Introduction to Life-Cycle Assessment

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http://go.ncsu.edu/SWM-LCA
What Is Life-Cycle Assessment?

Life-Cycle Assessment (LCA) is a framework used to examine, identify, and evaluate the energy, material, and environmental implications of a material, process, product, or system across its life span from cradle to grave.

How Can It Be Applied?

- Evaluation of alternate solid waste management strategies
  - Improvement assessment
- Guide for product design or product use
- Present policy makers with sound technical information in an easily understood format
- The life-cycle framework offers an opportunity to present credible information
- Hopefully, we will be able to use this framework to bring science and policy together
LCA Stages

Sources:
LCA is an iterative exercise
## Questions Answered by LCA Stage

| Goal Definition | • What is the purpose of the LCA?  
|                 | • Who is the target group?  
|                 | • Which decisions must the LCA support?  
|                 | • What is the extent of these decisions?  

| Scope Definition | • Which product/solution is to be assessed?  
|                 | • What is the service provided by the product?  
|                 | • How big a part of the product system is to be included?  
|                 | • Which environmental exchanges must be ascribed to this service?  

| Inventory | • What are the data requirements?  
|           | • What is the quality of the collected data?  
|           | • How is the product system modeled?  
|           | • How are the data aggregated and how are the uncertainties handled?  

| Impact Assessment | • Which resource consumption and environmental impact potential does the product entail?  
|                   | • Which contributions are the most important?  
|                   | • Which sources are the most important?  
|                   | • Which uncertainties and data gaps are the most significant?  

Defining the Goal and Scope

- What is the purpose of the LCA?
- Why is the assessment being conducted?
- How will the results be used, and by whom?
- What materials, processes, or products are to be considered?
- Do specific issues need to be addressed?
- How broadly will alternative options be defined?
- What issues or concerns will the study address?
Scope Defintion

• The objective of the study – the functional unit
  – 1 ton of MSW generated
  – 1 ton of recyclables at a MRF
• The boundaries of the system and exchanges over boundaries
• The assessment criteria to be applied
  – Global warming
  – Eutrophication
  – Fossil Energy Use
Scope Definition

- The time scale of the study
  - Changing waste composition
  - Delayed landfill emissions
  - Soil or landfill carbon storage

- The technologies representing the different processes
  - Windrow or In-Vessel composting
  - Traditional or bioreactor landfills

- Allocation for processes entering into other systems as well
  - What are the actual benefits of recycling glass?
  - If a combustion facility makes 1 kWh, is the avoided kWh from coal, natural gas, other, or some average?
Function and Functional Unit

**Function**: service provided by the system

E.g.,
- Solid waste treatment
- Electricity generation
- Fuel production

**Functional Unit**: means of quantifying the service

E.g.,
- 1 ton of MSW as generated
- 1 ton of MSW as received
- 1 MWh of electricity generated
- 1 m$^3$ of CNG produced
System Boundaries

- Include all that is relevant.
- Include only what is relevant.

Issues to consider:

- The infinite nature of the product system/cut-of-limits
- Allocation or system expansion
- System expansion:
  - Attributional approach (substitution is average)
  - Consequential approach (substitution is marginal)
System Boundaries

- System boundaries define which parts of the life cycle and which processes belong to the analyzed system – i.e. are required for providing its function as defined by its functional unit

Figure 12  Cradle to grave, cradle to gate and gate to gate data sets as parts of the complete life cycle; schematic. Each type fulfils a specific function as module for use in other LCA studies.

Adopted from ILCD (2010)
System expansion/substitution
Temporal Issues

• LCA traditionally does not differentiate impacts by time they occur
• Is this always the case in waste management?
• Time horizon. Often a 100 year period applied:
  – no time consideration within the time frame – or more precisely “integrating over time”
  – Unlimited time frame
  – “left-over” after the time horizon:
    • Sequestered carbon
    • Stored toxicity
• Building longterm infrastructure, so need to consider changes to the system.
  – Population, generation, composition.
  – Policy changes, changes to the energy system
Collection Activities

natural resources consumption

environmental emissions

energy consumption

electric power

truck manufacturing

petroleum
Collection Activities

system boundary

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Collection Activities

- Precombustion energy
- System boundary
- Collection activities involving natural resources consumption, energy consumption, and environmental emissions.
Assessment criteria

