Assessment of Environmental Impacts with Life Cycle Methods in Nanotechnology Industry

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Preface

I would like to thank my supervisor Professor Hannu Häkkinen who gave me free hands to fulfil myself and allowed me to do research in the area that I had most passion for. I am also grateful to Professor Hanna-Leena Pesonen who reviewed my thesis.

I would also like to thank Miktech Ltd. and especially my manager Juha Kauppinen and CEO Vesa Sorasahi for their support and for giving me a chance to conduct research that is highly relevant to the nanotechnology industry and companies operating in this field.

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Abstract

This thesis inspected how nanotechnology companies in Finland have been assessing the environmental impacts of their products and processes. The research focused on using life cycle based methods that take into account the environmental impacts during the whole lifetime of a product.

The subject was studied mainly through three qualitative case studies. Millidyne Oy, Vaisala Oyj and UPM-Kymmene Oyj were interviewed. Also quantitative research was used to some extend in the form of a company questionnaire.

This research showed that only 13 % of nanotechnology companies in Finland have done environmental assessments with life cycle methods, and that even this figure is likely to be biased and too large. Customer demand, legislation, cost savings, and product development were recognized as the main drivers for companies to do these assessments.

The main problem with environmental assessments of nanoproducts and materials was found to be the lack of reliable data on their properties related to the environment and health. Also it was found that more efforts are needed in developing the environmental assessment tools to be more user-friendly and suitable for small and medium-sized enterprises.

Tiivistelmä

Tämä tutkielma tarkasteli kuinka suomalaiset nanoteknologia-alan yritykset ovat arvioineet tuotteidensa ja prosessiensa ympäristövaikutuksia. Tutkimus keskittyi elinkaarimenetelmiin, jotka ottavat huomioon ympäristövaikutukset tuotteen koko elinaikana.

Aihetta tutkittiin pääasiassa kolmella kvalitatiivisella tapaustutkimuksella. Tätä varten haastateltiin Millidyne Oy:tä, Vaisala Oyj:tä ja UPM-Kymmene Oyj:tä. Myös kvantitatiivista tutkimusta tehtiin yrityskyselyn muodossa.

Tutkimus osoitti, että vain 13 % nanoteknologia-alan yrityksissä Suomessa on tehnyt ympäristöarviointeja elinkaarimenetelmillä, ja että tämäkin luku on todennäköisesti vääristynyt ja liian suuri. Asiakkaiden vaatimukset, lainsäädäntö, kustannussäästöjen haku ja tuotekehitys tunnistettiin yritysten tärkeimmiksi syiksi tehdä ympäristöarviointeja.

Suurimmaksi ongelmaksi nanotuotteiden ja -materiaalien ympäristöarvioinneissa havaittiin luotettavan tiedon puute niiden ympäristöön ja terveyteen liittyvistä ominaisuuksista. Tutkimuksessa havaittiin myös, että ympäristöarvioinneissa käytettävien työkalujen helppokäyttöisyyteen ja soveltuvuuteen pienille ja keskisuurille yrityksille täytyy panostaa tulevassa kehitystyössä.

Abbreviations

CH_4	Methane
CNT	Carbon nanotube
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DfE	Design for environment
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
SME	Small or medium-sized enterprise
SWCNT	Single-walled carbon nanotube
TMR	Total material requirement
TUT	Tampere University of Technology
UV	Ultraviolet

Contents

1 Introduction **1**
1.1 *Nanotechnology Industry in Finland* . . . 1
1.2 *Environmental Aspects Related to Nanotechnology* . . . 2
1.3 *Life Cycle Thinking* . . . 3
1.4 *Outline of the Thesis* . . . 4

2 Life Cycle Methods **6**
2.1 *Carbon Footprint* . . . 6
2.2 *Water Footprint* . . . 8
2.3 *Ecological Footprint* . . . 9
2.4 *Material Input Per Service Unit (MIPS)* . . . 9
2.5 *Life Cycle Assessment (LCA)* . . . 10
2.6 *Streamlined LCA* . . . 13

3 Nano and the Environment **14**
3.1 *Overview* . . . 14
3.2 *Reasons to Use Life Cycle Methods to Assess Nanotechnology* . . . 15
3.3 *Applicability of LCA to Nanoproducts* . . . 17
3.4 *Special Notes on Applying LCA to Nanoproducts* . . . 18

4 Materials and Methods **21**
4.1 *Company Questionnaire* . . . 21
4.2 *Case Studies* . . . 21

5 Results **24**
5.1 *Questionnaire Results* . . . 24
5.2 *Case 1: Millidyne* . . . 24
5.3 *Case 2: Vaisala* . . . 27
5.4 *Case 3: UPM* . . . 30

6 Discussion **36**
6.1 *Company Questionnaire* . . . 36
6.2 *Why to Measure Environmental Impacts with Life Cycle Methods?* . . . 36
6.3 *How to Measure Environmental Impacts?* . . . 37
6.4 *The Nanotechnological Point of View in Environmental Assessments* . . . 38
6.5 *Future* . . . 39

7 Conclusions **40**

References **41**

Appendix A The company interview outline in Finnish **A1**

1 Introduction

1.1 Nanotechnology Industry in Finland

Nanotechnology is already a part of almost every Finn's life. All consumer electronics for example in mobile phones and computers is made possible by nanotechnology. Electronic industry has been operating in the sub 100 nm scale already since 2002. We would not have any LED lighting without nanotechnology since 147 out the 155 key technologies in an LED lamp are based on nanoscale phenomena. Many people have suits that are dirt-repellent, or silver jewelry that don't tarnish so easily. Restaurant tables have easy-to-clean tablecloths that have been treated with nanomaterials and cross-country skis have been improved with nanoscale ingredients. [1]

The nanobusiness in Finland has been growing rapidly. A recent study by the Finnish Nanotechnology Cluster Programme shows that the number of Finnish companies using nanotechnology tripled between 2008 and 2011 [1, 2]. There are now reported to be 210 companies in Finland that provide a commercial product involving nanotechnology. In addition, about one hundred companies are at pre-commercial phase and another 170 at vision stage. The previous report by Tekes, the Finnish Funding Agency for Technology and Innovation, completed in late 2008 concluded that there were 65 companies in commercial phase at that time and a total of 200 companies if those at the vision phase were included (Figure 1).

Out of the 210 companies, around 140 offer nanomaterials, intermediate products (e.g. coatings), end products with at least one nanotechnology-enabled feature (e.g. a suit with dirt-repellent treatment), or equipment. Around 70 companies are service providers. Also, many companies offer services in addition to other products. The service companies can for exam-

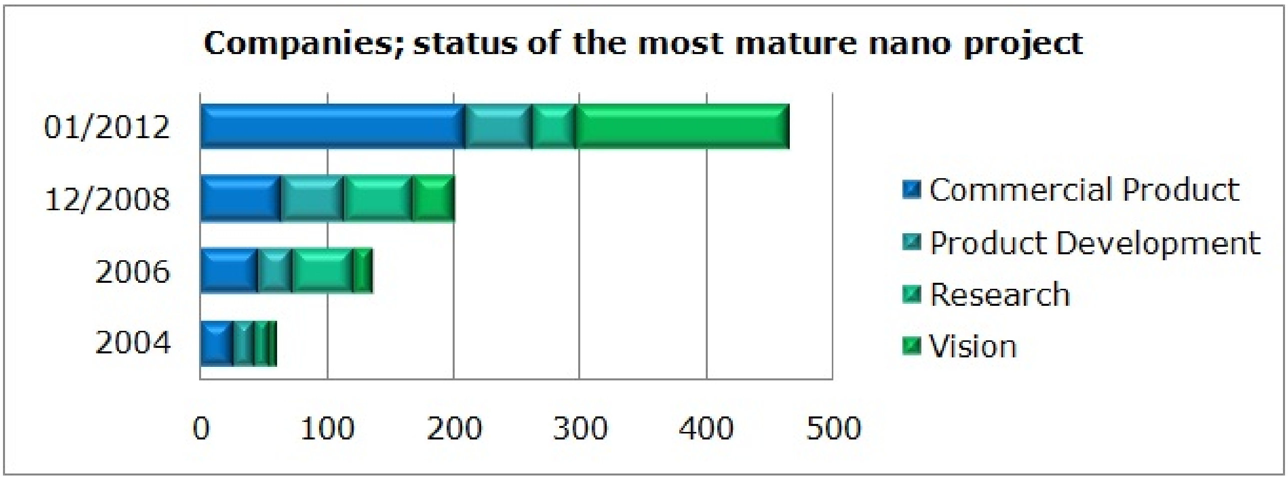

Figure 1: Number of Finnish nanotechnology companies in different commercialization phases. Figures from 2004 to 2008 are based on studies made in the Tekes FinNano programme and 2012 figures are from Nanotechnology Cluster Programme. Source: Nanotechnology Cluster Programme

