



Nanotechnology and Life Cycle Assessment

A Systems Approach to Nanotechnology and the Environment
March 2007



Synthesis of Results obtained
at a workshop in Washington, D.C., 2-3 October 2006

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**Synthesis of Results Obtained at a Workshop
Washington, DC
2–3 October 2006**

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About the Organizers

The **Project on Emerging Nanotechnologies** is an initiative launched by the Woodrow Wilson International Center for Scholars and The Pew Charitable Trusts in 2005. It is dedicated to helping business, government and the public anticipate and manage possible health and environmental implications of nanotechnology. For more information about the project, log on to www.nanotechproject.org.

The Pew Charitable Trusts is a national charitable organization serving the public interest by informing the public, advancing policy solutions and supporting civic life. Based in Philadelphia, with an office in Washington, D.C., the Trusts will invest \$248 million in fiscal year 2007 to provide organizations with fact-based research and practical solutions for challenging issues.

The **Woodrow Wilson International Center for Scholars** is the living, national memorial to President Wilson established by Congress in 1968 and headquartered in Washington, D.C. The Center establishes and maintains a neutral forum for free, open, and informed dialogue. It is a nonpartisan institution, supported by public and private funds and engaged in the study of national and international affairs.

The **European Commission** has adopted the Communication “Towards a European Strategy for Nanotechnology”¹ and the “Nanosciences and nanotechnologies: An action plan for Europe 2005-2009.”² In them, a safe, integrated and responsible strategy was proposed and it was stated that “risk assessment related to human health, the environment, consumer and workers should be responsibly integrated at all stages of the life cycle of the technology, starting at the point of conception and including Research and Development (R&D), manufacturing, distribution, use and disposal or recycling” and “R&D needs to take into account the impacts of nanotechnologies throughout the whole of their life-cycle, for example, by using Life Cycle Assessment (LCA) Tools.” The attention on environmental requirements of products throughout their life cycle is also explicitly mentioned in a number of EU policy documents, including the Sixth Community Environment Action Programme,³ the Green Paper and the Communication on Integrated Product Policy (IPP),⁴ the Thematic Strategies on Sustainable Use of Resources⁵ and Prevention and Recycling of Waste,⁶ and the Directive on Energy Using Products (EuP).⁷ The EC has also highlighted international cooperation as a key asset to advance R&D and pave the way for a leveled playing field in the global market.

In the area of LCA, many other activities are undertaken at European level such as the European Platform on Life Cycle Assessment (<http://lca.jrc.ec.europa.eu/>), a project funded by the European Commission, with the objective of providing reference data and recommended methods for more reliable LCA studies by establishing a European Reference Life Cycle Data System (ELCD). The European Commission has also recently funded an important Coordination Action (CALCAS)

¹ COM (2004) 338 <http://cordis.europa.eu.int/nanotechnology/actionplan.htm>

² COM (2005) 243 <http://cordis.europa.eu.int/nanotechnology/actionplan.htm>

³ DECISION No 1600/2002/EC of the European Parliament and of the Council of 22 July 2002 laying down the Sixth Community Environment Action Programme.

⁴ COM (2003) 302 – Communication from the Commission to the Council and the European Parliament, Integrated Product Policy – Building on Environmental Life-Cycle Thinking.

⁵ COM (2005) 670 – Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions, Thematic Strategy on the sustainable use of natural resources.

⁶ COM (2005) 666 - Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions, Taking sustainable use of resources forward: A Thematic Strategy on the prevention and recycling of waste.

⁷ Directive 2005/32/EC of the European Parliament and of the Council of 6 July 2005 establishing a framework for the setting of eco-design requirements for energy-using products.

expressly aiming at expanding the application scope of the LCA framework. This project foresees important and high quality actions in the domain of environmental LCA and its potential extension to other scientific areas like economic and social sciences, in order to move towards a sound methodology for Life Cycle Sustainability.

The research initiatives related to environmental implications of nanoparticles include several projects funded within the previous Framework Programs (FP5 and FP6) and will be reinforced within the current Seventh Framework Program for Research (FP7), both in the area of the environmental and health impact of nanoparticles and the area of Life Cycle Thinking approach.

This workshop was organized in this context by the Unit G4 “Nano S&T: Converging Science and Technologies” of the Directorate General for Research. For additional information please refer to: <http://cordis.europa.eu/nanotechnology/>

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International Society for Industrial Ecology

Per Martin Schmidt, European Commission, for editing the final version of this document and for his assistance with organizing the workshop.

Preface

As an international community, we face both the excitement and the challenge that arise with a new technology. With nanotechnology already touching most industries—from medicine to textiles to electronics—the potential for transformational benefits may reach further than revolutionary technologies of the past. At the same time, the challenge of understanding potential risks that nanomaterials and nanoproducts may pose to human health and the environment is critical. We must take complementary steps to resolve environmental, health and safety issues that might otherwise deprive us of many anticipated social and economic benefits, as nanotechnologies progress from the laboratory to the global marketplace.

One approach that can improve our understanding of the possible impacts of nanotechnology is Life Cycle Assessment (LCA). This comprehensive analysis tool can be used to evaluate how a product or material—from the start of production through end-of-life—affects ecosystems and human health. LCA is already widely used internationally by scientists, engineers, and product designers in universities and businesses. If applied in the nanotechnology realm, the tool has the potential to guide researchers, policymakers, and companies as they seek to realize the commercial and practical benefits of a nanoproduct, while avoiding potential risks.

To date, interaction between LCA practitioners and nanotechnology researchers has been minimal. The workshop on “Nanotechnology and Life Cycle Assessment,” held in Washington, DC, on October 2-3, 2006, and co-organized by the Project on Emerging Nanotechnologies and the European Commission, sought to bridge this gap. The Project on Emerging Nanotechnologies, a partnership between the Woodrow Wilson International Center for Scholars and The Pew Charitable Trusts, works to examine the potential human health and environmental implications of nanotechnologies and to identify policy options to limit risks and maximize benefits. Our Project, like the European Commission, would like to see a more thorough evaluation of risks and benefits of nanomaterials and nanoproducts, from “cradle-to-grave.”

We hope that this publication, which synthesizes the views of over 25 experts in the LCA and nanotechnology fields, will broaden the application of life cycle studies for nanotechnologies. Continuing international collaboration in this field will help us capitalize on nanotechnology’s promise and proactively address any challenges.

More information on the Project on Emerging Nanotechnologies is available at <http://nanotechproject.org> and <http://www.wilsoncenter.org/nano>.

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Foreword

It is my pleasure to present this publication, which is the outcome of the workshop on Nanotechnology and Life Cycle Assessment, Washington, DC, 2-3 October 2006 co-organized by the EC and the Woodrow Wilson Center.

The European Commission (EC) has adopted the Communication “*Towards a European Strategy for Nanotechnology*”⁸ and the “*Nanosciences and nanotechnologies: An action plan for Europe 2005-2009*.”⁹ In these publications, a safe, integrated and responsible strategy was proposed and it was stated that “*risk assessment related to human health, the environment, consumer and workers should be responsibly integrated at all stages of the life cycle of the technology, starting at the point of conception and including Research and Development (R&D), manufacturing, distribution, use and disposal or recycling*” and “*R&D needs to take into account the impacts of nanotechnologies throughout the whole of their life-cycle, for example, by using Life Cycle Assessment (LCA) Tools.*” The EC has also highlighted international cooperation as a key asset to advance R&D and to pave the way for a level playing field in the global market.

The EC also aims to address the mandate in the action plan by proposing to “*develop with Member States, international organizations, European agencies, industry and other stakeholders, terminology, guidelines, models and standards for risk assessment throughout the whole life-cycle of nanoproducts.*”

The 7th Framework Programme for research (FP7), the EU's instrument for funding scientific research and technological development over the period 2007 to 2013, is one of the most important elements for the implementation of the Lisbon agenda for growth and competitiveness. The programme places greater emphasis than in the past on research that is better suited to the needs of European industry to help it compete internationally. The European Commission is a leading international player in nanotechnology, both in terms of policy making and in research funding.

The research initiatives related to environmental implications of nanoparticles include several projects funded within the previous Framework Programmes (FP5 and FP6) and will be reinforced within the current Seventh Framework Programme for Research (FP7), both in the area of the environmental and health impact of nanoparticles and the area of Life Cycle Thinking approach.

More information on nanotechnology in Europe and in particular at the European Commission is available on <http://cordis.europa.eu.int/nanotechnology>, and www.nanoforum.org.

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⁸ COM (2004) 338 <http://cordis.europa.eu.int/nanotechnology/actionplan.htm>

⁹ COM (2005) 243 <http://cordis.europa.eu.int/nanotechnology/actionplan.htm>

Executive Summary

This report summarizes the results of “Nanotechnology and Life Cycle Assessment,” a two-day workshop jointly convened by the Woodrow Wilson Center Project on Emerging Nanotechnologies; the United States Environmental Protection Agency Office of Research and Development; and the European Commission, RTD.G4 “Nano S&T: Converging Science and Technologies.” Held in October 2006, the workshop involved international experts from the fields of Life Cycle Assessment (LCA) and nanotechnology.

