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The importance of life cycle concepts for the development of safe nanoproducts

Claudia Som[a,*], Markus Berges[b], Qasim Chaudhry[c], Maria Dusinska[d], Teresa F. Fernandes[e], Stig I. Olsen[f], Bernd Nowack[a]

[a] *Empa, Swiss Federal Laboratories for Materials Testing and Research, Technology and Society Laboratory, Lerchenfeldstrasse 5, CH-9014 St. Gallen, Switzerland*
[b] *BGIA, Institute for Occupational Safety and Health, D-53754 Sankt Augustin, Germany*
[c] *Central Science Laboratory, Sand Hutton, York, United Kingdom*
[d] *Norwegian Institute for Air Research, 2027 Kjeller, Norway*
[e] *School of Life Sciences, Edinburgh Napier University, Edinburgh, United Kingdom*
[f] *Technical University of Denmark, Department of Management Engineering (DTU-MAN), 2800 Lyngby, Denmark*

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ABSTRACT

Whilst the global players in industry are rapidly moving forward to take advantage of the new opportunities and prospects offered by nanotechnologies, it is imperative that such developments take place in a safe and sustainable manner. The increasing use of engineered nanomaterials (ENMs) in consumer products has raised certain concerns over their safety to human health and the environment. There are currently a number of major uncertainties and knowledge gaps in regard to behavior, chemical and biological interactions and toxicological properties of ENMs. As dealing with these uncertainties will require the generation of new basic knowledge, it is unlikely that they will be resolved in the immediate future. One has to consider the whole life cycle of nanoproducts to ensure that possible impacts can be systematically discovered. For example, life cycle assessment (LCA) – a formalized life cycle concept – may be used to assess the relative environmental sustainability performance of nanoproducts in comparison with their conventional equivalents. Other less formalized life cycle concepts in the framework of prospective technology assessment may uncover further detailed and prospective knowledge for human and environmental exposure to ENMs during the life cycle of nanoproducts. They systematically reveal impacts such as cross product contamination or dissipation of scarce materials among others. The combination of different life cycle concepts with the evolving knowledge from toxicology and risk assessment can mitigate uncertainties and can provide an early basis for informed decision making by the industry and regulators.

1. Introduction

The advent of nanotechnology has unleashed enormous potential for the development of new products and applications in a number of industrial and consumer sectors. This trend is driven by the promise that nanotechnologies can offer improved performance and new functionalities as well as a reduction in the use of hazardous chemical substances, the consumption of energy and materials, and the generation of waste, thus increasing profitability. Such benefits, and the prospects for a wide range of novel applications, have made nanotechnology regarded as the hotbed of a new industrial revolution (BMU, 2008). There is also some skepticism over whether these high expectations can actually be achieved. For example, Fiedeler (2008), p. 313) does not agree with the conclusion “that nanotechnologies can contribute in an exceptional manner to a large increase in substitution of hazardous substances”.

The Woodrow Wilson Database (Woodrow Wilson International Centre for Scholars, 2008) on currently available consumer products indicates that the largest number of nanotechnology products (over 60%) belong to the health and fitness sector, which includes cosmetics and personal care products. This is followed by other applications including paints and coatings, electronics, food and food packaging. The data need to be used with caution, as the database suffers from the problem of insufficient available information. One difficulty is the scarcity of detailed information on the scale of commercial activity in this area. It is possible that at least some of the products claimed to have been derived from nanotechnology may in fact not be so, whilst other products may contain a nano-component, which is not declared as such (Dekkers et al., 2007; Som et al., 2009). There is currently no obligation under the existing legislation for companies to label their products as having nano-components.

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[*] Corresponding author. Tel.: +41 71 274 78 43.
E-mail address: claudia.som@empa.ch (C. Som).

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The rapid technological development has also raised certain concerns over the health and environmental safety of ENMs used in consumer products. The main concerns relate to those products and applications that can lead to exposure to free ENMs. Currently, there are a number of major knowledge gaps in regard to the health and environmental effects posed by ENMs (Borm et al., 2006; Chaudhry et al., 2008; Handy et al., 2008; Klaine et al., 2008; Maynard et al., 2006; Nowack and Bucheli, 2007; Oberdörster et al., 2007; Wiesner et al., 2009). Rapid developments in the area of nanotechnologies have also raised questions over the applicability and adequacy of the current risk assessment (RA) paradigm and regulatory frameworks, in relation to the assessment and control of risks from the products and applications of nanotechnology. In the absence of a nano-specific regulation in the EU (Chaudhry et al., 2007; Führ et al., 2007) or elsewhere in the world (Hodge et al., 2007), the existing policies are based on conventional chemical substances and do not take into consideration the special physicochemical characteristics of ENMs (e.g. relevance of surface chemistry and structure of ENMs) (Breggin and Pendergrass, 2007; Chatterjee, 2008; Chaudhry et al., 2006; Franco et al., 2007). These major uncertainties over the effects and impacts of ENMs in relation to occupational and public health and the environment, are unlikely to be resolved in the short-term future and are impeding adjustment of regulation to ENMs.

