Life cycle assessment: a bridge between environmental sciences and bio(chemical) engineering

LABORATORY of CHEMICAL ENGINEERING
Processes and Sustainable development
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Introduction to the Laboratory of Chemical Engineering
University of Liège, Belgium

- 9 faculties, 1 institute, 1 school

- Philosophy & Letters
- Law and Criminology school
- Sciences
- Medecine
- Applied Sciences
- Veterinary Medecine
- Psychology and Education
- Architecture
- Human and Social Sciences

- Intro to LGC
- HEC ULg
- Management School - University of Liège
- Université de Liège
- LGC CHEMICAL ENGINEERING

- 38 bachelors
- 194 masters
- 68 complementary masters
Department of Applied Chemistry

- 3 groups

- Analysis and Synthesis of Chemical Systems – Cryotechnology laboratory
  (Pr G. Heyen, Pr J.-L. Bozet, Dr M.-N. Dumont)

- Catalytic and electrochemical engineering - Nanomaterials
  (Pr J.-P. Pirard, Pr B. Heinrichs, Dr N. Job, Dr S. Lambert, Dr C. Gommes)

- Chemical Engineering
  (Pr M. Crine, Pr D. Toye, Pr A. Léonard)

http://www.chimapp.ulg.ac.be/
Research: 3 main topics

- Drying of deformable materials
  - Both experimental and modeling approaches
  - Long expertise in sludge drying
  - Relation between drying process and product quality

- Characterization of porous materials by X-ray microtomography
  - Initially developed to follow sludge texture during drying
    - Cracks, shrinkage, moisture profiles
  - Extension to different types of cellular materials
  - Now used for product-oriented-engineering approach

- Environmental management: Life Cycle Assessment studies, environmental reporting
The team

- Drying
  - Prof. Michel Crine
  - Thierry Salmon (industrial engineer)
  - Dr Lyes Bennamoun (FRS-FNRS postdoc)
  - Laurent Fraikin (PhD student)
  - Yvon bert PAMBOU (PhD student)

- X-ray microtomography
  - Prof. Dominique Toye
  - Dr Erwan Plougonven (FRS-FNRS postdoc)
  - Charlotte De Bien (FRIA PhD student)
The team

- LCA
  - Sandra Belboom (PhD student)
  - Saïcha Gerbinet (PhD student)
  - Raphaëlle Melon (Industrial engineer)
  - Robert Renzoni (Senior researcher)
Expertise in environmental management

- LCA: more than 10 years of expertise
  - Evaluation of the environmental impact of processes
  - Redaction of environmental declarations
  - Development of databases
  - Academic research + external studies
  - Participation to several regional and European projects
  - ...

Intro to LGC
Expertise in environmental management

- LCA: some covered topics
  - Comparison of vehicles
  - Comparison of waste management scenarios
  - Comparison of packaging options
  - Comparison of several ways of renewable heat heat production
  - Comparison of several ways of renewable electricity production
  - Study of biofuels production
  - Study of agro-food by-products valorization ways
  - Impact of water management (whole anthropic water cycle)
  - CO$_2$ Life cycle inventory of a cement producer
  - Study of several fuel cells configurations
  - LCA training
Expertise in environmental management

- **LCA: current projects**
  - WALAID - Walloon Region
    - Valorization of the agrofood industry by-products
  - SOMABAT – FP7
    - Development of novel SOLid MAterials for high power Li polymer BATteries
      - LCA of the developed batteries + recyclability
  - Pierres et mabres de Wallonie
    - Realisation of environmental product declarations (FDES)
      - Blue stone, sand stone, ...
Expertise in environmental management

- Environmental management: Life Cycle Assessment studies, environmental reporting
  - LCA: formation
    - Greenwin
    - Master degree course (starting in 2011)
    - Carbon Management certificate (ULg – UCL)
  - LCA: publications
    - International journals
    - Conferences, ...
About (bio)chemical engineering
(Bio)chemical engineering

- Branch of engineering concerned with the design, operation, maintenance, and manufacture of the plant and machinery used in industrial (bio)chemical processes

- All the knowledge, the technologies and the practices necessary for the design the implementation, the operation and the optimization of the transformation processes of materials by chemical, physical or biological ways
(Bio)chemical engineering

Application fields

- Chemical industry
- Pharmaceutical and biotechnological industries
- Cosmetics
- Agrofood and agrochemical industry
- Pulp and paper
- Cement industry
- Energy production
- ...

About (bio)chemical engineering
(Bio)chemical engineering

- « Core curriculum »
  - Fundamentals of science and natural sciences
  - Thermodynamics
  - Heat and mass transfer
  - Biological engineering
  - Unit operations
  - Process design and modeling
  - Safety
  - Chemical reaction engineering
  - Catalysis
  - ...

