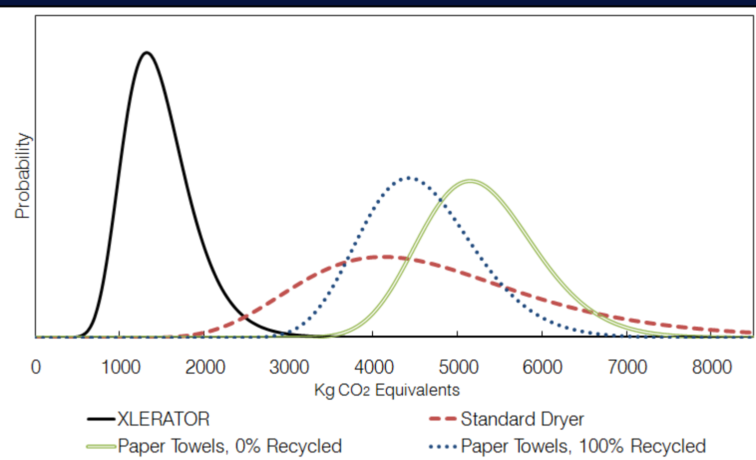
Analytical Uncertainty Propagation in Life Cycle Inventory and Impact Assessment: high-efficiency versus conventional hand dryers



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1. Introduction

- **Uncertainty analysis is essential to inform the decision maker on the reliability of the information**

- **Typically for an LCA want to know the degree of confidence in the information that impact of scenario A is lower than B or A/B<1**

- **Different types of uncertainty (Model, parameter) + variability. Focus is to look at the contribution of parameter uncertainty**

2. Method Monte Carlo and sensitivity

Monte-Carlo

- Advantage to avoid to define output distribution…but
- Rather resource intensive
- Difficult to assess contributions of individual parameters
- Only accounts for parameter uncertainty

- Alternative approaches to effectively estimate uncertainty contributions are highly needed.
- Combining uncertainty propagation in LCI and LCIA phases is important

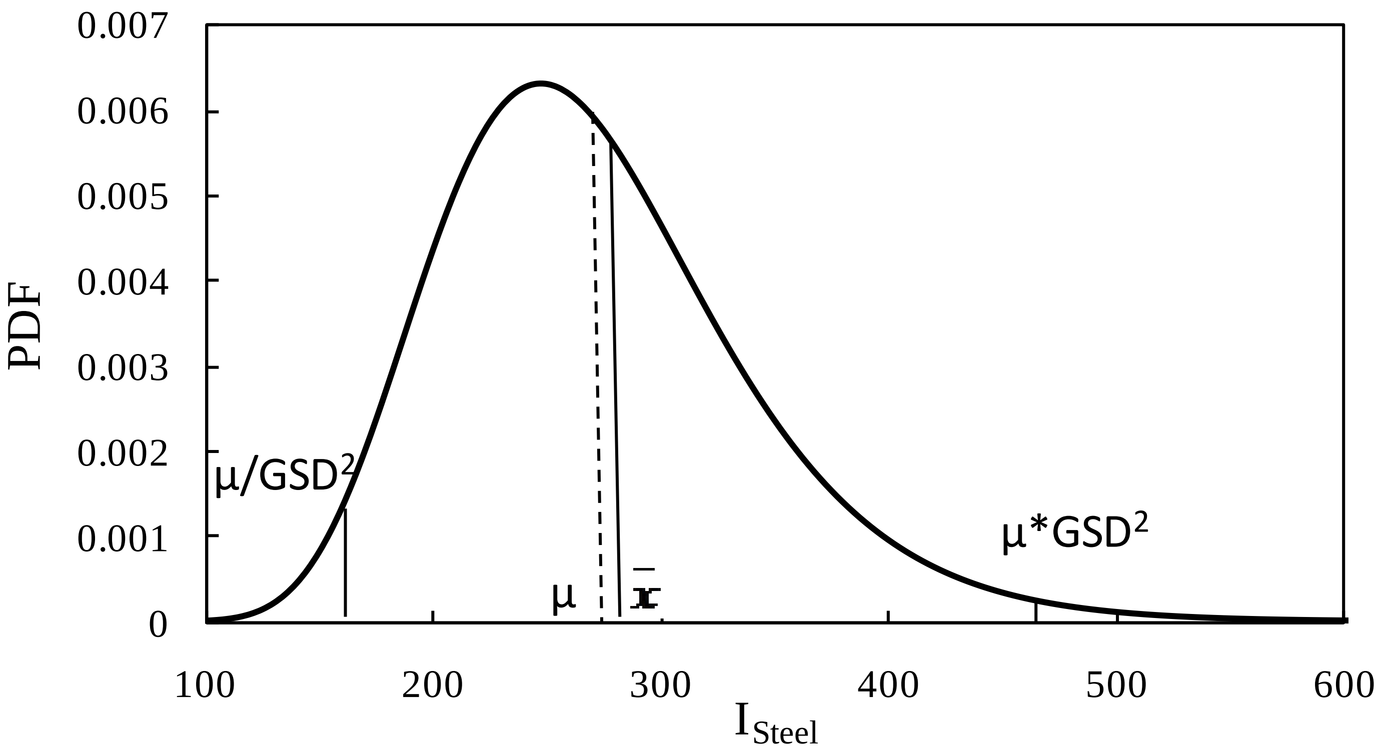
Sensitivity

$$S_i = \frac{\%\ \Delta Output_i}{\%\ \Delta Input_i} = \frac{\Delta O / O}{\Delta I / I}$$

1 variable at a time

do not account for inputs uncertainty

Log-normal distributions



Lognormal:
- μ is the median
- GSD^2 is the Geometric squared standard deviation or coefficient of variation:

GSD^2

$$probability\left\{\frac{\mu}{GSD^2} < X > GSD^2 \cdot \mu\right\} = 0.95$$

$if\ \ GSD^2 = 2,$ *95% twice lower to twice higher*

Method- Taylor series expansion

$$GSD_O^2 = exp[\, S_{I_1}^2 (ln\, GSD_{I_1}^2)^2 + S_{I_2}^2 (ln\, GSD_{I_2}^2)^2 + ... S_{I_n}^2 (ln\, GSD_{I_n}^2)^2 \,]^{1/2}$$

Geometric standard deviation on input

Sensitivity to input parameter i

Geometric standard deviation on output

Assumptions :

