Uncertainty analysis in LCA
Concepts, tools, and practice

Reinout Heijungs
Institute of Environmental Sciences (CML)
Leiden University

Universiteit Leiden

Contents

- Lectures on uncertainty analysis in LCA (8:30 - 10:00)
- Practical assignment on uncertainty with the CMLCA model (10:30 - 12:30)

Part 1

Uncertainty analysis in LCA

Concepts and tools

Contents

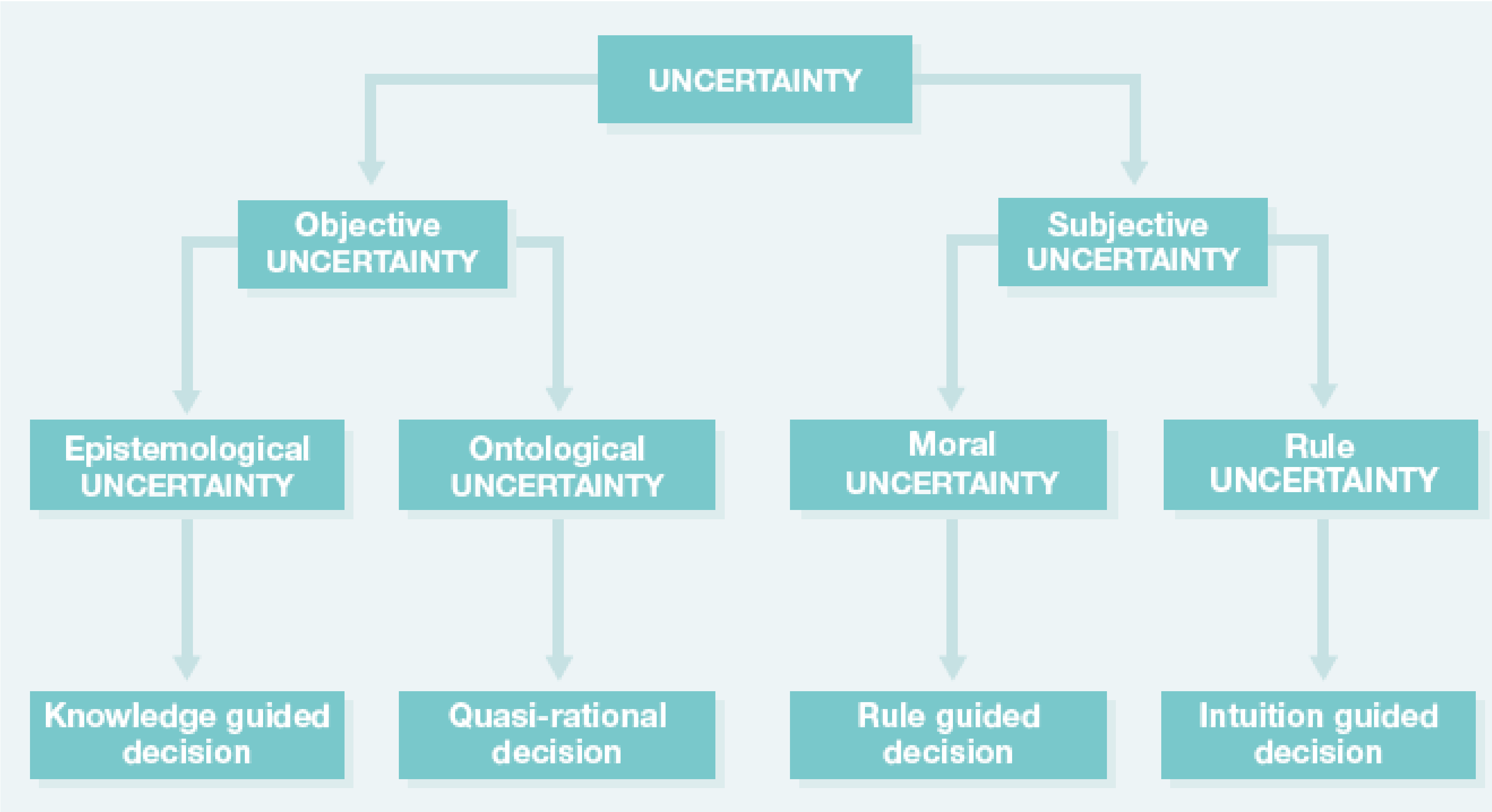
What is uncertainty? (1)

- Lots of meanings:
  - incomplete information
  - conflicting information
  - linguistic imprecision
  - variability
  - errors
  - ...

What is uncertainty? (2)

- Abundance of typologies and terminologies:
  - systematic errors, random errors, ...
  - data uncertainty, model uncertainty, completeness uncertainty, ...
  - scenario uncertainty, parameter uncertainty, model uncertainty, ...
  - uncertainty vs. accuracy vs. variability vs. sensitivity vs. ...
  - ...

What is uncertainty? (3)



EMBO 8:10 (2007)

How to deal with uncertainty? (1)

- Do more research
  - “recommendation for future research”
- Abandon LCA
  - not exactly ...
- Interpret LCA results very cautiously
  - of course, but how?
- Involve stakeholders
  - does this reduce or increase the uncertainty?
- ...

How to deal with uncertainty? (2)

- ...
- Rerun the LCA with different data
  - sounds not very systematic
- Use Monte Carlo analyses
  - please tell me more ...
- Use analytical approaches
  - please tell me more ...
- Use less traditional methods
  - please tell me more ...

Increasing interest in uncertainty in LCA (1)

Editorial and Call for Papers: Announcing the New Section 'Uncertainties'

Uncertainties in Life Cycle Assessment

Andreas Ciroth

Dr.-Ing. Andreas Ciroth, GreenDeltaTC GmbH, Raumerstrasse 7, D-10437 Berlin, Germany (ciroth@greendeltatc.com)

Uncertainties in LCAs are cumbersome, easily ignored, and not wanted. Why a new section 'Uncertainties in LCAs'? For several reasons.