The main program of the workshop consisted of introductory lectures, group discussions and a final plenary session. A writing group prepared the initial draft of this report based on workshop discussions, and the final report was reviewed by all workshop participants and outside experts. The contents are based on the results of the group discussions. The structure of this report follows the main topics identified and discussed by the groups.

The purpose of the workshop was to determine whether existing LCA tools and methods are adequate to use on a new technology. This document provides an overview of LCA and nanotechnology, discusses the current state of the art, identifies current knowledge gaps that may prevent the proper application of LCA in this field and makes recommendations on the application of LCA for assessing the potential environmental impacts of nanotechnology, nanomaterials, and nanoproducts. For the purposes of this report, “nanoproducts” are defined as products containing nanomaterials. A short version of this report will be published in an appropriate LCA and/or a technical nanotechnology journal.

The following presents a summary of the main conclusions and recommendations identified by the workshop participants and presented in this report.

Main Conclusions

- There is no generic LCA of nanomaterials, just as there is no generic LCA of chemicals.
- The ISO-framework for LCA (ISO 14040:2006) is fully suitable to nanomaterials and nanoproducts, even if data regarding the elementary flows and impacts might be uncertain and scarce. Since environmental impacts of nanoproducts can occur in any life cycle stage, all stages of the life cycle of nanoproducts should be assessed in an LCA study.
- While the ISO 14040 framework is appropriate, a number of operational issues need to be addressed in more detail in the case of nanomaterials and nanoproducts. The main problem with LCA of nanomaterials and nanoproducts is the lack of data and understanding in certain areas.
- While LCA brings major benefits and useful information, there are certain limits to its application and use, in particular with respect to the assessment of toxicity impacts and of large-scale impacts.
- Within future research, major efforts are needed to fully assess potential risks and environmental impacts of nanoproducts and materials (not just those related to LCA). There is a need for protocols and practical methodologies for toxicology studies, fate and transport studies and scaling approaches.
- International cooperation between Europe and the United States, together with other partners, is needed in order to address these concerns.
- Further research is needed to gather missing relevant data and to develop user-friendly eco-design screening tools, especially ones suitable for use by small and medium sized enterprises.

Key Recommendations

1. Case-studies/prioritizing efforts

With limited resources, a case-study research approach could be adopted to significantly enhance knowledge on environmental impacts of nanomaterials and nanoproducts.

2. LCA studies and presentations of results

Any LCA study on nanoproducts and nanomaterials most likely suffers from high uncertainty issues. Therefore, the report recommends:

- Do not wait to have near-perfect data.
- Be modest about uncertainties; clearly state relevant uncertainty aspects and assumptions.
- Draw conclusions in the case of major or significant improvements; otherwise, state that the nanoproducts and the conventional product are equivalent.
- At this early stage, studies should focus on protecting humans and the environment.
- Separate the category indicators, grouping them by relevance/uncertainty.
- Avoid overselling the benefits of the new nanoproduct, since assessment methodologies will improve and might show “problems” in the future.
- Work with toxicologists and other scientists (geographical and socio-economic impacts) to review data and bound the issue.
- Make disaggregated data available for future LCA comparisons.

3. Approaches

- Critical review should always be done to ensure credibility of LCA studies.
- An independent review should be made by an expert panel with balanced representation and wide range of expertise.
- Data for the critical review or other supporting data should be published.
- Panels of interested parties should be formed to establish rules for LCA of nanomaterials and nanoproducts.

4. Actions from stakeholders

Different stakeholders/authorities can potentially support the application and use of LCA for nanoproducts and nanomaterials through a large set of actions.

Government actions could include:

- Setting up research frameworks and programs for the methodology development of LCA in the field of nanotechnology and with nanoproducts.
- R&D activities, with special emphasis on multinational cooperation in fields related to health and environmental safety.
- Use of LCA results to design adapted economic instruments.
- Using LCA to help develop green purchasing and integrate nanotechnology criteria in green purchasing.
- Allocating a portion of current nano research funding to nano/LCA research to make it more attractive to the private sector for further R&D.
- Providing independent, standardized and reviewed LCA information that might be used by industry and other stakeholders.

- Covering different nanotechnologies' flows of substances (air emissions, water releases etc.) into the European Commission's "European Reference Life Cycle Data System" (ELCD), and the US Life Cycle Impact database.
- Working toward an international LCI database for nanomaterials.
- Improving data coordination among different government agencies, e.g., agencies responsible for product consumer safety evaluations, workplace safety evaluations and environmental issues.

Academia can potentially support the application and use of LCA to nanoproducts and nanomaterials through a large set of actions, including:

- Setting up databases for LCA case studies on nanotechnology and nanoproducts.
- Providing scholarships to the universities to hire Ph.D. students specifically for nano/LCA research.
- Carrying out research in LCA methods applied to nanotechnology and nanoproducts.

Industry can potentially support the application and use of LCA to nanoproducts and nanomaterials through a large set of actions, including:

- Undertake R&D activities.
- Use of LCA results to design improved products.
- Co-funding research on developing LCA methods, impact characterization metrics specific to nanotechnologies.
- Co-funding research on toxic effects of specific nanomaterials.
- Co-funding social science research on public concerns about nanotechnology and on developing effective risk-communication strategies using LCA data.
- Actively creating mechanisms for sharing confidential data without compromising competitiveness.

The report also notes that the insurance industry should play a leading role in assessing life cycle risk assessments of nanoproducts.

NGO and Consumer Associations can potentially support the application and use of LCA to nanoproducts and nanomaterials through a large set of actions, including:

- Communicating LCA study results to the public to inform consumers.
- Educating themselves and promoting LCA as a tool to assess nanotechnology.

1. Introduction:

The Role of Life Cycle Assessment in the Field of Nanotechnology

Nanotechnology and the production of nanomaterials and products containing nanomaterials (defined as “nanoproducts” for the purpose of this report) are rapidly developing fields with many opportunities for innovation. However, numerous uncertainties exist regarding their possible impact on the environment and human health. Therefore, holistic and comprehensive assessment tools such as Life Cycle Assessment (LCA) are essential to analyze, evaluate, understand and manage the environmental and health effects of nanotechnology. This approach could also be used to compare the environmental performance of these emerging technologies and products with that of conventional technologies. Despite its uncertain environmental, health and safety impacts, nanotechnology has shown a great potential for “smart” multifunctional and high-performance products for innumerable commercial and industrial applications. There may be tensions between the precautionary principle of avoiding environmental impacts by not applying nanotechnology and the potential benefits gained from applying it. Measures taken to protect the environment from possible adverse effects caused by nanomaterials may have unidentified effects on society. For example, changed societal behavior in using nanoproducts may counterbalance a part of the environmental improvements from the products themselves. However, society, as well as individuals, might accept the potential risks, if the benefits of nanotechnology (e.g., applications in cancer treatment and other areas of medicine and in more-efficient energy systems) are clear.

Nanotechnologies involve the purposeful design, characterization, production and application of structures, devices and systems by controlling shape and size at nanometer scale (The Royal Society & Royal Academy of Engineering 2004). Materials with unique structural features in the order of 1-100 nanometers are referred to as nanomaterials. They can be aggregates of nanoparticles as well as composites containing nanoparticles. Due to their exceptional size-dependent functions and properties (e.g., surface activity; electrical, magnetic and optical properties; and shape), nanomaterials are being developed for applications in a large variety of industrial sectors. These include, for example, “intelligent,” multifunctional nanoparticles for cancer diagnosis and treatment, high-performance batteries based on nanostructured electrodes, single-walled carbon nanotubes for diverse information and communication technology devices and antimicrobial nanomaterials for the cosmetics, food and clothing industries.

As a result of this broad range of potential applications of nanotechnology, a similarly broad range of environmental and human health impacts can arise from different exposure routes of nanoparticles (Figure 1-1).

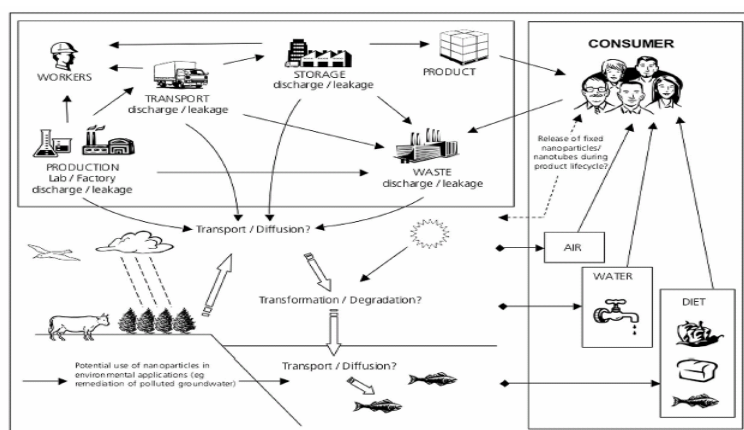


Figure 1-1: Possible exposure routes for nanoparticles based on current and potential future applications (adopted from The Royal Society & Royal Academy of Engineering 2004)

Currently, knowledge of the exposure routes as well as of the potential environmental impacts of nanoparticles is limited. In addition, potential resource and environmental advantages of nanomaterials and products using nanomaterials over conventional products have not been investigated. Therefore, a clear need exists to establish a full understanding of the environmental benefits and drawbacks of nanotechnology and nanomaterials compared with those of conventional technologies and products over their complete life cycles. LCA is the essential tool to achieve this.