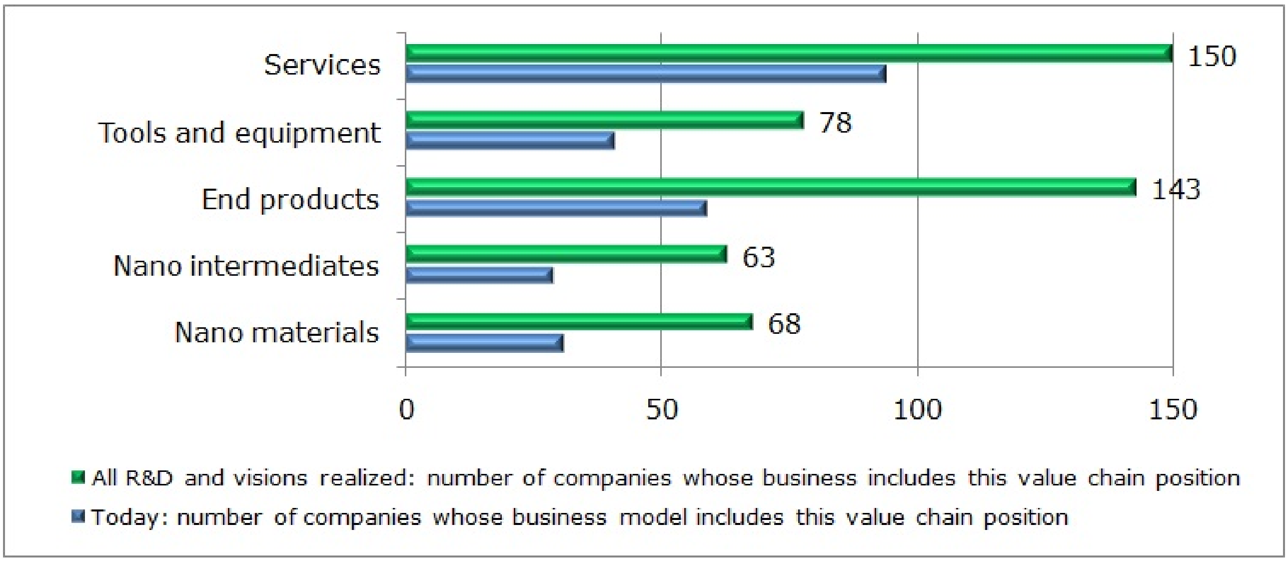

Figure 2: Value chain positions of Finnish nanotechnology companies. Intermediates include for example coatings and end products are products with at least one nanotechnology-enabled feature (e.g. a suit with dirt-repellent treatment). Source: Nanotechnology Cluster Programme

ple offer analytics, R&D, and coating services, and consultancy. The business focus of the industry is shifting from nanomaterials to finished products, machines, and equipment. Figure 2 shows that while also nanomaterial, intermediate and equipment business are growing, more and more companies are focusing on doing business with end products and services.

Nanotechnology Cluster Programme is the gateway to Finnish nanotechnology. It was initiated by the Ministry of Employment and the Economy in 2007 in order to promote nanotechnology based business in Finland and it is scheduled to end in 2013. The mission of the Programme is to foster growth of nanotechnology based business and to support implementation of nano and microtechnologies and future materials in Finnish companies. Nanocluster is a nationwide network reaching almost all of the nano and microtechnology related activities and stakeholders. Nanocluster operates through eight local Centers of Expertise in Helsinki region, Tampere, Turku, Jyväskylä, Mikkeli, Joensuu, Kokkola and Oulu.

1.2 Environmental Aspects Related to Nanotechnology

Nanotechnology is often referred to as being a key technology of the 21st century [3]. 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 [3]. 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.

1.3 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. [4] 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 [5].

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 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 3) 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.

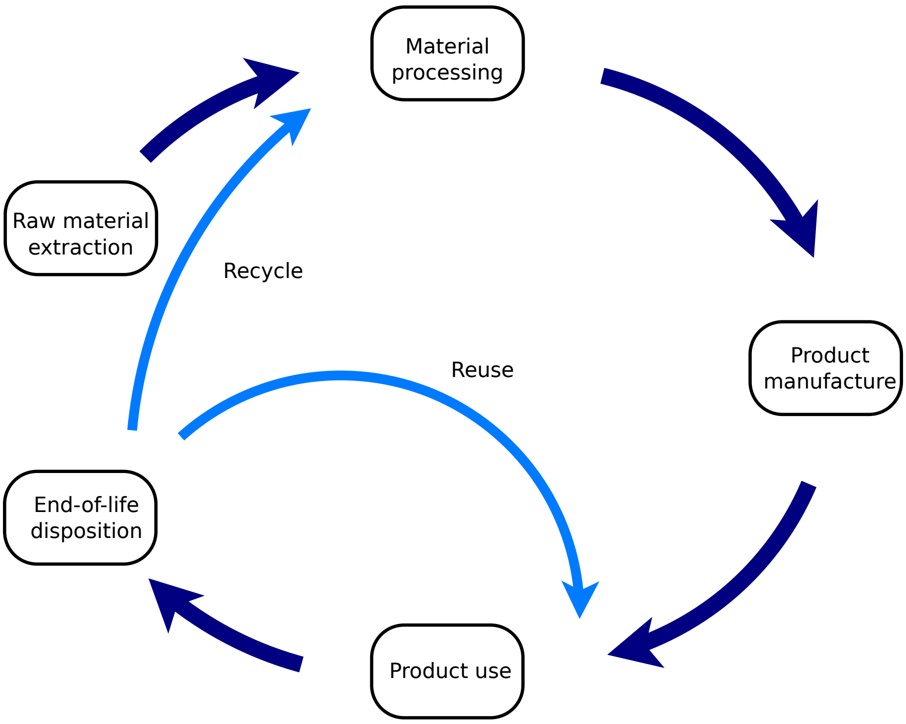

Figure 3: Product life cycle consists of raw material extraction, material processing, product manufacture, product use, and end-of-life disposition.

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. [6]

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.

1.4 Outline of the Thesis

The aim of this thesis is to give an overview of different life cycle methods that can be used to assess the environmental impacts of nanoproducts. This is done by reviewing the different methods, by surveying the usage of these methods among Finnish nanotechnology companies, and by conducting a qualitative interview research with selected companies. The selected companies are presented as case studies and the best practices of environmental assessment are compiled based on the interviews.

The main research questions are:

1. Why to measure environmental impacts with life cycle methods?
2. How to determine what to measure?
3. How to choose the right method?

All the questions are discussed from the point of view of nanotech companies and nanoproducts.

Chapter 2 introduces the most relevant assessment methods. Environmental impacts of nanotechnology are discussed in Chapter 3. Chapter 4 describes the used research methods and Chapter 5 provides the results of the research. The results are discussed in Chapter 6 and the key findings about assessing environmental impacts with life cycle methods are concluded in Chapter 7.

The three pillars of sustainability are environment, economy and society (Figure 4) [7]. While all of them are important this work concentrates on the assessment of the environmental impacts of nanoproducts with only reminders about the other two dimensions. However, it should be noted that when building a sustainable product, company, or world, all the three dimensions should be addressed [8].

