Life Cycle Methods for Environmental Assessment of Nanotechnology

Janne Kekäläinen

Bachelor's Thesis

University of Jyväskylä, Department of Physics

December 3, 2012

Supervisor: Prof. Hannu Häkkinen

Abstract

This thesis is a literature review giving an overview of different life cycle methods that can be used to assess the environmental impacts of products containing nanotechnology. The importance of the life cycle concept is explained and the different environmental assessment methods are described. The methods reviewed in this thesis are life cycle assessment (LCA), carbon footprint, water footprint, ecological footprint, and material input per service unit (MIPS). The environmental aspects related to nanotechnology are discussed and the application and applicability of life cycle methods to nanotechnology are explored. The thesis concludes that the described assessment methods are applicable to nanotechnology but also that there are major knowledge gaps in the environmental impacts of nanotechnology.

Tiivistelmä

Tämä tutkielma on kirjallisuuskatsaus, joka antaa yleissilmäyksen erilaisiin elinkaarimetodeihin, joilla voidaan arvioida nanoteknologiaa sisältävien tuotteiden ympäristövaikutuksia. Työssä selvitetään elinkaariajattelun tärkeys ja kuvataan erilaisia ympäristöarviointimenetelmiä. Tässä tutkielmassa tarkastellut menetelmät ovat elinkaariarvionti (LCA), hiilijalanjälki, vesijalanjälki, ekologinen jalanjälki ja ekologinen selkäreppu (MIPS). Työ käsittelee nanoteknologiaan liittyviä ympäristöasioita ja tarkastelee elinkaarimenetelmien soveltamista ja soveltuvuutta nanoteknologiaan. Työn tuloksena raportoidaan, että kuvatut ympäristöarviointimenetelmät soveltuvat nanoteknologian vaikutusten arviointiin, mutta toisaalta nanoteknologiaan liittyvät ympäristövaikutukset ovat vielä huonosti tunnettuja.

Abbreviations

CH_4	Methane
CNT	Carbon nanotube
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
EV	Electric vehicle
gha	Global hectare
GHG	Greenhouse gas
GM	Genetically modified
GWP	Global warming potential
ILCD	International Reference Life Cycle Data System
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LED	Light emitting diode
MFA	Material flow analysis
MIPS	Material input per service unit
N_2	Nitrous oxide
OLED	Organic light emitting diode
R&D	Research and development
SWCNT	Single-walled carbon nanotube
TMR	Total material requirement
UV	Ultraviolet

Contents

1 Introduction **1**
1.1 *Environmental Aspects Related to Nanotechnology* 1
1.2 *Life Cycle Thinking* 1

2 Life Cycle Methods **3**
2.1 *Life Cycle Assessment (LCA)* 3
2.2 *Streamlined LCA* 7
2.3 *Carbon Footprint* 7
2.4 *Water Footprint* 8
2.5 *Ecological Footprint* 9
2.6 *Material input per service unit (MIPS)* 10

3 Nano and the Environment **11**
3.1 *Overview* 11
3.2 *Reasons to Use Life Cycle Methods to Assess Nanotechnology* 12
3.3 *Applicability of LCA to Nanoproducts* 14
3.4 *Special Notes on Applying LCA to Nanoproducts* 15

4 Conclusions **18**

1 Introduction

1.1 Environmental Aspects Related to Nanotechnology

Nanotechnology is often referred to as being a key technology of the 21st century [1]. Nanotechnological products, processes, and applications are said to have the potential to make important contributions to environmental and climate protection by helping save raw materials, energy, and water, and by reducing greenhouse gases and waste. Nanomaterials can increase the durability of materials, dirt and water-repellent coating help reduce cleaning efforts, novel insulation materials will improve the energy efficiency of buildings, and using nanocomposites to reduce the weight of materials can help save energy in transportation.

These kind of sustainable potentials of nanotechnology are often emphasized but they in fact represent poorly verified expectations [1]. It is most probably true that products that incorporate materials manufactured at the nanoscale offer many potential benefits to society. However, these benefits must be weighed against potential costs to the environment and the public health. Even among a group of similar products, not every nanoproduct is automatically environmentally friendly.

Production of nanomaterials often requires large amounts of energy, water, and environmentally problematic chemicals. The negative environmental impacts during the manufacturing process may offset any positive impacts in the use stage of the product. Therefore determining a product's actual effect on the environment requires considering the whole life cycle of the product from the production of the base materials to disposal at the end of its useful life.

1.2 Life Cycle Thinking

When evaluating anticipated technologies, researchers have found that there can be surprising negative consequences with new innovations. In a recent study Hawkins et al. [2] studied the environmental impacts of electric cars by comparing them to petrol and diesel-powered cars. They found that the production of electric vehicles (EVs) is so environmentally intensive that these cars have already polluted a great deal by the time they hit the road. EVs have the potential to be more environmentally friendly compared to petrol and diesel-powered cars only if the electricity that they are charged with is generated from low-carbon sources. Although EVs don't emit pollution when they are used they are damaging to the environment if the electricity is mainly generated with fossil fuels.

The insights provided in this study came to light by considering the whole life cycle of the product instead of narrowly focusing on point-of-use air pollution. The main advantage of thinking about the whole life cycle of a product is that this way the potential environmental problems are not shifted from one life cycle stage to another [3].

Life cycle thinking is an approach that evaluates how products and activities impact the environment in a holistic way. For example, renting a movie may sound very harmless but

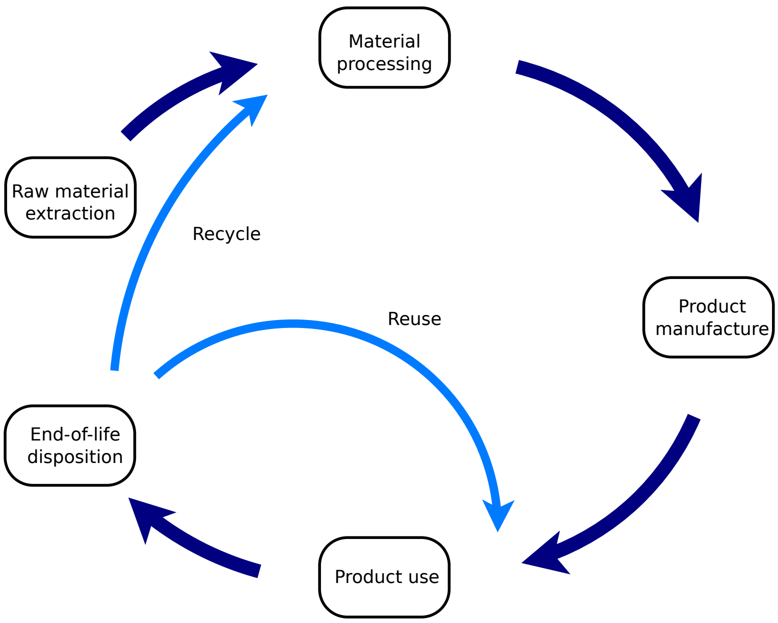

Figure 1: Product life cycle consists of raw material extraction, material processing, product manufacture, product use, and end-of-life disposition.

when considering the whole life cycle of the activity you would have to take into account matters like burning gasoline to drive to the video store, using electricity to power the television and DVD player, and consuming power from the remote's batteries.