Life Cycle Assessment is a method for estimating and assessing the resource usage and environmental impacts attributable to the entire life cycle of a product, from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end-of-life treatment and final disposal (ISO 14040:2006). The environmental and resource impacts include climate change, stratospheric ozone depletion, toxicological stress on human health and ecosystems, the depletion of resources, water use and many others. In principle, the LCA method encompasses four phases, as illustrated in Figure 1-2. For requirements and guidelines for all four phases, see ISO 14044:2006.

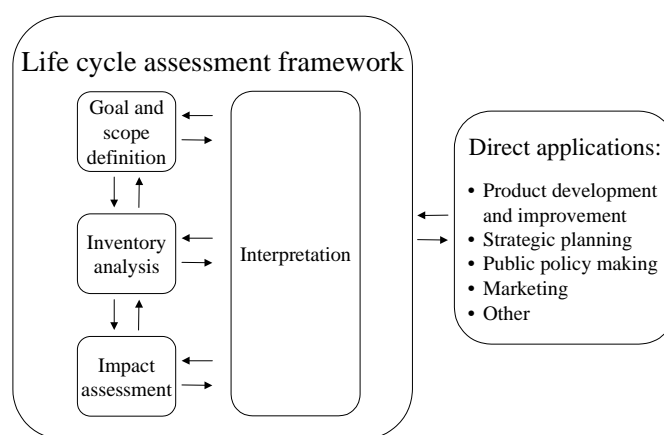


Figure 1-2: Stages of a Life Cycle Assessment (adapted from ISO 14040:2006)

The goal and scope definition of an LCA provides a description of the product system in terms of the system boundaries and a functional unit, i.e., the reference unit defining the function of the product system. The Life Cycle Inventory (LCI) aims at data collection and calculation procedures in order to quantify from cradle-to-grave the relevant inputs (e.g., material inputs) and outputs (e.g., emissions to air) of the product system. The purpose of the Life Cycle Impact Assessment (LCIA) is to aggregate the results from the inventory analysis and to evaluate the significance of the product's potential environmental impacts. This process involves connecting inventory data with specific environmental impact categories and the respective category indicators, such as global warming potential as an indicator for climate change. The interpretation considers the findings from both LCI and LCIA and should provide conclusions and recommendations.

Note that LCA is different from many other techniques, such as environmental performance evaluation and risk assessment (RA), as it is a relative and essentially comparative approach based on a functional unit, with all inputs and outputs accounted for in the LCI, and consequently in the LCIA profile, being associated with the functional unit. LCA is adequate to answer many, but certainly not all, questions on environmental and human-health impacts of nanotechnology in comparing different products with the same function. However, for assessing social and economic benefits and/or problems, as would be required in a full

sustainability assessment, a broader assessment framework is required. To this end, different sustainability tools, such as the life cycle management toolbox, can be used (UNEP 2006).

There are three major questions concerning the application of LCA to nanotechnology:

1. Why should LCA be performed on nanomaterials and nanoproducts?
2. Who is likely to perform an LCA on nanomaterials and nanoproducts?
3. What are the benefits of conducting an LCA for different stakeholders?

1. Why should LCA be performed on nanomaterials and nanoproducts?

Generally speaking, emerging technologies are not conducive to a full-spectrum LCA due to insufficient knowledge about the detailed inputs and outputs of the system. This has forced the consideration of LCA after the technology has matured. However, the recent application of LCA in alternative energy systems (e.g., solar, wind, bio-fuels) seems to change this general trend toward an earlier adoption of LCA. Similarly, assessing nanotechnology and nanoproducts with LCA gives an opportunity for proactive action of different stakeholders in order to prevent or minimize potential adverse effects to human health and the environment over the entire life cycles of nanoproducts. In the case of toxicological safety, LCA can add supplementary environmental information to support decisions on the development of certain nanomaterials or nanoproducts.

Specifically, LCA can answer questions on the environmental performance of nanoproducts and nanotechnology, such as the following:

- How do the life cycles of devices/products using nanomaterials compare with those of conventional devices/products? To what extent do savings in energy efficiency compared to those of conventional devices/products balance the energy consumption used in producing nanomaterials?
- Which specific phase in the life cycle (e.g., manufacturing, end-of-life) dominates energy use?
- Are there any issues in end-of-life management that are specific to nanomaterials, especially recovery and reuse or recycling?
- What are the key eco-toxicity and human-toxicity potentials for nanomaterials?
- How do we integrate toxicological RA methods into LCA for nanomaterials?
- Are there trade-offs between potential eco-toxicological and human toxicity impacts and a potential environmental gain related to global change and other pressing environmental problems?
- What are the geographical impacts of devices/products using nanomaterials compared to those of conventional devices/products?

2. Who is likely to perform an LCA on nanomaterials and nanoproducts?

LCA studies on nanotechnology, nanomaterials and nanoproducts will be performed primarily by the companies themselves, as well as by consultants and academia. Government-supported institutions may play a secondary role through assistance, e.g., by building databases, funding research and providing funds for method development and improvement.

3. What are the benefits of conducting an LCA for different stakeholders?

For government agencies:

- LCA studies can provide environmental information to aid in developing regulations and legislation in regard to occupational health and safety, consumer protection and environmental protection, including geographical impacts;
- Contracting officials may take LCA results into account as environmental information, including geographical impacts when procuring goods, services and works that include the application of nanoproducts and nanotechnologies (Green Public Procurement);
- Investigating environmental burdens and benefits of nanotechnology at an early stage is consistent with the policy of the European Commission and the United States to support the safe, responsible and sustainable development of nanotechnology; and
- LCA results can be used to inform the public of the potential benefits of nanoproducts as well as of their potential environmental harm.

For industry:

- Different decisions in product design, marketing, development and manufacturing can be influenced through LCA results such as research and development (R&D) choices of specific nanomaterials and nanotechnologies. The design of the product strongly predetermines its behavior in the subsequent life cycle phases (e.g., producer responsibility);
- LCA can be applied as a screening tool for different technologies to support the classical R&D decision process;
- Companies can proactively investigate the environmental performance of their nanoproducts and nanotechnologies in order to avoid hindering innovation, provide evidence of compliance with legislation and derive value from the LCA work;
- LCA results can provide a sound basis for marketing nanoproducts as environmentally friendly products, e.g., for private consumers or Green Public Procurement;
- LCA results can provide information for environmentally efficient products and production processes and thereby help save costs;
- LCA can help companies foresee and avoid likely environmental problems either upstream or downstream of their production/sales operations; and

- LCA can help support strategic decision-making in investment and production capacities.

In the field of nanotechnology, the broad framework of Life Cycle Thinking and the internationally standardized method of LCA can substantially help identify opportunities for pollution prevention and reductions in resource consumption while taking the entire life cycle of nanoproducts and the respective technologies into consideration.

The following chapters discuss how LCA can be applied immediately, which parts of the LCA methodology need to be adapted for application to nanotechnology and the conclusions and recommendations for different stakeholders.

2. What Can LCA Do Immediately in the Assessment of Nanotechnology? A Review of the State-of-the-Art

As discussed above, a life cycle perspective is essential in evaluating the potential environmental impacts of the emerging nanomaterials and nanoproducts from cradle to grave. It is important to distinguish between LCIA and other types of impact analysis, such as risk assessment (RA), which focuses on specific chemicals at defined exposures and target organs. The LCIA does not attempt to quantify any specific actual impacts associated with a product, a process or an activity. Instead, it seeks to establish a linkage between a system and potential impacts. The models used within LCIA are often derived and simplified versions of more sophisticated models within each of the various impact categories. These simplified models are suitable for relative comparisons of the potential to cause human or environmental damage, but are not indicators of absolute risk or actual damage to human health or the environment.

Applying LCA to nanomaterials and nanoproducts requires special consideration of certain aspects of data collection and impact modeling, such as the need to fully understand the toxicity potential of nanomaterials in humans. Theoretically, the general framework of LCA, as developed by the Society of Environmental Toxicology and Chemistry (SETAC 1990 and 1993) and standardized by the International Organization for Standardization (ISO) (ISO 14040:2006, ISO 14044:2006), can be applied to the nanotechnologies.