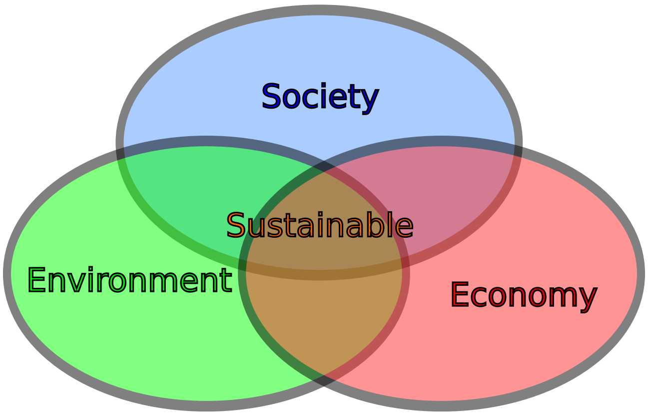

Figure 4: The three pillars of sustainability are environment, economy and society.

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 5 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 [9].

The following gives a general descriptions of the methods. Literature sources [6, 9, 10] provide a more thorough description of the possibilities, strengths and weaknesses of different methods.

2.1 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 [11].

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. [12, 13]

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 %

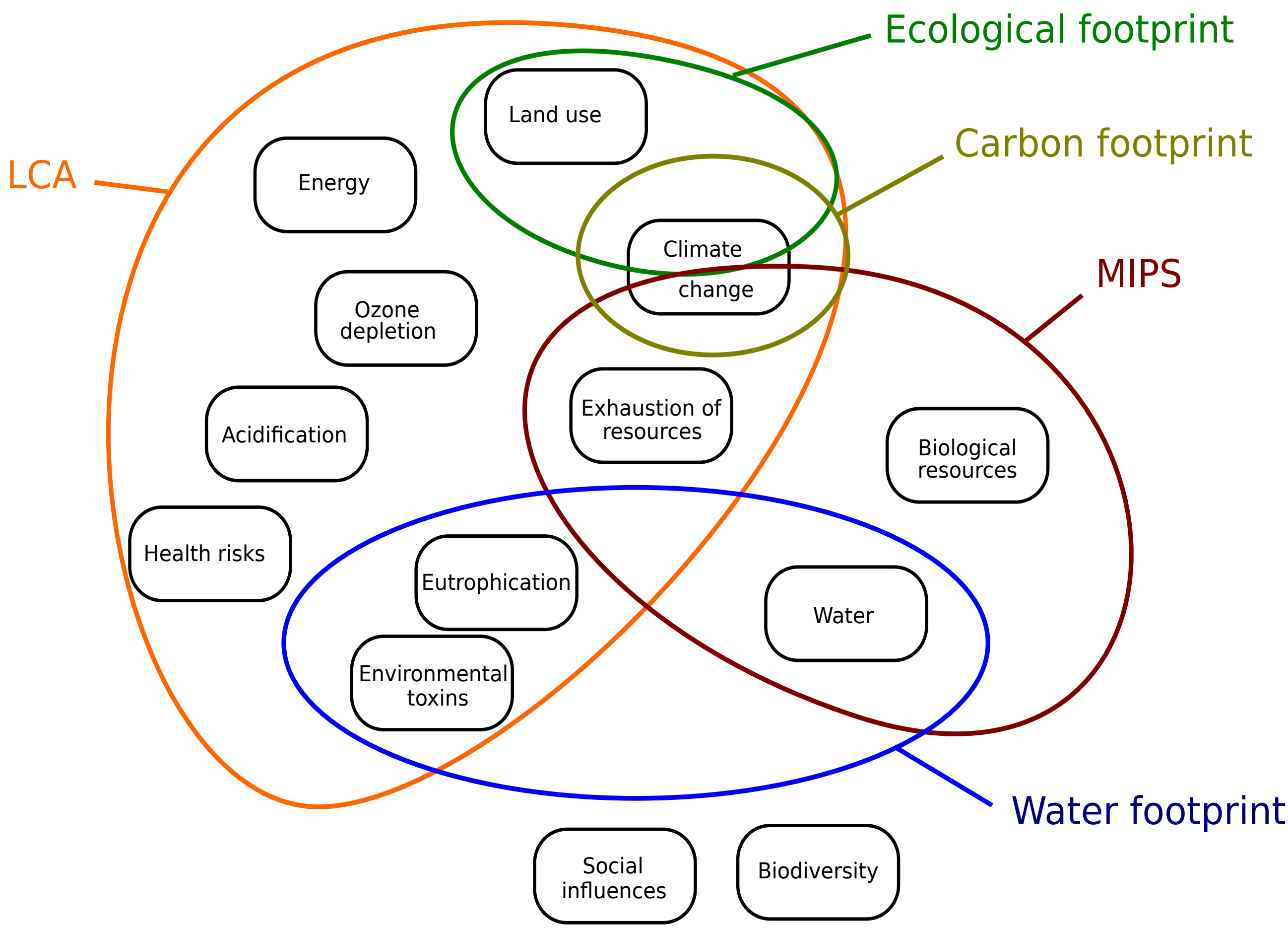

Figure 5: Different life cycle methods cover different aspects of environmental assessment. LCA is the most comprehensive assessment method while social influences and biodiversity are not covered by any of the methods.

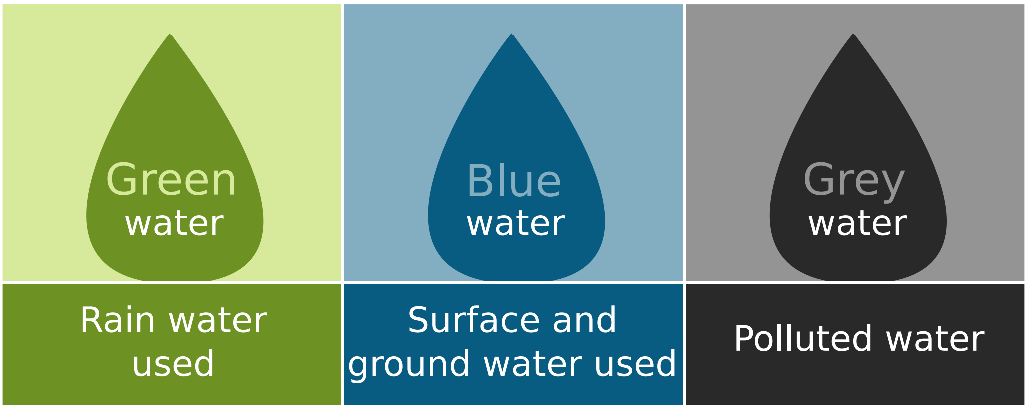

Figure 6: Water footprint consists of three components: green, blue, and grey.

of the total supply chain carbon emissions [12]. 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 [14].

2.2 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 [15].

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 6) [15]. Blue water refers to surface and groundwater, green water footprint is the amount of rainwater that has been evaporated (usually from agriculture and forestry [10]), 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 [9].

The International Organization for Standardization is preparing a standard, ISO 14046, for water footprint [16].

2.3 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 [17]. Regardless of its wide definition, ecological footprint only takes into account biomass based resources, and carbon dioxide as an emission [9].

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 [18]. 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 [19] and products [20, 21].

2.4 Material Input Per Service Unit (MIPS)

As the name suggests, material input per service unit (MIPS) is an indicator that tells about 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)**. [9]

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 [22] and FIN-MIPS Household [23] 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.

2.5 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. The variety of different environmental impacts covered by LCA can be seen in Figure 5.

One of the most important advantages of LCA over the more limited assessment methods 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.