As the negative effects and impacts of a number of previous technologies came to light only several years after the introduction of the technologies (EEA, 2001; Koehler and Som, 2008; Renn, 2002; Som et al., 2004), it is imperative that issues arising from nanotechnologies are addressed in a holistic manner, and as early as possible. A holistic view is necessary as potential side effects of new technology can be very easily overlooked if not all life stages of a product are considered. Although the knowledge available in the early stages of a technology development is usually limited and uncertain, the scope for influencing the development trajectories is substantial (Collingridge, 1980; Von Gleich, 2004). Davis (2007) has proposed using a comprehensive approach for new technologies, which combines a product life cycle perspective with the risk assessment paradigm.

The risk is determined by the effects of ENMs and by the exposure to ENMs. The effects of ENMs may embrace several types of effects such as (eco)toxicological effects, accumulation effects or carrier effects on pollutants in the environmental compartments. The level of current uncertainties over the effects of ENMs on human health and the environment necessitates a comprehensive risk assessment, taking into account all the potential exposure situations to ENMs that might arise throughout the life cycle of a ENMs or an ENM-containing product (Ostertag and Husing, 2008). This is where life cycle concepts can play a crucial role in dealing with the uncertainties encountered in relation to the effects of ENMs. Thus, a combination of life cycle concepts and the current evolving knowledge on effects of ENMs on human health and the environment could provide a basis for an adaptive risk assessment and informed decision making by industry and regulators at an early stage of the technology development to foster safe and also environmentally sustainable nanoproducts (Davis, 2007; Klöpffer et al., 2007; Shatkin, 2008; Wardak et al., 2008).

In this paper we aim to illustrate the interrelation between toxicology as part of risk assessment (RA) and the different life cycle concepts. The paper makes explicit what sort of questions can be answered by risk assessment methods and by the different life cycle concepts. The paper provides some insight into the state of the art regarding exposure to ENMs. Finally, we discuss why the combination of toxicology and life cycle concepts is valuable to mitigate the situation of having only limited information on the effects of ENMs.

2. Definitions

In an interdisciplinary framework, definitions are especially important. Analyzing the literature for different disciplines reveals that terms such as “engineered nanoparticles (ENPs)”, “engineered nanomaterials (ENMs)” and “nanoproducts” are not used in a uniform manner. This is caused by the novelty and the great interdisciplinarity of the field of nanotechnologies.

2.1. Engineered nanomaterials

In the literature published in areas related to nanotechnology and nanoscience, the term “nanomaterial” is often used as a collective term for any discrete piece of material with one or more external dimensions in the nanoscale, i.e. equal to or below 100 nm. SCENIHR (2007b) proposes that a “nanoparticle” is a discrete entity which has three dimensions of the order of 100 nm or less. The ISO technical committee 229 (ISO, 2008) also proposes to apply the term “nanoparticle” only to materials with all three external dimensions on the nanoscale. Consequently, carbon nanotubes (CNT), nanofibres, nanowires and nanoplates or nanosheets that have only two or one external dimensions in the nanoscale are no longer called “nanoparticles”. ISO (2008) proposes the term “nano-object” as a collective term for discrete pieces of material with at least one external dimension on the nanoscale. SCENIHR (2007b) proposes the collective term “nanomaterial” for “nano-objects” and “nanostructured material”. As we expect the reader to be unfamiliar with the collective term “nano-object”, we have used the frequently applied term “engineered nanomaterials (ENMs)” in this paper as a collective term for all discrete pieces of material that have one or more external dimensions on the nanoscale, even if this is not consistent with SCENIHR. The nanoscale range is between 1 and 100 nanometers (nm), but this does not imply that particles having larger or smaller dimensions might not be of significance from a health or environmental point of view (BSI, 2007b; Höck et al., 2008).

2.2. Nanostructured materials and nanoproducts

Nanostructured materials may be composed of discrete functional materials with one or more external dimensions on the nanoscale (e.g. polymer composites that contain ENMs, aggregates or agglomerates of ENMs). From this point of view, micrometer sized particles composed of aggregated or agglomerated ENMs can also be regarded as nanostructured materials. On the other hand, nanostructured materials may not contain ENMs at all (e.g. nanoporous polymers and nm-thin coatings) (Hansen et al., 2007).

We define “nanoproducts” as commercial products that either contain ENMs, or that derive specific functions from nanostructured materials with or without ENMs. Examples of nanoproducts are for example textiles containing nano-silver, sunscreens with nano-TiO_2, batteries containing CNTs or windows coated with a nm-thin layer of TiO_2. The focus of the risk assessment, however, rests on ENMs. Thus, in this paper we address mainly the risks of ENMs and nanoproducts containing ENMs. It is not investigated yet if nanoscale particles can be released by ENM-free nanostructures such as nm-thin coatings. The impacts of these unintentionally made nanoscale particles seem to have not been investigated at all so far.

