65th LCA Discussion Forum

# How suitable is LCA for Nanotechnology assessment?

## Overview of current methodological pitfalls and potential solutions

Wednesday May 24, 2017; 08:30 h – 17:15 h
Alumni Pavilion, ETH Zürich

*DF LCA*
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ESU-services fair consulting in sustainability

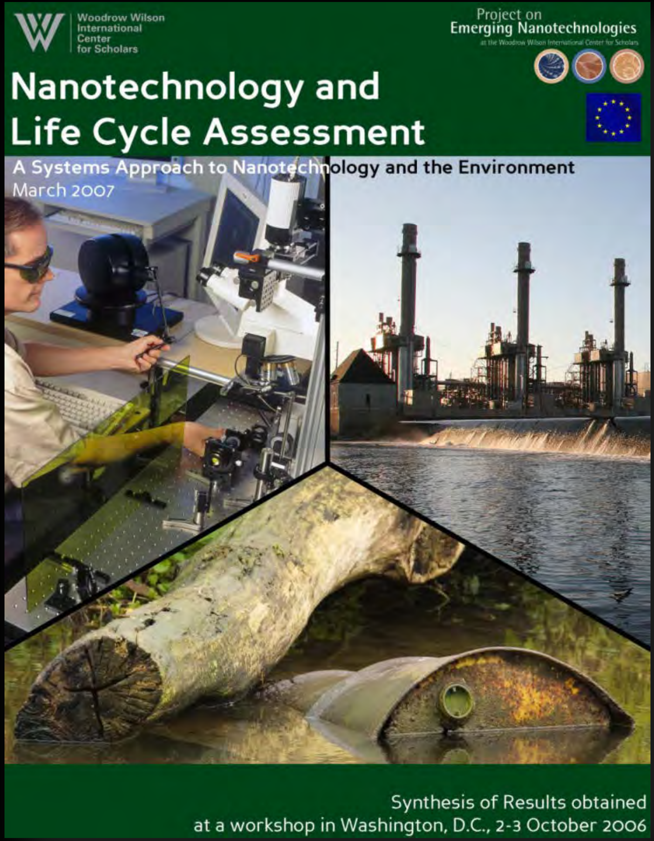
Empa Materials Science and Technology

treeze fair life cycle thinking

# LCA – a suitable tool for engineered Nanomaterials

- **the cradle-to-grave assessment of health and environmental impacts** of nanotechnology is **vital for a successful, safe commercialisation**
- Existing standards for LCA are fully suitable for use on nanomaterials and nanoproducts
- **Gives a more holistic view**; **allows for a comparison** with conventional products

[US-EPA & EU conference, October 2006]



# Welcome

- The **Advancing Life Cycle Assessment Group** at Empa further develops the LCA method in order to better support early phases of the technology development and to address environmental and societal implications of novel material and of emerging technology applications, by
  - extending the perspective of life cycle assessment to societal aspects;
  - supporting asustainable technology development combining the LCA framework with new, innovative approaches such as SbD (safe-by-design) or RRI (responsible research & innovation);
  - and further improving LCIA methods and LCI data availability.




# Introduction

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- ... the LCA ISO 14’040 framework is fully suitable for the assessment of nanomaterials and nanoproducts, despite notable shortcomings in availability of inventory data and missing evaluation instruments for impact assessment.
- Various actors have worked since then extensively on these aspects with goal of ensuring that traditional & nano-specific environmental issues can be assessed within a unified, comprehensive & consistent framework.

... but how far is this really the case ... ?
This day will give you some elements of an answer ...

# Program overview

Welcome & Introduction

**Part I – Perspectives on environmental assessment of nanotechnology**

State-of-the Art and Challenges when applying LCA / Regulatory Perspective / Industrial Perspective

**Part II – Prospective modelling (for nanotechnology)**

Prospective modelling concepts / Uncertainties in such models

**Part II.b – short presentations**

**Part III – Impact assessment methods for nanotechnology**

toxic effects of nanoparticles (limits, gaps) / Quantification of releases along the life cycle / Integration of fate and toxicity of nanoparticles into LCIA framework

**Part IV – Combining LCA and risk assessment for nanotechnology**

Merging / confronting various concepts, approaches

Closing Remarks

# Program overview

| Time | Title | Speaker [Moderator] |
| --- | --- | --- |
| 8:30 | Registration, coffee & croissants | |
| | Perspectives on environmental assessment of nanotechnology | [Arthur Haarman, Empa] |
| 9:00 | Welcome and introduction: State-of-art and challenges when applying LCA to nanotechnology | Roland Hischier, Empa, St. Gallen (CH) |
| 9:25 | Regulation of Nanomaterials – the relevance of LCA and RA | Tobias Walser, Vereala, Zürich (CH) |
| 9:50 | Industrial perspective on nanotechnology development | Karl Höhener, TEMAS, Zürich (CH) |
| 10:15 | Discussion | |
| 10:30 | Coffee break | |
| | Prospective modelling for nanotechnology | [Didier Beloin-Saint-Pierre, Empa] |
| 11:00 | Exploring prospective application of LCA to enhance technological development | Marco Villares, Delft (NL) |
| 11:25 | Prospective modelling and effect from uncertainties | MINES ParisTech, Nice (F) |
| 11:50 | Discussion | |
| | Short presentations | |
| 12:15 | A comparison of two methods for probabilistic modelling of ENM emissions along their life cycle | Véronique Adam, Empa, St. Gallen (CH) |
| 12:25 | Decision-making concept on medical nanoparticles | Peter Weyell, University of Jena (D) |
| 12:35 | A network perspective reveals decreasing material diversity in studies on nanoparticle interactions with dissolved organic matter | Nicole Sani-Kast, ETH, Zürich (CH) |

