**Introduction to Life Cycle Analysis and Environmental Decision Making**

Ivan J. Baiges, PhD
Department of Engineering Sciences and Materials
University of Puerto Rico at Mayaguez

**Outline**
- Environmental Decision Making
- What is Life Cycle Analysis?
- Main Components
- Process Flow Diagrams
- Uses of LCA
- Examples of LCA
- Streamlining and Functional Units

**Environmental decision making and energy production**
- Which energy source is better and why?

**Examples of LCA**

**Environmental Disputes**
- Traditional Conflict - economic progress vs environmental protection

**Paper vs Plastic**

- Decision making requires that we have the complete information or at least a good set of data/information
- We need to make the comparison of different energy sources on the same basis
### Environmental Decision-Making Framework

#### Air Emissions

<table>
<thead>
<tr>
<th></th>
<th>Paper</th>
<th>Plastic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorine, kg</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>Sulfur dioxide, kg</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>Reduced sulfur, kg</td>
<td>1 to 2</td>
<td>0</td>
</tr>
<tr>
<td>Particulate, kg</td>
<td>2 to 3</td>
<td>0.3 to 0.5</td>
</tr>
<tr>
<td>UHC, kg</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Pentane, kg</td>
<td>0</td>
<td>35 to 50</td>
</tr>
<tr>
<td>Sulfur dioxide, kg</td>
<td>10</td>
<td>3 to 4</td>
</tr>
</tbody>
</table>

#### Recycle Potential

- Primary use: no (easy to reuse)
- Postconsumer coating makes hard resins easy

#### Ultimate Disposal

<table>
<thead>
<tr>
<th></th>
<th>Paper</th>
<th>Plastic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incineration, MJ / kg</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Landfill mass, kg / per ton</td>
<td>10.1 g</td>
<td>1.5 g</td>
</tr>
<tr>
<td>Biodegradable</td>
<td>yes</td>
<td>no</td>
</tr>
</tbody>
</table>

### Life Cycle Assessment

- “The evaluation of the relevant environmental, economic and technological implications of a product, process or system from **cradle to grave**”.
- **LCA Stages**
  - material extraction and processing
  - manufacturing
  - transportation and distribution
  - use
  - end of life management

### What is Life Cycle Analysis?

- **The Life Cycle Assessment** is an objective process to evaluate the environmental burdens associated with a product, process or activity by:
  - identifying energy, materials and benefits
  - assessing the impact of the energy and materials
  - evaluating and implementing improvement plans

**Society of Environmental Toxicology and Chemistry**

#### Product Life Cycle Stages

- Extraction
- Processing
- Manufacture
- Landfill
- Disposal
- Use

#### Paper vs Plastic – 1000 bags

- 140 pounds each
- 3.5 pounds per bag
**LCA Framework**

- Developed by the Society of Environmental Toxicology and Chemistry (SETAC) in 1990.
- Several workshops in the Netherlands and the United States gave birth to LCA as we know it today.
- Comprised three fundamental stages: inventory, impact and improvement.

**LCA: An Environmental Decision-Making Tool**

- Good environmental decision-making tool.
- Possesses two unique attributes:
  - Considers whole life-cycle of a product or service; avoids problem shifting.
  - Allocates all environmental burdens to the functional unit, making easier value/impact assessments.

**Why is LCA Important?**

- Allows to identify when a selection of one alternative over another or when the modifications made to any part of the system has the desired end result of reducing environmental impacts from all life-cycle stages.

**LCA Conceptual Model**

- Goals & Goals &
- Impact assessment
- Improvement assessment
- Inventory assessment

**What is Life Cycle Analysis?**

- Raw materials
- Energy
- Natural resources
- Processes of the System’s Life Cycle
- Waste and emissions
- By products
- BENEFITS

**Life Cycle Assessment methodology**

- Inventory
- Impact
- Environmental η
- Improvement
**Life Cycle Assessment**

- Raw Materials
- Energy
- Recycle/Waste Management
- Manufacturing
- Use/Reuse/Maintenance

**Goals and Scoping**

- We must ask ourselves why we want to conduct an Life Cycle Assessment:
  - Implement a new product or process
  - Compare existing product or process to possible competitors
  - Determine the environmental friendliness of a product
  - Determine where to spend money on Environmental Improvement

**LCA - Components**

- **LCA Inventory** - quantifying the energy and materials used, and wastes generated
- **LCA Impact** - assess the effects of the inventory.
- **LCA Improvement** - Systematic evaluation of the needs and opportunities to reduce of the environmental burden.