When talking about product life cycle, the key life cycle stages (Figure 1) are:

1. Raw material extraction: Activities related to the acquisition of natural resources, including mining non-renewable material, harvesting biomass, and transporting raw materials to processing facilities.
2. Material processing: Processing of natural resources in preparation for the manufacturing stage, and transporting processed materials to product manufacturing facilities.
3. Product manufacture: Manufacture of product and transport to the consumers.
4. Product use: Use and maintenance activities associated with the product by the consumer.
5. End-of-life disposition: Disposition of the product after its lifespan, which may include transportation, recycling, disposal, or incineration. [4]

In addition to consuming resources, all of these steps result in environmental emissions and generate waste. By assessing and analyzing the whole supply chain and product life cycle manufacturers and users can not only reduce the negative environmental impacts of their activity but also improve their material and energy efficiency and thus reduce economic costs.

2 Life Cycle Methods

There are many different environmental assessment methods applying life cycle thinking. Life cycle assessment (LCA) is the most scientific and comprehensive assessment method but it is also time-consuming and expensive. Environmental decision making in companies requires different information that varies case by case in terms of particularity and time perspective.Therefore companies have had a need to take into use simpler life cycle methods that can still provide reliable information to support decision making. These kind of methods are for example simplified LCA, carbon footprint, water footprint, ecological footprint, and material input per service unit (MIPS). Figure 2 shows what kind of aspects each of these methods takes into account.

The applicability of life cycle methods varies for different purposes. Also a single method can be used in different scales and with varying levels of detail. At the moment the possibilities, strengths and weaknesses of different methods are poorly known in companies [5].

The following gives a general descriptions of the methods. Literature sources [4, 5, 6] provide a more thorough description of the possibilities, strengths and weaknesses of different methods.

2.1 Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is a systematic, analytical process for assessing the inputs and outputs associated with each life cycle stage for a given product. It is the most comprehensive method to assess the environmental impacts of a product, process, or activity throughout its entire life cycle.

LCA can assist in

- identifying opportunities to improve the environmental performance of products,
- informing decision-makers in industry, government or non-government organizations,
- the selection of relevant indicators of environmental performance, and
- marketing. [7]

The International Organization for Standardization (ISO) has standardized LCA. At the moment the standard framework for LCA is defined by two ISO standards (ISO 14040 [7], ISO 14044 [8]), two ISO technical reports (ISO/TR 14047, ISO/TR 14049) and an ISO technical specification (ISO/TS 14048).

There are four phases in the ISO 14040/44 LCA framework [7, 8]:

1. Goal and scope definition
2. Life cycle inventory (LCI) analysis
3. Life cycle impact assessment (LCIA)
4. Interpretation

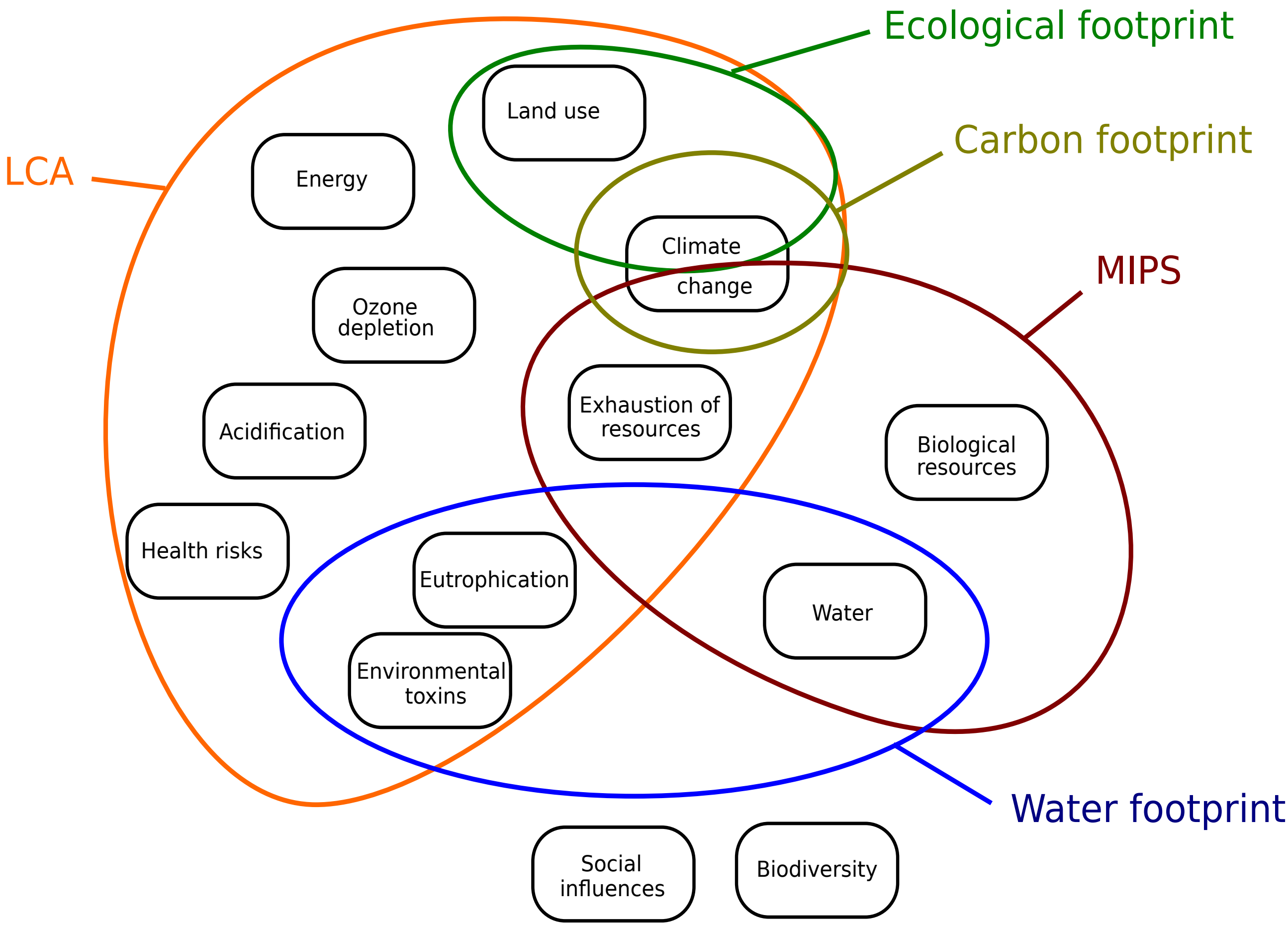

Figure 2: Different life cycle methods cover different aspects of environmental assessment. LCA is the most comprehensive assessment method while social influences and biodiversity are not covered by any of the methods.

