LCA - Life Cycle Assessment
Life Cycle Assessment


Decision support tool, generally for a single product, but can be applied to a system, process or management infrastructure (e.g. landfill).
Life Cycle Assessment

“Life Cycle Assessment is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing, extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal

(SETAC - Society of Environmental Toxicology and Chemistry)

• “From the cradle to the grave”: sustainability
• “From the cradle to the (factory) gate”
• Which emissions? In which quantity?
• Which are the environmental impacts? What is their level? (assessment)
• Which environmental aspects of the system are critical (and can be improved)?
• Which process is the most impacting?
The product system

MASS / ENERGY BALANCE

Raw materials and energy
Production
Distribution
Reuse
Recycling
Waste
Incineration, landfilling
Use

Resource
Emissions

Resource
Emissions

Resource
Emissions
The product system
Role of LCA

- LCA deals with “products” in a broad sense, including physical goods as well as services

- Ex. Physical goods:
  - Analysing the origins of problems in a product
  - Comparing improvement variants in a product
  - Designing new products
  - Choosing between comparable products

- Ex. Services:
  - Waste management
  - Transport
  - Energy production (biofuel)
  - Greening of the building industry
  - Agricultural products
Scope for product and for waste management system

- Raw material extraction
- Manufacturing
- Distribution
- Use
- Waste management

"From cradle to grave"

"From garbage can to grave"
## Role of LCA

<table>
<thead>
<tr>
<th>Active party</th>
<th>Application</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Authorities</td>
<td>Community action plans</td>
<td>▪ Incineration vs. recycling of paper</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ Recyclable glass bottles vs. other beverage containers</td>
</tr>
<tr>
<td></td>
<td>Environmentally conscious public purchase</td>
<td>▪ Cars, work clothes, canteen service, office furniture</td>
</tr>
<tr>
<td></td>
<td>Consumer information</td>
<td>▪ Ecolabels</td>
</tr>
<tr>
<td>Company</td>
<td>Establish environmental focus</td>
<td>▪ Identification of areas of improvement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ Product-oriented environmental policy</td>
</tr>
<tr>
<td></td>
<td>Design choices</td>
<td>▪ Choice of concept, component, material, or process</td>
</tr>
<tr>
<td></td>
<td>Environmental documentation</td>
<td>▪ Environmental information to consumers</td>
</tr>
<tr>
<td>Associations of interested</td>
<td>Guidance to environmentally conscious consumption</td>
<td>▪ Ecolabel</td>
</tr>
<tr>
<td>parties</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LCA of community actions</td>
<td>▪ Ecological or conventional farming</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ Transport systems</td>
</tr>
</tbody>
</table>
Limitations of LCA

The holistic approach of LCA is its main strength, but also its limitation:

- LCA cannot address local impacts
- The same applies for time aspects
- Involves technical assumptions and value choices
- Says nothing on economic or social aspects
- Availability and quality of data

In LCA we deal with “potential impacts”

LCA does not replace the decision making process itself... Decision making has to be multicriteria (Risk Assessment, Environmental Impact assessment, ..)
Some history…

60’s: energy balances (oil depletion)

Midwest Research Institute (1974):
Comparative study concerning 9 different beverage containers.

For the first time **products were studied**, not single industrial processes

80’s: problema MSW (Municipal Solid Waste)

90’s: evolution – more than a simple balance, analysis of potential impacts
Main guidelines in Europe and many other countries: **ISO 14040 1997.**

Following (1404x):


... possibility of a certification by a recognized body, reproducibility, completeness (vs. objectivity).
4 main steps

Goal and scope definition
- geographical, temporal and technological boundaries of the system
- definition of a functional unit
- data are identified

Inventory analysis
- of resources
- of impacts
- of consumptions
- etc.