Due to the newness of the field, only a few LCA studies of nanotechnologies have been published to date. Table 2-1 lists studies that were identified in a recent literature search (Lekas 2005). According to the table, LCAs have been performed mainly in the automotive, chemical, electronics and energy sectors. This summary, of course, includes only those studies that are available in the open literature. It is likely that manufacturers have conducted additional assessments but retained the results for in-house use only.

The main barriers for conducting LCAs in the nanotechnology field are the same as those in all other fields. The first barrier is the necessity to increase awareness of applying the life cycle concept in order to avoid the unintended shifting of environmental burdens. The second main barrier is the lack of reliable inventory (input and output) data as well as data on impact relationships. Proprietary information on manufacturing processes, the absence of toxicological test results, a general lack of data and wide process-to-process variation are other examples of the barriers for all LCA work.

The LCA studies listed here typically address some, but not all, life cycle stages. Researchers have limited the scope of the LCA primarily because of the lack of readily accessible data or because they deemed that background processes have minimal environmental impact and, hence, can be omitted from the study. Nevertheless, it is encouraged that such qualitative and

quantitative findings are included, together with detailed reasons for their omission, to satisfy transparency, acceptability and credibility criteria for such analyses. While the manufacturing and use stages were usually included, impacts from transportation and end-of-life activities were often excluded, or at best, only minimally addressed. Therefore, not all studies that are described as LCAs meet the full scope of an LCA as defined by the ISO standard (ISO14040:2006, ISO14044:2006).

Table 2-1: Nanotechnology Sector Applications (VDI 2004) and Published LCA Studies Identified in a Recent Literature Search (Lekas 2005)

Sector/Application	LCA Studies Performed
Automotive	
Lightweight Construction	Lloyd & Lave 2003 (clay polypropylene nano-composite)
Catalysts	Lloyd et al. 2005 (nano-scale platinum-group metal [PGM] particles)
Painting; Tires; Sensors; Windshield; Body Coating	
Chemical	
Fillers for Paints	Steinfeldt et al. 2004 (nano-varnish with sol-gel technology) Harsch & Schuckert 1996 (powder coating technology)
Composite Materials; Impregnation of Papers; Adhesives; Magnetic Fluids	
Construction	
Materials; Insulation; Flame Retardants; Surface Coatings; Mortar	
Cosmetics	
Sunscreens	
Lipsticks; Skin Creams; Toothpaste	
Electronics	
Displays	Steinfeldt et al. 2004 (semiconductor crystals in organic light-emitter displays and carbon nanotubes) EPA 2001 (desktop computer displays - flat panel and cathode ray tube)
Data Memory	
Laser Diodes; Fiber-optics; Optical Switches; Filters; Conductive, Anti-static Coatings	
Energy	
Lighting	Steinfeldt et al. 2004 (quantum dots and semiconductor crystals in light-emitting diodes)
Fuel Cells; Solar Cells; Batteries; Capacitors	
Engineering	
Protective Coatings for Tools and Machines; Lubricant-free Bearings	
Environmental	
Environmental Monitoring; Soil and Groundwater Remediation	
Toxic Exposure Sensors; Fuel-Changing Catalysts; Green Chemistry	
Food and Drink	
Packaging; Storage Life Sensors; Additives; Juice Clarifiers	
Household	
Ceramic Coatings for Irons; Odor Removers; Cleaners for Glass, Ceramics and Metals	
Medicine	
Drug Delivery Systems; Contrast Medium; Rapid Testing Systems; Prostheses and Implants; Anti-microbial Agents; In-Body Diagnostic Systems	
Sports	
Ski Wax; Tennis Racquets; Golf Clubs; Tennis Balls; Anti-fouling Coatings for Boats; Anti-fogging Coatings for Glasses and Goggles	
Textiles	
Surface Coatings; "Smart" Clothes	
Warfare	
Neutralization Materials for Chemical Weapons	

For LCI, data from similar technologies can be applied to nanotechnology as an approximation. Lack of data for the impact assessment phase is a more serious impediment. However, performing LCA should not be delayed until complete data are available. An alternate approach is to place reasonable upper and lower bounds on the expected impacts in order to continue with the rest of the analysis. However, it is also essential to ensure that all the applied assumptions and caveats are clearly spelled out to satisfy transparency, acceptability and credibility criteria for such analyses.

An important distinction exists between LCIA and other types of impact analysis, such as RA for toxicological effects (HERA 2006). The LCIA does not attempt to quantify any specific actual impacts associated with a product, process or activity at any particular point in time or space. Instead, unlike toxicological RAs conducted, e.g., in a regulatory context, LCIAs provide relative comparisons of the potential to cause human or environmental damage.

3. Applicability of the ISO-LCA Framework to Nanomaterials and Nanoproducts

The ISO framework for LCA (ISO 14040:2006; ISO 14044:2006) is fully applicable to LCAs involving nanomaterials and nanoproducts. In some phases and steps, however, a number of issues need to be addressed in more detail.

It must be stressed that all stages of the life cycle of nanomaterials and nanoproducts should be covered in an LCA study. In principle, this also includes geographical impact information and capital equipment, such as the construction and operation of high-precision equipment and clean rooms. Thus, data are needed for the inventory phase and for the impact assessment phase in every stage of the life cycle. The acquisition and provision of these data by engineers (for the inventory data), toxicologists and socio-economists (for a comprehensive data set), pose a challenge, both with respect to data quality and confidentiality.

There already exist many nanoproducts, all with their specific characteristics as to composition and use pattern (see Table 2-1). There are also many nanomaterials, all with their specific modes of production and possible impacts. Therefore, there is no generic LCA of nanomaterials, just as there is no generic LCA of chemicals; it only makes sense to calculate the cradle-to-grave LCA of a specific nanoproduct or the cradle-to-(factory) gate LCA of a specific nanomaterial. Nanomaterials, in turn, may show up in many products. Thus, the suitability of the LCA framework for dealing with nanomaterials is essential, even for LCA studies of products for which the nanotechnology is not a central issue. The cradle-to-gate data of the nanomaterials used can be applied in the full LCA studies of the products using the specific materials.

3.1 Goal and Scope Definition

The most important issue to consider in the goal and scope definition is the choice of the functional unit. Nanoproducts fulfill functions that are quite new and for which it may be difficult to specify functional alternatives. Consider, for example, stain-resistant nanocoatings on trousers. In a comparative analysis with traditional trousers, one should take care to specify the exact conditions of wearing and cleaning these trousers. Another example is the use of nanomaterials in pharmaceutical applications for which a functional equivalent may even not exist.

In every case of considering emerging technologies, behavioral aspects may also be important. Will consumers indeed use the new nanoproducts in the way that is recommended or predicted? Can we foresee any rebound effects? The goal and scope definition may address strategies to answer these questions, for instance, using sensitivity analyses in the interpretation phase.

In certain cases, such as for medical applications, LCA will probably primarily be used as a management tool, not to support go/no-go decisions.

3.2 Life Cycle Inventory

A crucial problem in the inventory analysis is ensuring the collection and use of complete and reliable data and the availability of clear explanations of applied assumptions, advantages and disadvantages, as well as caveats to satisfy transparency, acceptability and credibility criteria for such analyses. This problem shows up even more markedly for nanotechnologies. Cut-offs based on mass could be misleading with nanoparticles and should not be applied. Production processes for nanomaterials are evolving much more rapidly than those for other traditional manufacturing processes. Moreover, many of these process data may be subject to confidentiality constraints. Data should be specified according to the goal and scope of the study. For instance, an LCA for a producer of nanomaterials should use company-specific data whenever possible, but an LCA for governmental-strategy determination could be based on sector-wide averages and possibly take into account the future consequences of a decision. It remains a difficult task to collect proprietary information from companies, and it is very important to have information from the producers of the materials. As such, we do not need a specific LCI methodology for nanoproducts, but we do need an approach to data estimation.

A major concern is that nanotechnology is a technology that requires large and energy-consuming capital equipment that, moreover, tends to rapidly become outdated due to new developments. Equipment for lithography and ultra-clean rooms are just two examples. Nanotechnology may turn out to be an example of an activity where the impacts of providing and using capital equipment cannot always be ignored. Yet, the data on the capital equipment will be difficult to obtain.

Another issue is that the capital equipment mentioned will serve several different nanomaterials or nanoproducts. Thus, an allocation problem exists for the simultaneous service provision of these capital goods to an array of nanogoods.

As nanoproducts are only starting to enter the market, it is at present unclear how processes related to use, maintenance and end-of-life services (e.g., disposal, recycling) will proceed. Some materials will be released during use, either intentionally (e.g., nano-additives in gasoline) or unintentionally (e.g., nano-additives in tires). Exact release rates are not always available, especially when these are condition-dependent (e.g., when they depend on the driving style of the car driver or on the weather). The behavior of nanomaterials that have been discarded after use is also not yet clear. For instance, their reaction with other materials in an incinerator or at a dump site is uncertain, yet these are required data in an LCA study.