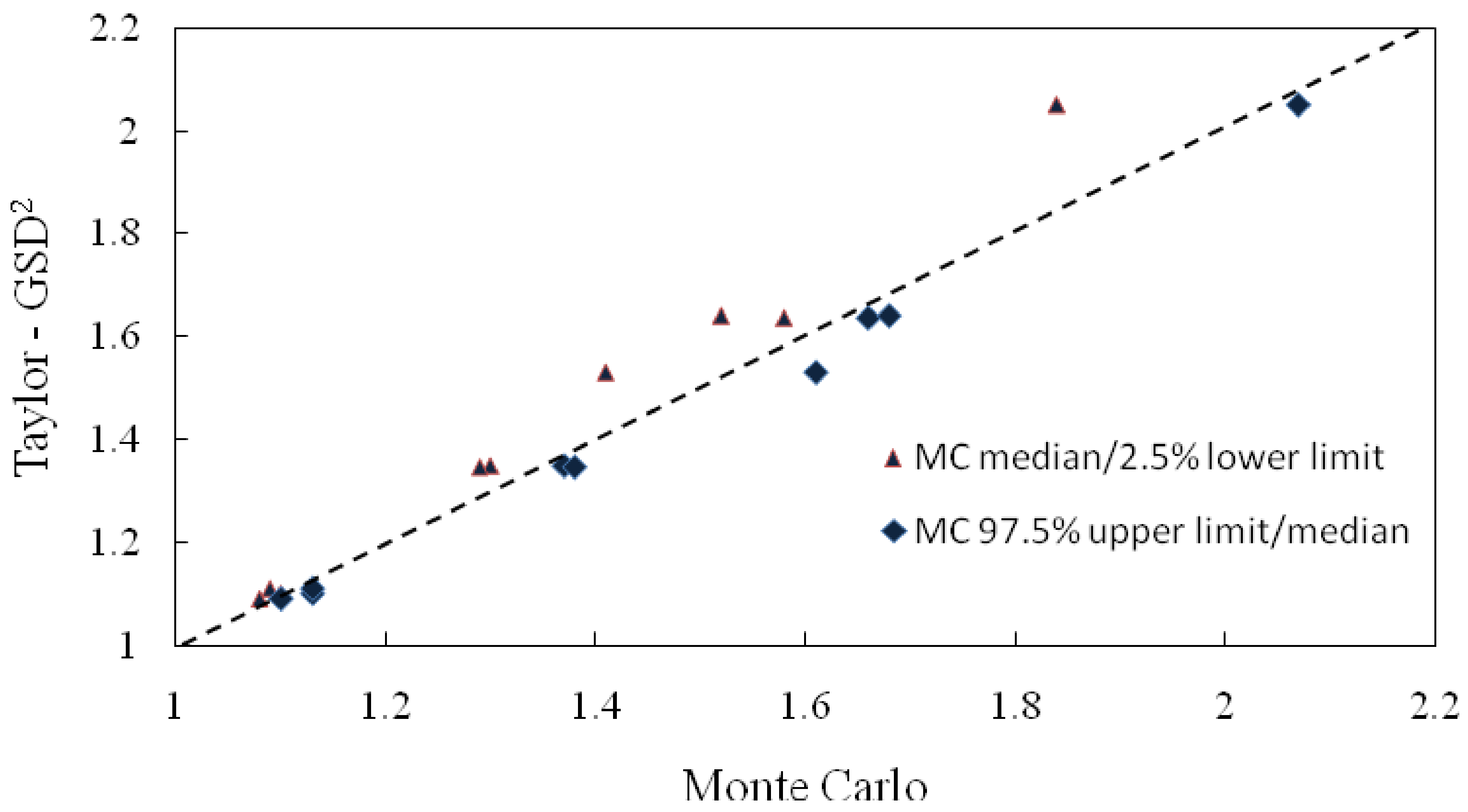
1) Lognormal distribution

2) Independence of all inputs

3) Linear first-order kinetics

MacLeod et al., 2002 , More general form by Heijungs et al., 1995

Comparison of 2.5% lower and 95% upper limit: Taylor vs Monte-Carlo: front end panel



Case study: hands dryer

XLERATOR Dryer 10s.

Conventional Dryer 30s.

Paper Towels

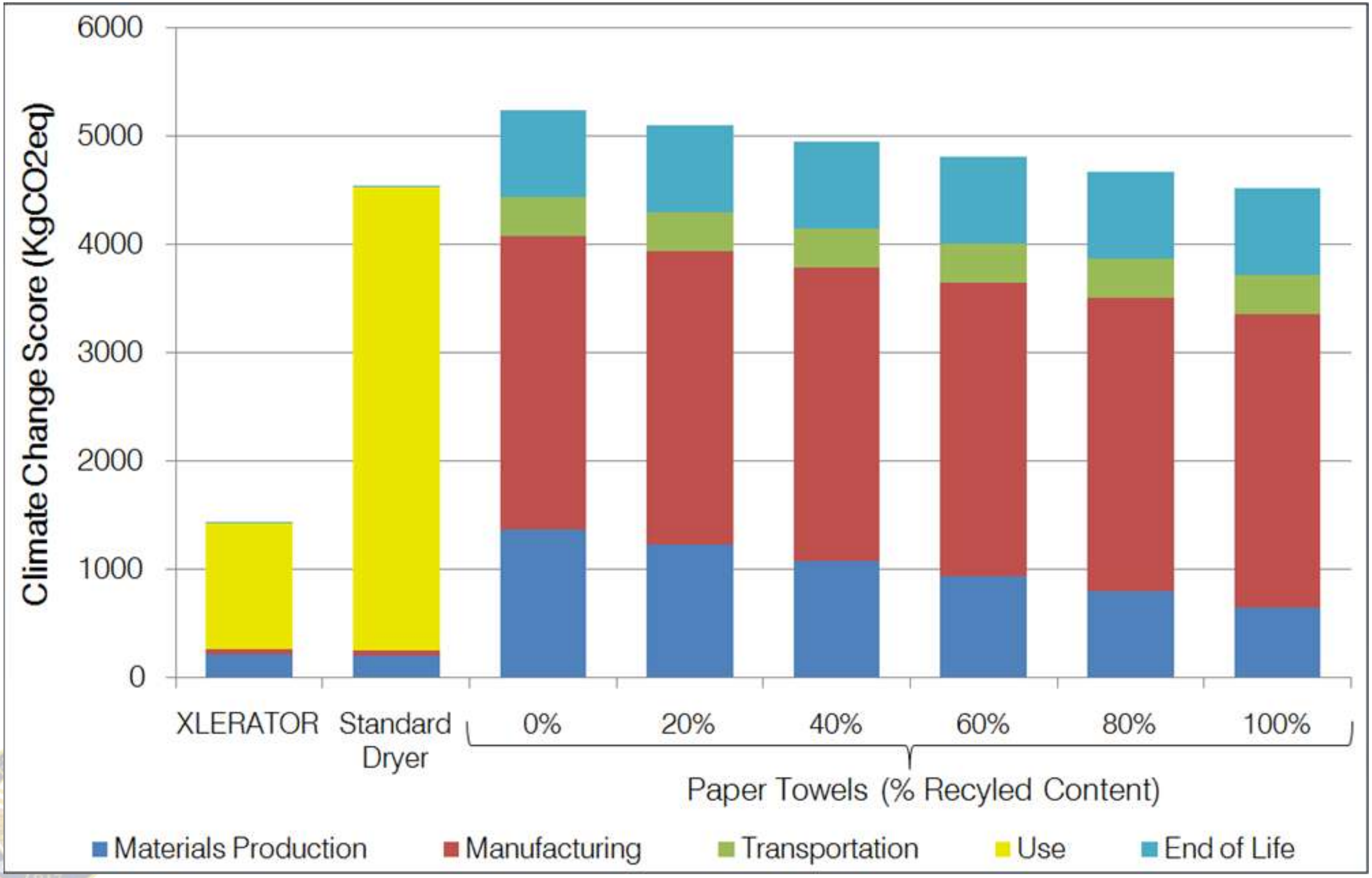
Function:
transport over car lifetime

Functional Unit :
1 pair dried hands

Objective:

Compare the climate change impact of three types of hand dryers

Climate change impacts



Input data

Square of the geometric standard deviation
(95% confidence interval : between μ/SD95 and μ/SD95)

$$SD_{95} = \exp^{\sqrt{\ln(U_1)^2 + \ln(U_2)^2 + \ln(U_3)^2 + \ln(U_4)^2 + \ln(U_5)^2 + \ln(U_6)^2 + \ln(U_b)^2}}$$

