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# Environmental Life Cycle Assessment – Principles, challenges and application

Shaping and Transformation in the Engineering of Polysaccharides (STEP)

Ecole des Mines de Paris / Cemef,
Sophia Antipolis, France, 28 September 2010

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Department of Science, Technology & Society
Utrecht University, Netherlands
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Manufacturing
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100% ECO-BIODEGRADABLE

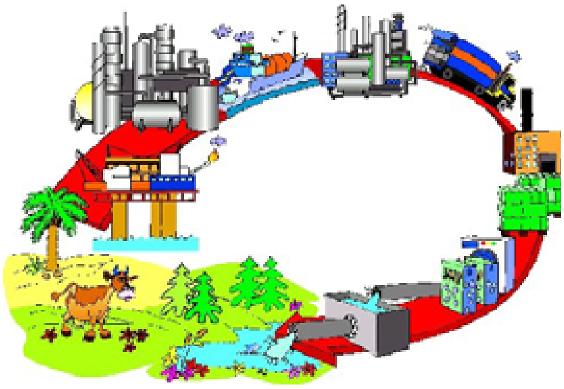

going green

# Outline

1. What is Life Cycle Assessment (LCA)?
2. Why LCA?
3. What is the difference between LCA and Green Chemistry principles?
4. How to prepare an LCA?
5. What are critical issues in LCA?

# 1.) What is Life Cycle Assessment?

- Assessment of Environmental impacts
- of Products/Processes or Services
- throughout the Life Cycle: resource extraction, manufacturing, product use, waste management



# 1.) What is Life Cycle Assessment?

- Assessment of Environmental impacts
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Typical types of use:

Compare new product with conventional product

Compare design alternatives

# 2.) Why LCA?

## Objectives

- **Understand:** Overview of environmental impacts by process step
- **Reduce:** Identify possibilities for reducing environmental impacts (industrial process, R&D)
- **Communicate:** Towards clients and stakeholders

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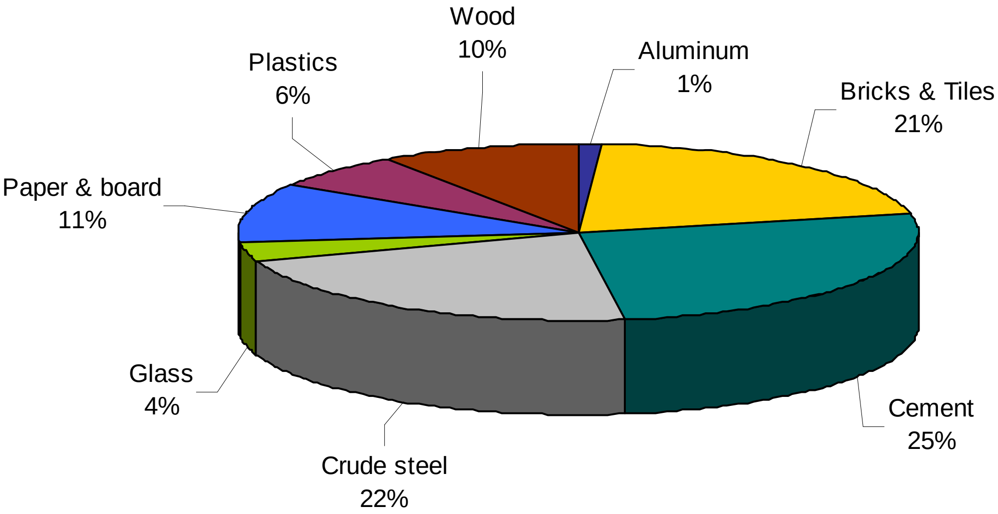
# EU-27 production of bulk materials in 2004 (920 Mt in total)



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# Energy for producing bulk materials

| | Non-renewable energy use (NREU), cradle-to-factory gate, GJ/t |
|---|---|
| Cement | 3 - 6 |
| Steel | |
| - Primary | 20 - 25 |
| - Secondary | 7 - 8.5 |
| Paper/board | 10 - 20 |
| Plastics*) | <70 - >85 |
| Glass | 6 - 8 |
| Aluminium | |
| - Primary | 180 |
| - Secondary | 25 |

*) Examples:

HDPE: 77
LDPE: 78
LLDPE: 73
PP: 73
PET: 81
PS: 86
PVC: 56
PA: 120 - 140

Sources: various; for plastics: PlasticsEurope, see http://lca.plasticseurope.org/main2.htm

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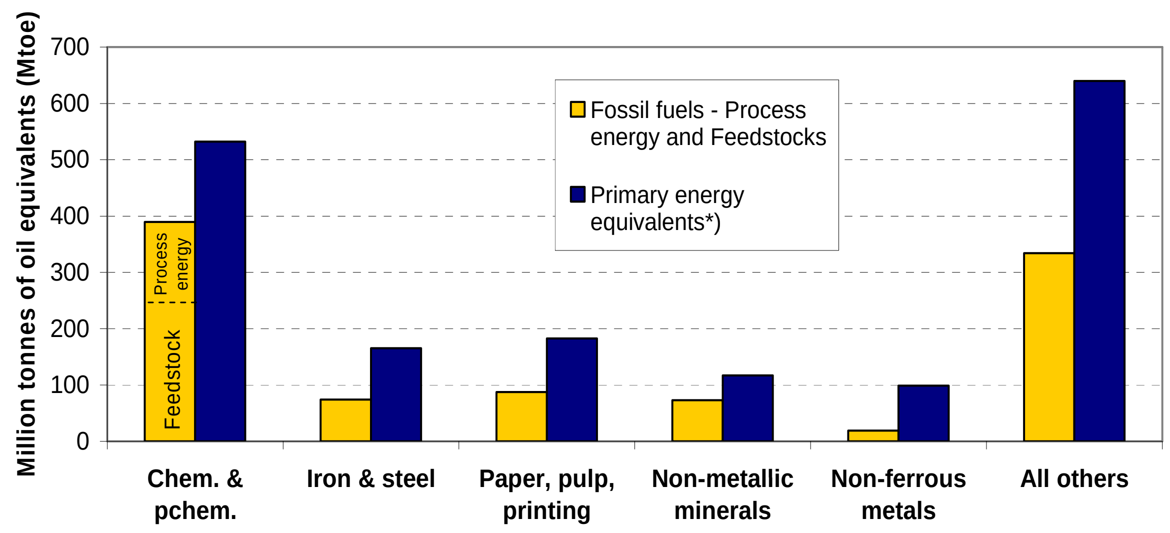
# Energy use by the industrial sector

## OECD, Total



*) Including primary energy equivalents of electricity; assumed efficiency of power generation: 35%
Source: Energy Balances of OECD Countries 2006, IEA/OECD, Paris, 2008

# “Bioplastics are becoming a burden for the environment”

## *“Bioplastik wird zur Belastung für die Umwelt”*

**Kireev, M. in “Welt am Sonntag”, 12. Oktober 2008**
**http://www.welt.de/wams_print/article2564545/Bioplastik-wird-zur-Belastung-fuer-die-Umwelt.html**

Wolfgang Beier, German Federal Ministry of the Environment (Umweltbundesamt):

- “So far, we are skeptical or even negative towards bioplastics.”
- “Nobody has so far presented an LCA which complies with all requirements and standards.”
- “Claims according to which bioplastics offer $CO_2$ savings are biased.”
- Other aspects mentioned:
  - Land requirements
  - Experience made with PHB, by BASF, Siemens and partners
  - $CO_2$ savings only possible if green power is used
  - Waste management

## 3.) What is the difference between LCA and Green Chemistry principles?

# Green Chemistry principles

Prevent Wastes
Renewable materials
Omit derivatization steps
Degradable chemical products
Use safe synthetic methods
Catalytic reagents
Temperature, pressure ambient
In-process monitoring
Very few auxiliary substances
E-factor [and atom economy]
Low toxicity of chemical products
Yes, it is safe.

