Life-Cycle Assessment (LCA)

What it is
How to perform one

Primary goal:
SUSTAINABILITY
(responsibility toward future generations)

Basic approach:
INDUSTRIAL ECOLOGY
(imitation of nature)

Imitation of ecosystem:
ECO-INDUSTRIAL PARKS
(closing material loops, energy efficiency)

GREEN TECHNOLOGIES
(pollution avoidance rather than pollution treatment)

LIFE-CYCLE ASSESSMENT
(considering all steps, from manufacture, use and end of life)

DESIGN FOR ENVIRONMENT
(green design)

DESIGN FOR RECYCLING
Life-Cycle Assessment (LCA) – also called Life-Cycle Analysis – is a tool for examining the total environmental impact of a product through every step of its life – from obtaining raw materials all the way through making it in a factory, selling it in a store, using it in the workplace or at home, and disposing of it. (Bishop, 2000, p. 252)

![Life-Cycle Assessment Diagram](http://www.environment.gov.au)

Life-Cycle Assessment is an *objective procedure* used to evaluate the environmental impacts associated with a product’s entire life cycle, through the *quantitative determination of all exchange flows* between the product-system and the ecosphere in all the transformation processes involved, from the extraction of raw materials to their return into the ecosphere in the form of waste. (Giudice et al., 2006, page 83 – emphasis added)

from the procurement of materials (these may be recycled instead of new) to their end for this product (*i.e.* disposal or recycling into a new product).
Historical perspective

1960s:
Coca-Cola explores alternative containers besides the glass bottle. Life-cycle analysis is performed for them by the Midwest Research Institute (MRI).

1970s:
Oil embargos in the United States create concerns about energy supplies. The US Department of Energy commissions studies on "net energy analysis". They call their method "Resources & Environmental Profile Analysis" (REPA).


1980s:
"Green Movement" in Europe brings focus back on emissions and need to recycle. European industries study their pollution releases and begin comparing alternatives.

In 1988, Procter & Gamble has Franklin Assoc. compare laundry detergent packaging. In 1989, Procter & Gamble has Franklin Assoc. compare surfactants.

Notorious battle between cloth and disposable diapers:

1990 – The American Paper Institute finds disposable diapers to be preferable. (study by Franklin Associates)

1991 – The National Association of Diaper Services concludes the opposite. (study by Lehrberger & Jones)

1992 – Procter & Gamble reverses the conclusion once more. (study by A. D. Little)

Each time, additional considerations were brought in:
- indirect of paper production (increasing impacts of disposables)
- production of detergents (increasing impacts of washing cloth)

1992 – New study by Franklin Associates, concluding that the answer depends on whether one looks at energy or water or solid waste.
The diaper LCA study by Franklin Associates, Ltd., 1992

Figure 1 - Total energy used by each diaper type in one year. Feedstock and process energy includes energy used through cotton growing, material processing and diaper manufacture. It also includes energy used and embodied in bleach and detergent.

Figure 2 - Volume of solid waste per year. Industrial Waste includes waste used to produce the diaper such as raw material production and process, manufacture trimmings, and ash from electricity generation. Post consumer waste refers to substances thrown out: the diaper itself, child waste, and packaging.


The diaper controversy illustrates the importance of

- What impact is being considered: Energy? Water? Solid waste?
- Where are the boundaries of the study placed?

Also, when conclusions of an LCA study are easily reversed, it is a close call, and we may consider the alternatives as about equally impacting the environment.

Most LCAs, however, do lead to definite conclusions.
Various forms of LCAs have been proposed over recent years. The method is showing signs of maturation.

**FIGURE 4.1** Evolution of LCA. (Giudice et al., 2006, page 87)

**UNEP** = United Nations Environmental Programme  
**REPA** = Resources & Environmental Profile Analysis  
**SETAC** = Society for Environmental Toxicology & Chemistry  
**ISO** = International Standards Organization

Reasons cited why companies perform LCAs, some but not all have an environmental character

**FIGURE 6.2** Motivations for implementing LCA. (Adapted from Foust and Gish, 1996)  
(Bishop, 2000, page 253)
STEPS in an LCA:

1. **Goal and Scope**: Select product or activity
   Define purpose of study (comparison? improvement?)
   Fix boundaries accordingly

2. **Inventory Analysis**: Identify all relevant inputs and outputs
   Quantify and add
   (At this stage, data are in terms of energy consumed, solid waste produced,
   amounts emitted, etc.)