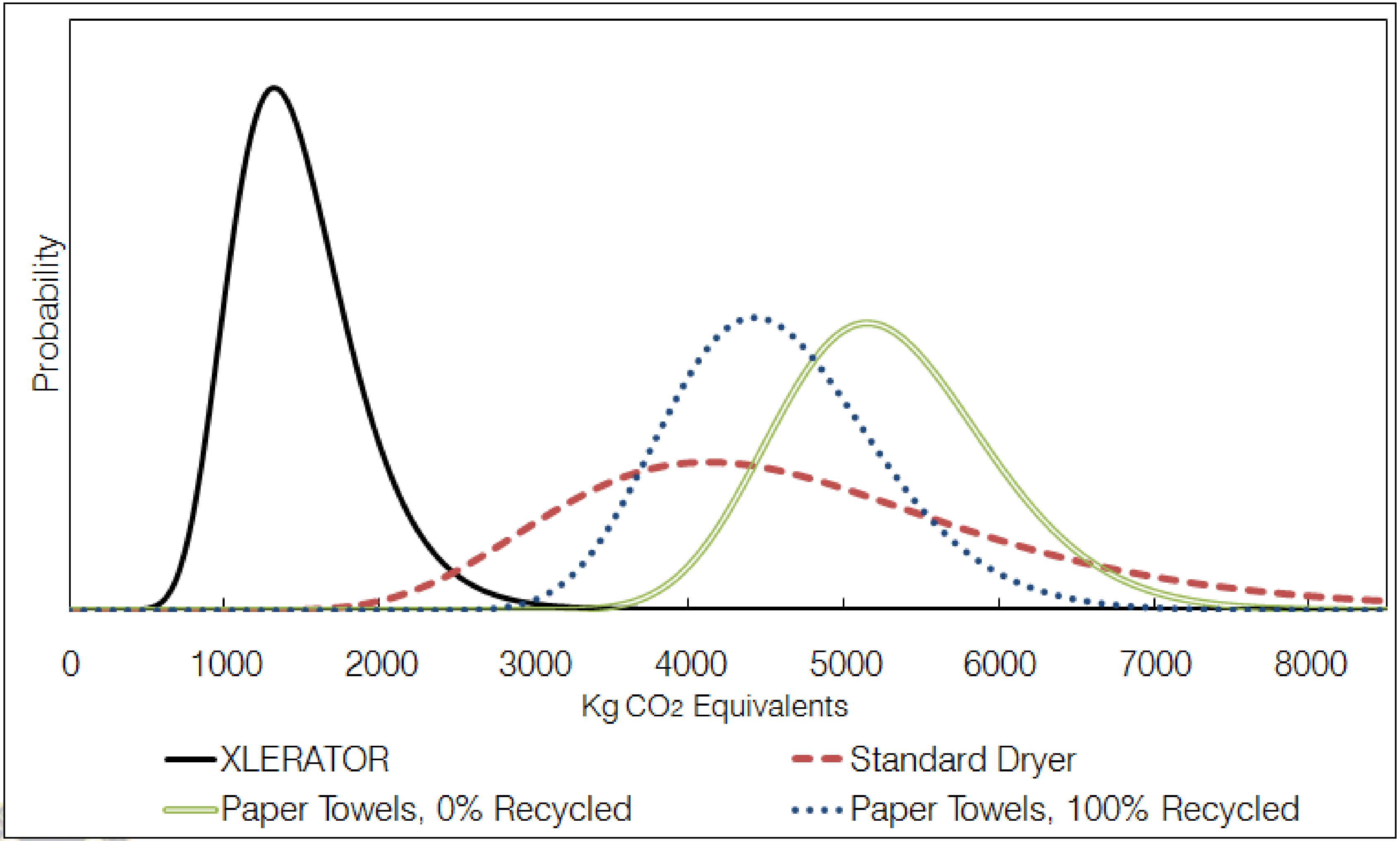
Ub **Basic uncertainty factor**

U1 **Uncertainty factor for reliability,**
U2 **Uncertainty factor for completeness,**
U3 **Uncertainty factor for temporal correlation,**
U4 **Uncertainty factor for la geographic correlation,**
U5 **Uncertainty factor for other technological correlation,**
U6 **Uncertainty factor for sample size,**

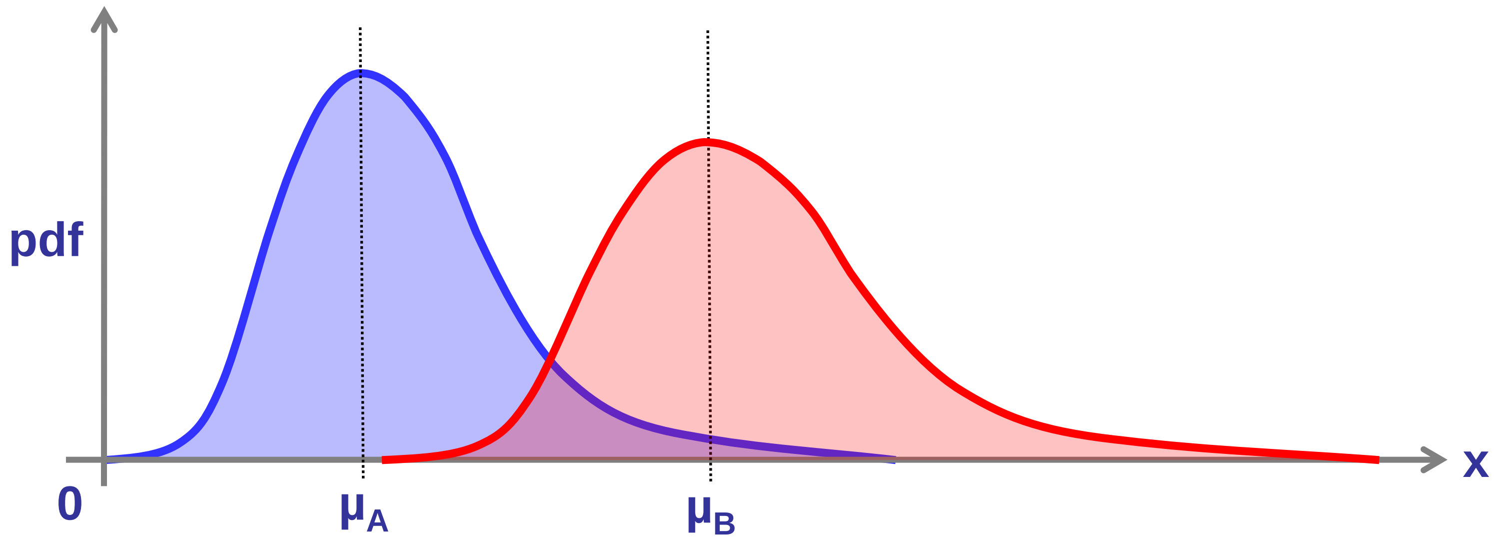
Example Aluminum:

$$SD_{95} = exp^{\sqrt{ln(1{,}00)^2 + ln(1{,}02)^2 + ln(1{,}00)^2 + ln(1{,}02)^2 + ln(1.00)^2 + ln(1{,}20)^2 + ln(1{,}05)^2}} = 1{,}21$$

Comparison of single scenarios

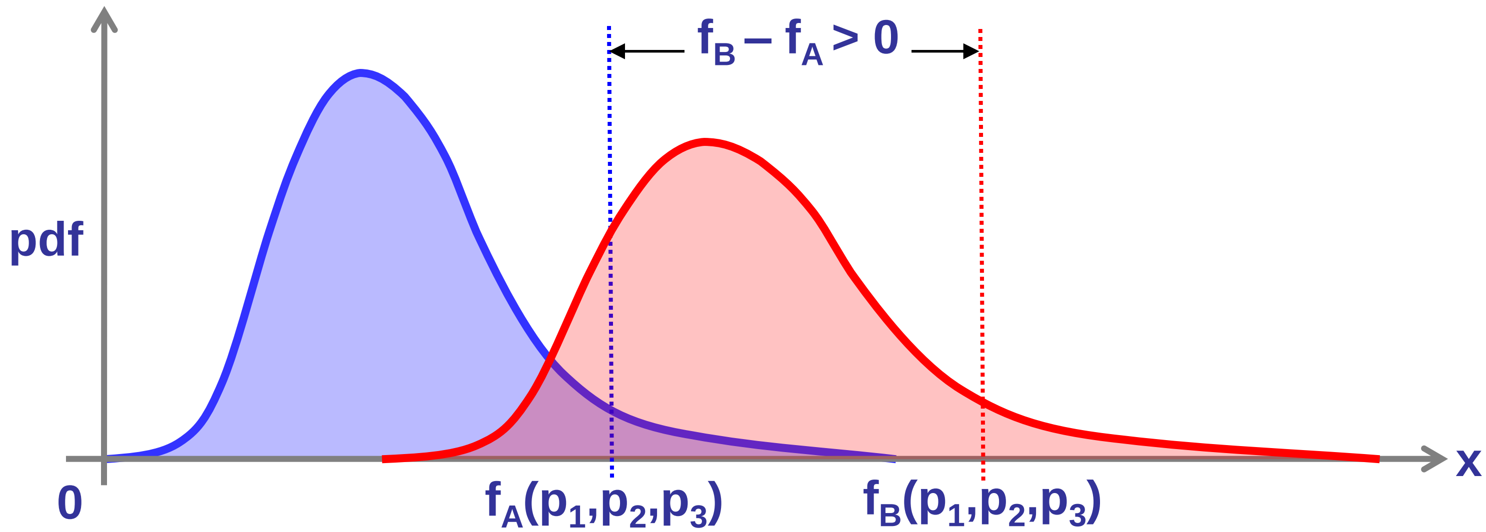


Distribution: log-normal - overlapping



- **Based on these distributions, one might think that the probability that scenario A is higher than scenario B is the area of intersection**

Distribution: log-normal - overlapping



- **HOWEVER, the two scenarios are always dependent → depend on the same parameters.**
- **Therefore when one set of parameters (p_1,p_2,p_3) yields a high result in scenario A, it is likely to also yield a high result in scenario B.**
- **Difference is generally more robust in LCA → Run A and B in parallel and determine P(A-B>0) or P(A/B>1)**