LCA can assist in

- identifying opportunities to improve the environmental performance of products at various points in their life cycle,
- informing decision-makers in industry, government or non-government organizations,
- the selection of relevant indicators of environmental performance, and
- marketing. [24]

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 [24], ISO 14044 [25]), 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 as seen in Figure 7 [24, 25]:

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

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

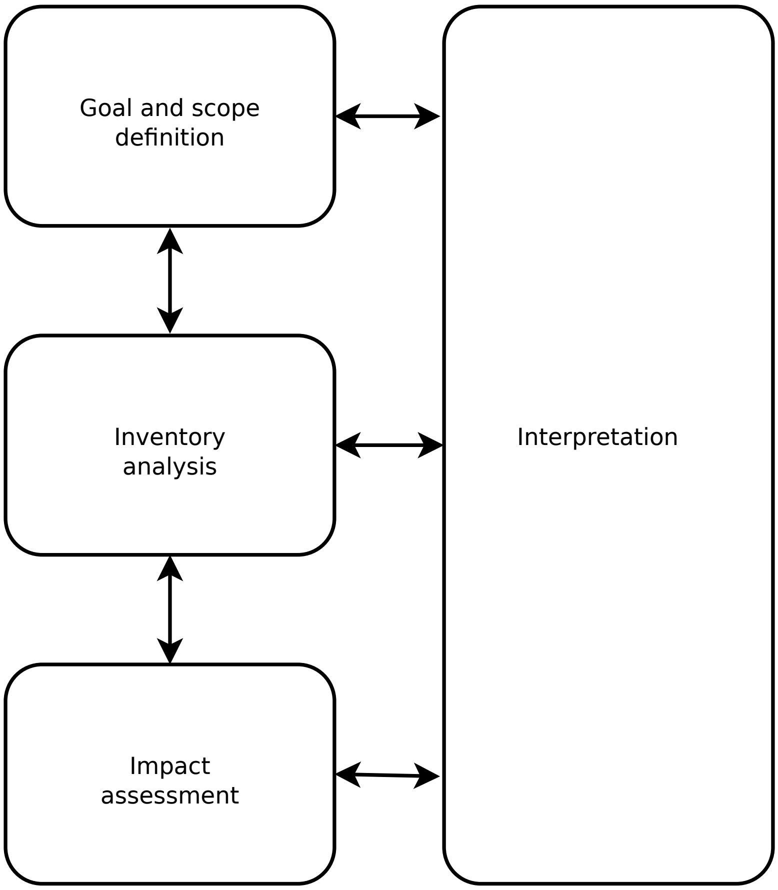

Figure 7: Life cycle assessment consists of four different phases: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation. All of these phases are iterative.

frame of an LCA may vary to a large extent, depending on the goal and scope definition [24].

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 [9]. 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 [26]. 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 [24].

The plain inventory data does not 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 [9, 27]:

- 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 [26]. Understanding and communicating the uncertainties and limitations in the results is equally as important as the final recommendations [27]. 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 [24, 27]. Also, there are specific requirement to LCA if the results are to be used in comparative statements, such as product comparisons, that are intended to be disclosed to the public.

As depicted in Figure 7, 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 [28, 29, 30, 31, 32, 33, 34, 35, 36] 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. [27]

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. [9]

2.6 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. [37]

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 [26].

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 [38].

Even though there are many international research programmes tackling the question of nanosafety [39], especially the toxicological effects of nanoparticles are still largely unknown.

Some of the potential positive environmental impacts of nanotechnology [3]:

- 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 can replace the environmentally damaging 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 [26]. 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 [26]. 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 [5] and the ISO framework for LCA has been found fully applicable to LCAs involving nanoproducts and materials [40]. Even though only few studies have been conducted, some show clearly reduced environmental impacts [3]. LCA has been used for nanomaterials (e.g. carbon nanofibres [41]), products containing nanomaterials (e.g. polymer nanocomposites [42], quantum dot photovoltaics [43], wind turbine blades [44], and socks with silver nanoparticles [45]), and manufacturing processes involving nanomaterials (e.g. semiconductor manufacturing [46], plasma spraying [47], and titanium dioxide production [48]).

Few studies have addressed the end of life stage of LCA [49] 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 [50] 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 [51]. 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 [51]. 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 [40]. 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. [40]

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 [41]. However, this condition is applicable to all emerging products and technologies and cannot 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. [5]

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. [5]

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 [40] 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 [52].

   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 [40].

   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. [40]

   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. [40]

   At present, the available LCI databases are populated mainly with material and product flows that do not distinguish between the bulk and corresponding nanomaterial. [53, 49]

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 [40]. 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 [53].

   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 [40].

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 [40].

4 Materials and Methods

The subject was studied mainly qualitatively through three case studies. Also quantitative research was used to some extend in the form of a company questionnaire.

A simple company questionnaire was mainly used to identify companies that could be studied further as case studies. In addition, simple statistical analysis could be made about how many companies have done environmental assessments based on life cycle methods.

4.1 Company Questionnaire

The company questionnaire simply asked whether the company has done any environmental assessments for their products using life cycle methods, and if so, would they like to participate in the research by giving an interview. The questionnaire was done by email.

The companies were chosen based on analysis of the environmental information available on their web sites and through Nanotechnology Cluster Programme and personal contacts. Based on the initial analysis, 29 Finnish companies were seen as the most promising ones and they were approached with personal messages. The approached persons in the organizations were mainly CEOs or environmental managers. Each company was approached a maximum of three times between June and September of 2012 before it was determined that they are not providing an answer.

A simple statistics was made by looking at how many companies have done environmental assessments and how many have not.

4.2 Case Studies

Three companies were identified with the company questionnaire for further study. The aim was to find one small company, one medium-sized company, and one large company in order to see how the size of the company affects the environmental assessment activities. However, one small (Millidyne Oy) and two large companies (Vaisala Oyj, UPM-Kymmene Oyj) were found.

These companies were interviewed and case studies were made based on the interviews. Interviews were made by phone in Finnish or English, depending on the interviewee, in August and September of 2012. The interviewed persons were a CEO, an environmental engineer, and an environmental director. The conversations lasted between 30 and 60 minutes. The conversations were recorded with TotalRecall 5.0 application on Nokia E7 phone and the recordings were transcribed with Express Scribe 5.52 application. The transcription was made with medium precision. Unnecessary and meaningless sounds were omitted but for example meaningful pauses were acknowledged.

The companies were interviewed with thematic interviews. In thematic interviews there are no exact questions that have to be answered rigorously. Instead the interview is structured around specific themes that are discussed in a conversational style. The strengths of thematic interviews are flexibility and the chance to ask the interviewees to further define their answers. However, it must be made sure that all the planned themes are dealt with. Therefore in this study a list of supporting questions was prepared beforehand to outline the conversation. The set consisted of 29 questions:

Who

1. What does the company do?
2. What is the turnover of the company?
3. Is the company profitable?
4. How many personnel are there working in the company?
5. When was the company founded?

What

6. Have you done a life cycle assessment or is it still in planning stage?
7. What kind of assessment is it?
8. Is the studied product in production or in development stage?

Why

9. What is your company's relationship to environment like? Do you see yourselves more environmentally friendly than an average company?
10. What was the situation like in the company when you started thinking about such an assessment?
11. Why did you do the assessment?
12. Was there any external pressure that made you do the assessment?
13. What did you expect from the assessment?
14. Why did you choose the method that you used? How did you choose what to measure?
15. What other methods did you consider?
16. Why they weren't suitable?
17. How have you used the obtained results?
18. Have you used the results in marketing?
19. Have you used the results in product development?

How

20. Who conducted the assessment (in-house personnel or external consultant)?
21. How did you undertake the assessment?
22. Was it easy to find information about the assessment method and where did you find it?
23. How was the assessment process conducted in practice?

24. How did the poorly known environmental impacts of nanoparticles and the general lack of knowledge affect the assessment?
25. How much time was used to conduct the assessment?
26. How much did it cost?
27. Did you get any financial or know-how help from external sources?
28. What kind of person is the right one to be in charge of such an assessment process?

Future

29. Are you going to continue or do more environmental assessments?

The original interview outline in Finnish can be found in Appendix A.

5 Results

5.1 Questionnaire Results

The questionnaire was sent to 29 companies out of which 23 provided an answer. Thus the response rate was 79 %. The answers showed that only three out of 23 companies (13 %) had done an environmental assessment with some type of life cycle method. The rest 20 companies (87 %) had only planned or not even planned such assessments for their products (Figure 8).

5.2 Case 1: Millidyne

Who

Millidyne Oy is a small company from Tampere, Finland. The company provides advanced coating materials and surface treatment technologies for customers in the metal, electronics, construction, and process industries. They develop and manufacture specialty coating raw materials combining nanotechnology and surface engineering.

