Life Cycle Modeling and Assessment

CEE 111/211
Multi-disciplinary Modeling

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Outline

• Industrial Ecology
• Life Cycle Assessment
• BEES
Industrial Ecology

• “systematically examines local, regional, and global uses and flows of materials, and energy in products, processes, industrial sectors and economies”
  – Journal of Industrial Ecology

• “the study of the flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, regulatory, and social factors of the flow, use and transformation of resources.”
  – Robert White, President of the US Academy of Engineering
Nature as a model

• “The industrial ecosystem would function as an analogue of biological ecosystems. (Plants synthesize nutrients that feed herbivores, which in turn feed a chain of carnivores whose wastes and bodies eventually feed further generations of plants.)” Frosch and Gallopoulous, 1989

**FIGURE 1:** This diagram shows the relations between typical terrestrial organisms. The arrows connect the prey (diet) to the predator (consumer). The colored dots on the animals are coded to the colors in the triangular diagram at the upper right.

**FIGURE 2:** This diagram shows the relations between typical aquatic organisms. The arrows connect the prey (diet) to the predator (consumer). Several different food webs are shown.
Production/Consumption Processes and Material/Energy Flows

Raw Material Acquisition

Material Processing

Manufacture & Assembly

Use

Service

Retirement & Recovery

Disposal

recycling

remanufacture

reuse
Sustainability Indicators

Populations → Human Needs

Social Demographic Indicators
- Sustenance
  - Clothing
  - Shelter
  - Health

Economic Indicators
- Manufacturing
  - Construction
- Agriculture
- Services
- Education
  - Utilities
  - Infrastructure
  - Recreation

Ecological Indicators
- Materials Resource Use
- Energy Resource Use
- Waste/Emissions
  - Atmosphere
  - Lithosphere
  - Hydrosphere
  - Biosphere

Human Needs → Production & Consumption Activities

Changes in Ecosystem States → Material & Energy Flows
Outline

• Industrial Ecology

• Life Cycle Assessment

• BEES
LCA Standards

- ISO: International Organization for Standardization
- LCA standards are voluntary
- Part of 14000 Environmental Management Series
- LCA Standards:
  - 14040  Principles and Framework
  - 14044  Goal and Scope, Inventory, Impact, and Interpretation
  - 14020 series: Environmental Labeling
LCA Requirements (ISO:14040)

Goal and scope definition

Inventory analysis

Impact assessment

Interpretation
Goal and Scope

• Goal of the study
  – State the intended application
  – Identify the intended audience

• Scope of the study
  – Function and functional unit
  – System boundaries
  – Data requirements/assumptions/limitations
  – Critical review and report format
Attributional vs. Consequential LCA

• Attributional LCA
  – Measuring the impacts of products, processes, or systems as they currently exist
  – Used for decision-making between existing alternatives

• Consequential LCA
  – Measuring the impacts of products, processes, or system as they would exist after a decision has been made
  – Used for decision-making between existing and planned alternatives
Functional Unit

• Function
  – Service provided by system; performance characteristics of the product

• Functional unit
  – Means for quantifying the product function
  – Basis for an LCA
  – Reference for normalization of input and output data
LCA Requirements (ISO:14040)

Goal and scope definition

Inventory analysis

Impact assessment

Interpretation
Production/Consumption Processes and Material/Energy Flows

Primary Materials
(e.g., ores, biotic resources)

Recycled Materials
(open loop recycling)

Primary Energy
(e.g., coal)

Capital
($)

Labor
(e.g., human labor, biological labor)

Raw Material Acquisition

Material Processing

Manufacture & Assembly

Retirement & Recovery

Use

Disposal

Service

Air pollutants
(e.g., Hg)

Water pollutants
(e.g., BOD)

Solid waste
(e.g., MSW)

Products
(e.g., goods, services)

Co-products
(e.g., recyclables, energy)

Processes and flows are spatially and temporally distributed
Example – MBARI Aquarium
Two Comparisons