Method- Taylor series expansion scenarion comparison A/B

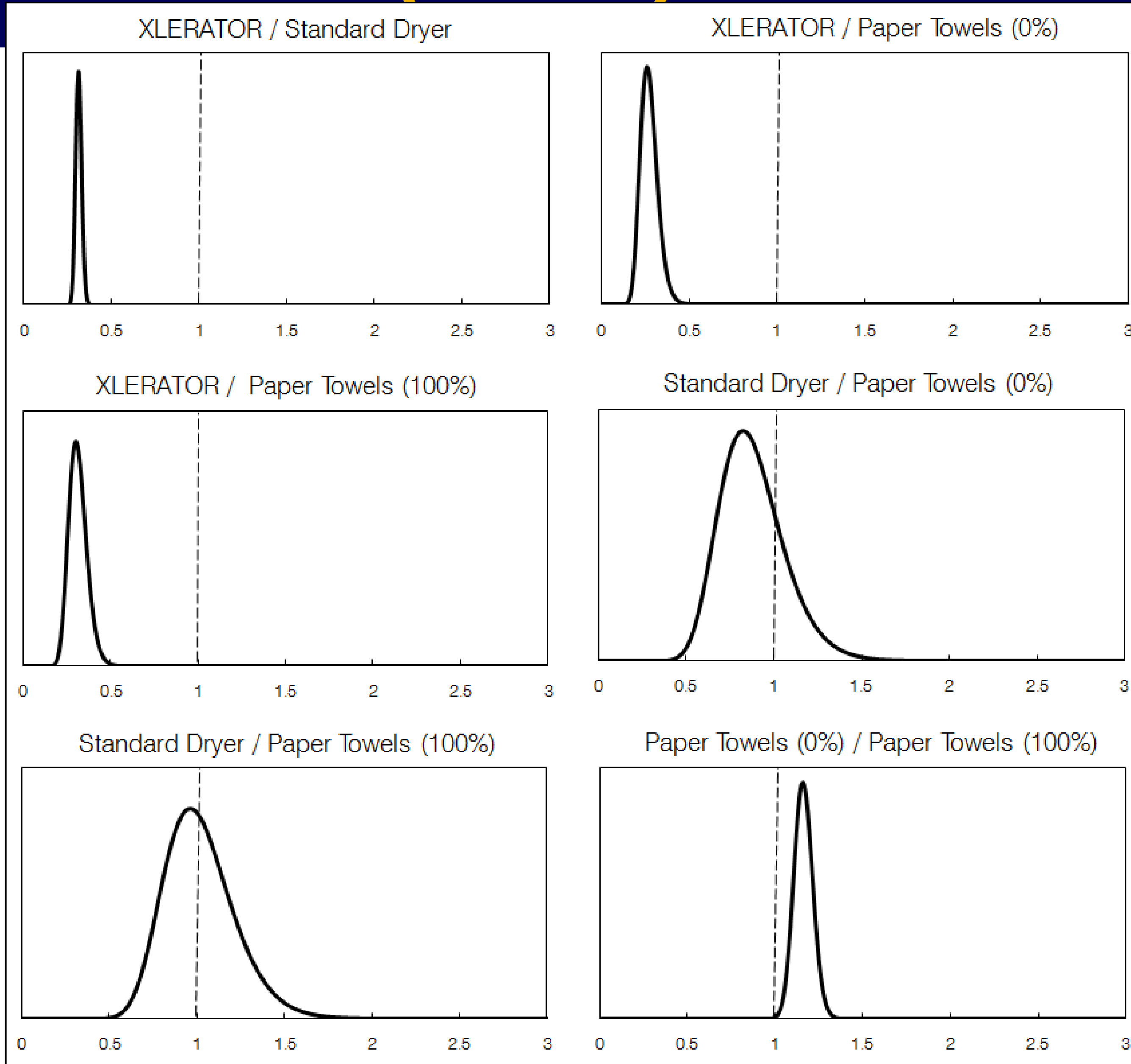
$$(\ln GSD_{\frac{A}{B}})^2 = \sum_{i}^{l} S_{A_i}^2 (\ln GSD_i)^2 + \sum_{j=l+1}^{m} S_{B_j}^2 (\ln GSD_j)^2 + \sum_{k=m+1}^{n} (S_{A_k} - S_{B_k})^2 (\ln GSD_k)^2$$

Independent parameters for scenarios A and B
Sum of all parameters

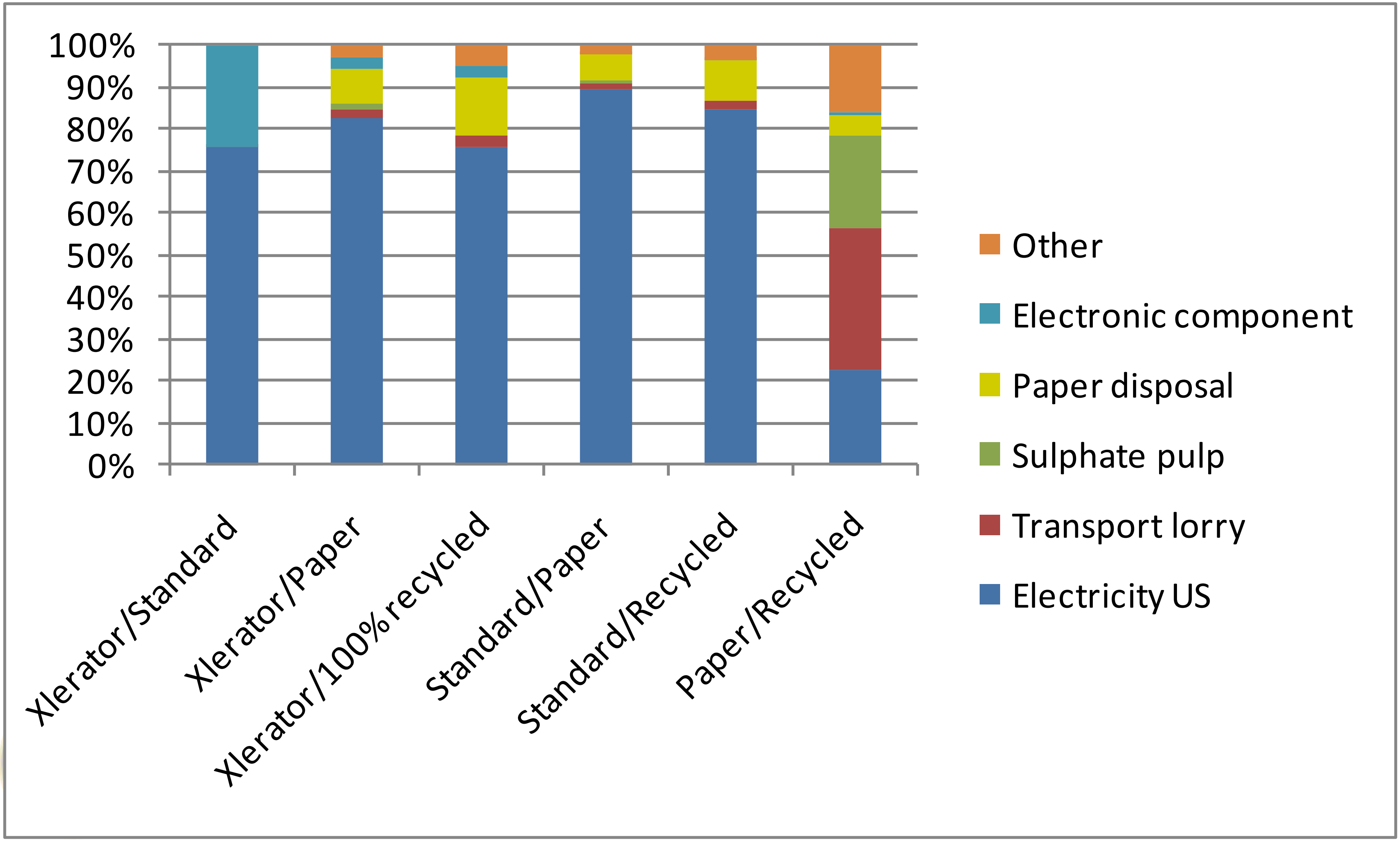
Common parameters to A and B
Take the difference in sensitivity

$$P\left(\frac{A}{B} < 1\right) = \frac{1}{2} + \frac{1}{2}\operatorname{erf}\left[\frac{-\xi_{\frac{A}{B}}}{\ln GSD_{\frac{A}{B}}\sqrt{2}}\right]$$

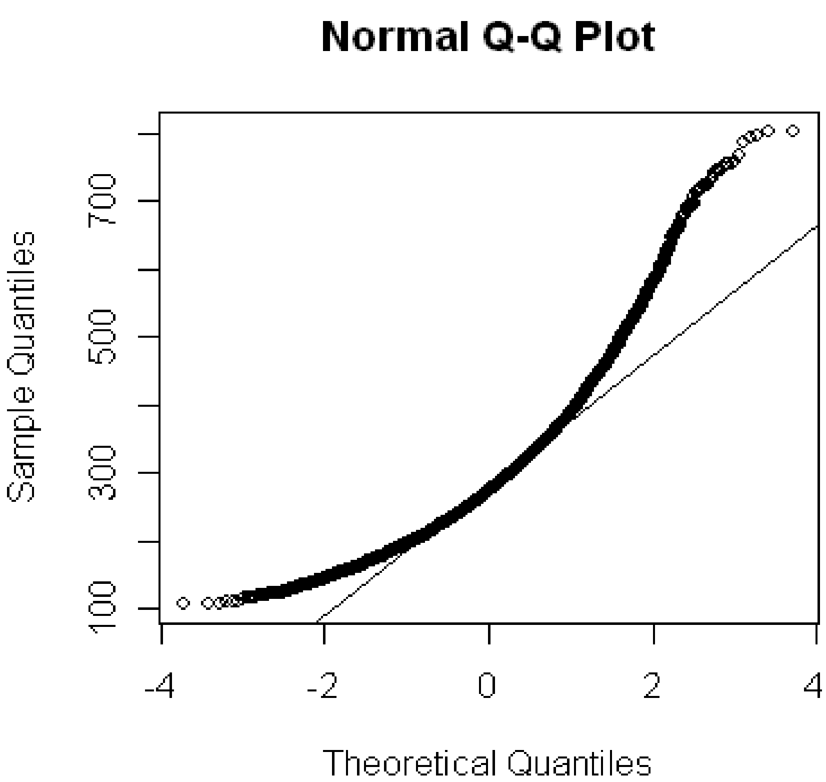
P (A/B<1)