First, there are an increasing number of papers dealing with uncertainties in Life Cycle Assessment and sustainability measures to be found in this Journal: 50 papers have uncertainty as a keyword; the SETAC annual meeting in Prague dedicated an interactive poster session to this topic; the upcoming International Environmental Modelling and Software Society Conference to be held in Osnabrueck, Germany (IEMS, 14–17 June 2004) has a section Uncertainty in LCA, to name just a few.

All these efforts aside, there still seems to be a lack of appropriate methods and ideas on how to deal with uncertainty in LCAs, an

assurance analyses in product development, and in other fields where a decision based on a result of a study has relevance, uncertainty frequently is addressed.

Recently, LCA has gained attention in legislation, e.g. on the national, German level (the German 'VerpackV' – packaging regulation) and on the EU level (e.g. the eco-design requirements for energy using products Directive), and is discussed as a tool for backing political decisions about the environmental performance of products, or for motivating, case specific deviances from general requirements. This puts more emphasis on the uncertainty question in LCAs.

In addition to this main reason, there are a number of others: Decision makers may have different attitudes towards different

IntJLCA 9:3 (2004)

Increasing interest in uncertainty in LCA (2)

JIE 11:1 (2007)

Characterizing, Propagating, and Analyzing Uncertainty in Life-Cycle Assessment

A Survey of Quantitative Approaches

Table 2 LCA Studies Performing Quantitative Uncertainty Analysis and Reviewed in this Survey

Year	*Journal publication or published conference proceeding reference*
1996	Chevalier and Le Téno 1996; Heijungs 1996; Kennedy and colleagues 1996; Weidema and Wesnæs 1996
1997	Kusko and Hunt 1997; Steen 1997
1998	Huijbregts 1998; Raynolds and colleagues 1998; Saur and colleagues 1998
1999	LeTéno 1999; Checkel and colleagues 1999
2000	Geldermann and colleagues 2000; Maurice 2000
2001	Weckenmann and Schwan 2001
2002	Canter and colleagues 2002; McCleese and LaPuma 2002; Tan and colleagues 2002
2003	Huijbregts and colleagues 2003; Sonnemann and colleagues 2003
2004	Basset-Mens and colleagues 2004; Basson and Petrie 2004; Ferret and colleagues 2004; Geisler and colleagues 2004; Tan and colleagues 2004

Increasing interest in uncertainty in LCA (3)

- Case studies
  - Meier, Maurice et al., Sonneman et al, Rogers et al., etc.
- Methodological proposals
  - Huijbregts, Ciroth, Hofstetter, Heijungs & Suh, etc.
- Data (LCI, LCIA)
  - ecoinvent, Guinée et al., Goedkoop & Spriensma, etc.
- Software
  - GaBi, SimaPro, CMLCA, etc.

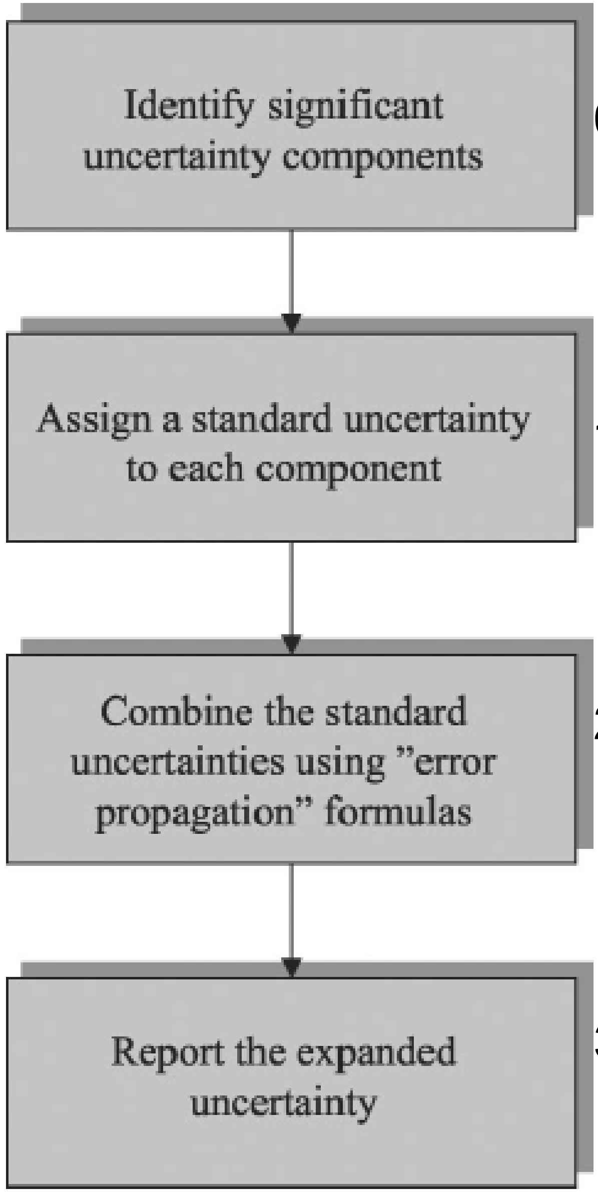
Treatment of uncertainties (1)

- Four main paradigms:
  1. “scientific” approach (more research, better data)
  2. “social” approach (stakeholders, agreements)
  3. “legal” approach (authoritative bodies)
  4. “statistical” approach (Monte Carlo, confidence intervals)
- What makes 4 special?