# Part I – Perspectives …

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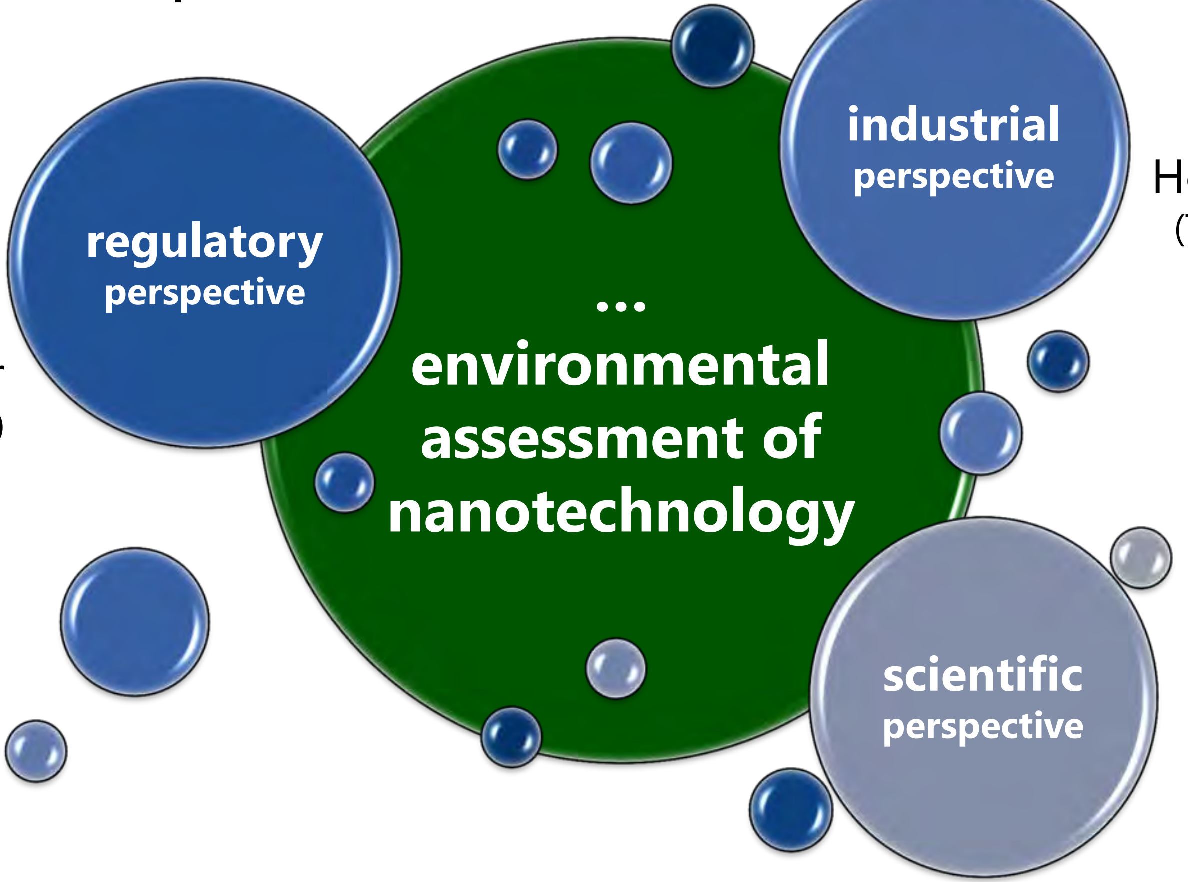


Tobias Walser (Vereala)

Karl Höhener (TEMAS)

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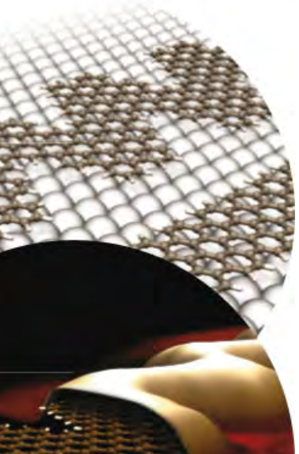
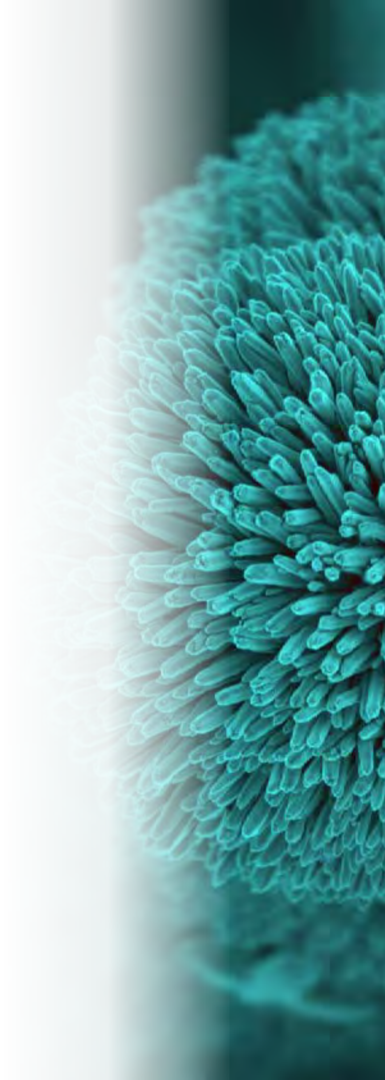
# State-of-art and challenges when applying LCA to nanotechnology




Roland Hischier
Advancing Life Cycle Assessment (ALCA) Group
Empa, St. Gallen, Switzerland

# Publications in the field «LCA & Nano» ?

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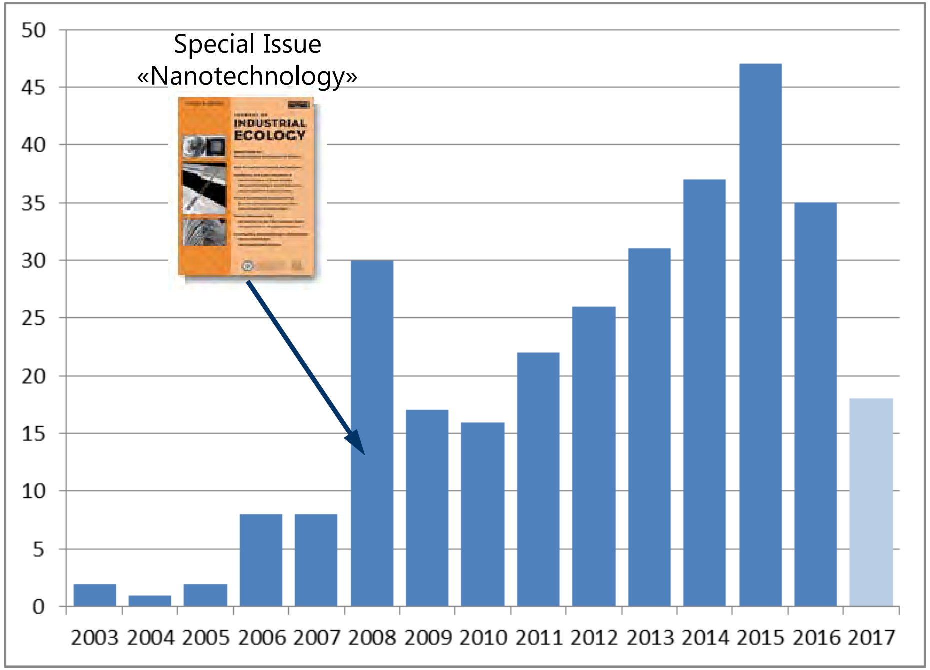
- LCA and Nanotechnology … a hype that seems already beyond its «zenith» …