A potential tool to aid LCI efforts given these identified problems is input-output-based life cycle assessment approaches (IO-LCA) (Lave et al. 1995, Hendrickson et al. 1998). Input-output-based models consider all of the elements of a product's supply chain by default. Thus, they include equipment and other expenditures, as well as other purchases. The supply chain referred to here includes not only the "direct" purchases needed for the final product (e.g., chemicals for nanomaterial production), but also the "indirect" purchases to make all products that go into the final product (e.g., equipment and inputs needed to make chemicals for nanomaterials).

It is because of these supply chain features that IO-LCA methods may prove useful. These existing data sources may be helpful in assessing new nanoproducts. An IO-LCA model of semiconductor manufacturing (which will include all upstream purchases of equipment, chemicals, etc.) may be altered by hand to better represent some known differences between semiconductors and nanomaterials, but still keep intact all of the other parts of the LCA to ensure a fairly complete representation of the life cycle.

Nanotechnologies have quite a few features in common with the semiconductor industry. The production of semiconductors, especially the advanced integrated circuits, requires large equipment, which is rapidly outdated, and intensive use of clean rooms. Possible strategies to address the data constraints by estimation are as follows:

- Start from process mass balances, extend to cradle-to-gate, then extend to the product functionality;
- Characterize the main chemicals used and then several of the dedicated processes to obtain the right form and/or functionality; also try to characterize the main manufacturing pathways/technologies (e.g., lithography, precipitation, depositions); and
- Perform a screening using default processes with orders of magnitude of energy related and auxiliary chemicals as for processes using high pressure, etc.

Further, it might be useful to create a national, or even an international, database on leveling the inputs and outputs, breaking down the process at different levels, from individual processes to sector-wide global averages. It would also be desirable to establish a tiered approach for product designers using nanomaterials.

The inventory analysis should always connect to the impact assessment. In standard LCI tables, only the quantity and the chemical composition of releases are reported. For instance, a typical inventory contains items such as "12 kg CO₂" and "0.36 kg 1,1,1-trichloroethane." Only for some chemicals an additional characteristic is required, for instance, its isotope (for radioactive releases), its stereo-isomer (for a chemical like cyclohexane) or its valence (for an ion such as chromium). For nanoparticles that are released during any life-cycle stage, additional parameters will be of importance in the impact assessment (either for fate, exposure or effect modeling). Parameters that most likely influence toxicity of nanomaterials include the chemical composition, particle size, shape, aspect ratio, crystal structure, surface area, surface chemistry and charge, solubility, as well as adhesive properties. As nanoparticles may also be coated, it is important to find out whether to report the pure material or the composite. In this context, it is also important to know whether nanoparticles change their form (shape, coating, etc.) during their life cycle, for instance, due to aging and other influences such as weather, mechanical stress/pressure, electromechanical fields or catalysis. As a result, the elementary flows characterizing nanomaterials in the inventory may require that these additional characteristics be described.

Nanomaterials offer significant savings in raw material and energy requirements (e.g., more powerful and higher-energy rechargeable batteries); however, materials used for new products should be ideally sourced from renewable or abundant sources. This is particularly important when rare materials, especially metals, are used in small amounts that are widely distributed in products and that can consequently be widely dispersed in the environment.

3.3 Life Cycle Impact Assessment – A General Overview

The production, use and disposal of nanoproducts are associated with the standard impact categories, either at the midpoint level (e.g., climate change, human toxicity, eco-toxicity and acidification) or at the endpoint level (e.g., human health, ecosystem health and resource depletion).

The toxic and health effects of nanomaterials in their use and end-of-life stages seems to be a key issue of impact assessment (this is discussed further in Section 3.4). Several methodologies have been proposed by LCA experts to assess the environmental significance of the elementary flows in the inventory, see e.g., the ISO-based Dutch guidelines (Guinée 2002). There is consensus (ISO 14044:2006) in distinguishing the four stages of the impact assessment: classification, characterization, normalization and weighting. Classification concerns the assignment of LCI results to the impact category, i.e., the data from the inventory table are grouped together into a number of impact categories. The characterization is the actual calculation of category indicator results and concerns the analysis and estimation of the magnitude of potential impacts on the ecological health, human health or resource depletion for each of the impact categories. Each emission will contribute differently to the impact categories depending on the specific substance properties and thus has a distinguished characterization factor that quantifies the impact potential per kilogram of substance. Normalization and weighting are optional and will not be further explained here.

A general framework for the impact assessment can be seen in Figure 3-1 (Wenzel et al. 1997). A more recent presentation and discussion of the impact assessment framework can be found in Udo de Haes et al. (2002a).

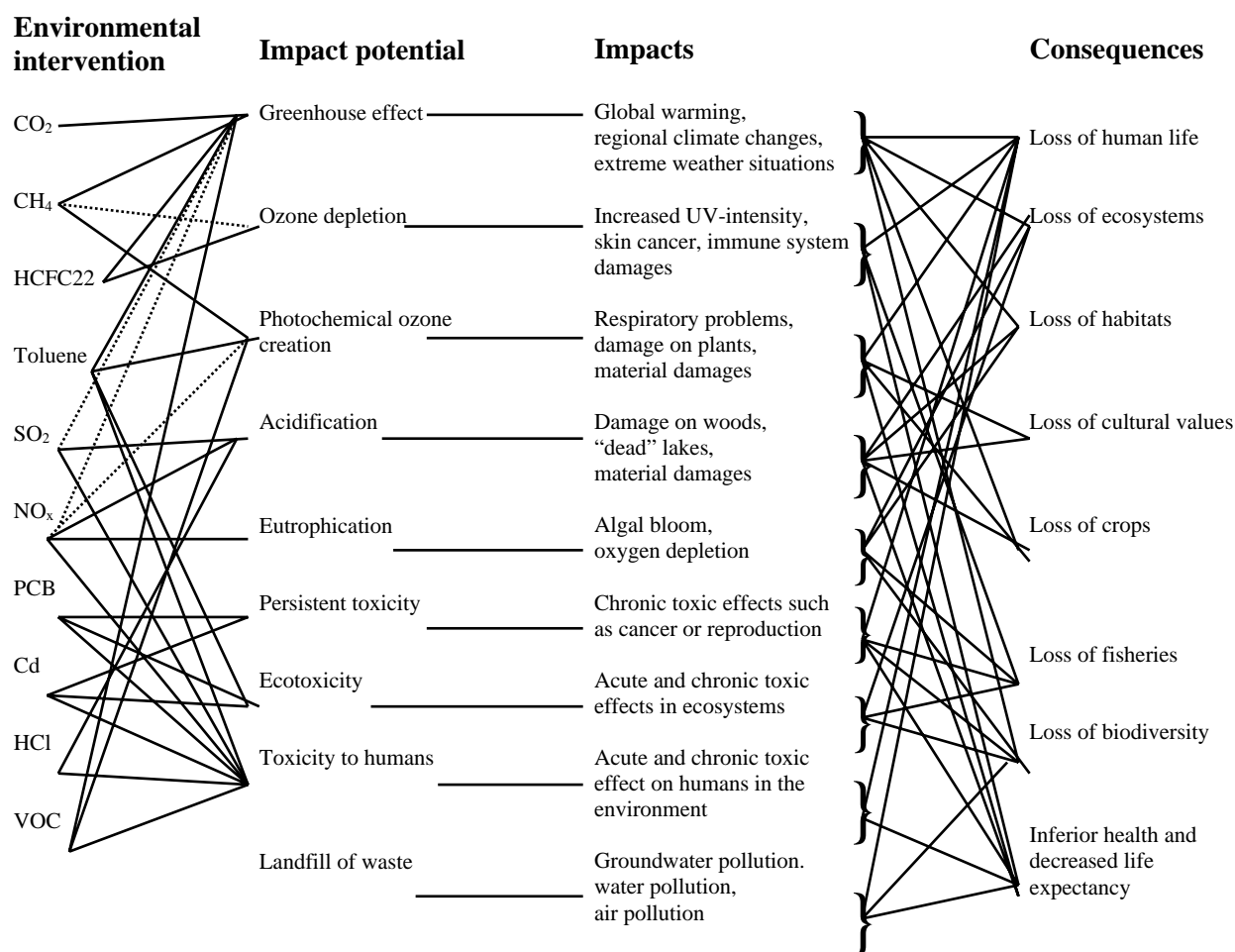


Figure 3-1: The concept of impact assessment: relationship between the life cycle inventory results (environmental interventions) impact potentials (midpoints) and their consequences (endpoints).

Traditionally, as in many other environmental assessments, LCIA uses linear modeling and takes the effects of the substances into account, but not their background concentrations and the geographical dependency on fate. The method aggregates the environmental consequences over release points in time, release locations and substances (chemicals). This allows calculating potential impact scores, which reflect contributions to environmental burdens. This can be different from RAs that aim to ensure the safety of people or the environment and to identify the risks due to a certain activity in a specific site or region and in a given time period. Risk assessment can therefore take a conservative approach. LCA, on the other hand, is a comparative framework in which it is essential that the potential impacts be compared on a realistic basis (see Introduction). Additionally, LCIA has a broad scope in terms of impacts covered, whereas RA has a clear focus on chemicals and their effects on the environment and human health.