About (bio)chemical engineering
About LCA
LCA: a standardized methodology

- General framework defined by international standards ISO 14040 - 14044

- « studies all the environmental aspects and potential impacts associated with all the stages of a product's life from cradle to grave, i.e. from raw material extraction to end of life »

- Product = product, activity, system or process
LCA: a standardized methodology

- Life cycle includes
  - Raw material extraction
  - Production
  - Transport
  - Packaging
  - Distribution
  - Use
  - Maintenance - Repair
  - Reuse or recycling
  - Disposal

- «Cradle to grave» approach

LCA: typical results

- Life cycle steps ‘ranking’ following their environnemental impacts
- Identification of substances responsible for major environmental impacts

**CO\textsubscript{2} footprint = 1 inventory among many others**

- Determination of categories with highest environmental impacts
  - Human health, climate change, ecotoxicity ...

About LCA
**LCA: why?**

**Strategy**
- Potential impacts of products on environment
- Investments decision support

**R & D products/process**
- Early identification of problems/opportunities
- Assistance in projects selection
- Assistance in defining objectives

**Marketing**
- Comparative analyses

**Policy**
- Best information of authorities, consumers, etc. (legislation/regulation, eco-labels ...)
- Comparative analyses

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**Internal**

**External**

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*About LCA*
LCA associated steps

- Four steps defined by ISO 14040 – 14044

Goal and scope definition

Inventory analysis (LCI)

Impact assessment (LCIA)

Interpretation
LCA associated steps

- Four steps defined by ISO 14040 – 14044

1. **Goal and scope definition**
2. **Inventory analysis (LCI)**
3. **Impact assessment (LCIA)**
4. **Interpretation**
LCA: goal and scope definition

- Goal of the study
  - Why?
  - For whom?
  - ...

- Scope
  - Choice of the functional unit
    - Production of 1 kg of yeast
    - Treatment of 1 ton of waste
    - Valorization of 1 ton of biomass
    - ...

About LCA
LCA: goal and scope definition

- **Scope**
  - Delimitation of the system boundaries
    - Determination of all the elementary processes to be included in the analysis
  - Process tree
  - Data quality requirements
  - Cut-off rules
LCA: goal and scope definition

- Example: process tree + boundaries

LCA associated steps

- Four steps defined by ISO 14040 – 14044

Goal and scope definition

Inventory analysis (LCI)

Impact assessment (LCIA)

Interpretation
LCA: Inventory

**Inputs**
- Raw materials
- Energy
- Water, etc.

**Raw materials**
- Processing
- Assembly
- Transport & distribution
- Use
- Final disposal

**Outputs**
- Air emissions
- Water emissions
- Soil emissions
- Solid waste
- Products
- Others emissions

**About LCA**
LCA associated steps

- Four steps defined by ISO 14040 – 14044

1. Goal and scope definition
2. Inventory analysis (LCI)
3. Impact assessment (LCIA)
4. Interpretation
LCA: impact assessment

- Estimation of environmental impacts based on the inventory

- Mandatory elements
  - Selection of impact categories, indicators, methods
  - Classification
  - Characterization

- Optional elements
  - Normalisation
  - Grouping
  - Weighting
LCA: impact assessment

Impact categories

## LCA: impact assessment

### Impact assessment methods

<table>
<thead>
<tr>
<th>Method name</th>
<th>Temporal validity</th>
<th>Regional validity</th>
<th>Type of impact category (IC) indicators</th>
<th>Weighting principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>CML 2002</td>
<td>Present state (year 2002)</td>
<td>Global, except for acidification (Europe) and photo-oxidant formation (European trajectory)</td>
<td>Midpoint</td>
<td>No baseline method is proposed</td>
</tr>
<tr>
<td>ECO-indicator 99</td>
<td>Present state (year 1999)</td>
<td>Global for the impact categories (IC) climate, ozone depletion and resources. European model for the other IC. Acidification and eutrophication based on Dutch model, land use based on Swiss model.</td>
<td>Midpoint and Endpoint</td>
<td>Three options: Panel method is used for default weights. Monetization and a specific weighting triangle can also be used.</td>
</tr>
<tr>
<td>Eco-scarcity</td>
<td>Actual flows reflect 2004 state and critical flows correspond to 2005 political objectives.</td>
<td>Originally developed for Switzerland, but versions for Netherlands, Sweden, Norway, and Japan are also available.</td>
<td>Midpoint-distance to target principle. Endpoints indirectly considered by political targets.</td>
<td>Relative reduction of distance to target by multiplying by the square of the ratio of actual flow and critical flow.</td>
</tr>
<tr>
<td>EDIP</td>
<td>Present state (year 2003)</td>
<td>Global</td>
<td>Midpoint</td>
<td>Distance to political targets.</td>
</tr>
<tr>
<td>EPS 2000</td>
<td>Present state (year 1999)</td>
<td>Majority global, the largest exception is for Biodiversity where Swedish models are used.</td>
<td>Endpoint effects</td>
<td>Willingness To Pay to avoid changes on safeguard subjects.</td>
</tr>
<tr>
<td>ReCiPe</td>
<td>Present state (year 2010)</td>
<td>Europe, but global for climate change, ozone layer and resources.</td>
<td>Combination of midpoint and endpoint methodologies in a consistent way.</td>
<td>Three options: For midpoints a monetization method on the basis of the prevention costs is provided. For endpoints panel weighting is used and monetization on the basis of damage costs can be used.</td>
</tr>
</tbody>
</table>