Anastas, P.T. and Warner, J.C.: Green Chemistry – Theory and Practice, 2000

Poliakoff, M. and Licence, P.: Green Chemistry. Nature, 2007

Sheldon et al., 2007

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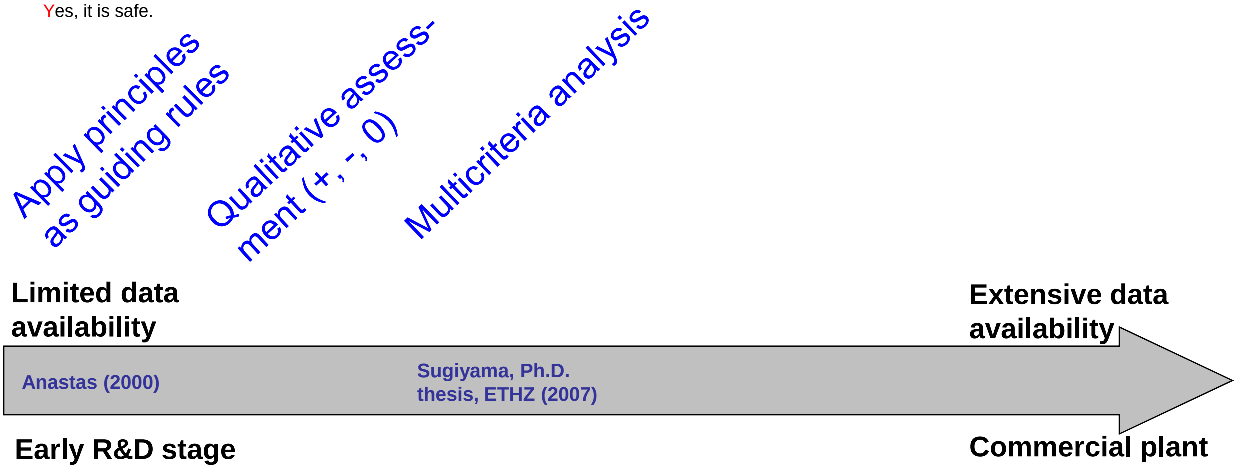

Apply principles as guiding rules

Qualitative assessment (+, -, 0)

Multicriteria analysis

**Limited data availability**

**Extensive data availability**

**Anastas (2000)**

**Sugiyama, Ph.D. thesis, ETHZ (2007)**

**Early R&D stage**

**Commercial plant**

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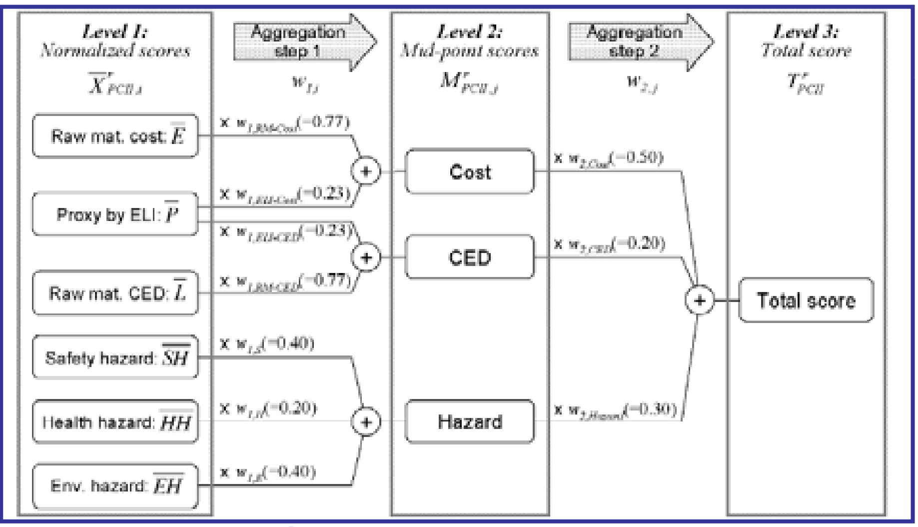

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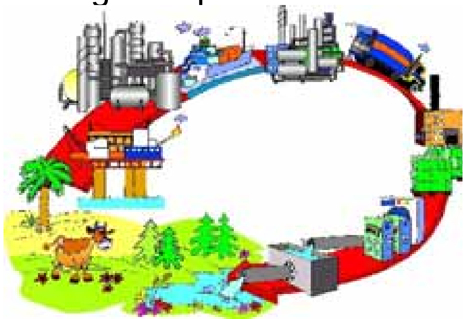
## LCA
### Environmental Life Cycle Assessment

- Provides quantitative environmental indicators
- Based on flowsheet and considers all stages of process chain



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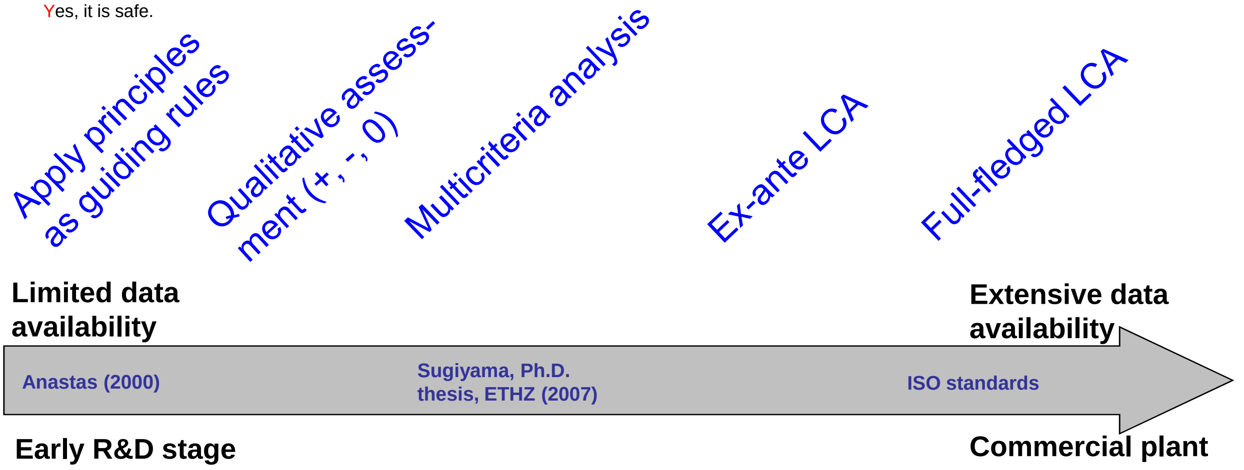
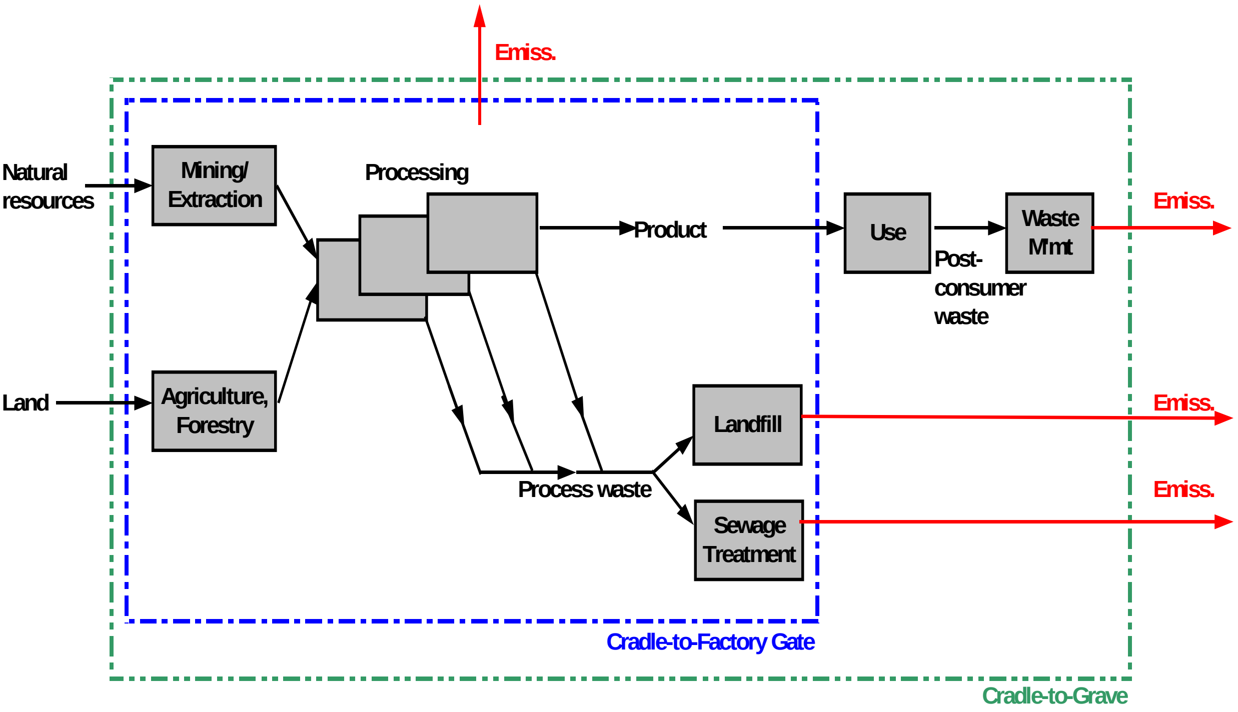