Millidyne specialises in developing easy-to-clean surfaces. Their product, Avalon®, is a sol-gel coating that is used in various surfaces to create protection from rust and scratches and to improve the properties of the surface with respect to cleaning. Recently the windows of

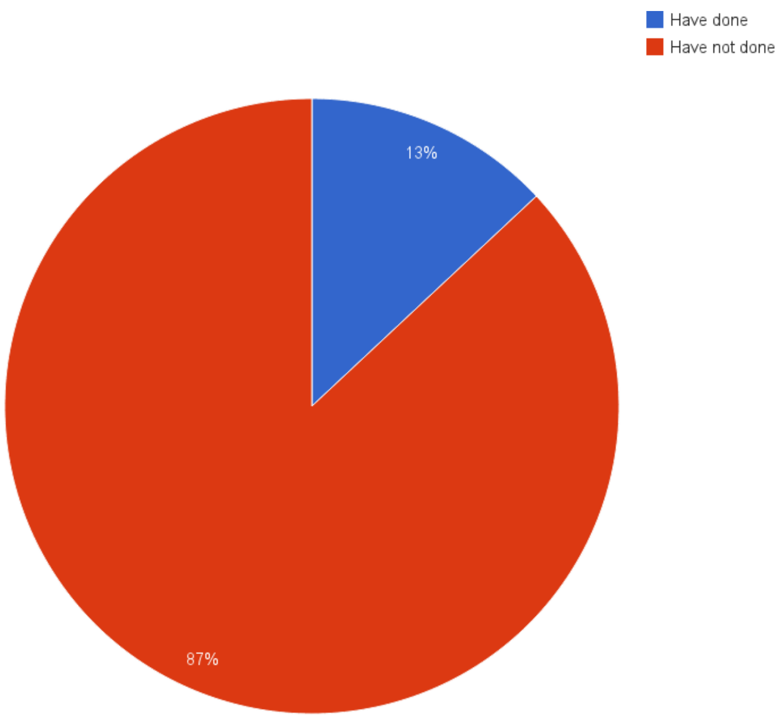

Figure 8: Only 13 % of the companies that responded to the questionnaire had done environmental assessments with life cycle methods while 87 % had not.

Finnish VR Pendolino trains and a Norwegian Color Line passenger cruiser were coated with Avalon® coating in order to keep the windows cleaner and to increase their lifetime.

Millidyne was founded in 1997 as a spin-off from Tampere University of Technology. The company has now ten employees and a turnover of about a million euros, and is profitable.

What, why

Millidyne has done a carbon footprint analysis for one of their commercial products. The assessment was done after a customer requested it. The company said that they probably would not have done the assessment without the external pressure.

The company said that the data in the data libraries used by the assessment programs was hardly applicable and relevant to their raw materials. The data is scarce and its quality is poor. General and cursory data produces such a large uncertainty to the accuracy of the results that in reality the results are pretty much useless. If these results were used for product development it could be very misleading. Millidyne felt that there was a problem of how to assess the validity of the results.

Before beginning the assessment the company was interested and curious about what information this kind of analysis could tell them but they did not have any special expectations about the results. At some point they were hoping to be able to compare the assessment results of this particular product with their other products or other development versions of the same product but the inaccuracy of the results made this pointless. It seemed to them that the assessment results of all their products could fall in within the same inaccuracy range.

Millidyne did not consider doing any other type of environmental assessment at this time even though the customer would have originally wanted them to conduct a full LCA study. The company saw that an LCA would not have been a reasonable approach for one single product. There was not such an achievable benefit to be seen that would have justified all the effort and costs of such a process. LCA is after all a very time-consuming process. Therefore Millidyne wanted to have a cheaper and easier first contact to environmental assessments and in the end also the customer agreed to a carbon footprint assessment.

Carbon footprint was chosen of all the methods because the company knew that manufacturing of their products consumes quite much energy. Also the products are organic chemicals in type and there are some organic compounds evaporating from them. The customer who requested the environmental assessment had good understanding of carbon footprint and that also affected the choice. Millidyne itself did not know much about the subject beforehand.

After conducting their own study and getting uncertain results the company became sceptical also about the carbon footprint assessments that others have done. With their own experiences they started wondering if also others have equally uncertain results and whether any positive messages are barely marketing talk.

The usual places to use the results of these kind of assessments are marketing and product development. Millidyne has not used their results in these or any other ways except for delivering the results to the customer. They have thought about using the carbon footprint in their marketing materials but they also recognize that using an unreliable result publicly may turn out negatively if somebody questions their result.

The company also sees that carbon footprint and other environmental assessments could be an integral part of product development if the tools to conduct this kind of assessments were reliable and easy to use. With proper tools the R&D personnel could make informed decisions when choosing materials or processes, and thus environmental aspects could become a directive force in product development. Millidyne looked into if services related to this could be bought from Finland, Sweden, or the UK but they found that the costs would have been unsustainable high. Their materials are so atypical that a lot of base data is missing or it is difficult to interpret and therefore a lot of analytical would be needed which results in high costs. However, the company stresses that if good quality data and easy-to-use tools were available they would be very interested in using them as a part of product development.

How

Millidyne started the assessment process first by looking for a consultant who could have done it for them. The customer who demanded the assessment was able to help here and gave some contacts. The company found that there were not that many players in Finland who could have been seriously considered. The organizations that Millidyne was considering were at least VTT, Apila Group, and Bionova. None of these were suitable because of either high costs or long delivery times. Therefore they decided to do the assessment themselves. As a positive side to this they saw that anyway somebody in the organization would have needed to get deeply involved in the assessment by providing all the necessary data, and now this way they could develop their in-house knowledge of the subject better.

Millidyne conducted the carbon footprint analysis on their own without external help using the assessment program Simapro. A Simapro version aimed specially at carbon footprint assessment was used. The assessment was done by a product engineer using about one person-month. According to Millidyne's experience no special environmental training or education is needed from the person conducting the assessment. However, the company feels that prior experience of the assessment tools and local regulations and legislation would make it easier to start an assessment.

After setting up the assessment project the next thing to do was to open up the recipe of the product. All the different raw material providers were looked up and contacted for any parameters related to carbon footprint. This phase of the assessment was described by the company as follows: "Some provided some information, some did not provide anything. We were calling people all over the world and noticed that these things are not really on top of companies priority lists." In addition to gathering the data themselves the company inspected the data libraries available with the assessment program.

The special properties of nanostructures in the product were not specifically considered.

However, the lack of good-quality data on the nanoscale raw materials resulted in the high error margins of the assessment results. They consider it important that the health and environmental impacts of nanostructures and products are studied. The company notified that they are not using actual nanoparticles in their products but only larger nanoscale structures and clusters. They see that the uncertain health and environmental effects of separate nanoparticles play some role in why they do not want to use them, but the main reason for not using them is still the problems with the processability of the particles.

The assessment ended up costing about 10 000 euros of which about 6000 euros was the licence for the assessment program Simapro and the rest was mainly personnel costs. Millidyne did not get any financial or know-how support from external parties for the assessment.

In future, Millidyne is going to keep following the situation surrounding the environmental assessments. They are hoping for simpler assessment tools that could be used to make the assessment in a day instead of a month. They say: "The program should work so that you just put in the CAS numbers (Chemical Abstracts Service registry numbers are unique numerical identifiers assigned to every chemical) and give their shares and then the program tells you the carbon footprint. It should be that easy."

5.3 Case 2: Vaisala

Who

Vaisala Oyj is a global leader in environmental and industrial measurement. They provide a large range of observation and measurement products and services for weather-related and industrial markets. Meteorological institutes, airports, and armed forces all over the world, among others, use Vaisala's products to measure for example humidity, pressure, temperature, and wind speed, and to measure and observe precipitation with weather radars. Energy and life science industries use Vaisala's products to monitor their processes. Vaisala has even gone extraterrestrial with its humidity and pressure sensors on Curiosity rover on Mars.