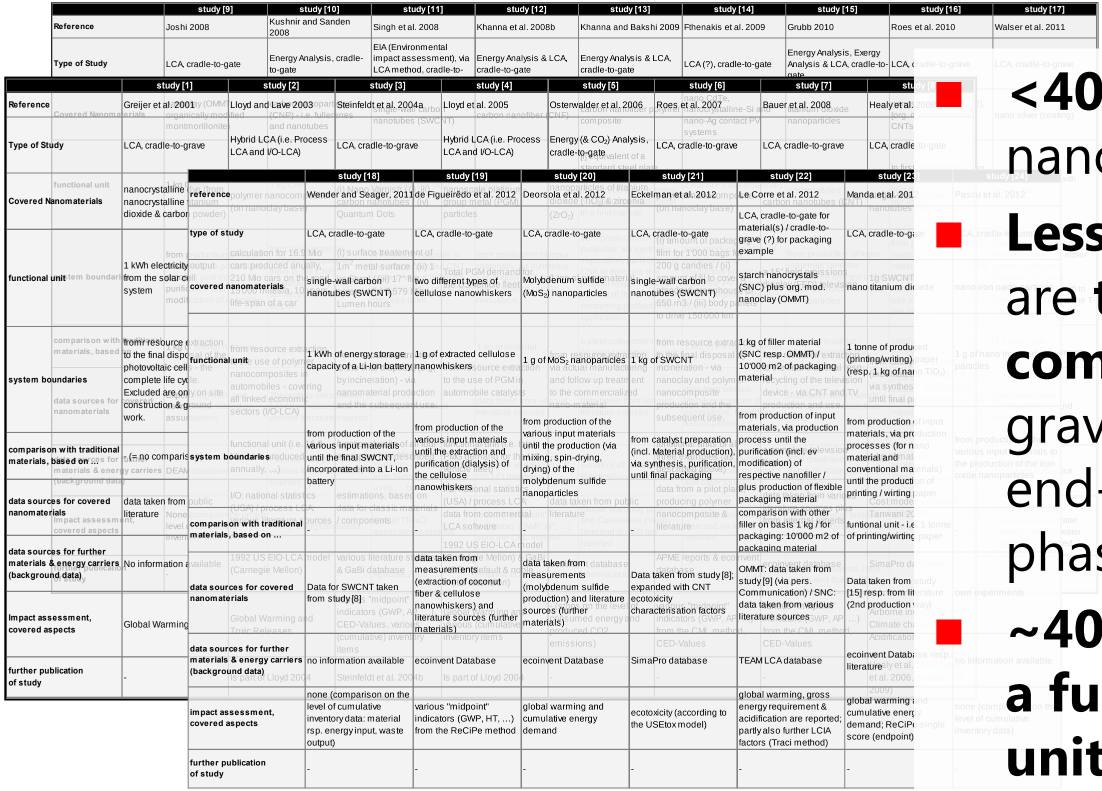
  or

- … what are possible reasons that the # of publications is still not really «taking off» … ?




# of hits on www.scopus.com when searching for TITLE-ABS-KEY (**nanomaterial** OR **nanomaterials** OR **nanoparticle** OR **nanotechnology** OR **nanotechnologies**) AND TITLE-ABS-KEY ("**life cycle assessment**" OR "**life cycle analysis**")

# Review study «LCA & Nano» (2012)



| | study [9] | study [10] | study [11] | study [12] | study [13] | study [14] | study [15] | study [16] | study [17] |
|---|---|---|---|---|---|---|---|---|---|
| Reference | Joshi 2008 | Kushnir and Sanden 2008 | Singh et al. 2008 | Khanna et al. 2008b | Khanna and Bakshi 2009 | Fthenakis et al. 2009 | Grubb 2010 | Roes et al. 2010 | Walser et al. 2011 |
| Type of Study | LCA, cradle-to-gate | Energy Analysis, cradle-to-gate | EIA (Environmental impact assessment), via LCA method, cradle-to- | Energy Analysis & LCA, cradle-to-gate | Energy Analysis & LCA, cradle-to-gate | LCA (?), cradle-to-gate | Energy Analysis, Exergy Analysis & LCA, cradle-to-gate | LCA, cradle-to-grave | LCA, cradle-to-grave |

| | study [1] | study [2] | study [3] | study [4] | study [5] | study [6] | study [7] | study [8] |
|---|---|---|---|---|---|---|---|---|
| Reference | Greijer et al. 2001 | Lloyd and Lave 2003 | Steinfeldt et al. 2004a | Lloyd et al. 2005 | Osterwalder et al. 2006 | Roes et al. 2007 | Bauer et al. 2008 | Healy et al. 2008 |
| Type of Study | LCA, cradle-to-grave | Hybrid LCA (i.e. Process LCA and I/O-LCA) | LCA, cradle-to-grave | Hybrid LCA (i.e. Process LCA and I/O-LCA) | Energy (& $CO_2$) Analysis, cradle-to-gate | LCA, cradle-to-grave | LCA, cradle-to-grave | LCA, cradle-to-gate |