Concrete Tank

FRP Tank
Process Flow – Water Tank

Concrete Tank

- Raw materials (e.g. limestone, cement rock, waste oil, gypsum)
- Aggregate / sand
- Cement
- Water
- Steel
- Plywood
- Releas e agent
- Timber
- Concrete
- Gel coat
- Rebar
- Formwork

FRP Tank

- Raw materials (e.g. pig iron, oxygen, alloy metals)
- Timber
- Electricity
- Sand
- Feldspar
- Sodium Sulfate
- Borax
- Boric Acid
- Fuel
- Resin Production
- Glass Fiber Compression, Curing, Cooling, and Fabrication
- Process Energy
- Process Mat’ls (Epoxy)
- Gel coat
- Steel
- Plywood
- Releas e agent
- Rebar
- Formwork

Material Production

- Electricity
- Sand
- Feldspar
- Sodium Sulfate
- Borax
- Boric Acid
- Fuel
- Process Energy
- Process Mat’ls (Epoxy)
- Resin Production
- Glass Fiber Compression, Curing, Cooling, and Fabrication

End of Life

- Landfill
- Labor (e.g. engineering, construction, inspection)

Recycled aggregate

Reused forms

Steel scrap

Concrete Tank

Electricity

SAND

Feldspar

Sodium Sulfate

Borax

Boric Acid

Fuel

Process Energy

Process Mat’ls (Epoxy)

Glass Materials Handling, Transport, Melting, and Refining

Resin Production

Glass Fiber Compression, Curing, Cooling, and Fabrication

Electricity

Oil

Fuel

Laying of FRP

Scrap/Waste

Labor

Concrete Tank

FRP Tank
Initial System Boundaries

• Determine which unit processes should be included.

• Example
  – Construction of a building…
  – Building components?
Lifecycle Inventory (LCI)

- The identification and quantification of relevant inputs and outputs for a given system throughout its life cycle
  - Franklin and Associates
  - EcoInvent
  - BEES
  - APME
  - NREL
  - ELCD
  - Others…
# US Electricity Life Cycle Inventory

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

<table>
<thead>
<tr>
<th>Substance</th>
<th>US average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butadiene</td>
<td>6.08E-08</td>
</tr>
<tr>
<td>Butane</td>
<td>3.18E-04</td>
</tr>
<tr>
<td>Cadmium</td>
<td>4.31E-06</td>
</tr>
<tr>
<td>Calcium</td>
<td>1.25E-07</td>
</tr>
<tr>
<td>Carbon dioxide (biomass)</td>
<td>2.97E-04</td>
</tr>
<tr>
<td>Carbon dioxide (fossil)</td>
<td>1.83E+02</td>
</tr>
<tr>
<td>Carbon disulfide</td>
<td>4.46E-06</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>5.10E-02</td>
</tr>
<tr>
<td>Chlorides</td>
<td>8.78E-05</td>
</tr>
<tr>
<td>Chlorine</td>
<td>1.23E-09</td>
</tr>
<tr>
<td>Chloroacetonaphthalene</td>
<td>2.41E-07</td>
</tr>
</tbody>
</table>

LCA Requirements (ISO:14040)

- Goal and scope definition
- Inventory analysis
- Impact assessment
- Interpretation
LC Impact Assessment

• Evaluation of the magnitude and significance of the potential environmental impacts of a product system
  – using inventory analysis results
Characterization methods

• Loading assessment
  – a “less is better” approach
  – sums inventory inputs and outputs on a mass or energy basis into impact categories

• Equivalency assessment
  – applies equivalency factors to inventory data and aggregates results
    • e.g., GWP, ODP, AP
Figure 3-5. Example of Multiple Inventory Items Leading to Similar Impacts
## Global Warming Potentials