# System boundaries



Emiss.

Natural resources

Mining/ Extraction

Processing

Product

Use

Waste Mʼmt

Emiss.

Post-consumer waste

Land

Agriculture, Forestry

Landfill

Emiss.

Process waste

Sewage Treatment

Emiss.

Cradle-to-Factory Gate

Cradle-to-Grave

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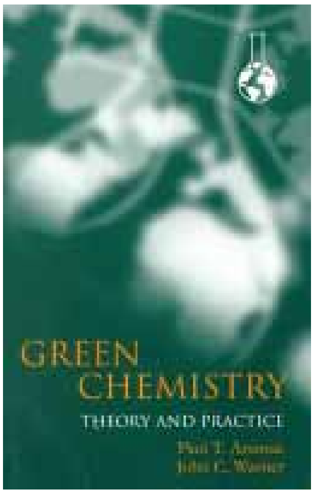
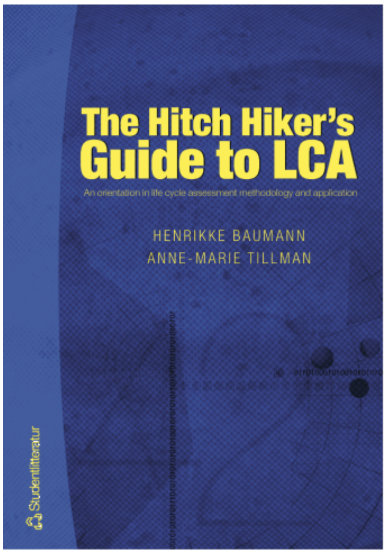
## Green Chemistry principles



Paul T. Anastas, John C. Warner, Green Chemistry: Theory and Practice, 2000, 135 pages

## LCA

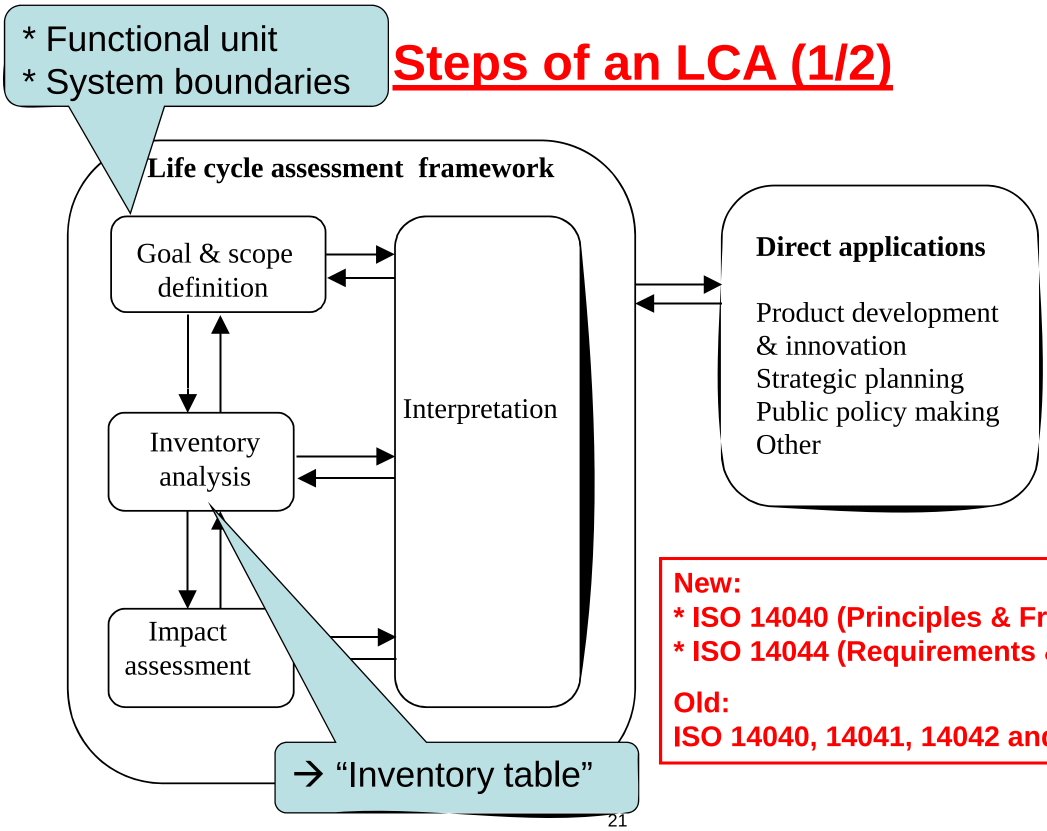
### Environmental Life Cycle Assessment



Henrikke Baumann, Anne-Marie Tillman, The Hitch Hikers Guide to LCA. Studentlitteratur, Lund, 2004, 543 pages

# 4.) How to prepare an LCA?

# Steps of an LCA (1/2)


* Functional unit
* System boundaries

**Life cycle assessment framework**

Goal & scope definition

Inventory analysis

Impact assessment

Interpretation

→ “Inventory table”

