has intrinsic value, revealed through economic activity.
- Sustainability = maintain stocks of both human and natural capital
- Decoupling of biophysical from economic growth – steady flow
- Policy strategy
  - "Ecologize economy"
  - Moral/ethical transformation to instill environmental concerns.
  - Technological realism;
    precautionary principle to handle uncertainty.
  - Life cycle framework; product policy, "Pollution prevention pays"
  - Policy equity

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Deep Ecology

- **Earth is a closed system.**
- **Human society and natural ecosystems have co-evolved.**
  - **Nature has value and a .right. to exist independent of human claims of hegemony.**
  - **Nature.s intrinsic value is hidden by economic activity.**
- **Sustainability is the wrong question as it comes out of human-centeredness.**
- **Policy strategy**
  - **Human transformation of .self. to realize a harmony with nature.**
  - **Technological pessimism; the value of technological innovation must be proven.**
  - **Level of economic activity ultimately consistent with solar inputs.**

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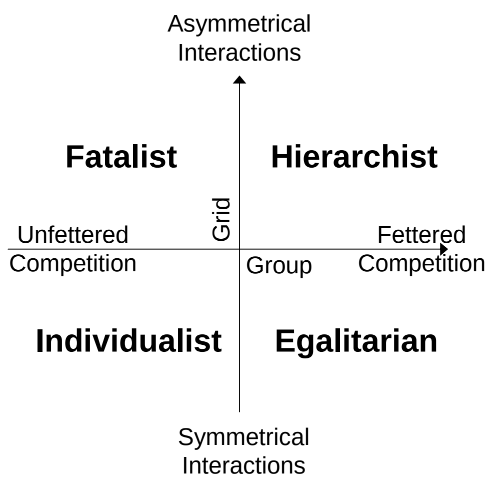
Another perspective on paradigms: Cultural Theory*

- **"Group" perspective,** extent to which an individual is **incorporated (or perceives incorporation) into bounded units**
  - **Greater incorporation → subordination of individual to whole**
- **"Grid" perspective**, extent to which individual is **influenced by externally imposed prescriptions**
  - **Greater influence → less perceived ability to negotiate individual solutions**
  - **Controllable / controlled**



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*M. Thompson, "Understanding Environ. Values: A Cultural Theory Approach", Carnegie Council on Ethics & International Affairs.

Cultural Theory Perspectives on the Environment

- Hierarchist
  - Lays down the rules
  - Takes calculated / analyzed / controllable risk
- Individualist
  - Unconstrained innovator
  - Risks create opportunities
- Egalitarian
  - Disagrees with rules and exploitative attitude
  - Reject risk-taking
- Fatalist
  - Sees no opportunity to take action
  - See risk taking as necessary consequence of fate

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Cultural Theory Perspectives on the Environment

- Individualist:
  - Optimistic: Nature is benign and resilient
  - Institutions are not trusted
  - Prefers market-based trial-and-error
- Hierarchist:
  - Optimistic: nature is stable until pushed beyond limits, World is controllable
  - Institutions can be trusted to prevent going beyond limits
  - Analytically based regulation
- Egalitarian:
  - Pessimistic: Nature is fragile, intricately interconnected and ephemeral
  - Institutions are not trusted
  - Voluntary simplicity is only solution to enviro problems
- Fatalist
  - Pessimistic: Man and nature are fickle and unpredictable
  - No management strategy

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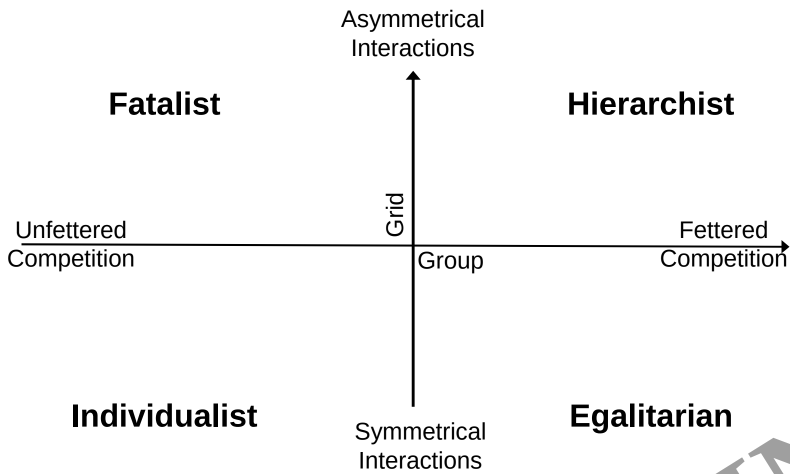
Locating Enviro-management Paradigms



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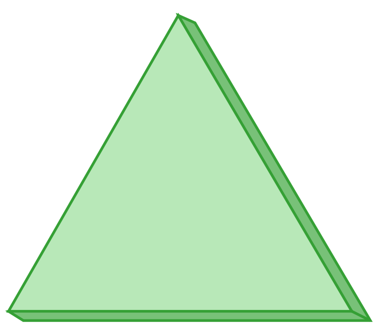
Three voices of climate change debate

Hierarchical Solidarity
Problem: Too many people
Solution: Population control



Market Solidarity
Problem: Prices do not reflect environmental costs
Solution: Price reform

Egalitarian Solidarity
Problem: Too much consumption
Solution: Frugality

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Figure by MIT OCW.

Reference: Thompson, M., *Cultural Theory and integrated assessment.* Enviro Model Assesst, **2**(3): p. 139-150, 1997.

Environmental Policymaking: Policy Definitions and Frameworks

ESD.123, Spring 2006

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Some Definitions of Policy on the WWW

- A line of argument rationalizing the course of action of a government
  - *wordnet.princeton.edu/perl/webwn*
- A guiding principle designed to influence decisions, actions, etc. Typically, a policy designates a required process or procedure within an organization.
  - *www.pmostep.com/290.1TerminologyDefinitions.htm*
- A plan or course of action, as of a government, political party, or business, intended to influence and determine decisions, actions, and other matters.
  - *youthink.worldbank.org/glossary.php*
- A written principle or rule to guide decision-making.
  - *www.clemson.edu/research/orcSite/orcIRB_DefsP.htm*

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A Notable Summary

"Policy can be defined in many different ways but it is more than simply a statement of belief (O'Brien, 1980). Its major purpose is to guide action (Caldwell, 1980). In general, policy is philosophically based, implies intention and suggests a pattern for taking action... It creates a framework for action with some basis for discretion within which {school personnel} can discharge their duties with clear direction (Caldwell, 1980)...

Policy is not a goal or aim even though the latter may be implicit in the statements of policy, while specific objectives, as statements of outcomes, may often be set as part of policy implementation. Policy produces guidelines for the preparation of rules and procedures which are the first steps in policy implementation. They direct action and specify the individuals responsible for such action" (Caldwell, 1980).

In Turney, C., Hatton, K., Laws, K., Sinclair, R. and Smith, D. (1992). *The School Manager: Educational Management Roles and tasks.* North Sydney: Allen and Unwin, p. 122.

From "What is Policy?" http://www.slaq.org.au/SubCommittees/Murrumba/PD/whatispolicy.htm

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Technical Definitions, Too

- A rule established by the manager of a digital library that specifies which users should be authorized to have what access to which materials.
  - *www.cs.cornell.edu/wya/DigLib/MS1999/glossary.html*
- The set of rules that govern the interaction between a subject and an object. For example, when an Internet Protocol (IP) security agent (the subject) starts on a given computer (the object) a policy determines how that computer will participate in secure IP connections.
  - *www.microsoft.com/windows2000/techinfo/howitworks/activedirectory/glossary.asp*

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Why Do We Have "Policy?"

- Other Mechanisms Exist
  - Legislation
  - Regulation
  - Enforcement Agencies
  - Markets
  - Social Conventions
  - Nature
- Why "Policy?"

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Common Elements

- Overt
  - Objective(s)
  - Presumptive mechanism(s) for action to achieve the objective
  - Context
    - *Institutional*
    - *Instrumental*
  - Implementation
- Implicit
  - Legitimacy
  - Mechanisms for enforcement
  - Complexity
  - Political

Policy vs. Mechanism

- Difficulties in reducing to "determined system"
  - Very complex and dynamic system
    - *By design*
  - Imperfect instruments of control
  - Imperfect ability to design instruments
  - Ideology and goals
- Preservation of flexibility necessary
- Policy as vital complement to system flexibility

Starting Points in Policy Development

- ❑ Goals: what are they?
- ❑ Framing the goals: how to talk about them
- ❑ Legitimacy: how
- ❑ Constituencies
  - Who cares
  - Who agrees with the goals
  - Who is opposed to the goals
  - Who benefits/loses from the policy (distinct from the goals!)
    - *How to measure benefits/losses*
    - *What to do about them*
- ❑ Mechanisms of control: implementation
- ❑ How will you know the policy is "working?" What does that mean?

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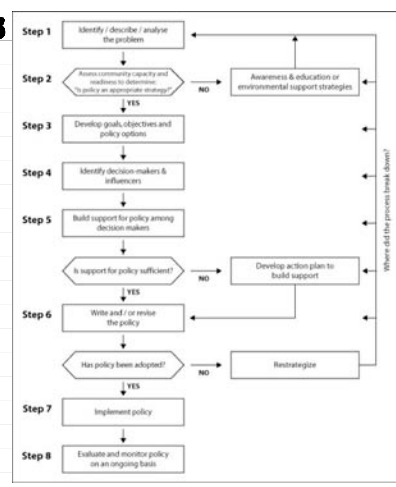
Implications of a Process

- ❑ A graphic from "What is Policy?" Sherri Torjman. September 2005. www.caledoninst.org
- ❑ A typical sort of representation
  - A focus on implementation, especially constituency-building



Courtesy of The Health Communication Unit (THCU) at The Centre for Health Promotion, Department of Public Health Sciences, University of Toronto. Used with permission.

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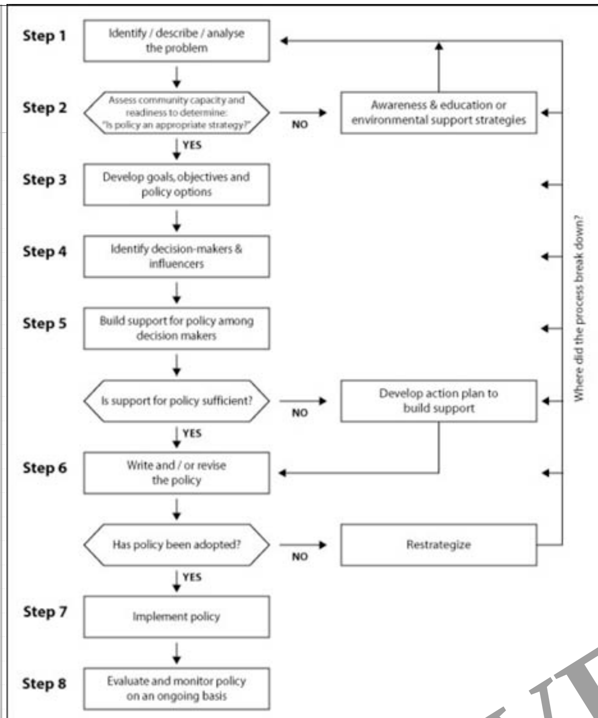
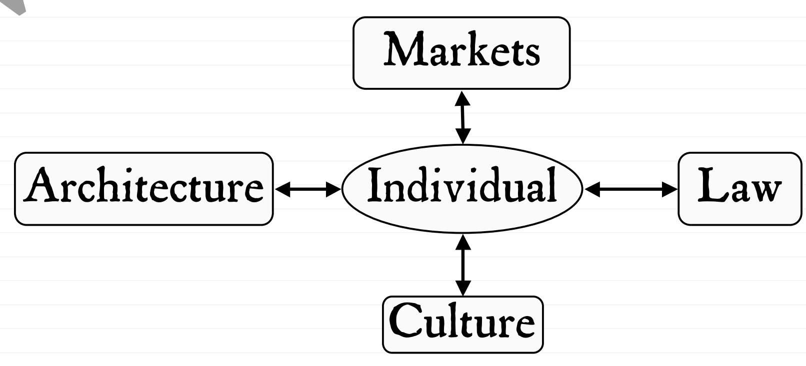
Cambridge, Massachusetts http://www.thcu.ca/infoandresources/roadmap.htm



Courtesy of The Health Communication Unit (THCU) at The Centre for Health Promotion, Department of Public Health Sciences, University of Toronto. Used with permission.

Getting People To "Behave" (Modalities of Control)

- Lessig's "New Chicago School" – **A** framing of the instruments of action **and** control



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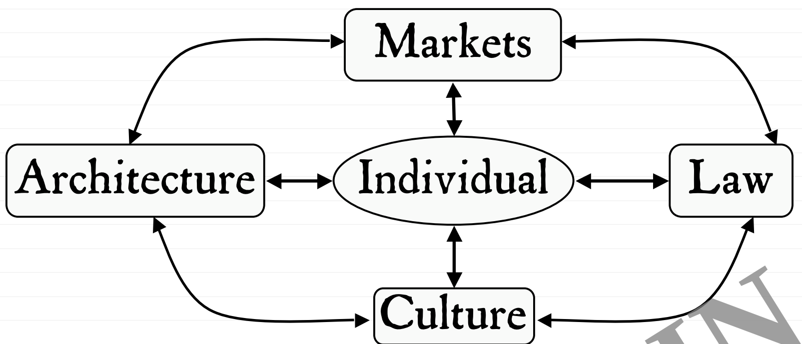
6

Modalities Need Not Be Unilateral

- Some interaction among modalities typical



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Some Fundamental Policy Frameworks

- Ideology/Culture in Policy (from Stone)
  - What is Justice?
  - What is Freedom/Liberty?
  - What is Property?
  - What Motivates human action?
  - ...

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Constructions of Justice – #1

- Justice is process
  - Historical Process Justice
  - Voluntary and fair process
  - Question: What is a fair process
  - What is fair about *ab initio* distributions/transactions

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Constructions of Justice – #2

- Justice is social construct
  - End-Result Justice
  - Social goods must be distributed equitably
  - What are the characteristics of goods that make them "social;" what are the characteristics of individuals that make them a member of society

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Constructions of Justice – #3

- Justice is innate/universally defined
  - Universal standards of justice, independent of context
  - Unjust allocations must be rectified according to these standards

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Liberty, Property & Motivation

- Liberty
  - Freedom from constraint on action
  - Freedom to act as one wants
- Property
  - An individual construct
  - A social construct
- Human Motivation
  - Need Motivates
  - Need Inhibits

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Dichotomy?

- Social Conservatism
  - (Distributive) Justice
    - *Fair Process*
  - Liberty
    - *Freedom to act*
  - Property
    - *Individual creation*
  - Need Motivates
- Social Liberalism
  - (Distributive) Justice
    - *Fair shares of social resources*
  - Liberty
    - *Freedom from constraints*
  - Property
    - *Social creation*
  - Need Inhibits

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Some Fundamental Policy Frameworks

- The Legal System
  - Legislation
    - *Political bodies (legislatures) construct*
    - *Executives implement*
    - *Courts interpret and enforce*
  - Regulation
    - *Delegation of functions of legislatures and executive*
    - *Constrained by legislation*
- Basics
  - Focus on process as mechanism for fairness
  - Trial by combat
  - "Rights" and harms ("torts")
  - Argument
- Fundamental metaphors
  - Truth via "trial by combat"
  - Rights (natural and otherwise) and Harms ("torts")
  - Common law; precedent; consistency

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Some Fundamental Policy Frameworks

- The Economic System
  - The market
    - *Producers*
    - *Consumers*
    - *"Referees"*
  - Transactions of exchange
- Fundamental metaphors
  - Opportunity available to all
  - Efficiency and equality
  - Competition
- Basics
  - Focus on efficient use/allocation of resources
    - *Social welfare*
  - Competition as goad to achieve efficiency
  - Remediation by institutions when competition cannot be sustained
  - Harms in terms of metrics of suboptimality
    - *Theory of second best?*

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Language and Rhetoric

- Rhetoric: "The art of using language so as to persuade or influence others; the body of rules to be observed by a speaker or writer in order that he may express himself with eloquence" (OED)
- Better:
  - the use of discourse to understand and influence the quality of our lives through interaction and cooperation with others
  - the use of language to negotiate the meaning of events & coordinate response with others
  - the strategic use of language to motivate the public to coordinated action

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- How will you know the policy is "working?" What does that mean?

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Some Ideologies and Environmental Politics

- Conservative ideology –– preservation ethos
- Authoritarianism –– command and control
- Liberal ideology –– eco-centric ethos
- Also consider anarchy & feminism
- Democratic ideals/decentralism/coordination problems
- Complex domain of political action

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Sustainable Development:

What is it?

Why does it matter?

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Sustinability: Slide 1

What is Sustainable Development?

- **Context**
  - **Sustainable Development as a concept dominates much of the literature concerning the *broader* implications of technology and modernity**
- **Goal: To make students aware of**
  - **Prevailing thinking about sustainability**
  - **Challenges regarding synthesizing the impact of a technology within a broader context**

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Sustainability: Slide 2

What is Sustainable Development?

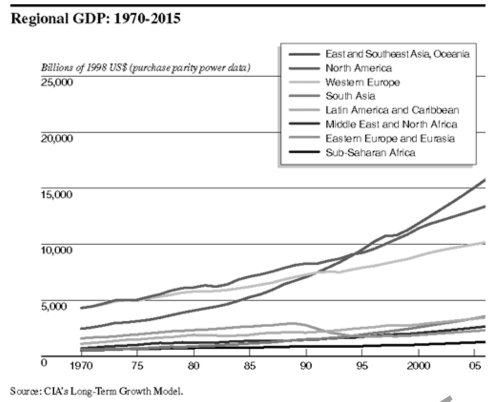
Firstly, what is "Development"?

Development Economics

- Emerged in the 1940's
- Goal:
  To raise the standard of living throughout the world
- After World War II, often tied up with Cold War goals.
  - Seminal Text:
    The Stages of Economic Growth: A Noncomunist Manifesto (Rustow)
- Led to the creation of World Bank, IMF, and GATT

Development Economics: Measures of Success

- Concept widely accepted
- Global improvement
  - Possible exception Sub-saharan Africa



Source: Figure 1.4, Human Development Report 2005, UNDP

What is Sustainable Development?

Classic Definition

- *"Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs"*
  (The World Commission on Environment and Development, United Nations,1987)

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Sustainability: Slide 7

Other Definitions of Sustainable Development

- *Improvement in the quality of human life within the carrying capacity of supporting ecosystems*
  (World Wildlife Fund)
- *A condition in which the ecosystem maintains its diversity and quality— and thus its capacity to support people and the rest of life—and its potential to adapt to change and provide a wide change of choices and opportunities for the future*
  A condition in which all members of society are able to determine and meet their needs and have a large range of choices to meet their potential
- *Economic growth that provides fairness and opportunity for all the world's people, not just the privileged few, without further destroying the world's finite natural resources and carrying capacity*
  (Pronk and ul Haq 1992).

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Sustainability: Slide 8

Key Questions:

What?

... to Sustain?

... to Develop?

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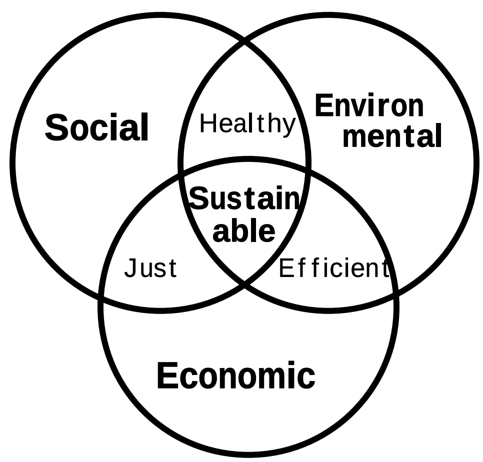
What is to be Sustained?:

Broadly Accepted Elements of Sustainability

- **Economic**
  - **Human Capital**
  - **Human-made Capital**
- **Environment**
  - **Natural Capital**
- **Social**
  - **Social Capital**



Adapted from http://www.state.nj.us/dep/dsr/sustainable-state/what-is.htm

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What is Economic Sustainability?

- **Human-made Capital**
  - **Traditional economic capital**
  - **Produced means of production**
- **Human Capital**
  - **Often simply refers to labor**
  - **More subtly, the ability of an individual to produce or increase income**
    - Knowledge
    - Skills
    - Health
    - Values
  - **Activities that increase human capital**
    - Education
    - Training
    - Medical care

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Environmental Sustainability

- **Maintenance of Natural Capital**
  - **Ecosystem services that enable life**
- **Sources**
  - **Stocks of raw materials**
  - **Flows of renewable resources**
- **Sinks**
  - **Capacity to assimilate wastes**

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Environmental Sustainability: Goodland 95

- **Output Rule:**
  - **Waste emission can't exceed assimilative capacity of local environment**
- **Input Rule**
  - **Renewables:**
    Harvest rates should be within regenerative rates
  - **Non-renewables:**
    Harvest rates should be below that rate at which renewable substitutes are developed

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Social Sustainability

- **Social Capital**
  - **No Consensus definition**
  - **Knowledge and rules of interaction in culture and institutions**
    - Legal system
    - Government
- **Social Sustainability general includes addressing basic needs of population**
    - Recognitions of social issues in traditional development economics predate environmental concerns
  - **Income distribution**
  - **Quality of life**
    - Illiteracy
    - Hunger
  - **Institutional participation**
  - **Increasing choice**

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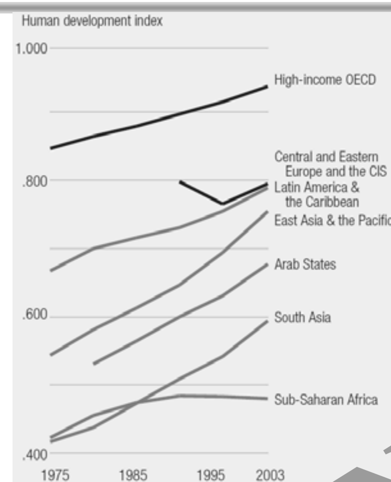
Development Economics: Measures of Success

- UN Development Program – Human Development Indicator
  - GDP
  - Education
  - Life-expectancy
- Troubled Areas
  - Sub-saharan Africa



Source: Figure 1.4, Human Development Report 2005, UNDP
Courtesy of United Nations Development Programme.

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Sustainability: Slide 16

How much is to be sustained?

Quantity
or
Quality

Timeframe

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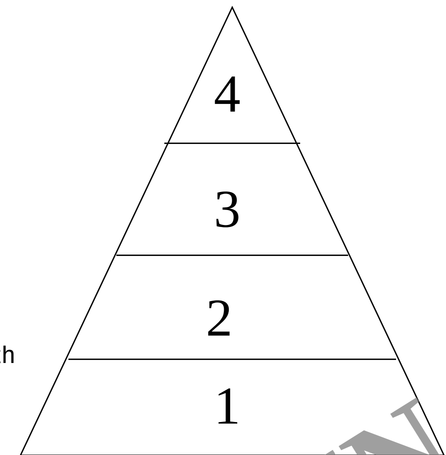
Sustainability: Slide 17

What is to be Sustained?
Sustainability Hierarchy (Marshall and Toffel)

- **Actions are unsustainable that**
  - **Level 4**
    - Reduce quality of life
    - Violate other values
  - **Level 3**
    - Cause species extinction
    - Violate human rights
  - **Level 2**
    - Significantly reduce life-expectancy or basic health
  - **Level 1**
    - Endanger human survival



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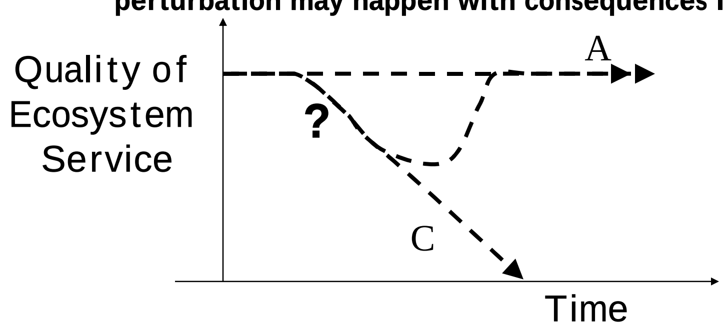
Sustainability: Slide 18

Over what time frame should we care about sustainability?