3. **Impact Analysis**: Determine the resulting environmental impacts
   (At this next stage, the previous data are translated in additional cancer rates,
   fish kill, habitat depletion, etc.)

4. **Interpretation**: Use value judgment to assess or decide
   in relation to the objectives of the study.

   Most often, an iteration occurs: Following the first interpretation, the product may
   be revised or the boundaries modified.

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**FIGURE 2.4** The elements of a life cycle inventory analysis. (Adapted from
Society of Environmental Toxicology and Chemistry (SETAC). A Technical
(Graedel, 1998, page 23)
Parallel between LCA and DfE

Both LCA and DfE consider all steps of the product, from beginning to end. The difference is that LCA is about \textit{knowing} what the impacts are, while DfE is about \textit{acting} so that impacts are reduced.

\textbf{Product Design}
- Component selection (toxicity, renewable resources, recycled materials, water)
- Packaging (minimization, renewable or recycled, reusable or recyclable, disposal)
- Product Risk Assessment (toxicity, possible accidents)

\textbf{Process}
- Safety, health & Environment
- Waste and emission reduction
- Efficient energy use

\textbf{Distribution & Use}
- Safe transportation & handling
- Safety
- Identification and prevention of misuse
- Waste and emission reduction
- Energy use

\textbf{Disposal}
- Reusability, recyclability
- Incinerability, degradability
- Safe disposal

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\textbf{Figure 15.4}

Electric power generation by wood burning. The boundary for the LCA might be chosen to include the shaded areas or to exclude them. The implications of this choice are discussed in the text. (Adapted from L.-G. Lindfors, et al., \textit{Technical Report No. 4}, Tema Nord 1995.)
Where boundaries may be placed in an LCA study of paper
LCA of the automobile

![Life Cycle Assessment Diagram]

Figure 5-1. The life cycle of the automobile and the processes that occur during that cycle. The processes listed at the bottom of the chart are treated by nation in the life cycle steps shown in the flow diagram above. (Adapted from a diagram devised by G. Kolbauer, Univ. of Maryland.)


LCA of women's polyester blouses

![Energy Requirements Diagram]

FIGURE 5.4 Data from an inventory assessment analysis of women's polyester blouses. (a) Allocation of total energy requirements per million launderings. (b) Allocation of manufacturing energy requirements. (c) Allocation of consumer use energy requirements. (d) Allocation of total solid residues per million launderings. (Reproduced with permission from American Fiber Manufacturers Association, Resource and Environmental Profile Analysis of a Manufactured Apparel Product: Women's Knit Polyest...
Ways to reduce impact of laundering:

- Design fabric that needs no laundering (silver nanoparticles?)
- Front loading wash machine (using less water and therefore less hot water)
- Cold wash, air dry

A solution to fiber procurement

Bamboo Clothing

http://eartheasy.com/wear_bamboo_clothing.htm

Bamboo is one of the world’s most sustainable resources.

Environmental benefits of bamboo:

- Renewable: bamboo grows three to six times faster than trees, enabling the resource to replenish itself.
- Requires less energy, water and gas: bamboo does not require pesticides, fertilizers, or herbicides (as do cotton, wool, or silk).
- Reduces land use and soil erosion: bamboo is a fast-growing, non-invasive plant that can thrive in areas where other crops fail.
- Can be grown without fertilizers or pesticides: bamboo does not require the use of chemicals, making it a sustainable alternative.
- Carbon sequestration: bamboo absorbs carbon dioxide from the atmosphere and stores it in its biomass, making it a valuable carbon sink.

Bamboo is a versatile material that can be used in clothing, furniture, and household products. It is a renewable resource that can help reduce the impact of laundering and improve sustainability.
Are natural fiber composites environmentally superior to glass fiber reinforced composites?