**Direct applications**

Product development & innovation
Strategic planning
Public policy making
Other

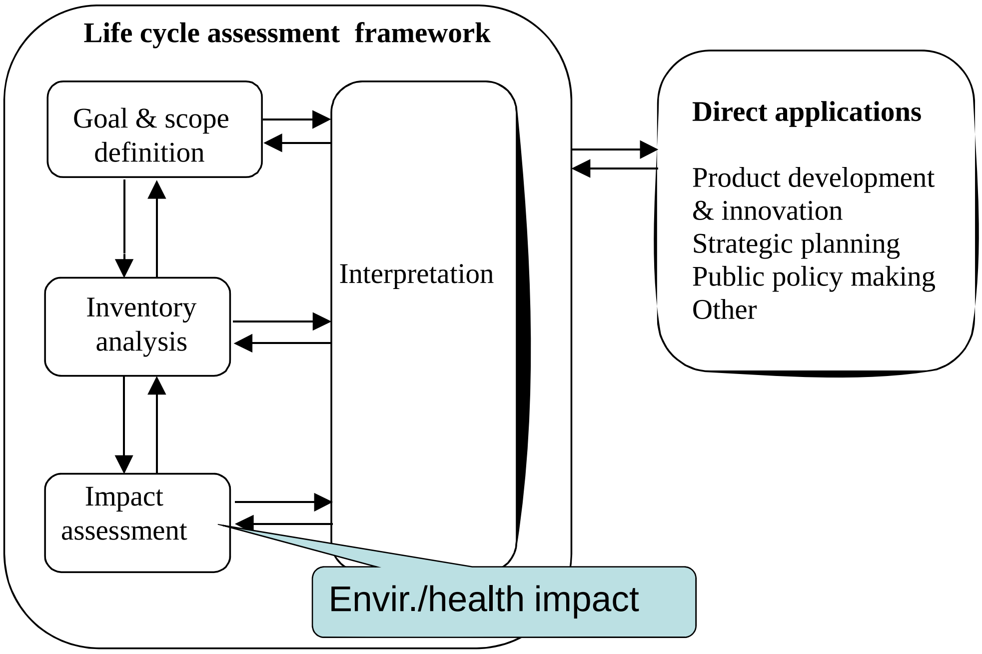
**New:**
*** ISO 14040 (Principles & Framework)**
*** ISO 14044 (Requirements & Guidelines)**

**Old:**
**ISO 14040, 14041, 14042 and 14043**

## How to conduct an inventory analysis and an impact assessment?

1. Make a flowsheet
2. Determine the mass flows of all compounds (mass balance)
3. For commodity products (e.g., PE): Extract from databases impact per tonne product, e.g. $CO_2$/t.
4. For unknown/new products or process steps (e.g., nanoparticle production): Investigate data.
5. Multiply each mass flow (from 2) with impact per tonne product (from 4 and 5)
   → Inventory table

# Steps of an LCA (2/2)



**Life cycle assessment framework**

Goal & scope definition

Inventory analysis

Impact assessment

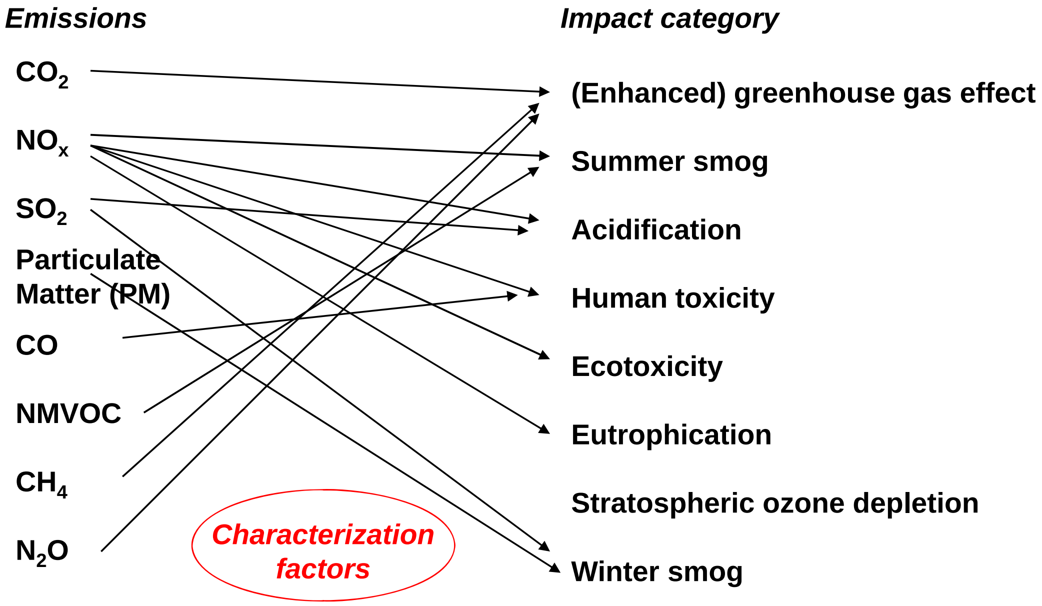
Interpretation

**Direct applications**

Product development & innovation
Strategic planning
Public policy making
Other

Envir./health impact

# From Environmental intervention to Environmental/health impact



*Emissions*

$CO_2$

$NO_x$

$SO_2$

Particulate Matter (PM)

CO

NMVOC

$CH_4$

$N_2O$

*Impact category*

(Enhanced) greenhouse gas effect

Summer smog

Acidification

Human toxicity

Ecotoxicity

Eutrophication

Stratospheric ozone depletion

Winter smog

*Characterization factors*

Source: E. Nieuwlaar, Lecture “Analyse Energie en Materiaal-ketens”, course “Chemie en Duurzame Ontwikkeling (CDO)”, Utrecht University

## Characterization factors for climate change

Compounds contributing to Climate Change (100 year time period):

- $CO_2$ : 1.0 kg $CO_2$ equivalents/kg $CO_2$
- $N_2O$ : 296 kg $CO_2$ equivalents/kg $N_2O$
- $CH_4$ : 25 kg $CO_2$ equivalents/kg $CH_4$
- etc.

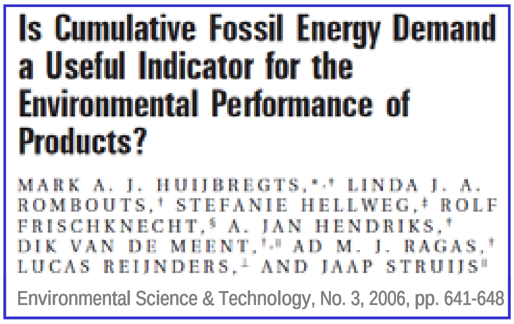
# Environmental Impact Categories (ReCiPe method)

Midpoint level

1. Climate change (CC)
2. Ozone depletion (OD)
3. Terrestrial acidification (TA)
4. Freshwater eutrophication (FE)
5. Marine eutrophication (ME)
6. Human toxicity (HT)
7. Photochemical oxidant formation (POF)
8. Particulate matter formation (PMF)
9. Terrestrial ecotoxicity (TET)
10. Freshwater ecotoxicity (FET)
11. Marine ecotoxicity (MET)
12. Ionising radiation (IR)
13. Agricultural land occupation (ALO)
14. Urban land occupation (ULO)
15. Natural land transformation (NLT)
16. Water depletion (WD)
17. Mineral resource depletion (MRD)
18. Fossil fuel depletion (FD)

Endpoint level

Damage to
1. Human health (HH)
2. Ecosystem diversity (ED)
3. Resource availability (RD)