- **Are these sustainable?**
  - **Some would disagree with labeling B as acceptable**
  - **During perturbation B, it is possible that another perturbation may happen with consequences like C**



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Sustainability: Slide 20

Is it sustainable if we allow some forms of capital to deteriorate while others are maintained?

Examples?

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Capital Substitutability: Trading off over resources or time

- **Strong Sustainability**
  - Cannot make tradeoffs among sustainability of various resources
  - What is an example of a potential tradeoff?
- **Weak Sustainability**
  - Some resources / ecosystem capabilities may deteriorate if the value extracted is reinvested in substitutable capabilities

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Mapping the Environmental Consequence of Design Decisions: Introduction

Professor Randolph Kirchain
Department of Materials Science & Engineering and
Engineering Systems Division

Overview

- Goal
  - Examine the need for an environmental evaluation method
  - Provide an overview of Life Cycle Assessment

What are some examples of products that compete on environmental characteristics?

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How would you make a engineering decision to evaluate options?

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Example: Comparing Grocery Sacks

- Your firm is going to launch a new line of grocery stores that focuses on environmentally and socially conscious consumers
  – Stop & Care & Shop
- Your task has been to identify the type of grocery sacks you will offer
  – Paper or plastic?
- What do you need to know?

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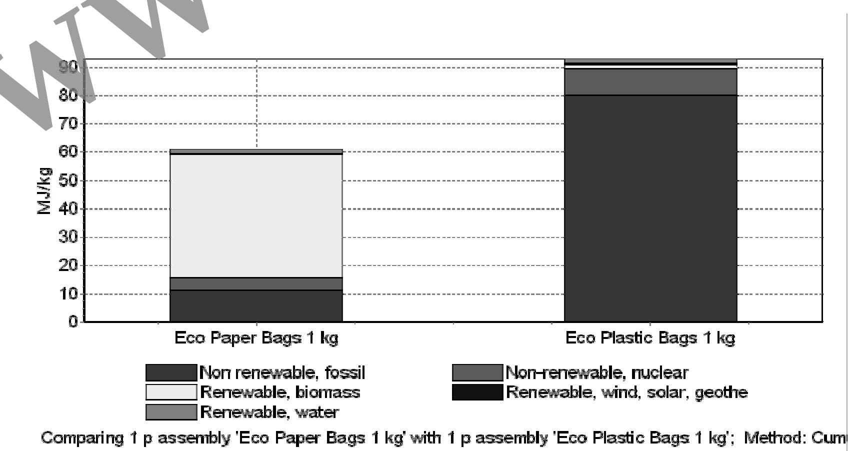
Comparing Paper and Plastic:
Comparing Unit Production Energy



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What about product design?

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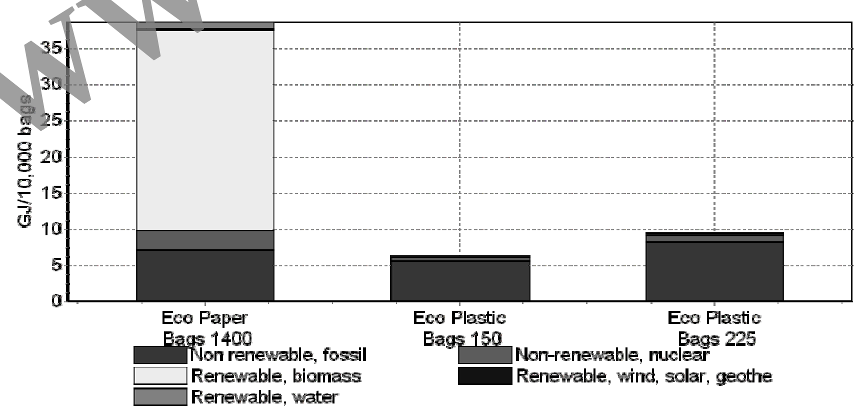
Comparing Paper and Plastic:
Production Energy of a Single Bag



Comparing 1 p assembly 'Eco Paper Bags 1400 lb' with 1 p assembly 'Eco Plastic Bags 150 lb' and with 1

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What happens to the bag after production?

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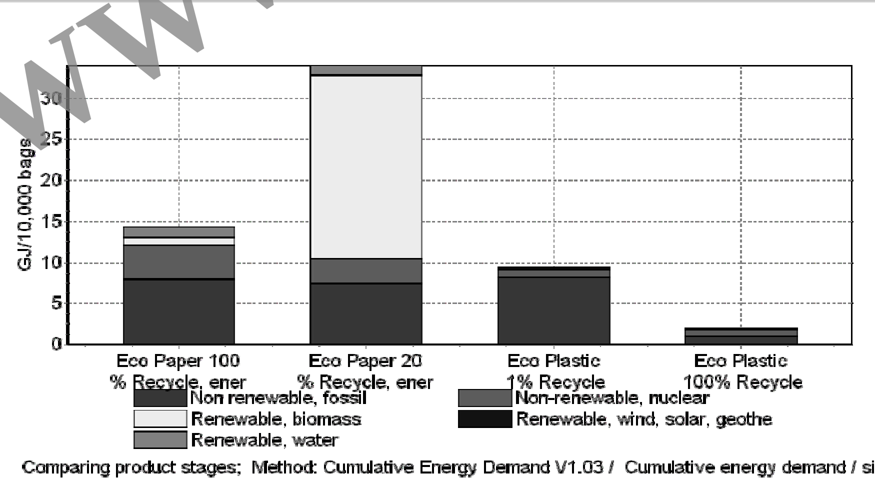
Comparing Paper and Plastic:
Comparing Unit Production Energy with Recovery



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Materials Substitution:
Making Better Materials Choices

Which Material would you Choose?

Material A		**Material B**	
CO_2	2 kg / kg	CO_2	11 kg / kg
SO_2	0.008	SO_2	0.4
NOx	0.007	NOx	0.3

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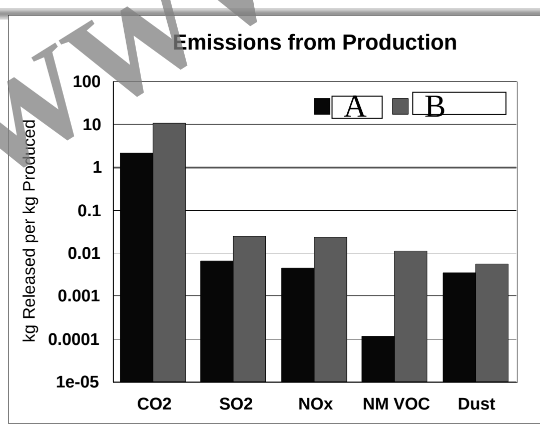
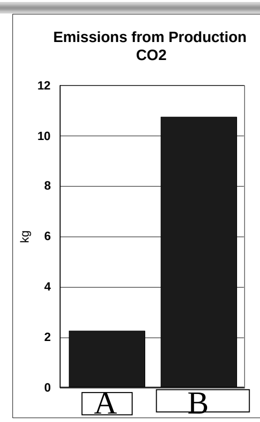
Which would you choose?





Why does B advertise itself as Environmental?

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What is Life-cycle Assessment?

- **SETAC Definition:**
  "The life cycle assessment is an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials usage and environmental releases, to assess the impact of those… and to evaluate and implement opportunities to effect environmental improvements…"

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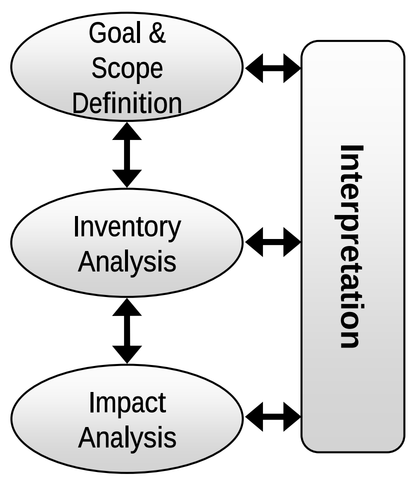
LCA: Methodology

- **Goal & Scope Definition**
  - **What is the unit of analysis?**
  - **What materials, processes, or products are to be considered?**
- **Inventory Analysis**
  - **Identify & quantify**
    - Energy inflows
    - Material inflows
    - Releases
- **Impact Analysis**
  - **Relating inventory to impact on world**



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Establishing Common LCA Practice

- **SETAC**
  (Society of Environmental Toxicology and Chemistry)
  - **Regarded as pioneering organization establishing LCA procedures**
- **ISO 14040 (1997) – 14043 (2000)**
  - **Defines LCA as:**
    "compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life-cycle"

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Why Carry Out a Life-Cycle Assessment? Goals

- **Decision-making**
  - **Product design**
  - **Process design**
  - **Purchasing**
  - **Policy-making**
- **Communication**
  - **Eco-labeling**
  - **Product declarations**
  - **Benchmarking**
- **Learning / exploration**
  - **Identifying improvement opportunities**
  - **Identify liability concerns**
  - **Selecting performance indicators**
  - **Research**

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Why Carry Out a Life-Cycle Assessment? Advantages

- Systems perspective
  - Many impacts occur because of decisions we control, but not directly due to our actions
  - Avoids media shifting
- Product / activity focus
  - Allows consideration of alternative paths to fulfilling objective
- Analytical
  - Provides orderly structure to evaluation
  - Not value-free

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LCA Limitations

- Holistic point of view is a strength and weakness
  - Tends to simplify to achieve scope
- Does not fully capture localized effects
- Tends to be static analysis
- Tends to be linear analysis
- Ignores other impacts
  - Economic
  - Social
- Data availability
- Analytic intensity

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What are the key issues to consider?

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Key Issues to Consider

- **Functional Unit**
  - **What is compared to what?**
    - Aluminum cans
    - Laundry Detergent
- **System boundaries**
  - **What will be included?**
- **Allocation**
  - **What about other useful outflows?**
- **Type of data**
  - **Local specifics vs. Averages**
- **Impact assessment method**

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Resources

- **Text:**
  - **"The Hitch Hiker's Guide to LCA" Baumann and Tillman**
    - On reserve in the library
    - $39 on Amazon
- **Readings on MIT server**
  - **"LCA: What is it?" & "LCA: How to do it?", UNEP**
  - **"Intro to LCA with SimaPro", Pre Consulting**
- **Readings**
  - **Today – Chapter 1**
  - **Thurs (3/9) – "Intro with Simapro"**
  - **3/14 – Ch 3**
    - Goal & Scope Assignment
  - **3/16 – No class**
  - **3/21, 3/23, & 4/4 – Ch 4**
  - **4/6 – Case 1 Presentations**
  - **4/13 & 4/20 – Ch 5**

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Assignment #4: Considering LCA Goal & Scope

- **Select a product or activity**
- **Characterize two distinct goals for carrying out an LCA**
  - **Both goals should represent distinct stakeholder perspectives**
    - Producer, consumer, regulator, NGO …

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Assignment #4: G&S Characterization

- Describe activity
- Identify stakeholder and motivations of stakeholder
- What alternatives are being compared?
- What is functional unit?
- What are geographical system boundaries?
  - Should export be considered?
  - Activities outside of US?
- What is the time horizon of the study?
- What are the conceptual boundaries of the study?
  - What activities are included?
  - What about capital goods?

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Case 1 – LCA of a Product – (April 4)

- Select a set of product or activity on which to perform a comparative LCA
- Presentation:
  - What is product?
    - Overview of environmental concerns raised publicly
  - Goal & scope
    - Goal
    - What alternatives are being considered?
    - Boundaries
  - Inventory
    - How is product made?
    - Major assumptions
    - Data sources
  - Impact assessment
  - Recommendations
- Writeup – 3-5 page writeup of case and recommendations

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Session 2: Defining Goal & Scope

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Goal & Scope Definition: Study Goals

- **Intent: Intended application of the study**
  - **For what purpose**
  - **Examples**
    - Identifying major problems
    - Selecting the preferred option
- **Context: For whom and compared to what**
- **Output: How will results be communicated**

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Why Carry Out a Life-Cycle Assessment?

- Decision-making
  - Product design
  - Process design
  - Purchasing
  - Policy-making
- Communication
  - Eco-labeling
  - Product declarations
  - Benchmarking
- Learning / exploration
  - Identifying improvement opportunities
  - Identify liability concerns
  - Selecting performance indicators
  - Research

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Goal & Scope Definition: Study Scope

- Functional Unit (Unit of analysis)
- System boundaries:
  - Conceptual
  - Geographic
  - Time period of study
- Types of impacts to consider
- Required level of detail

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Defining the Functional Unit

- Reference flow against which all others are related
  - Establishes a common level of performance across the systems to be considered
- Examples
  - Light bulbs
  - Wallpaper vs. paint
  - Newspapers
  - Bread

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Goal & Scope Definition: How far do we go?

- Defining boundaries
  - No theoretical basis for exclusion
  - Often broken at environmental flows or economic flows of + value
  - Generally includes only processes in direct contact with product & raw materials entering that product
- Example: Oil Use
  - Combustion
    - If electricity, consider: conversion efficiency & transmission eff.
  - Extraction
  - Transport
  - Refining

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Session 3: Inventory Analysis

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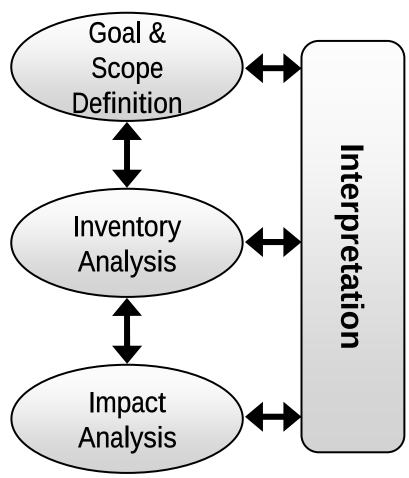
LCA: Methodology

- **Goal & Scope Definition**
  - **What is the unit of analysis?**
  - **What materials, processes, or products are to be considered?**
- **Inventory Analysis**
  - **Identify & quantify**
    - Energy inflows
    - Material inflows
    - Releases
- **Impact Analysis**
  - **Relating inventory to impact on world**



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Inventory Analysis

- **Building a system model of the flows within your system**
  - **System boundaries and flow types defined in Goal & Scope**
  - **Typically includes only environmentally relevant flows**
    - E.g., exclude waste heat, water or O_2 emissions
- **Steps**
  - **Catalog what activities to include (draw a flowchart)**
  - **Data collection**
  - **Computation of flows per unit of analysis**
    - Serious challenges around allocation

Flowchart Examples: Intl Al Inst. 2003

2.1. Goal and Scope Definition

The intended purpose of this Inventory report is to accurately characterize resource consumption and significant environmental aspects associated with the worldwide production of primary aluminium. It reflects the fact that primary aluminium is a globally traded commodity.

Intl Al Inst. 2003

Figures removed due to copyright restrictions.

Source: Flowcharts on p. 5 and p. 15 in "Life Cycle Assessment of Aluminum: Inventory Data for the Worldwide Primary Aluminium Industry." International Aluminium Institute. March 2003.

Flowchart Examples: Intl Al Inst. 2003

Figures removed due to copyright restrictions.

Source: Flowcharts on p. 5 and p. 15 in "Life Cycle Assessment of Aluminum: Inventory Data for the Worldwide Primary Aluminium Industry." International Aluminium Institute. March 2003.

Inventory Analysis: Data collection

- **Data collection**
  - **Inflows**
    - Materials
    - Energy
  - **Outflows**
    - Primary product
    - Other products
    - Releases to land, water and air
  - **Transport**
    - Distance
    - Mode
- **Data collection (cont.)**
  - **Qualitative**
    - Description of activity under analysis
    - Geographic location
    - Timeframe
- **Key issue:**
  - **Site specific vs. Industry Avg**
- **Data sources**
  - **Scientific literature, Published studies**
  - **Industry & government records**
  - **Industry associations**
  - **Private consultants**

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Calculating the Inventory

- **Identify interconnection flows**
- **Normalize data**
  - **Convert all absolute flows to a quantity relative to one outflow**
  - **Typically reference flow serves as interconnection**

    Note: Since LCAs are typically linear, choice of reference outflow is arbitrary
- **Calculate magnitude of interconnection flows**
  - **For linear system, soluble using linear algebra**
- **Scale all flows relative to interconnection flows**
- **Sum all equivalent flows**

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Product Production Overview

- Product *P* produced in plant *C*
  - *C*: Metal sheets cut and pressed to make *P*
- Plant *B* delivers metal sheets to plant *C*
  - *B*: Ingots melted and rolled into sheets
- Ingots come from plant *A*
  - *A*: Mineral is extracted, turned into metal, cast into ingots

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Product Production Details

- Transport:
  - *A* to *B*: 1000 km, by truck
  - *B* to *C*: 0 km (adjacent)
- Scrap:
  - Process scrap from *C* returned to *B* for remelting
- Product *P*:
  - Weight = 40 g
  - 6 m^2 metal sheet needed to make 1,000
  - Metal thickness = 1.0 mm
  - Metal Density = 8,000 kg/m^3

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Environmental Data – Plant A

Summary

Products Metal ingots

Raw Material Mineral

Inputs/Outputs

Description	Quantity	Units	Details
Total Annual Production	1200	tonnes/year	Product A
Use of raw material	4800	tonnes/year	Raw A
Use of energy in the process	6.00E+06	MJ/year	Oil Combustion
Emissions to air	600	kg/year	HCl
Emissions to water	600	kg/year	Cu
Non-hazardous solid waste	3800	tonnes/year	Solid Waste

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Environmental Data – Plant B

Summary

Products Metal Sheets

Raw Material Metal ingots and process scrap

Inputs/Outputs

Description	Quantity	Units	Details
Total Annual Production	1600	tonnes/year	Sheets
Use of raw material - ingots	900	tonnes/year	Ingots
Use of raw material - scrap	700	tonnes/year	Scrap
Use of energy - heating	5.63E+05	kWh/year	Electricity
Use of energy - rolling	3.26E+05	kWh/year	Electricity
Emissions to air	480	kg/year	HC

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Environmental Data – Plant C

Summary

Products Consumer Product *P*
Raw Material Metal Sheets

Inputs/Outputs

Description	Quantity	Units	Details
Total Annual Production	400	tonnes/year	Product *P*
Use of raw material	480	tonnes/year	Sheets
Use of energy - oil	3.00E+05	MJ/year	Oil
Use of energy - electricity	2.22E+05	kWh/year	Electricity
Emissions to air	250	kg/year	HC
Process Scrap for Recycling	80	tonnes/year	Scrap

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Environmental Data – Transportation and Energy Production

Transportation – Diesel Fuel

Energy

Driving Conditions	Energy Consumption	Units
Long Haul	1	MJ/tonne-km
City Traffic	2.7	MJ/tonne-km

Energy Production Emissions

Emissions (g/MJ fuel consumed)		
Substance	**Oil**	**Diesel**
HC	0.018	0.208
NOx	0.15	1.3
CO2	79.8	78.6

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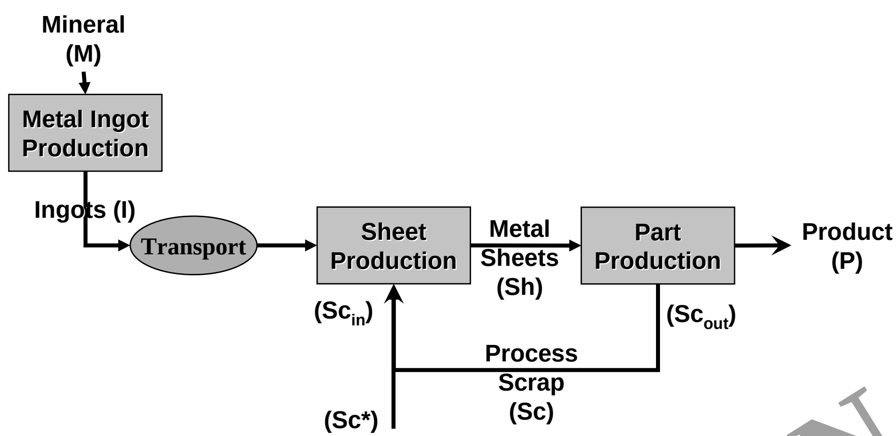
Flowchart of System Being Analyzed



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Calculating the Inventory

- Identify interconnection flows
- Normalize data
  - Convert all absolute flows to a quantity relative to one outflow
  - Typically reference flow serves as interconnection

    Note: Since LCAs are typically linear, choice of reference outflow is arbitrary
- Calculate magnitude of interconnection flows
  - For linear system, soluble using linear algebra
- Scale all flows relative to interconnection flows
- Sum all equivalent flows

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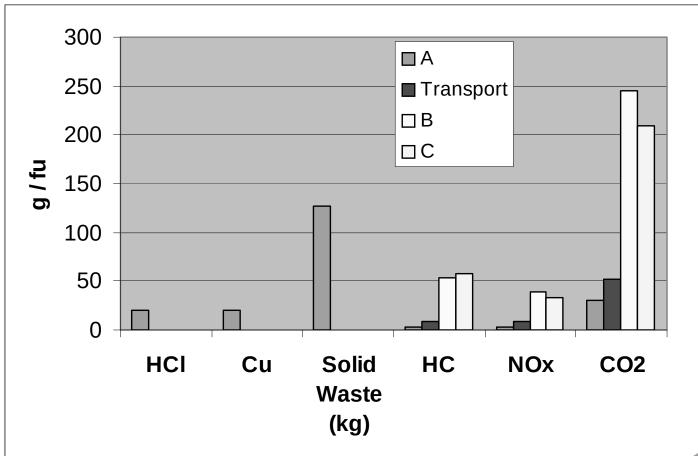
Results – Total Inventory



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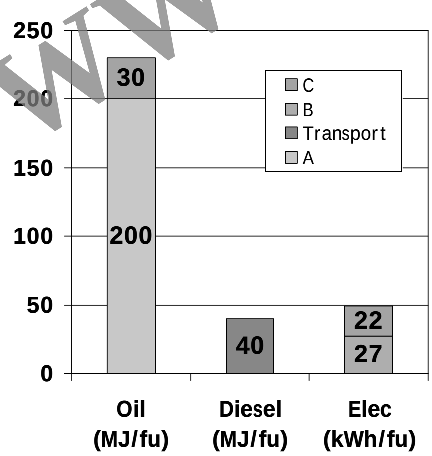
Results – How Much Energy?