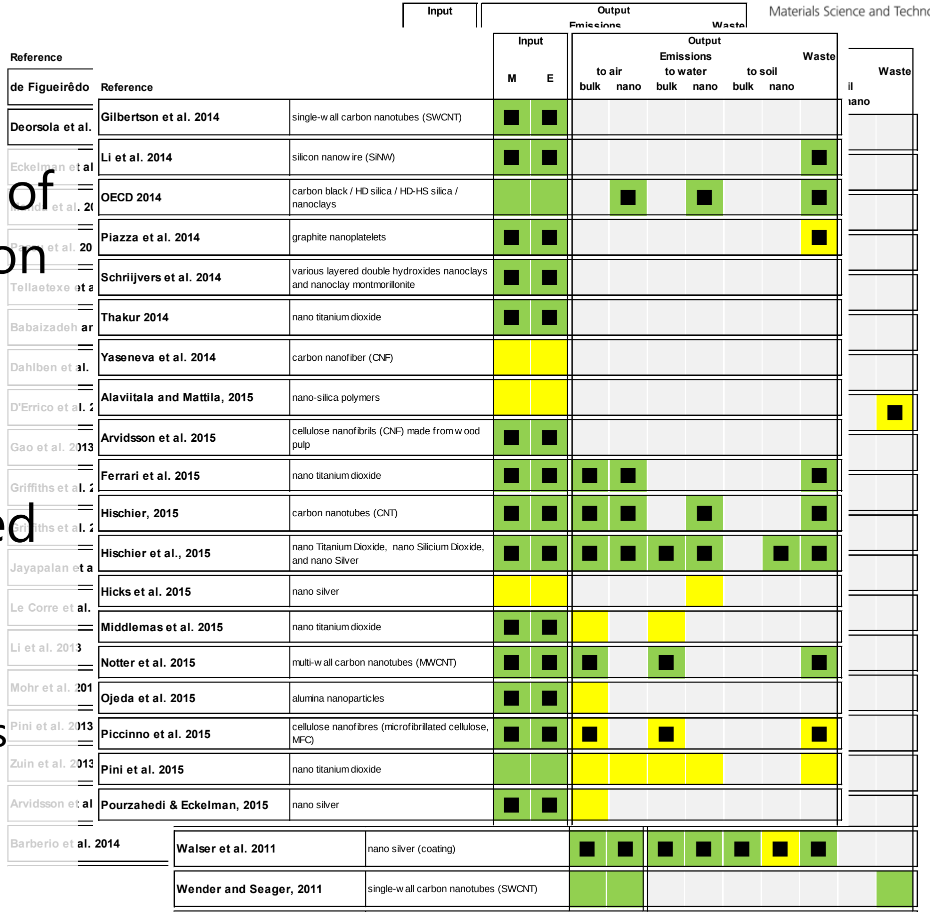
| | study [18] | study [19] | study [20] | study [21] | study [22] | study [23] |
|---|---|---|---|---|---|---|
| reference | Wender and Seager, 2011 | de Figueirêdo et al. 2012 | Deorsola et al. 2012 | Eckelman et al. 2012 | Le Corre et al. 2012 | Manda et al. 201 |
| type of study | LCA, cradle-to-gate | LCA, cradle-to-gate | LCA, cradle-to-gate | LCA, cradle-to-gate | LCA, cradle-to-gate for material(s) / cradle-to-grave (?) for packaging example | LCA, cradle-to-ga |
| covered nanomaterials | single-wall carbon nanotubes (SWCNT) | two different types of cellulose nanowhiskers | Molybdenum sulfide ($MoS_2$) nanoparticles | single-wall carbon nanotubes (SWCNT) | starch nanocrystals (SNC) plus org. mod. nanoclay (OMMT) | nano titanium di |
| functional unit | 1 kWh of energy storage capacity of a Li-Ion battery | 1 g of extracted cellulose nanowhiskers | 1 g of $MoS_2$ nanoparticles | 1 kg of SWCNT | 1 kg of filler material (SNC resp. OMMT) / 10'000 m2 of packaging material | 1 tonne of produc (printing/writing) (resp. 1 kg of na |
| system boundaries | from production of the various input materials until the final SWCNT, incorporated into a Li-Ion battery | from production of the various input materials until the extraction and purification (dialysis) of the cellulose nanowhiskers | from production of the various input materials until the production (via mixing, spin-drying, drying) of the molybdenum sulfide nanoparticles | from catalyst preparation (incl. Material production), via synthesis, purification, until final packaging | from production of input materials, via production process until the purification (incl. ev modification) of respective nanofiller / plus production of flexible packaging material | from production materials, via pr processes (for n material and conventional ma until the producti printing / wirting |
| comparison with traditional materials, based on ... | - | - | - | - | comparison with other filler on basis 1 kg / for packaging: 10'000 m2 of packaging material | funtional unit - i.e of printing/wirting |
| data sources for covered nanomaterials | Data for SWCNT taken from study [8] | data taken from measurements (extraction of coconut fiber & cellulose nanowhiskers) and literature sources (further materials) | data taken from measurements (molybdenum sulfide production) and literature sources (further materials) | Data taken from study [8]; expanded with CNT ecotoxicity characterisation factors | OMMT: data taken from study [9] (via pers. Communication) / SNC: data taken from various literature sources | Data taken from [15] resp. from lit (2nd production |
| data sources for further materials & energy carriers (background data) | no information available | ecoinvent Database | ecoinvent Database | SimaPro database | TEAM LCA database | ecoinvent Databa literature |
| impact assessment, covered aspects | none (comparison on the level of cumulative inventory data: material rsp. energy input, waste output) | various "midpoint" indicators (GWP, HT, …) from the ReCiPe method | global warming and cumulative energy demand | ecotoxicity (according to the USEtox model) | global warming, gross energy requirement & acidification are reported; partly also further LCIA factors (Traci method) | global warming cumulative energ demand; ReCiPe score (endpoint) |
| further publication of study | - | - | - | - | - | - |

- **<40 LCA studies** of engineered nanomaterials published so far;
- **Less than 30%** of the studies are **taking into account the complete life cycle** (cradle-to-grave), while most studies omit end-of-life treatment or use phase, respectively;
- **~40%** of studies are **based on a functional unit of 1 weight unit** of produced nanomaterial.