For the impact categories most frequently used in LCIA, no special difficulties can be foreseen in applying these for the assessment of nanomaterials and nanoproductions. However, for toxicological impacts, the current understanding of effect mechanisms, dose-response relationships, as well as transport and transformations in the environment may not be sufficient to ascertain a representative characterization of nanomaterials. This will be further discussed below.

Additionally, it may be foreseen that an increased dissipative use of very scarce resources will occur in nanotechnological products. For instance, the available reserve of the metal indium is quite small. The present use of indium for exotic semiconductors allows for years of abundant use. A society-wide use of indium in the production of nanomaterials, however, could be of a different and significantly higher magnitude. This highlights the need for reaching consensus on a framework for characterization of abiotic resource depletion.

Finally, the large surface-volume ratio of nanoparticles could be relevant for certain other impact categories, notably ozone layer depletion and photochemical smog.

3.4 Life Cycle Impact Assessment – Toxic Impacts on Human Health

Overall, it was concluded that the UNEP/SETAC framework (Udo de Haes et al. 2002b) for toxic impacts (as illustrated in Figure 3-2) can, in principle, be used for specific impacts caused by nanoparticles and nanoproducts given that (nanomaterial-specific) fate, exposure and effects have been adequately identified. Examples of some considerations that must be taken into account include:

- Traditional dose-response relationships based on mass or dose will not suffice since impacts may be linked to other aspects of the nanomaterials, e.g., surface area, chemical composition, particle size, shape and others (see Section 3.2);
- Transformation and structural changes could occur in the environment after release;
- Dermal uptake may have significance and should be covered for relevant applications;
- Fate and exposure models and Physiologically Based Pharmacokinetic Models (PBPK) based on basic nanoparticles properties (e.g., fullerene partition coefficients) may be useful to predict exposure;
- It may be useful to differentiate between bioactive and non-bioactive nanoparticles;
- It is an open question how to deal in toxicology with structural/physical mechanisms rather than chemical interactions/virus or enzyme-like behavior (which do not fit into classical toxicological models); and
- There may be synergistic or antagonistic interactions between nanomaterials and existing sources of environmental impacts such as current chemicals.

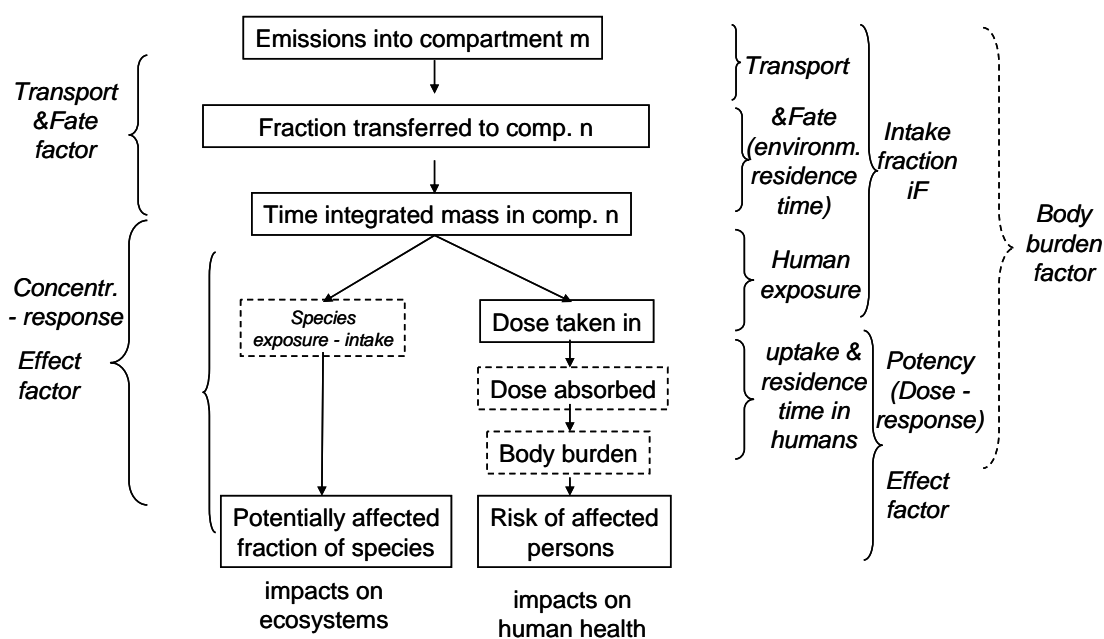


Figure 3.2: The UNEP/SETAC framework for assessment of toxic impacts (Jolliet et al. 2004)

To be able to properly assess the impacts from nanomaterials and nanoproducts, development of approaches to regulative RA of nanomaterials should be awaited in order to adapt these into the comparative assessment of potential impacts in LCA. There is still a need for:

- Protocols and practical methodologies for toxicological studies;
- Fate and transport studies; and
- Scaling studies (i.e., how properties such as surface area, conductivity and magnetism change with the size of the nanomaterial).

Currently, it is difficult to address potential toxic impacts of nanomaterials on humans. One possibility for immediate action could be attempts to define categories of nanomaterials for the purpose of LCIA. These categories, which might include reactivity, degradability/fate and transport, and eco-toxicity vs. human toxicity, should be based on available information regarding nanomaterials. The categorization should address:

- Dispersive vs. non-dispersive uses (addressed in inventory, e.g., as additional information on the corresponding elementary flow);
- Chemical composition (addressed in inventory);
- Form and structure (e.g., by similarities); and
- Mobility of releases in the environment (air emissions, water release, waste, etc.) at each life cycle stage. Reactivity, fate and transport, and interactions with other sources of environmental impacts should also be addressed.

Another option considered is that, in cases of low data availability, one could perform a screening and explore the possibility of a worst-case scenario where nanomaterials have an impact potential as high as that of the most toxic chemicals or nanomaterials and additionally the highest intake fraction. Alternatively, it is worthwhile to determine the threshold at which toxicity becomes important in the LCA study using a sensitivity analysis. In other words, how toxic would the nanomaterials have to be in order to contribute significantly to the overall toxic impacts in the LCA study?

3.5 Life Cycle Interpretation

Life cycle interpretation of nanoproducts does not seem to be different from that of standard products. Uncertainty and sensitivity analyses are indispensable in the case of products with incomplete and uncertain production characteristics and impacts.

Another issue is that nanotechnology has the potential of being used at a society-wide scale. When an LCA for one window glass favors a nano-coated form, it may still be that an upscaling to the society-wide use of such glass is seen as problematic. Such issues might be discussed in the interpretation.

4. Life Cycle Thinking for Sustainability: Integrating Social, Economic and Environmental Benefits

Life Cycle Thinking is an important platform for understanding the potential environmental impacts associated with the various stages of a product system. LCA alone cannot address all the questions that should be asked in any sustainability or environmental management process; therefore, a broader assessment is needed to include social and economic considerations. In addition, a type of hybrid approach is needed in order to integrate RA with LCA. Understanding the value flow and consumer behavior is another important aspect in

product development. The challenge is to bridge these different aspects in a flexible, integrated framework.

4.1 Integrating Economic and Environmental Benefits

The LCA community has not been able to agree on a unified framework for integrating all the system variables of concern. However, there are instances for a number of mostly industry-based applications.

For example, BASF's Eco-Efficiency tool is a strategic tool that allows the company to examine both costs and environmental impacts of its products, processes or whole-system solutions, with trade-offs between economical and ecological impacts. To date, about 220 different products and manufacturing processes have been analyzed using this technique, which takes into account six categories: consumption of resources and energy, emissions to air, emissions to water, emissions to soil, land use, and toxicity. BASF is currently developing an updated assessment tool, aiming at including social aspects. Samsung Electronics developed an information technology system called EcoProduct System (EPS) to evaluate and manage eco-product data in a systematic manner. EPS consists of five modules: LCA, Eco-Design, Green Purchasing, Environmental Accounting and Environmental Customer Treatment.

4.2 A Practical Implementation of Life Cycle Thinking: A Possible Approach in the Absence of Data

The process of estimating, comparing and making decisions based upon risks is a complex mixture of science and value judgments. There is a need to broaden the inputs into the decision-making process in order to better consider the potential trade-offs (precautionary principle balanced against potential benefits) along a product's life cycle. Over the years, a number of tools and conceptual frameworks have been developed to help decision-makers in industry and government. This growing "toolbox" includes risk assessment, as well as other environmental and human-health assessment tools. It is believed that the emerging nanomaterials and nanoproducts will have a higher probability of social acceptance and economic success if the related benefits and risks are clearly understood and communicated.