- **Totals:**
  - **Oil = 230 MJ / fu**
  - **Diesel = 40 MJ / fu**
  - **Electricity = 49 kWh/fu**
- **If electrical generation is 50% oil / 50 % Diesel, what is total energy carrier consumption?**
  - **24.5 kWh from Oil**
  - **24.5 kWh from diesel**
- **Units Conversion:**
  1 kWh = 3.6 MJ

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Considering Energy from Electricity

- **Although we are consuming 49 kWh of energy, with 50% from Oil and 50% from Diesel**
- **We are NOT consuming**
  49 kWh x 3.6 MJ/kWh **= 176 MJ of energy carriers**

  Why?
- **Energy conversion to electricity is far from 100% efficient**

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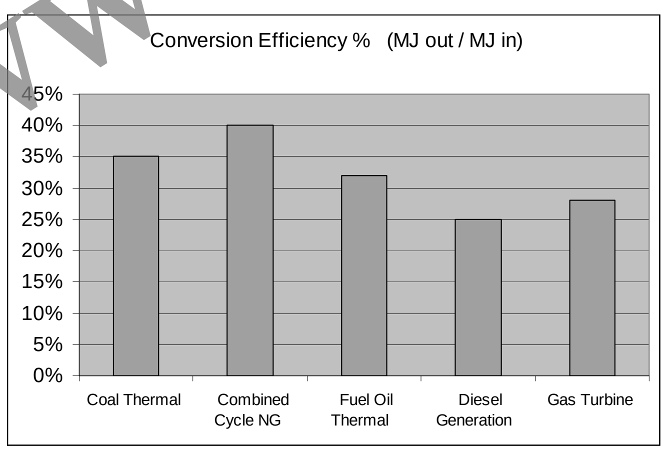
Considering Energy from Electricity



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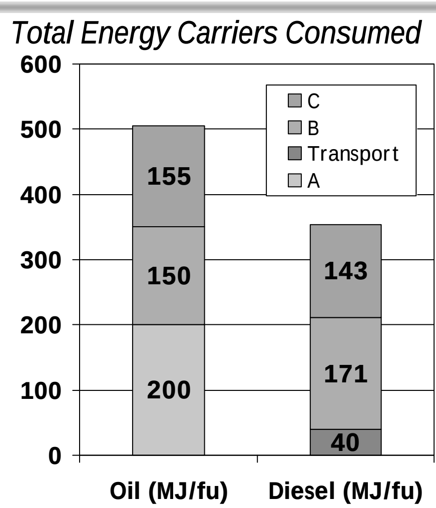
Results – How Much Energy?



- Assuming a conversion efficiency of
  - Oil = 32%
  - Diesel = 28%

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Does this matter?

IAI Inventory for 1000 kg of Primary Aluminum

	Usage		Unit Energy Content		Total Energy Consumed
Coal	186	kg	32.5	MJ / kg	6,045
Diesel Oil	13	kg	48	MJ / kg	624
Heavy Oil	238	kg	42	MJ / kg	9,996
Natural Gas	308	m3	41	MJ / m3	12,628
Total Thermal				MJ	29,293
Electricity	15711	kWh	w/o efficiency (MJ)		56,560
			w/ efficiency (MJ)		171,393
Total			w/o efficiency (MJ)		85,853
			w/ efficiency (MJ)		200,686

Ignoring efficiency of electrical conversion, drastically alters energy picture!

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Session 4: Inventory Allocation

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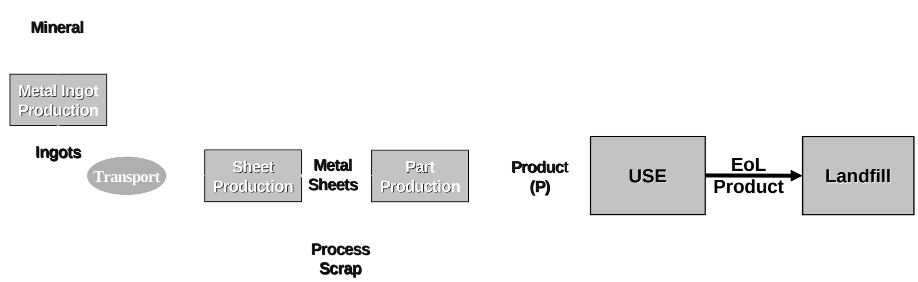
Issues in Calculating an Inventory -- Allocation

Consider adding two elements to the scope of the analysis
-- Use
-- Disposal



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Environmental Data – Use

Summary

Products	EoL products of P
Raw Material	Products P

Inputs/Outputs

Description	Quantity	Units	Details
Annual Purchsed Nationwide	4.00E+07	kg / year	Product *P*
Annual Dispoal	4.00E+07	kg / year	EoL P
Emissions to air	1.00E+05	kg/year	HC

Environmental Data – Disposal to Landfill

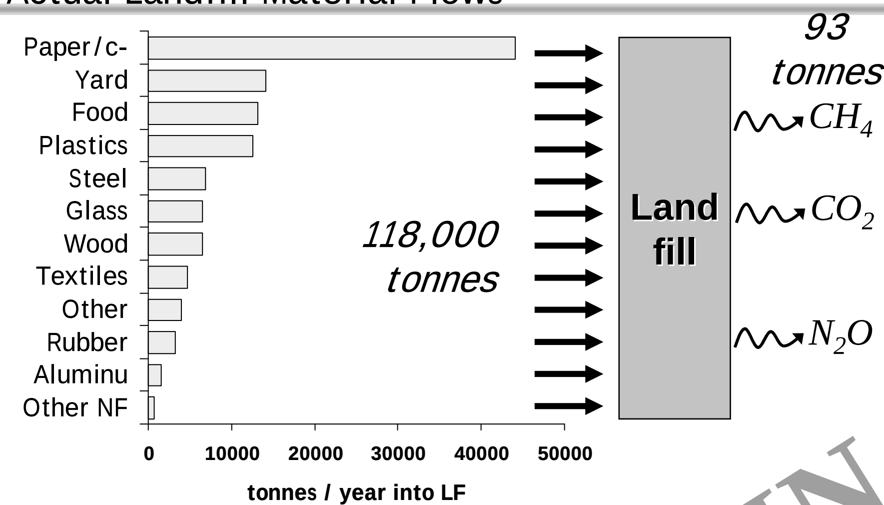
Summary

Products	Methane
Raw Material	EoL products of P, MSW

Inputs/Outputs

Description	Quantity	Units	Details
Total annual methane	93	tonnes/year	HC
Use of raw material	118000	tonnes/year	Solid Waste
Emissions to air	93	tonnes/year	HC

How Much Should be Allocated to Metal Wastes?
Actual Landfill Material Flows



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How Much Should be Allocated to Metal Wastes?
Observed Landfill Emissions

(a) Material	(b) Net GHG Emissions from CH_4 Generation (MTCE/Wet Ton): Landfills Without LFG Recovery	Landfills With LFG Recovery and Flaring	Landfills With LFG Recovery and Electric Generation	Year 2000 National Average
Aluminum Cans	0.00	0.00	0.00	0.00
Steel Cans	0.00	0.00	0.00	0.00
Glass	0.00	0.00	0.00	0.00
Corrugated Cardboard	0.48	0.12	0.06	0.29
Magazines/Third-class Mail	0.26	0.07	0.03	0.16

"Solid Waste Management And Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks", EPA530-R-02-006, May 2002.

Courtesy of U. S. EPA.

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Allocation Issues in Inventory Analysis

- **ISO Definition:**
  Inventory allocation : *Partitioning the input or output flows of a unit process to the product system under focus*
- **Emerges when a process within your product system is associated with a flow that is part of another product system (i.e., another life-cycle)**
  - **Multi-outflow**
  - **Multi-inflow**

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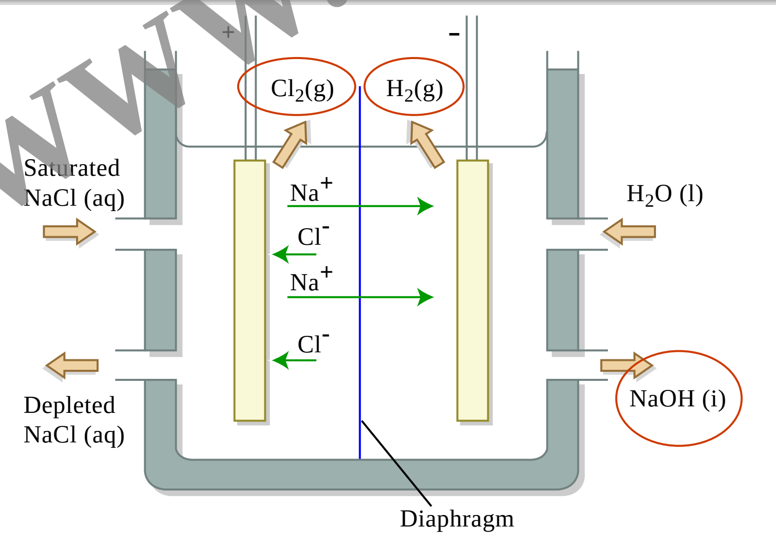
Allocation Examples: Chlor-Alkali Process



Schematic of a Diaphragm or Membrane Cell

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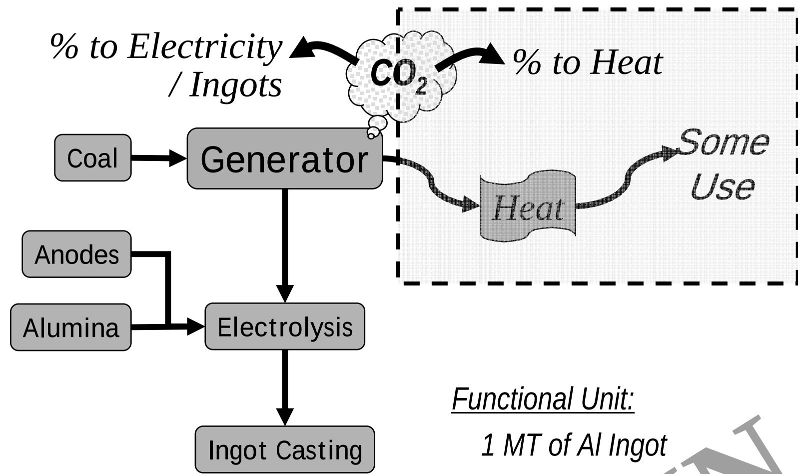
Figure by MIT OCW.

How can we handle allocation?

Addressing Allocation Approaches

- Partitioning:
  Method to apportion impacts between life-cycle under analysis and "other" flows
  - More applicable to accounting-oriented analysis
- System expansion:
  Avoiding problem by expanding scope of analysis to include "other" flows
  - More applicable to change-oriented analysis

Classic Allocation Example:
Electricity with Surplus Heat — **Partitioning**



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Partitioning Strategies

- **Technical causality**
  - **Established relationship between magnitude of specific flows**
    - e.g., science based assessment of landfill emissions
  - **Usually requires treatment of intra-process flows to a great level of detail**
    - E.g., energy used only for HCl production in chlor-alkali
- **Physical quantity**
  - **Mass**
  - **Volume**
  - **Area**
  - **Energy content**
  - **Moles**
- **Social causality**
- **Arbitrary number**
  - **E.g., 50/50**

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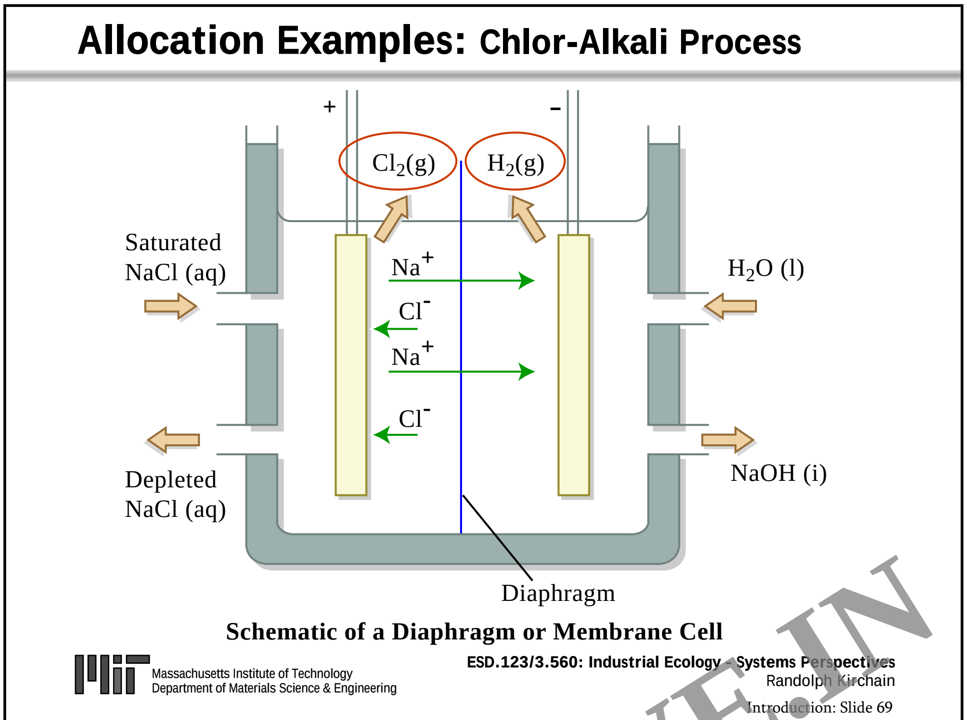
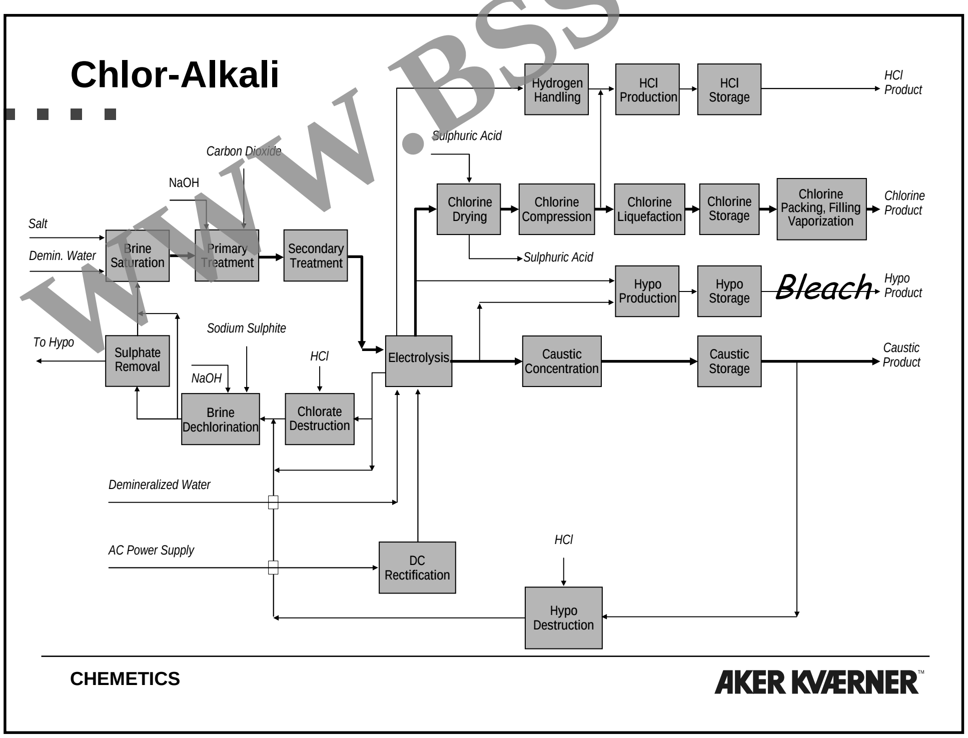


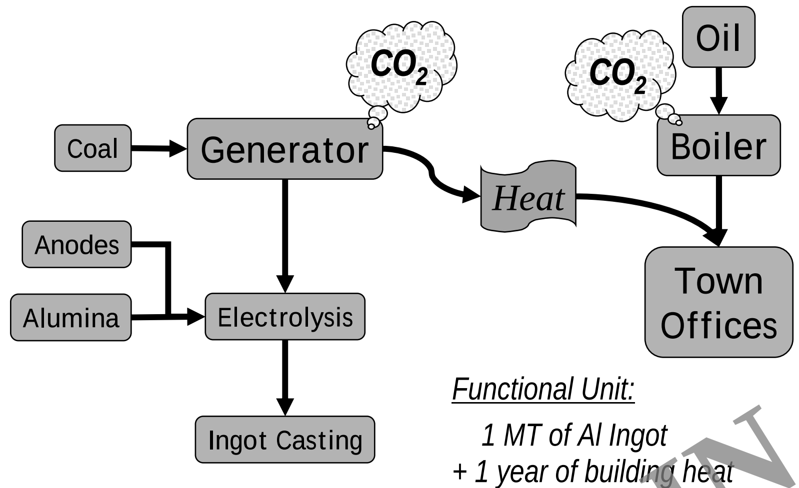
Figure by MIT OCW.



Courtesy of Aker Kvaerner Chemetics. Used with permission.

See http://www.akerkvaerner.com/Internet/IndustriesAndServices/Pulping/BleachingChemicals/ChloralkaliProcess.htm

Classic Allocation Example:
Electricity with Surplus Heat — **System Expansion**



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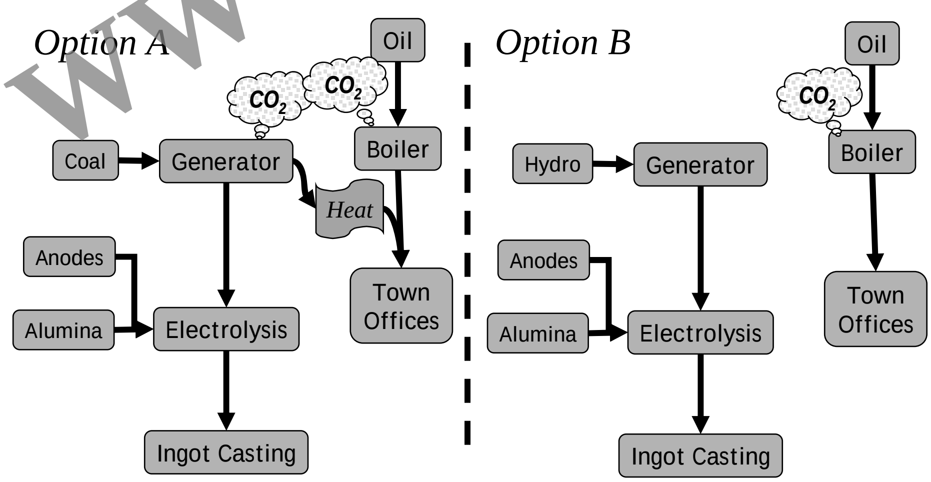
Why System Expansion?



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Why System Expansion?

- At first look, system expansion seems to greatly increase the scale of the analysis
- In fact, much of the implied expanded analysis can be excluded in a comparative analysis (i.e., change-oriented assessments)
- In practice
  - Scope should include activities required for credibility
  - Must be careful that activities are the same in different scenarios

Preferred Characteristics of an Allocation Scheme (Ekvall and Tillman 98, Klöpffer 96)

- Effect-oriented (non-perverse)
  - Activities with higher impact should receive higher load of inventory
- Politically acceptable to end-users
- Applicable with available information
- Consistent
- Prevents double counting

Preferred Allocation Approach

1. System Expansion
2. Technical Causality
3. Social Causality
4. Physical Quantity
5. Arbitrary Quantity

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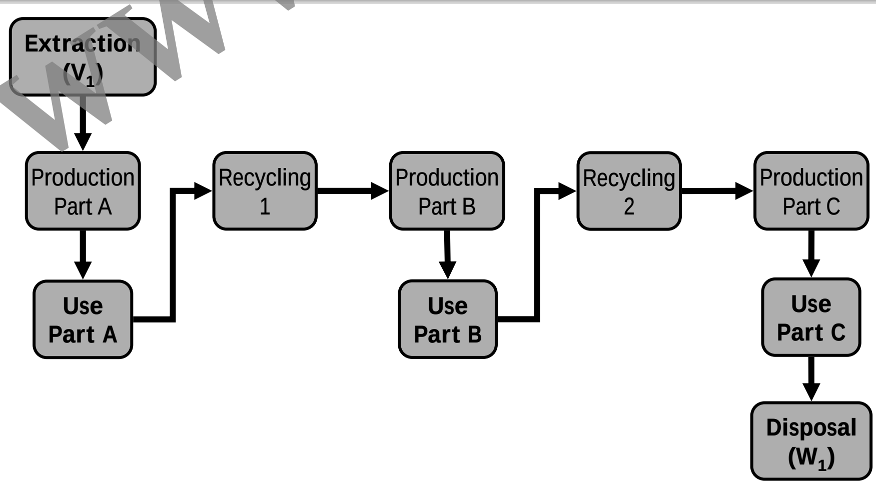
Open-loop Recycling:
A common allocation challenge



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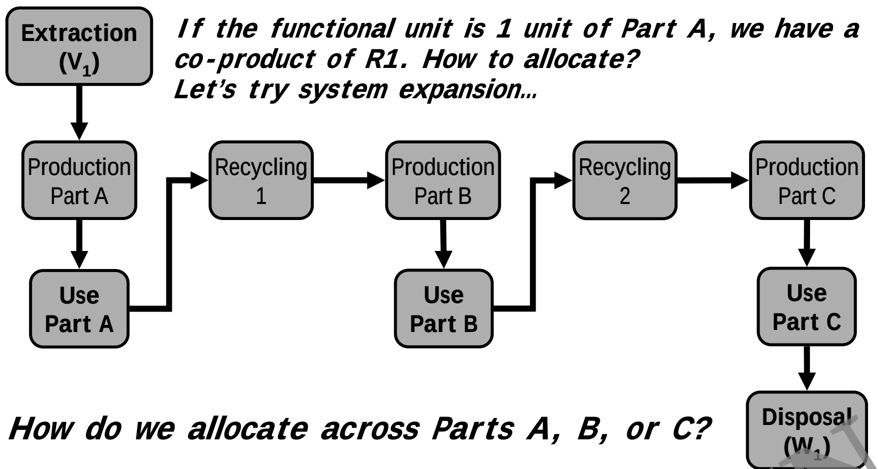
Open-loop Recycling:
A common allocation challenge

If the functional unit is 1 unit of Part A, we have a co-product of R1. How to allocate?
Let's try system expansion…



How do we allocate across Parts A, B, or C?

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Approaches to Open-Loop Allocations

- **Cut-off method**
  - **Only loads directly caused by a product are assigned to that product**
  - **No data from outside of life-cycle are required**
- **Loss of Quality**
  - **Allocated according to "quality" of material used**
- **Closed-loop Approximation**
  - **All activities are part of a general materials system**
  - **Allocation across products could follow any partitioning strategy**
    - Social causality, Mass
- **50/50 Approximation**
  - **Initial and terminal life-cycles share virgin production and disposal**
  - **Recycled life-cycles share recycling burden**

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Common Open-Loop Recycling Method

- System expansion approximation
  - Compared against lack of recycling (or another disposal option)
  - Typically only one generation
  - Easily extensible to multiple generations, but requires data
  - Leads to credits given to inventory

  - Very widely applied
  - Implicitly gives significant credit to primary production for making recyclable resources available (Newell & Field 98)
  - In practice, often does not preserve additivity
  - Generally, should be reserved for comparitive assessments (change oriented LCA)

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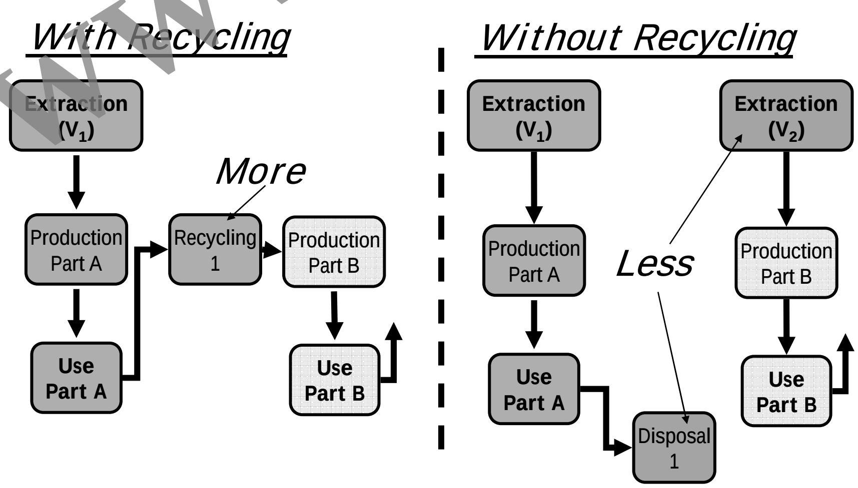
System Expansion Approximation



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Preferred Allocation Approach

1. System Expansion
2. Technical Causality
3. Social Causality
4. Physical Quantity
5. Arbitrary Quantity

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Material Flow Analysis

Jeremy Gregory

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What is Material Flow Analysis?