Vaisala was founded in 1936 when professor Vilho Väisälä first started commercial production of radiosondes to be used with weather balloons in atmospheric weather measurements. The company is listed in Helsinki stock exchange and employs 1400 people worldwide. Turnover of the company was about 290 million euros with a profit of about 30 million euros in 2012. [54]

What

Vaisala has done three full LCA studies on three different products. These were done in 2002, 2007, and 2012. The first two assessments were made for products that were already on the market and the latest assessment was done in product development stage. The studies considered a dozen different impact categories, e.g. global warming potential, acidification, and human toxicity potential.

The 2002 study was revised and used when further developing the product in question. For example, when choosing a new casing for the device the environmental impacts of the different options were assessed and when they were developing the battery solution of the device they especially compared and looked at the ecotoxicity results. Based on the study Vaisala has expanded their battery options from alkaline batteries to more environmentally friendly lithium batteries.

The three studies have been individual ones, and they have been based on projects or needs of that moment. The company does not yet have a systematic practice to do environmental life cycle assessments on their products.

Why

At the same time when doing the first LCA study in 2002, Vaisala was receiving the ISO 14001 environmental management certification. The company wanted to take ”design for environment” (DfE) thinking, environmentally-friendly product development, into practice and the LCA project was a kick-off for that.

The assessments have been used to identify ”hot spots”, that is, issues or features that could then be improved in the next product version. It has also been important to learn if the choices, for example with the different casing options, have any significant environmental impact, or is it irrelevant which option is chosen. In addition, when the company has conducted such studies the personnel and especially project managers have learned a lot about taking the environmental aspects into account in product development.

The latest assessment in 2012 was done purely to improve the eco-efficiency of the product and to be able to communicate the properties of the product better to customers. The company wanted to know which stage of the product life cycle affects the most to the environment. In electronics industry the supply chains are long so Vaisala was interested if that is the hot spot that should be improved, or are the hot spots more related to the used materials or production methods. As the assessment was done with a product development orientation, the R&D personnel were especially interested in learning what are the parts of the product that should be focused on.

Vaisala is receiving questions about the environmental aspects of their products but actual demands for environmental life cycle assessments are still scarce. However, they feel that regulation and legislation, and people’s interests, require that companies should be more and more aware and informed about the environmental impacts of their products. They see that it is quite natural to start making environmental assessments because they are a good way to communicate that they know their products’ environmental impacts and how to further improve the impacts in the next product version. The assessments give concrete answers to customers’ questions.

Regarding the 2012 assessment, Vaisala did not even consider doing anything less than a full LCA study. The company already had some prior knowledge of the environmental aspects of the product in question and therefore they wanted to extend their knowledge to the whole product during its entire life cycle. A simple carbon footprint, for example, would not have sufficed because the company wanted something more precise and informative so that the information is more useful in product development. They also felt that once you start the assessment and begin collecting data you may as well gather all the data and make a full LCA out of that.

All the assessments at Vaisala have originated from the needs in product development. The development personnel have always been involved in the studies and the driving force has been the desire to make the next product version better than the previous one. The studies have not been used in pure marketing purposes but the results have been used to answers customers' questions.

Vaisala has a large range of different products and some thought has been given to which products to assess. The company has considered which are the products they want to focus on, have the largest production volumes, and might have the largest environmental impacts.

How

The first two LCA studies were joint projects with Tampere University of Technology (TUT) with several people from both Vaisala and TUT working together. TUT has been the party responsible for the actual assessment and calculations while Vaisala has been mainly providing data about the contents of the products and logistics chains, for example. At the time Vaisala did not have so much know-how and resources to do the assessments themselves so they outsourced the analytical work to TUT.

Assessment program Gabi was used to conduct the studies. When all the different material and energy inputs and outputs are entered to the program it gives the results in a dozen different impact categories.

In the latest 2012 study Vaisala took a bigger role and the process was organized and coordinated by an environmental engineer at Vaisala. The possible collaborators in this study are classified.

The company started the 2012 assessment by first thinking what they want to measure and why, determining the scope of the study. Next they considered what data they can obtain and how. The third step was to revise the scope based on what data can be obtained and what can not. They ended up wanting to have extensive assessment in a way that the results could also be used to communicate about the product to customers.

Vaisala uses nanotechnology in different sensors which are then used in almost all of their products. In the LCA study they did not pay much attention to any special properties of the nanomaterials. They see that the sensors are such a small part of the whole product that their environmental impacts disappear when looking at the bigger picture. They say that of course all the manufacturing processes, and the materials and energy used and pollution created in them, are accounted for but no special emphasis has been put on nanotechnology.

Vaisala experienced some difficulties in getting reliable data for the assessment. Some of the materials of the product and their properties were not listed in the databases provided with the assessment program. In that kind of cases they had to make educated guesses by looking at the values of another similar materials and then making estimations. The error caused by such estimations was analyzed by removing the particular component from the complete model, or by changing the estimated values, and looking at how the final results changed because of this. Usually they noticed that this kind of estimations had negligible effect on the final results. The company stressed that it is nevertheless important to include all the components in the assessment and to try to avoid doing too many educated guesses.

In addition to the lack of data, also the complex supply chains with large number of different components and materials from suppliers all over the world was difficult, or at least laborious, to handle. Further complexity came from the fact that Vaisala has many suppliers supplying the same or similar components for the same function, and therefore the components can change for the same product between the production batches.

Each of the assessments at Vaisala has taken a few months to complete. Typically there has been one person coordinating the process and several other people in smaller roles providing the data. Vaisala could not comment on how much their assessments have ended up costing but they say that the costs consists of personnel expenses, program and database licences, and external consultants.

Vaisala sees that in the assessment team there should be at least one person who has some initial knowledge and prior experience of the subject. The subject is so large that without any initial knowledge it is quite difficult to start an LCA process. However, the company does not think that the person responsible for an assessment should have a special education in the area.

In the 2012 study the project coordinator, an environmental engineer, had some theoretical background in the area through a university-level course on the subject. Regardless, it took him quite some time to learn the assessment process in practice. Sources used for learning in this case include published university theses and books, for example Cradle to Cradle by Michael Braungart and William McDonough, and LCA: A Practical Guide for Students, Designers and Business Managers by Joost G. Vogtländer.

There is a strong belief at Vaisala that they will continue making environmental assessments also in future.

5.4 Case 3: UPM

Who

UPM-Kymmene Corporation is one of world's largest forest industry companies. UPM's products range from pulp and paper to timber, plywood and wood and plastic composites, and they are moving towards the newer generation products like fibrous cellulose and biochemicals.

UPM employes about 22 000 people in 17 different countries. In 2012, the company's turnover was about 10 440 million euros and the company made a profit of about 530 million euros. [55]

What

Environmental responsibility has been a big part of UPM's operations for a long time. However, for a long time it had mostly been focused on production phase and less on product design. The company had been focusing on minimizing the impact on the environment at the pulp, paper, plywood and saw mills by concentrating very much on production and wood sourcing efficiency. They had not spent so much time optimizing logistics chains beyond the factory, the impact of the product chain in use, the products' lifetime, or the selection of raw materials.

Three years ago UPM reorganized their environment team and redefined their strategy and focus areas. One of those areas was to apply ecodesign to each of their products. They wanted to understand the environmental impacts of their products by using life cycle assessment. They wanted to look at the whole value chain that they could influence and identify the hotspots and value creation points in there in order to focus their efforts.

Nowadays LCA helps UPM to identify the hotspots for label and new products. For example, in label products the LCA shows that the biggest impacts in the life cycles of their products are caused by raw material choices and the end-of-life scenarios related to them. Energy, waste, and water use in production cause less than 20 percent of the impacts and about 65 percent of the impact comes from the raw material choices. The company has acknowledged that they should focus on the raw materials but there is work to be done in cooperation with the sourcing team. Huge majority of their environmental managers are still working on factory side and in the forest to minimize impacts on soil, water, air and biodiversity during the manufacturing processes.

Once the company knows their hotspots they try to use ecodesign to minize the specific impacts in different areas. The work also requires collaborating with customers, end-users, and even beyond that to the end-of-life parts of the chain.