**Steps of a LCA**

- define scope
- Inventory Analysis
- Impact Analysis
- Implement
- Improvement Analysis
- environmental efficiency

**LCA Stages and Boundaries**

- Inputs:
  - Raw Materials Acquisition
  - Manufacturing
  - Use/Reuse/Maintenance
  - Waste Management
  - Natural Resources

- Outputs:
  - Crede
  - Waste
  - Emission
  - Coproducers
  - Benefits

- system boundaries
LCA Scoping
Example - Environmental Impact of using fossil fuels for energy production

LCA Process Flow Diagrams
✓ Process Flow Diagram - It indicates the processes and the hierarchy of the system to be evaluated by a LCA Study
✓ The flow diagram indicates the processes for which materials and energy will be evaluated

From materials to products

LCA Scoping, Flow Diagram
Raw Materials Extraction and Processing

LCA Scoping, Flow Diagram
Raw Materials Extraction and Processing – fossil fuels
LCA Scoping

Example - Environmental Impact of making coffee cups

Inputs
- Raw Materials Acquisition
- Manufacturing
- Use/Reuse/Maintenance
- Waste Management

Outputs
- Gravel
- Benefits

LCA Flow Diagrams

Manufacturing

Energy production with fossil fuels / biofuels

Energy production with solar radiation

Energy production with wind

LCA Flow Diagrams

Example – Environmental Impact of Operating a Car
LCA Flow Diagrams

Use / Reuse / Maintenance

Finished products → distribution → USE → maintenance → Distribution → Disposal

Inventory Assessment and Applications of LCA

Application of LCA Studies
- Identify major contributors to environmental impact
- Compare options based on environmental impact
- System Environmental Strategic Planning
- Evaluate resource effects of existing and new systems

Energy use in IC vehicle

- Standby
- Engine losses
- Drivetrain
- Braking
- Rolling friction
- Accessories
- Air drag
- Passenger

Examples of LCA Studies

Life Cycle Energy Requirements for a Polyester Blouse

82% production, 17% use, 1% disposal

Material Processing

Virgin materials → extraction → concentrated materials → Refining → refined materials

Physical, Chemical Preparation

Processed materials → separation & cleaning → segregated materials,

Collection → collected materials
The REAL environmental impact of driving

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>1950's Auto (kg)</th>
<th>1990's Auto (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastics</td>
<td>0</td>
<td>191</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0</td>
<td>68</td>
</tr>
<tr>
<td>Copper</td>
<td>26</td>
<td>22</td>
</tr>
<tr>
<td>Lead</td>
<td>23</td>
<td>15</td>
</tr>
<tr>
<td>Zinc</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td>Iron</td>
<td>220</td>
<td>267</td>
</tr>
<tr>
<td>Steels</td>
<td>1290</td>
<td>793</td>
</tr>
<tr>
<td>Glass</td>
<td>64</td>
<td>38</td>
</tr>
<tr>
<td>Rubber</td>
<td>85</td>
<td>61</td>
</tr>
<tr>
<td>Fluids</td>
<td>96</td>
<td>81</td>
</tr>
<tr>
<td>Other</td>
<td>83</td>
<td>38</td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td><strong>1901</strong></td>
<td><strong>1434</strong></td>
</tr>
</tbody>
</table>

Life Cycle Impact Assessment

**STEPS**
- **Categorization** - determine impact consequences
- **Characterization** - determine how the actions affect the categories
- **Valuation** - determine which impact are more relevant to society

Impact Assessment

**Stressors - Categories**

Stressors describe Impact Categories,
The main stressors are:
- Resource Consumption - How an action affects the supply of important resources
- Ecological Health - How an action affects the Ecosystem
- Human Health - How an action affects the wellbeing of human beings