  1, 2, 3 reduce uncertainty

  4 incorporates uncertainty

Treatment of uncertainties (2)



0: scanning uncertainties

1: input uncertainties

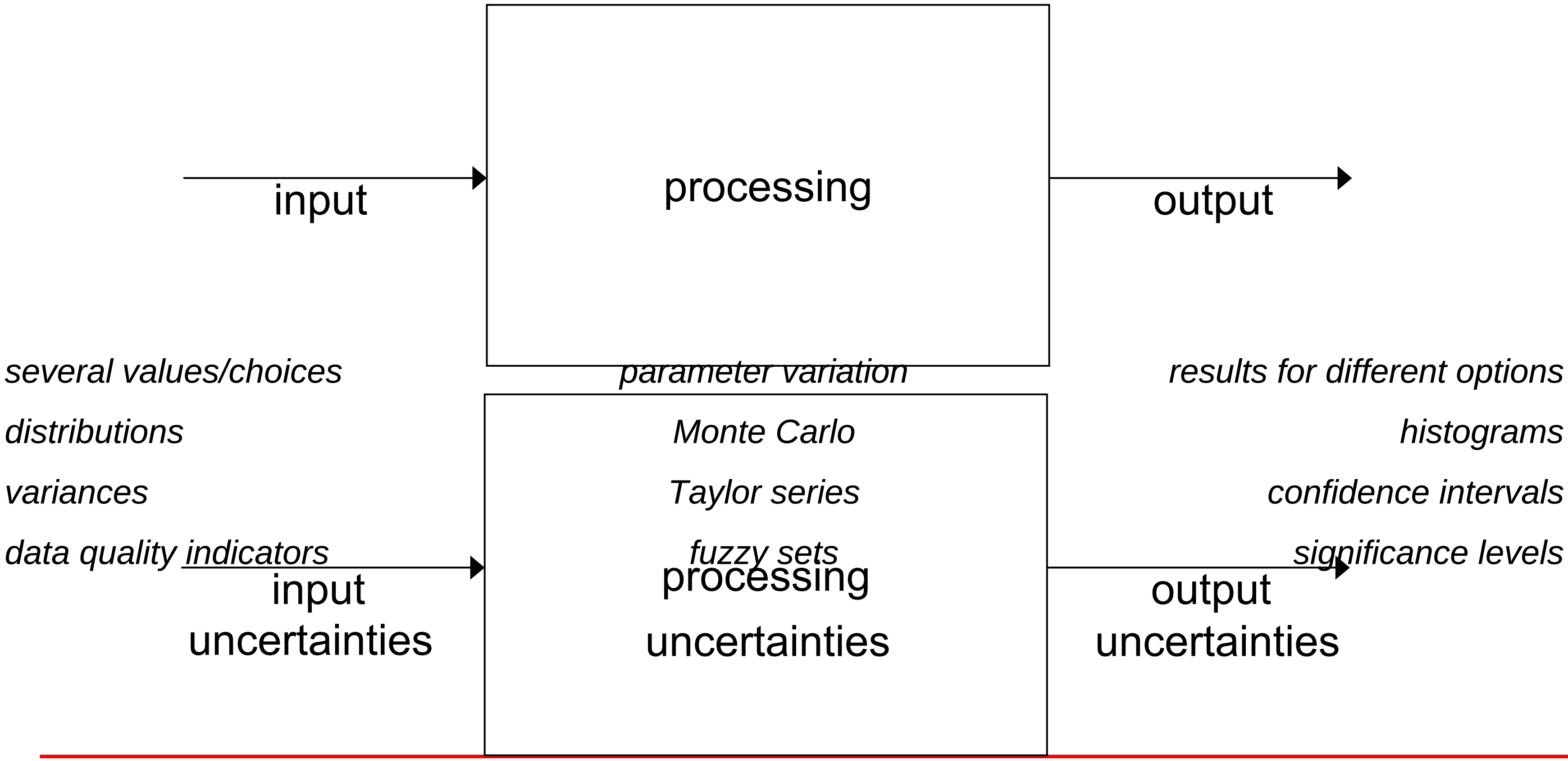
2: processing uncertainties

3: output uncertainties

Clin.Chem. 49:11 (2003)

Treatment of uncertainties (3)

- General modeling framework for LCA



Elements in uncertainty handling (1)

- Standardization
  - terminology (what is the difference between sensitivity and uncertainty analysis)
  - symbols (what do we mean with μ?)
  - data format (how to report a lognormal distribution?)

Elements in uncertainty handling (2)

- Education
  - concepts (what is a significant difference?)
  - reporting (how many digits?)
  - value of not reducing but incorporating uncertainty
  - communication (how to tell?)

Elements in uncertainty handling (3)

- Development
  - approaches (Monte Carlo, bootstrapping, principal components analysis, condition number, etc.)
  - software (with lots of approaches)
  - databases (which supports lots of approaches)
  - guidelines (for applying which approach in which situation)

Input uncertainties (1)

- All data and choices that are input in the LCA model
  - unit process data
  - selection of technologies
  - the LCI model choices
  - characterization
  - normalization
  - weighting
  - ...

Input uncertainties (2)

- Unit process data
  - material and energy use
  - production
  - emissions
  - ...
- Example
  - the fuel consumption and CO_2 emission for one km car driving

Input uncertainties (3)

- Selection of technologies
  - geography
  - time
  - technology
  - ...
- Example
  - electricity production

Input uncertainties (4)

- The LCI model choices
  - system boudnaries & cut-off
  - allocation
  - attributional/consequential
  - linearity
  - steady-state
  - ceteris paribus assumption
  - ...

Input uncertainties (5)

- Characterization
  - choice of impact categories and characterization models
  - characterization factors
  - ...
- Example
  - climate change?
  - GWP?
  - GWP100?
  - GWP100(CH_4) = ?

Input uncertainties (6)

- Normalization
  - choice of reference area and period
  - normalization data
  - ...
- Weighting
  - principle
  - factors
  - ...

Input uncertainties (7)

- How to specify?
  - several values (choices and data)
  - range (min & max)
  - probability distribution (empirical, theoretical, fuzzy)
  - DQI/NUSAP
  - ...