"Material flow analysis (MFA) is a systematic assessment of the flows and stocks of materials within a system defined in space and time."

Brunner and Rechberger, 2004

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Applications of MFA: Industrial Ecology

- IE design principles related to MFA:
  - Controlling pathways for materials use and industrial processes
  - Creating loop-closing industrial practices
  - Dematerializing industrial output
  - Systematizing patterns of energy use
  - Balancing industrial input and output to natural ecosystem capacity

Applications of MFA: Environmental Management and Engineering

- Environmental impact statements
- Remediation of hazardous waste sites
- Design of air pollution control strategies
- Nutrient management in watersheds
- Planning of soil-monitoring systems
- Sewage sludge management

Applications of MFA: Resource and Waste Management

- Resource Management: Analysis, planning and allocation, exploitation, and upgrading of resources
- MFA uses in waste management
  - Modeling elemental compositions of wastes
  - Evaluating material management performance in recycling/treatment facilities
- Examples:
  - Regional material balances
  - Single material system analysis

Applications of MFA: Human Metabolism

- Metabolism of the anthroposhpere
- Key processes and goods
  - Inputs: water, food, building and transport materials
  - Outputs: sewage, off-gas, solid waste

The first application of MFA?

- Santorio Santorio (1561-1636)
- Measured human input and output
- Output weighs much less
- Hypothesis: output of "insensible perspiration"

MFA Objectives

- Delineate system of material flows and stocks
- Reduce system complexity while maintaining basis for decision-making
- Assess relevant flows and stocks quantitatively, checking mass balance, sensitivities, and uncertainties
- Present system results in reproducible, understandable, transparent fashion
- Use results as a basis for managing resources, the environment, and wastes
  - Monitor accumulation or depletion of stocks, future environmental loadings
  - Design of environmentally-beneficial goods, processes, and systems

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
  - As many substances as possible
- MFA strives for transparency and manageability
  - Limited number of substances

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Types of Material Flow-Related Analysis

Type I		
a	b	c
Impacts per unit flow of		
substances	**materials**	**products**
e.g., Cd, Cl, Pb, Zn, CO_2, CFC	e.g., energy carriers, excavation, biomass, plastics	e.g., diapers, batteries, cars
within certain firms, sectors, regions		
Type II		
a	b	c
Throughput of		
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

Definitions

- Material: substances and goods
- Substance: single type of matter (elements, compounds)
- Goods: substances or mixtures of substances that have economic values assigned by markets
  - Can include immaterial goods (energy, services, or information)
- Process: transport, transformation, or storage of materials (natural or man-made)
- Stocks: material reservoirs within the analyzed system

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Definitions (cont.)

- **Flows: mass per time (link processes)**
- **Fluxes: mass per time and cross section**
- **Imports/exports: flows/fluxes across *system* boundaries**
- **Inputs/outputs: flows/fluxes across *process* boundaries**
- **System: set of material flows, stocks, and processes within a defined boundary**
- **Activity: set of systems needed to fulfill a basic human need (nourish, reside, transport, etc.)**

Generic MFA Procedure

- **Systems Definition**
  - **Target Questions: What are primary objectives?**
  - **Scope: Spatial, temporal, functional**
  - **System Boundary: Defines start and end of flows**
- **Process Chain Analysis: Defines processes using** *accounting and balancing*
  - **Mass balancing to determine inputs and outputs**
  - **Modeling may be applied**
- **Evaluation**
  - **May involve impact criteria**

Type Ia: Anthropogenic Copper Cycle

Generic System Boundary

Diagram removed due to copyright restrictions.
Figure in Graedel, T. E., et al. "Multilevel Cycle of Anthropogenic Copper."
Environmental Science and Technology 38 (2004): 1242-1252.

China Copper Cycle, 1994 (Gg/yr)

Diagram removed due to copyright restrictions.
Figure in Graedel, T. E., et al. "Multilevel Cycle of Anthropogenic Copper." *Environmental Science and Technology* 38 (2004): 1242-1252.

North American Copper Cycle, 1994 (Gg/yr)

Diagram removed due to copyright restrictions.
Figure in Graedel, T. E., et al. "Multilevel Cycle of Anthropogenic Copper." *Environmental Science and Technology* 38 (2004): 1242-1252.

World Copper Cycle, 1994 (Gg/yr)

Diagram removed due to copyright restrictions.
Figure in Graedel, T. E., et al. "Multilevel Cycle of Anthropogenic Copper."
Environmental Science and Technology 38 (2004): 1242-1252.

What is the value of this analysis?

Type IIc: Anthropogenic Metabolism

Prehistoric

Breath 5.1

Image of caveman removed due to copyright restrictions.

Goods 6

Excreta 0.8

Stock ~0

Solid Waste 0.1

Modern

Off gas 19

Consumption 86

Sewage 61

Stock 260

Solid Waste 3

Units: tonnes/capita (stocks) or tonnes/capita/year

Direct material flows only

Source: Brunner and Rechberger, 2004

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Anthropogenic Metabolism of Modern Man

Material Flows and Stocks for Selected Activities of Modern Man

Activity	Input t/(c yr)	Output, t/(c yr)			Stock t/c
		Sewage	Off Gas	Solid Residues	
To nourish	5.7	0.9	4.7	0.1	<0.1
To clean	60	60	0	0.02	0.1
To reside	10	0	7.6	1	100
To transport	10	0	6	1.6	160
Total	86	61	19	2.7	260

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Type IIc: Economy-Wide Material Flows Metrics

Inputs

- DMI (Direct Material Input)= Domestic Extraction + Imports
- TMR (Total Material Requirement)= DMI + Domestic Hidden Flows + Foreign Hidden Flows

Outputs

- DPO (Domestic Processed Output)= Emissions + Waste = DMI – Net Additions to Stock - Exports
- DMO (Direct Material Output)= DPO + Exports
- TDO (Total Domestic Output)= DPO + Domestic Hidden Flows

Type IIc: Economy-Wide Material Flows Metrics (cont.)

Consumption

- DMC (Direct Materials Consumption)= DMI - Exports
- TMC (Total Materials Consumption)= TMR – Exports – Hidden Flows from Exports

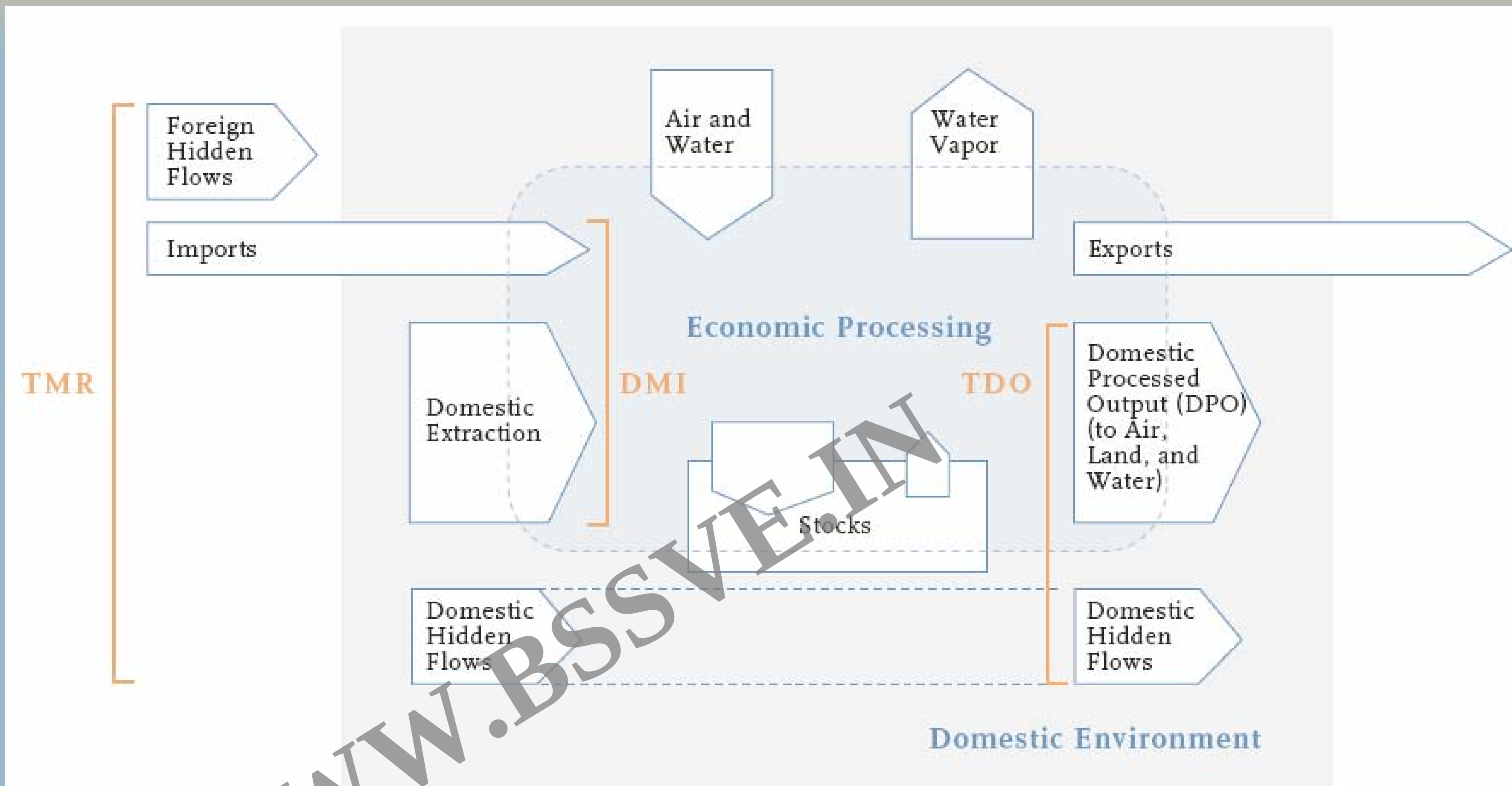
Balance

- NAS (Net Additions to Stock)= DMI – DPO – Exports
- PTB (Physical Trade Balance)= Imports – exports

Efficiency

- Input or Output/GDP (Material Productivity)
- Unused/used (Resource efficiency of materials extraction)= Unused (hidden or indirect) / used (DMI) materials

Economy-Wide Material Flows: Material Cycle



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Regional Material Balances: Vienna, 1990s

Air: 36

Off-gas: 43

Water: 147

Sewage: 144

Fossil Fuels: 2

Export Goods: 3

Construction Materials and Consumer Goods: 12-18

Solid Wastes: 3

Stock: 350

Municipal Solid Wastes: 0.3

Photo courtesy of Premshree Pillai.

Units: tonnes/capita (stocks) or tonnes/capita/year

Source: Brunner and Rechberger, 2004

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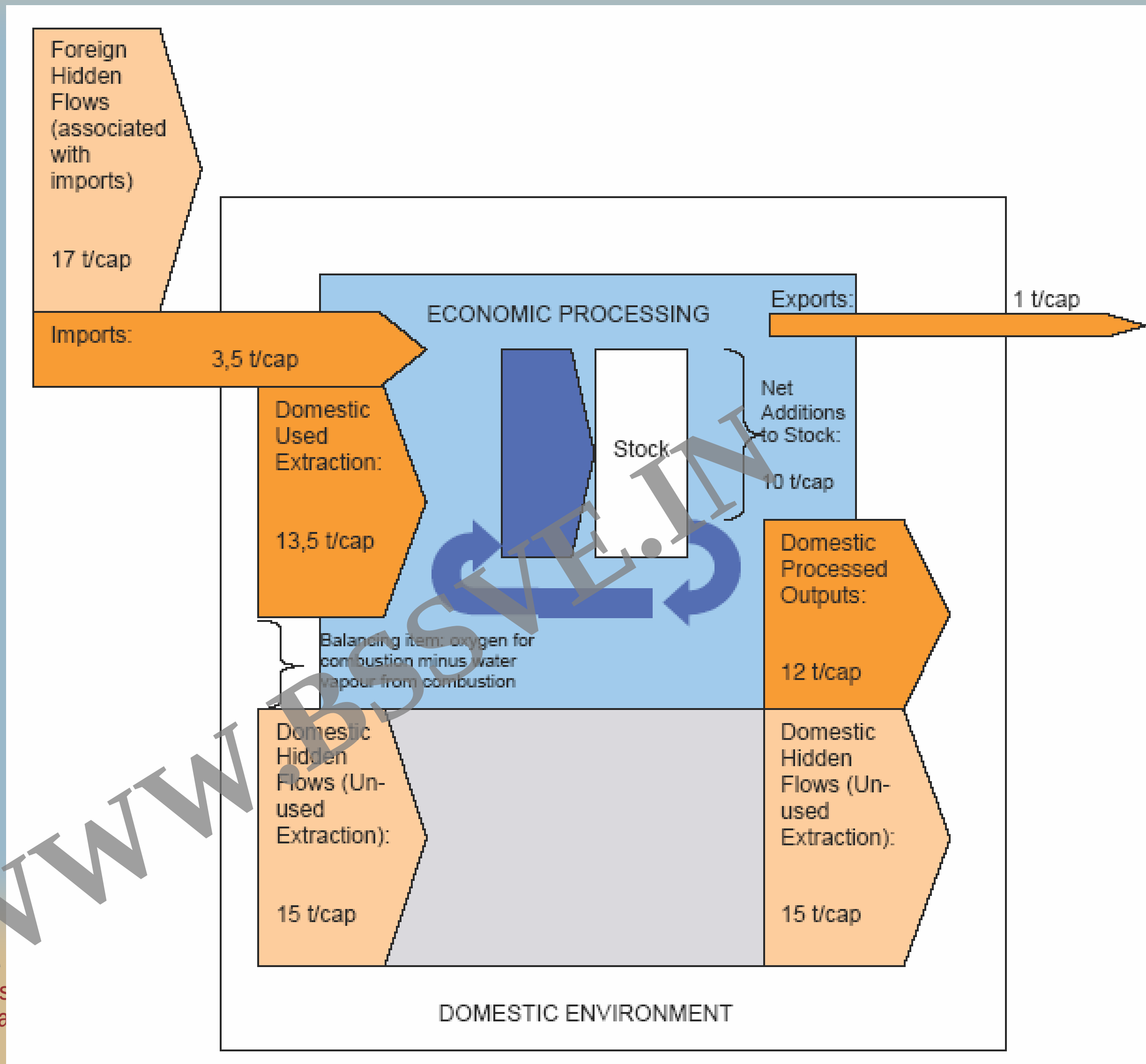
EU Economy-Wide Material Flows: 1990s (t/c/yr)



US Material Flows, 1990 (Mt)

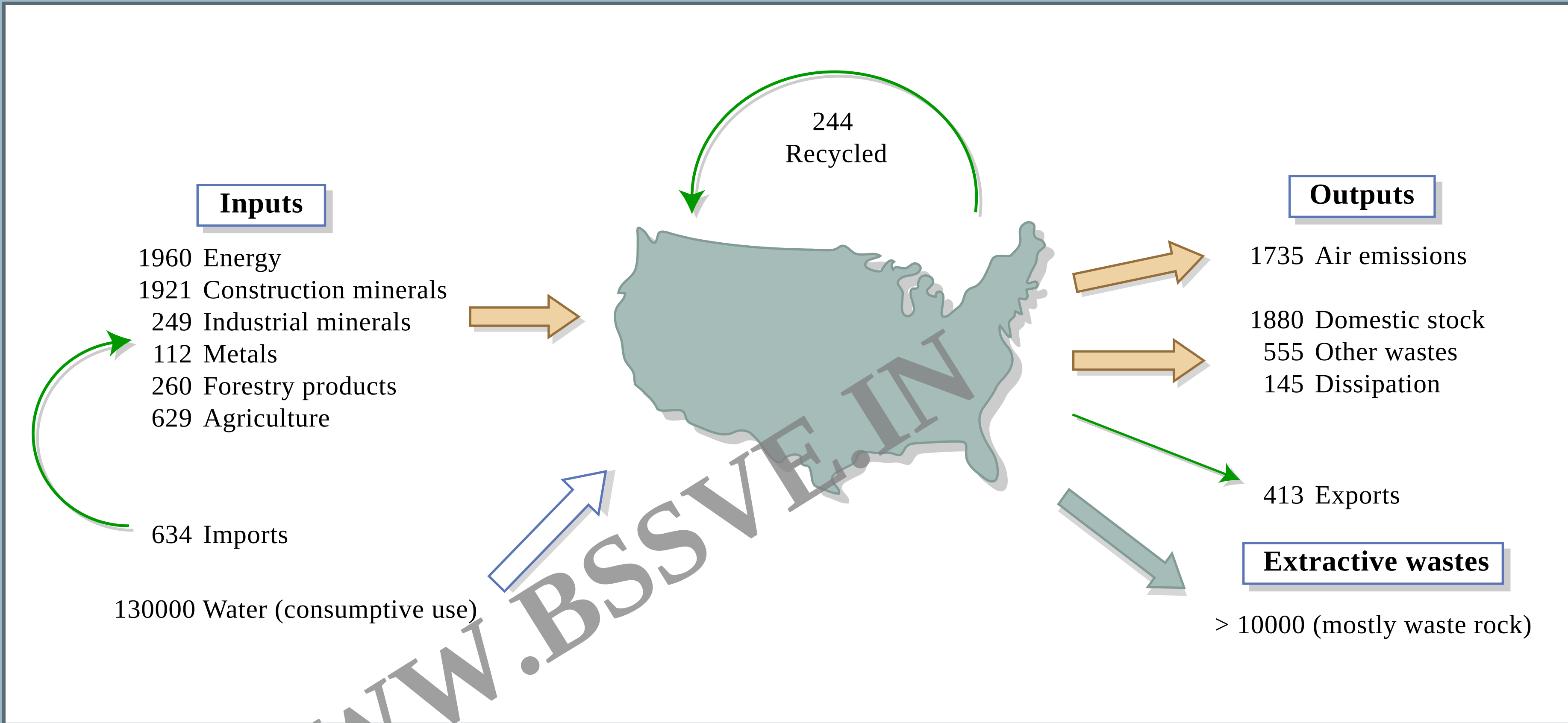
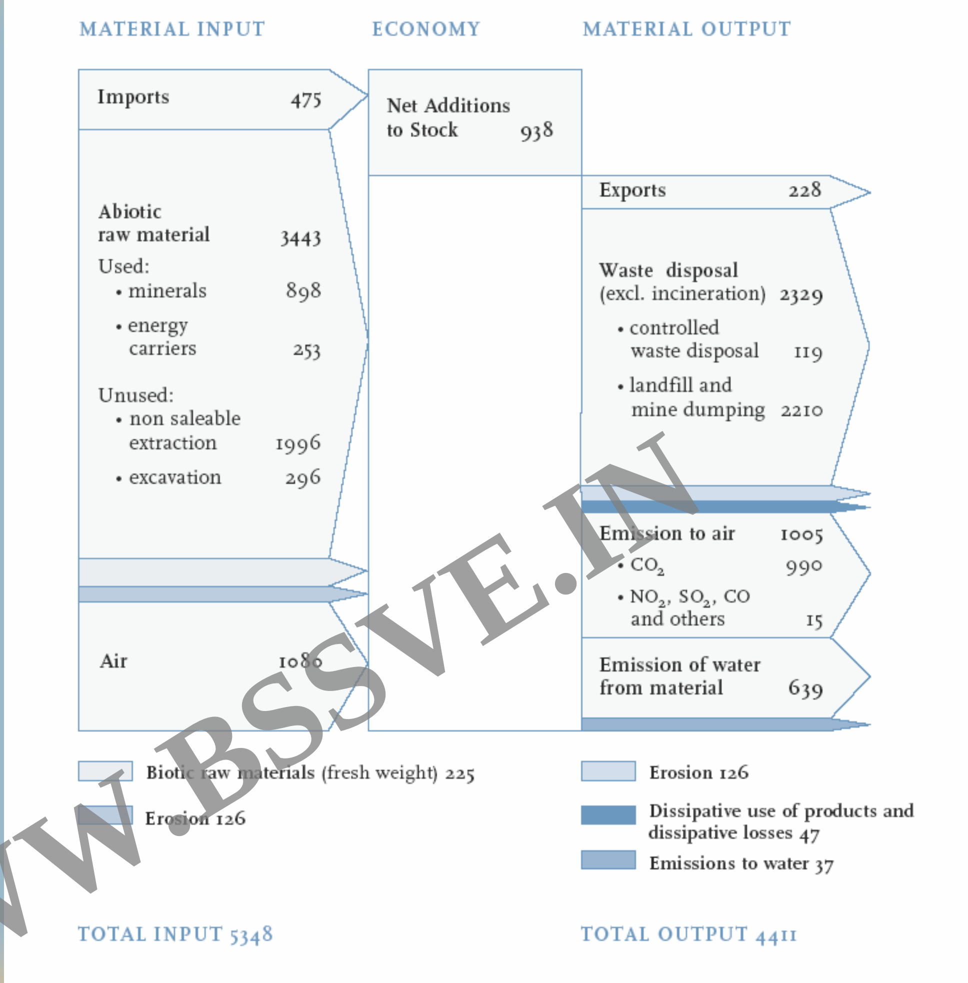


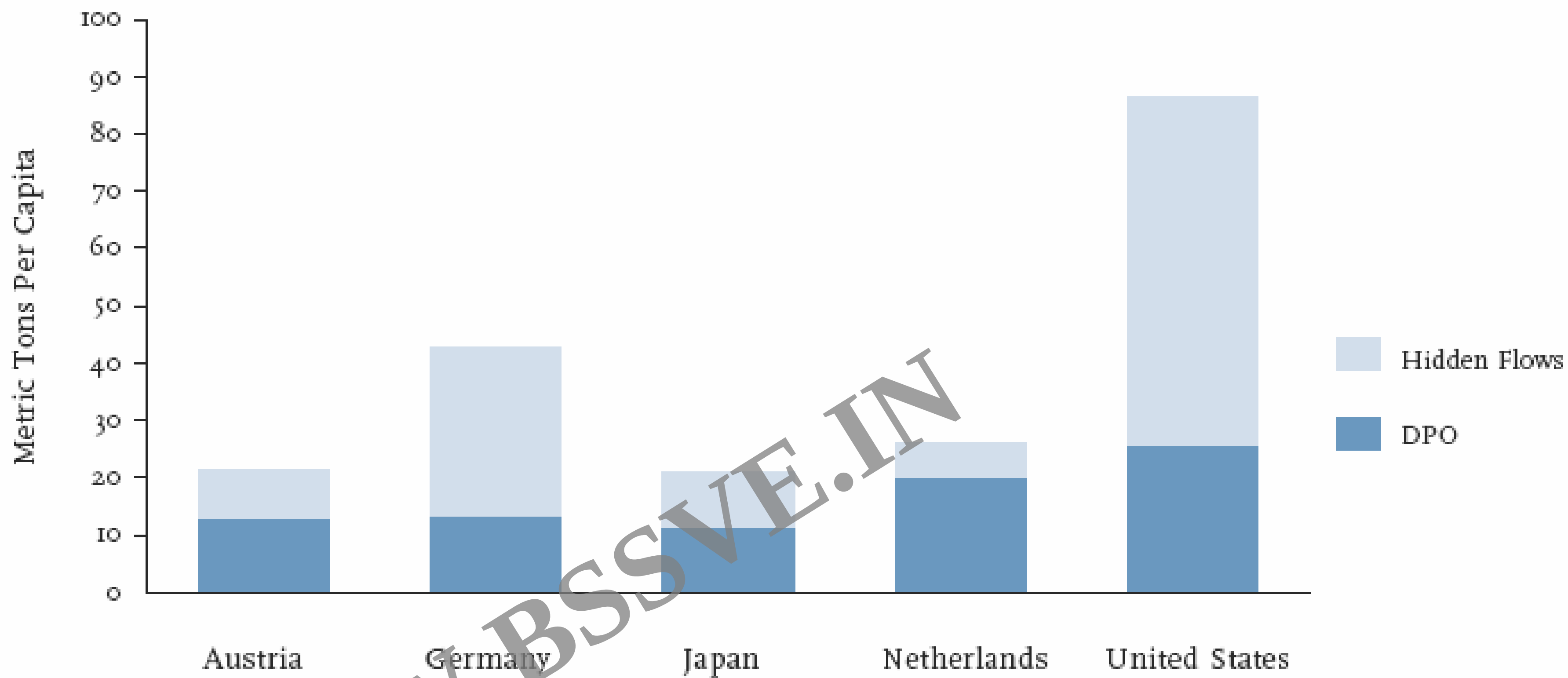
Figure by MIT OCW.