Life Cycle Impact Assessment

**Inventory**
- batteries
- CO
- HC
- oil

**Impact**
- greenhouse effect
- ozone depletion
- smog
- Global warming
- Respiratory diseases

**Valuation**
- Loss of Biodiversity
Life Cycle Impact Assessment

Impact category

Characterization Method

Impact Descriptor

Valuation

LCA Improvement - Env. Responsibility Matrix

<table>
<thead>
<tr>
<th>Life Stage</th>
<th>Materials Choice</th>
<th>Energy Use</th>
<th>Solid Residues</th>
<th>Liquid Residues</th>
<th>Gaseous Residues</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource Extraction</td>
<td>1,1</td>
<td>1,2</td>
<td>1,3</td>
<td>1,4</td>
<td>1,5</td>
<td></td>
</tr>
<tr>
<td>Product Manufacture</td>
<td>2,1</td>
<td>2,2</td>
<td>2,3</td>
<td>2,4</td>
<td>2,5</td>
<td></td>
</tr>
<tr>
<td>Product Delivery</td>
<td>3,1</td>
<td>3,2</td>
<td>3,3</td>
<td>3,4</td>
<td>3,5</td>
<td></td>
</tr>
<tr>
<td>Product Use</td>
<td>4,1</td>
<td>4,2</td>
<td>4,3</td>
<td>4,4</td>
<td>4,5</td>
<td></td>
</tr>
<tr>
<td>Reuse, Recycle, Disposal</td>
<td>5,1</td>
<td>5,2</td>
<td>5,3</td>
<td>5,4</td>
<td>5,5</td>
<td></td>
</tr>
<tr>
<td>Totals</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>46%</td>
</tr>
</tbody>
</table>

Environmentally Responsible Product Matrix element 1, 1 resource extraction / materials choice

question

Are all materials the least toxic for the function?  
Yes =1, no = 0

Are all materials environmentally preferable for the function?  
Yes =1, no = 0

Is the product designed to minimize the use of nonrenewable materials?  
Yes =1, no = 0

Is the product designed to use renewable materials?  
Yes =1, no = 0

LCA Improvement - Env. Responsibility Matrix

<table>
<thead>
<tr>
<th>Life Stage</th>
<th>Materials Choice</th>
<th>Energy Use</th>
<th>Solid Residues</th>
<th>Liquid Residues</th>
<th>Gaseous Residues</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource Extraction</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>Product Manufacture</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Product Delivery</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>Product Use</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Reuse, Recycle, Disposal</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>Totals</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>46%</td>
</tr>
</tbody>
</table>
Benefit Assessment and Streamlining

LCA Benefits

Inputs
- Raw Materials
- Energy
- Natural Resources

Outputs
- Creata
- Raw Materials Acquisition
- Manufacturing
- Use/Reuse/Maintenance
- Waste Management
- Grease

system boundaries

LCA Functional Unit

- The Functional Unit is the basis used to establish the LCA Study.
- It is very important that FU be carefully selected, if not it can invalidate the LCA Study
- An inappropriate FU can be used to develop a misleading LCA Study

Selecting the FU

Soft Drink Containers on a 1000 gallon basis -

<table>
<thead>
<tr>
<th></th>
<th>PET 64 oz</th>
<th>Al 12 oz Can</th>
<th>Glass 16 oz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Tbtu</td>
<td>14.6</td>
<td>15.9</td>
<td>20.9</td>
</tr>
<tr>
<td>Emissions lb</td>
<td>44.8</td>
<td>48.3</td>
<td>73.5</td>
</tr>
<tr>
<td>Solid waste lb</td>
<td>189.5</td>
<td>198.3</td>
<td>762.5</td>
</tr>
</tbody>
</table>

Selecting the FU for Energy Production

- KW hr produced
- KW hr produced / $ spent
- KW hr produced / m² of used area
- KW hr produced / m³ of greenhouse gases
- KW hr produced / environmental impact
- KW hr produced / energy of infrastructure
Streamlining LCA
- LCA Studies can be time-consuming and costly.
- Streamlining is an approach for making LCA more accessible.
- The main limitation on Full Scale LCA is the amount of data required.