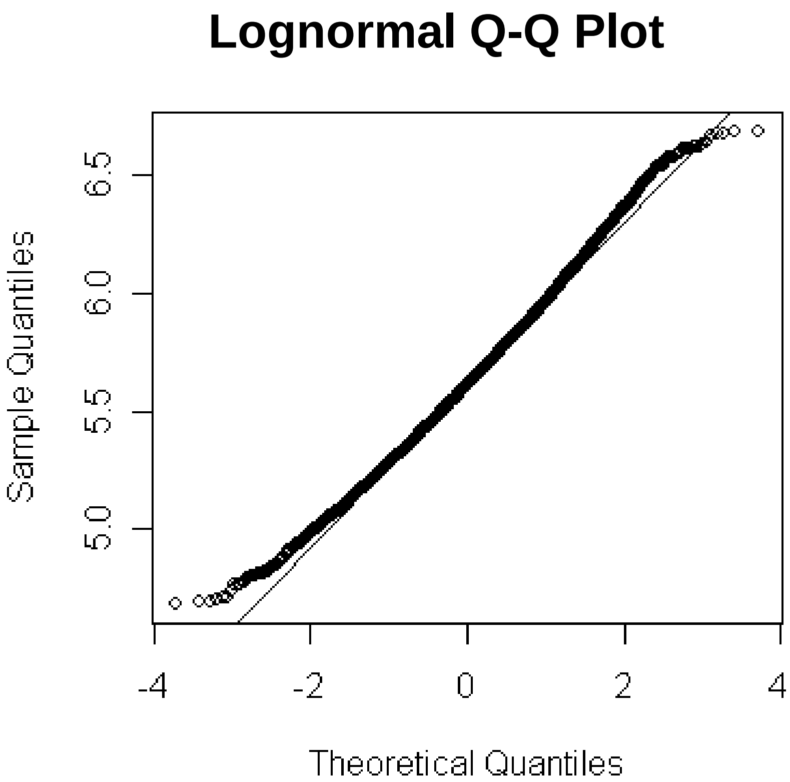

XLERATOR / Standard Dryer
XLERATOR / Paper Towels (0%)
XLERATOR / Paper Towels (100%)
Standard Dryer / Paper Towels (0%)
Standard Dryer / Paper Towels (100%)
Paper Towels (0%) / Paper Towels (100%)
0 0.5 1 1.5 2 2.5 3

Main parameters contributing to uncertainty



Test of log normality: the only hypothesis is that the output is lognormal





5. Conclusions

- Demonstrates the feasibility of this method and illustrates its simultaneous and consistent application to both inventory and impact assessment.
- This simple and reliable approach can easily show the contribution of each process.
- This detailed and modular approach coupled with a LCA is a very relevant and efficient way to get an accurate overall LCA uncertainty.
- The fairly simple procedure very strongly reduce calculation time. Because the approximate method relies on representative GSD2 and therefore needing little calculation resources was presented.

2. Methodology-Approach method

- Determine the output sensitivity to each input parameter

- Assesses the overall coefficient of variation on the final result as a function of the coefficient of variation of each individual input.

- The advantage of this procedure is to explicitly provide the contribution from each parameter as well as very strongly reduce calculation time.

- Compare results with Monte- Carlo analysis. Probability distributions obtained with this approach are compared to classical Monte Carlo distributions for test scenarios.

Case study Car front end panel

Car front-end panel

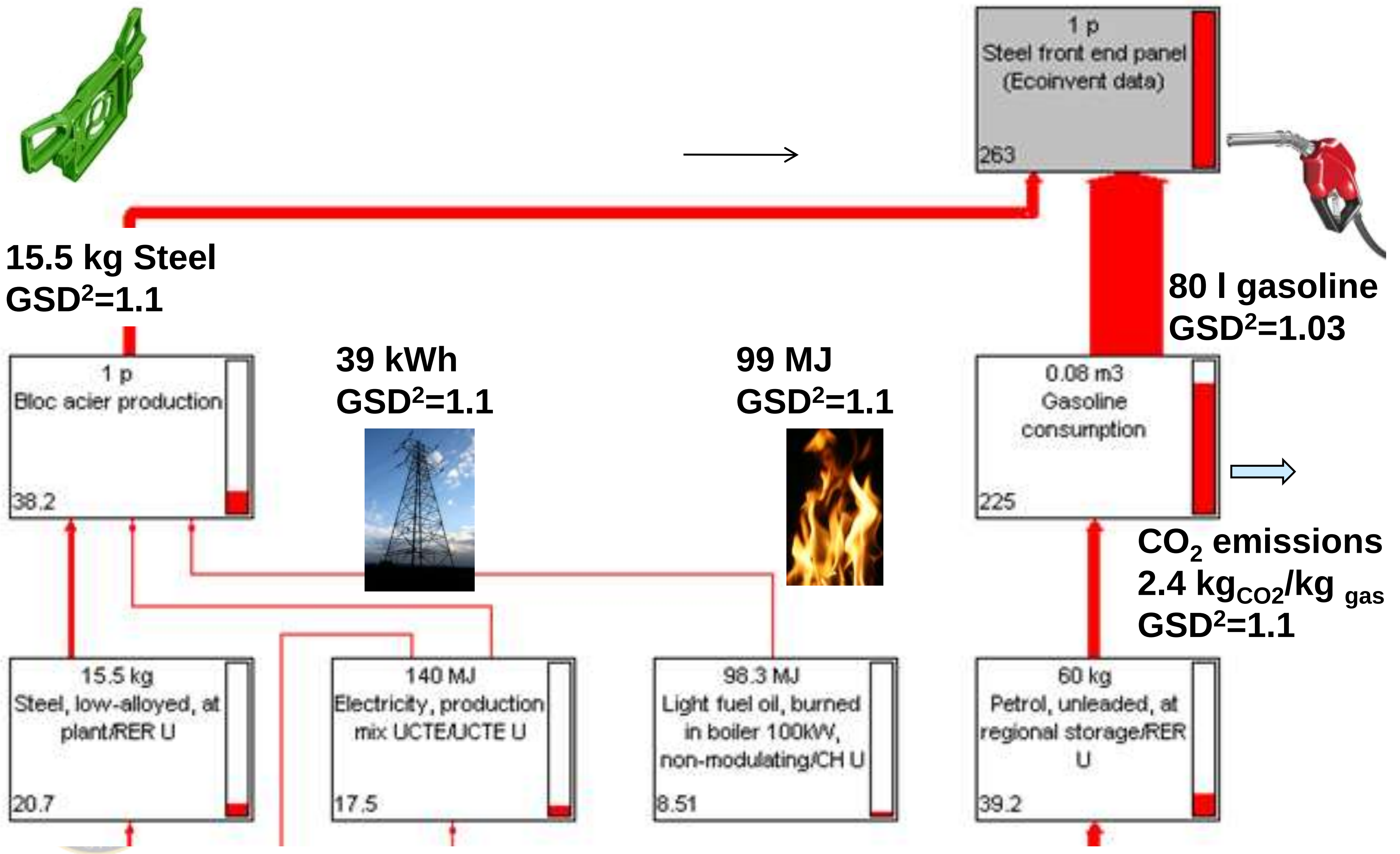
Function:
transport over car lifetime

Functional Unit :
1 front-end panel of equivalent rigidity for a 200'000 km service.