**Is Cumulative Fossil Energy Demand a Useful Indicator for the Environmental Performance of Products?**

MARK A. J. HUIJBREGTS,[*,†] LINDA J. A. ROMBOUTS,[†] STEFANIE HELLWEG,[‡] ROLF FRISCHKNECHT,[§] A. JAN HENDRIKS,[†] DIK VAN DE MEENT,[†,∥] AD M. J. RAGAS,[†] LUCAS REIJNDERS,[⊥] AND JAAP STRUIJS[∥]

Environmental Science & Technology, No. 3, 2006, pp. 641-648

Goedkoop, Heijungs, Huijbregts, De Schryver, Struijs, van Zelm: ReCiPe method, 2009

# Experience from LCA studies - Contribution of steps to overall envir. impact

- Production of bulk materials often dominant
- Assembly often minor
- For products using energy during use phase:
  Use phase often dominates, otherwise
  production usually dominates
- Transportation: often small contribution
- Waste management: usually rather small contribution

The Hitch Hiker’s Guide to LCA, p. 278 (extended: waste)

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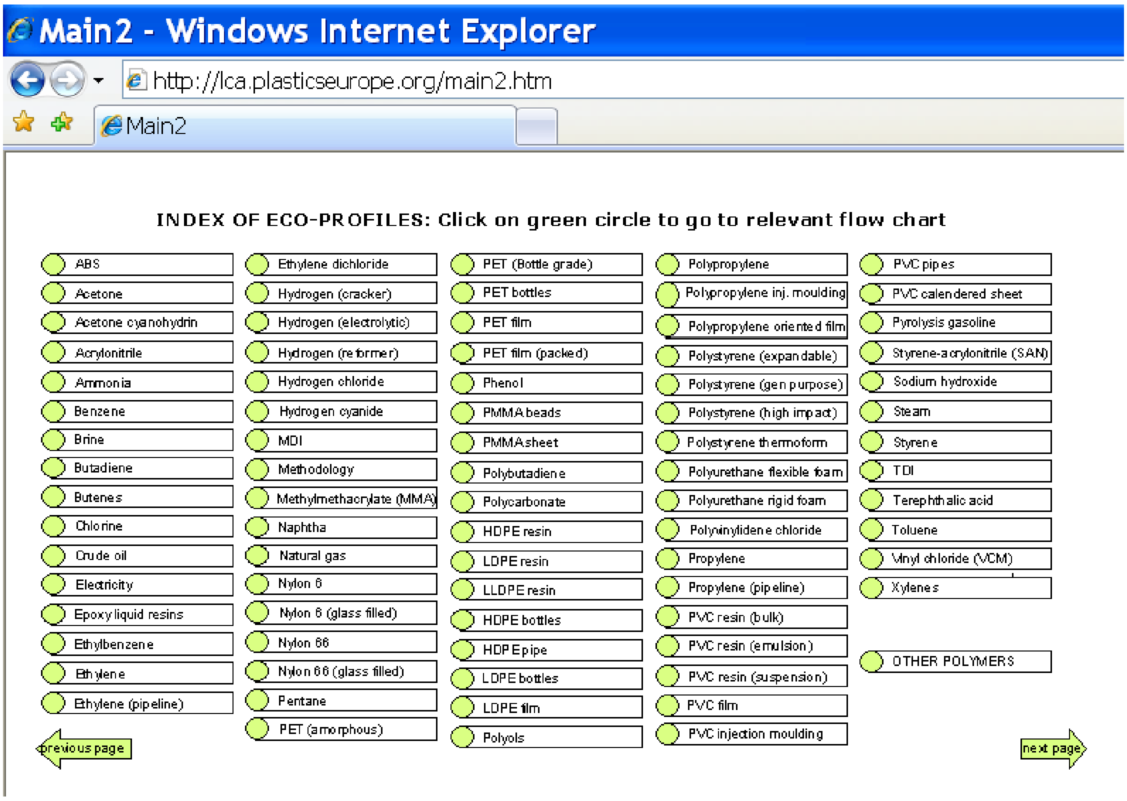
http://lca.plasticseurope.org/main2.htm



INDEX OF ECO-PROFILES: Click on green circle to go to relevant flow chart

- ○ ABS
- ○ Acetone
- ○ Acetone cyanohydrin
- ○ Acrylonitrile
- ○ Ammonia
- ○ Benzene
- ○ Brine
- ○ Butadiene
- ○ Butenes
- ○ Chlorine
- ○ Crude oil
- ○ Electricity
- ○ Epoxy liquid resins
- ○ Ethylbenzene
- ○ Ethylene
- ○ Ethylene (pipeline)
- ○ Ethylene dichloride
- ○ Hydrogen (cracker)
- ○ Hydrogen (electrolytic)
- ○ Hydrogen (reformer)
- ○ Hydrogen chloride
- ○ Hydrogen cyanide
- ○ MDI
- ○ Methodology
- ○ Methylmethacrylate (MMA)
- ○ Naphtha
- ○ Natural gas
- ○ Nylon 6
- ○ Nylon 6 (glass filled)
- ○ Nylon 66
- ○ Nylon 66 (glass filled)
- ○ Pentane
- ○ PET (amorphous)
- ○ PET (Bottle grade)
- ○ PET bottles
- ○ PET film
- ○ PET film (packed)
- ○ Phenol
- ○ PMMA beads
- ○ PMMA sheet
- ○ Polybutadiene
- ○ Polycarbonate
- ○ HDPE resin
- ○ LDPE resin
- ○ LLDPE resin
- ○ HDPE bottles
- ○ HDPE pipe
- ○ LDPE bottles
- ○ LDPE film
- ○ Polyols
- ○ Polypropylene
- ○ Polypropylene inj. moulding
- ○ Polypropylene oriented film
- ○ Polystyrene (expandable)
- ○ Polystyrene (gen purpose)
- ○ Polystyrene (high impact)
- ○ Polystyrene thermoform
- ○ Polyurethane flexible foam
- ○ Polyurethane rigid foam
- ○ Polyvinylidene chloride
- ○ Propylene
- ○ Propylene (pipeline)
- ○ PVC resin (bulk)
- ○ PVC resin (emulsion)
- ○ PVC resin (suspension)
- ○ PVC film
- ○ PVC injection moulding
- ○ PVC pipes
- ○ PVC calendered sheet
- ○ Pyrolysis gasoline
- ○ Styrene-acrylonitrile (SAN)
- ○ Sodium hydroxide
- ○ Steam
- ○ Styrene
- ○ TDI
- ○ Terephthalic acid
- ○ Toluene
- ○ Vinyl chloride (VCM)
- ○ Xylenes
- ○ OTHER POLYMERS

# Discussion and interpretation of the results

**Discussion:**

- For how many impact categories is new product/process better?
- By how much (in %)?
- Is this a lot or little in view of the uncertainties?