3. The different meanings of the term “life cycle”

The term “life cycle” is generally understood as the life-span covering production, use and disposal of a material/chemical or

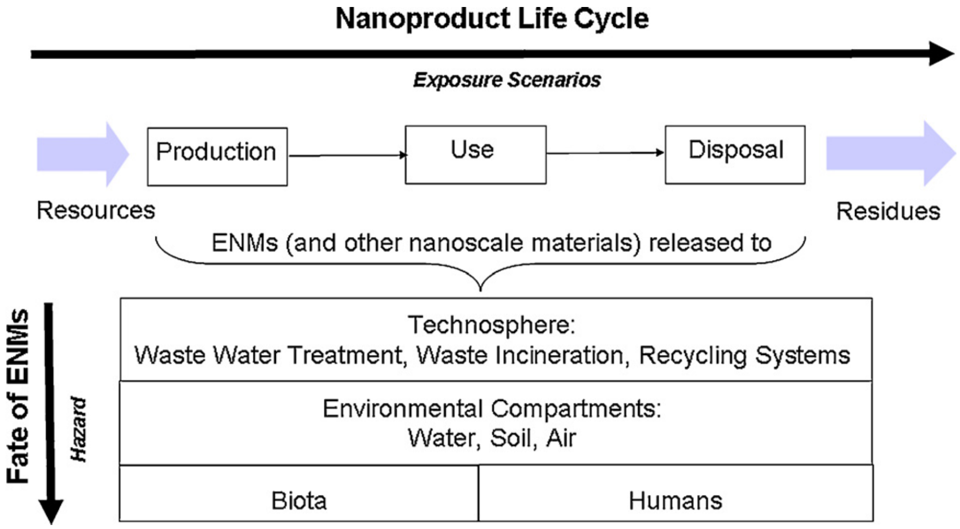

Fig. 1. Simplified stages of the nanoproduct life cycle and the fate of ENMs.

a product (Fig. 1), although biologists may understand the term differently. There may be a difference in how the "life cycle" is perceived within different areas of expertise depending on the interpretation of the term (Christensen and Olsen, 2004).

The term "life cycle" can be used for both nanoproducts and ENMs (Fig. 2). This ambiguity needs clarification. A given ENM (e.g. TiO_2) can form part of numerous nanomaterials (such as polymer-ENM-composites, e.g. polyamid-TiO_2-composite). Similarly, a given nanomaterial can form part of numerous products (e.g. a T-shirt, food packaging, etc.). Consequently, the use stage and end-of-life stage of the "life cycles" of ENMs depend on the life cycles of the specific products they are used for, of which there may be many for any given ENM.

4. Scope and value of life cycle concepts

Considering the fact that the life cycles of ENMs are determined by their application within nanoproducts, it becomes clear that the exposure scenarios and potential adverse effects, as well as opportunities for novel applications, are strongly dependent on the life cycle of nanoproducts that contain ENMs.

The terms "life cycle concepts", "life cycle thinking", "life cycle considerations", "life cycle approach", and "life cycle perspective" embrace methods that take into consideration the life cycle of products, such as life cycle assessment (LCA, ISO 14040 series), design for environment, eco-design, life cycle management, life cycle costing, material flow analysis, product road-mapping, prospective technology analysis methods, value chain analysis, and many others (Davis, 2007). All these methods consider the stages of a nanoproduct life cycle such as the production of ENMs, transport to a manufacturer (and any subsequent transportation), manufacture of ENMs-containing product(s), use of the product(s), recycling and final disposal of the product(s).

Depending on the aim of the study, an appropriate life cycle method and scope have to be chosen. Most of the methods consider all stages of a nanoproduct life cycle, or focus on specific parts of the life cycle. Some methods focus on the environmental health effects of ENMs only, whereas for example life cycle assessment (LCA) focuses on environmental health impacts of all other materials in a nanoproduct also, and on environmental sustainability effects such as e.g. energy and material consumption.

4.1. Life cycle assessment (LCA)

In the context of assessing the potential risks of ENMs, sometimes the use of "life cycle assessment" has been suggested to represent a holistic view on the impacts of ENMs. The term "life cycle assessment" is, however, misunderstood as equivalent to life cycle concepts. The wording "life cycle assessment" stands exclusively for a clearly defined methodological framework that was developed in the early 1990s as reported e.g. in the ISO 14040/14044 standards (ISO, 2006a,b). An LCA comprises four main steps: goal and scope definition, inventory analysis, impact assessment and interpretation.

