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PHD THESIS REPORT

Life cycle assessment of manufactured nanomaterials: inventory modelling rules and application example

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Nanotechnology—sometimes designated as a ‘defining technology for the twenty-first century’—was first mentioned as a new field at the end of the 1950s in the famous speech by Richard P. Feynman (Feynman 1959). Two key characteristics of nanomaterials show up in the various developments in this area: the scale of the material and, related to this, its changes in properties and functionalities, but despite all these opportunities and the growing importance of nanotechnology, knowledge about the potential risks and hazards that may be linked to the various facets of this new technology is still incomplete. Using life cycle assessment (LCA) as a tool to address potential impacts on the natural environment and human health is a natural application of this methodology, both for the evaluation of manufactured nanomaterials (MNMs) and the products they are used in. However, so far, LCA has not been completely adopted for such a use. In fact, none of the public LCI databases contain a single data set for any type of MNM, despite the conclusions from an international workshop of LCA experts who consider LCA to be a suitable tool for an application in the area of nanotechnology (Klöpffer et al. 2006). There have been a few examples of LCA studies published, but most of these studies are far from being comprehensive and complete LCA studies. These weak points, such as the lack of inventory data and missing characterisation factors, are at least partly due to a lack of clear modelling rules for a LCA of MNM, an issue that a recently finished PhD thesis of ETH in Zürich (Hischier 2013c) has taken up. The objective of this PhD work is the provision of the foundation for a clear guidance for coherent and comprehensive inventory modelling of nanomaterials along their complete life cycle. In order to achieve this objective, the thesis work consists of the following elements:

1. A general set-up that allows the application of life cycle thinking principles (being the driving force behind the LCA tool) to the whole spectrum of applications of MNM;
2. An up-to-date and comprehensive overview of current published work in the area of ‘LCA and nanotechnology’ in order to clearly identify weaknesses and missing elements that have so far prevented a coherent and comprehensive application of the LCA process along the complete life cycle of MNM;
3. A framework on the level of inventory modelling that eliminates these weaknesses and missing elements identified beforehand, by keeping in mind the requirements from (the subsequent) impact assessment step; and
4. A first application example of the methodological developments by applying the framework on a display technology (the field emission display technology) using carbon nanotubes.

With the developed framework, the thesis aims to contribute to an increased effectiveness in the future, when LCA is used in the area of nanotechnology. For this, the findings of each of these elements have been published as individual papers in a scientific journal (Bauer et al. 2008; Hischier and Walser 2012; Hischier 2013a, b). The first of these publications by Bauer et al. (2008) investigates the first of these above-mentioned elements, i.e. the general set-up for the application of the life cycle thinking approach in general and LCA, specifically in the area of nanotechnology. Two simple case studies (one on physical vapour deposition coatings and the other on a field emission display screen containing carbon nanotubes) are used for the illustration of this investigation. Actually, these two cases are used to substantiate and illustrate

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the need for a framework to harmonise existing, ongoing and future LCA applications in this field covering the following three key points: (1) the identification of those (additional) functions of a nanomaterial which have to be taken into account when one is modelling the application of the material, (2) the inventory modelling of nanomaterials and (3) an evaluation of any releases of nanomaterials into the environment.

In Hischier and Walser (2012), the second element—i.e. the state-of-the-art environmental assessments in the area of nanotechnology together with their weaknesses and gaps—is investigated. A comprehensive analysis of the life cycle assessment studies in the area of nanotechnology published by the end of 2011 is established, and existing methodological shortcomings across these studies are identified. Based on these findings, strategies are proposed to overcome the identified pitfalls with the main objective of giving a clearer picture of the current situation from the point of view of life cycle assessment/inventory modelling. Notably, this review process has shown that studies applying life cycle assessment in the area of nanotechnology have been scarce so far. On the level of inventory modelling, the conclusion from this paper is that the production data of important nanomaterials should be collected and made available in a widely accepted format. On the level of impact assessment, relevant physical characteristics have to be identified for a toxicity assessment of nanoparticles.