**Further questions:**

- What to conclude in the case of a mixed overall picture?
- Is a 50% reduction for one impact category as meaningful as a 50% reduction for another?
  →Normalisation

| ***Impact category*** | **Conventio-neel** | **Nieuw** |
|---|---|---|
| **Climate change.** | 20 kg $CO_2$/f.e. | 10 kg $CO_2$/f.e. |
| **Photochem. smog** | 40 eenh./f.e. | 20 eenh. /f.e. |
| **Acidification** | 20 eenh./f.e. | 20 eenh./f.e. |
| **Human toxicity** | 20 eenh./ f.e. | 30 eenh./ f.e. |
| **Ecotoxicity** | 20 eenh./f.e. | 40 eenh./f.e. |
| **Eutrophication** | 20 eenh./f.e. | 60 eenh./f.e |
| **Ozone depletion** | 20 eenh./f.e. | 5 eenh./f.e. |
| **Winter smog** | 20 eenh./f.e. | 20 eenh./f.e. |

## Normalisation (LCA)

- = Optional step in an LCA
- Main aim: Better understand the relative importance of a value (or a Δ) for a given impact category
- Approach: Divide result by reference value, e.g.
  - total emissions or resource use for a given region
  - per capita emissions or resource use for a given region

# Data for normalization

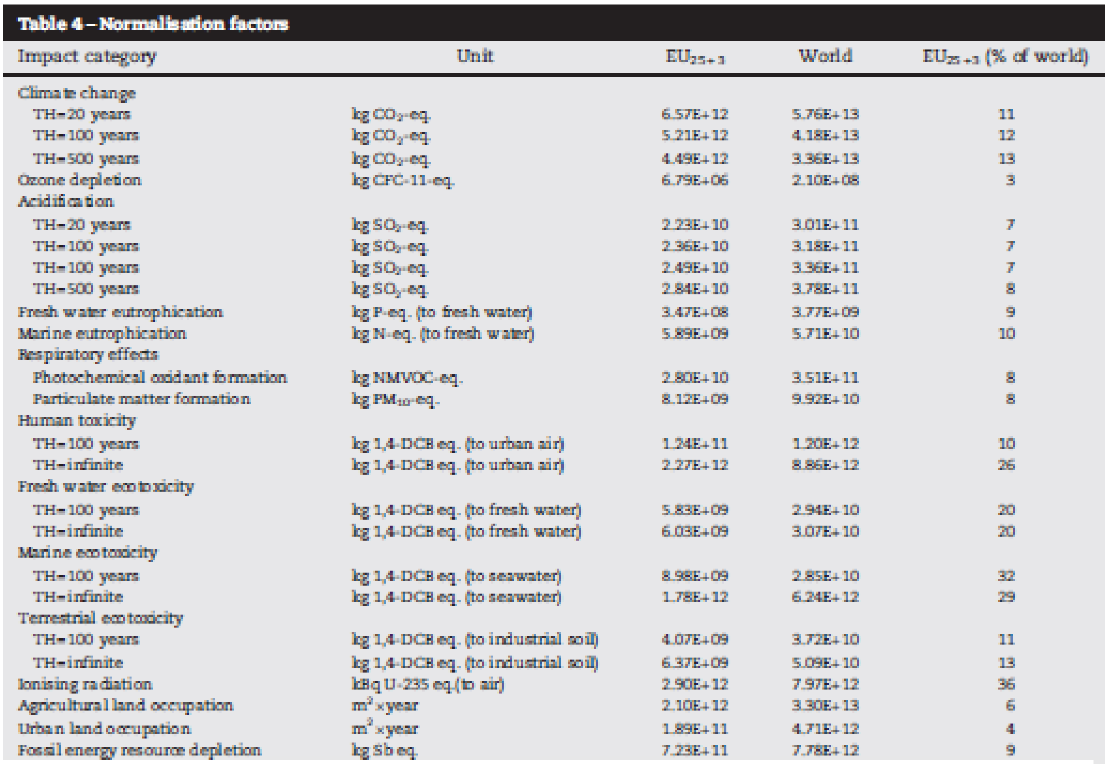


**Table 4 – Normalisation factors**

| Impact category | Unit | EU$_{25+3}$ | World | EU$_{25+3}$ (% of world) |
|---|---|---|---|---|
| Climate change | | | | |
| TH=20 years | kg $CO_2$-eq. | 6.57E+12 | 5.76E+13 | 11 |
| TH=100 years | kg $CO_2$-eq. | 5.21E+12 | 4.18E+13 | 12 |
| TH=500 years | kg $CO_2$-eq. | 4.49E+12 | 3.36E+13 | 13 |
| Ozone depletion | kg CFC-11-eq. | 6.79E+06 | 2.10E+08 | 3 |
| Acidification | | | | |
| TH=20 years | kg $SO_2$-eq. | 2.23E+10 | 3.01E+11 | 7 |
| TH=100 years | kg $SO_2$-eq. | 2.36E+10 | 3.18E+11 | 7 |
| TH=100 years | kg $SO_2$-eq. | 2.49E+10 | 3.36E+11 | 7 |
| TH=500 years | kg $SO_2$-eq. | 2.84E+10 | 3.78E+11 | 8 |
| Fresh water eutrophication | kg P-eq. (to fresh water) | 3.47E+08 | 3.77E+09 | 9 |
| Marine eutrophication | kg N-eq. (to fresh water) | 5.89E+09 | 5.71E+10 | 10 |
| Respiratory effects | | | | |
| Photochemical oxidant formation | kg NMVOC-eq. | 2.80E+10 | 3.51E+11 | 8 |
| Particulate matter formation | kg $PM_{10}$-eq. | 8.12E+09 | 9.92E+10 | 8 |
| Human toxicity | | | | |
| TH=100 years | kg 1,4-DCB eq. (to urban air) | 1.24E+11 | 1.20E+12 | 10 |
| TH=infinite | kg 1,4-DCB eq. (to urban air) | 2.27E+12 | 8.86E+12 | 26 |
| Fresh water ecotoxicity | | | | |
| TH=100 years | kg 1,4-DCB eq. (to fresh water) | 5.83E+09 | 2.94E+10 | 20 |
| TH=infinite | kg 1,4-DCB eq. (to fresh water) | 6.03E+09 | 3.07E+10 | 20 |
| Marine ecotoxicity | | | | |
| TH=100 years | kg 1,4-DCB eq. (to seawater) | 8.98E+09 | 2.85E+10 | 32 |
| TH=infinite | kg 1,4-DCB eq. (to seawater) | 1.78E+12 | 6.24E+12 | 29 |
| Terrestrial ecotoxicity | | | | |
| TH=100 years | kg 1,4-DCB eq. (to industrial soil) | 4.07E+09 | 3.72E+10 | 11 |
| TH=infinite | kg 1,4-DCB eq. (to industrial soil) | 6.37E+09 | 5.09E+10 | 13 |
| Ionising radiation | kBq U-235 eq.(to air) | 2.90E+12 | 7.97E+12 | 36 |
| Agricultural land occupation | $m^2$ ×year | 2.10E+12 | 3.30E+13 | 6 |
| Urban land occupation | $m^2$ ×year | 1.89E+11 | 4.71E+12 | 4 |
| Fossil energy resource depletion | kg Sb eq. | 7.23E+11 | 7.78E+12 | 9 |

Sleeswijk et al.: Normalisation in product life cycle assessment: An LCA of the global and European economic systems in the year 2000. *Science of the Total Environment*, 2008