LCA is essentially a comprehensive tool for environmental sustainability assessment. In theory, it takes into account all inputs (i.e. materials, energy, chemicals, land use, etc.) and all outputs (i.e. emissions, solid waste, products, etc.) throughout the life cycle of a product – from the extraction of the resources to the final disposal of the product. LCA evaluates thereby the overall impacts of a product system on the natural environment, human health, natural resources, and the man-made environment (Udo de Haes and Lindeijer, 2002). The main contribution of LCA is often in terms of impact categories such as resource use, global warming, acidification, ecotoxicity, human welfare and other. Whereas risk assessment of ENMs focuses on the toxic impacts of ENMs, LCA provides a more comprehensive overview of the potential environmental impacts of nanoproducts, including all other substances used during manufacturing of the product (Table 1). In addition applying LCA may avoid the unintended shifting of environmental burdens (Klöpffer et al., 2007).

LCA is a powerful tool for comparing different options/products with respect to their potential impacts on the environment, and to identify the critical points within the product life cycle that contribute most to these impacts (Klöpffer et al., 2007). LCA can be used for comparing a product that includes ENMs with similar products without ENMs, and thus to assess the relative environmental performance of nanoproducts in comparison with their conventional equivalents. The potential added benefits of the use of ENMs may be reflected, for example, in the form of differences in the energy consumption for production of materials or products (Khanna et al., 2008; Kushnir and Sanden, 2008), or in the potential use of scarce resources in the production processes. Thereby LCA may also quantify the expected positive potentials of nanoproducts for

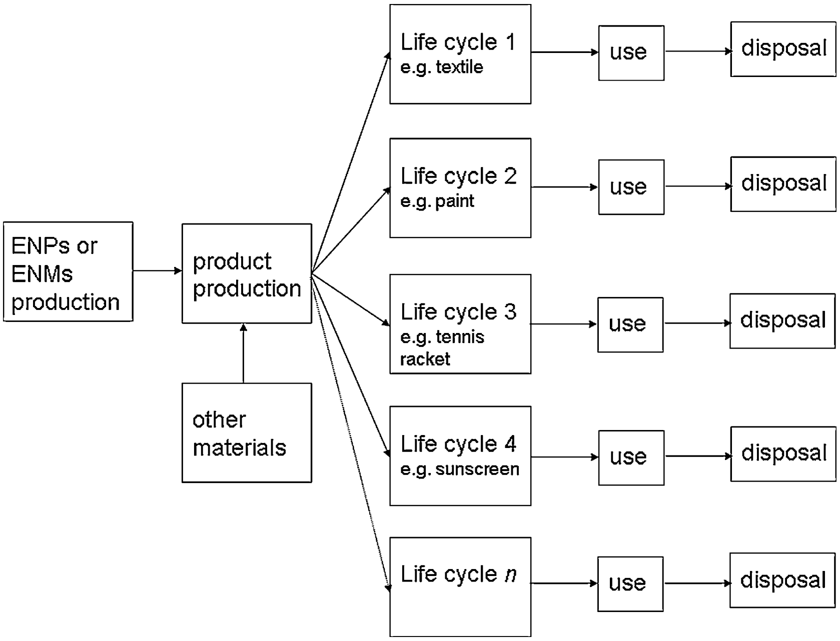

Fig. 2. The cycles for ENMs are determined by the life cycles of the nanoproducts.

the substitution of hazardous chemicals, the reduction in use of materials, and energy consumption, as well as waste reduction.

To date, however, only a few studies (less than 10) have been reported for nanoproducts, and only some of them have applied up-to-date data for the nanotechnological production methods (Bauer et al., 2008; Healy et al., 2008; Joshi, 2008; Khanna et al., 2008; Krishnan et al., 2008; Kushnir and Sanden, 2008; Lloyd and Lave, 2003; Lloyd et al., 2005). Furthermore, although aspects relating to (eco)toxicity are usually assessed in LCA, the specific potential impacts of ENMs have not been included in the studies done so far due to a lack of knowledge in relation to risk assessment (Bauer et al., 2008; Klöpffer et al., 2007).

Hence, there is an urgent need in obtaining datasets about the most important nanotechnological processes and publishing these datasets in well-known LCA databases (inventory analysis). In parallel, there is also the need to develop a methodological approach for the handling of the assessment of ENMs by identifying what needs to be measured as outputs, and how the impacts can be assessed in an impact assessment (Seager and Linkov, 2008). The latter needs to be done in continuous collaboration with toxicologists and other risk assessors (for example for ozone depletion and global warming), and whilst keeping track of the new knowledge that is likely to be generated in due course. So far, toxicological characterization factors for ENMs have not been defined yet, nor do toxicological models for ENMs exist in the life cycle impact assessment methodology. Despite the lack of toxicological characterization factors and toxicological models, LCA provides valuable insight into the relative environmental sustainability potential of nanoproducts in comparison to conventional products.