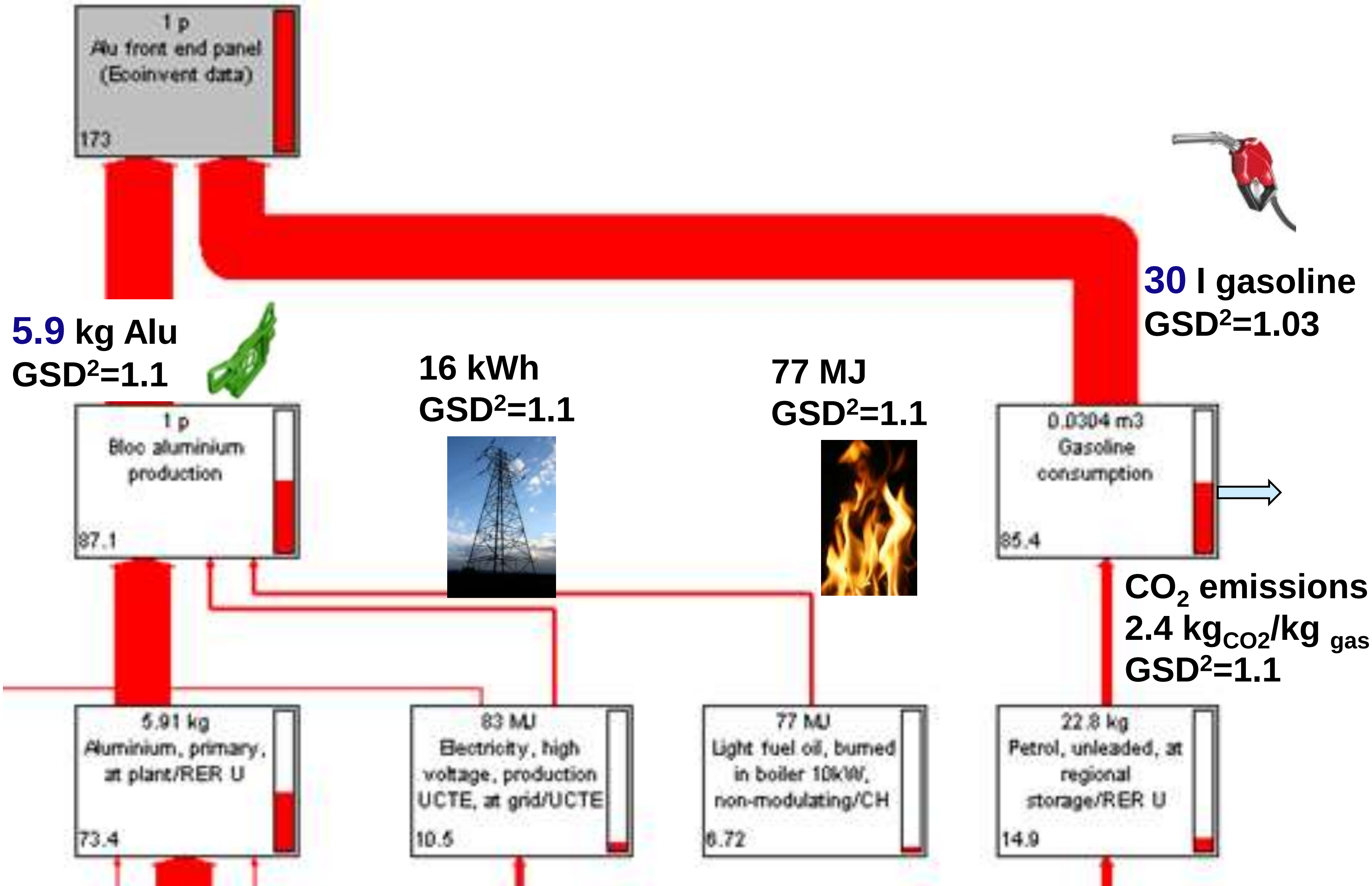
Objective:

Compare the climate change impact of a steel versus an aluminium front end panel

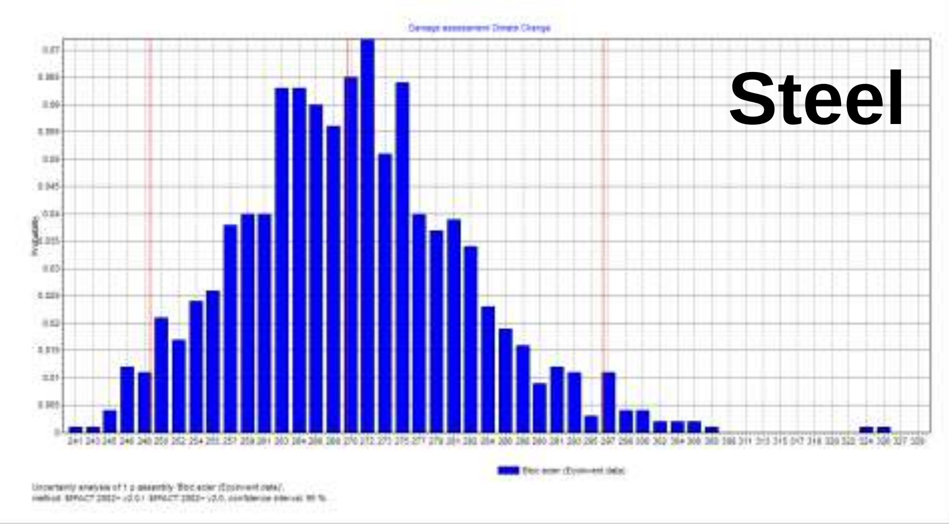
Process tree – steel (263 $kgCO_{2\ equ}$/FU)

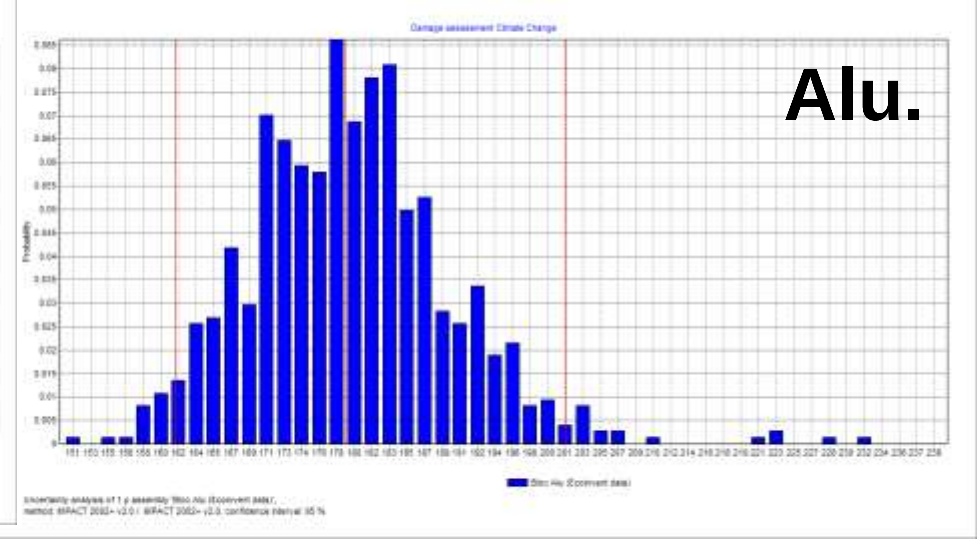


Process tree – aluminium (173 $kgCO_{2\ equ}$/FU)



4. Results - For single scenario





Monte carlo **GSD^2 = 1.08 - 1.10**

Taylor series **GSD^2 = 1.09**

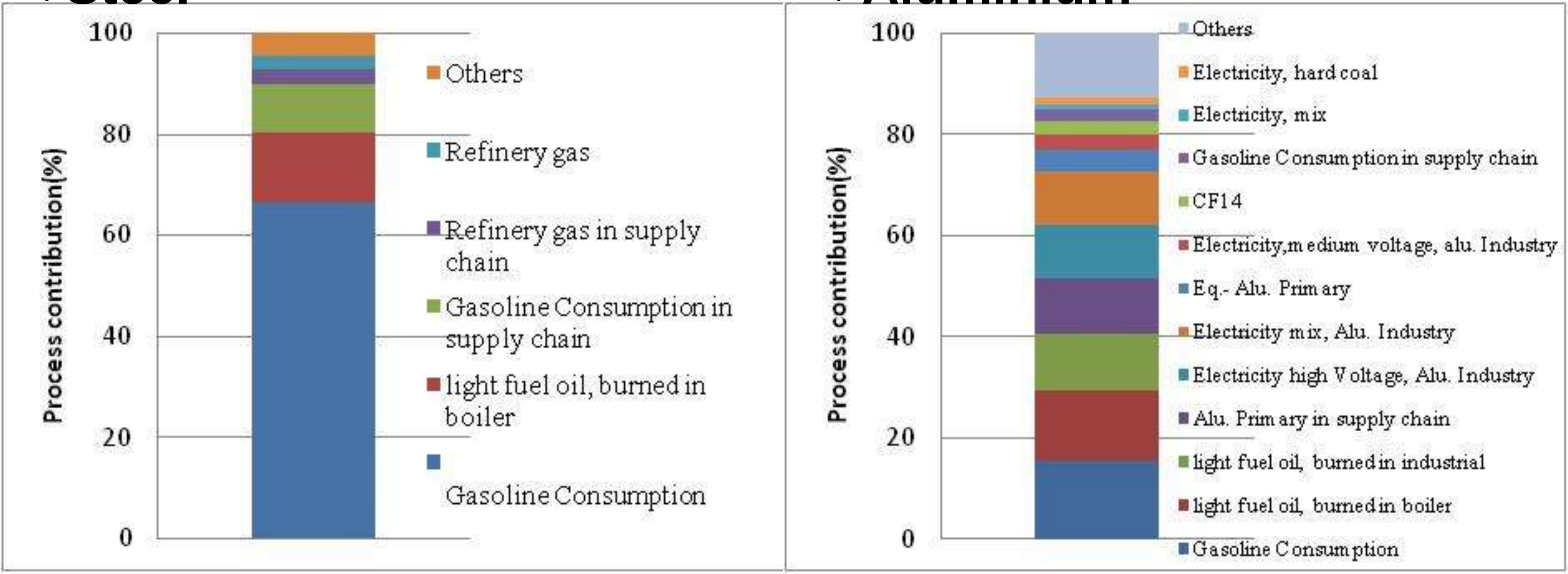
Monte carlo **GSD^2 = 1.11 - 1.12**

Taylor series **GSD^2 = 1.10**

$$GSD_o^2 = \exp[S_{I_1}^2 (\ln GSD_{I_1}^2)^2 + S_{I_2}^2 (\ln GSD_{I_2}^2)^2 + \ldots S_{I_n}^2 (\ln GSD_{I_n}^2)^2]^{1/2}$$