Hischier & Walser (2012)

# … updated (2017)

- most studies still **omit** majority of **difficult issues** (like e.g. inclusion and subsequent assessment of releases of nanoparticles).
- **Up to summer 2016**, still only few **studies** have been published that are **covering releases of nanoparticles** in their studies,
- … dealing with nano silver, CNT, various forms of silica, nanocellulose and nano titanium dioxide (2 studies).



| Reference | | Input M | Input E | Emissions to air bulk | Emissions to air nano | Emissions to water bulk | Emissions to water nano | Emissions to soil bulk | Emissions to soil nano | Waste |
|---|---|---|---|---|---|---|---|---|---|---|
| Gilbertson et al. 2014 | single-wall carbon nanotubes (SWCNT) | ■ | ■ | | | | | | | |
| Li et al. 2014 | silicon nanowire (SiNW) | ■ | ■ | | | | | | | ■ |
| OECD 2014 | carbon black / HD silica / HD-HS silica / nanoclays | | | | ■ | | ■ | | | ■ |
| Piazza et al. 2014 | graphite nanoplatelets | ■ | ■ | | | | | | | ■ |
| Schrijvers et al. 2014 | various layered double hydroxides nanoclays and nanoclay montmorillonite | ■ | ■ | | | | | | | |
| Thakur 2014 | nano titanium dioxide | ■ | ■ | | | | | | | |
| Yaseneva et al. 2014 | carbon nanofiber (CNF) | | | | | | | | | |
| Alaviitala and Mattila, 2015 | nano-silica polymers | | | | | | | | | |
| Arvidsson et al. 2015 | cellulose nanofibrils (CNF) made from wood pulp | ■ | ■ | | | | | | | |
| Ferrari et al. 2015 | nano titanium dioxide | ■ | ■ | ■ | ■ | | | | | ■ |
| Hischier, 2015 | carbon nanotubes (CNT) | ■ | ■ | ■ | ■ | | ■ | | | ■ |
| Hischier et al., 2015 | nano Titanium Dioxide, nano Silicium Dioxide, and nano Silver | ■ | ■ | ■ | ■ | ■ | ■ | | ■ | ■ |
| Hicks et al. 2015 | nano silver | | | | | | | | | |
| Middlemas et al. 2015 | nano titanium dioxide | ■ | ■ | | | | | | | |
| Notter et al. 2015 | multi-wall carbon nanotubes (MWCNT) | ■ | ■ | ■ | | ■ | | | | ■ |
| Ojeda et al. 2015 | alumina nanoparticles | ■ | ■ | | | | | | | |
| Piccinno et al. 2015 | cellulose nanofibres (microfibrillated cellulose, MFC) | ■ | ■ | ■ | | ■ | | | | ■ |
| Pini et al. 2015 | nano titanium dioxide | | | | | | | | | |
| Pourzahedi & Eckelman, 2015 | nano silver | ■ | ■ | | | | | | | |
| Walser et al. 2011 | nano silver (coating) | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | |
| Wender and Seager, 2011 | single-wall carbon nanotubes (SWCNT) | | | | | | | | | |



(in prep.)



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# Conclusion – sounds somehow familiar …

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Relevant to **take into account all nano-related functionalities** and to **cover them adequately** by choosing an **appropriate functional unit** as well as respective system boundaries.

Establishing **Generic Life Cycle Inventory Models** of most common production ways of most important **nanomaterials**

Establishing clear **rules how releases of ENM need to be taken into account** on level of LCI modelling (what elements, what properties need to be reported for emission of $ENM_x$ ?)

(in a close collaboration of Toxicologists & Life Cycle Assessment Specialists) systematically establishing missing **LCIA factors for releases of nanomaterials**.

Hischier & Walser (2012)

NanoImpact 7 (2017) 17–26

Contents lists available at ScienceDirect

NanoImpact

journal homepage: www.elsevier.com/locate/nanoimpact

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# Most important factors of variability and uncertainty in an LCA study of nanomaterials – Findings from a case study with nano titanium dioxide

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... Science and Technology (Empa), Technology and Society Lab (TSL), Lerchenfeldstrasse 5, 9014 St. Gallen, Switzerland

... 42100 Reggio Emilia, Italy

**Which** of these **challenges** is **responsible for highest variability** – and with this, brings the highest uncertainty currently in LCA studies of nano-enabled applications ?

LCA
Impact assessment

the toxicity potential evaluation.

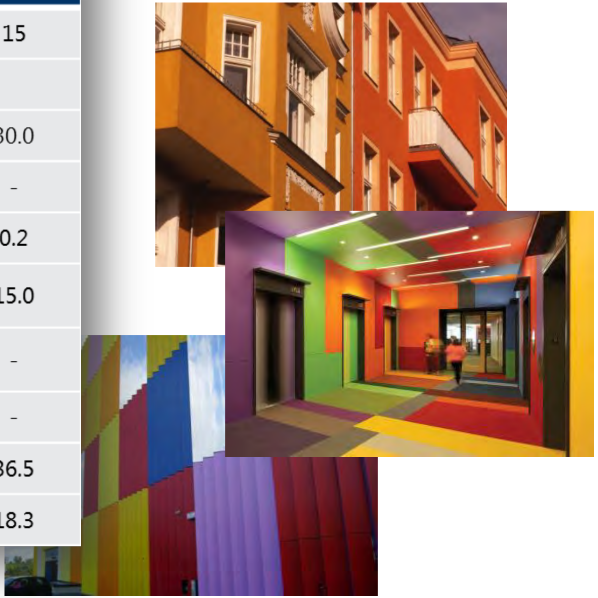
Hence, in order to apply Life Cycle Assessment in a more efficient way in the area of nano-enabled applications it would make sense to identify those challenges that result in the largest variation of the results; ... highest research priority in order to reduce their variability and/or ...