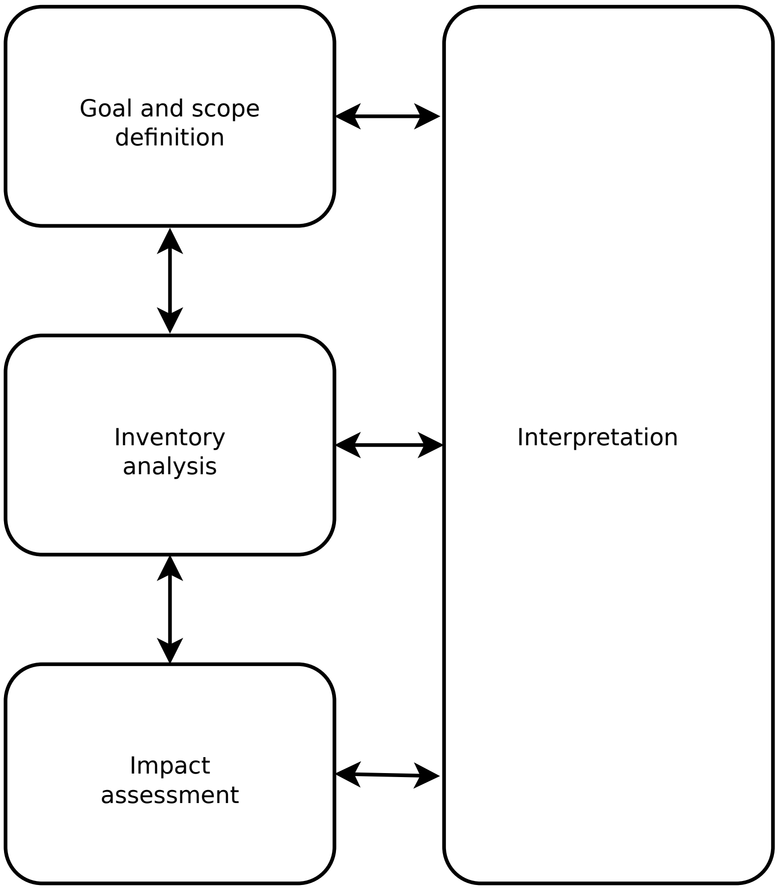

Figure 3: Life cycle assessment consists of four different phases: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation. All of these phases are iterative.

Goal definition specifies the reasons for carrying out the study, the intended use of study results, and the intended audience. Scope definition identifies for example system boundaries, data requirements, assumptions, and study limitations. The depth of detail and time frame of an LCA may vary to a large extent, depending on the goal and scope definition [7].

Life cycle inventory analysis consists of collecting, validating, and aggregating input and output data to quantify material use, energy use, environmental emissions, and waste associated with each life cycle stage. Nowadays also land use is included here [5]. Data should be evaluated for its accuracy and representativeness. A key challenge in LCI is to reduce and include uncertainty in input and output data [9]. The process of conducting an inventory analysis is iterative. As data is collected and more is learned about the system, new data requirements or limitations may be identified. Sometimes there can be issues that require revisions to the goal or scope of the study [7].

The plain inventory data doesn't easily tell the actual environmental impacts of the product or process. Therefore **the impact assessment** phase of LCA is aimed at understanding and evaluating the environmental relevance of all the inputs and outputs that are recorded in the LCI phase. Inventory data is grouped into specific environmental impact categories based on their cause-effect relationship (for example, carbon dioxide causes global warming) and each category is assigned with a category indicator (for example, the effect of carbon dioxide and other greenhouse gases on global warming is measured with global warming potential, GWP). Commonly used impact categories are for example [5, 10]:

- Global warming
- Ozone depletion
- Acidification
- Eutrophication
- Photochemical smog
- Ecotoxicity
- Human health
- Resource depletion

The basis of life cycle impact assessment is characterization of the different inventory items. Impact characterization uses science-based conversion factors to convert and combine LCI results into representative indicators of impacts to human and ecological health. For example, characterization would provide an estimate of the relative global warming potential between carbon dioxide, methane, and nitrous oxide.

Impact indicators are typically characterized using the following equation

$$\text{Inventory Data} \times \text{Characterization Factor} = \text{Impact Indicator}$$

For example, in order to compare and combine the global warming potential of different greenhouse gases, the gases can be expressed in terms of CO_2 equivalents (CO_2e) by multiplying the relevant LCI results by an CO_2 characterization factor.

Life cycle interpretation provides an objective summary of the results, assesses whether results are in line with defined goals and scope, defines significant impacts, and recommends methods for reducing the negative impacts. A key challenge in life cycle interpretation is to improve the transparency of the assessment [9]. Understanding and communicating the uncertainties and limitations in the results is equally as important as the final recommendations [10]. It is important to note that the results of LCA cannot be reduced to a single overall score or number. This would require weighting the different impact categories and thus requires value choices [7, 10].

As depicted in Figure 3, each phase is an iterative process where it is possible to go back to the earlier phases and check their premises.

In addition to the framework defined by ISO standards, LCA is further defined by instructions and directions given by different authorities. The most comprehensive and up-to-date guidance is the ILCD Handbook (International Reference Life Cycle Data System) published by the European Commission. The ILCD Handbook is in line with the ISO standards and has been established through a series of extensive public and stakeholder consultations. The Handbook consists of a series of documents [11, 12, 13, 14, 15, 16, 17, 18, 19] that cater both for beginners and experienced LCA practitioners.