S.V. Joshi, L.T. Dzidz, A.K. Mohanty, S. Arora

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Fig. 1: Life cycle of a glass fiber reinforced composite component.

Fig. 2: Life cycle of a natural fiber reinforced composite component.
Table 2
Comparative life cycle environmental performance of China need reinforced, and glass fiber reinforced transport pallets

<table>
<thead>
<tr>
<th>Environmental indicator</th>
<th>Glass fiber pallet</th>
<th>China need pallet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulative non-renewable energy use (MWh)</td>
<td>1400</td>
<td>717</td>
</tr>
<tr>
<td>Carbon dioxide emissions (kg)</td>
<td>75.1</td>
<td>45</td>
</tr>
<tr>
<td>Carbon monoxide (g)</td>
<td>54.3</td>
<td>54.6</td>
</tr>
<tr>
<td>NOx, SOx emissions (g)</td>
<td>313</td>
<td>349</td>
</tr>
<tr>
<td>Sulphur oxides (SOx) in emissions (g)</td>
<td>280</td>
<td>185</td>
</tr>
<tr>
<td>Water consumption (m3)</td>
<td>414</td>
<td>366</td>
</tr>
<tr>
<td>Waste generation (kg)</td>
<td>172</td>
<td>123</td>
</tr>
<tr>
<td>Waste generation — phosphates (g)</td>
<td>0.58</td>
<td>1.07</td>
</tr>
<tr>
<td>CML — human toxicity (kg 1,4-dioxane)</td>
<td>312.5</td>
<td>90.01</td>
</tr>
<tr>
<td>CML — terrestrial toxicity (kg 1,4-dioxane)</td>
<td>5750</td>
<td>4808</td>
</tr>
<tr>
<td>CML — ozone depletion (kg CO2 eq)</td>
<td>75.3</td>
<td>48.4</td>
</tr>
<tr>
<td>Eco-indicator 99 — carcinogenicity</td>
<td>7.11</td>
<td>4.48</td>
</tr>
<tr>
<td>Eco-indicator 99 — acidification (kg SO2 eq)</td>
<td>0.68</td>
<td>0.41</td>
</tr>
</tbody>
</table>

Table 3
Non-renewable energy requirements for production of different fibers (MWh)

<table>
<thead>
<tr>
<th>Fiber type</th>
<th>Glass fiber</th>
<th>Flax fiber</th>
<th>China need fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw materials</td>
<td>1.7</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Transport</td>
<td>1.6</td>
<td>Transport cost</td>
<td>0.5</td>
</tr>
<tr>
<td>Transport</td>
<td>25.5</td>
<td>Cultivation</td>
<td>0.4</td>
</tr>
<tr>
<td>Spinning</td>
<td>0.9</td>
<td>Fiber spining</td>
<td>0.4</td>
</tr>
<tr>
<td>Total production</td>
<td>25.0</td>
<td>Total production</td>
<td>0.9</td>
</tr>
<tr>
<td>Total</td>
<td>54.7</td>
<td>Total</td>
<td>9.35</td>
</tr>
<tr>
<td>Total energy</td>
<td>36.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4
Life cycle environmental impacts from production of glass fiber, china need fiber, Epoxy resin, ABS and polypropylene