# Case study

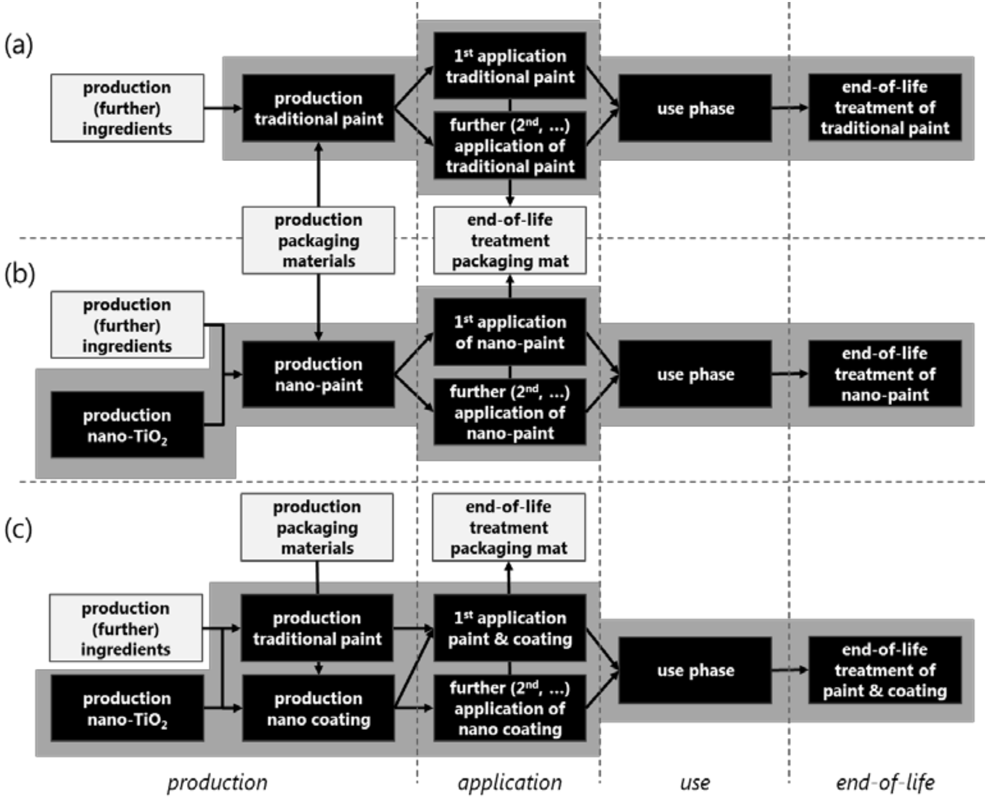


## Outdoor facade paintings and coatings with and without nano titanium dioxide

| | nano paint | traditional paint | nano coating |
|---|---|---|---|
| **Lifetime [years]** | 27 | 20 | 15 |
| **Composition [% w/w]** | | | |
| – **nano-$TiO_2$** | 3.0 | - | 30.0 |
| – **$TiO_2$, pigment-grade** | 13.58 | 16.58 | - |
| – **Silicone defoamer** | 10.97 | 10.97 | 0.2 |
| – **Styrene/acrylic copolymer** | 14.62 | 14.62 | 15.0 |
| – **Calcium carbonate (filler)** | 31.75 | 31.75 | - |
| – **Talcum (filler)** | 6.58 | 6.58 | - |
| – **Further ingredients** | 5.2 | 5.2 | 36.5 |
| – **Water** | 11.3 | 14.3 | 18.3 |



# Goal & Scope




- **Functional unit**
  1 m$^2$ of wall, protected over time of 80 years
- **Background data**
  ecoinvent version 3.1 (recycled-content model)
- **Applied LCIA methods**
  ReCiPe Midpoints and USEtox

# Challenges within this study

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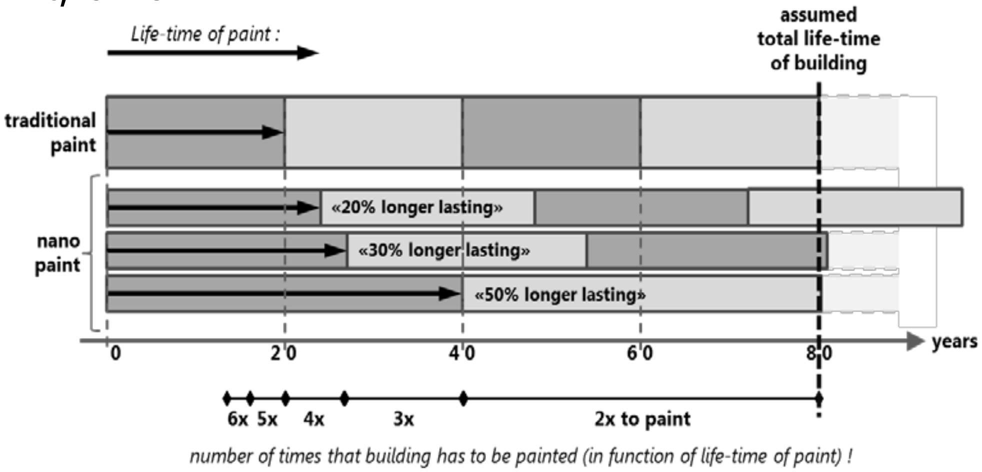
- [*Study setup*] Influence of chosen characteristics (e.g. life times) of here examined ENM-containing paint? Use of other alternatives (containing ENM) – what would change?

- [*LCI data*] Influence of using various data (and methods) covering the production of the required nanomaterial (nano-$TiO_2$)

- [*Releases of nanoparticles*] Are there any releases of nanoparticles taking place along the life cycle? What amount? How to assess such releases (i.e. what characterisation factors are available for this kind of releases?)

# Scenarios «Study setup»

(i) the influence of a change of the actual life-time of the nano-$TiO_2$ containing paint, and




(ii) a change in the formulation (i.e. applying a nano-coating on top of the paint, instead of an actual paint formulation with ENM).

# Scenarios «Releases of nanoparticles»

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## (i) Release of Nanoparticles along the life cycle

## (ii) Characterisation Factors (CF) for toxicity assessment :

| LCIA factor | Value | Unit | Further Information | Source | |
|---|---|---|---|---|---|
| **All factors** | 0 | | No CF applied for all toxicological impacts | | A |
| **Freshwater ecotoxicity** | 2.80E-01 | PAF $m^3$ day/kg | Lowest value based on weighted size distribution of nano-$TiO_2$ in freshwater | Salieri et al., 2015a | B |
| | 3.21E+01 | PAF $m^3$ day/kg | Highest values " – with α=0.001; nano-TiO2 diameter=8 nm | | - |
| | 1.30E+02 | PAF $m^3$ day/kg | USEtox & SimpleBox4Nano combined | Salieri et al.,2015b | C |
| | 2.62E+01 | PAF $m^3$ day/kg | simplified FF / EF from $HC_{50}$ values | Miseljic et Olsen, 2014 | - |
| **Human Toxicity, carcinogenic** | 5.98E-06 | cases/kg | outdoor, CONTINENTAL | Pini et al., 2016 | B |
| | 1.43E-02 | cases/kg | outdoor, SWITZERLAND | | C |
| **Human toxicity, non-carcinogenic** | 2.45E-10 | cases/kg | outdoor, CONTINENTAL (lower value) | | B |
| | 5.85E-07 | cases/kg | outdoor, SWITZERLAND (higher value) | | C |

