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Combining life cycle assessment and qualitative risk assessment: The case study of alumina nanofluid production

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HIGHLIGHTS

- RA and LCA are applied for assessing the sustainability of new technologies
- A framework for combining RA and LCA and overcome their limits is proposed
- A case study of alumina nanofluid production is presented
- Two different pilot lines are analyzed: single-stage and two-stage
- Results show that RA and LCA have a complementary role in the impact assessment

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ABSTRACT

In this paper the authors propose a framework for combining life cycle assessment (LCA) and Risk Assessment (RA) to support the sustainability assessment of emerging technologies. This proposal includes four steps of analysis: technological system definition; data collection; risk evaluation and impacts quantification; results interpretation. This scheme has been applied to a case study of nanofluid alumina production in two different pilot lines, "single-stage" and "two-stage". The study has been developed in the NanoHex project (enhanced nano-fluid heat exchange). Goals of the study were analyzing the hotspots and highlighting possible trade-off between the results of LCA, which identifies the processes having the best environmental performance, and the results of RA, which identifies the scenarios having the highest risk for workers. Indeed, due to lack of data about exposure limits, exposure–dose relationships and toxicity of alumina nanopowders (NPs) and nanofluids (NF), the workplace exposure has been evaluated by means of qualitative risk assessment, using Stoffenmanager Nano. Though having different aims, LCA and RA have a complementary role in the description of impacts of products/substances/technologies. Their combined use can overcome limits of each of them and allows a wider vision of the problems to better support the decision making process.

1. Introduction

The environmental effects of a technology depend on the use done by society, the interaction with technological systems, the physical context and the quantity of use (Mulder et al., 2011). The environmental assessment of emerging technologies is particularly challenging. Firstly, these technologies propose new products with different functions and a wide range of (unforeseen) applications. Secondly, the environmental assessment is often conducted when the emerging technologies are developed only at laboratory scale with high uncertainty on scaling-up effects. Finally, the emerging technologies could produce rebound effects in the market, society and environment (Zamagni et al., 2012). In order to assess their sustainability the European Commission encourages life cycle thinking (LCT) and related life cycle-based methods. LCT is a holistic approach to avoid shifting burdens to other life cycle stages, regions of the world and environmental impacts (UNEP, 2011). Life cycle assessment (LCA), regulated by the international standards ISO 14040 series (ISO, 2006a,b), is the main tool of LCT for environmental evaluations.

To date, nanotechnology is an emerging sector; about 1.720 new nanoproducts have been introduced into the market since 2005.[1] Databases have been developed in the framework of projects and national initiatives to provide consumers, citizens, policymakers, and others stakeholders with information about the nanotechnology market (some examples are reported in the Nanotechnology Consumer

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[1] http://www.nanotechproject.org/cpi/, accessed February 3rd 2014.

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Products Inventory (NCPI),[2] in Wissensplattform DaNa,[3] Nanotechnology Products database[4] and the RIVM initiative "Nanomaterials in consumer products" (2010)). These new products have a broad range of applications, often with innovative functions that cover new production sectors. An LCT approach is suitable to promote a sustainable development of nanotechnologies. LCA is especially important in the early development stages, because it helps to consider the environmental impacts during the product-design process, to suggest improvement measures for scaling-up and to compare scenarios based on innovative and conventional processes. Nevertheless, the data gap on LCA in the area of nanotechnology environmental assessment is still broad, several issues are not clearly defined and more information is necessary (Gavankar et al., 2012; Hischier and Walser, 2012; Kim and Fthenakis, 2013).

Moreover, health and environment effects of nanotechnologies and nanomaterials (NMs) are still much uncertain. The international scientific community is working hard on this issue. Recommendations of the European Commission for a responsible strategy that aims to enable the safe development and use of NMs and nanotechnology (COM 243, 2005; COM 338, 2004) include the proposal of integrating risk assessment (RA) of chemicals at all stages of the life cycle of the nanotechnology-base product. Human Health Risk Assessment (HHRA) and Ecological Risk Assessment (ERA) are the methods to evaluate the possible risks due to the exposure to dangerous substances and probability of adverse health effects in humans and ecosystems, now or in the future (U.S. EPA, 2000). However, toxicity of NMs cannot be extrapolated by the toxicity of their related bulk form (COM 572, 2012; SCENIHR, 2007). OECD (Organisation for Economic Co-operation and Development) Working Party on Manufactured Nanomaterials proposes a document including current practices, challenges and strategies for assessing risk although the available data are limited. It underlines the necessity for more research on specific risk assessment issues and defines a brief strategy and research needs for RA of NMs (OECD, 2012).