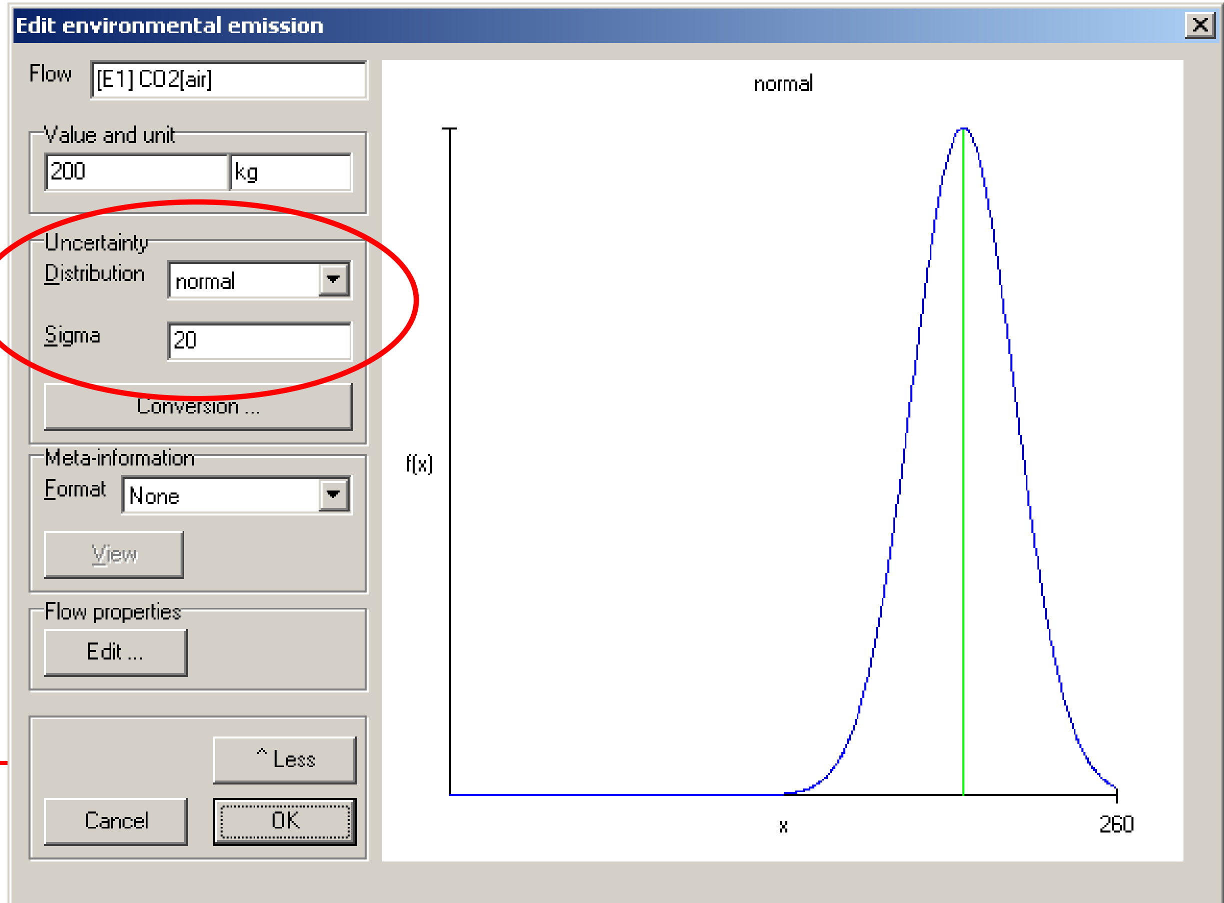
Input uncertainties (8)

- Probability distributions & DQI
  - example from EcoSpold


```
- <exchange number="1069" category="metals" subCategory="extraction" localCategory="Metalle"
    localSubCategory="Gewinnung" name="cast iron, at plant" location="RER" unit="kg"
    uncertaintyType="1" meanValue="50000" standardDeviation95="1.22"
    generalComment="(2,3,1,1,1,5)" localName="Gusseisen, ab Werk" infrastructureProcess="false">
    <inputGroup>5</inputGroup>
  </exchange>
```

Input uncertainties (9)

- Probability distributions & DQI
  - example from CMLCA



Processing uncertainties (1)

- The question of LCA methodology:
  - How to combine input data into output results?
- The question of LCA uncertainty methodology:
  - How to combine input uncertainties into output uncertainties

Processing uncertainties (2)

- Some main schools:
  - parameter variation
  - sampling methods
  - analytical error propagation
  - fuzzy sets
  - Bayesian statistics
  - expert elicitation
  - ...

Processing uncertainties (3)

- Parameter variation
  - just try a smallest and a largest value
  - just take another allocation principle
  - just use another impact assessment method
  - ...

Processing uncertainties (4)

- Sampling methods
  - create a sample of results
  - using brute computational force (Monte Carlo)
  - or using more sophisticated methods (Latin hypercube, etc.)

Processing uncertainties (5)

- Monte Carlo analysis in 5 steps
  1. Consider every input parameter as a stochastic variable with a specified probability distribution
     - e.g., CO_2-emission of electricity production follows a normal distribution with a mean of 1 kg and a standard deviation of 0.05 kg
  2. Construct the LCA-model with one particular realization of every stochastic parameter
     - e.g., CO_2-emission of electricity production is 0.93 kg

Processing uncertainties (6)

3. Calculate the LCA-results with this particular realization
   - e.g., CO_2-emission of system is 28,636 kg
4. Repeat this for a large number of realisations
   - e.g., number of runs N = 1000
5. Investigate statistical properties of the sample of LCA-results
   - e.g., the mean, the standard deviation, the confidence interval, the distribution

Processing uncertainties (7)

- Analytical treatment in 2 steps
  1. Consider every input parameter as a stochastic variable with a specified mean and standard deviation (or variance)
     - e.g., CO_2-emission of electricity production has a mean of 1 kg and a standard deviation of 0.05 kg
  2. Apply classical rules of error propagation
     - e.g., elaborate formula for standard deviation (or variance) of CO_2-emission of system

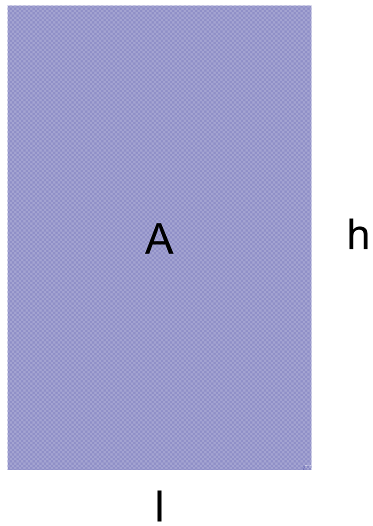
Processing uncertainties (8)