# … in total about 180 different runs …

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**Default scenario**

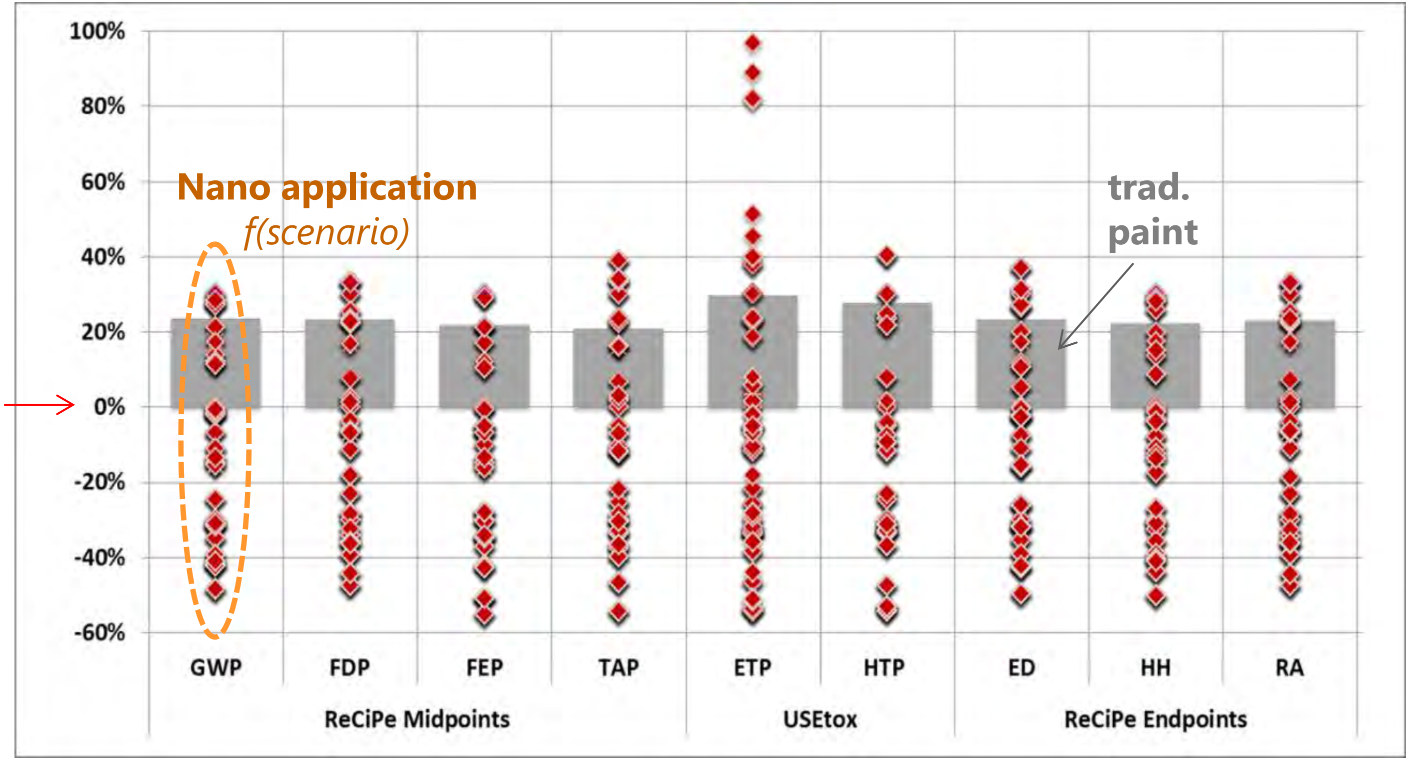
**1-a-i-A**

| | | |
|---|---|---|
| *applied CF* | **A** | no characterisation applied for releases of nanoparticles |
| | **B** | lower CFs for ecotoxicity and human toxicity impacts of releases of nanoparticles applied |
| | **C** | higher CFs for ecotoxicity and human toxicity impacts of releases of nanoparticles applied |
| *release scenario* | **i** | "Realistic" release scenario for releases of nanoparticles along life cycle |
| | **ii** | "High" release scenario for releases of nanoparticles along life cycle |
| *LCI model nano-$TiO_2$* | **a** | LCI model for nano TiO2 according to [13] |
| | **b** | LCI model for nano TiO2 according to [23] |
| | **c** | LCI model for nano TiO2 according to [20] |
| | **d** | LCI model for nano TiO2 according to [24], sulphate pathway |
| | **e** | LCI model for nano TiO2 according to [24], chlorine pathway |
| *study setup* | **1** | apply Nano paint with a 33% longer life time (i.e. 27 years) instead of traditional paint |
| | **2** | apply Nano paint with a 20% longer life time (i.e. 24 years) instead of traditional paint |
| | **3** | apply Nano paint with a 50% longer life time (i.e. 40 years) instead of traditional paint |
| | **4** | Application of a Nano coating on the traditional paint - life time of coating: 15 years |
| | **5** | Application of a Nano coating on the traditional paint - life time of coating: 10 years |
| | **6** | Application of a Nano coating on the traditional paint - life time of coating: 20 years |