On the other hand, carrying out a full LCA and/or RA study is often a time-consuming and costly exercise. Is there a way to implement Life Cycle Thinking in practice without a major investment in LCA? Theoreticians and practitioners of LCA agree that performing a LCA at the beginning of a technology or product development is the best way to identify the main areas of concern in relation to the potential environmental impacts.

At the workshop, participants discussed an alternative, pragmatic approach combining the use of LCA, risk analysis and scenario analysis. This screening approach is meant to be for general use by industries, especially Small and Medium-Sized Enterprises (SMEs), and by other stakeholders involved in the development of nanomaterials and nanoproducts. This streamlined approach can be carried out faster and at a lower cost than a full LCA, and can provide timely and reliable answers. The proposed scheme is a screening process (go/no go decisions) exploiting complementary information from different assessment tools, while aiming at minimizing the total analysis effort. It is structured in five main steps:

- The first step is to check for obvious harm of the new nanoproduct. This is what all companies would initially do anyway, using "usual" assessment methods in order to comply with health, safety and environmental regulation.

- The second step is to assess the benefits of the nanoproduct compared to a conventional product with respect to “traditional” potential impact category indicators (e.g., global climate change, acidification, eutrophication). This should be done by carrying out a full LCA (i.e., covering all life-cycle product stages), but excluding toxicity impact assessment. If the benefits of the nanoproduct over the life cycle are significant, the design and further assessment should continue (go decision). Otherwise, it should be better stopped, since it is assumed that potential toxic risks are not offset by other environmental and energy-saving benefits.
- The third step is to carry out a thorough toxicity and RA of the product to estimate the likely adverse risks to which humans and the environment are exposed under certain circumstances. Since exposure risks might be different, the analysis will have to be done for each life cycle stage.
- The fourth step is to combine the results of “traditional” LCA with those of toxicity and RA. It is the combination of these results that will enable the assessment of the overall impacts and trade-offs. The combination might likely occur in mixed quantitative/qualitative form. To this end, LCA and RA experts should collaborate to implement a comparative RA framework for nanoproducts. As stated above, the acceptance of potential risks of the latter may be easier if other benefits are clearly assessed and communicated.
- While the combination of LCA and RA allows for a marginal comparative assessment of products, other potential significant impacts might occur due to a large-scale diffusion. For example, if a very small quantity of a nanomaterial is used in billions of products, the overall impact might be significant. With this specific respect it is crucial to look at the potential dispersion into the environment and the eventual related loss of strategic scarce materials. To this end, using a scaling-up scenario analysis to assess the traceability of nanomaterials in time and space and to evaluate the sustainability of different trajectories is recommended (Reller 2006). While this analysis will certainly be affected by a high degree of uncertainty, it is an important piece of complementary information and one that is particularly relevant for policy-making decision support.

The proposed five-step screening approach is summarized in Table 4-1.

Table 4-1: Proposed Step-Wise Life Cycle Thinking Approach

Steps	Purpose	What Is Available	What Is Missing
1. Check for obvious harm	-Compliance with health, safety and environmental regulation	-Usual assessment methods in industry	
2. Traditional LCA without toxicity study (focus on environmental impacts)	-Understanding burdens versus benefits -If substantial benefits, then go forward	-Analogies with existing materials -Confidential info available to the “right” people -Software with easy-to-use interface -If material is not listed, use what’s similar	-Some LCI data on nanomaterial production -Interface – to be developed to deal with fuzzy inputs - should this be sector- or region- specific? -Find ways to make confidential information available within industry
3. Toxicity and RA (or qualitative analysis) could include toxicity and risk questions	-What are the likely adverse risks that humans and other organisms will be exposed to at each life cycle stage -How structure of material influences behavior (surface, area, shape, etc.)	-Confidential information available to the “right” people -Quantitative or fuzzy -Published information is available	Hazard and exposure data (potential primary and secondary transformation into unknown toxic substances across life cycle stages) -Find ways to make confidential information available within industry
4. Combine LCA and RA	-To assess overall impacts over whole life cycle -Can evaluate impacts from the interaction of materials		-No standard quantitative tool available to merge the data
5. Scenario Analysis	-To scale- up to society-wide use (consider issues such as resource depletion)		-Lack of reasonable upper and lower bounds for scaling and impact estimations

The advantage of the proposed step-wise screening approach is to reduce the actual number of design options by applying Life Cycle Thinking in an early stage of product design. In turn, this will reduce the time and costs for the analysis.

Ideally, the proposed framework could be used by designers, LCA experts and non-experts alike. In order to accomplish this, a substantial effort is needed to develop user-friendly eco-design tools with easy-to-use interface for non-experts. These tools also need to include clear explanations on all applied assumptions, their inherent advantages and disadvantages, as well as their caveats, if any, to satisfy transparency, acceptability and credibility criteria for such analysis.

5. Conclusions

1. *Complexity and scope*

Nanotechnology is an enabling technology with applications in many industrial sectors (Karn 2006). There are many nanoproducts, all with their specific characteristics as to composition and use pattern. There is, therefore, no generic LCA of nanomaterials, just as there is no generic LCA of chemicals. It is likely that there will be a variety of LCA applications to nanotechnology, each with the ability to calculate the cradle-to-grave impacts of a specific nanoproduct or the cradle-to-gate LCA of a specific nanomaterial. No generic rules apply, i.e., it cannot be said in general that one life cycle stage dominates (see Chapter 3).

2. *Suitability of ISO/LCA framework for nanoproducts and nanomaterials*

Despite the complexity and the very large set of different nanoproducts, one general and important answer can be given: the ISO framework for LCA (ISO 14040:2006) is fully suitable to nanomaterials and nanoproducts, even if data regarding the elementary flows and impacts might be uncertain and scarce.

Since environmental impacts of nanoproducts can occur in any life cycle stage (depending on the specific product category and even the specific product), all stages of the life cycle of nanoproducts should be assessed in a LCA study.

3. *Operational issues to be addressed*

While the ISO 14040 framework is appropriate, a number of operational issues need to be addressed in more detail in the case of nanomaterials and nanoproducts. These issues are related to all four LCA phases:

- Goal and scope: Nanoproducts fulfill functions that are quite new and for which it may be difficult to specify functional alternatives. Therefore, a particular focus on this issue must be given while carrying out comparative assessments. In specific cases (e.g., pharmaceutical and medical applications), a comparison may be impossible, and LCA might be used rather as a managing tool.
- Inventory: Capital equipment cannot be ignored, as it is often large and energy-consuming (e.g., equipment for lithography and ultra-clean rooms). As this equipment will most likely serve to produce several nanomaterials and nanoproducts, specific allocation rules may apply. Cut-off rules based on mass alone are not applicable (as foreseen in the ISO standards, e.g., in the case of high toxicity or other environmental impacts). While “traditional” inventories are based on mass, additional information is needed in the case of nanomaterials and nanoproducts (e.g., chemical composition, particle size, shape, aspect ratio, crystal structure, surface area and activity), which is relevant to assess fate, exposure or effect.
- Impact assessment: There are no particular difficulties with “traditional” LCA-impact categories (e.g., global warming, acidification, eutrophication). For this phase, toxic impacts are a major issue, which deserves special attention (see below). Also, abiotic resource depletion may be important in the case of rare elements.
- Interpretation: Life cycle interpretation is not different for nanoproducts, but it is more important than for regular products. Uncertainty and sensitivity analyses are crucial to address uncertain manufacturing data and estimate impacts, which may depend on conditions of use, user behavior and specific end-of-life circumstances (including

interaction with other materials in different media). They also serve to take into account that nanoparticles may change their form as they go through different life cycle stages.

4. *Major specific issues to be addressed*

The main problem with LCA of nanomaterials and nanoproducts is the lack of data and understanding in certain areas.

- The first major issue is the uncertainty and rapid production of scientific data. Specific strategies are to be adopted in order to tackle the lack of data and/or other constraints. For example, similar strategies as those applied in rapidly evolving sectors (e.g., the semiconductor industry) can be adopted. Some sample approaches might be to use mass balances, or screening procedures on chemicals, energy and processes, etc.
- The second major problem is confidentiality. While some LCA data may exist, they most likely are proprietary data of companies. In some cases, even the exact composition of nanomaterials is strictly confidential. The challenge is how to involve industry, making sure that data are provided at an adequate aggregation level and ensuring at the same time the confidentiality needs of companies. Developing appropriate critical review procedures is crucial in this respect.
- The assessment of toxic impacts of nanoproducts is a major area of concern (which goes beyond LCA) and needs major research efforts. Overall, it was concluded that the UNEP/SETAC framework for toxic impacts can be used in principle, provided that nanomaterial-specific issues have particular attention, e.g., dose-response based on specific characteristics (e.g., surface area and activity), transformation and structural changes, dermal uptake and bioactivity. Some problems may be unique to nanomaterials, e.g., how to measure toxic effects with structural/physical mechanisms rather than chemical interactions or how to assess virus or enzyme-like behavior that does not fit into classical toxicological models. Strategies to estimate worst-case scenarios may be adopted, and the LCA should be accompanied by RA.