LCA: impact assessment

Classification

- Assignment of inventory results to the selected impact categories

- Global warming (g eq. CO$_2$)
LCA: impact assessment

Characterization

- Conversion of LCI results into representative indicators of impact using characterization factor
- Substances belonging to the same impact category are expressed in ‘equivalent’ units

Inventory Data × Characterization Factor = Impact Indicators

\[
\begin{align*}
\text{kg CO}_2/\text{FU} & \Rightarrow \text{eq}-\text{kg CO}_2/\text{FU} \\
\text{kg CH}_4/\text{FU} & \\
\text{kg N}_2\text{O}/\text{FU} & \\
\text{Global warming: } & \text{eq-kg CO}_2/\text{FU} \\
\text{Acidification: } & \text{eq-kg SO}_2/\text{FU} \\
\text{Ozone depletion: } & \text{eq-kg CFC-11/FU} \\
\text{Fossil fuels: } & \text{MJ/FU} \\
\text{...} & 
\end{align*}
\]
LCA: impact assessment

Characterization: example - Vials comparison

LCA: impact assessment

- Normalisation
  - Tool to express impact indicator data in a way allowing to compare among impact categories
  - Indicator normalisation by dividing results by a selected reference value such as global or regional averages

- Grouping
  - Impact categories are sorted and grouped, depending on the chosen impact assessment method
LCA: impact assessment

Normalization/Grouping: vials comparison

LCA: impact assessment

Grouping
LCA: impact assessment

Weighting

- Indicator results for different impact categories are converted to a common unit by using factors based on value-choices → “Single score” result

![Bar chart showing environmental impact categories for different countries and PV systems](chart.png)
### Important role during impact assessment

- **Determination of characterization factors!**
  - Land use, water use, still in development

<table>
<thead>
<tr>
<th>Land Use</th>
<th>Global Regional Local</th>
<th>Quantity disposed of in a landfill or other land modifications</th>
<th>Land Availability</th>
<th>Converts mass of solid waste into volume using an estimated density.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Use</td>
<td>Regional Local</td>
<td>Water used or consumed</td>
<td>Water Shortage Potential</td>
<td>Converts LCI data to a ratio of quantity of water used versus quantity of resource left in reserve.</td>
</tr>
</tbody>
</table>
LCA associated steps

- Four steps defined by ISO 14040 – 14044

1. Goal and scope definition
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3. Impact assessment (LCIA)
4. Interpretation
Links between LCA and bio(chemical) engineering
Important role during LCA inventory

**Inputs**
- Raw materials
- Energy
- Water, etc.

**Raw materials**
- Processing
- Assembly
- Transport & distribution
- Use
- Final disposal

**Outputs**
- Air emissions
- Water emissions
- Solid waste
- Products
- Others emissions

LCA and (bio)chemical engineering
Important role during LCA inventory

- Practically ...
  - Commercial databases
  - Data provided by industrials
  - (Inter)national databases
  - Scientific and technical literature

- But ... data are often missing or quality is questioning
  - Process modeling
  - Data reconciliation
  - Knowledge of unit operations, ...
LCA = tool to improve existing processes

- Identification of more ‘penalizing’ steps
- Identification of harmful substances
  - ways of improvement

LCA = way to « ecodesign » new processes

- 70% of « the environmental impact » already fixed during the design step

L’écoconception, source d’innovation dans l’approche cycle de vie; l’expérience du Québec, Guy Belletête, Congrès ACV, Lilles, 4/11/2011

LCA and (bio)chemical engineering
LCA = way to « ecodesign » new processes

- Ecodesign = integration of environmental aspects into product or process design with the aim of improving the environmental performance throughout the whole life-cycle

https://www.ecobilan.com/uk_lca07.php
Links between LCA and environmental sciences
## Important role during impact assessment