4.2. Other life cycle methods

Other life cycle methods used to analyze nanoproducts are not fully formalized, and are more qualitative in nature than LCA and more directed towards the specific risks of ENMs. These methods that like LCA may be part of prospective technology assessment (Fleischer and Grunwald, 2008; von Gleich et al., 2008) may generate detailed knowledge in relation to the design of nanoproducts and the potential human and environmental exposure to ENMs (Sweet and Strohm, 2006); for example, in what stage of the life cycle of a nanoproduct:

- ENMs could be released to which technosphere (e.g. wastewater treatment plant, landfill) or environmental compartment (exposure routes),
- humans could be exposed to ENMs and how ENMs could enter the body (dermal, oral, inhalation, injection, how they interact with cells, are transported through barriers, translocated, released),
- the nanoproduct is exposed to conditions that could cause the release of ENMs,
- ENMs could be released in what forms (e.g. as single ENMs, ENMs incorporated in nano- or micro-sized particles, pristine or transformed, or functionalized ENMs).

This information is key for the establishment of comprehensive exposure scenarios (Fig. 1), and thus may provide further relevant inputs for human and environmental risk assessment (and thus for the integration of nano-specific aspects into the assessment step in the LCA approach).

Furthermore, these methods may also consider, for example, the diffusion of present and future nanoproducts on the market and indicate other ENMs specific risks such as, for example:

- cross product contamination by ENMs,
- changed product recyclability of the ENM-containing nanoproducts,
- other important environmental impacts (e.g. caused by increased energy use for ENMs production, hazardous waste generation or the use of ancillary chemicals),
- hazardous byproducts,
- the risks of explosion and other incidents (Fig. 1).

From this information, advice may be deduced for the safe handling of ENMs and nanoproducts, and for the safe design of nanoproducts. The information obtained from such approaches will also in most cases be gathered as necessary inputs for the formalized LCA.

Table 1
The scope of life cycle concepts and risk assessment methods is roughly outlined by showing which relevant information for the development of safe nanoproducts is gained by the application of the different methods or concepts.

	Risk assessment				Life cycle concepts		
Methods provide information on:	Toxicology translocation	Ecotoxicology and environmental behavior	Monitoring	Exposure – effect studies, biomonitoring (incl. occupational health)[a]	Life cycle thinking in the framework of technology assessment, e.g. foresight, roadmapping etc.	Material flow analysis	LCA
Future nanoapplication and -products					×		(×)
Mode of ENMs integration into nanoproducts (e.g. amount and types of ENMs)					×		×
Release scenarios for ENMs from nanoproducts (product life cycle stage, compartment released to, quantities, "forms")			×	×	×	×	×
Exposure routes		×		×	×	×	
Quality of exposure: potential uptake paths (e.g. respiratory system, dermal, gut)	×	×			×		
Behavior of ENM in technosphere and environmental compartments		×	×	×			
Occupational health scenarios	×		×	×	×	×	
Consumer exposure scenarios	×		×	×	×	×	
Dose/response relationships for ENMs	×	×					
Bioavailability of ENMs	×	×					
Biopersistency of ENMs	×	×	×				
Degradation of ENMs in technosphere and environmental compartments under what conditions		×	×				
Relative impact of nanoproducts on human health and the environment	×	×		×			×
Environmental sustainability: opportunity for material and energy savings or risk for increased resource consumption							×

[a] Risk assessment methods, as well as life cycle methods contribute to exposure studies.

5. Potential release of and exposure to ENMs during different life cycle stages of a nanoproduct

5.1. Common issues

In all life stages, the assessment of the likelihood of human and environmental exposure is a key question to address and it is closely linked to the release potential of ENMs during different life stages. It is also important to know in what forms ENMs can be released (Koehler and Som, 2008), whether as (1) free ENMs, (2) in an aggregated or agglomerated form, or (3) integrated in an nm or micrometer (μm) sized material. The conditions under which ENMs can be released, in what amounts, and into which technosphere (e.g. air filter, waste water treatment plant, incineration), and environmental compartments, are questions that need to be answered for all life stages of a nanoproduct. The characteristics of ENMs formulations can change during their life cycle (e.g. because of physical/chemical interactions and changes) and the aging of the ENMs (Höck, 2008; SCENIHR, 2007a).

Two distinct, yet related exposure areas need to be further investigated: the occupational/consumer exposure, and the environmental exposure. In this context it is important to consider the quantity and quality of information available to workers and consumers throughout the life cycle of a nanoproduct, and if safety measures in place can afford appropriate protection. Whereas workers may be exposed to ENMs during the production, use or recycling of industrial nanoproducts, consumers may be exposed mainly during the use of consumer products. But sooner or later these ENMs are likely to enter the environment and thus assessing occupational and consumer exposure forms the basis for assessing the environmental exposure. Indirect exposure of humans to nanoparticles in the environment cannot be ignored. An example for such an indirect effect is the exposure of children to lead through uptake of soil and dust contaminated by lead-based paints falling off walls and facades (Mielke and Reagan, 1998).

Cross product contamination is an issue that has not yet received much attention, although it may be important for all stages of the life cycle (Koehler et al., 2008). The contamination of ENM-free products may take place during production, as well as during use: for example, washing of nano-textiles could contaminate other textiles. There is also a strong likelihood of contamination during recycling, e.g. from textiles being fed into the paper industry, and from nanotechnology-derived food packaging materials being fed into recycled packaging materials.