The third element, i.e. the framework described in the study of Hischier (2013a), is the core element of the mentioned thesis. It describes clear rules of how emissions of nanomaterials need to be taken into account on the level of inventory modelling (i.e. what elements and what properties need to be reported for such an emission) in order to allow an adequate and comprehensive assessment in the subsequent step of life cycle impact assessment. For this, a three-step method is used to identify all the properties that are necessary for an adequate integration of releases of nanomaterials into LCA studies. In the first step, nanomaterials are described or characterised as completely as possible, based on scientific publications, results from expert workshops and reviewed publications from public authorities and international organisations. Among the dozen properties identified in this way, the second step identifies those that are effectively relevant for life cycle assessment studies, i.e. properties that influence the resulting toxicological effect of a release of a nanomaterial, applying the USEtox framework for the assessment of the ecotoxicity and human toxicity potentials. As the application of scholarly knowledge has not resulted in any reduction of this list of one dozen properties, the analysis is further enhanced by prioritising the list, covering in a qualitative way the issues of life cycle view, drivers for human toxicity and decision tools for a safe use of nanomaterials. The properties ‘composition’, ‘amount’, ‘shape’ and ‘size (distribution)’ result as the first priority level out of this second step. Finally, in the third step, these findings are then translated into the life cycle assessment language by exemplifying how these properties, specifically shape and size (distribution), should be integrated into current life cycle assessment data formats. The result in Hischier (2013a) is a clear proposal of a life cycle inventory modelling framework for the integration of releases of nanomaterials in life cycle assessment studies—representing a compromise between scholarly knowledge and the (toxicological) reality. This list can be seen as a clear manual towards the specialists for life cycle impact assessment, instructing them which of the properties would need to be taken into account when establishing characterisation factors for releases of nanomaterials.

As a first application example of this framework, Hischier (2013b) presents a more detailed life cycle assessment study of the field emission display (FED) technology. The main objective of this publication is the demonstration of the application of this framework for the modelling of nanomaterials in LCA studies. For this, a 36-in. FED television device is modelled in detail along its complete life cycle—from the extraction of the resources until the final disposal. The result from this in-depth analysis of the FED television technology is dominated by the production phase, as the electronics parts (i.e. the printed wiring boards) with clearly the highest contribution take place there, while the carbon nanotubes production is of an only very minor influence, but also, releases of carbon nanotubes during the end-of-life treatment do not contribute to the overall impact in the area of ecotoxicity (showing a value of <0.01 % of the total ecotoxicity potential of such a screen for these releases) when using conservative characterisation factors. However, due to the lack of respective characterisation factor for human toxicity, the influence of a carbon nanotubes release in this instance cannot be evaluated, and this fact is a good example of the dependency between the inventory modelling and the subsequent life cycle impact assessment; then, as long as there are no characterisation factors available that take into account more than just the amount of a release, the latter one does not have to be characterised in a more comprehensive way (i.e. no further properties of releases of nanomaterials are needed to be collected). By the way, compared with the display technologies used today, it appears that the FED technology seems to have an environmental advantage over these other technologies.

The thesis ends with a critical appraisal of the elements limiting a broader and more adequate application of the life cycle assessment approach in the area of nanotechnology (i.e. (1) taking into account in an appropriate way any additional functionalities of nanomaterials in the goal and scope step of a life cycle assessment study, (2) the creation of inventory data of nanomaterials often used, (3) the definition of characterisation factors for the life cycle impact assessment of releases of nanomaterials and (4) the documentation of a framework to model releases of nanomaterials in an adequate manner), especially the last of these four points. The prioritisation introduced in the study of Hischier (2013a) concerning the integration of further properties into the inventory modelling of releases of nanomaterials makes a stepwise expansion possible; starting with two additional properties (shape and size distribution). Such a stepwise procedure facilitates the coordination between life cycle inventory modelling and life cycle impact assessment and the related definition of characterisation factors. On the level of inventory modelling, only an integration of those properties makes sense that can be taken into account in the subsequent impact assessment step as well. This coordination makes it possible to keep the related uncertainty as low as possible. The quantification of this uncertainty for the starting level (i.e. the use of shape and size (distribution) as the only additional properties) is not possible; the developed framework needs to be applied to a wide variety of different cases and different nanomaterials first.

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