5. *Proposed approach: stakeholder involvement*

Implementation of LCA requires a multi-stakeholder strategy. This strategy depends on the specific product category, and even on the particular product. The proposed approach calls for the involvement of all stakeholders, i.e., industry, research/academia and governments. Experts should meet/convene and decide what is relevant for the LCA of specific nanoproducts, e.g., what are the hotspots, the main indicators to be used, allocation and cut-off rules, data-gap, uncertainty and sensitivity analyses. This approach is similar to the concept of Product Panel Groups within the EU Integrated Product Policy (IPP) framework,¹⁰ and to the one of Product Category Rules (PCR) for ISO-type III environmental declarations (ISO 14025: 2006).

6. *Added value of LCA of nanoproducts and nanomaterials*

The added value of carrying out an LCA of nanoproducts and nanomaterials is basically twofold:

¹⁰ For more details on stakeholder involvement and their role and responsibilities, see COM (2003) 302 - Communication from the Commission to the Council and the European Parliament, Integrated Product Policy - Building on Environmental Life Cycle Thinking.

- LCA gives a more holistic picture of the environmental impacts of products than does RA alone. Furthermore, it allows the identification of the life cycle stages, the stage at which major environmental impacts may occur, and the potential risk of exposure for different people along the product-transformation chain. LCA provides very useful indications for improvement and potential impact minimization. The earlier this information is available in the product-design process, the more easily improvement measures can be taken.
- LCA allows for comparisons with conventional products, provided that an appropriate functional unit is identified. LCA also allows for the assessment of environmental benefits (or disadvantages) of nanoproducts with respect to “conventional” potential environmental impact indicators. This is a crucial added value to industry, because the acceptance of risks related to nanotechnology is easier if the benefits for the consumer are clearly assessed and communicated. In addition, LCA can help prevent unnecessary regulation.

7. Limits of LCA – Complementarities with other tools

While LCA brings major benefits and useful information, there are certain limits to its application and use, in particular with respect to the assessment of toxicity impacts and of large-scale impacts. In fact, LCA is complementary with other tools, and its information becomes more meaningful when LCA is used in combination with those tools. More specifically:

- LCA cannot and should not be a substitute for RA; LCA and RA experts should collaborate to implement a comparative RA framework, adapted to nanoparticles.
- Scenarios for large-scale applications need other assessment tools (e.g., Material Flow Analysis - MFA, Input/Output LCA, consequential LCA).

8. Proposal: A practical tool for implementation of Life Cycle Thinking

As discussed above, nanotechnology includes a very wide set of products and materials. Ideally, a full assessment (both LCA and RA) would be needed for any nanoproduct and/or variant. However, full LCA studies are often costly and time-consuming. The questions become how to address the multitude of design options involving nanoparticles, and what to do while waiting for reliable risk and LCA data?

While the full LCA is considered to be the best way to identify environmental impact concerns in relation to nanotechnology-based products, in the absence of data, a screening approach was discussed. The proposed approach is a five-step screening process for practical implementation of Life Cycle Thinking. It exploits complementary information from different assessment tools, while aiming at minimizing the total analysis effort. The basic features are that:

- LCA without toxicity impact assessment is used to select just those nanoproducts that have significant benefits in terms of conventional impact indicators with respect to conventional products. This likely reduce the number of options to be studied; and
- LCA results are combined with those of RA and scenario analysis to assess overall results and trade-offs, as well as large-scale impacts and sustainability of nanoparticle trajectories.

In the mid to long term, a Life Cycle Thinking approach should also integrate economic and social aspects, which require other complementary tools.

9. Needs for future research

Research efforts are needed to fully assess potential risks and environmental impacts of nanoproducts and materials (not just those related to LCA). A major concern with respect to toxicity (e.g., persistence and bioaccumulation, specific exposure routes, size) was expressed at the workshop (Clift 2006). There is a need for protocols and practical methodologies for toxicology studies, fate and transport studies and scaling approaches (e.g., surface area). International cooperation between Europe and the United States, together with other partners, is needed in order to address these concerns.

For LCA, a case-study approach was proposed. To this end, the first step is to define categories of materials as a function of dispersive vs. non-dispersive uses, chemical composition, form and structure, and mobility (or non-mobility) of releases in the environment (air emissions, water release, waste, etc.) at each life cycle stage. Moreover, further research is needed to gather missing relevant LCI data and to develop user-friendly eco-design screening tools, especially ones suitable for use by SMEs.

6. Recommendations

1. Case studies/prioritizing efforts

The first recommendation is to significantly enhance knowledge on environmental impacts of nanomaterials and nanoproducts through further research activities. Since resources are limited, a case-study approach should be adopted. The selection of case studies should follow prioritization criteria, which include the following aspects/priorities:

- Most toxic products;
- Nature of dispersion;
- High volume production; and
- Fate and transport issues.

Depending on the selected case study and product category (or single product), specific eco-design tools using the above-mentioned screening approach should be developed. They should be user-friendly and targeted to SMEs and industrial applications.

2. LCA studies and presentations of results

As illustrated in the previous chapters, any LCA study on nanoproducts and nanomaterials most likely suffers from high uncertainty issues. Therefore, we recommend:

- Do not wait to have near-perfect data;
- Be modest about uncertainties; clearly state relevant uncertainty aspects and assumptions;
- Draw conclusions in the case of major or significant improvements; otherwise, state that the nanoproduct and the conventional product are equivalent;
- At this early stage, target estimates in the direction of protecting humans and the environment;
- Separate the category indicators, grouping them by relevance/uncertainty;

- Take care about overselling the benefits of the new nanoproduct, since assessment methodologies will improve and might show “problems” in the future;
- Work with toxicologists and other scientists (geographical and socio-economic impacts) to review data and bound the issue;
- Make data available for future LCA comparisons:
 - at the highest disaggregation level that is acceptable from a confidentiality perspective;
 - at a disaggregation level that is compatible with data availability (in terms of breakdown of processes); and
 - as disaggregated as possible for further applications in assessment; and
- Include explanations of assumptions and approaches.

3. *Approaches*

- Critical review should always be done to ensure credibility of LCA studies;
- The independent review should be made by an expert panel with balanced representation and wide expertise comprised of, for example, company representatives in the supply chain and outside LCA and nanotechnology experts;
- Data for the critical review or other supporting data should be published; and
- Panels of interested parties should be formed to establish rules for LCA of nanomaterials and nanoproducts. This approach is similar to the one of Product Category Rules (PCR) for ISO-type III environmental declarations, as ruled by ISO 14025:2006.

4. *Actions from stakeholders*

Different stakeholders/authorities can potentially support the application and use of LCA to nanoproducts and nanomaterials through a large set of actions.

Government stakeholders' actions could include:

- Setting up research frameworks and programs for the methodology development of LCA in the field of nanotechnology and nanoproducts;
- R&D activities, with special emphasis in multinational cooperation in fields related to health and environmental safety;
- Use of LCA results to design adapted economic instruments (IPP enforcement/implementation, with, e.g., tax and funding incentives and tax benefits);
- Using LCA to help develop green purchasing and integrate nanotechnology criteria in green purchasing;
- Allocating a portion of current nano-research funding to nano/LCA research to make it more attractive to the private sector for further R&D;
- Providing independent, standardized and reviewed LCA information that might be used by industry and other stakeholders;

- Covering different nanotechnologies' flows of substances (air emissions, water releases, etc.) into the European Commission's "European Reference Life Cycle Data System" (ELCD), and the US Life Cycle Impact database;
- Working toward an international LCI database for nanomaterials; and
- Improving data coordination among different government agencies, e.g., agencies responsible for product consumer safety evaluations, workplace safety evaluations and environmental issues.

Academia can potentially support the application and use of LCA to nanoproducts and nanomaterials through a large set of actions, including:

- Setting up databases for LCA case studies on nanotechnology and nanoproducts;
- Providing scholarships to the universities to hire Ph.D. students specifically for nano/LCA research; and
- Carrying out research in LCA methods applied to nanotechnology and nanoproducts.

Industry can potentially support the application and use of LCA to nanoproducts and nanomaterials through a large set of actions, including:

- R&D activities;
- Use of LCA results to design improved products;
- Co-funding research on developing LCA methods and impact characterization metrics specific to nanotechnologies:
 - Co-funding research on toxic effects of specific nanomaterials;
 - Co-funding social science research on public concerns about nanotechnology and on developing effective risk-communication strategies using LCA data; and
 - Actively creating mechanisms for sharing confidential data without compromising competitiveness.
- The insurance industry should play a leading role in assessing life cycle RAs of nanoproducts.

Nongovernmental Organizations and Consumer Associations can potentially support the application and use of LCA to nanoproducts and nanomaterials through a large set of actions, including:

- Communicating LCA study results (elaborated by academia) to the public to inform consumers; and
- Educating themselves and promoting LCA as a tool to assess nanotechnology.

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