Impact assessment
- Classification
- Characterisation (equivalency factor)
- Normalization
- Weight assignment

Interpretation
Goal and scope definition (step 1)

- goal of the study (object, people to which the study is addressed, how results will be used),

- definition of the “system”, i.e. the set of different, inter-connected processes or subsystems that make a specific function in the life cycle of a product or process; with physical boundaries and exchanges with the external environment (in & out):
  - Temporal boundaries (long- vs short-term)
  - Geographical context (e.g. energy production)
  - Technological context
Goal and scope definition

- Functional unit (the “currency”),
  - allow the comparison of different systems performing the **same function** (es. P removal by precipitation or biological treatment); depends on the aim of the analysis
  - Examples: comparison of wastewater treatment methods – treatment of $X \text{ m}^3$ of wastewater in one year, including disposal/treatment of sludge; comparison of the env. impact of glass and plastic bottles – distribution of $10^6$ liters of water in bottles
  - Non-trivial choice - example
    - comparing paints with different qualities: 1 l of paint vs paint covering 1 m$^2$ of wall for 5 years)
    - composting
In LCA the focal point is not the product, but the service or function provided by the product. Two different products cannot be compared directly, it is the service provided by them which is compared.

"1 million bottles for distributing water"

"Distributing 1 million litres of bottled water"
Function and functional unit

Goal and scope definition
Inventory analysis
Impact assessment
Interpretation

Maintain tidy haircut for one year
- Plastic comb 1 unit per year + haircut
- Wooden comb 1 unit per year + haircut
- Steel comb 1/2 unit per year + haircut
- Razors 4 units per year

Mowing 100 m² lawn for one year
- Goat 1/5 unit per year
- Manual lawn mower 1/7 unit per year
- Motorized lawn mower 1/5 unit per year + petrol and oil
Goal and scope definition

- Definition of the boundaries of the system: what’s impact and what’s process (e.g. landfill)? How can the analysis be done?
  - Disaggregation into basic processes
  - Cut off rules
Boundaries of a LCA Landfill

- Transport
- Landfill
- Biogas treatment
- Leachate treatment

Energy
Waste
Raw materials (Clay, sand, etc.)

Energy
Emissions to air
Emissions to water
Emissions to land
Cut-off rules

- We can put thresholds to the inflows and outflows
- Criteria for inclusion of inputs and outputs
  - Mass of the inflow
  - Economic value of the inflow
  - Contribution to the environmental impact

Flows with a low value or mass could have significant environmental impact.

This can not be known before the flow is investigated...
Goal and scope definition

• [ ... ]

• Type of data:
  ▪ *environmental impacts*
  ▪ *usage of resources;*
  ▪ *working conditions.*

• Analysis rule:
  ▪ *global life cycle,*
  ▪ *some subsets*

Spatial and temporal disaggregation
Inventory (step 2)

Input and output data are organised as:

- *usage of raw materials*;
- *water usage*;
- *energy consumption*;
- *emissions into water*;
- *emissions into air*;
- *emissions into soil*
- *wastes*

Inputs and outputs are quantified
Inventory

Indicate:

• *data source*;
• *reference process*;
• *reference technology*;
• *geographical area*;
• *monitoring details*;
• *measurement method*;
• *specific unit of measurement*;
• *method for calculating average values*;
• *variance and irregularities in the measurements*
Multifunctionality and allocation

- Most industrial processes are multifunctional
- Their output can be more than one product, intermediates, discarded products
- Product systems then provide more functions than the one included in our functional unit

**ALLOCATION:**

Which flows and environmental interventions must be allocated to our functional unit, and which should be allocated to other product systems?
Multifunctionality and allocation

ISO 14.041 provides the following guidelines on allocation:

- **Step 1**
  Avoid allocation by dividing multiple processes or enlarging the system so that the other products are included

- **Step 2**
  If step 1 is not possible, allocation should be based on causal physical relationships

- **Step 3**
  If step 2 is not possible, other relations should be used, such as economic value of final products (widely varying!), mass or volume
Multifunctionality and allocation

- System expansion is one of the most common ways of avoiding allocation
- Our system has two functions:
  - Packaging for a liquid (function A)
  - Raw material for textile production (function B)

Impact calculation:

- Impact AB = 10
- Impact B’ = 4

Expanded system:

- Impact A = AB - B’ = 10 - 4 = 6

Saved impacts
Impact assessment (step 3): LCIA

How does the system affect the environment?