• Why are we doing LCA?
  – Consistent with goal and scope

Global impacts
• Global warming
• Ozone depletion

Regional impacts
• Smog formation
• Acidification
• Terrestrial and aquatic eutrophication
• Human toxicity

Local impacts
• Land use
• Odor
• Stored toxicity
• Spoiled groundwater resources

Resource Depletion (oil, coal, aluminum, P, freshwater, forest biomass)
Inventory Analysis

Often referred to as a Life-Cycle Inventory (LCI).

Describe all of the inputs and outputs in a product’s life cycle from cradle to grave (similar to material flow analysis (MFA))

Inputs include materials and energy
Outputs include the desired products as well as by-products and wastes.

- Quantifies resource and energy consumption, and environmental emissions associated with all processes in a system
  - emissions are post-treatment
    - apply to collection, MRF, landfill, combustion
Inventory Analysis: Process-based Approach

Itemize the inputs (materials and energy resources) and the outputs (emissions and wastes to the environment) process-by-process in the product life-cycle.

Identification of system boundaries is critical (i.e., what should be included and what can be ignored)

Narrow system boundaries can lead to inaccurate life-cycle assessment, too broad can lead to “circularity” effects
Data for Inventory Analysis

Literature
- extrapolation from similar processes
- papers, books
- databases
  - ecoinvent (commercial) - http://www.ecoinvent.org/
  - NREL (free) - https://www.lcacommons.gov/nrel/

Questionnaires
- data sought upstream (contractors)
- send questionnaire and follow up (often visit)

Estimates
- Modeling from process knowledge.
- Measurements
- average performance
Mass balance (conceptual)

Waste system:

- Waste
- Fuel, water, etc.
- Emission to water and soil
- Wastewater
- Emissions to atmosphere
- Remanufacturing
- Use on land
Example: Mass balance

1000 t/y (distributed as exponential decay over decades) as CH₄, CO₂, and H₂O

1500 t/y (distributed as exponential decay over decades) as LFG for utilization
Mass balances, energy and emissions

- **Mass balance:**
  - All generated waste as well as residues from treatment are tracked (nothing forgotten)
  - All emissions can be conceptually identified by evaluating all discharges from the waste system, intended or unintended

- **Energy budgets:**
  - All energy consumed (fuels, electricity etc.) is known
  - All energy containing outputs can be utilized

- **Emission accounts:**
  - Direct environmental loads can be monitored, assessed and maybe reduced
  - Indirect or pre-combustion emissions are included
Precombustion Emissions

- Precombustion or “well-to-pump” or “well-to-tank” emissions are the emissions associated with extracting, processing, and transporting fuels (e.g., coal, diesel, natural gas) prior to use.

![Precombustion Processes Diagram]

Example: Emission account

Meaning of <0
-Net reduction in emissions due to offsets or carbon storage
Recycling and Beneficial Use

• When recyclables are converted to new products:
  – resource consumption and emissions are associated with recyclables collection, separation, and reprocessing
  – some extraction, processing, and transportation of virgin materials is avoided which reduces resource consumption and emissions

• Combustion is a net producer of energy and this offsets energy produced from utilities

• Landfill gas can also be converted to energy
Material substitution - processes/crediting

Material recycling:

**Net Emissions = Emissions from processing recovered materials – emissions from avoided virgin production**

If the reprocessing and the virgin production takes place at the same plant and in the same process then estimation of the benefits of recycling is possible and likely to be correct.

If the reprocessing takes place at a separate plant (e.g., paper mill) there is no direct link between reprocessing and the avoided virgin production and the avoided virgin production and benefits are more difficult to estimate.
The Output of Inventory Analysis…

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<tr>
<th>Substance</th>
<th>Alternative A</th>
<th>Alternative B</th>
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<td></td>
<td>To air</td>
<td>To water</td>
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<td></td>
<td>g</td>
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<td>5.0E-02</td>
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<td>1.3E-05</td>
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<td>6.3E-07</td>
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<td>4.5E+01</td>
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<td>Zinc ( Zn )</td>
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</table>

How do we use this data to meet LCA goal?