Performing an LCA can be resource and time intensive. Depending upon how thorough an LCA the user wishes to conduct, gathering the data can be problematic, and the availability of data can greatly impact the accuracy of the final results. Therefore, it is important to weigh the availability of data, the time necessary to conduct the study, and the financial resources required against the projected benefits of the LCA. [10]

LCA has been developed since the beginning of the 1990s and the method is still being actively improved as the world is aiming at sustainable production and consumption. On the other hand methodological development is needed because conducting a full LCA is expensive and time-consuming. Often a full LCA is not necessary and a lighter, streamlined version of LCA could be used. [5]

2.2 Streamlined LCA

Sometimes it's justified to streamline an LCA and make a ”light” assessment. In a streamlined LCA simplifications are made by using substitutive data, reducing the number of processes, resources, emissions and environmental impacts under investigation, opting out of the detailed impact assessment, or replacing quantitative data with qualitative information. [20]

2.3 Carbon Footprint

Carbon footprint is an indicator that measures an impact on global climate change. It is the total set of greenhouse gas (GHG) emissions caused by a product, process, organization, event, person, or other such entity. In addition to carbon dioxide (CO_2) this includes for example methane (CH_4) and nitrous oxide (N_2O) which are converted to carbon dioxide equivalents (CO_2e).

There are many different solutions to measure carbon footprint ranging from simple household calculators, that aim at raising awareness of global warming, to full LCA. Traditionally carbon footprint has been calculated at company or household level but with life cycle methods companies can calculate product carbon footprints for their individual products. For example the University of Manchester has produced a simple, free-of-charge calculator [21].

Some of the so called carbon footprint calculators take only a limited amount of the emissions into account. In different assessments there can be differences in which greenhouse gases are taken into account, what kind of conversion data is used (e.g. how much CO_2 is produced when burning a kilogram of certain fuel), and which stages of the life cycle are included. These differences are naturally reflected in the results and therefore the results of many carbon footprint calculators are only suggestive. [22, 23]

It should be noted that many of the carbon footprint calculators only consider direct emissions and emissions from purchased energy and ignore secondary emissions produced in the supply chain. However, direct emissions from an industry are, on average, only 14 % of the total supply chain carbon emissions [22]. Using comprehensive life cycle methods is therefore suggested in order to ensure that large sources of environmental effects are not ignored across the supply chains.

Because there has been a lack of consensus on the exact definition of the term carbon footprint and how to measure it the International Organization for Standardization is preparing a standard on carbon footprint of products. This ISO 14067 is expected to be published in 2013 [24].

2.4 Water Footprint

Water footprint indicates how much freshwater is used to produce a product or to run a company, both directly and indirectly. It is defined as the total volume of freshwater that is used to produce the goods and services, measured over the full supply chain [25].

Availability and quality of freshwater isn't a problem in Finland but in many other places in the world scarcity and poor quality of water is a real life-threatening problem. Therefore also Finnish companies should pay attention to their water footprint especially if their supply chain extends to the drier areas of the world.

Water footprint consists of three different components: blue, green and grey water (Figure 4) [25]. Blue water refers to surface and groundwater, green water footprint is the amount of rainwater that has been evaporated (usually from agriculture and forestry [6]), and grey

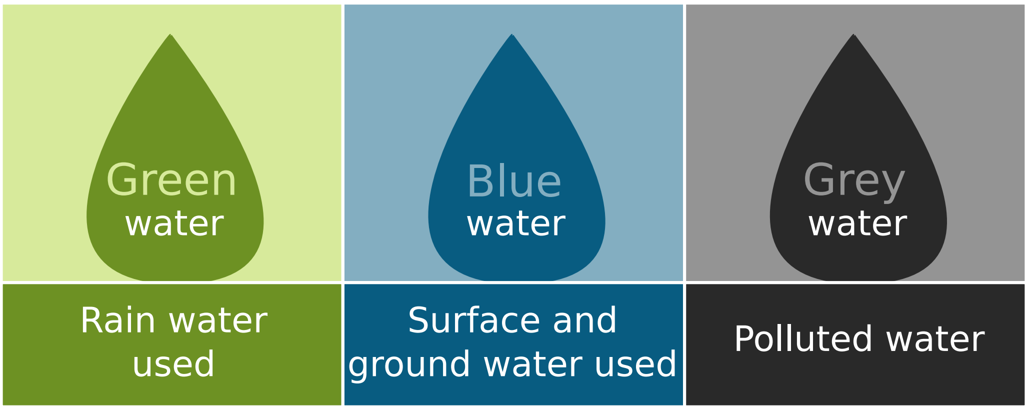

Figure 4: Water footprint consists of three components: green, blue, and grey.

water describes the polluted water volume (the amount of water that is needed to dilute environmental emissions to an acceptable level). Water footprint only considers the resource perspective of water and does not take into account potential environmental and social impacts [5].

The International Organization for Standardization is preparing a standard, ISO 14046, for water footprint [26].

2.5 Ecological Footprint

Ecological footprint measures human demand on nature by assessing how much biologically productive land and sea area, biocapacity, is required to produce the consumed resources. Comparing the footprint to the actual available biocapacity reveals whether the human consumption is sustainable or not.

Ecological footprint consists of direct land use (cropland, grazing land, fishing grounds, forest, built-up land) and also of the uptake land to accommodate the produced carbon footprint. For comparability across countries and land use types, ecological footprint and bioproductivity are expressed in terms of global hectares (gha), i.e. the world-average bioproductive area that is needed to produce the consumed resources and to process the wastes [27]. Regardless of its wide definition, ecological footprint only takes into account biomass based resources, and carbon dioxide as an emission [5].

A typical resulting figure is how much of the Earth, or how many planet Earths, it would take to support humanity. At the moment humanity's total ecological footprint is estimated at 1.5 planet Earths [28]. That means that humanity is overshooting the available resources by 50 percent - it takes 1.5 years to generate the renewable resources that are used during one year. Finland is one of the few countries in Europe that have more biocapacity than they are using.

Ecological footprint is usually calculated for countries or other geographical areas but it can be applied also to companies [29] and products [30, 31].

2.6 Material input per service unit (MIPS)

As the name suggests, material input per service unit (MIPS) is an indicator that tells the amount of used resources per an instance of use of a product or service. MIPS builds on another environmental assessment method, **material flow analysis (MFA)**. [5]

Material flow analysis inspects the flows and stocks of materials in a system. The analyzed system can be a geographical area or, in the spirit of life cycle thinking, a process to manufacture a product. Instead of assessing the potential environmental impacts, MFA (and therefore also MIPS) measures the amount of used natural resources. The indicator calculated with MFA is called total material requirement (TMR). In addition to the direct raw materials also by-products and waste materials (e.g. logging waste, straw, attle) are calculated into TMR.