4 steps:
1. classification;
2. characterisation;
3. normalization;
4. weight assignment
Impact assessment

- **Classification**: assess which local/global impact(s) the input/output is contributing to

<table>
<thead>
<tr>
<th>Scale</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>Climate change</td>
</tr>
<tr>
<td></td>
<td>Stratospheric ozone depletion</td>
</tr>
<tr>
<td></td>
<td>Depletion of non-renewable resources</td>
</tr>
<tr>
<td>Regional</td>
<td>Acidification</td>
</tr>
<tr>
<td></td>
<td>Eutrophication</td>
</tr>
<tr>
<td></td>
<td>Photo-oxidant formation</td>
</tr>
<tr>
<td></td>
<td>Water resources depletion</td>
</tr>
<tr>
<td>Local</td>
<td>Human toxicity</td>
</tr>
<tr>
<td></td>
<td>Soil degradation</td>
</tr>
<tr>
<td></td>
<td>Landscape degradation</td>
</tr>
<tr>
<td></td>
<td>Soil erosion</td>
</tr>
<tr>
<td></td>
<td>Biodiversity loss</td>
</tr>
</tbody>
</table>
## Selection of impact categories

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A. Baseline impact categories</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depletion of abiotic resources</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Impacts of land use</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Land competition</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Climate change</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Stratospheric ozone depletion</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Human toxicity</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Ecotoxicity</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Freshwater aquatic ecotoxicity</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Marine aquatic ecotoxicity</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Terrestrial ecotoxicity</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Photo-oxidant formation</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Acidification</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Eutrophication</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

**B. Study-specific impact categories**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Impacts of land use</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Loss of life support function</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Loss of biodiversity</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Ecotoxicity</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Freshwater sediment ecotoxicity</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Marine sediment ecotoxicity</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Impacts of ionising radiation</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Odour</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Malodorous air</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Noise</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Waste heat</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Casualties</td>
<td>yes</td>
<td>no</td>
</tr>
</tbody>
</table>

**C. Other impact categories**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Depletion of biotic resources</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Desiccation</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Odour</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Malodorous water</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>

There are:

- **Input-related categories**
- **Output-related categories**

There are about ten impact categories which are commonly used in most LCAs (baseline).

Several impact categories still under development.
Baseline impact categories

- **ABIOTIC RESOURCE DEPLETION**
  - Deals with contributing to the depletion of valuable abiotic resources, by means of consumption
  - Increase in world resource consumption 1960-1995*
    - Minerals: 2.5
    - Metals: 2.1
    - Fossil fuels: 5.6
  
  * The state of the world 1999

<table>
<thead>
<tr>
<th>Resource</th>
<th>World annual extraction (x 1000 Tm)</th>
<th>Known reserves (x 1000 Tm)</th>
<th>Supply horizon (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td>3.132.500</td>
<td>135.400.000</td>
<td>43</td>
</tr>
<tr>
<td>Coal</td>
<td>3.038.300</td>
<td>521.413.000</td>
<td>170</td>
</tr>
<tr>
<td>Natural gas</td>
<td>2.019.600</td>
<td>124.000.000</td>
<td>60</td>
</tr>
<tr>
<td>Iron</td>
<td>544.300</td>
<td>64.648.000</td>
<td>120</td>
</tr>
<tr>
<td>Aluminium</td>
<td>17.900</td>
<td>3.488.000</td>
<td>200</td>
</tr>
<tr>
<td>Zinc</td>
<td>7.300</td>
<td>144.000</td>
<td>20</td>
</tr>
</tbody>
</table>

* The state of the world 1999

Baseline impact categories

- **CLIMATE CHANGE**

  - Greenhouse effect increased by emissions derived from human activity
  - Antropogenic emissions mainly from fossil fuels and land use change

**Indicators of the human influence on the atmosphere during the Industrial Era**

- Global atmospheric concentrations of three well mixed greenhouse gases
  - Carbon dioxide
  - Methane
  - Nitrous oxide