<table>
<thead>
<tr>
<th>Greenhouse Gases</th>
<th>GWP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide (CO\textsubscript{2})</td>
<td>1</td>
</tr>
<tr>
<td>Methane (CH\textsubscript{4})</td>
<td>23</td>
</tr>
<tr>
<td>Nitrous Oxide (N\textsubscript{2}O)</td>
<td>296</td>
</tr>
<tr>
<td>Hydrofluorocarbons (e.g. HFC 134a)</td>
<td>1 300</td>
</tr>
<tr>
<td>Perfluorocarbons (e.g. CF\textsubscript{4})</td>
<td>5 700</td>
</tr>
<tr>
<td>Sulfur Hexafluoride (SF\textsubscript{6})</td>
<td>22 200</td>
</tr>
</tbody>
</table>

IPCC 2007
Life Cycle Impact Categories

• Input related categories
  – abiotic resource extraction
  – biotic resource extraction
  – land use

• Output related categories
  – global change (climate, ecosystem, etc.)
  – stratospheric ozone depletion
  – human toxicity (cancer, noncancer, criteria pollutants)
  – ecotoxicity
  – photo-oxidant formation
  – acidification
  – nutrification
## MBARI Life Cycle Impacts

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Concrete</th>
<th>FRP</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acidification (kg SO2)</td>
<td>271</td>
<td>118</td>
<td>130%</td>
</tr>
<tr>
<td>Carcinogens (kg B(a)P)</td>
<td>0.008</td>
<td>0.006</td>
<td>59%</td>
</tr>
<tr>
<td>Energy resources (MJ LHV)</td>
<td>560,000</td>
<td>278,000</td>
<td>101%</td>
</tr>
<tr>
<td>Eutrophication (kg PO4)</td>
<td>28.0</td>
<td>11.8</td>
<td>138%</td>
</tr>
<tr>
<td>Greenhouse (kg CO2)</td>
<td>36,500</td>
<td>16,600</td>
<td>120%</td>
</tr>
<tr>
<td>Heavy metals (kg Pb)</td>
<td>0.300</td>
<td>0.190</td>
<td>58%</td>
</tr>
<tr>
<td>Ozone layer (kg CFC11)</td>
<td>0.0009</td>
<td>0.0006</td>
<td>38%</td>
</tr>
<tr>
<td>Pesticides (kg act.sub)</td>
<td>0</td>
<td>0</td>
<td>NA</td>
</tr>
<tr>
<td>Solid waste (kg)</td>
<td>283,000</td>
<td>77,200</td>
<td>367%</td>
</tr>
<tr>
<td>Summer smog (kg C2H4)</td>
<td>18.5</td>
<td>7.34</td>
<td>153%</td>
</tr>
<tr>
<td>Winter smog (kg SPM)</td>
<td>3,360</td>
<td>842</td>
<td>300%</td>
</tr>
</tbody>
</table>
LCA Requirements (ISO:14040)

Goal and scope definition

Inventory analysis

Impact assessment

Interpretation
Life Cycle Interpretation

• Draw conclusions and recommendations from inventory analysis and/or impact assessment
  – weighting among various indicators
  – identify major burdens and impacts
  – select among alternative designs or materials

• Peer Review
  – Internal Review
  – External Review
Valuation Techniques

• Highly Uncertain
• Policy Question
• Value Judgement

• Distance-to-Target
• Environmental Control Costs
• Economic Damage Approaches
• Scoring Techniques
Distance to Target

• Derived from extent to which actual environmental performance deviates from some goal or standard.
  – Ambient concentration of CO is 1.1 mg CO/m³
  – Standard is 1.0 mg CO/m³
  – Weight attached to standard is 10%
Environmental Control Costs

- Weights are derived from the expenditure necessary to control environmental damage.
  - $2 to control pollutant A
  - $1 to control pollutant B
  - A has a weight twice that of B

- Society has expressed a “willingness to pay” for achieving a standard.
Environmental Damage Costs

- Derived from Willingness to Pay (WTP) to avoid impacts identified in LCA.
  - Economic values available for air pollution, casualties from road traffic accidents, road congestion.
  - One unit ($)
- Acceptability of individual preferences as a policy guide
  - Imperfect information (Pearce, 1994)
Valuing the Ecosystem