MIPS is calculated by dividing TMR by the number of instances of use, or other relevant service unit. For example in case of a passenger car, the number of service units is the total number of passenger kilometres during the whole lifespan of the vehicle. MIPS provides a rough but easily understandable tool to measure overall volume and efficiency of resource use.

MIPS has been used in Finland for example in FIN-MIPS Transport [32] and FIN-MIPS Household [33] projects. FIN-MIPS Transport project studied the Finnish transport system both from passenger and goods transport perspective whereas the FIN-MIPS Household project examined material intensity of housing, mobility, foodstuffs, household goods, tourism, leisure and sport activities in Finland.

3 Nano and the Environment

3.1 Overview

The new functionalities that nanotechnology provides are often in correlation with environmental friendliness. They will allow a more efficient use of materials and energy and reduce waste and pollution. For instance, lighting technologies based on nanotechnology could reduce the total global energy consumption by 10 % and lighter automotive parts made of nanocomposites could save billions of litres of gasoline annually and thus reduce carbon dioxide emissions by billions of kilograms [9].

However, these examples focus on the product use stage of its whole life cycle. It might turn out that when considering the whole life cycle of the product, including production and disposal stages, the net impact on environment is negative. Not only are carbon nanotubes the strongest and stiffest material ever known but also their manufacturing process is one of the most energy intensive of all man-made materials. An estimate of total embodied energy for carbon nanotubes is of the order of 0.1–1.0 terajoules per kilogram [34].

Even though there are many international research programmes tackling the question of nanosafety [35], especially the toxicological effects of nanoparticles are still largely unknown.

Some of the potential positive environmental impacts of nanotechnology [1]:

- Reduced use of raw materials through miniaturization
  - Reducing the thickness of coatings
  - Decreasing the amounts of food additives and cosmetic ingredients
- Energy savings through weight reduction or through optimized function
  - Nanocomposites, e.g. plastics and metals with carbon nanotubes, make airplanes and vehicles lighter and thus reduce fuel consumption
  - With new lighting materials, e.g. OLEDs, organic light-emitting diodes, the conversion rate from energy to light can reach 50 % (conversion rate with traditional light bulbs is about 5 %)
  - Adding nanoscale carbon black to automobile tyres reinforces the material and reduces rolling resistance which leads to fuel savings up to 10 %
  - Self-cleaning or easy-to-clean coatings, for example on glass, help save energy and water in facility cleaning
  - Nanotribological wear protection products as fuel or motor oil additives reduce fuel consumption of vehicles and extend engine life
  - Nanoparticles as flow agents allow plastics to be melted and cast at lower temperatures
  - Nanoporous insulating materials in the construction business help reduce the energy needed to heat and cool buildings
- Energy and environmental technology
  - Various nanomaterials can improve the efficiency of photovoltaics

  - Dye-sensitized solar cells, i.e. Grätzel cells, with nanoscale semiconductor materials could have a price/performance ratio that allows solar energy to compete with fossil fuels without external subsidies
  - CNT-nanocomposites on the rotor blades of wind turbines make them lighter and increase energy yield
  - Nanotechnologically optimized lithium-ion batteries have an improved storage capacity and lifespan and they can be used in electric vehicles
  - Fuel cells with nanoscale ceramic materials for energy production require less energy and resources at the production stage
  - Nanoporous membranes and filters with nanomaterials are used in water treatment and purification
  - Nanoparticular iron compounds are used in groundwater remediation to remove chlorinated hydrocarbons
  - The effectiveness of catalytic converters in vehicles can be increased by using catalysts (i.e. catalytically active precious metals) that are in the nanoscale
  - Nanoporous particle filters reduce emissions in motor vehicles
- Replacement of hazardous materials
  - Nanosilver can potentially replace hazardous biocides for example in wood preservation and paints
  - Nanoceramic corrosion coatings for metals can replace toxic products with heavy metals for example in household appliances and automobiles
  - Nanoscale titanium dioxide and silica replace the environmentally hazardous bromine in flame retardants
  - Nanoparticular titanium dioxide as a mineral UV-filter in suncreens is an alternative to organic filters which are a health concern
- Energy and resource efficiency in the chemical industry
  - Nanocatalysts can be used to increase the yield of chemical reactions and reduce the amount of environmentally damaging byproducts

3.2 Reasons to Use Life Cycle Methods to Assess Nanotechnology

There are several different reasons motivating the use of LCA to compare the environmental impacts of nanoproducts with conventional products and to inform nanotechnology R&D.

1. Reduce material and energy consumption

   With ever increasing global population and consumption per capita, it is becoming increasingly more important to pursue technological advances that reduce the amount of energy and materials required. By offering control over matter at the most basic levels, nanotechnology has the potential to use energy and materials more efficiently.

However, the whole life cycle has to be analyzed in order to avoid offsetting the energy savings by the energy required to produce the materials and products.

2. Reduce environmental discharges

   In addition to the conventional pollutant emissions, nanotechnology R&D, manufacture, and products may release new engineered nanoparticles into the environment. There is little knowledge about the behaviour of nanoparticles in the environment and their effect on biological systems but there are studies that hint that some manufactured nanoparticles may be harmful to living organisms [9]. Life cycle assessments can be used to identify what kind of nanoparticles are likely to become prevalent in natural systems and toxicity studies can be prioritized accordingly.

3. Evaluate life cycle effects early in the product life cycle

   More than 75 % of a product's overall life cycle cost is determined by the end of the product planning stage. Also most of the product's material, energy, and environmental loadings are determined at the same time even though they are not realized until later in the product life cycle. Changing a product to reduce its environmental impact after the product has been developed can cost more than 1000 times the cost of making the changes during research and development [9]. Sometimes it can be very difficult to make any changes at all. Therefore assessing the whole life cycle of the product in an early development stage can save money and the environment.

4. Identify regulatory needs

   The amount of resources needed to manufacture future nanoproducts and their environmental and human health impacts are unknown. There are likely to be undesired side effects that could be disruptive and costly unless we deal with them in advance. Life cycle assessment can provide understanding and information about energy and material requirements, waste and pollution, and health and environmental implications that are needed to determine if current regulatory mechanisms are sufficient.