- Example: area of sheet of paper

$$A = l \times h$$

$$\text{var}(A) = \left(\frac{\partial A}{\partial l}\right)^2 \text{var}(l) + \left(\frac{\partial A}{\partial h}\right)^2 \text{var}(h)$$

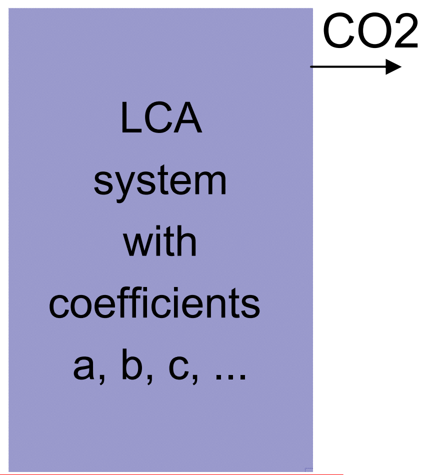
$$\text{var}(A) = h \times \text{var}(l) + l \times \text{var}(h)$$



- Same idea for LCA:

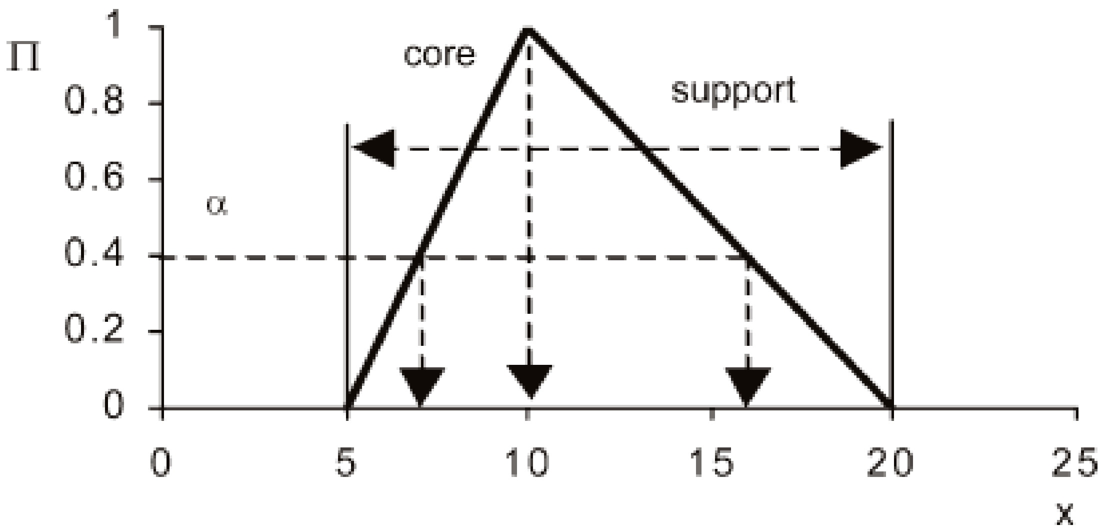
$$\text{CO2} = f(a,b,c,\ldots)$$

$$\text{var}(\text{CO2}) = \left(\frac{\partial f}{\partial a}\right)^2 \text{var}(a) + \left(\frac{\partial f}{\partial b}\right)^2 \text{var}(b) + \left(\frac{\partial f}{\partial c}\right)^2 \text{var}(c) + \cdots$$



Processing uncertainties (9)

- Fuzzy sets
  - Benetto, Ardente, Tan, ...



IntJLCA 13:7 (2008)

Output uncertainties (1)

- All results that are output of the LCA model
  - CO2 and other emissions and resources
  - climate change and other midpoint impact scores
  - human health and other endpoint scores
  - ecopoints and other aggregated scores
  - eco-efficiency and other indicators
  - contribution analyses
  - ranking of alternatives
  - recommendations
  - ...

Output uncertainties (2)

- Different formats
  - several values
  - ranges
  - standard deviation/variance/geometrical sd
  - histograms/boxplots
  - statistical tests
  - ...

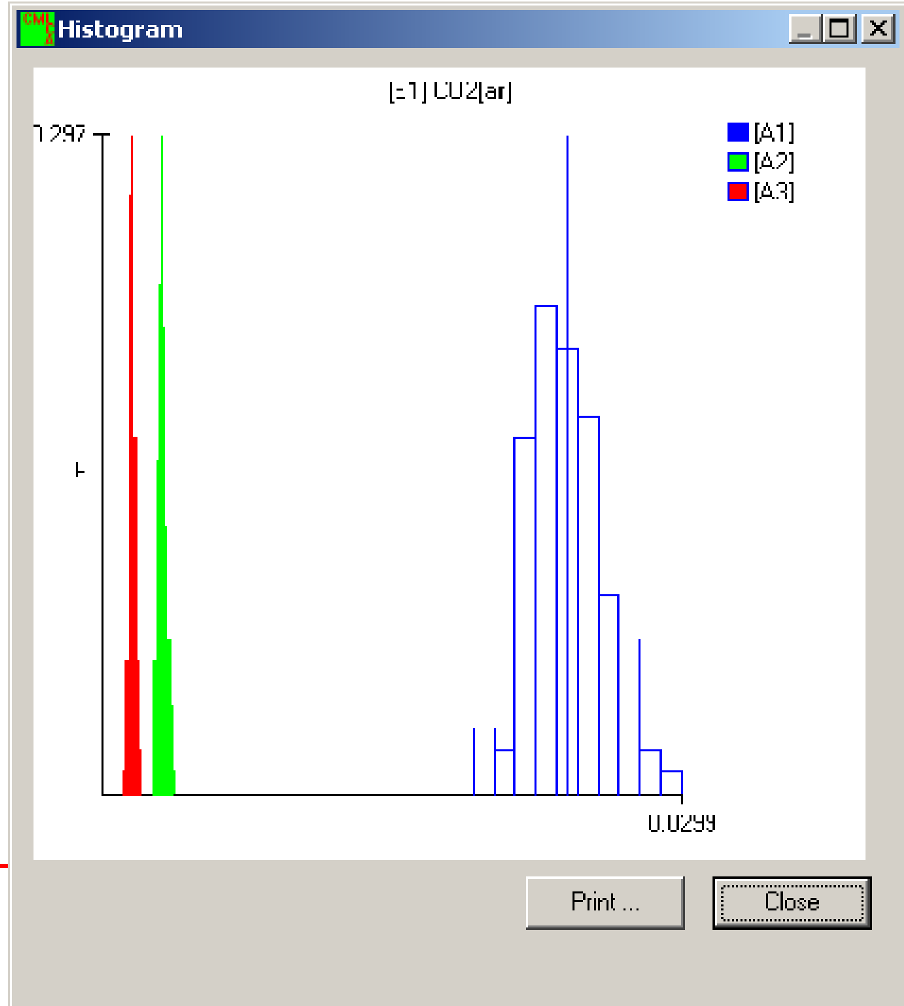
Output uncertainties (3)