The value of the world’s ecosystem services and natural capital


* Center for Environmental and Estuarine Studies, Zoology Department, and † Institute for Ecological Economics, University of Maryland, Box 38, Solomons, Maryland 20688, USA

Value of Ecosystem Services = $33 trillion
range:  $16 - $54 trillion
1.8 x Global GNP

The services of ecological systems and the natural capital stocks that produce them are critical to the functioning of the Earth’s life-support system. They contribute to human welfare, both directly and indirectly, and therefore represent part of the total economic value of the planet. We have estimated the current economic value of 17 ecosystem services for 16 biomes, based on published studies and a few original calculations. For the entire biosphere, the value (most of which is outside the market) is estimated to be in the range of US$16–54 trillion (10^{12}) per year, with an average of US$33 trillion per year. Because of the nature of the uncertainties, this must be considered a minimum estimate. Global gross national product total is around US$18 trillion per year.
Scoring Approaches

- Weights from group of experts or stakeholders
  - Rank impacts in order
  - Rank relative to other pollutants and impacts
- Delphi Technique (decision theory)
- Practicality varies with completeness
- Scientific vs. Socially Aware experts?
Outline

• Industrial Ecology
• Life Cycle Assessment
  • BEES
BEES Interface

Analysis Parameters

Environmental Impact Category Weights

- No Weighting
- View Predefined Weights

BEES Stakeholder Panel

<table>
<thead>
<tr>
<th>Impact</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Warming</td>
<td>29</td>
</tr>
<tr>
<td>Acidification</td>
<td>3</td>
</tr>
<tr>
<td>Eutrophication</td>
<td>6</td>
</tr>
<tr>
<td>Fossil Fuel Depletion</td>
<td>10</td>
</tr>
<tr>
<td>Indoor Air Quality</td>
<td>3</td>
</tr>
<tr>
<td>Habitat Alteration</td>
<td>6</td>
</tr>
<tr>
<td>Water Intake</td>
<td>8</td>
</tr>
<tr>
<td>Criteria Air Pollutants</td>
<td>9</td>
</tr>
<tr>
<td>Smog</td>
<td>4</td>
</tr>
<tr>
<td>Ecotoxicity</td>
<td>7</td>
</tr>
<tr>
<td>Ozone Depletion</td>
<td>2</td>
</tr>
<tr>
<td>Human Health</td>
<td>13</td>
</tr>
<tr>
<td>Sum</td>
<td>100</td>
</tr>
</tbody>
</table>

Select No Weighting for environmental claims

Performance Weights
- Environmental Performance (%): 50
- Economic Performance (%): 50
- Discount Rate (%)(Excluding Inflation): 2.7

Building Element for Comparison

Major Group Element
- Building Maintenance

Group Element
- Cleaning Products

Individual Element
- Bath and Tile Cleaners

View Product List

Click the Next button to select product alternatives.
BEES Interface

The image shows a screen from the BEES Interface with options for environmental impact category weights. The interface allows users to view predefined weights, including:

- BEES Stakeholder Panel
- EPA Science Advisory Board-based Equal Weights
- User-Defined

The table below lists the impact categories and their corresponding weights:

<table>
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<th>Impact Category</th>
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<td>Global Warming</td>
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</tr>
<tr>
<td>Eutrophication</td>
<td>6</td>
</tr>
<tr>
<td>Fossil Fuel depletion</td>
<td>10</td>
</tr>
<tr>
<td>Indoor Air Quality</td>
<td>3</td>
</tr>
<tr>
<td>Habitat Alteration</td>
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<tr>
<td>Ozone Depletion</td>
<td>2</td>
</tr>
<tr>
<td>Human Health</td>
<td>13</td>
</tr>
<tr>
<td>Sum:</td>
<td>100</td>
</tr>
</tbody>
</table>