# Results



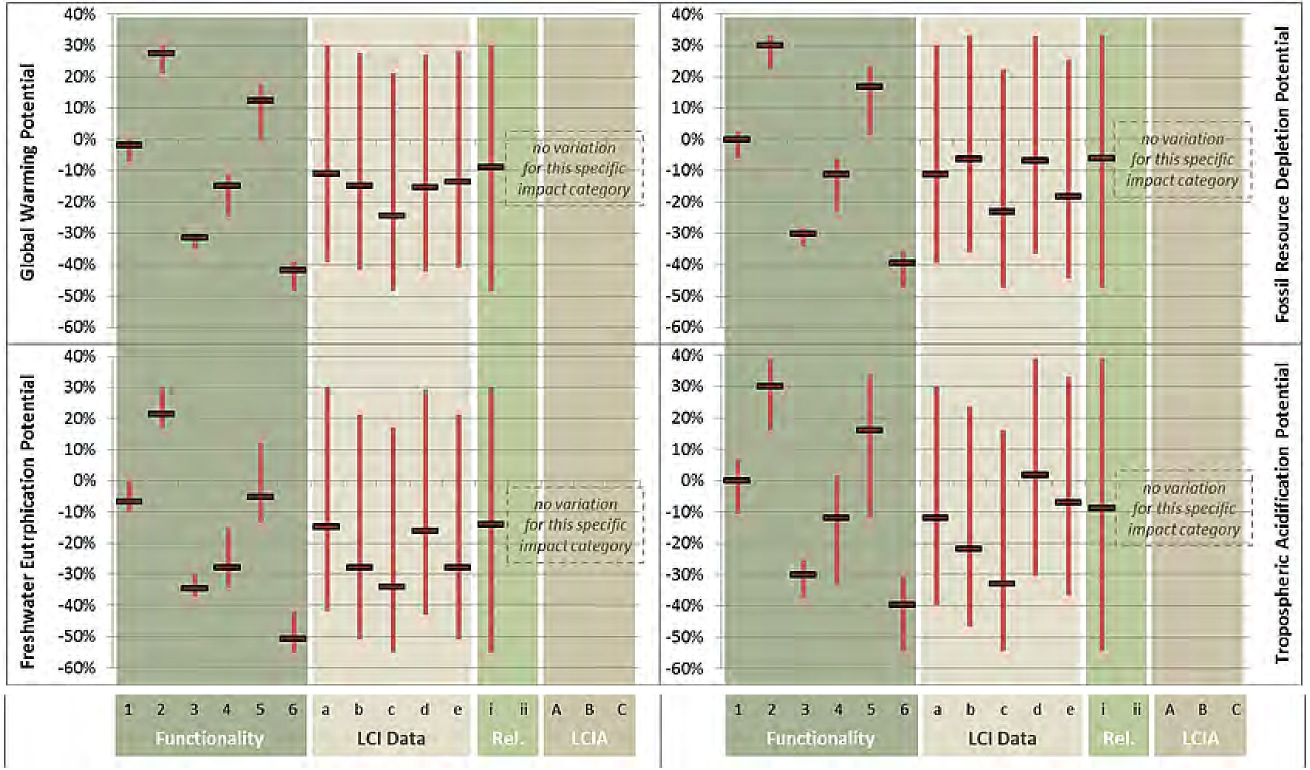
Default scenario




**Relative results – in comparison to the default scenario (set as 0%)**

# Results

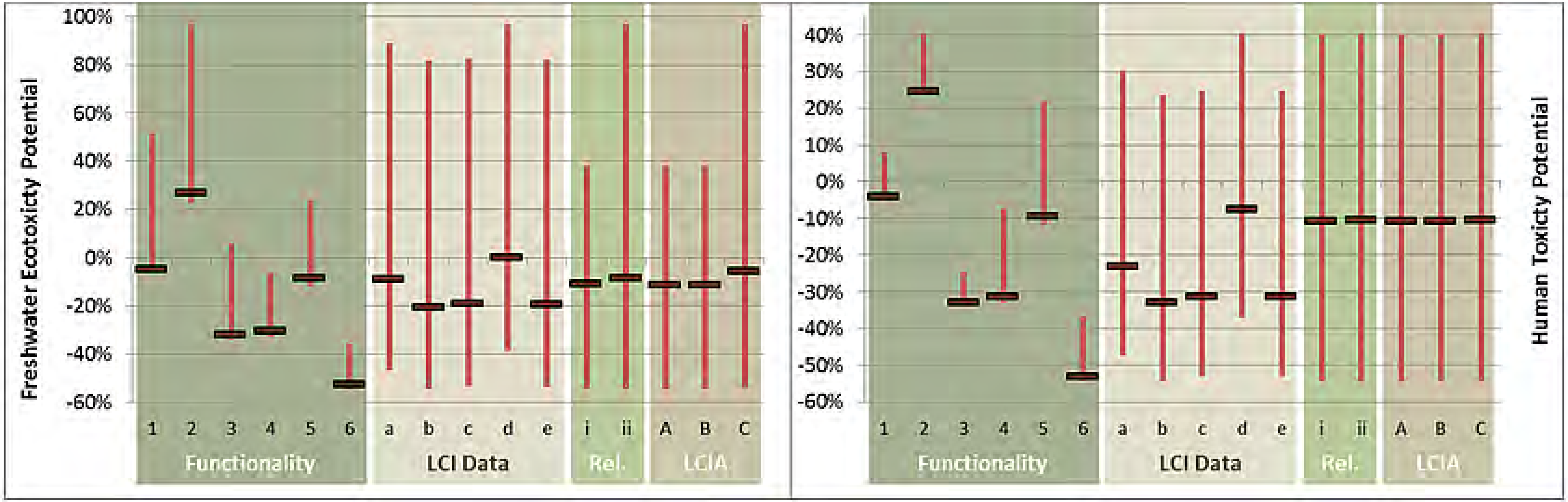





**Variability of the results for each of the four issues when the parameter of one scenario (shown as name on the horizontal axis) is kept constant, while all further parameters are varied.**

# Results






**Variability of the results for each of the four issues when the parameter of one scenario (shown as name on the horizontal axis) is kept constant, while all further parameters are varied.**

# Conclusion

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- main factor for the variability in the results lies at the very beginning of the LCA study – i.e. the adequate setup of the system is a crucial prerequisite for a fair and objective result !
- Precondition is that respective inventory data and/or LCIA factors are available and are taken into account in the study – however, accuracy of these issues (i.e. inventory data and LCIA factors) is of much lower relevance than the adequate study setup
- Not quantifiable is uncertainty related to unknown issues and/or those not included (e.g. in the case examined here the relevance of releases of nano-$TiO_2$ into air, as no respective LCIA CF is available) … one possibility to handle this point could be analogy considerations !

# Outlook / recommendations

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- First identify thoroughly all functionalities of a nano-enabled application and align them with traditional counterpart in a way that all aspects get covered in an equal way, allowing a fair (& comprehensive) comparison ;
- then follow the general recommendations for LCI data of MNMs and LCIA factors of releases of nanoparticles, in order to ensure the use of the most complete and comprehensive data possible.

- As long as some issues are covered by assumptions, it is important that a reasonable amount of sensitivity (or scenario) analysis are established in order to evaluate the relevance of all applied assumptions, and
- all this needs to be documented as transparently as possible …


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