Streamlining LCA Approaches
- Limit or eliminate LCA Stages
- Focus on specific environmental impacts or issues
- Eliminate specific inventory parameters
- Limiting impact assessment
- Use qualitative and quantitative data

Streamlining LCA Approaches
- Use surrogate data
- Establish criteria to be used as “showstoppers”
- Limit constituents studied to those meeting a threshold quantity
- Combine streamlining approaches

Streamlining LCA Approaches
- Focus on the raw material and “energy manufacturing” stages
- Evaluate the equipment manufacturing impact
- Use EPA and DOT Data
- Use qualitative scales for comparing energy alternatives

Streamlining LCA Energy Production
- Energy Production

Application of LCA Studies
- Training of environmental professionals
- Develop Environmental Policy
- Determine Resource Allocation
- Develop Eco-Labeling Programs
- Develop Environmental Standards
Car Emissions - A Problem

- In numerous cities across the country, the personal automobile is the single greatest polluter
- Many countries have established vehicle emissions programs in an effort to attack this problem.

Think.....

- Do we need to control emissions?
- Are emissions the main problem with cars?
- How do we do it?
- Do we have to own cars?

Automobile Usage

The Car as Symbol - “I’m too Sexy for my car”

- I have a car because:
  - How it looks
  - To get a girlfriend
  - To show off my wealth
  - I am too cool to walk
  - Everybody has one
  - I need it
  - To show my independence
The “Benefits” of having a Car

- Mobility
- Accessibility
- Independence
- Commute
- Transportation
- “Investment”

The Present “Needs”

- Motor 8.6L
- Weight - 6,400 lbs.
- Gas mileage – 15/10 mpg
- 32 gallons/tank
- $80 to $90 tank
- Price $80,000 +

The REAL environmental impact of driving

<table>
<thead>
<tr>
<th>Materials</th>
<th>Vehicle manufacture, use, infrastructure, consumables and disposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>Vehicle use, infrastructure development, material disposal</td>
</tr>
<tr>
<td>Ecological</td>
<td>Air Quality, Water Quality, Habitat Destruction, Noise</td>
</tr>
<tr>
<td>Social</td>
<td>Urban burden, health degradation</td>
</tr>
</tbody>
</table>

The REAL environmental issue

The automobile and Society

- Social Structure
  - Infrastructure
  - The Automobile
    - mfg - use - dispose
    - Automobile Components

The REAL environmental impact of driving - oil use %

- Engine
  - Standby 17.2 (3.6)
  - Engine losses 62.4 (9.2)
- Accessories 2.2 (1.5)
- Air drag 2.6 (0.8)
- Rolling 4.2 (1.1)
- Braking 5.6 (2.3)

The REAL environmental impact of driving

- Energy

The Present “Needs”

- Motor 8.6L
- Weight - 6,400 lbs.
- Gas mileage – 15/10 mpg
- 32 gallons/tank
- $80 to $90 tank
- Price $80,000 +

The REAL environmental impact of driving - oil use %

- Engine
  - Standby 17.2 (3.6)
  - Engine losses 62.4 (9.2)
- Accessories 2.2 (1.5)
- Air drag 2.6 (0.8)
- Rolling 4.2 (1.1)
- Braking 5.6 (2.3)
**The REAL environmental impact of driving**

<table>
<thead>
<tr>
<th>Category</th>
<th>Embedded Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural Highways</td>
<td></td>
</tr>
<tr>
<td>Energy per lane</td>
<td>8.4 TJ / km</td>
</tr>
<tr>
<td>Energy per 12 m bridge</td>
<td>1.6 TJ</td>
</tr>
<tr>
<td>World road distance</td>
<td>9.5 x million kms</td>
</tr>
<tr>
<td>Embedded roadway energy</td>
<td>170 EJ</td>
</tr>
<tr>
<td>Embedded bridge energy</td>
<td>0.73 EJ</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>191.5 EJ</strong></td>
</tr>
</tbody>
</table>