- Consensus for some impact categories

<table>
<thead>
<tr>
<th>Impact Category</th>
<th>Scale</th>
<th>Examples of LCI Data (i.e. classification)</th>
<th>Common Possible Characterization Factor</th>
<th>Description of Characterization Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Warming</td>
<td>Global</td>
<td>Carbon Dioxide (CO₂) Nitrogen Dioxide (NO₂) Methane (CH₄) Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Methyl Bromide (CH₃Br)</td>
<td>Global Warming Potential</td>
<td>Converts LCI data to carbon dioxide (CO₂) equivalents Note: global warming potentials can be 50, 100, or 500 year potentials.</td>
</tr>
<tr>
<td>Stratospheric Ozone Depletion</td>
<td>Global</td>
<td>Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Halons Methyl Bromide (CH₃Br)</td>
<td>Ozone Depleting Potential</td>
<td>Converts LCI data to trichlorofluoromethane (CFC-11) equivalents.</td>
</tr>
<tr>
<td>Acidification</td>
<td>Regional Local</td>
<td>Sulfur Oxides (SOₓ) Nitrogen Oxides (NOₓ) Hydrochloric Acid (HCL) Hydrofluoric Acid (HF) Ammonia (NH₃)</td>
<td>Acidification Potential</td>
<td>Converts LCI data to hydrogen (H⁺) ion equivalents.</td>
</tr>
</tbody>
</table>
Important role during impact assessment

- Determination of characterization factors!
  - Toxicity: need for more data and modeling tools

<table>
<thead>
<tr>
<th>Terrestrial Toxicity</th>
<th>Local</th>
<th>Toxic chemicals with a reported lethal concentration to rodents</th>
<th>LC$_{50}$</th>
<th>Converts LC$_{50}$ data to equivalents; uses multimedia modeling, exposure pathways.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquatic Toxicity</td>
<td>Local</td>
<td>Toxic chemicals with a reported lethal concentration to fish</td>
<td>LC$_{50}$</td>
<td>Converts LC$_{50}$ data to equivalents; uses multimedia modeling, exposure pathways.</td>
</tr>
<tr>
<td>Human Health</td>
<td>Global Regional</td>
<td>Total releases to air, water, and soil.</td>
<td>LC$_{50}$</td>
<td>Converts LC$_{50}$ data to equivalents; uses multimedia modeling, exposure pathways.</td>
</tr>
</tbody>
</table>

- Difficulty to get the same toxicity characterization score for a substance when using different methods
Important role during impact assessment

About land use and land use change

- No established and globally applicable practice on land use occupation and transformation available for use in LCA
- A lot of associated impacts

Important role during impact assessment

About land use and land use change

- A lot of different indicators
  - resource depletion
  - soil quality impacts
    - changes in soil organic carbon and soil organic matter
    - erosion resistance
    - filtration potential
    - ...
  - biodiversity
  - ...
- A lot of research needs
  - regional data en soil quality
  - criteria to select effective ecological indicators, ...
Some examples ...
Bluestone vs. Chinese stone

Impact of transport on environmental impact

LCA as decision tool for sustainable choices in mineral materials field: environmental declarations of Belgian products and their foreign equivalents, S. Belboom et al. Congrès ACV, Lilles, 3-4 novembre 2011
Comparison of drying technologies

- Production of carbon xerogels: ecodesign approach

```
H₂O  C₆H₄(OH)₂  CH₂O  Na₂CO₃
    |        |        |
    v        v        v
Homogenization

Aging

Drying

Vacuum  Convective  Microwave

Pyrolysis

Carbon xerogels
```

Analyse du cycle de vie de xérogels de carbone, R. Melon et al.
Congrès ACV, Lilles, 3-4 novembre 2011
Comparison of drying technologies

- Weighted results

Best environmental choice = convective drying

Analyse du cycle de vie de xérogels de carbone, R. Melon et al.
Congrès ACV, Lilles, 3-4 novembre 2011
Comparison of waste treatment technologies

- Before 1970: wild landfilling
- From 1990 until 2009: waste grinding and sorting
- From 2009 until now: incineration of the whole waste fraction
- Short term project: methanation of the biodegradable fraction after collect and sorting

Some examples
To conclude ...
To conclude

(Bio)chemical engineering

Process modeling
Data reconciliation
...

LCA

Process improvement
Sustainable process design
...

Focus on environmental concerns
Create needs for new data
...

Characterization factors
Assessment methods
...

Environmental sciences

Conclusions
To conclude

- LCA $\rightarrow$ environmental impact evaluation
  - 1 aspect of sustainable development
- Development of other tools
  - LCC = Life cycle cost
  - SLCA = Social LCA

**LCSA = Life Cycle Sustainability Assessment**
Thanks for your kind attention!
Thanks to the LCA team!

Some questions?