Process contribution to uncertainty

a) **Steel** b) **Aluminium**



Process contribution to uncertainty score

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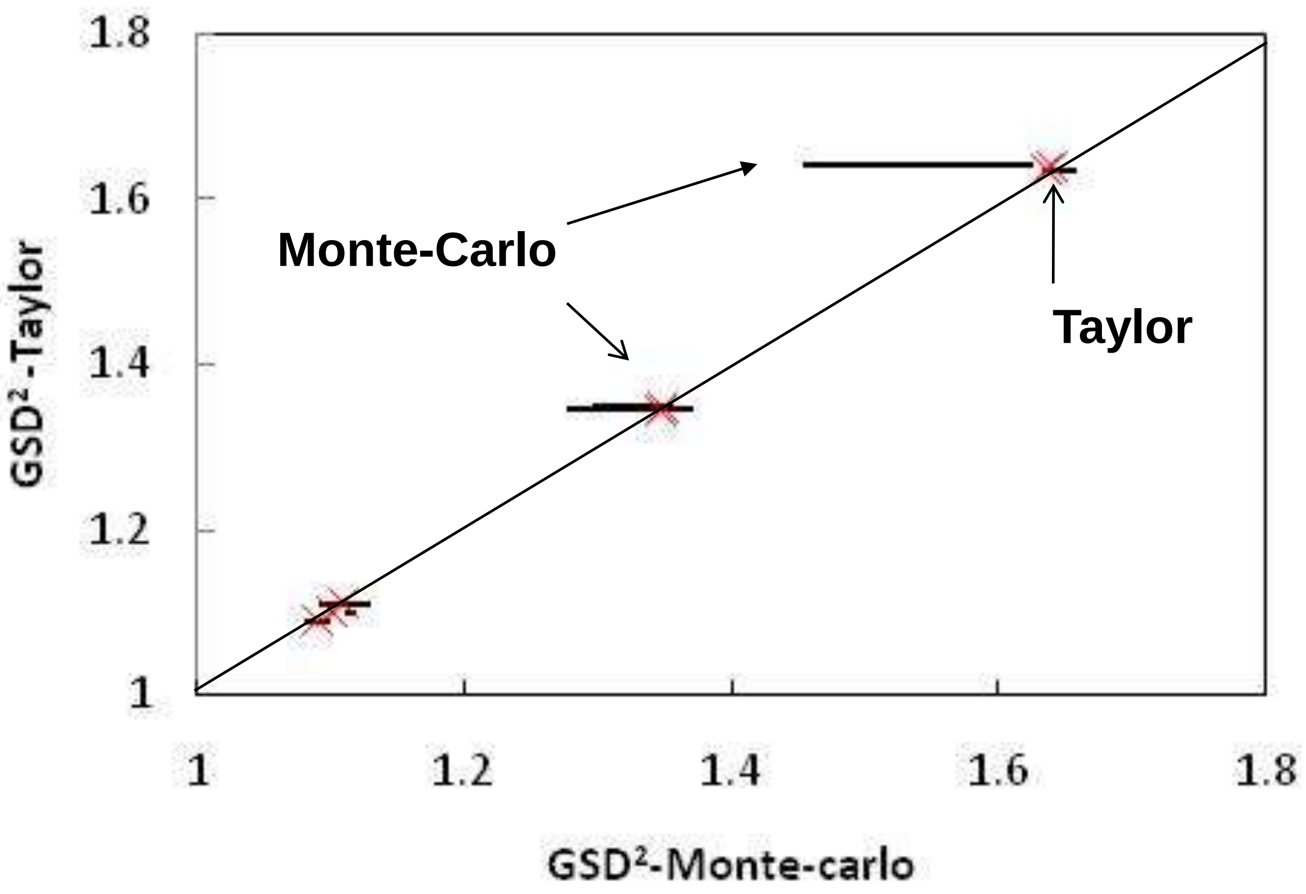
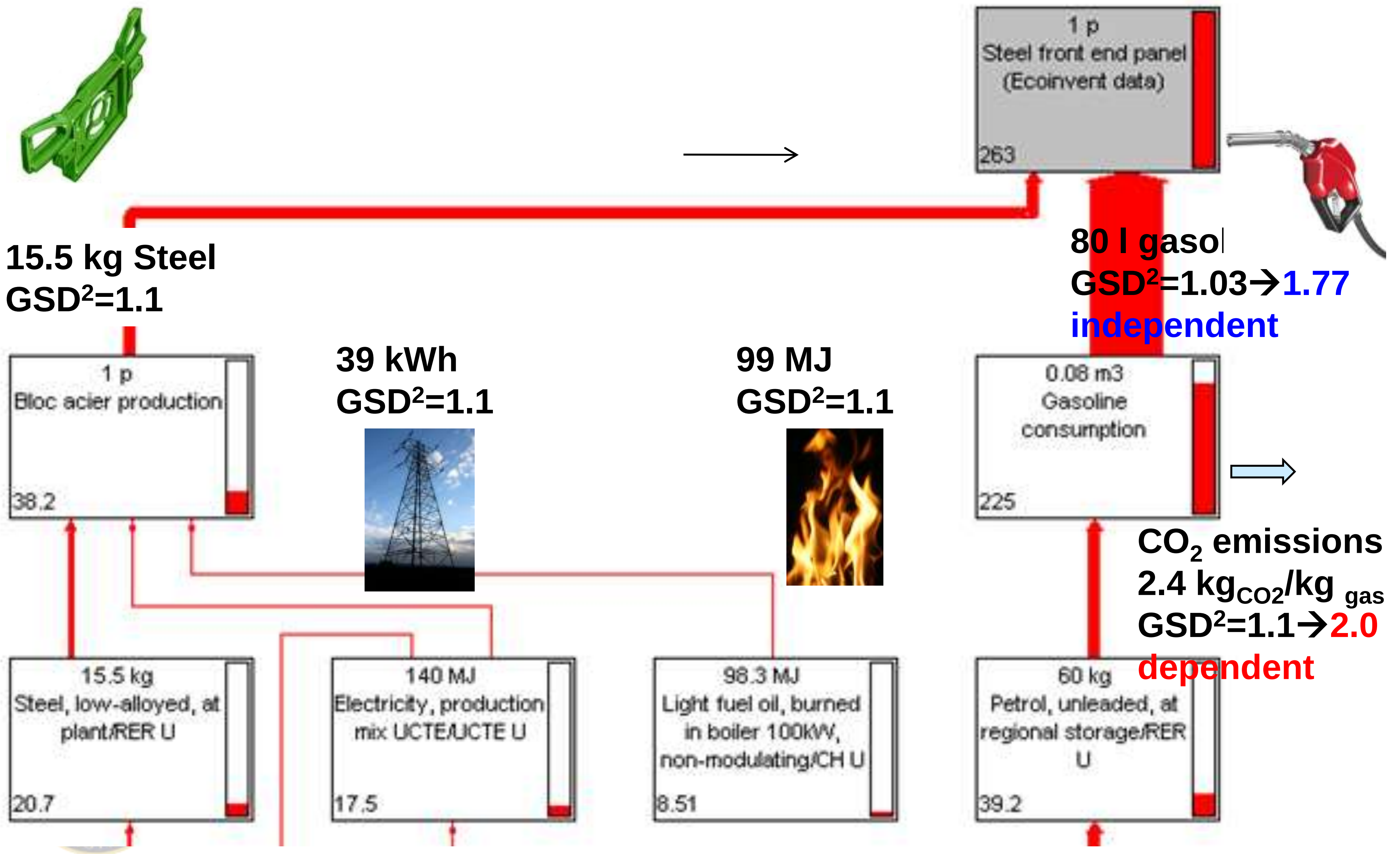
This Taylor extension serie is appropriate to easily determine the contribution of each process.