LCA and RA have different aims but they seem to have a complementary role in the description of environmental impacts. Complementary use of LCA and RA has been suggested by many authors in the last decades for overcoming limits and optimizing benefits. They have analyzed differences at methodological level (Bare, 2006; De Haes Udo et al., 2006; Hellweg et al., 2009) and have proposed applications on chemicals and bulk forms related to NMs (Nishioka et al., 2005; Ribera et al., 2014; Scheringer et al., 2001; Socolof and Geibig, 2006; Walser et al., 2014; Wang et al., 2013; Wright et al., 2008). Different approaches for combining these methods could be found in the literature. They describe the degree of integration from the complete separation to the perfect complementarity (Flemström et al., 2004), the relevance of taking into consideration spatial and temporal differences and the level *only above threshold* (Potting et al., 1999) and the possibility of using risk or hazard phrases (Askham et al., 2013). Currently, the most common approach of combining LCA and RA is to use the ecotoxicological and toxicological parameters in the development of the life cycle impact assessment (LCIA) methods. There is a general consensus in the scientific community that toxicity indicators in LCIA cannot provide the same detailed and specific information as RA does, but they can help identifying where RA is necessary (Pant et al., 2004). As a consequence, the two tools should be used in combination to better support business and policy decisions.

The aim of this paper is to propose an approach for combining RA and LCA and to present its application to the NMs. Some literature studies and also some specific initiatives at national level propose recommendations and suggestions concerning the use of methodological frameworks, additional knowledge instruments such as experts' elicitation, decision tree, multicriteria analysis (Davis, 2007; Grieger et al., 2012; Seager and Linkov, 2008; Shatkin, 2008; Som et al., 2010; Sweet and Strohm, 2006; Wardak et al., 2008). However, it is very difficult to find quantitative case studies and robust results due both to data gap on NMS and to methodological barriers. Starting from the analysis of the main characteristics and differences of RA and LCA applied to NMS, a framework for their combined use and its application to the production of alumina NF with two different processes, single-stage and two-stage, are here presented.[5] The qualitative RA has shown the potential effects of these productions on workers who are directly exposed to relatively high direct concentrations and LCA has allowed analyzing their environmental profile.

2. Method

RA (TGD, 2003) is focused on chemicals and their effects on the environment and human health. For a specific substance release, it allows the identification at a local scale of situations above threshold and possible contaminations. Notably, RA is focused on the toxicity of materials and doesn't take in account other environmental impacts. LCA (ISO, 14040 2006a,b), instead, allows the environmental assessment of products/services throughout their life cycle by considering several environmental issues. Existing impact assessment methods include the evaluation of the impacts at a global/regional scale, though the development of spatial differentiated Characterisation factors and the collection of site-specific inventory data could allow overcoming this limit of the method (Zamagni et al., 2008a,b). A significant difference between the two methods concerns the reference flow considered. RA identifies the risk of each substance and the cumulative effects, so the emissions are expressed as total emissions into an environmental medium (soil, water or air) with volume known, in order to obtain a concentration value. In LCA, the Functional Unit (FU), a quantitative measure of the functions that the goods (or service) provide, is the basis for comparing products: all data collected throughout the life cycle and the potential impacts are referred to it.

As regards the toxicity assessment, RA aims to risk minimization ("only above threshold"), in agreement with the assumption that toxic effects are caused by concentrations above a certain threshold; while LCA has a prevention approach ("less is better"), with the assumption that the relationship between emissions and environmental/human health damage is linear (Sleeswskij, 2011). Therefore also the goals of the two methods are different. RA guarantees the safety of the population and/or the environment by modeling the impact caused by the absolute quantities of toxic substances emitted with focus on receptors. LCA assesses the overall pressure on the environment of a product from cradle to grave (life-cycle perspective), focusing on the product's total releases and resources consumption and offering the best framework to avoid shift of burdens.

The differences above mentioned, which are weaknesses in case of separate use of each method, could be overtaken by their combined use. In this study, the development of a framework for a combined use of RA and LCA started with an analysis highlighting synergisms and interaction levels between the two methods.

In Fig. 1, the potential similarities between the RA and LCA frameworks are critically analyzed:

- The left side of Fig. 1 shows the main steps of RA, reworked from TGD (2003). In agreement with this document, the first phase is the hazard definition and concerns the identification of the substances, the targets and the whole scenario/context. This phase is called *Problem Formulation* in Fig. 1. Other phases are *Exposure Assessment*, *Effect Assessment* and *Risk Characterization*. Fig. 1 highlights the step of data collection, which is included in the exposure assessment

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[2] http://chemicalwatch.com/17214/us-consumer-nano-product-database-updated.

[3] http://nanopartikel.info/cms.

[4] http://www.nanowerk.com/products/products.php.

[5] This case study is part of the research project NanoHex - enhanced nanofluid heat exchange- aimed at translating promising laboratory nanotechnology results into pilot lines for the production of nanofluid coolant.