Source: M. Hauschild, DTU
Making Sense of the Inventory

### Emission Prices

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<th>CAS.no.</th>
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<td>Hydrogen ions (H+)</td>
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<td>VOC, stationary combustion (coal fired)</td>
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<td>VOC, stationary combustion (natural gas fired)</td>
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<td>Zinc (Zn)</td>
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<td>8,9E-05</td>
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</tbody>
</table>

### Environmental Impacts

- **Global warming**: 174,000 kg CO₂-eq
- **Ozone depletion**: 0 kg CFC11-eq
- **Acidification**: 868 kg SO₂-eq
- **Photochemical ozone formation**: 200 kg C₂H₄-eq
- **Nutrient enrichment**: 3,576 kg NO₃-eq
- **Human toxicity**: 3,40·10¹¹ m³ air
- **Ecotoxicity**: 2,16·10⁷ m³ water
- **Land use**: 170 ha-yr
- **Volume waste**: 9,450 kg
- **Hazardous waste**: 248 kg

Source: M. Hauschild, DTU
Purpose of Impact Assessment

How do we use inventory data to make a rational, defensible decision among a set of alternatives?

We must quantify:

1. The environmental influences of relevant activities on specific environmental properties
2. The relative changes in the affected environmental properties can be given some type of priority ranking

.. This constitutes life-cycle impact assessment (LCIA)
Planning LCIA

- Life-cycle impact assessment (LCIA) aggregates life-cycle inventory data to support interpretation of results.
- Choices need to be consistent with goal and scope definition.

Adopted from ILCD (2010)
Impact Assessment

**Classification:** Assignment of emissions to impact categories according to their potential effects

- “What does this emission contribute to?”

**Characterization:** Quantification of contributions to the different impact categories

- “How much does it contribute?”

**Normalization:** Expression of the impact potentials relative to a reference situation

- “Is that much?”

**Weighting:** Ranking, grouping or assignment of weights to the different impact potentials

- “Is it important?”
Typical LCIA Categories

- Global warming
- Acidification
- Eutrophication
- Stratospheric ozone depletion
- Ecotoxicity
- Human toxicity
- Land use
- Water use
- Resource use
Global Warming Potential Example

\[ \text{Impact} = \sum_{p \in P} \text{CF}_{i,p} \cdot \text{MassEmitted}_p \]

*Impact:* The environmental impact under consideration.

*MassEmitted*\( _p \): The mass of pollutant, \( p \), emitted.

*CF*\(_{i,p} \): The characterization factor for pollutant, \( p \), and impact, \( i \) (aka Impact Factor).

\[ \text{Global Warming Impact } [kg \ CO_2e] = \sum_{p \in P} \text{GWP}_p \left[ \frac{kg \ CO_2e}{kg \ p} \right] \cdot \text{MassEmitted}_p[kg \ p] \]

*GWP:* Global Warming Potential – the Characterization Factor for global warming, measured in kg CO\(_2\)-equivalents based on radiative forcing.

\[ \text{Global Warming Impact } [kg \ CO_2e] = 1 \ \frac{kg \ CO_2e}{kg \ CO_2F} \cdot kg \ CO_2\text{Fossil} - 1 \ \frac{kg \ CO_2e}{kg \ CO_2S} \cdot kg \ CO_2\text{Stored} + 25 \ \frac{kg \ CO_2e}{kg \ CH_4} \]

\[ \cdot \ kg \ CH_4 + 298 \ \frac{kg \ CO_2e}{kg \ N_2O} \cdot kg \ N_2O \]
Interpretation

- Consider goal, scope and results together
- Improvement assessment
- Sensitivity analysis: Address uncertainty (boundary choices, incomplete inventories, data uncertainty)
- Decision support regarding environmental issues: In real world also social aspects and economy
Limitations

- The decisions on what inventory parameters are most critical may be site-specific
  - NOx may be more important in some areas of U.S. than others; so too for water consumption
    - Multi-criteria decision-making
    - emissions location: local/global
- Similar data across unit operations must be available to do meaningful comparisons
Acknowledgments

http://go.ncsu.edu/SWM-LCA