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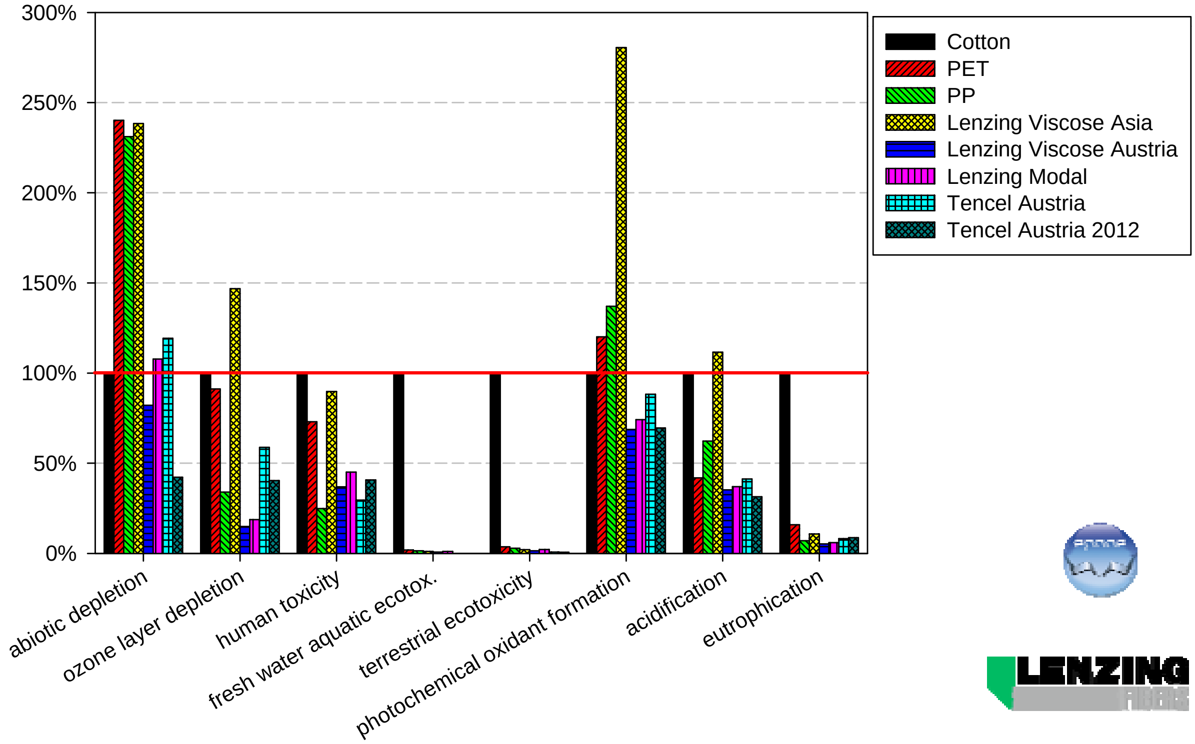
# Environmental impact categories (CML)
# Cradle-to-factory gate, 1 tonne fibre (cotton = 100)



LENZING FIBERS

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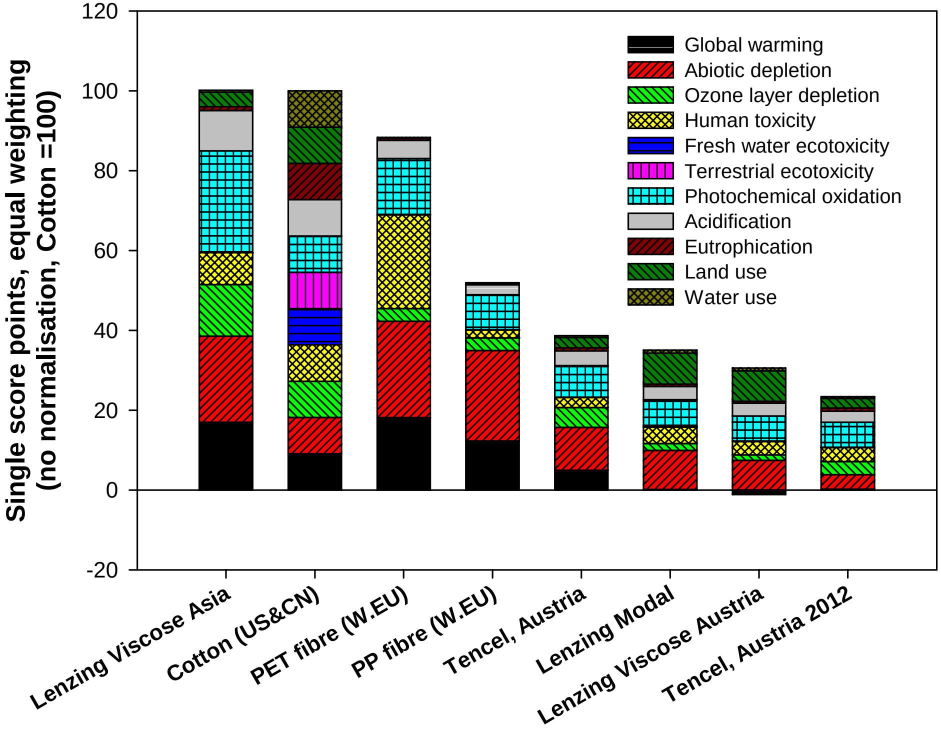
# Single-score result (I) - Equally weighted, Cotton = 100
# 1 tonne fibre, cradle-to-factory gate



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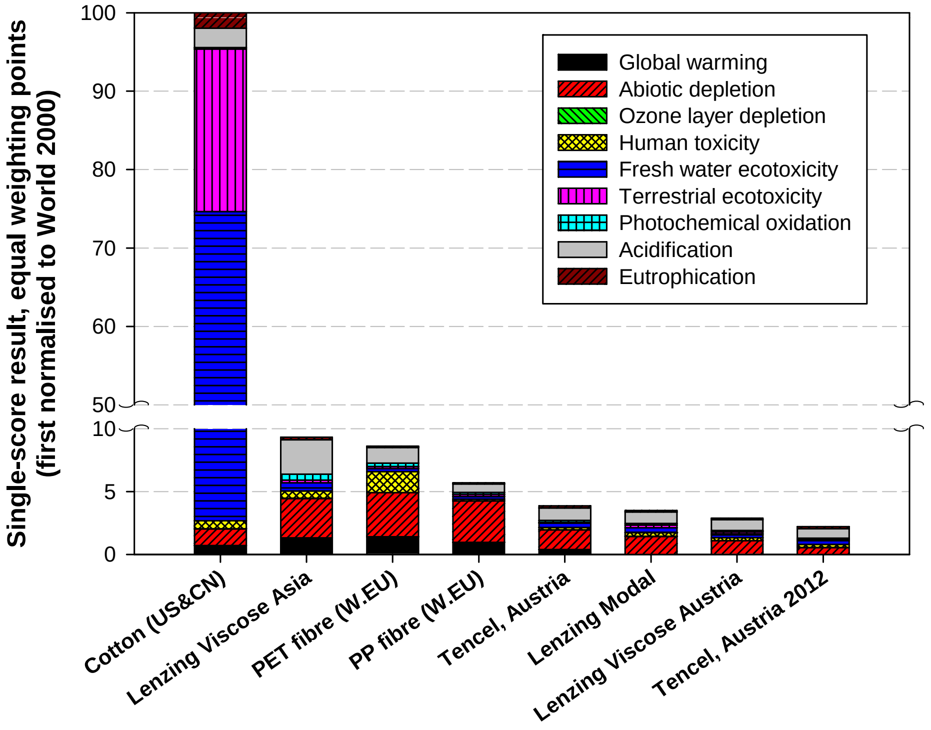
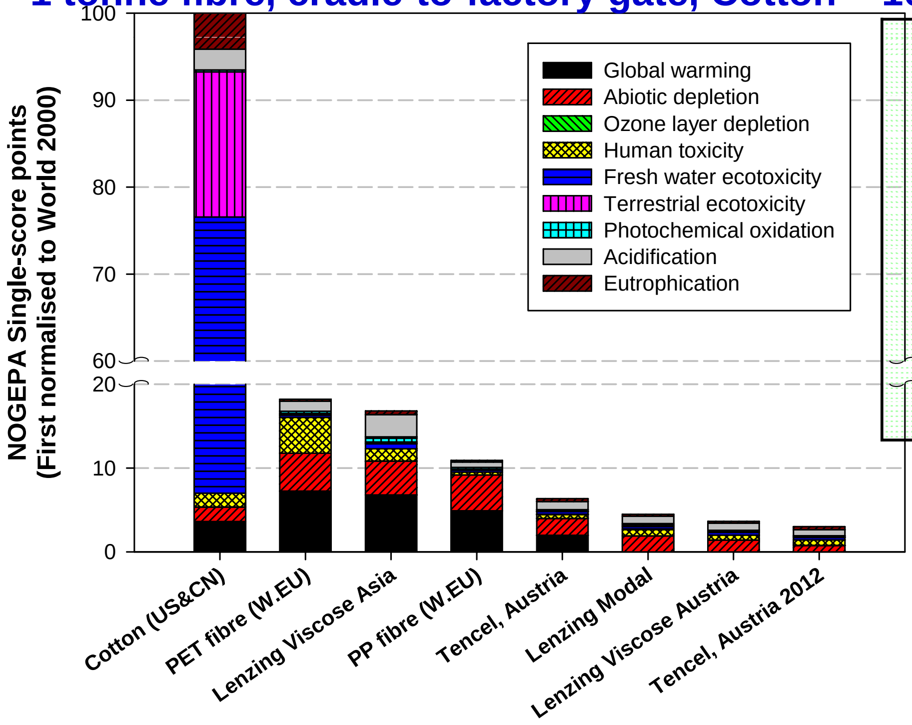
# Single-score result (II)
## Equally weighted, normalised to World 2000
## 1 tonne fibre, from cradle to factory gate, Cotton = 100