Select No Weighting for environmental claims.
Product List

- Substructure--Foundations--Slab on Grade
  - Generic 100% Portland Cement
  - Generic 15% Fly Ash Cement
  - Generic 20% Fly Ash Cement
  - Generic 20% Slag Cement
  - Generic 35% Slag Cement
  - Generic 50% Slag Cement
  - Generic 5% Limestone Cement
  - Generic 10% Limestone Cement
  - Generic 20% Limestone Cement
  - Lafarge Silica Fume Cement
  - Anonymous IP Cement Product
  - Lafarge NewCem Slag Cement (20%)
  - Lafarge NewCem Slag Cement (35%)
  - Lafarge NewCem Slag Cement (50%)
  - Generic 35% Fly Ash Cement
  - Lafarge Portland Type I Cement

- Substructure--Basement Construction--Basement Walls
  - Generic 100% Portland Cement
  - Generic 15% Fly Ash Cement
  - Generic 20% Fly Ash Cement
  - Generic 20% Slag Cement
  - Generic 35% Slag Cement
  - Generic 50% Slag Cement
  - Generic 5% Limestone Cement
  - Generic 10% Limestone Cement
  - Generic 20% Limestone Cement
  - Lafarge Silica Fume Cement
  - Anonymous IP Cement Product
  - Lafarge NewCem Slag Cement (20%)
  - Lafarge NewCem Slag Cement (35%)
  - Lafarge NewCem Slag Cement (50%)
  - Lafarge BlockSet
  - Lafarge Portland Type I Cement

- Shell--Superstructure--Beams
- Shell--Superstructure--Columns
- Shell--Superstructure--Roof Sheathing
BEES Product Selection

Select Product Alternatives

- Anonymous IP Cement Concrete Product
- Asphalt with GSB88 Seal-Bind Maintenance
- Generic 100% Portland Cement
- Generic 15% Fly Ash Cement
- Generic 20% Fly Ash Cement
- Generic Asphalt, Traditional Maintenance
- Lafarge Alpena Type I Cement

Update Product Details

View Product Data

Generic 100% Portland Cement
Transportation distance from manufacture to use: 200 miles
321 kilometers Update

Select Alternative
BEES Results

- Economic Results

![Economic Evaluation Diagram](image)
BEES Results

• Environmental Performance - Points
BEES Results

• Environmental Performance – LC Stage
BEES Results

- Environmental Flows – Global Warming
### BEES Results

- **Environmental Flows – Global Warming**

<table>
<thead>
<tr>
<th>Category</th>
<th>100% OPC</th>
<th>Asph/Trad</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Carbon Dioxide (CO2, biomass)</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>(a) Carbon Dioxide (CO2, fossil)</td>
<td>12300.0000</td>
<td>4100.0000</td>
</tr>
<tr>
<td>(a) Carbon Tetrachloride (CCl4)</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>(a) Carbon Tetrafluoride (CF4)</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>(a) CFC 12 (CCl2F2)</td>
<td>0.0014</td>
<td>0.0027</td>
</tr>
<tr>
<td>(a) Chloroform (CHCl3, HC-20)</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>(a) Halon 1301 (CF3Br)</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>(a) HCFC 22 (CHF2Cl)</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>(a) Methane (CH4)</td>
<td>299.0000</td>
<td>333.5000</td>
</tr>
<tr>
<td>(a) Methyl Bromide (CH3Br)</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>(a) Methyl Chloride (CH3Cl)</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>(a) Methylene Chloride (CH2Cl2,</td>
<td>0.0013</td>
<td>0.0009</td>
</tr>
<tr>
<td>(a) Nitrous Oxide (N2O)</td>
<td>19.1808</td>
<td>15.5400</td>
</tr>
<tr>
<td>(a) Trichloroethane (1,1,1-CH3C</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Sum</td>
<td>12618.1835</td>
<td>4449.0436</td>
</tr>
</tbody>
</table>
BEES Results

- Embodied Energy
Summary

• Life cycle assessment (LCA) is a useful tool for quantitative measurement of environmental, social, and economic impacts
• Significant work remains in the areas of valuation, application of LCA in decision-making, and understanding of complex system interactions
• LCA models can be integrated with other models to provide environmental information
CEE 226
LCA for Complex Systems
Autumn Quarter
Questions?

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