- Standard deviation and range
  - example from EcoSpold


```
- <exchange number="2529" category="air" subCategory="high population density" localCategory="Luft"
    localSubCategory="Stadt" CASNumber="000075-07-0" name="Acetaldehyde" unit="kg"
    meanValue="0.10063" standardDeviation95="0.037117" minValue="0.054566" maxValue="0.1932"
    formula="CH3CHO" localName="Acetaldehyd" infrastructureProcess="false">
    <outputGroup>4</outputGroup>
  </exchange>
```

Output uncertainties (3)

- Histograms
  - example from CMLCA



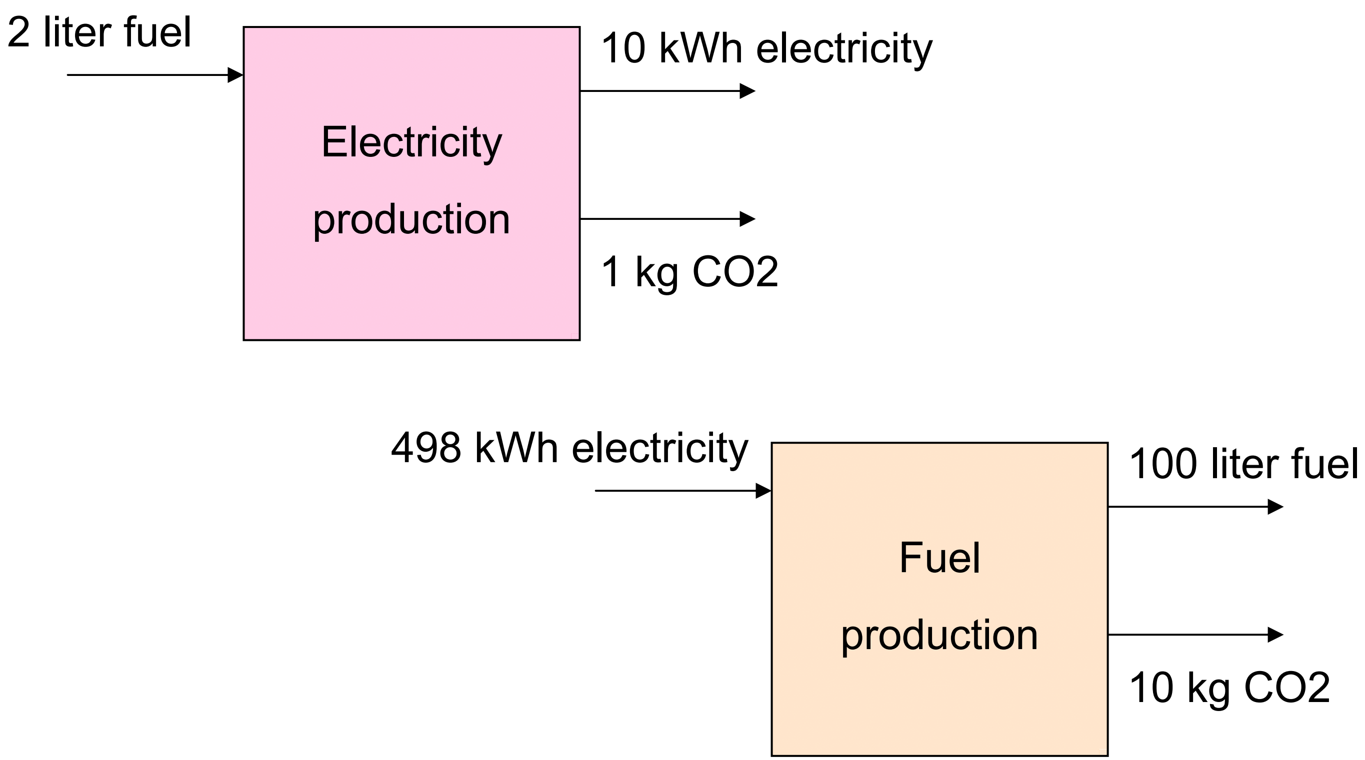
Output uncertainties (4)

- Statistical tests
  - is the CO_2 emission < 120 kg?
  - with what probability?
  - is $CO_2(A) < CO_2(B)$?
  - with what probability?

Sensitivity analysis

- Two distinct meanings:
  - how sensitive is an output result to an input change?
  - which input uncertainty contributes most?