5. Address public concerns

   Research on the environmental and health implications of nanotechnology lags behind nanoscale science and technology. This has led non-govermental organizations, activist groups, and members of the scientific community to call for more research investigating nanotechnology's risks. A similar gap in biotechnology and a failure to address public concerns resulted in a backlash against GM food. An early mishap with nanotechnology or failure to respond to public concerns could turn public opinion against it, leading to costly regulation. While toxicological studies are needed to assess human health risks from exposure to engineered nanoparticles, life cycle assessment can be used to identify those life cycle stages that are likely to result in the release of nanoparticles. LCA can also be used to communicate expected benefits and risks to the public.

3.3 Applicability of LCA to Nanoproducts

It is widely accepted that the LCA approach is the proper way to assess the environmental impacts of nanoproducts [3] and the ISO framework for LCA has been found fully applicable to LCAs involving nanoproducts and materials [36]. Even though only few studies have been conducted, some show clearly reduced environmental impacts [1]. LCA has been used for nanomaterials (e.g. carbon nanofibres [37]), products containing nanomaterials (e.g. polymer nanocomposites [38], quantum dot photovoltaics [39], wind turbine blades [40], and socks with silver nanoparticles [41]), and manufacturing processes involving nanomaterials (e.g. semiconductor manufacturing [42], plasma spraying [43], and titanium dioxide production [44]).

Few studies have addressed the end of life stage of LCA [45] and therefore none or almost none of the studies are fully ISO-compliant. Many studies are so called cradle to gate studies which consider only the raw material extraction and production stages of the life cycle. However, there are also specific studies being made only on the end of life stage of product life cycle [46] and combining these studies with other complementary studies could provide a full LCA.

It seems that most of the challenges of applying LCA to nanomaterials are not in fact specific to applying the methodology to these materials. The challenges are rather related to the uncertainty in the underlying data which could also exist for other substances such as chemicals [47]. Majority of the LCA studies on nanoproducts and materials have relied upon generic life cycle impact databases or general literature in formulating the inventories and impact assessment criteria [47]. This probably results from the lack of data related to nanomaterials and products made of them.

Instead of waiting for complete data, LCA can be made using reasonable upper and lower boundaries on the expected impacts in order to continue with the rest of the analysis. For LCI, data from other similar products and materials can be applied to nanoproducts as an approximation [36]. One must however remember that it is essential to report and be open about the made assumptions in order to meet the transparency, acceptability and credibility criteria for the assessment. [36]

It must be noted that the industrial scale nano-LCA results could be gross overestimates as the nano-manufacturing processes are likely to become more efficient with higher yields over time and volume [37]. However, this condition is applicable to all emerging products and technologies and can not be considered nano-specific.

There are, however, certain matters that must be looked into in more detail when assessing the environmental impacts of nanoproducts.

One of the obstacles to understanding the environmental impacts of nanoproducts and materials is characterization of the materials themselves. Even within a seemingly narrow class of nanomaterials, for example single-walled carbon nanotubes (SWCNT), it is essential to understand the uniformity (e.g. length, diameter, conductivity) and purity as well as the relationship between these characteristics and their functionality in the end-use application. There are no standard specifications among nanomaterial suppliers and therefore even the quality and contents of a ”high-purity” material may be very variable. For example, SWCNT may contain as little as 10 % by mass of actual nanotubes with the rest being simpler forms of carbon. The experimental characterization methods to address these problems are still evolving. [3]

Nanomaterials are especially problematic with regard to toxicity. Toxicity is an important factor in LCA because typical LCAs look into one or more impact categories that are related to human or ecotoxicological health. With conventional chemicals it is usually appropriate to express toxic doses in terms of mass but it is not yet clear if mass concentration drives toxicity at the nanoscale. Surface properties, functionalization, interaction with the surrounding media, and microbial activation may be more important factors with regard to toxicity than the absolute amount (i.e. mass or volume) of the material. [3]

As nanoproducts are just starting to enter the market in larger scales, it is still unclear what kind of impacts they will have to the environment during the use and disposal or recycling stages of their life cycle. Some materials will be released during use either intentionally (e.g. nanoadditives in gasoline) or unintentionally (e.g. nanomaterials in tyres) and their release rates are not always available. The behaviour of nanomaterials that have been discarded after use is also not yet clear. For example, their reaction with other materials in an incinerator or at a dump site is uncertain [36] and there are doubts whether these materials can be recycled at all.

3.4 Special Notes on Applying LCA to Nanoproducts

There are certain spesific issues that have to be taken into account in the four different phases of the nanoproduct life cycle assessment.

1. Goal and scope definition

   When defining the goal and scope of the assessment the most important matter to consider is the choice of the functional unit, the target of the assessment. Functional unit represents the demand, activity, or product that is the purpose of the production system. With conventional materials, such as steel or aluminium, this can be for example one kilogram of the material produced. With most nanoproducts, however, the functional unit should be defined based on the provided service of the product because with nanomaterials the same functionality and similar properties can be achieved with much lower weights [48].

The choice of the functional unit may turn out to be tricky since many nanoproducts provide brand new and unique functionalities and it may be difficult to specify functional alternatives. For example, it may be possible to compare trousers with dirt-repellent nanotreatment with traditional trousers once the exact conditions of wearing and cleaning are specified but for pharmaceutical applications functional equivalents may not even exist. Another issue to consider with all emerging technologies is the behaviour of the end-user. Does the consumer use the new nanoproduct as it is meant to be used?

2. Life cycle inventory analysis

Preparing life cycle inventory is a crucial phase of LCA and the challenge here is to ensure the collection and the use of complete and reliable data. Also the applied assumptions have to be clearly explained. With some products it may be possible to simplify the assessment by ignoring materials that constitute only a very small percentage of the product. With conventional materials these kind of cut-offs can be based on the mass of the material but with nanoparticles cut-offs based on mass can be misleading and should not be applied [36].

Nanotechnology requires usually large and energy-consuming equipment that also tend to rapidly become outdated because of new developments. Therefore the impacts of building and using the equipment can not always be ignored. Equipment for lithography, coating deposition and clean rooms are only a few examples. Another issue is that the equipment is used to manufacture or process several different nanoproducts or materials. Thus, the environmental impacts of the equipment have to be allocated between different end products.

Typically the materials in a life cycle inventory are reported with their masses and the inventory contains items such as "22 kg CO_2" and "0.54 kg 1,1,1-trichloroethane". For nanoparticles also additional parameters will be important in the impact assessment phase of LCA. Parameters that can influence toxicity and the environmental impacts of nanomaterials include, for example, particle size, shape, solubility and adhesive properties. For nanoparticles with coating it is important to find out whether to report the pure material or the composite. [36]

Yet another challenge can be knowing whether nanoparticles change their form (shape, coating, etc.) during their life cycle, for example, because of aging or external conditions such as weather, mechanical stress or catalysis. All of these characteristics may need to be described in the life cycle inventory. [36]

At present, the available LCI databases are populated mainly with material and product flows that do not distinguish between the bulk and corresponding nanomaterial. [49, 45]

3. Life cycle impact assessment

   The life cycle impact assessment phase of an LCA is the evaluation of potential impacts on human health and the environment by the items identified in the LCI. The production, use and disposal of nanoproducts and materials are associated with the impact categories such as climate change, human toxicity, ecotoxicity and acidification.