Material Flow Balance of Germany, 1996 (Mt)



Courtesy of World Resources Institute. Used with permission. Source: Matthews, E., et al. "The Weight of Nations." World Resources Institute, 2000.

Total Domestic Output, 1996



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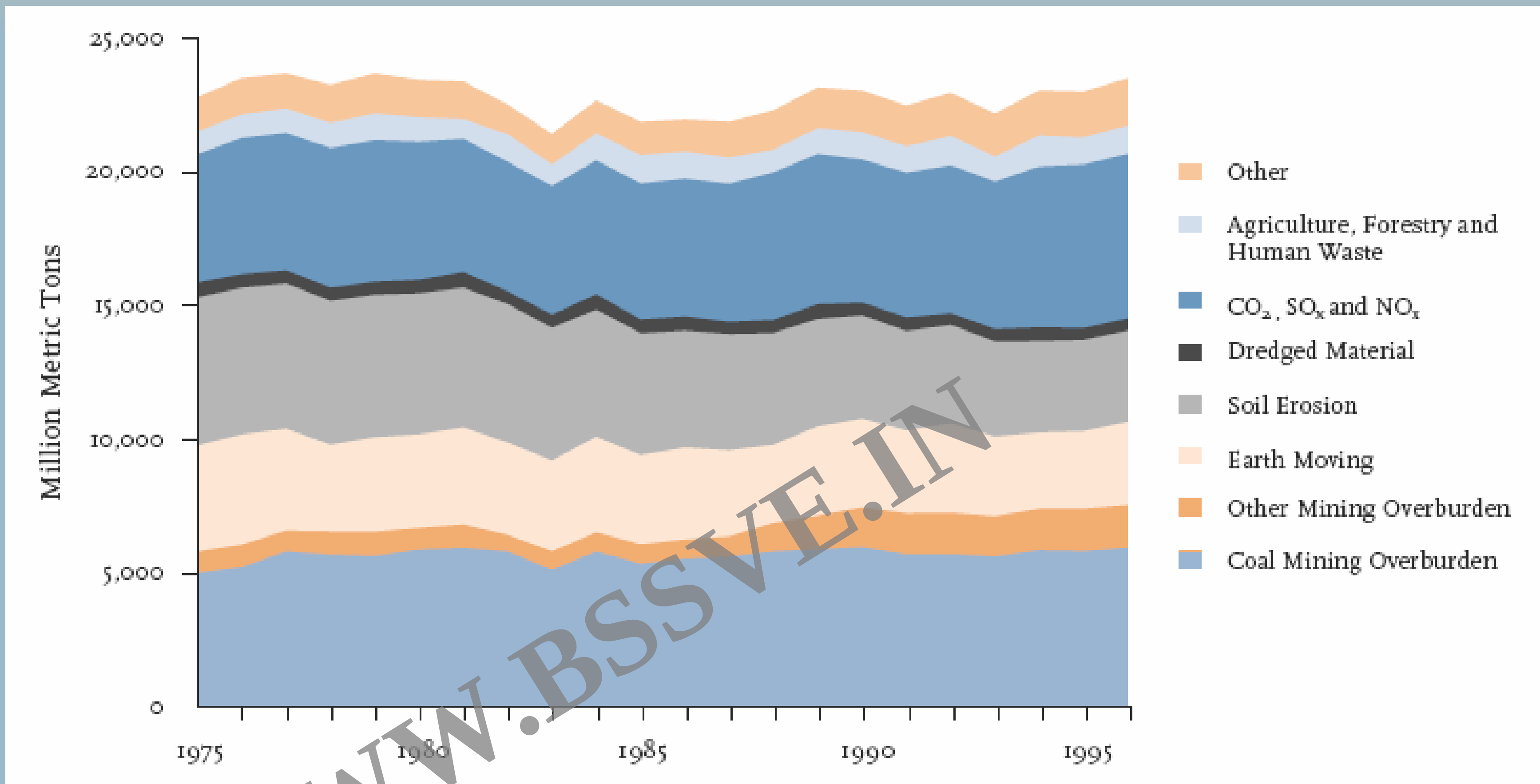
US TDO Composition



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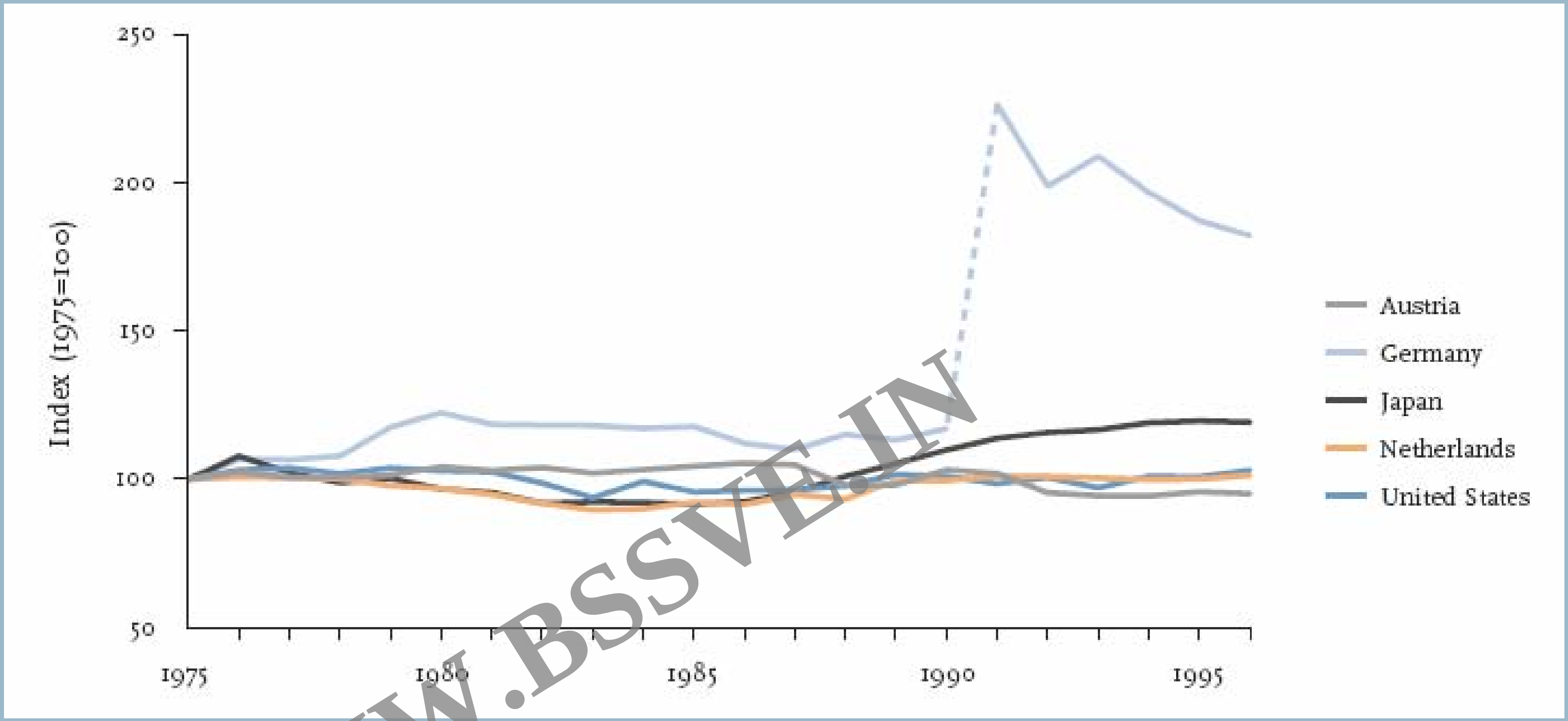
Relation Between Monetary and Material Output Flows, 1996

Country	GDP		DPO		TDO	
	Billion $US	Ratio	Million Metric Tons	Ratio	Million Metric Tons	Ratio
Austria	235.3	1.0	100.8	1.0	171.3	1.0
Netherlands	410.5	1.7	281.3	2.8	381.1	2.2
Germany	2,446.6	10.4	1,074.7	10.7	3,492.2	20.4
Japan	5,338.9	22.7	1,406.5	14.0	2,632.1	15.4
United States	7,390.6	31.4	6,773.8	67.0	23,261.0	135.8

Trends in TDO



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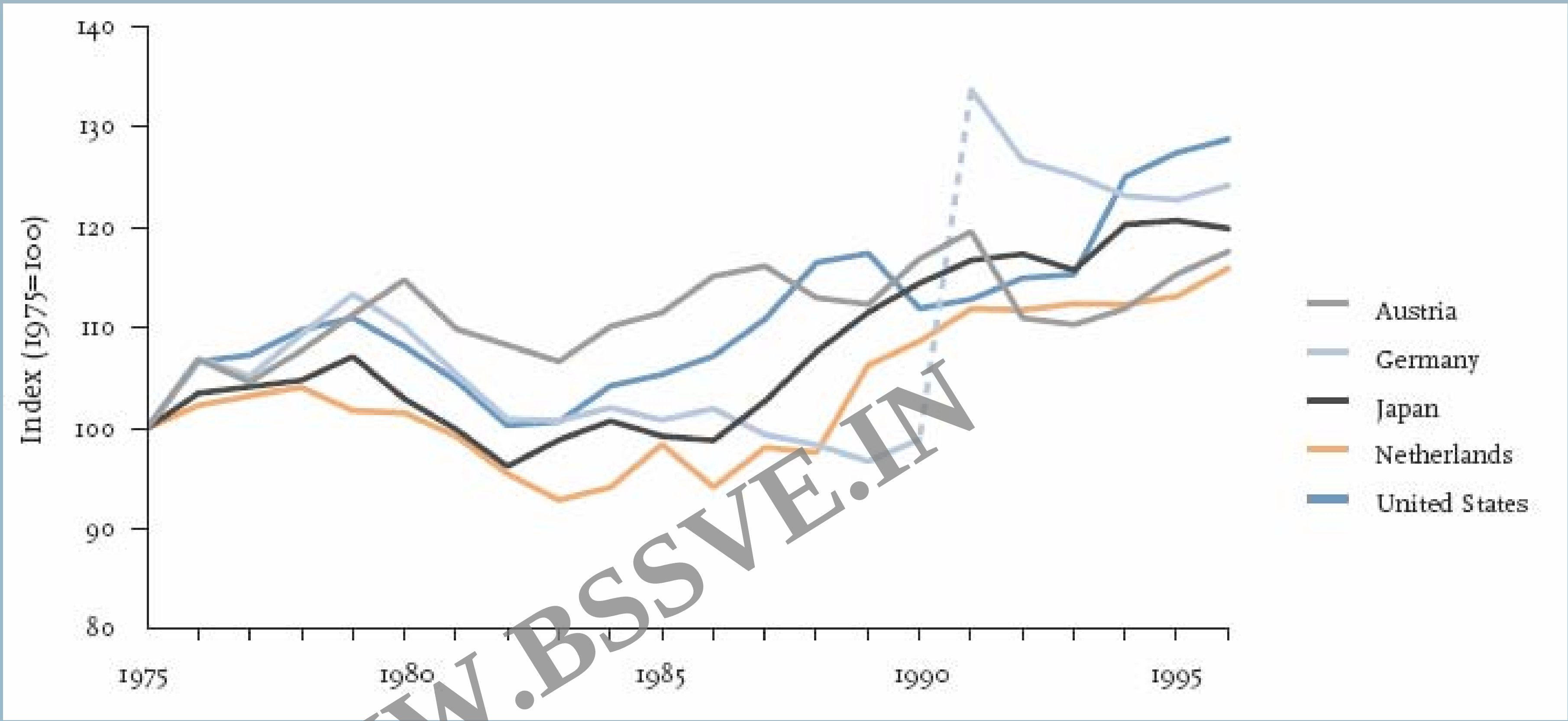
Domestic Material Output (DPO)



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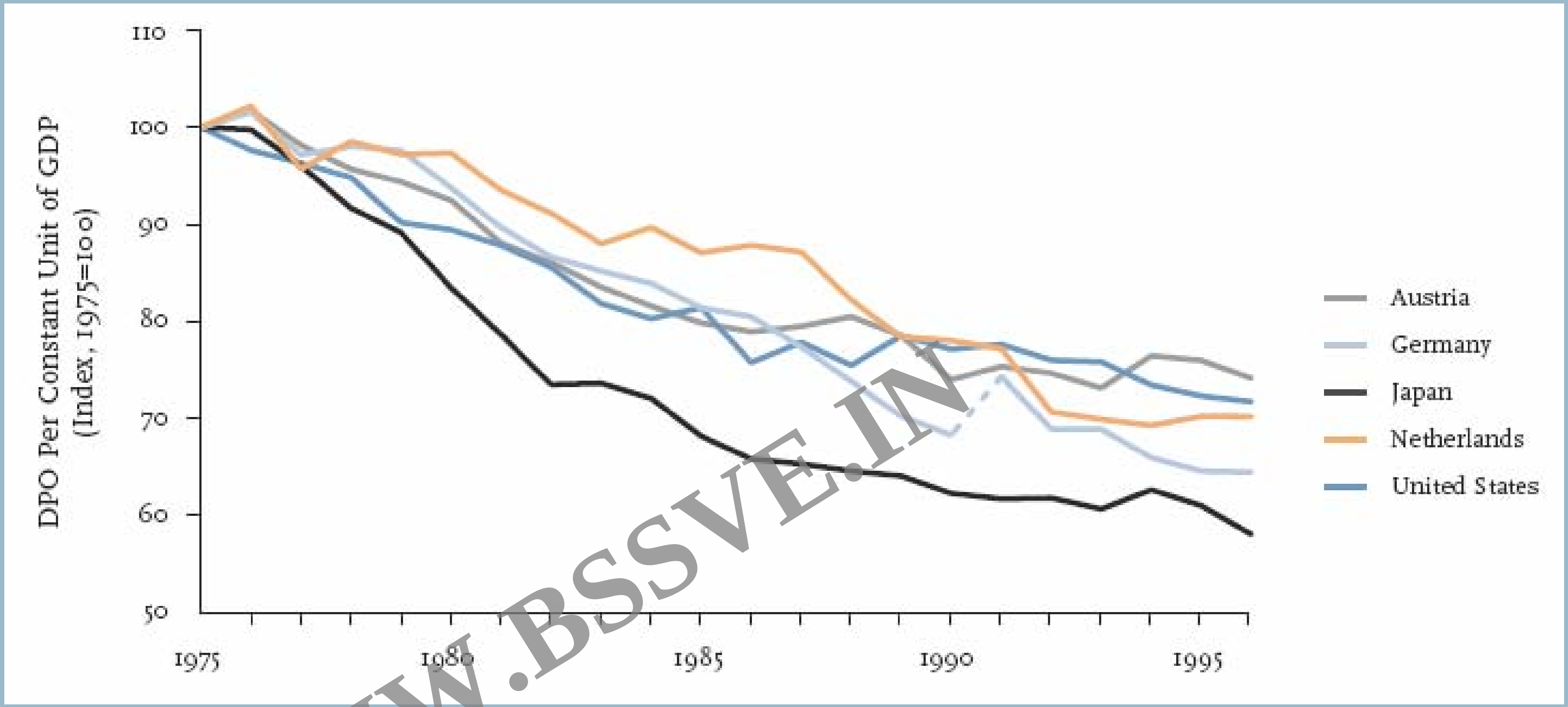
Source: Matthews, E., et al. "The Weight of Nations." World Resources Institute, 2000.

Material Outflow Intensity (DPO/GDP)



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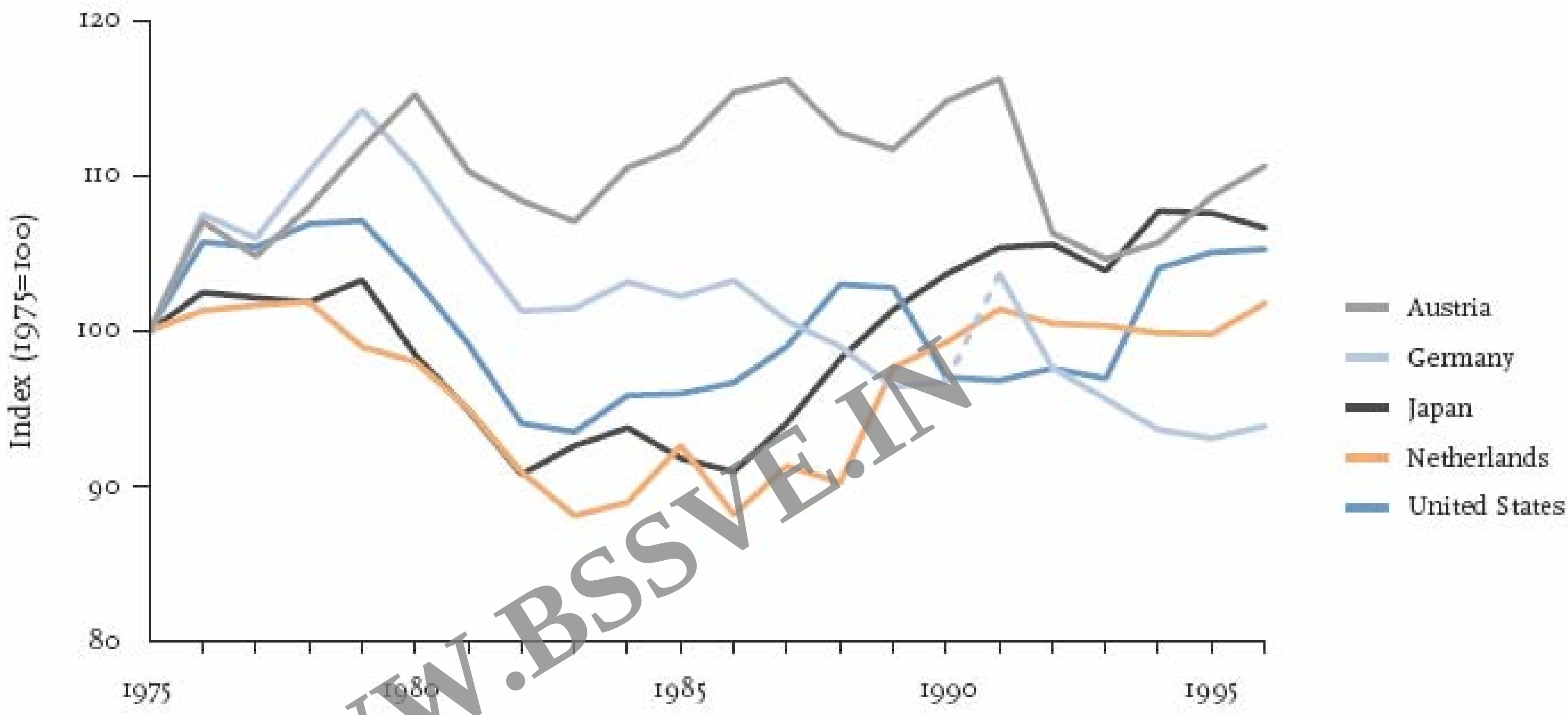
Material Outflow Intensity (DPO per Capita)



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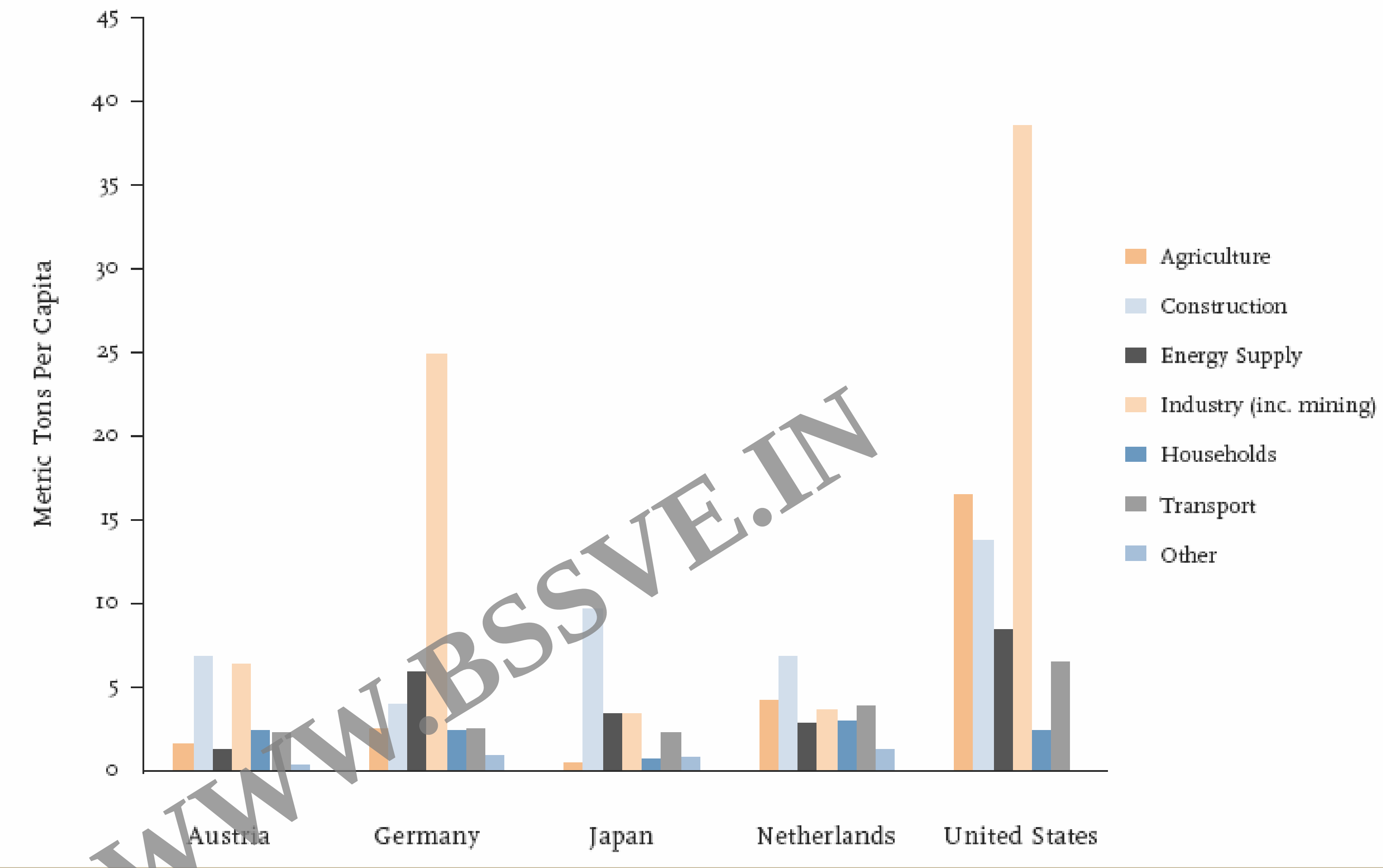
Population, Economic, and DPO Trends