Sensitivity of LCA results (1)

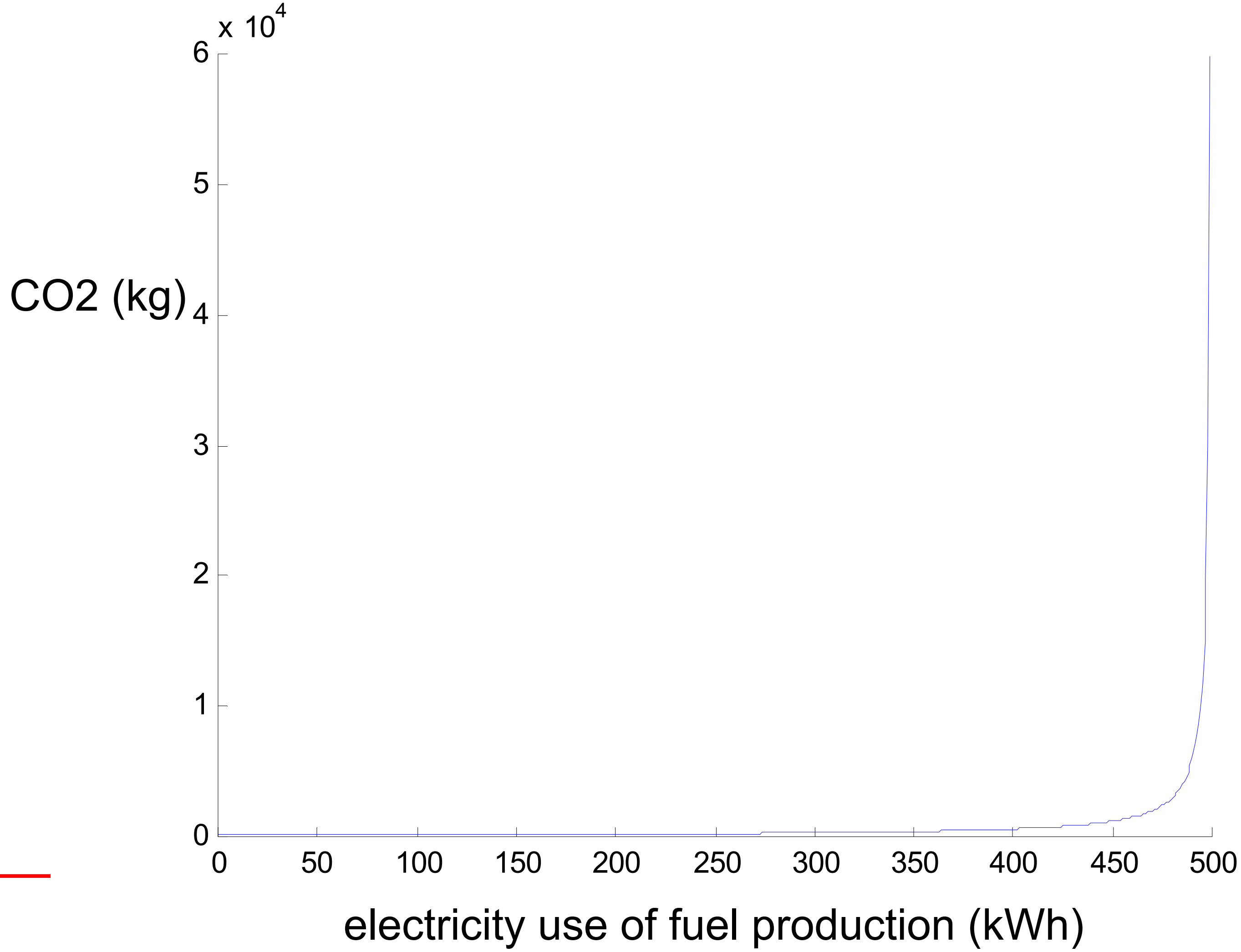


- Reference flow: 1000 kWh electricity
- Inventory result: 30,000 kg CO2

Sensitivity of LCA results (2)

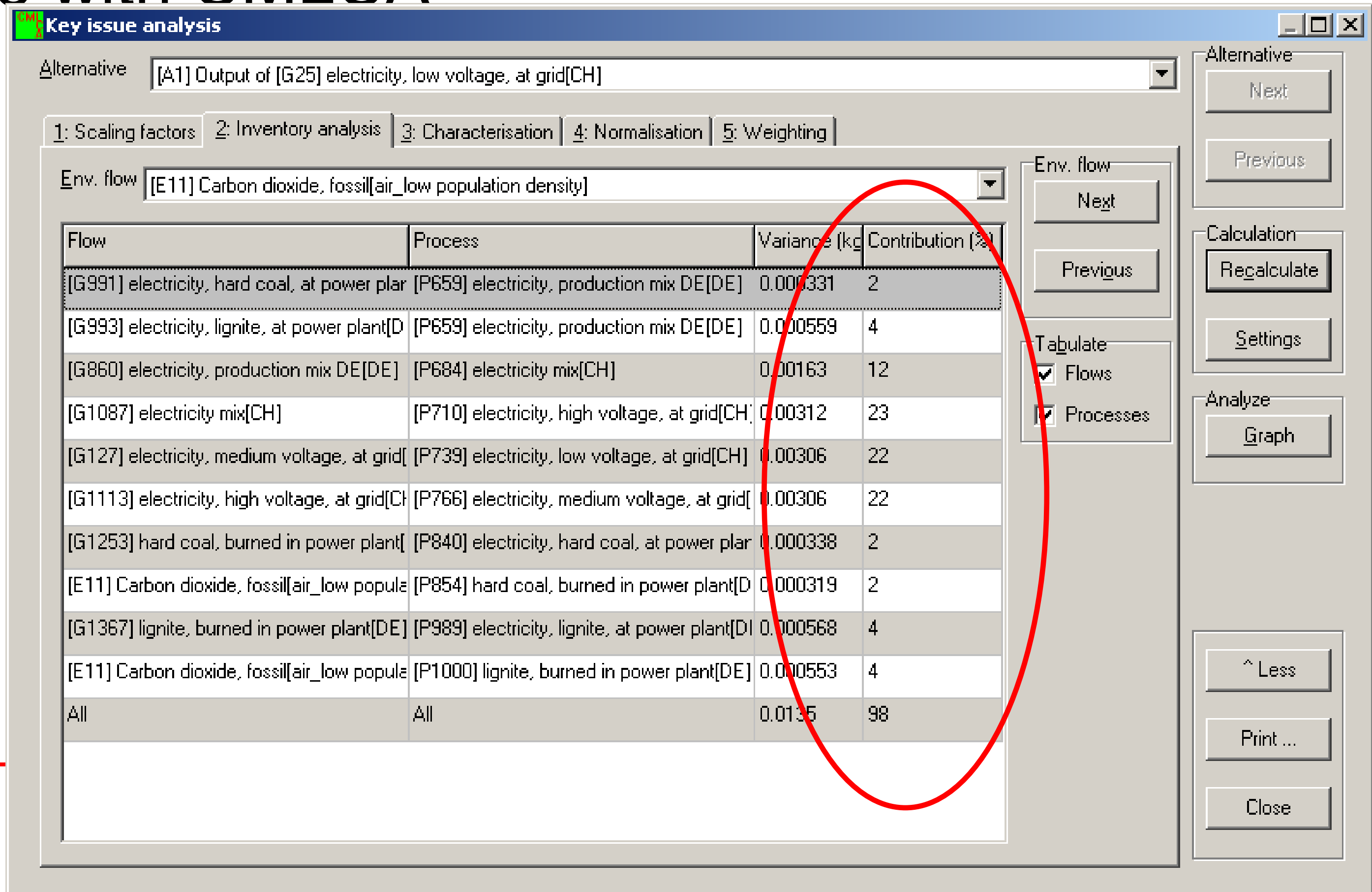
- Change “498” into “499” (i.e. 0.2% change)
  - “30.000” is changed into “60.000” (i.e. 100% change)
- Magnification of uncertainty by a factor 500 is possible in a system that is
  - small
  - linear
- Can we understand this?