# Single-score result (III)
# NOGEPA weighting factors (normalised to world)
# 1 tonne fibre, cradle-to-factory gate, Cotton = 100



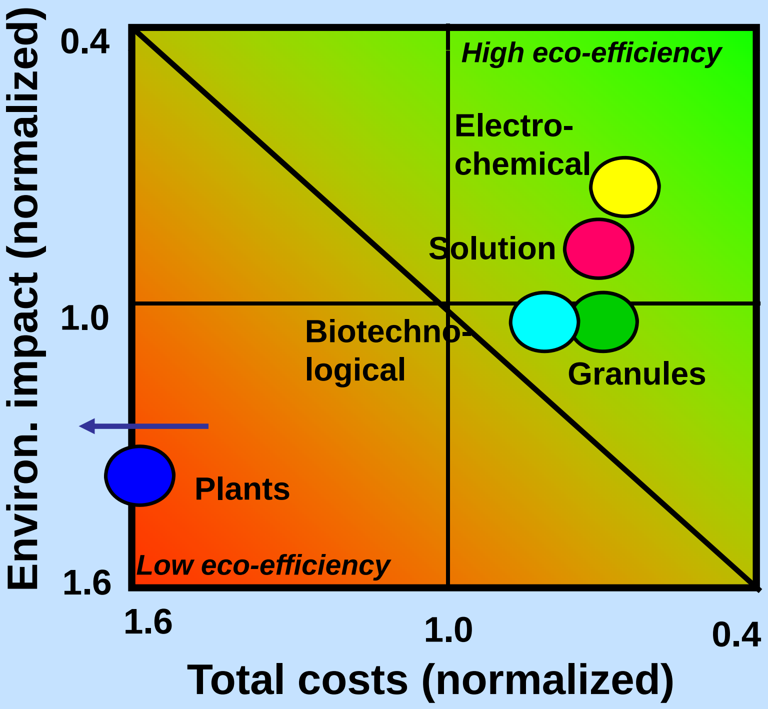
| Weighting factors (NOGEPA) | |
|---|---|
| Climate Change | 32 |
| Abiotic depletion* | 8 |
| Ozone layer depletion | 5 |
| Human toxicity | 16 |
| Fresh water ecotoxicity | 6 |
| Terrestrial ecotoxicity | 5 |
| Photochemical oxidation | 8 |
| Acidification | 6 |
| Eutrophication | 13 |
| Total | 99 |

Source: Huppes et al (2003), except for abiotic depletion (marked with *), which is not excluded by Huppes et al. and is determined based on own estimation.

**BASF**

## In the ecoefficiency portfolio, the environmental impact is plotted against the costs

Benefit: 1000
jeans dyed
with indigo



The electrochemi
indigo variant is t
most eco-efficien
one

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# 5.) What are critical issues in LCA?

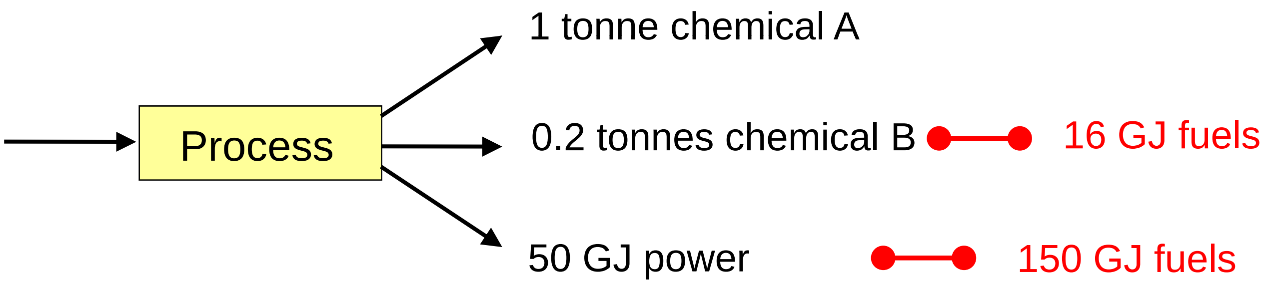
# Critical issues in LCAs - General

| | |
|---|---|
| **Weighting**<br>**(→ single score)** | **ISO: Weighting […] shall not be used in LCA studies intended to be used in comparative assertions intended to be disclosed to the public.** |

| **Phase** | **Problem** |
|---|---|
| Goal and Scope Definition | Functional unit definition<br>Boundary selection<br>Social and economic impacts<br>Alternative scenario considerations |
| Life Cycle Inventory analysis | Allocation<br>Negligible contribution ('cutoff criteria')<br>Local technical uniqueness |
| Life Cycle Impact Assessment | Impact category and methodology selection<br>Spatial variation<br>Local environmental uniqueness<br>Dynamics of the environment<br>Time horizons |
| All phases | Data availability and quality |

Reap J., Roman, F., Duncan, S., Bras, B., 2008a, "A Survey of Unresolved Problems in Life Cycle Assessment", International Journal of Life Cycle Assessment 13(4): 290-300

# What is allocation?



Process

1 tonne chemical A

0.2 tonnes chemical B → 16 GJ fuels

50 GJ power → 150 GJ fuels

**Relevant options**

**a) Partitioning:**

- Mass
- Economic value
- Energy content (calorific value)

**b) System expansion:**

- Credits for chemical B and for power

# Critical issues in LCAs for Bio-based products

- Allocation
- Valuation of embedded bio-based carbon
- Default datasets for bio-based feedstocks
- Land use efficiency
- Soil carbon
- Land use change (e.g. LUC in PAS 2050; ILUC)
- Other

## How can you check whether/ensure that an LCA leads to robust results?

Check

- Suitable functional unit
- Allocation (judgment; test & present alternative approaches)
- System boundaries
  - C2F vs. C2G
  - Carbon storage in products
  - Factor in land use
  - Clean distinction between Technology perspective and Company perspective
  - etc.
- Environmental impact categories
- Availability and quality of LCA data

## What this presentation aimed to answer

1. What is Life Cycle Assessment (LCA), also in comparison to Green Chemistry principles?
2. Why do LCA?
3. How does it roughly work?
4. What are critical issues in LCA?
5. Would it make sense to conduct an LCA in your project?