Country		Population (millions)	DPO (million metric tons)	GDP (own currency *See notes*)	DPO/GDP (metric tons per million constant monetary units, own currency)	DPO/Capita (metric tons per capita)
Austria	1975	7.6	85.7	1,441.0	0.059	11.3
	1996	8.1	100.8	2,415.0	0.042	12.5
	% change	+6	+18	+68	−29	+10
Germany[1]	1975	61.8	865.3	1,838.5	0.47	14.0
	1996	81.8	1,074.7	3,541.5	0.30	13.1
	% change	+32	+24	+93	−36	−6
Japan	1975	111.9	1,173.0	244.3	4.80	10.5
	1996	125.9	1,406.5	504.4	2.78	11.2
	% change	+13	+20	+106	−42	+7
Netherlands	1975	13.6	242.6	413.0	0.59	17.8
	1996	15.5	281.3	667.6	0.42	18.1
	% change	+14	+16	+62	−29	+2
United States	1975	220.2	5,258.7	4,253.9	1.24	23.9
	1996	269.4	6,773.8	7,390.6	0.92	25.1
	% change	+23	+28	+74	−26	+5

Economic Sectors' Contribution to TDO



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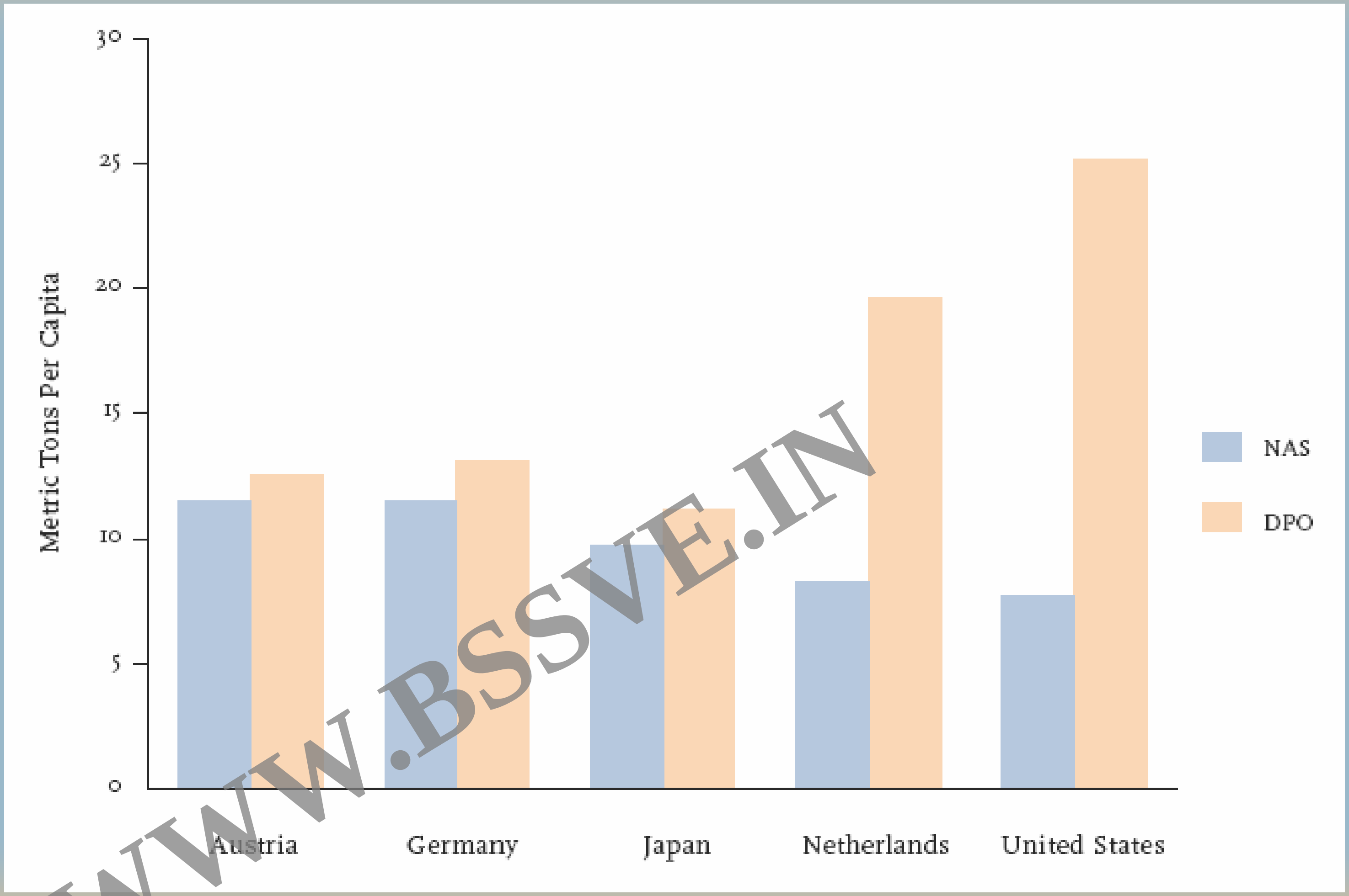
NAS and DPO, 1996



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Courtesy of World Resources Institute. Used with permission. Source: Matthews, E., et al. "The Weight of Nations." World Resources Institute, 2000.

Key Findings from "Weight of Nations"

- Industrial economies are becoming more efficient in their use of materials, but waste generation continues to increase.
- One half to three quarters of annual resource inputs to industrial economies are returned to the environment as wastes within a year.
- Outputs of some hazardous materials have been regulated and successfully reduced or stabilized but outputs of many potentially harmful materials continue to increase.
- The extraction and use of fossil energy resources dominate output flows in all industrial countries.
- Physical accounts are urgently needed, because our knowledge of resource use and waste outputs is surprisingly limited.

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Valuation of Life Cycle Inventories
The EPS System

ESD.123; 2006

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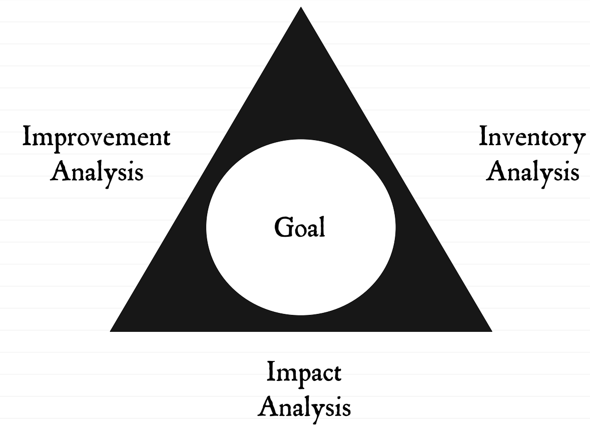
Life Cycle Analysis: Three stage Process SETAC Life Cycle Framework



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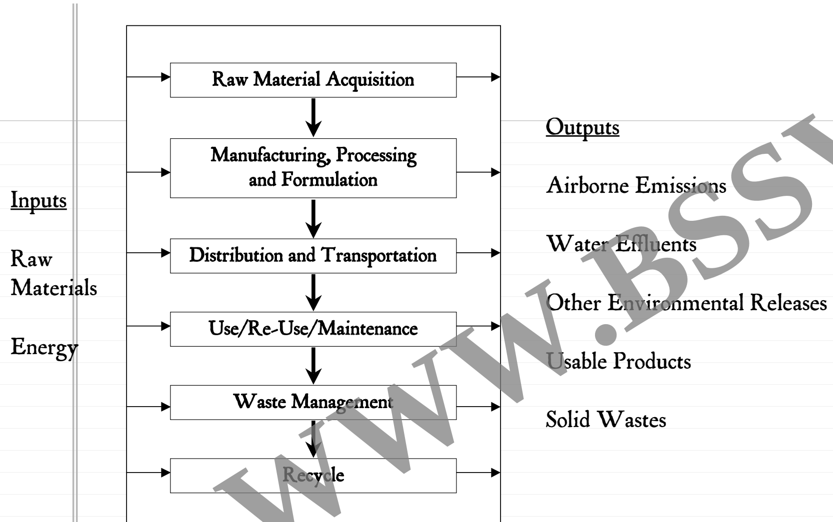

Life Cycle Inventory

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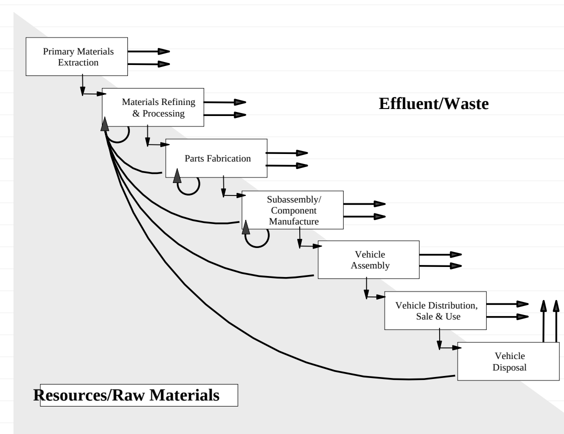
Complex When Dealing With A Real Problem



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Inventory Analysis Goals

- To Establish <u>Baseline Information</u> for Specific Products or Activities
- To Rank the <u>Relative Contributions</u> from Specific Stages in Life Cycle
- To Understand <u>Relative Environmental Burdens</u> of Competing Products or Activities
- To Use as Guide for :
  - Process and Product Evaluation by Designers
  - Information and Assessment for Consumers
  - Guidelines and Indications for Government
- Issue of Valuation for Improvement Analysis

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Improvement Analysis

- Based on Pertinent Metrics, Make Decisions to Improve Environment
- How to Decide Between Two "Evils:"
  - Product A, w/ 1,000 kg of CO_2 emissions? => Global Warming
  - Product B, w/ 3,000 kg of CO_2 emissions? => Global Warming
  - Product C, w/ 1,000 kg of SO_2 emissions => Acid Rain
- Valuation: Balance of Trade-Offs Between
  - Environmental
  - Economic
  - Technological / Engineering

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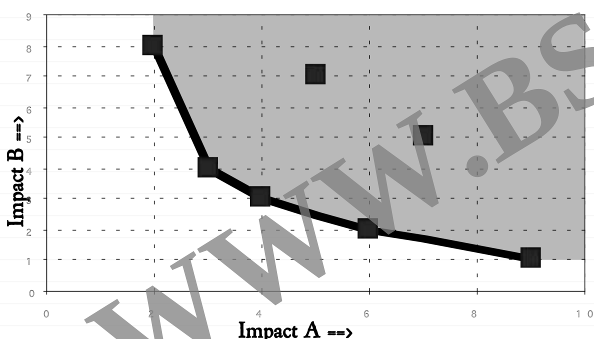
Improvement Analysis & Valuation



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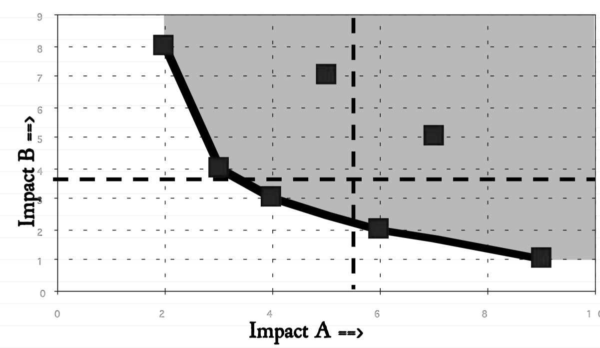
Screening



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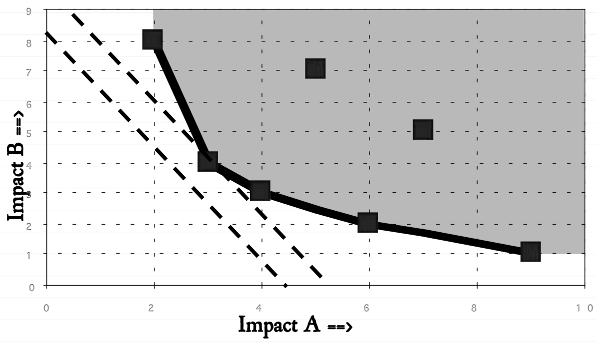
Indexing



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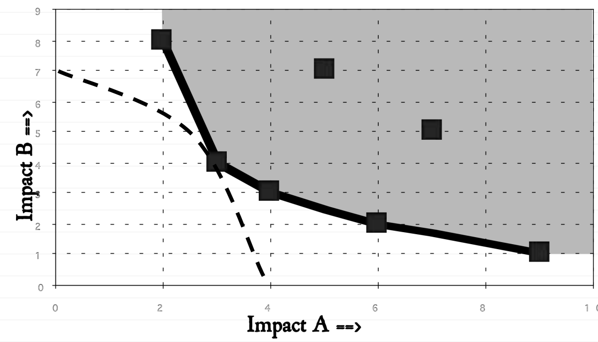
More Complex Valuations



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Impact Assessment

- Attempt to describe environmental consequences of the activity being studied
  - Accomplished by translating inventory into consequence (or impact)
- Aggregation of inventory information into fewer metrics
- Mechanics complex (and controversial)

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Issues - 1

- Translating "emissions" into "impact"
  - CO_2 release → increased thermal absorption
    → raises terrestrial temperature
  - So what?
    higher temps → increase desertification
    → increase glacial melting
    → increase ocean temperature
    → ...
- Cause and effect chains; necessary, but lengthy
  - Recall issues of scoping in inventory, leading to....

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Issues - 2

- Which effects to track?
- ISO establishes 3 broad categories of concern
  - Resource use
  - Human health
  - Ecological consequences
- Objections
  - Complete list?
  - Double counting?

Impact Assessment

- Impact category definition
  - Which impacts are of concern
  - How to go from emissions to impacts
- Classification
  - Categorize impacts according to key environmental stressors (e.g. "global warming potential," etc.
- Characterization (or quantification)
  - What's the size of the impact?
- Valuation
  - Rank or aggregate for comparative assessment

Lots of approaches

- In the end, all trying to do the same thing

  inventory of emissions → consequences of emissions

- Do it yourself?
- Or rely on others to do it for you.....

Environmental Priorities Strategy: EPS

- System Objectives
  - Introduce Environmentally Sound Product Development
  - Establish Common Database for Life Cycle Inventories
  - Develop PC-Based Tools for Eco- Product Design
  - Delineate Environmental Effects throughout Product Life
  - Inform & Educate Industrial Target Groups

Features of Environmental Priority Strategies

- Based on Swedish Parliament's Safeguard Subjects:
  - Biodiversity
  - Production (reproduction of biological organisms)
  - Human Health
  - Resources
  - Aesthetics
- "Environmental Burden" Determined For Activities & Processes

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Features of Environmental Priority Strategies

- System Designed to Allow "Objective" Decisionmaking
- Monetization Reduces Complex Data To One Numerical Value
- "Environmental Load" Assigned To Each Resource, Emission & Activity On A Per Unit Mass Basis
- Load Applied For Each Element Of LCA Inventory & Summed

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Institutional Features of EPS

- Scientific Analysis of Effects of Emissions
  - Done at Chalmers Institute
- Inventory Work To Be Done By Individual Firms
- Values From Various Sources

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EPS Basic Principle

Environmental Load Index x Quantity = Environmental Load Value

Units for ELI: Environmental Load Units / quantity
= ELU / kg or ELU/part or ELU/ m^2

Units for ELV: Environmental Load Units
= ELU

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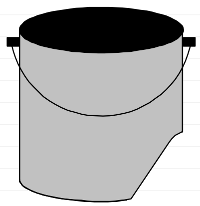
Case I: Polypropene Bucket

- Weight: 0.7 kg
- Material: Polypropene
  - Environmental Load Index: 0.68 ELU / kg
- Process: Injection Molding
  - Environmental Load Index: 0.08 ELU / kg



EPS Calculation of ELV for Bucket

Materials & Processes	ELV = ELI * Quantity
Material: Polypropene	0.68 ELU/kg * **0.7 kg** = 0.48 ELU
Process: Injection Molding	0.08 ELU/kg * **0.7 kg** = 0.06 ELU
Total Environmental Load Value:	0.48 ELU + 0.06 ELU = 0.54 ELU

Defined Safeguard Subjects

- Biodiversity
- Human Health
- Production
- Resources
- Aesthetic Values

"Unit Effects" for Safeguard Subjects

- Human Health: Unit Effects for CO_2
  - Excess mortality due to increased temperature in tropics
  - Temperature increase leads to flooding and therefore accidental deaths
  - Global warming leads to increased desertifcation; less food; more starvation

"Value Factors" for Unit Effects

- F1 Relative Cost to Reduce 1 kg Emission
- F2 Extent of Affected Area
- F3 Regularity of the Problem
- F4 Duration of Effect
- F5 Significance of 1 kg Substance wrt Total

EPS Valuation Bases -- 1995

Biodiversity			
Impact	ELU of impact	sd factor	Notes
Extinction of medium sized animals and plants	1.0E+15	10	10 ELU per person per year; 1E+09 persons; 1E+05 years
General and global impact on diodiversity	5.0E+11	5	100 ELU per person; 5E+09 persons

Biological Production			
Impact	ELU of impact	sd factor	Notes
1 kg of crop seed	0.2	2	economic value
1 kg of wood	0.025	2	economic value
1 kg of meat or fish	1	3	economic value
1 kg of fresh water	0.003	4	economic value in areas with water deficiency

EPS Valuation Bases – 1995 (continued)

Energy			
Impact	ELU per impact	sd factor	Notes
1 MJ renewable electrical	0.02	2	economic value
1 MJ renewable thermal	0.01	2	economic value

Human Health			
Impact	ELU per impact	sd factor	Notes
1 excess death	1,000,000	10	normalized from
1 man-yr painful morbidity	100,000	10	several studies
1 man-yr other morbidity	10,000	10	
1 man-yr severe nuisance	1,000	10	
1 man-yr moderate nuisance	100	10	

EPS Valuation Bases – 2000

1	**Impact Category - Human health**	**Category indicat**	**Indicator unit**	**Weighting facto**	**Un**
1	Life expectancy	YOLL	Person-years	85000	
2	Severe morbidity	Severe morbidity	Person-years	100000	
3	Morbidity	Morbidity	Person-years	10000	
4	Severe nuisance	Severe nuisance	Person-years	10000	
5	Nuisance	Nuisance	Person-years	100	
2	**Impact Category - Ecosystem proc**	**Category indicat**	**Indicator unit**	**Weighting facto**	**Un**
1	Crop growth capacity	Crop	kg	0.15	
2	Wood growth capacity	Wood	kg	0.04	
3	Fish and meat production capacity	Fish and meat	kg	1	
4	Soil acidification	Base cat-ion capa	mole H+ -equivaler	0.01	
5	Production capacity for irrigation wat	Irrigation water	kg	0.003	
6	Production capacity for drinking wate	Drinking water	kg	0.03	

EPS Valuation Bases - 2000

3	Impact Category - Abiotic stock re	Category indicat	Indicator unit	Weighting facto	U
1	Depletion of oil reserves	Fossil oil	kg	0.506	
2	Depletion of coal reserves	Fossil coal	kg	0.0498	
3	Depletion of natural gas reserves	Natural gas	kg	1.1	
4	Depletion of Ag reserves	Ag reserves	kg of element	54000	
5	Depletion of Al reserves	Al reserves	kg of element	0.439	
6	Depletion of Ar reserves	Ar reserves	kg of element	0	
7	Depletion of As reserves	As reserves	kg of element	1490	
8	Depletion of Au reserves	Au reserves	kg of element	1190000	
9	Depletion of B reserves	B reserves	kg of element	0.05	
10	Depletion of Ba reserves	Ba reserves	kg of element	4.45	
11	Depletion of Bi reserves	Bi reserves	kg of element	24100	

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EPS Valuation Bases - 2000

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
74	Depletion of Tm reserves	Tm reserves	kg of element	9900	
75	Depletion of U reserves	U reserves	kg of element	1190	
76	Depletion of V reserves	V reserves	kg of element	56	
77	Depletion of W reserves	W reserves	kg of element	2120	
78	Depletion of Y reserves	Y reserves	kg of element	143	
79	Depletion of Yb reserves	Yb reserves	kg of element	1980	
80	Depletion of Zn reserves	Zn reserves	kg of element	57.1	
81	Depletion of Zr reserves	Zr reserves	kg of element	12.5	
4	Impact Category - Biodiversity	Category indicat	Indicator unit	Weighting facto	Un
1	Species extinction	NEX	dimensionless	1.1E+11	

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Environmental Load Index:

$$ELI = \Sigma_{k=1,5} \; \Sigma_{j=1,n} \; \Pi_{i=1,5} \; F_{ijk}$$

safeguard subjects — unit effects — value factors

Units for ELI: Environmental Load Units / quantity
= ELU / kg or ELU/part or ELU/ m²

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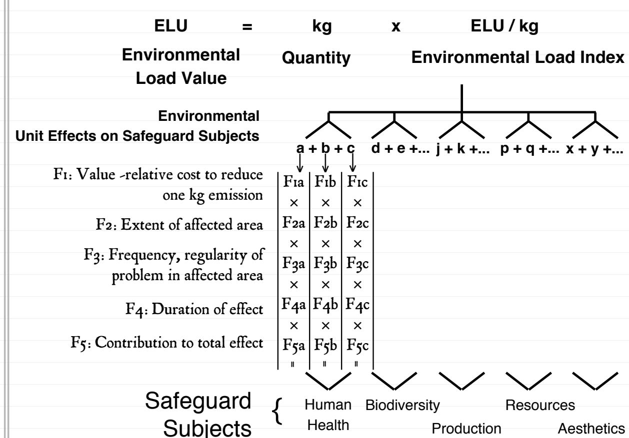
EPS Concept



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EPS Estimated Emission Indices for CO_2 ELI

Substance	Activity	Safegd	Unit	Impact	F1	F2	F3	F4	F5	ELI
		Subject	Effect	Type	Cost	Extent	Frequency	Duration	Contribution	(ELU/KG)
CO2	air emiss	Health	Death: heat	Temp.	1E+06	-3E+06	1	100	2.9E-16	-0.087
	air emiss	Health	Death: flood	Temp.	1E+06	1E+04	1	100	2.9E-16	0.00029
	air emiss	Health	Death: starv	Temp.	1E+06	1E+05	1	100	2.9E-16	0.0029
	air emiss	Health	Starvation	Temp.	1E+05	5E+07	1	100	2.9E-16	0.145
	air emiss	Biodiversity	Decrease	Temp.	5E+11	1	2	100	2.9E-16	0.029
	air emiss	Production	^ wood	Temp.	2.5E-02	-7.2E+10	1	100	2.9E-16	-0.0000522
	air emiss	Production	^ crops	Temp.	2E-01	-2.3E+11	1	100	2.9E-16	-0.001334
	air emission	Production	V crops	Temp.	2E-01	1.2E+10	1	100	2.9E-16	0.0000696
									ELI =	0.0888734

Estimated Emission Indices: 2000 CO_2 ELI

	A	B	C	D	E	F	G	H	I	J	K
1	CO2										
2	1	Human health	1	Life expectancy	YOLL	85000	5.90E+06	100	1.26E-16	7.43E-08	6.32E-03
3	1	Human health	1	Life expectancy	YOLL	85000	5.40E+09	1	1.26E-16	6.80E-07	5.78E-02
4	1	Human health	1	Life expectancy	YOLL	85000	4.50E+07	1	1.26E-16	5.67E-09	4.82E-04
5	1	Human health	1	Life expectancy	YOLL	85000	2.63E+06	100	1.26E-16	3.31E-08	2.81E-03
6	1	Human health	2	Severe morbidi	Severe r	100000	2.50E+09	1	1.26E-16	3.15E-07	3.15E-02
7	1	Human health	2	Severe morbidi	Severe r	100000	3.00E+08	1	1.26E-16	3.78E-08	3.78E-03
8	1	Human health	3	Morbidity	Morbidity	10000	2.50E+09	1	1.26E-16	3.15E-07	3.15E-03
9	1	Human health	3	Morbidity	Morbidity	10000	2.70E+09	1	1.26E-16	3.40E-07	3.40E-03
10	2	Ecosystem product	1	Crop growth ca	Crop	0.15	6.00E+12	1	1.26E-16	7.56E-04	1.13E-04
11	2	Ecosystem product	2	Wood growth c	Wood	0.04	-9.20E+12	1	1.26E-16	-1.16E-03	-4.64E-05
12	2	Ecosystem product	2	Wood growth c	Wood	0.04	-3.12E+12	100	1.26E-16	-3.93E-02	-1.57E-03
13	4	Biodiversity	1	Species extinct	NEX	1E+11	1.00E+00	100	1.26E-16	1.26E-14	1.39E-03
14											1.09E-01 /kg