   There are no special difficulties in impact assessment for most of the common categories but for assessing toxicological impacts the current knowledge and understanding are not sufficient [36]. However, even if the assessment of potential risks for the environment due to intended and also accidental releases may be partly impossible in LCA for now, it is important to support the assessment by a thorough description of potential releases in the LCI phase [49].

   It should also be noted that the large surface-to-volume ratio of nanoparticles can be relevant to certain other impact categories, especially ozone layer depletion and photochemical smog [36].

4. Life cycle interpretation

   Interpreting the assessment results for nanoproducts is not different from standard products. However, the role of uncertainty and sensitivity analyses must be emphasized with products and materials that are lacking reliable inventory data and data on impact relationships.

   Another issue to discuss in the interpretation stage of LCA is the potential of nanotechnology of being used at a society-wide scale. For example, an LCA for one window glass may favour a nanocoated form but upscaling the technology and production to society-wide use could potentially bring problems [36].

4 Conclusions

Nanotechnology offers great potential and possibly great risks. It would be foolish for society to endanger the benefits by rushing recklessly into commercialization without assessing the risks. What is needed is scientifically sound research to identify and address any negative impacts in order to avoid jeopardizing the realization of the potential benefits.

A life cycle perspective is essential in evaluating the potential environmental impacts of nanoproducts and materials from cradle to grave. The different environmental assessment methods are suited for different needs while LCA is the most comprehensive of them all.

One of the most important advantages of LCA is that it helps to avoid shifting environmental problems from one place to another. Even though the point of all life cycle methods is the same, the less comprehensive methods take into account only the shifting between different life cycle stages. LCA accounts also for the shifting between different types of environmental impacts. For example, a carbon footprint analysis may show that Option A is better because the CO_2 emissions are reduced during the whole life cycle. However, carbon footprint does not reveal if the reduction of CO_2 emissions causes increases in the amount of solid waste, or in the ecotoxicity of waste water. Therefore, after analyzing all the impacts, LCA may show that Option B is still more environmentally friendly even though it causes more CO_2 emissions.

Final remarks:

- The current methodological tools are applicable to assessing the environmental impacts of nanoproducts.
- Major work is needed to fully assess the potential environmental impacts of nanoproducts and materials.
- All stages of the life cycle should be considered when assessing the environmental impacts.
- The main problem with LCA of nanoproducts and materials is the lack of inventory data and data on impact relationships.
- Further research is needed to collect missing data and to develop user-friendly assessment tools.
- Uncertainty in LCA studies should be acknowledged and quantified.

References

[1] Michael Nentwich and Sabine Greßler. Nano and the environment - part I: Potential environmental benefits and sustainability effects. *NanoTrust Dossiers*, March 2012.

[2] Troy R. Hawkins, Bhawna Singh, Guillaume Majeau-Bettez, and Anders Hammer Strømman. Comparative environmental life cycle assessment of conventional and electric vehicles. *Journal of Industrial Ecology*, 2012.

[3] Thomas P. Seager and Igor Linkov. Coupling multicriteria decision analysis and life cycle assessment for nanomaterials. *Journal of Industrial Ecology*, 12(3):282–285, 2008.

[4] Tarsha Eason, David E. Meyer, Mary Ann Curran, and Venkata K. K. Upadhyayula. *Guidance to Facilitate Decisions for Sustainable Nanotechnology*. U.S. Environmental Protection Agency, Washington, D.C., USA, 2011.

[5] *Elinkaarimenetelmät yrityksen päätöksenteon tukena - FINLCA-hankkeen loppuraportti*. Finnish Environment Institute, Helsinki, Finland, 2012.

[6] *Elinkaarimetodiikkojen nykytila, hyvät käytännöt ja kehitystarpeet*. Finnish Environment Institute, Helsinki, Finland, 2010.

[7] *ISO 14040:2006: Environmental management – Life cycle assessment – Principles and framework*. International Organization for Standardization, Geneva, Switzerland, 2006.

[8] *ISO 14044:2006: Environmental management – Life cycle assessment – Requirements and guidelines*. International Organization for Standardization, Geneva, Switzerland, 2006.

[9] Shannon Marie Lloyd. *Using Life Cycle Assessment to Inform Nanotechnology Research and Development*. PhD thesis, Carnegie Mellon University, Pittsburgh, PA, USA, 2004.

[10] *Life Cycle Assessment: Principles and Practice*. U.S. Environmental Protection Agency, Cincinnati, OH, USA, May 2006.

[11] *ILCD Handbook - General guide for Life Cycle Assessment - Detailed guidance*. European Commission - Joint Research Centre - Institute for Environment and Sustainability, Luxembourg, March 2010.

[12] *ILCD Handbook - General guide for Life Cycle Assessment - Provisions and Action Steps*. European Commission - Joint Research Centre - Institute for Environment and Sustainability, Luxembourg, March 2010.

[13] *ILCD Handbook - Specific guide for Life Cycle Inventory data sets*. European Commission - Joint Research Centre - Institute for Environment and Sustainability, Luxembourg, March 2010.

[14] *ILCD Handbook - Analysing of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment*. European Commission - Joint Research Centre - Institute for Environment and Sustainability, Luxembourg, March 2010.