When developing new products such as nanocellulose, UPM is taking the environmental impacts into account already in the product development stage. With nanocellulose they have been gathering environmental impact and risk assessment data from what they know from existing pulp processes and from test facilities in Otaniemi, Espoo. The company acknowledges that there are a lot of assumptions in the data based on the present facilities but it is important for them to understand the main environmental impacts and risks even before starting actual production. They have been estimating, for example, the impact on waste water, emissions to air, waste itself, energy consumption, and the impact of logistics from inbound raw materials and outgoing products.

Nanocellulose production will likely happen as an addition to an existing pulp production process and therefore the additional environmental impacts on soil, water and air are expected to be minimal, especially when compared to existing permit limits. The least known topic under discussion, especially among the authorities, is the potential impact on health. UPM does studies with various organizations also on that to make sure that their products are safe. The environmental research and data gathering supports also that work.

Even though UPM is applying ecodesign already in the research and product development stages they do not do actual LCA, carbon or water footprint, or other such assessments before they have scaled the production to commercial quantities. This is because LCA and carbon and water footprints are expensive and are done according to the needs of product related legislation, product marketing or when the production of new products are scaled up to commercial quantities. Thus, they have not done actual assessments on fibrious cellulose yet. Actually the only products that they do full LCA on at the moment are their label products and biocomposite products because in those markets LCAs are looked at. In addition they have carbon and water footprints available for paper products, plywoods, timber, label, and wood-plastic composites.

Why

UPM says that even though the company culture and demands from customers are relevant to why to do environmental assessments, the biggest driver for these assessments is legislation. Legislation demands certain environmental information and in future that will become even more so. The standardization processes in Europe are ongoing right now so that, for example, to be able to sell plywood in Europe very soon the seller will need to have LCA-level data of the product.

The company sees that the biggest possible driver beyond legislation is actually potential for operational cost savings or value creation in the market. They can identify, for example, the hotspots where they can potentially reduce cost in terms of raw materials, energy efficiency, and logistics. If environmental hotspots appear they quite often match the areas where the highest cost is and therefore the company has an opportunity there to push cost efficiency in the business through product and process development. In the market, the LCA may identify opportunities beyond the factory gate which offer competitive advantage.

Ultimately UPM wants to influence product development already when developing a new concept so that they have a more sustainable product. However, there are so many unknowns in the early development stage that UPM wants to influence hotspot in different parts throughout the whole life cycle instead of just focusing on early product development. Nanocellulose is a good example of this. It is very difficult to quantify what the potential environmental impacts will be before there is a commercialized product. At this stage the company knows what the production facility is going to be like, where it might be, what are the requirements on the environmental permit, and how the product is going to delivered logistically so these are the viewpoints that they have started working on and the rest will follow as the commercialization process proceeds.

Customer demand is not yet so high for LCA but UPM believes that the demand will increase in future. The demand for carbon footprint on the other hand has already been high and growing. Water footprint is less demanded even though that is something that UPM has to offer.

Other reasons to put efforts on environmental assessments at UPM are finding a market advantage when selling and marketing products, branding themselves as UPM the Biofore company, and maintaining the strong reputation in the market for environmental responsibility as there are competitors in the same field.

How

UPM is mostly using external consultants to do the environmental assessments. Normally paper or pulp business is about one or two products and it does not make sense for that particular business to buy an LCA tool, keep it updated, and have an extra employee just to manage that. UPM's label business is different because in there the company has about 4000 different products. Therefore they have a dedicated person in the label division who takes care of the environmental assessments. At the head office level the company has only two LCA experts but all of their environment managers have to have some basic understanding and knowledge about the subject.

The company is doing their own tests and recording data from their test facilities. They acknowledge that there could be large uncertainty ranges with novel nanomaterials and their unknown properties but so far they have observed that the environmental impacts of nanocellulose can not be distinguished from the impacts of an existing pulp mill and therefore nanocellulose does not give them cause for concern. UPM has a firm confidence in their environmental impact measurements because they feel that the impacts are relatively easy to record and measure as they have such a long history doing that. They feel that there are greater uncertainties on the potential risk to health.

The normal time to finish an environmental assessment for a new UPM product is about three months. That requires that they have enough basic raw data. With existing products slight improvements can be modified to the environmental models within a day. For example, the LCA tool that they use in label business has the basic data in there and making a new calculation requires only changing whatever needs to be changed in the calculation model and then pressing the button.

The company says that the cost of making an environmental assessment varies between different products and consultants but for simple processes the range can be from ten to twenty thousand euros.

UPM sees that if a small or medium-sized enterprise (SME) is interested in improving their environmental responsibility and making environmental assessments for their products or operations the company should start by employing someone with a background in environmental issues. The person does not have to be there 100 percent for the environmental work but it is important to have someone with the right mindset inside the organization. If an SME can not do that, then they should use a reputable consultant who will be able to provide the support that is needed. However, if the company is already considering these things then the chance are that they are going to have to employ somebody anyway at some point. UPM's advice is to look at having the expertise within one's own organization so that the person knows well the production processes, the product, and also how it is used and disposed of at end of life.

If an SME wants to understand the potential environmental impact of its operations and products then it is possible just look at a basic very simple ecodesign approach where the value chain is broken down and the environmental impacts in different stages are tried to be understood. Even an non-expert could make estimations whether the raw materials are sustainably sourced or not, how is the production efficiency, and whether the company is using energy based on fossil fuels or renewable sources. Yet another thing to consider is the logistics. For example, is the company using an old truck, a new truck, and are they using route optimization. With a very basic ecodesign approach SMEs can do a preliminary assessment of their environmental impacts and catch the low-hanging fruits. From there they can proceed to carbon and water footprints and eventually to a full LCA if they can get a return on that from the market.

Even though all UPM factories have somebody responsible for environment, only in a small portion of the factories there is somebody who is trained and knowledgeable as an expert in environmental impact assessment. In many factories environmental responsibilities are combined with quality and safety issues. The company says that the key for environmental management in these factories is that the responsible person has had some very basic training, for example, just even simple ISO 14001 environmental management training. Sending the designated environmental person to that kind of course gives them a very basic knowledge but at least it gets them to understand the requirements of environmental legislation, policies, stance on environmental impacts and aspects, how to minimize those, and how to do environmental audits. With this basic training a person can get enough knowledge to be able to at least look at the value chain, to take the ecodesign approach to use, and understand where the hotspots and low-hanging fruits are. This kind of approach may also suit SMEs.

Future

UPM will continue being active in environmental aspects. They believe that there will an increasing requirement of legislation both in Europe, Americas, and even in Asia. Also investors, customers and other stakeholders are increasingly valuing environmental performance.

While they will not be doing any less than they are doing today, the company's focus might change. For the last ten years one of the biggest things that UPM has been focusing on is production. Now they are turning their focus on other parts of the life cycle and product safety through, for example, what is the potential impact of the chemicals which are in the products. It is not enough anymore to manage the chemical content based on the legislative requirements because society is increasingly more aware on the subject. The issue of public health is increasing and with nanocellulose that is exactly the issue. The issue is not about where the pulp is coming from, whether it is coming from Russia, Canada, or a tropical forest. The issue is actually the health concerns and that is replicated across all the product groups.

In future, UPM is also hoping to have a greater role in their products' life cycle. Taking plywood as an example, one of the things they would like to develop is a system whereby they could sell the plywood but then collect it back at the end of use. Construction and waste management companies could provide the material back to UPM who would then have the material further processed or recovered for energy.

6 Discussion

6.1 Company Questionnaire

The company questionnaire showed that only 13 % of nanotechnology companies had done an environmental assessment with some type of life cycle method. However, the result is likely to be biased because the 29 companies, to which the questionnaire was sent, were hand-picked as the most likely nanotechnology companies that would have done environmental assessments. This was done to support the search for the interviewable companies. Therefore the actual percentage of nanotechnology companies that have done environmental assessments for their products with life cycle methods is probably even lower than the 13 % obtained in this study.

The most likely reason for such a small percentage is that the companies in this business area are typically small or medium-sized enterprises (SMEs). SMEs may often have issues to handle that they consider more pressing than environmental impacts. It may be that only when the company has grown so that they can employ and name a person responsible for environmental management that they really start paying attention also to their environmental impacts. This is supported by what UPM said in their interview about the importance of having environmental talent in the company.