**Evaluating the Ecoefficiency Matrix**

<table>
<thead>
<tr>
<th>Life Stage</th>
<th>Materials Choice</th>
<th>Energy Use</th>
<th>Solid Residue</th>
<th>Liquid Residue</th>
<th>Gasous Residue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource Extraction</td>
<td>1.1</td>
<td>1.2</td>
<td>1.3</td>
<td>1.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Product Manufacture</td>
<td>2.1</td>
<td>2.2</td>
<td>2.3</td>
<td>2.4</td>
<td>2.5</td>
</tr>
<tr>
<td>Product Delivery</td>
<td>3.1</td>
<td>3.2</td>
<td>3.3</td>
<td>3.4</td>
<td>3.5</td>
</tr>
<tr>
<td>Product Use</td>
<td>4.1</td>
<td>4.2</td>
<td>4.3</td>
<td>4.4</td>
<td>4.5</td>
</tr>
<tr>
<td>Waste, Recycle, Dispose</td>
<td>5.1</td>
<td>5.2</td>
<td>5.3</td>
<td>5.4</td>
<td>5.5</td>
</tr>
</tbody>
</table>

**Could we substitute the Car Emissions Program with a program that**

1. Consider the real impacts of a vehicle
2. Would assess part of the costs of these impacts to the owners
3. The greener vehicle, the lower these imposed costs to the owners
4. We would develop a vehicle green index or environmental score

**Evaluating the Matrix element 2.1 manufacturing / materials choice**

<table>
<thead>
<tr>
<th>question</th>
<th>Yes = 1</th>
<th>No = 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Are materials used generate the less amount of toxic in manufacturing?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Has the product been designed to minimize materials restricted supply?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Has the use of radioactive materials been reduced?</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Evaluating the Matrix element 4.1 product use / material choice**

<table>
<thead>
<tr>
<th>question</th>
<th>Yes = 1</th>
<th>No = 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>If the product is disposable, have other options been developed with the same performance?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Are the consumables in restricted supply?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Do the consumables contain toxic materials?</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Evaluating the Matrix element 4.2 product use / energy use**

<table>
<thead>
<tr>
<th>question</th>
<th>Yes = 1</th>
<th>No = 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Has the product been designed to reduce energy consumption during use?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Have energy saving measure been incorporated in the design?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Can the product monitor and display energy use?</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Does the product require the periodical disposal of solid materials?

Have alternatives to solid consumables been developed?

Do intentional emissions of the product enter the land?

TOTAL

<table>
<thead>
<tr>
<th>Life Stage</th>
<th>Material Choice</th>
<th>Energy Use</th>
<th>Solid Residue</th>
<th>Liquid Residue</th>
<th>Biogenic Residue</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource Extraction</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.675</td>
</tr>
<tr>
<td>Product Manufacture</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.40</td>
</tr>
<tr>
<td>Product Delivery</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.70</td>
</tr>
<tr>
<td>Product Use</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
<td>0.90</td>
</tr>
<tr>
<td>Borne, Reuse, Disposal</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.80</td>
</tr>
</tbody>
</table>

Evaluating the Matrix

Evaluating the Matrix weighting life cycle stages

<table>
<thead>
<tr>
<th>Life Stage</th>
<th>Materials Choice</th>
<th>Energy Use</th>
<th>Solid Residue</th>
<th>Liquid Residue</th>
<th>Biogenic Residue</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource Extraction</td>
<td>0.125</td>
<td>0.125</td>
<td>0.112</td>
<td>0.097</td>
<td>0.045</td>
<td>0.45</td>
</tr>
<tr>
<td>Product Manufacture</td>
<td>0.105</td>
<td>0.09</td>
<td>0.079</td>
<td>0.065</td>
<td>0.035</td>
<td>0.40</td>
</tr>
<tr>
<td>Product Delivery</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.187</td>
<td>0.90</td>
</tr>
<tr>
<td>Product Use</td>
<td>0.89</td>
<td>0.89</td>
<td>0.89</td>
<td>0.89</td>
<td>0.89</td>
<td>3.56</td>
</tr>
<tr>
<td>Borne, Reuse, Disposal</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.60</td>
</tr>
<tr>
<td>Totals</td>
<td>1.87</td>
<td>1.87</td>
<td>1.87</td>
<td>1.87</td>
<td>1.87</td>
<td>7.70</td>
</tr>
</tbody>
</table>

Environmental Efficiency

Life Cycle Assessment

- Allows to evaluate the complete environmental impact of a product, process or system during its complete life cycle.
- The LCA is still an evolving, unfinished methodology.

Questions ???