ELU s for Processes

For Process: ELU = {ELI} * {Inventory} * {Quantity}

- Matrix Multiplication
  - –ELI Dimensions: 1 x n
    - –*With n emissions, resources used*
  - –Inventory Dimensions: n x m
    - –*With m subprocesses represented*
  - –Quantity dimension - Scalar
    - –*Input by User*

Summing Subprocesses: ELU(process) = Σ ELU(subs)

Environmental Load Value For Steel Grill Opening Panel

Material/ Product	Process/ Activity	Environmental Load Unit	Quantity	Environmental Load Value
Production Galv. Steel	Manufact	0.98 ELU/kg	9.0 kg	8.82 ELU
	Stamping	0.06 ELU/kg	9.0 kg	0.54 ELU
	SpotWeld	0.004 ELU/spot	48 spots	0.19 ELU
	Painting	0.01 ELU/m^2	0.6 m^2	0.01 ELU
Steel Scrap	Recycled Material	-0.92 ELU/kg	3.0 kg	-2.76 ELU
Product Use Fuel /Petrol	Manufact/ Combustion	0.82 ELU/kg	48 kg	39.36 ELU
Disposal Galv. Steel	Material	-0.92 ELU/kg	6.0 kg	-5.53 ELU
			TOTAL:	**40.64 ELU**

Environmental Load Value: GMT Composite Grill Panel

Material/ Product	Process/ Activity	Environmental Load Unit	Quantity	Environmental Load Value
Production				
GMT- Comp	Manufact	0.58 ELU/kg	4.0 kg	2.32 ELU
	Pressing	0.03 ELU/kg	4.0 kg	0.12 ELU
	Painting			
GMT- Comp	Recycld Matl	-0.58 ELU/kg	0.3 kg	-0.17 ELU
Product Use				
Fuel /Petrol	Manufact/ Combustion	0.82 ELU/kg	29.6 kg	24.27 ELU
Disposal				
GMT- Comp	Energy Reuse	-0.21 ELU/kg	3.7 kg	-0.78 ELU
			TOTAL:	**25.76 ELU**

Limitations of EPS

- Monetary Value of Each Resource and Emission Determined By:
  - Market Prices
  - Government Allocations
  - Contingent Valuation
- Money As A Measure of Value
  - Implies Construction of Linear Value Function
  - Each Unit Effect Adds Linearly to Final ELI
    - *Independent of Size of Each Unit Effect*

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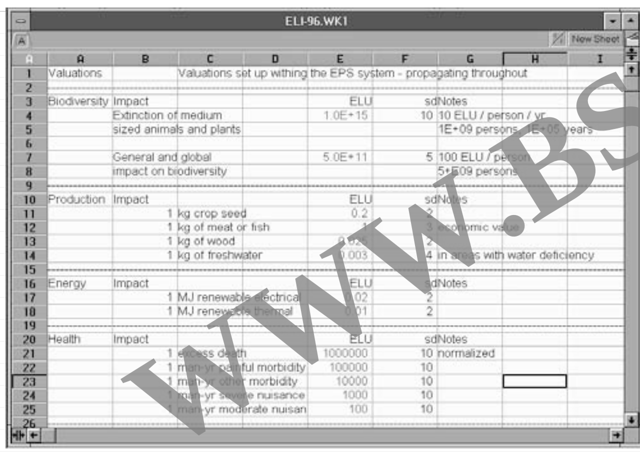
Basic Valuations - EPS


ELI-96.WK1

	A	B	C	D	E	F	G
1	Valuations		Valuations set up withing the EPS system - propagating throughout				
2							
3	Biodiversity	Impact			ELU	sd	Notes
4		Extinction of medium			1.0E+15	10	10 ELU / person / yr
5		sized animals and plants					1E+09 persons, 1E+05 years
6							
7		General and global			5.0E+11	5	100 ELU / person
8		impact on biodiversity					5+E09 persons
9							
10	Production	Impact			ELU	sd	Notes
11		1	kg crop seed		0.2	2	
12		1	kg of meat or fish		1	3	economic value
13		1	kg of wood		0.025	2	
14		1	kg of freshwater		0.003	4	in areas with water deficiency
15							
16	Energy	Impact			ELU	sd	Notes
17		1	MJ renewable electrical		0.02	2	
18		1	MJ renewable thermal		0.01	2	
19							
20	Health	Impact			ELU	sd	Notes
21		1	excess death		1000000	10	normalized
22		1	man-yr painful morbidity		100000	10	
23		1	man-yr other morbidity		10000	10	
24		1	man-yr severe nuisance		1000	10	
25		1	man-yr moderate nuisan		100	10	
26							

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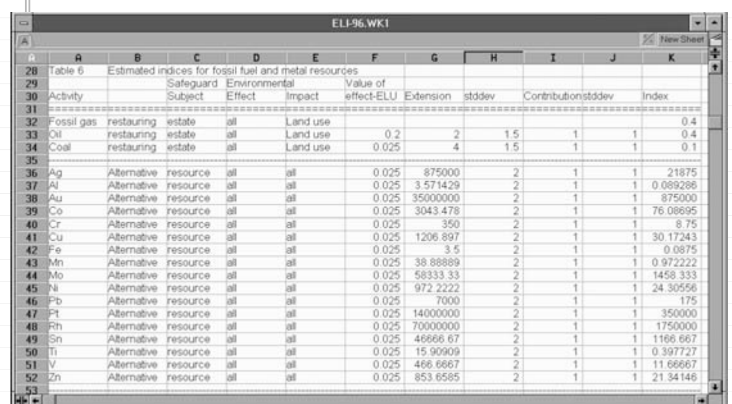
Resource Consumption ELI Table


ELI-96.WK1

	A	B	C	D	E	F	G	H	I	J	K
28	Table 6	Estimated indices for fossil fuel and metal resources									
29			Safeguard	Environmental		Value of					
30	Activity		Subject	Effect	Impact	effect-ELU	Extension	stddev	Contribution	stddev	Index
31											
32	Fossil gas	restauring	estate	all	Land use						0.4
33	Oil	restauring	estate	all	Land use	0.2	2	1.5	1	1	0.4
34	Coal	restauring	estate	all	Land use	0.025	4	1.5	1	1	0.1
35											
36	Ag	Alternative	resource	all	all	0.025	875000	2	1	1	21875
37	Al	Alternative	resource	all	all	0.025	3.571429	2	1	1	0.089286
38	Au	Alternative	resource	all	all	0.025	35000000	2	1	1	875000
39	Co	Alternative	resource	all	all	0.025	3043.478	2	1	1	76.08695
40	Cr	Alternative	resource	all	all	0.025	350	2	1	1	8.75
41	Cu	Alternative	resource	all	all	0.025	1206.897	2	1	1	30.17243
42	Fe	Alternative	resource	all	all	0.025	3.5	2	1	1	0.0875
43	Mn	Alternative	resource	all	all	0.025	38.88889	2	1	1	0.972222
44	Mo	Alternative	resource	all	all	0.025	58333.33	2	1	1	1458.333
45	Ni	Alternative	resource	all	all	0.025	972.2222	2	1	1	24.30556
46	Pb	Alternative	resource	all	all	0.025	7000	2	1	1	175
47	Pt	Alternative	resource	all	all	0.025	14000000	2	1	1	350000
48	Rh	Alternative	resource	all	all	0.025	70000000	2	1	1	1750000
49	Sn	Alternative	resource	all	all	0.025	46666.67	2	1	1	1166.667
50	Ti	Alternative	resource	all	all	0.025	15.90909	2	1	1	0.397727
51	V	Alternative	resource	all	all	0.025	466.6667	2	1	1	11.66667
52	Zn	Alternative	resource	all	all	0.025	853.6585	2	1	1	21.34146
53											

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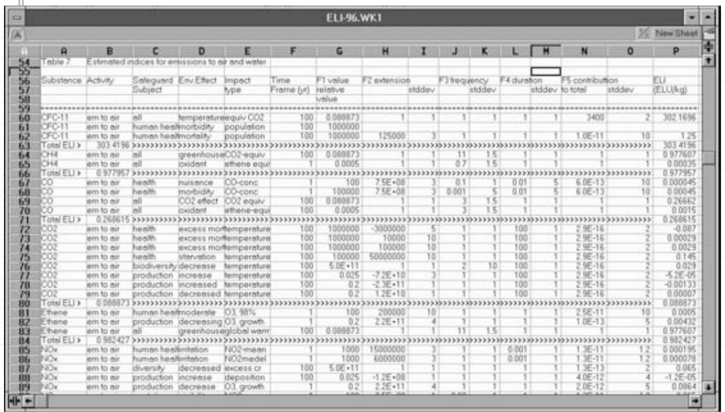
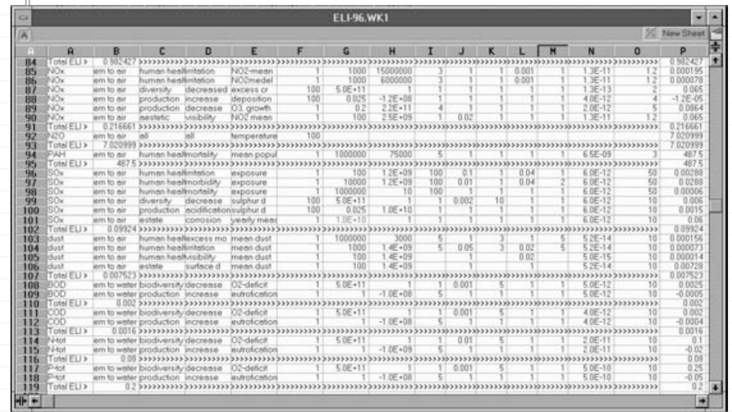
Air and Water ELIs (part 1)



Air and Water ELIs (part 2)



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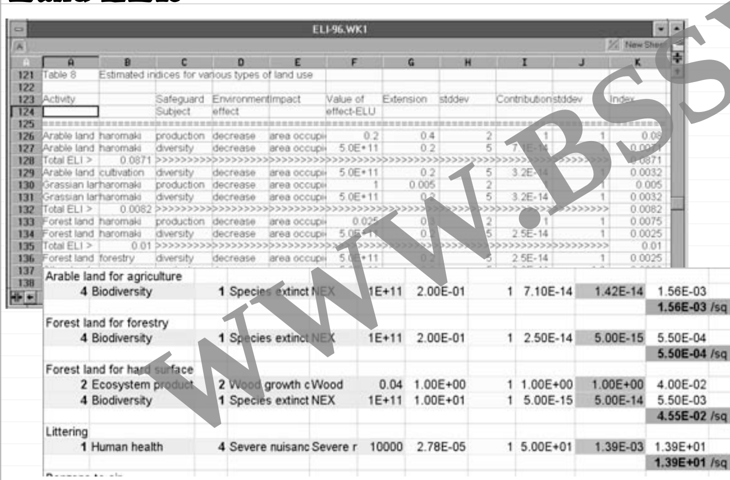
Land ELIs



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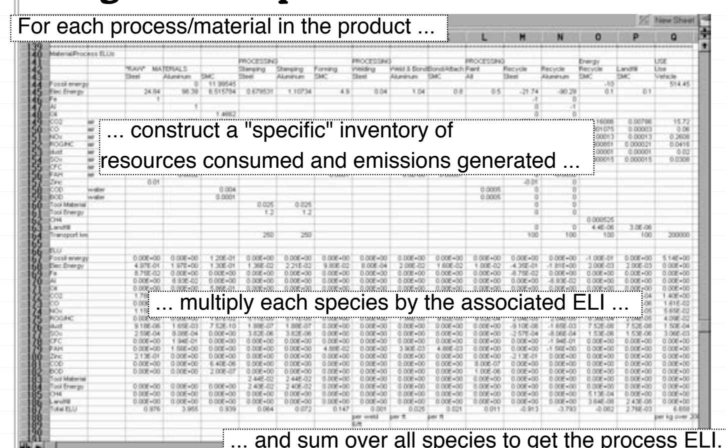
Using EPS - Step 1 & 2



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Using EPS - Step 3 (or 1): Describe The Process Steps For Each Alternative

ELI-96.WK1

	W	X	Y	Z	AA	AB	AC	AD	AE
1	Example Comparison								
2									
3									
4				Material	ELI				
5			Process	Affected	Value	Units			
6		Raw Matls	Extract/Refine	Steel	0.976	ELU/kg			
7		|	Extract/Refine	Al	3.955	ELU/kg			
8		|	Extract/Refine	SMC	0.939	ELU/kg			
9		Manufacture	Stamping	Steel	0.064	ELU/kg			
10		|	Stamping	Al	0.072	ELU/kg			
11		|	Forming	SMC	0.147	ELU/kg			
12		|	Welding	Steel	0.001	ELU/weld	(6 welds/ft)		
13		|	Weld & Bond	Al	0.025	ELU/ft			
14		|	Bond/Attach	SMC	0.021	ELU/ft			
15		|	Paint	All	0.011	ELU/m2			
16		Disposal	Recycle	Steel	-0.913	ELU/kg			
17		|	Recycle	Aluminum	-3.793	ELU/kg			
18		|	Recycle	SMC	-0.082	ELU/kg			
19		|	Landfill	SMC	2.76E-03	ELU/kg			
20		Use	Use	Vehicle	6.658	ELU/kg vehicle transported 200,000 km			
21									
22									

Using EPS - Final Comparison

Find the mass of material used in each step (or the relevant rate of use) ...

... multiply by the process ELI ...

... and add to get the environmental loads.

	W	X	Y	Z	AA	AB	AC	AD	AE
23						Steel Inner	SMC Inner	SMC Inner	
24						Steel Outer	Steel outer	Aluminum Outer	
25					Minner	8	6	6	
26					Mouter	10	10	6	
27		Raw Matls	Extract/Refine	Steel		[illegible]	[illegible]		
28		|	Extract/Refine	Al				23.73	
29		|	Extract/Refine	SMC			5.63	5.63	
30		Manufacture	Stamping	Steel		1.15	0.64		
31		|	Stamping	Al					
32		|	Forming	SMC			0.88		
33		|	Welding	Steel	10	0.05			
34		|	Weld & Bond	Al					
35		|	Bond/Attach	SMC			0.21	0.21	
36		|	Paint	All	0.6	0.01	0.01	0.01	
37		Disposal	Recycle	Steel		-16.44	-9.13		
38		|	Recycle	Aluminum				-22.76	
39		|	Recycle	SMC			-0.49	-0.49	
40		|	Landfill	SMC			0.02	0.02	
41		Use	Use	Vehicle		119.85	106.53	79.90	
42									
43					Total	122.18	114.54	88.06	
44					Net use	2.33	8.01	8.16	
45					If incin	2.33	7.50	7.65	

Impact Assessment 2

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What is Impact Assessment?

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What is Impact Assessment?

- **Attempt to describe the** *environmental consequence* **of the activity being studied**
  - **Accomplished by translating inventory into consequence (impact)**

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Why Impact Assessment?

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Why Impact Assessment?

- Reduces number of data points against which to make a decision
  - If taken to single score, then complementary with decision theory
  - Monetized methods may be comparable with other metrics
- Adds information
  - Provides input from a range of sciences and other stakeholders

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What is Impact Assessment?
ISO Definition

- **Impact Category Definition**
  - **Identify what impacts are of concern and which models will be used to translate inventory to impact**
- **Classification:**
  - **Environmental stressors are correlated with specific impact categories**
- **Characterization**
  - **Quantify amount of impact**
  - **Damage assessment**
    - Aggregate similar impacts
- **Normalization**
- **Valuation**
  - **Possibly weighting impacts to rank or aggregate**

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Your thoughts:

What do you see as the key issues?

What is most challenging step?

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Issue 1: Relevance

- **Translating from inventory to impact is**
  - **Introduces numerous assumptions**
    - What are examples of assumptions?
  - **Controversial**
  - **Necessity depends on context**
    - Expertise / influence of decision-makers may influence the extent of aggregation required
    - ISO excludes weighting / valuation from comparisons for external distribution

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Issue 2: Translating Environmental Impact

- **The impact of pollution is rarely a simple one**
  - **C02 → Increases thermal absorption → Raises Temperature**
    - So what?
  - **Increased temperature →**
    - Ice melting
    - Desertification
    - …
- **Assessment method, must take into account causal chain**

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Which Environmental Impacts should we care about?

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Issue 3: What Effects to Track?

- ISO establishes three broad categories of concern
  - Resource use
  - Human health
  - Ecological consequence
  - There is debate over whether to include damage to the man-made environment (e.g., acid rain damage to ancient structures)
    - What about aesthetics? Comfort?
- Key issue: Double counting
  - Boundary between categories is fuzzy
    - Oil depletion vs. Emissions from oil use

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Impact Categories: Many differing approaches

- Nordic Guidelines
  - Resource depletion
    - Energy & material
    - Water
    - Land use
  - Human health
    - Toxicological
    - Non-toxicological
    - Work/living environment
  - Ecological
    - Global warming
    - Photochemical oxidation
    - Acidification
    - Ozone depletion
    - Eutrophication
    - Ecotoxicological
    - Bio-diversity
- Environmental priorities system
  - Human health
  - Biological diversity
  - Ecosystem production capacity (crops…)
  - Abiotic resources (metals…)
  - Cultural & recreational value (e.g., aesthetics…)

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Example Method 2: Eco-Indicator

- **Commissioned by Dutch Ministry of Housing, Spatial Planning, and the Environment to support goals of Integrated Product Policy**
- **Aimed particularly at influencing design practice**
  - **Extensive documentation for product designers**
- **Fundamental basis / Weighting factor:**
  - **Original (95):**
    - Impact oriented
    - Based on distance to target
  - **Current (99)**
    - Damage oriented
    - Expert panel / differing perspectives
- **Generally represents impacts based on average conditions in Europe**

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Characterization

- **Expresses relative contribution of specific impact to the category of impact**
  - **E.g., Impact of CO2 release = 1**
    Impact of methane release = 21
- **Mid point vs end-point**
  - **Increase in acidification vs. Increase in species depletion**
  - **Impact indicator vs. damage indicator**
  - **Less uncertainty vs. easier to value**
  - **Eco-indicator 99 is an endpoint / damage-based method**
  - **Eco-indicator 95 was a midpoint based method**

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Characterization: Eco-Indicator Damage Model

- **Fate**
  - **Where does the emission end up**
    - Water soluble → likely in water supply
    - Insoluble → soil
  - **How durable is the emission**
    - Some substances degrade quickly, reducing the opportunity for impact.
- **Exposure**
  - **How many / much are effected?**
    - How much of a specific emission is taken in by persons/ecosystem?
- **Effects analysis**
  - **What does the emission change?**
    - Types and frequencies of certain diseases
    - How many years of disability or years of life lost

- **Damage analysis**
  - **Effects are aggregated and weighted based on system developed by WHO**

Characterization: Specific Emphasis

- **Emissions**
  - **Carcinogens**
  - **Respiratory agents**
  - **Respiratory inorganics**
  - **Climate change**
  - **Radiation**
  - **Ozone layer**
  - **Eco-toxicity**
  - **Acidification / eutrophication**
- **Land use**
  - **Species diversity per unit of typical land (Based on field research)**
  - **Damage occurs due to land use or land occupation**
  - **Potentially disappeared fraction**
- **Resource depletion**
  - **Surplus energy**

Eco-Indicator 95 Weighting factors

- **Distance to target**
  - **The further away current conditions are to an established target the more serious it is to worsen those conditions**
    - Current CO2 per year vs. Desired CO2 per year: 2.5X
      - Actually for GWP
    - Current Ozone Depletion Potential vs. desired : 100x
  - **The targets are set according to**
    - At target level the effect will cause 1 excess death per million per year
    - At target level the effect will disrupt fewer than 5% of the ecosystems in Europe
    - At target level the occurrence of smog periods is extremely unlikely

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Eco-Indicator 95 Weighting factors

	Reduction factor	Criterion
Greenhouse	2.5	0.1° per decade, 95th percentile?
Ozone layer	100	Prob of 1 death per year per million
Acidification	10	95th percentile ecosystems
Eutrophication	5	95th percentile ecosystems
Summer smog	2.5	Prevent smog periods, health complaints
Winter smog	5	Prevent smog periods
Pesticide	25	95th percentile ecosystems
Heavy metals in Air	5	Lead content in blood of children
Heavy metals in H_2O	5	Cadmium content in rivers
Carcinogenic Subst	10	Prob of 1 death per year per million

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Eco-Indicator 99

- **Extension of Eco-Indicator 95**
- **Focus is on weighting method**
  - **Don't weigh impact categories**
  - **Weigh only different types of damage**
- **Limits type of damage categories to 3**
  - **Damage to human health**
    - Expressed as number of years of life lost and number of years of life lived disabled
  - **Ecosystem quality**
    - Expressed as species lost over a certain area for a period of time
  - **Damage to resources**
    - Surplus energy needed for future extraction of minerals
- **Specific weighting determined by panel evaluation**

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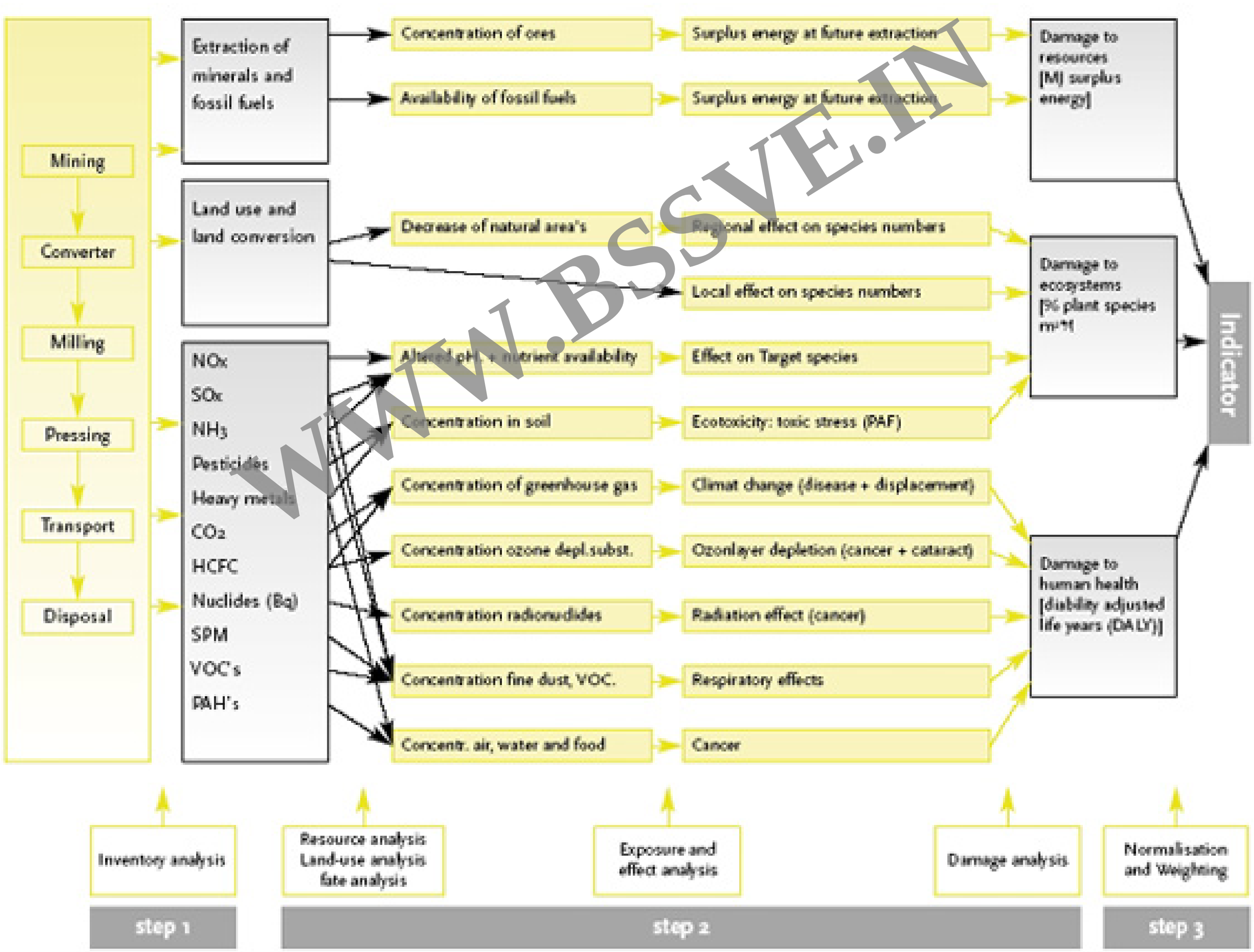