**Changes in GHGs from ice core and modern data**

- Carbon Dioxide
- Radiative Forcing (W/m²)
- Atmospheric concentration (ppm)
Baseline impact categories

Environmental consequences of climate change

- Flooding of coastal areas, deltas and islands
- Increase of extreme meteorological events
- Loss of agricultural productivity, plagues
- Desertification
- Increase of tropical disease areas
- Loss of biodiversity
Baseline impact categories

- DEPLETION OF STRATOSPHERIC OZONE
  - Caused by man-made halocarbons which provoke catalytic destruction of O3
  - Increase in UV light can provoke
    - Skin cancer
    - Cataract
    - Immune depression
    - Loss of agricultural productivity
    - Reduction of ocean phytoplankton

Ozone hole evolution
09 to 12 1995
Baseline impact categories

- ACIDIFICATION

- Environmental effects
  - Material degradation
  - Forest damage
  - Respiratory irritation
  - Death of aquatic organisms
Baseline impact categories

AQUATIC EUTROPHICATION

- Nutrient enrichment of the aquatic environment that causes algae and aquatic plants to grow drastically, which in turn decreases water quality
- Caused by emissions of N, P in untreated wastewater, cattle raising, agricultural fertilisers
- Environmental effects
  - Death of aerobic organisms
  - Odours
  - Local loss of biodiversity
  - Changes in ecosystem functioning
PHOTOCHEMICAL OR SUMMER SMOG

- The interaction between traffic emissions and sunlight creates reactive chemical compounds

- Environmental effects
  - Material degradation
  - Vegetation damage
  - Respiratory irritation

Solar light

VOC, CO → OH· NOx → PAN, O₃

Reactive forms of oxygen
Baseline impact categories

TOXICITY (TO HUMANS AND ECOSYSTEMS)

- The ability of a substance to cause damage to a living organism
- Substances causing toxic effects
  - Heavy metals (Cd, Hg, Cr...)
  - Persistent (and not persistent) organic compounds (pesticides, dioxins, PAHs...)
  - Inorganic compounds (NOx, SOx...)

Cancer, irritation, enzyme inhibition, endocrine disruptors...
Environmental interventions quantified in the inventory are assigned on a qualitative basis to the various pre-selected impact categories.

Substances can contribute to more than one problem.

- CO2
- CH4
- SOx
- NOx
- Toluene
- Metals

- Global warming
- Acidification
- Toxicity
- Photochemical smog
Impact assessment

• **Characterization**: impacts are quantified within given categories

\[
EP(j)_i = Q \times EQ(j)_i
\]

Q is the quantify of a given substance, transformed in the proper equivalent measure

\( EQ(j)_i \) is a factor weighting the substance contribution

• **Normalization** (optional): values are divided by a "reference value" usually with reference to a standard value in a given time period (e.g. to compare with average global values).

• A **weight** can be assigned to each normalized data (optional), i.e. a dimensionless value that indicates the relative importance of that specific impact in relation to other impacts→ “global” impact
Characterisation

- Different substances contributing to an environmental impact are quantitatively aggregated taking into account their substance-specific effect

- **This is done using scientific models. In this way characterisation can be considered as objective**

- An indicator value is obtained for each impact category

- The complete set of category indicator results is called the “environmental profile” of the system (PROFILO AMBIENTALE)
Characterisation

Example: Global Warming Potential

<table>
<thead>
<tr>
<th>Substance</th>
<th>GWP (CO₂ eq.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Half life (y)</td>
</tr>
<tr>
<td>CO₂</td>
<td>500</td>
</tr>
<tr>
<td>CH₄</td>
<td>10</td>
</tr>
<tr>
<td>N₂O</td>
<td>150</td>
</tr>
</tbody>
</table>

Source: Intergovernmental Panel on Climate Change (IPCC)

50 kg CO₂ → 1 kg CH₄ → GWP → x 1 → x 25 → 75 Kg eq. CO₂
Normalisation

- ISO 14.042: “Calculation of the magnitude of indicator results relative to reference information”

- The aim of normalising the category indicator results is to better understand the relative importance of these results

- The reference information can be:
  - A country
  - Europe
  - The World
  - An Italian citizen
  - ...
Weighting

- In the weighting phase the normalised category results are assigned numerical factors according to their importance.
- Multiplied by these factors and finally aggregated in a single “impact score”.