At the moment, the assessment of any potential release of ENMs is mainly qualitative due to the lack of analytical methods that could enable adequate monitoring of trace concentrations of ENMs under environmental conditions and distinguish between natural and engineered nanoparticles and between dissolved and the different forms of particulate metals (Tiede et al., 2008). Whereas sensitive methods to count nanoparticles in air are available, the methods normally do not distinguish between natural and engineered particles and are thus not specifically analyzing ENMs. The analytical methods that are needed thus have to be able to detect and quantify trace concentrations of ENMs within the background of natural nanoparticles. To date published reports about ENMs in the environment have used microscopic techniques or filtration/sedimentation based separation of ENMs (Kaegi et al., 2008; Kiser et al., 2009). In order to get an idea of the current environmental concentrations of ENMs, we thus have to use modeling approaches.

A recent study modeled the dissolved silver (Ag) emissions from nano-Ag containing biocidal products and compared the expected concentrations in the environment with those of reference emission (Blaser et al., 2008). The authors concluded that nano-Ag is only responsible for a small share of the total dissolved Ag flow in the environment, but did not consider any particulate emissions. Also (Luoma, 2008) estimated silver concentrations in the environment produced by nanoproducts and concluded that silver nanotechnologies will only marginally affect the silver concentrations in water.

Another study used a life cycle perspective to model the quantities of ENMs released into the environment (Mueller and Nowack, 2008). The ENMs nano-Ag, nano-TiO_2 and CNT were studied. The quantification was based on a substance flow analysis from products to air, soil and water in Switzerland. The life cycle of the nanoproducts formed the basis for assessing the mass flows of the ENMs from the products to the environment. The following parameters were used as model inputs: estimated worldwide production volume, allocation of the production volume to product categories, particle release from products and flow coefficients within the environmental compartments. The results of this study have made it possible for the first time to carry out a quantitative risk assessment of nanoparticles in the environment and suggest further detailed studies of nano-TiO_2.

A similar study has been done in the UK (Boxall et al., 2007), although with a different approach. Based on assumed market penetrations of nanoproducts and the known usage of these products, likely concentrations in water, air and soil were predicted through modeling. For the 10% market penetration model, which probably overestimates current exposure levels, concentrations of silver, aluminum oxide and fullerene were predicted to be in the ng/l in wastewaters, whereas nano-TiO_2, silica, ZnO and hydroxyapatite were predicted to be in the μg/L range. These estimates are, however, based on simple modeling parameters and do not take into account the persistence, concentration or accumulation of ENMs in the environment.

5.2. The product design stage

During the development of an innovative product, the information usually needed is whether there are any alternatives to ENMs to develop the product with a specific function or functionality. Such information is either scarcely available, or altogether lacking for the majority of industrial sectors. If the concepts of green chemistry are correctly applied to ENMs, then this should result in a reduction of waste, the design of safer products (of low or no toxicity), the use of renewable raw materials, safer solvents and reaction conditions, increased energy efficiency, and materials and products that degrade after use (Anastas and Warner, 2000). At this stage prospective life cycle studies could have a significant contribution to the product development (Som et al., 2009).

5.3. The production/integration of ENMs in end-products

The greatest likelihood of direct exposure to free ENMs is during manufacture, and a level of awareness to potential adverse effects exists in this regard (Helland et al., 2007; Maynard et al., 2004). Initial measurements undertaken at companies producing different ENMs indicate that worker exposure may occur, mainly during the production and handling of dry powders (Bello et al., 2008; Fujitani et al., 2008; Han et al., 2008; Mazzuckelli et al., 2007; Yeganeh et al., 2008). However, compared to the occurrence of ultrafine particles (UFP, <100 nm) at workplaces (Möhlmann, 2005), the total particle number concentrations of ENMs are significantly lower and mainly in the range of the ambient UFP number concentration.

A common denominator of these studies is the difficulty of distinguishing between ENMs and ultrafine particles in background air because the methods commonly used for analysis in air only count particles and do not specifically analyze ENMs. Therefore further analytical methods, e.g. imaging techniques such as scanning electron microscopy or transmission electron microscopy, with or without the combination of electron energy loss spectroscopy, have to be employed to identify the shape and chemical nature of the ENMs. Currently available data mostly relate to particle numbers only and little information on the identity of distinct ENMs is available. Current measurement methods for the detection of ENMs at the workplace generate virtually no information on the state of attachment of ENMs to larger dust particles.

The conventional engineering controls, especially those to reduce the concentration of dust at workplaces, used at the companies investigated have so far appeared to be effective against ENMs (Han et al., 2008; Yeganeh et al., 2008). This also appeared to be true for personal protective equipment (NanoSafe2, 2008; Riediger and Möhlmann, 2001). Gerritzen et al. (2006) addressed the current practices in the nanotechnology workplace and found that current safety practices do not significantly differ from conventional practice for handling chemicals. Hallock et al. (2009) state that ENMs of uncertain toxicity should be handled like other materials of unknown toxicity and refer to best practices guides for working with ENMs posted by universities and research laboratories.