[15] *ILCD Handbook - Framework and Requirements for Life Cycle Impact Assessment*

Models and Indicators. European Commission - Joint Research Centre - Institute for Environment and Sustainability, Luxembourg, March 2010.
[16] *ILCD Handbook - Recommendations for Life Cycle Impact Assessment in the European context*. European Commission - Joint Research Centre - Institute for Environment and Sustainability, Luxembourg, November 2011.
[17] *ILCD Handbook - Review schemes for Life Cycle Assessment*. European Commission - Joint Research Centre - Institute for Environment and Sustainability, Luxembourg, March 2010.
[18] *ILCD Handbook - Reviewer qualification for Life Cycle Inventory data sets*. European Commission - Joint Research Centre - Institute for Environment and Sustainability, Luxembourg, March 2010.
[19] *ILCD Handbook - Nomenclature and other conventions*. European Commission - Joint Research Centre - Institute for Environment and Sustainability, Luxembourg, March 2010.
[20] Joel Ann Todd and Mary Ann Curran, editors. *Streamlined Life-Cycle Assessment: A Final Report from the SETAC North America Streamlined LCA Workgroup*. Society of Environmental Toxicology and Chemistry (SETAC) and SETAC Foundation for Environmental Education, July 1999.
[21] CCaLC carbon footprinting tool. http://www.ccalc.org.uk/, accessed Nov 13, 2012.
[22] H. Scott Matthews, Chris T. Hendrickson, and Christopher L. Weber. The importance of carbon footprint estimation boundaries. *Environmental Science & Technology*, 42(16):5839–5842, 2008.
[23] T. Kenny and N. F. Gray. Comparative performance of six carbon footprint models for use in Ireland. *Environmental Impact Assessment Review*, 29(1):1–6, 2009.
[24] ISO 14067 – carbon footprint of products. http://www.pcf-world-forum.org/initiatives/international-standards/iso-14067/, accessed Nov 8, 2012.
[25] Arjen Y. Hoekstra, Ashok K. Chapagain, Maite M. Aldaya, and Mesfin M. Mekonnen. *The Water Footprint Assessment Manual: Setting the Global Standard*. Earthscan, 2011.
[26] ISO/CD 14046: Life cycle assessment – water footprint – requirements and guidelines. http://www.iso.org/iso/catalogue_detail?csnumber=43263, accessed Nov 14, 2012.
[27] Brad Ewing, Anders Reed, Alessandro Galli, Justin Kitzes, and Mathis Wackernagel. *Calculation Methodology for the National Footprint Accounts, 2010 Edition*. Global Footprint Network, Oakland, CA, USA, 2010.
[28] *Living Planet Report 2012*. WWF, Glant, Switzerland, 2012.
[29] Thomas Wiedmann, Jan Minx, John Barrett, and Mathis Wackernagel. Allocating ecological footprints to final consumption categories with input–output analysis. *Ecological Economics*, 56(1):28–48, 2006.
[30] Mark A. J. Huijbregts, Stefanie Hellweg, Rolf Frischknecht, Konrad Hungerbühler, and A. Jan Hendriks. Ecological footprint accounting in the life cycle assessment of products. *Ecological Economics*, 64(4):798–807, 2008.

[31] Global Footprint Network. *Ecological Footprint Standards 2009*. Global Footprint Network, Oakland, CA, USA, 2009.

[32] Satu Lähteenoja, Michael Lettenmeier, and Arto Saari. *Transport MIPS - The natural resource consumption of the Finnish transport system*. Ministry of the Environment, Helsinki, Finland, 2006.

[33] Elli Kotakorpi, Satu Lähteenoja, and Michael Lettenmeier. *Household MIPS - Natural resource consumption of Finnish households and its reduction*. Ministry of the Environment, Helsinki, Finland, 2008.

[34] Timothy G. Gutowski, John Y. H. Liow, and Dusan P. Sekulic. Minimum exergy requirements for the manufacturing of carbon nanotubes. In *IEEE International Symposium on Sustainable Systems and Technology 2010*, July 2010.

[35] EU nanosafety cluster. http://www.nanosafetycluster.eu/, accessed Nov 19, 2012.

[36] *Nanotechnology and Life Cycle Assessment. A Systems Approach to Nanotechnology and the Environment.*, Synthesis of Results Obtained at a Workshop in Washington, DC 2–3 October 2006, March 2007.

[37] Vikas Khanna, Bhavik R. Bakshi, and L. James Lee. Carbon nanofiber production. *Journal of Industrial Ecology*, 12(3):394–410, 2008.

[38] Vikas Khanna, Bhavik R. Bakshi, and L. James Lee. Assessing life cycle environmental implications of polymer nanocomposites. In *IEEE International Symposium on Electronics and the Environment 2008*, volume 0, pages 1–6, Los Alamitos, CA, USA, 2008. IEEE Computer Society.

[39] Hatice Şengül and Thomas L. Theis. An environmental impact assessment of quantum dot photovoltaics (QDPV) from raw material acquisition through use. *Journal of Cleaner Production*, 19(1):21–31, 2011.

[40] L. A. Merugula, V. Khanna, and B. R. Bakshi. Comparative life cycle assessment: Reinforcing wind turbine blades with carbon nanofibers. In *IEEE International Symposium on Sustainable Systems and Technology 2010*, pages 1–6, July 2010.

[41] David E. Meyer, Mary Ann Curran, and Michael A. Gonzalez. An examination of silver nanoparticles in socks using screening-level life cycle assessment. *Journal of Nanoparticle Research*, 13:147–156, 2011.

[42] Nikhil Krishnan, Sarah Boyd, Ajay Somani, Sebastien Raoux, Daniel Clark, and David Dornfeld. A hybrid life cycle inventory of nano-scale semiconductor manufacturing. *Environmental Science & Technology*, 42(8):3069–3075, 2008.

[43] A. Moign, A. Vardelle, N. J. Themelis, and J. G. Legoux. Life cycle assessment of using powder and liquid precursors in plasma spraying: The case of yttria-stabilized zirconia. *Surface and Coatings Technology*, 205(2):668–673, 2010.

[44] Geoffrey F. Grubb and Bhavik R. Bakshi. Life cycle of titanium dioxide nanoparticle production. *Journal of Industrial Ecology*, 15(1):81–95, 2011.

[45] Sheetal Gavankar, Sangwon Suh, and Arturo F. Keller. Life cycle assessment at

nanoscale: review and recommendations. *The International Journal of Life Cycle Assessment*, 17:295–303, 2012.

[46] Satu Ikonen. Nanomaterials and the environment. To be published in 2013.

[47] Khara D. Grieger, Alexis Laurent, Mirko Miseljic, Frans Christensen, Anders Baun, and Stig I. Olsen. Analysis of current research addressing complementary use of life-cycle assessment and risk assessment for engineered nanomaterials: have lessons been learned from previous experience with chemicals? *Journal of Nanoparticle Research*, 14:1–23, 2012.

[48] Roland Hischier and Tobias Walser. Life cycle assessment of engineered nanomaterials: State of the art and strategies to overcome existing gaps. *Science of The Total Environment*, 425(0):271 – 282, 2012.

[49] C. Bauer, J. Buchgeister, R. Hischier, W. R. Poganietz, L. Schebek, and J. Warsen. Towards a framework for life cycle thinking in the assessment of nanotechnology. *Journal of Cleaner Production*, 16(8-9):910–926, 2008.