- Weighting factors are inherently subjective. (How much more should we care about acidification than about global warming?)

- ISO 14.042 does not permit weighting in public comparative assertions.
Uncertainty in LCIA

A compromise should be found between easily interpretable results and uncertainty/scientific soundness.
Interpretation of results (step 4) - LIFE CYCLE INTERPRETATION

• Results from inventory analysis and impact assessment are evaluated

• conclusions and recommendations (which system is the best? Which sub-process should be improved first? What would happen if…?)

• sensitivity analysis (optional) on the assumptions
Critical review

- Optional
- The critical review can reinforce credibility of the study
- Is not concerned with the results, but with transparency. Must ensure that in a LCA study:
  - Methods are consistent with the ISO framework
  - Methods are technically and scientifically valid
  - Data are appropriate enough
  - Interpretation reflects limitations and the goal of the study
  - Is properly reported
Critical review

- Types of CR:
  - By internal expert/s
  - By external expert/s
  - By interested parties

- The kind of C.R. and the people involved must be stated in the scope of the study

- The CR report and the comments from and to the authors must be included in the report of the study (for example as an appendix)
Software for LCA

- LCA calculations involve a vast multitude of input data, and clearly such an analysis cannot be undertaken by hand

- Ways of using computers for LCA studies
  - Use of conventional spreadsheets (e.g. excel)
  - Specific LCA software
  - Both things
Software for LCA

**FREE SOFTWARE**
- Gemis  [www.oeko.de/service/gemis/](http://www.oeko.de/service/gemis/)
- Eiolca  [www.eiolca.net](http://www.eiolca.net)

**BASIC COMMERCIAL SOFTWARE**
- Eco-it  [www.pre.nl/eco-it/default.htm](http://www.pre.nl/eco-it/default.htm)
- Idemat  [www.io.tudelft.nl/research/dfs/idemat/menu.htm](http://www.io.tudelft.nl/research/dfs/idemat/menu.htm)
Software for LCA

ADVANCED COMMERCIAL SOFTWARE

- Simapro  [www.pre.nl/simapro/default.htm](http://www.pre.nl/simapro/default.htm)
- Boustead Model  [www.boustead-consulting.co.uk](http://www.boustead-consulting.co.uk)
- Ecopro  [www.sinum.com/htdocs/e_software_ecopro.shtml](http://www.sinum.com/htdocs/e_software_ecopro.shtml)
- GaBi  [www.gabi-software.com/](http://www.gabi-software.com/)
- LCAiT  [www.lcait.com/](http://www.lcait.com/)
- Team  [www.ecobalance.com/uk_team.php](http://www.ecobalance.com/uk_team.php)
- Umberto  [www.umberto.de/english/](http://www.umberto.de/english/)
- Edip PC-tool  [www.mst.dk/activi/08030000.htm](http://www.mst.dk/activi/08030000.htm)
Software for LCA - Waste Management

- **Gemis 4.1**: Institute for Applied Ecology (Darmstadt, Germany) - public domain software

- **DCS-Decision Support Tool**: Environmental Protection Agency (EPA)

- **GaBi 3**: Institute for Polymer Testing and Polymer Science of the University of Stuttgart and PE Europe - liable for costs

- **Umberto 4**: Institute for Energy and Environmental Science Heidelberg (ifeu) and Institute for Environmental Informatics Hamburg (ifu) - liable for costs

- **IWM-2**: Purchased together with the book: "Integrated Solid Waste Management: a Life Cycle Inventory" (McDougall et al., 2001)
Literature and links

- JOURNALS
  - International Journal of LCA
    www.sciencificjournals.com
  - Journal of Cleaner Production
    www.sciencedirect.com
  - Resources, conservation and recycling
    www.sciencedirect.com

Many others frequently published papers about LCA.