<table>
<thead>
<tr>
<th>Environmental impact</th>
<th>Glass fiber</th>
<th>China need fiber</th>
<th>Epoxy resin</th>
<th>ABS</th>
<th>Polypropylene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy use (MWh)</td>
<td>48.33</td>
<td>3.64</td>
<td>10.71</td>
<td>93.62</td>
<td>75.10</td>
</tr>
<tr>
<td>Carbon dioxide emissions (kg)</td>
<td>209</td>
<td>0.66</td>
<td>5.99</td>
<td>3.09</td>
<td>1.85</td>
</tr>
<tr>
<td>CO emissions (g)</td>
<td>0.88</td>
<td>0.44</td>
<td>2.20</td>
<td>3.00</td>
<td>0.72</td>
</tr>
<tr>
<td>S02 emissions (g)</td>
<td>8.79</td>
<td>1.33</td>
<td>10.00</td>
<td>10.00</td>
<td>12.64</td>
</tr>
<tr>
<td>NOx emissions (g)</td>
<td>2.97</td>
<td>4.07</td>
<td>35.00</td>
<td>11.00</td>
<td>9.57</td>
</tr>
<tr>
<td>Particulate matter (g)</td>
<td>1.06</td>
<td>6.74</td>
<td>15.00</td>
<td>7.50</td>
<td>1.48</td>
</tr>
<tr>
<td>BOD to water (mg/l)</td>
<td>1.75</td>
<td>0.26</td>
<td>3200</td>
<td>33</td>
<td>33.04</td>
</tr>
<tr>
<td>COD to water (mg/l)</td>
<td>18.3</td>
<td>7.27</td>
<td>31,000</td>
<td>2200</td>
<td>178.52</td>
</tr>
<tr>
<td>Metals to water (mg/l)</td>
<td>16.66</td>
<td>24461</td>
<td>220</td>
<td>320</td>
<td>3.39</td>
</tr>
</tbody>
</table>

Figure 1.62
A life cycle process diagram for women's footwear. (Reproduced with permission from BLH, et al, 1999—see Better Footwear).
Contributions of different life-cycle stages in women's footwear to major environmental concerns.
(Reproduced from MBå, et al., 1998)

Paper or Plastic?

Life cycle of paper grocery sack

Life cycle of polyethylene grocery sack
Profile of air emissions, in lbs per 1000 sacks (Franklin Associates, Ltd., 1990)

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Plastic sacks</th>
<th>Paper sacks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0% recycling</td>
<td>100% recycling</td>
</tr>
<tr>
<td>Particulates</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Nitrogen oxides</td>
<td>2.1</td>
<td>1.7</td>
</tr>
<tr>
<td>Hydrocarbons</td>
<td>5.8</td>
<td>3.2</td>
</tr>
<tr>
<td>Sulfur dioxides</td>
<td>2.6</td>
<td>2.7</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>Aldehydes</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Other organics</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Odorous sulfur</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Comparison of air emissions and energy consumption in the production of paper and polyethylene ("plastic") grocery sacks (Franklin Associates, Ltd., 1990)

<table>
<thead>
<tr>
<th>Life cycle stages</th>
<th>Air emissions (oz/sack)</th>
<th>Energy consumption (Btu/sack)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Paper</td>
<td>Plastic</td>
</tr>
<tr>
<td>Materials processing + product manufacture</td>
<td>0.0516</td>
<td>0.0146</td>
</tr>
<tr>
<td>+ product use</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raw materials acquisition + product disposal</td>
<td>0.0510</td>
<td>0.0045</td>
</tr>
</tbody>
</table>

So, which one is better?

It is a “no-brainer”!

Not everybody agrees. Here the conclusion is reached that paper becomes preferable to plastic at high recycling rates.

Grams of atmospheric and waterborne waste at current recycling rates. Atmospheric waste contributes to smog and acid rain. Waterborne waste disrupts associated ecosystems.

Choice table. Determines bag preference at varying recycling rates. Either was used when the difference between energy efficiencies are inconsequential.

Source: web.mit.edu/course/3/3.a30/www/refs/Institute for Lifecycle Environmental Assessment.pdf
Beverage cup: Waxed paper or styrofoam?

<table>
<thead>
<tr>
<th>Material</th>
<th>Paper cup</th>
<th>Polyfoam cup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood and bark</td>
<td>5.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>PET</td>
<td>1.3%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Other charbons</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Finished weight</td>
<td>1.5 g</td>
<td>1.5 g</td>
</tr>
</tbody>
</table>

- **Per unit:**
  - Wood and bark: 2.5 to 27 g
  - PET: 1.5 to 2 g
  - Other charbons: 1.3 to 5.7 g
  - Finished weight: 10.1 g

- **Per metric ton of material:**
  - Wood: 9900 to 12,000 kg
  - PET: 9.2 kg
  - Other charbons: 0.0 kg

- **Recycle potential:**
  - Paper: 100% (easy, negligible water uptake)
  - Polyfoam: 0% (requires recovery of adhesive or foaming agents)

- **Ultimate disposal:**
  - Paper: Incineration, heat recovery, mass to energy, biodegradable
  - Polyfoam: Incineration, heat recovery, mass to energy, biodegradable

**Table:** Flow material, utility, and environmental summary for hot drink containers.

1. Decoated fully Marwood Kraft paper cup.
2. Molded polypropylene foam board (foamex) cup.
3. Many producers of foamable foams have entered CFCs.