Relationship between Taylor serie - Monte Carlo for GSD^2 in single scenario



GSD^2 calculated by using Taylor serie consistent with Monte carlo

Process tree – steel (263 kg$CO_{2\,equ}$/FU)



15.5 kg Steel
GSD^2=1.1

39 kWh
GSD^2=1.1

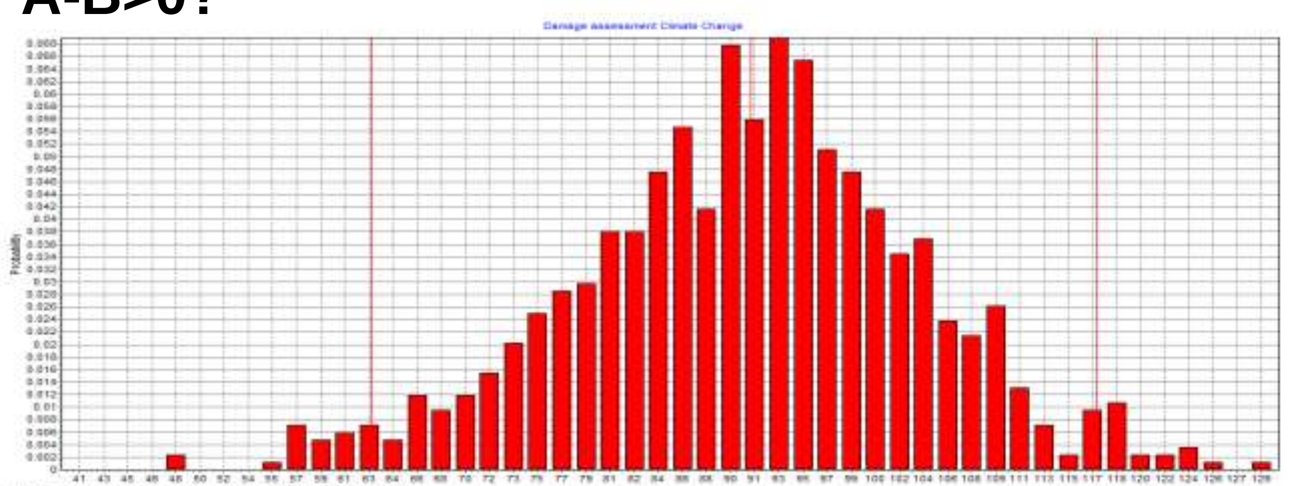
99 MJ
GSD^2=1.1

80 l gasol
GSD^2=1.03→1.77
independent

CO_2 emissions
2.4 kg_{CO2}/kg $_{gas}$
GSD^2=1.1→2.0
dependent

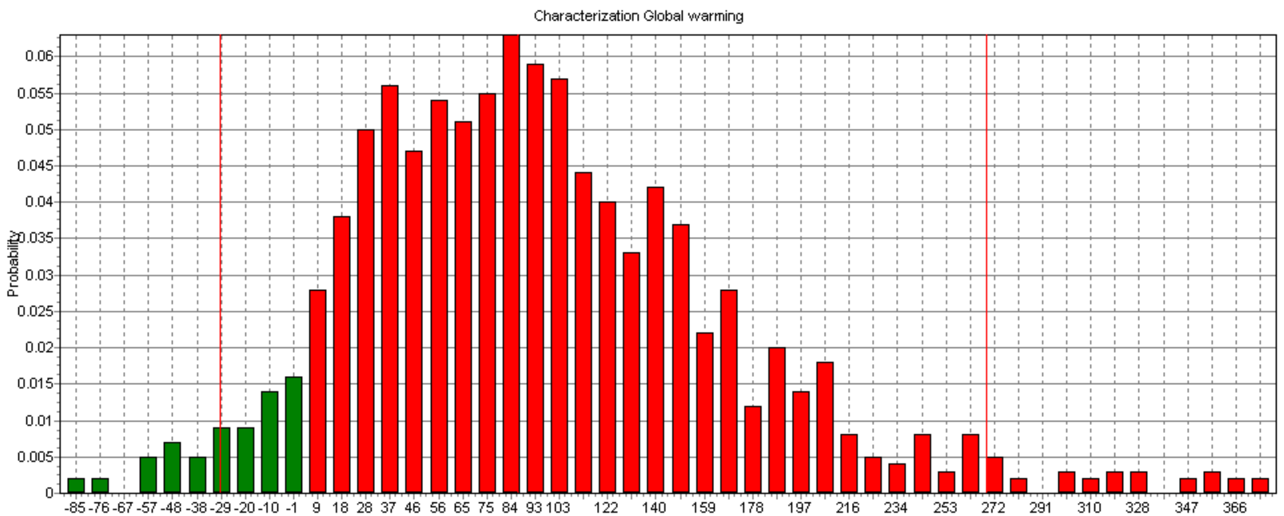
Equal uncertainty on equal scenario, independent vs dependent

A-B>0?



Varying the same parameter (dependent)

Probability A-B<0 = 0.2%



Uncertainty analysis of 1 p assembly 'Steel front end panel (Ecoinvent data)1.77' (A) minus
1 p assembly 'Bloc Alu (Ecoinvent data) 1.77' (B),
method: IMPACT 2002+ v2.0 / IMPACT 2002+ v2.0 , confidence interval: 95 %

Varying independent parameters

Probability A-B<0 = 6%

Scenario Steel-Alu. Crosses Zero

For comparing two scenarios

$$\ln GSD^2_{\frac{A}{B}} = \ln GSD^2_A + \ln GSD^2_B + 2Cov(\ln Y_B, \ln Y_B)$$

$$\frac{GSD_A{}^2}{GSD_B{}^2} \le GSD_{\frac{A}{B}}{}^2 \le GSD_A{}^2 GSD_B{}^2$$

- Fully positively correlated $GSD_{\frac{A}{B}}{}^2 = \frac{GSD_A{}^2}{GSD_B{}^2}$
- Independent $GSD_{\frac{A}{B}}{}^2 = \{\exp[((\ln GSD_A)^2 + (\ln GSD_B)^2)^{\frac{1}{2}}]\}^2$
- Fully negatively correlated $GSD_{\frac{A}{B}}{}^2 = GSD_A{}^2 GSD_B{}^2$

$$GSD^2_{\frac{Steel}{Alu.}} = 0.99 - 1.14$$

Results - For comparison two scenarios : Steel / Alu.

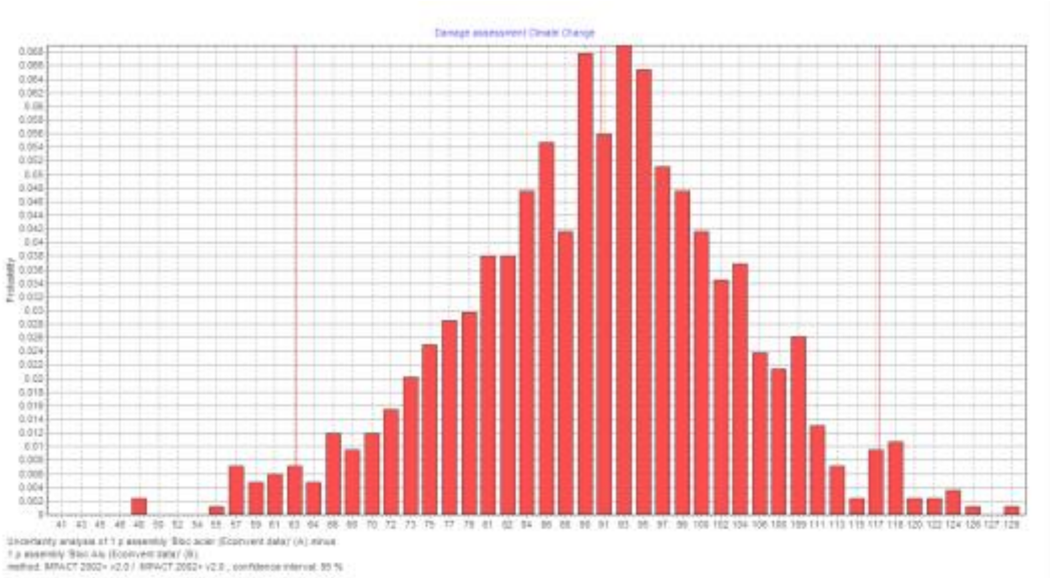


Fig. 3 Comparison of Monte-Carlo and Taylor series for steel-aluminum scenario

Taylor series

- Fully positively correlated $GSD_{\frac{\text{Steel}}{\text{Alu.}}}{}^{2} = 0.99$
- Fully negatively correlated $GSD_{\frac{\text{Steel}}{\text{Alu.}}}{}^{2} = 1.20$
- Independent $GSD_{\frac{\text{Steel}}{\text{Alu.}}}{}^{2} = 1.14$

Since, most cases in LCA is positively correlated

$$GSD^{2}_{\frac{\text{Steel}}{\text{Alu.}}} = 0.99 - 1.14$$