Sensitivity of LCA results (3)



Sensitivity as decomposition

- "Key issues"
  - example with CMLCA



Flow	Process	Variance (kg	Contribution (%)
[G991] electricity, hard coal, at power plar	[P659] electricity, production mix DE[DE]	0.000331	2
[G993] electricity, lignite, at power plant[D	[P659] electricity, production mix DE[DE]	0.000559	4
[G860] electricity, production mix DE[DE]	[P684] electricity mix[CH]	0.00163	12
[G1087] electricity mix[CH]	[P710] electricity, high voltage, at grid[CH]	0.00312	23
[G127] electricity, medium voltage, at grid[	[P739] electricity, low voltage, at grid[CH]	0.00306	22
[G1113] electricity, high voltage, at grid[CH	[P766] electricity, medium voltage, at grid[	0.00306	22
[G1253] hard coal, burned in power plant[	[P840] electricity, hard coal, at power plar	0.000338	2
[E11] Carbon dioxide, fossil[air_low popula	[P854] hard coal, burned in power plant[D	0.000319	2
[G1367] lignite, burned in power plant[DE]	[P989] electricity, lignite, at power plant[DI	0.000568	4
[E11] Carbon dioxide, fossil[air_low popula	[P1000] lignite, burned in power plant[DE]	0.000553	4
All	All	0.0135	98

The future of uncertainties (1)

- Methods
  - further development of concepts
  - translation to LCA
- Data
  - LCI databases
  - LCIA factors
- Software
  - implementation
  - electronic exchange formats

The future of uncertainties (2)

- Illustrative cases
  - journal requirements
- Standardization
  - Code of Practice
  - nomenclature, formats
- Education
  - like today

Part 2

Practical assignment on uncertainty analysis with the CMLCA model

Contents

- A short introduction to CMLCA
- Uncertainty analysis in CMLCA
- Sensitivity analysis in CMLCA
- Sensitivity of LCA results

A short introduction to CMLCA (1)

- CMLCA
  - Chain Management by Life Cycle Assessment
  - developed for educational purposes
  - gradually evolved for scientific research
  - stable version 4.2
  - “sneaky preview” of version 5.1
  - Website http://www.cmlca.eu

A short introduction to CMLCA (2)

- Some features
  - fully based on matrix algebra
    - (Heijungs & Suh, The computational structure of LCA, Springer, 2002)
  - LCI, LCIA, but especially strong in interpretation
    - (Heijungs et al, Numerical approaches towards life cycle interpretation, Int.J.LCA, 2001, 2005)
  - many more features
    - LCC, eco-efficiency, EIOA, hybrid LCA, import/export

A short introduction to CMLCA (3)

- Life cycle interpretation
  - uncertainty analysis
    - choice between sampling and analytical error propagation
    - incorporating paired comparisons (correlated results)
    - including statistical tests
  - sensitivity analysis
    - perturbation analysis
    - key issue analysis

Uncertainty analysis in CMLCA (1)

- Input data
  - coefficients to represent parameter uncertainty
    - unit processes (technology matrix & intervention matrix)
    - characterization factors
    - normalization data
    - weighting factors
  - specification as baseline value + uncertainty parameter
    - Gaussian (sd)
    - uniform (width)
    - triangular (width)
    - lognormal (phi)

Uncertainty analysis in CMLCA (2)

- Possibilities
  - levels: inventory, characterization, normalization, weighting
  - methods: 1st order Taylor expansion, Monte Carlo

Uncertainty analysis in CMLCA (3)

- Results
  - independent parametric: mean, standard deviation, 95% limits, ...
  - independent non-parametric: median, quartile variation, ...
  - dependent parametric: t-test with H0: mean(A)=mean(B)
  - dependent non-parametric: t-test with H0: median(A)=median(B)
  - runs of the Monte Carlo simulation

Sensitivity analysis in CMLCA (1)

- Perturbation analysis
  - change each coefficient 1% and see how much the results change
  - numerical or analytical
- Key issue analysis
  - decompose uncertainty of result into contributions by uncertainties in input data
  - analytical (or sampling with regression)

Sensitivity analysis in CMLCA (2)

- Input data
  - perturbation analysis: no uncertainty data needed
  - key issue analysis: same data requirements as for uncertainty analysis

Sensitivity analysis in CMLCA (3)

- Possibilities
  - levels: inventory, characterization, normalization, weighting
  - methods:
    - perturbation analysis: numerical, 1st order Taylor expansion
    - key issue analysis: Monte Carlo

Sensitivity analysis in CMLCA (4)

- Results
  - perturbation analysis: list of sensitive input parameters
  - key issue analysis: list of parameters of which the uncertainty contributes a lot

Thank you!

- Leiden University, Institute of Environmental Sciences, Department of Industrial Ecology
  - http://cml.leiden.edu
  - http://www.cmlca.eu