6.2 Why to Measure Environmental Impacts with Life Cycle Methods?

Of the three interviewed case companies, Millidyne had done only carbon footprint analysis for one of their products. Vaisala had done LCA studies for a few different products and at UPM using LCA was already a common practice.

Millidyne reported that the reason to perform the carbon footprint analysis was the external pressure coming from a customer. The customer would have wanted first a full LCA study but after talking with Millidyne they settled for a carbon footprint. Millidyne said that they would not have done the environmental assessment without an external pressure.

At Vaisala the reason to begin environmental assessments was more of the internal type. After adopting their new environmental management system they wanted to bring the design for environment thinking into practice in product development. For this they needed information about their products' environmental impacts.

The main driver for UPM to do environmental assessments was legislation that requires information from the environmental impacts. The second most important reason for them was money because through energy and material efficiency they can reduce their costs.

Interestingly all three companies pointed out different reasons when asked for the drivers behind their environmental assessments. However, behind Vaisala's product development aims there might actually be a more fundamental reason such as a wish for cost reductions but this did not come up in the research. Overall, we can see that there is no single most important reason why a company would do this kind of assessments.

The reason for the varied drivers for environmental assessments may be in the different size of the interviewed companies and scale of their operations. Small companies like Millidyne may need the push from the customers to start making environmental assessments, whereas bigger companies like Vaisala are already implementing environmental management systems and gathering also environmental information for their product development. Large multinational corporations like UPM are optimizing their material and energy consumption in order to save money, and also in UPM's line of business international legislative requirements play their role. Further research would be needed in order to find out whether these points stand also for other similarly sized companies.

6.3 How to Measure Environmental Impacts?

Millidyne said that they chose carbon footprint of all the assessment methods because they have identified that their production is relatively energy intensive. Also the customer that requested the assessment had good understanding of carbon footprint and that also affected the decision.

Vaisala on the other hand did not even consider doing anything less than a full LCA study because the company wanted to use the information in product development and thus they needed more information than can be acquired with a carbon footprint.

Like Vaisala, also UPM reported that they are thriving to take the environmental impacts of the whole product life cycle into account already in the product development phase. This ecodesign approach is supported also by Lloyd who wrote in her Ph.D. thesis [26] that life cycle thinking should be applied already in the product and concept development stage. Nowadays life cycle assessment is typically used to estimate the resource and environmental impacts of existing products. 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. Sometimes it can be very difficult to make any changes at all.

UPM said that they do full LCAs only on their label products and carbon and water footprints on their paper, plywood and composite products. They said that in the label market LCA is really looked at. With the other product markets there is a high customer demand for carbon footprint so it has been measured.

It seems that at least Vaisala has understood that 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 such as carbon footprint used by Millidyne and UPM take into account only the shifting between different life cycle stages. LCA accounts also for the shifting between different types of environmental impacts.

We can see that there are different reasons for companies to choose what to measure and how to measure. These reasons can be the properties of the product and the production method (energy or water intensity for example), straight demands from customers, or the precision of data needed in product development.

From the practical point of view, Millidyne conducted the carbon footprint analysis on their own without external help. They said that a product engineer with no training or earlier experience on the matter had done the assessment in a month. They also felt that some prior experience and knowledge would have made the assessment easier.

Vaisala first collaborated with Tampere University of Technology so that the experts at the university led and made the assessment. However, recently Vaisala hired an in-house expert, an environmental engineer, to lead and organize the assessments. Vaisala sees that the responsible person for an environmental assessment does not have to have a special education in the area but at least one person in the assessment team should have some initial knowledge and earlier experience about the subject.

UPM mainly uses external consultants to do the assessments. However, there are designated persons in their organization who are responsible for environmental issues on top of their other work, and collaborate with the consultants. These key people are not experts in environmental impact assessment but they have taken some very basic training such as ISO 14001 environmental management training. This kind of training gives them the basic skills to be able to work in this area.

All in all, the three companies agreed that with some basic training a normal product engineer, for instance, could start making some basic environmental assessments. It does not take an environmental specialist and five years of university studies to make an environmental assessment.

6.4 The Nanotechnological Point of View in Environmental Assessments

All three interviewed companies said that the special properties of nanostructures in the products had not been specifically considered. This can be seen as nanotechnology being just another technology among all others. Nanotechnology has become a part of common everyday life and companies do not consider it anymore as something very special.

Millidyne said that the data libraries used by the assessment programs were hardly applicable and relevant to their raw materials. Thus the lack of good-quality data on the nanoscale raw materials resulted in the high error margins of the assessment results. Furthermore, Millidyne felt that there was a problem in quantifying the uncertainty and assessing the validity of the results.

UPM said that while they have observed very minimal impact from their nanocellulose production at least to waste water they are lacking information about the potential risk to health. UPM sees that more information is needed and they are working on that in collaboration with various different organizations.

These findings about using environmental assessment with nanoproducts are in correlation with the inhibiting barriers reported in literature [40]:

- Lack of reliable inventory data and data on impact relationships
- Lack of awareness of applying life cycle thinking in order to avoid the unintended shifting of environmental burdens
- Proprietary information on production methods and processes
- Absence of toxicological test results
- Wide process-to-process variation

6.5 Future

Millidyne pointed out the need for more reliable and easy-to-use environmental assessment tools that could be used as an integral part of product development. They said that with proper tools the R&D personnel could make informed decisions when choosing materials or processes, and thus environmental aspects could become a directive force in product development.

This need is not limited only to Millidyne or other small-sized companies. Also multinational telecommunications company Nokia Siemens Networks has announced that they would need more practical ecodesign tools that could be used in everyday product development [56].

Vaisala and UPM, and also Millidyne if provided good enough tools, were positive about environmental assessments and believed that they will continue or increase using them.

7 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 main findings of this research:

- Only 13 % of Finnish nanotechnology companies have done environmental assessments with life cycle methods.
- The main reasons to do environmental studies are customer demand, legislation, cost savings, and product development.
- Companies have chosen their assessment methods based on the properties of the product and the production method (energy or water intensity for example), straight demands from customers, and the precision of data needed in product development.
- With some basic training almost anyone in the organization could start making basic environmental assessments. No special university education is needed for that.
- The main problem with environmental assessments of nanoproducts and materials is the lack of inventory data and data on impact relationships.
- Uncertainty in environmental studies should be acknowledged and quantified.
- Further research is needed to collect missing data and to develop user-friendly assessment tools, especially ones that are suitable for small and medium-sized businesses.

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Appendices

A The company interview outline in Finnish

Haastattelurunko

Kuka

- mitä tekee
- liikevaihto
- kannattavuus
- henkilöstö
- milloin perustettu

Mitä

- onko elinkaariselvitys suunnitteilla vai toteutettu
- millainen selvitys
- onko selvityksen kohteena oleva tuote tuotannossa vai suunnitteluvaiheessa

Miksi

- Millaisessa tilanteessa / yrityksen kehitysvaiheessa ajatus selvityksen tekemisestä syntyi?
- Miksi teitte selvityksen?
- Kuinka valitsitte mitä haluatte mitata?
- Koitteko ulkoisia paineita, jotka ajoivat selvityksen tekoon?
- Mitä odotitte selvitykseltä?
- Kuinka valitsitte käyttämänne menetelmän?
- Mitä muita menetelmiä harkitsitte?
- Miksi ne eivät olleet sopivia?
- Kuinka olette käyttäneet saatuja tuloksia?
- Oletteko hyödyntäneet tuloksia markkinoinnissa?
- Entä tuotesuunnittelussa?

Miten

- kuka: itse / konsultti
- kuinka lähditte liikkeelle
- oliko helppo löytää tietoa aiheesta ja mistä sitä löytyi

- kuinka selvitys tapahtui
- Kuinka nanohiukkasten huonosti tunnetut ympäristövaikutukset vaikuttivat selvitykseen?
- paljonko meni aikaa
- paljonko aiheutui kuluja
- Saitteko rahallista tai tiedollista tukea ja apua joltakin ulkopuoliselta taholta?
- Millainen henkilö on oikea johtamaan selvityksen tekoa?

Tulevaisuus?