The effects of hazardous byproducts of ENM production should not be neglected. The production process of carbon nanotubes has been shown to produce toxic byproducts such as polycyclic aromatic hydrocarbons (Plata et al., 2008). It is also known that production of some ENMs, such as fullerenes or carbon nanotubes, also results in the production of a much greater proportion of wastes that contain a variety of carbon based structures. No full characterization of substances in such wastes, co-produced during ENMs manufacture, is available. Currently, it is not clear how to dispose of such waste safely. For example, it is not clear if such wastes should be considered and treated as normal waste, hazardous waste, waste for incineration and/or for landfilling (Breggin and Pendergrass, 2007; Chaudhry et al., 2006).

ENMs are produced not only by chemical companies and universities that have a long tradition of handling hazardous materials, but also by small and medium sized companies (SMEs) or by companies who before that produced bulk materials and later entered into ENMs production (top down approach); these later companies may not have the necessary experience or equipment for handling potentially hazardous materials (Koehler and Som, 2008; Schmid and Riediker, 2008). Another survey showed that the majority of companies did not perform any form of risk assessment or risk management (Helland et al., 2008).

Industrial nanomaterial waste should be handled as hazardous waste according to NanoSafe2 (2008) and BSI (2007a). Hallock et al. (2009) describe in detail how universities and research laboratories take a cautious approach to nanowaste management. Also Gerritzen et al. (2006) reports that most organizations recommend "disposal of nanoproducts as hazardous waste, though they did not frequently report conveying this information to their customers".

5.4. *The product use stage*

Exposure to ENMs during the use stage can be from intended applications (e.g. putting ENMs-containing sunscreen onto the skin) but also from unintended sources (e.g. from the release of ENMs from nano-textiles). In the absence of any labeling, the consumer will be totally unaware of the potential exposure. The exposure of consumers could, however, be estimated using behavioral and anthropometric data, usage statistics, and from the prevalence and manner of integration of ENMs in different product categories. So far there are no studies available in this regard.

Whereas the magnitude and source of ENMs is known for intentional releases into the environment, e.g. during groundwater remediation, this is not the case for inadvertent releases. The latter can occur throughout the whole life cycle of products (Koehler et al., 2008). Potential critical points are likely to be (i) during the production and shipping of the ENMs where release into air is most likely, (ii) during production of final product, (iii) during use and (iv) during disposal or recycling. The amount of nanoparticles released by the different processes depends on several factors: the ENMs amount in the product, the product's lifetime, the way ENMs are incorporated in the material and the actual use/usage of the article (Koehler et al., 2008). Products that have a loose incorporation of ENMs, and/or an intense use (e.g. through frequent cleaning) will probably not contain ENMs at the time of disposal. On the other hand, factors such as a low rate of usage, and strong fixation of ENMs increase the likelihood that particles will not be released until disposal (Türk et al., 2005). Options for the reduction of adverse effects include optimization of the nanoparticle surface, better fixation of nanoparticles in the material and design changes leading to the release of relatively large particles (Reijnders, 2009).

Experimental data on the release of ENMs during use or disposal are very scarce. The release of nano-TiO_2 from coatings on wood, polymer and tile has been reported to be the highest from coated tile, and UV-light increased the release of ENMs (Hsu and Chein, 2007). Nguyen et al. (2009) showed that epoxy matrix containing CNTs undergoes photodegradation resulting in a concentration increase of CNTs on the nanocomposite surface. Initial results on the abrasion of nanomaterial-containing products, e.g. of ZnO-containing coatings, show that no significant release of nanoparticles were detected and that the ENMs were still embedded in larger particles (Vorbau et al., 2008). Ag is also released in ionic form from ENMs, and this was considered to be the major process of its release from plastics and textiles (Blaser et al., 2008). However, an experimental study showed that nanoparticles can also be released during washing from nano-silver containing textiles (Benn and Westerhoff, 2008).

Kaegi et al. (2008) observed engineered nano-TiO_2 in surface water and traced the origin of the particles to leaching from façades that had been treated with nano-TiO_2 containing paint. Electron microscopy of the façades and the released particles showed that they were still partially embedded in the organic binder but that also many single particles were observed from aged façades.