**WHICH CUP SCORES BEST WITH OUR ENVIRONMENT?**

<table>
<thead>
<tr>
<th>Environmental Impact</th>
<th>Foam Plastic</th>
<th>China/Glass</th>
<th>Paper</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy Conservation</strong></td>
<td>✔ Needs relatively little energy to make</td>
<td>POOR: Needs high energy to run kiln and wash for reuse</td>
<td>POOR: Requires high energy to run mills</td>
</tr>
<tr>
<td><strong>Water Conservation</strong></td>
<td>✔ EXCELLENT: Little required</td>
<td>POOR: Needs large quantities to make and wash</td>
<td>POOR: Requires large quantities to make</td>
</tr>
<tr>
<td><strong>Waste-to-Energy Conversion</strong></td>
<td>✔ EXCELLENT:</td>
<td>NONE:</td>
<td>POOR:</td>
</tr>
<tr>
<td><strong>Recyclability</strong></td>
<td>✔ TOTAL:</td>
<td>PARTIAL:</td>
<td>PARTIAL:</td>
</tr>
<tr>
<td><strong>Landfill Contamination</strong></td>
<td>✔ NONE:</td>
<td>NONE:</td>
<td>NONE:</td>
</tr>
<tr>
<td><strong>Air Pollutants When Properly Incinerated</strong></td>
<td>✔ NONE:</td>
<td>NONE:</td>
<td>VIRTUALLY NONE</td>
</tr>
<tr>
<td><strong>Impact on Ozone Layer</strong></td>
<td>✔ POSITIVE: Contains no CFCs</td>
<td>✔ POSITIVE: Contains no CFCs</td>
<td>✔ POSITIVE: Contains no CFCs</td>
</tr>
<tr>
<td><strong>Relative Pocketbook Impact (price)</strong></td>
<td>✔ LOW</td>
<td>HIGH</td>
<td>HIGH</td>
</tr>
</tbody>
</table>
Petroleum-based OR Biomass-derived plastics?

LCA RESULTS

Per kg of material, either conventional polystyrene or biomass-derived PHA

<table>
<thead>
<tr>
<th></th>
<th>Polystyrene</th>
<th>PHA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw materials</td>
<td>1.78 kg petroleum</td>
<td>31.218 kJ</td>
</tr>
<tr>
<td>Steam</td>
<td>7.0 kg</td>
<td>2.78 kg</td>
</tr>
<tr>
<td>Electricity</td>
<td>0.30 kWh</td>
<td>5.32 kWh</td>
</tr>
</tbody>
</table>

Converted into fossil-fuel equivalent (FFE):

<table>
<thead>
<tr>
<th></th>
<th>Polystyrene</th>
<th>PHA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Materials</td>
<td>1.78 kg</td>
<td>0.80 kg</td>
</tr>
<tr>
<td>Steam</td>
<td>0.4 kg</td>
<td>0.14 kg</td>
</tr>
<tr>
<td>Electricity</td>
<td>0.08 kg</td>
<td>1.45 kg</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>2.26 kg</strong></td>
<td><strong>2.39 kg</strong></td>
</tr>
</tbody>
</table>
Streamlining an LCA

- Limit or eliminate life-cycle stages
- Focus on specific environmental impacts or issues
- Eliminate specific inventory parameters
- Do not include small parts (use a mass minimum threshold)
- Limit or eliminate impact assessment
- Use qualitative data instead of hard numbers
- Use surrogate data
- Establish shop-stopper criteria