Courtesy of The Netherlands Ministry of Housing, Spatial Planning and the Environment (VROM). Used with permission.
Source: *Eco-indicator 99: Manual for Designers*

Comparing Impact Assessment

Inventory

Change in …	*Impact on …*	*Damage to …*
Atmospheric concentration	Species number	Human health
Land availability	Global Warming	Ecosystem
Ore availability	Ozone Depletion	Resources
	• • •	

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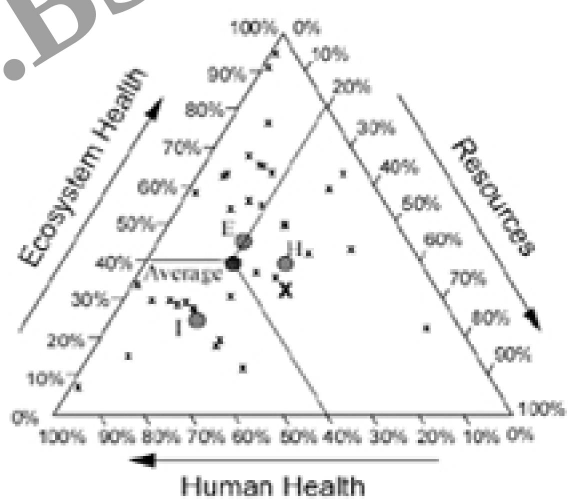
Weighting via Panel

- Surveyed 365 persons
- Reviewed Eco99
- Rank categories
- Provide relative importance of categories
- Limited statistical significance



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Courtesy of The Netherlands Ministry of Housing, Spatial Planning and the Environment (VROM). Used with permission.
Source: *Eco-indicator 99: Manual for Designers*

Weighting via Panel

	Hierarchist	Egalitarian	Individualist
Human Health	40%	30%	55%
Ecosystem	40%	50%	25%
Resources	20%	20%	20%

Valuation Perspective: Hierarchist

- Long time perspective
- Substances included if there is consensus
  - Class 1 and 2 carcinogens are included
  - Class 3 are excluded
- Damages are excluded if good management could avoid
  - Life lost due to flood
- Fossil fuel substitution is difficult
- No age weighting of DALYs

Valuation Perspective: Egalitarian

- Time perspective: Extremely long term
- Substances are included if there is an indication of impact
  - Classes 1 -3 carcinogens are included to the extent that information is available
- Damages are included if possible
- Fossil fuel cannot be subsituted
  - Cost of replacement is high
- DALYs are not age weighted

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Valuation Perspective: Individualist

- Time perspective is 100 years
- Impact from substances is included only when complete proof exists
  - Only Class 1 carcinogens are included
- Damages are assumed to be recoverable
- Fossil fuels cannot be depleted
  - Ignored
- DALYs are age weighted

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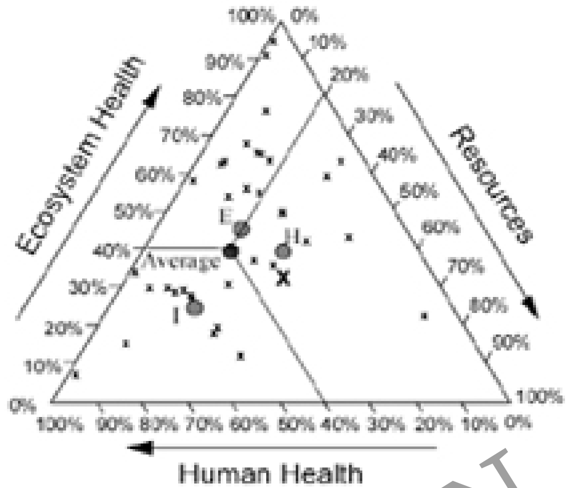
Weighting via Panel

- Surveyed 365 persons
- Reviewed Eco99
- Rank categories
- Provide relative importance of categories
- Limited statistical significance



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Courtesy of The Netherlands Ministry of Housing, Spatial Planning and the Environment (VROM). Used with permission.
Source: *Eco-indicator 99: Manual for Designers*

Weighting via Panel

	Hierarchist	Egalitarian	Individualist
Human Health	40%	30%	55%
Ecosystem	40%	50%	25%
Resources	20%	20%	20%

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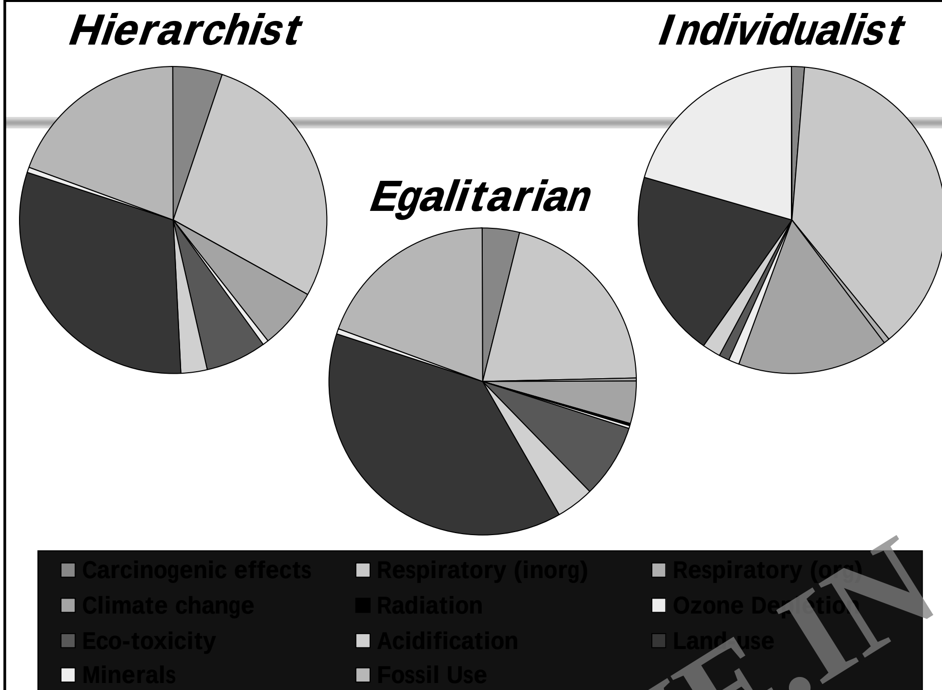

LCA: Slide 117

Issues with Eco-Indicator

- **Weaknesses**
  - **Limited to three impacts**
    - Human health
    - Biodiversity
    - Resource depletion
  - **Highly European focused**
  - **Controversial panel weighting**
  - **Still many inventory items to model**
- **Strengths**
  - **Comparatively comprehensive**
  - **Provides consistent mechanism for weighting**
  - **Well documented**

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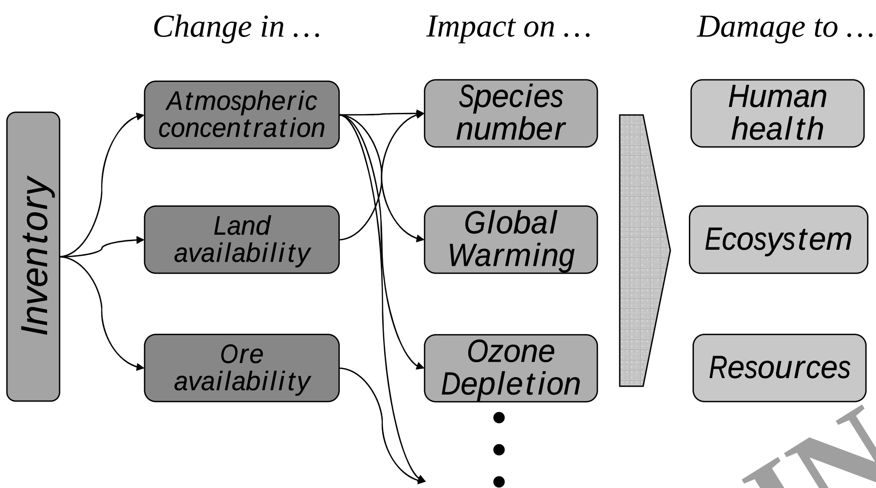
LCA: Slide 118

Comparing Impact Assessment



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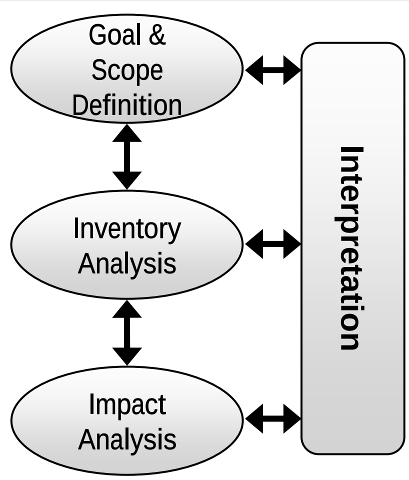
LCA: Methodology

- **Goal & Scope Definition**
  - **What is the unit of analysis?**
  - **What materials, processes, or products are to be considered?**
- **Inventory Analysis**
  - **Identify & quantify**
    - Energy inflows
    - Material inflows
    - Releases
- **Impact Analysis**
  - **Relating inventory to impact on world**



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ESD.123 / 3.560

Systems Perspectives on Industrial Ecology:

Evaluation Concepts and Methods on
the Environmental Impact of Systems

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Instructors

- **Randolph Kirchain**
  - **Assistant Professor, Department of Materials Science and Engineering & Engineering Systems Division**
- **Frank Field**
  - **Associate Director for Education, Technology and Policy Program**
  - **Senior Research Engineer**
- **Jeremy Gregory**
  - **Research Associate, Materials Systems Laboratory**

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Today's Mechanics

- Please fill in the sign-up sheet which is going around
  - Email list will be important for communicating with you about course updates

- Information requested
  - Name
  - Department
  - Year
  - Email

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Central Question of the Course:

How can Engineers make

Economically & Environmentally Informed

Material, Process, Architecture, & Policy

Decisions?

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3.080 Econ & Enviro Issues In Materials Selection
Randolph Kirchain
Introduction: Slide 4

Overview of Course: Philosophy

- Conceptual
  - Engineers can fundamentally change the environmental footprint of modernity
  - To effect change, engineers require tools to identify “better” design and operational options
- Pedagogical
  - Engineers are highly trained in analysis
  - Engineers receive little training in evaluation
  - Engineers receive effectively NO training in evaluating environmental impact

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Overview of Course: Learning Objectives

- Learning Objectives
  - Awareness of environmental perspectives on technological activity
  - Awareness of environmental evaluation theories and tools
  - Proficiency with
    - Life-cycle thinking
    - Life-cycle assessment methods
  - Awareness of policy mechanisms for driving environmental decisions
  - Ability to address analyses with incomplete data
  - Appreciation for multi conditional solutions

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Why Do We Care?

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Introduction: Slide 7

Global Warming

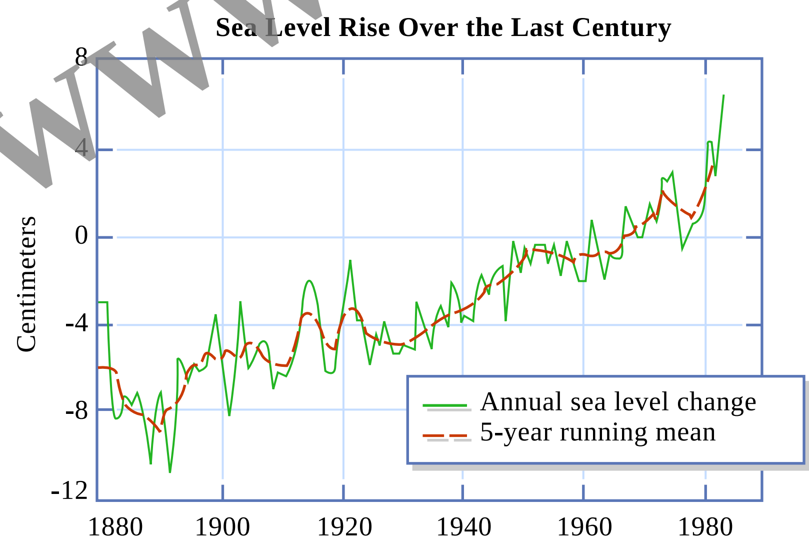

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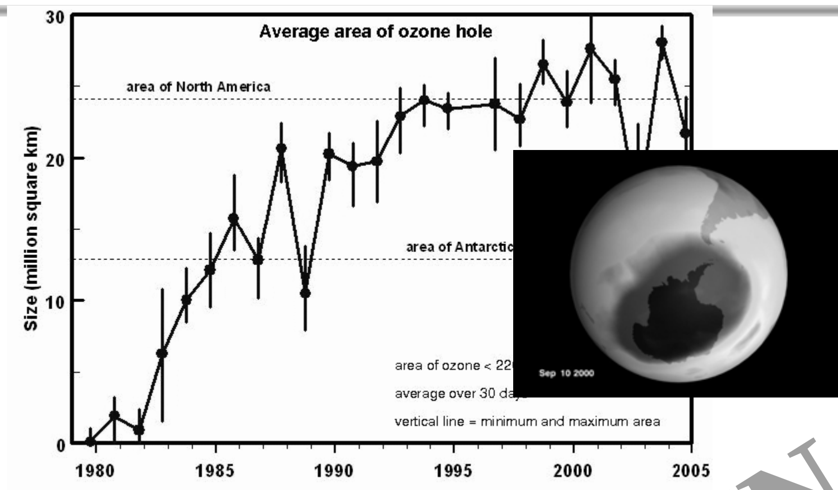
Figure by MIT OCW.

Ozone Hole



Courtesy of NASA.

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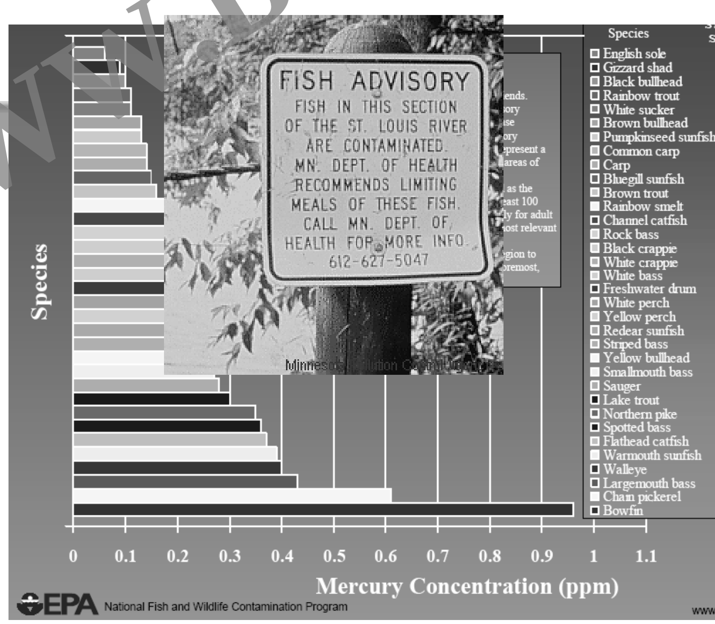
Toxics



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Current Issues of Concern

- Global warming & climate change
- Ozone layer depletion
- Soil degradation and loss of wetlands & agricultural land
- Species extinction
- Concentration of toxics
- Depletion & degradation of resources

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How does Industrial Activity Affect the Environment?

- **Direct**
  - **Manufacturing burden**
    - Consumption of energy
    - Emissions to the environment
  - **Concentration in the environment**
    - Most materials still eventually in up in landfills
    - Toxicity for some materials
- **Indirect**
  - **Performance of the products into which they are transformed**
    - Energy Efficiency
    - Recyclability

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Is this *really* a problem?

How much do

YOU

consume per day?

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How much do YOU use per day (kilograms)?

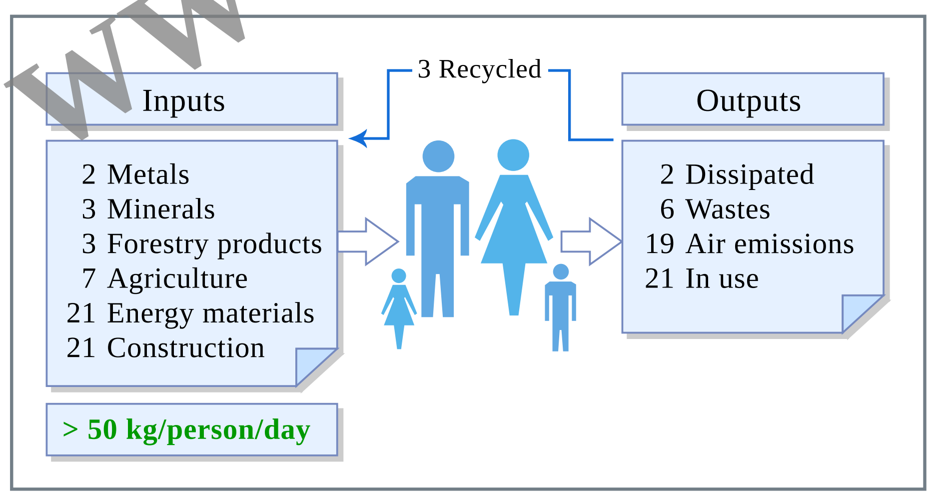

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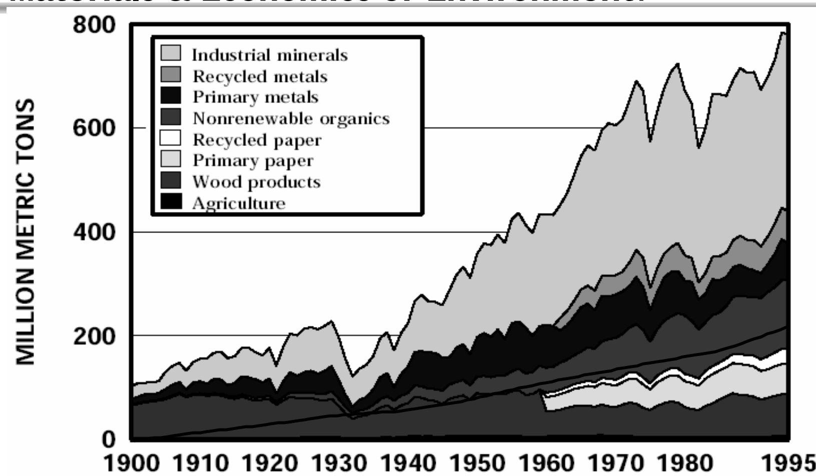
Figure by MIT OCW.

Why Care About Materials & Economics or Environment?



Courtesy of Annual Review, Inc. Used with permission.
Source: Figure 3 in Matos, G., and L. Wagner. "Consumption of Materials in the United States, 1900-1995." *Annu Rev Energy Environ* 23 (1998): 107–22.

How Can We Affect This?

- **Human Behavior**
  - **Change patterns of consumption**
    - Waste less
- **Change the rules**
  - **Dematerialization**
    - Get the same function from less material
  - **Materials substitution**
    - Apply less harmful materials
  - **Waste Mining – Reuse, Recycle**
    - Find ways to make use of streams currently wasted

Course Materials

- Readings will be distributed online
  - Used to distribute key course materials
    - Syllabus, Lecture Notes, Solutions, Case Tools
- Texts on Reserve:
  - *The Hitch Hiker's Guide to LCA*, H Bauman and A Tillman, Studentlitteratur AB, 2004
- Software
  - SimaPro – Life-cycle Analysis

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Grading Guidelines

• Assignments	35%
• Case 1 Presentation / Report	20%
• Case 2 Presentation / Report	30%
• Class Participation	15%

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Calendar

- Today: Intro and Overview
- Feb 9 – Mar 2: Views on Industrial Ecology
- Mar 7 – Apr 4: LCA: Method Basics
- Apr 6: Case 1 Presentations
- Apr 11 – Apr 20: Environmental Evaluation & Advanced Methods
- May 2 – May 4: Aggregate Materials Flows
- May 9 – May 16: Environmental Policy Strategies
- May 18: Case 2 Presentations

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Initial Assignments

- **Assignment 1 – NEXT Class – Thurs Feb. 9**
  - **Read Frosch Paper**
  - **<1 Page Writeup**
    - Definition in your words of industrial ecology
    - Description of a technological activity (i.e., product, system, or technology policy) which serves as a good example of industrial ecology principles or where strong opportunity exists
  - **Select Environmental Paradigm from Colby to defend**
- **Assignment 2 – Session 3 – Tuesday Feb 14**
  - **Prepare short (15 min) presentation on selected paradigm**
    - Describe paradigm
    - Defend paradigm using at least one concrete example of product or material/product system

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Initial Assignments

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    - Describe paradigm
    - Defend paradigm using at least one concrete example of product or material/product system

Assignment 3:
Exploring the limits of Sustainability Theory

- Next class we will explore economics perspectives on
  - Weak vs. strong sustainability
  - Optimal rate of resource consumption
- Assignment prepare a presentation (10 minutes) on
  - Resource which shows that natural and human-made resources are substitutable (Weak Sust.) or
  - Resource which shows that resources cannot be substituted (Strong Sust.)
- Presentation should describe
  - What is resource?
  - How is it used?
  - Why is scarcity of this resource of concern?
  - Evidence of position
- Do not choose resources which are valued for
  - Aesthetics (Art, Jewels)
  - Existence (Paul Revere's House)
  - Being Oil, Water, or FIsh

Assignment #4: Considering LCA Goal & Scope

- **Select a product or activity**
- **Characterize two distinct goals for carrying out an LCA**
  - **Both goals should represent distinct stakeholder perspectives**
    - Producer, consumer, regulator, NGO …

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Assignment #4: G&S Characterization

- **Describe activity**
- **Identify stakeholder and motivations of stakeholder**
- **What alternatives are being compared?**
- **What is functional unit?**
- **What are geographical system boundaries?**
  - **Should export be considered?**
  - **Activities outside of US?**
- **What is the time horizon of the study?**
- **What are the conceptual boundaries of the study?**
  - **What activities are included?**
  - **What about capital goods?**

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Case 1 – LCA of a Product – (April 4)

- **Select a set of product or activity on which to perform a comparative LCA**
- **Presentation:**
  - **What is product?**
    - Overview of environmental concerns raised publicly
  - **Goal & scope**
    - Goal
    - What alternatives are being considered?
    - Boundaries
  - **Inventory**
    - How is product made?
    - Major assumptions
    - Data sources
  - **Recommendations**
- **Writeup – 3-5 page writeup of case and recommendations**

Case Project #2: Identifying Drivers & Mechanisms of Change

- **Fundamental Question:**
  - **What drives the environmental performance of your product?**
  - **Would it be reasonable for the relative standing of your products to change? Under what context?**
    - Focus on system changes
- **System changes:**
  What is something outside of your product that could alter your preference?
  - **Quantify the nature of such a change that would drive a different decision.**
- **Policy drivers**
  Discuss 2-3 policy options which could drive that change
  - **How would you implement?**
  - **Pros and Cons**

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