5.5. *The disposal stage*

Release of ENMs into the environment can also occur at the end-of-life of nanoproducts when they are disposed of in landfills or burned in waste incineration plants. Although the particle filters of incineration plants are very effective, low concentrations of ENMs may leave the stack and be transported by air. Modern waste incineration plants are equipped with different types of filters. Most also have a multistage flue gas cleaning system consisting of electrofilters, a flue gas scrubber, a catalytic NO_x/furan/dioxin removal and possibly a fabric filter. The concentration of particles smaller than 100 nm is reduced by such filters by around 99.9% and in the subsequent wet filter by another 95% (Burtscher et al., 2002). There is no information available about the behavior of ENMs during waste incineration. It is unknown what ENMs fraction stays in the slag and what percentage becomes airborne, and whether ENMs degrade under incineration conditions (e.g. high temperature). A single study has been performed on the thermal reactivity of carbon materials (Cataldo, 2002) that indicates a thermal stability of CNTs that is close to diamond (i.e. up to app. 850 °C), whereas fullerenes are less stable. Here investigations based on material science could provide some clarity. However, we can assume that even if ENMs become airborne during combustion, they are likely to be efficiently removed by the filters (Mueller and Nowack, 2008).

In a globalized world, it has been shown that many waste products end up in developing countries, or countries of transition, where the disposal or recycling is not well organized and thus products may end up in landfills or even on unpoliced dumping sites throughout the area. The containment of ENMs throughout the product life cycle does not seem likely for most nanoproducts (Hansen et al., 2008; Koehler et al., 2008) and the Royal Society and Royal Academy of Engineering (2004) assumes that there is a high risk of release of ENMs during disposal and recycling. The degradation of nanoproducts containing ENMs in landfill has not yet been the subject of investigations, and the disposal of nanoproducts will need clarity over regulation (Breggin and Pendergrass, 2007). Another open question is the "recyclability" of the nanostructured materials containing ENMs. BMU (2008) describes some nanoproducts such as lithium batteries with a complete recycling system and expects no release of ENMs in the environment. Nevertheless, for most products the recycling figures quoted even in industrialized countries is seldom more than 90% (Bundesamt für Statistik, 2008) and during the recycling process "shredding" may not be excluded and may lead to occupational and environmental health problems.

6. Conclusions

Life cycle concepts provide a means for identification of priorities for risk assessment (hazard and exposure), and analysis of ENMs release and monitoring. The use of life cycle concepts also raises some points that may be considered more intensively in the future by eco- and human toxicologists. In many nanoproducts the ENMs used are further functionalized in order to avoid aggregation and agglomeration or to stabilize them in the product matrix. Additionally, nanoproducts do not contain a uniform group of ENMs. Often the used ENMs used differ in size, shape, impurity and other physicochemical properties. Thus, it is assumed that based on their diverse properties different health and environmental impacts may be caused by the ENMs of one nanoproduct. Furthermore, ENMs may be released in different forms from nanoproducts, such as free ENMs, agglomerated or aggregated forms, or ENMs partly or completely integrated in nano- or micro-sized matrix particles (EMP-containing nanostructured materials).

Considering the life cycle of specific products provides information in relation to the release and exposure scenarios throughout the whole product life cycle. Thus, measures to impede the unintended release of ENMs from products and to decrease humans' exposure to ENMs may be analyzed and proposed (Reijnders, 2006; Som et al., 2009).

Life cycle concepts foster communication among the actors of the value chain and throughout the various life stages of a nanoproduct. This communication is important, because the knowledge of the ENM content in a product and safe handling usually decreases along the life cycle of a product (Koehler and Som, 2008). This is especially true for nanotechnology, which is a novel, enabling, cross-cutting and pervasive technology for many sectors. Thus, many actors are likely to be new in this field, and may not have much experience in handling the potential hazardous substances or possess adequate safety equipment.

Application of life cycle assessment (LCA) may provide added benefits in that it considers environmental sustainability impacts such as material and energy consumption, hazardous byproducts of ENM production, among others, to provide a comprehensive input for evaluation of the environmental sustainability potential of a nanoproduct (Meyer et al., 2009; Sengül et al., 2008).

The currently evolving (eco)toxicological data, despite uncertainties, already provide valuable advice for the safe and highly functional design of nanoproducts (e.g. for medical applications) in relation to their specific life cycle and also feed into adaptive regulation (Höck et al., 2008). Furthermore, (eco)toxicological methods support the assessment of materials that can be used as alternatives to the substitution of hazardous materials in conventional products.

Risk assessment and life cycle concepts are two different methodologies dealing with the uncertainty related with the effect of ENMs on health and the environment. The strategy for risk assessment of ENMs should take life cycle concepts into consideration and vice versa in order to mitigate the situation of having only limited knowledge on the risks inherent in ENMs. It is extremely important that both methods use the same terminology, data and information flow (e.g. consider the numbers of particles instead of the weights of substances). There is a need to find out how to integrate them for mutual benefit in providing a holistic approach to assess ENMs impact.

In conclusion, the combination of evolving toxicological knowledge with life cycle concepts could mitigate the uncertainty about the effects of ENMs on human health and the environment, and answer at an early stage some basic questions for decision making in the innovation and regulation processes and thus foster safe and sustainable development of the new technology.

Conflict of interest statement

The authors declare that there are no conflicts of interest.

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