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NEWS AND OPINIONS

Sustainable nanotechnology: Defining, measuring and teaching

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Summary The complexity of nanomaterials themselves as well as the enabling nature of nanotechnology in general results in significant difficulties in defining and measuring sustainability associated with emerging materials and products. Defining metrics of environmental, societal, and economic impacts and integrating them into a multi-criteria decision analysis model is one way to assess the sustainability of nanoproducts and processes through an application-focused top-down approach. Given the current high level of uncertainty in many aspects of nanotechnology and the unknown trajectory of a field still in its infancy, it is important to teach nanotechnology in a contextual setting where discussions of uncertainty and variability are strongly encouraged. Sustainability should be linked to technology management processes to capture evolving technology and understanding of its benefits and risks.

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The enhanced properties of engineered nanomaterials (ENMs) are suited to applications in information technology, energy production, environmental protection, biomedical applications, food and agriculture [1]. The market for ENMs has grown rapidly, from a reported $147 billion value in 2007 to an estimated $3.1 trillion value by 2015 [2]. ENMs with complex functionality have already been developed that present significant uncertainties for regulation [3]. This rapid growth emphasizes the need for integrative and adaptive processes in nanotechnology management and for incorporating relevant criteria at the technology design stage. Sustainable nanotechnology is being touted as a holistic and pragmatic concept that can guide incremental nanotechnology development amidst significant data gaps and uncertainty. A Google Scholar search shows that the number of documents using the term was ~4500 annually in 2009—2011, doubling in 2012, and reaching over 9000 as of 1 November 2013. The Sustainable Nanotechnology Organization was created in 2011, attracting several hundred scientists to its annual meetings (http://www.susnano.org/), and the European Commission has recently funded a €14M project on sustainable nanotechnology (SUN, http://www.sun-fp7.eu/). Although there is increasing interest in the topic, there is little consensus on how sustainable nanotechnology is defined and measured.

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A common 'global definition' of sustainability is the Brundtland Commission's definition as ''development that meets the needs of the present without compromising the ability of future generations to meet their own needs'' [4]. The Brundtland Commission, or the World Commission on Environment and Development as it is formally known, was convened in 1983 by the UN in order to create solutions to environment and development issues. While the Commission's definition points at the broad societal needs of social equity, environmental protection, and economic stability it has limitations in addressing specific issues such as those related to the production and use of ENMs. In 1994, John Elkington coined the term Triple Bottom Line (TBL) as a form of accountability that envisions the environment, society, and economy as three pillars of sustainability [5]. TBL requires consideration of each pillar and the interactions between them, and can, in principle, systematically 'trickle down' to technology design details [6].

Conceptualizing sustainable nanotechnology within the TBL framework can be utilized to help solve nanotechnology problems that have many variables and which call for detailed analysis. A Multi Criteria Decision Analysis (MCDA) model is one method of systematic top-down decision making appropriate for risk-based fields such as nanotechnology [7]. In this approach, TBL pillars form the first level of the decision tree, which is further divided into subsequent levels of criteria until the problem is articulated in sufficient breadth and detail. The empirical dimension of a sustainable nanotechnology MCDA model comprises (a) metrics associated with MCDA criteria and (b) weights associated with nanotechnology stakeholder preferences at each branch of the decision tree. Thus, the MCDA methodology can provide a complete framework for measuring and monitoring sustainable nanotechnology, including conceptual framework, empirical indicators, and stakeholder values.

In an effort to assess the application of sustainability criteria to ENM selection using the TBL approach, a project course was developed at Ca'Foscari University of Venice (Italy) in the Fall of 2013. Twenty students were tasked with conducting a literature search on sustainable nanotechnology definitions and operationalizing the TBL approach for evaluating sustainable nanotechnology. Six student groups reviewed government agency documents, peer-reviewed and gray literature, as well as websites of major ENM manufacturers and consumer groups. Though the volume of literature containing an association between sustainability and nanotechnology was significant, the search yielded no concise definitions for sustainable nanotechnology.

As a starting point to conceptualize sustainable nanotechnology as a decision problem, the class adopted a TBL definition of sustainability recommended by the Institute of Chemical Engineers (ICE) [8]. Supplementing the ICE definition with nano-specific criteria from their literature review, the class then developed an MCDA model (Fig. 1). MCDA models allow explicit integration of technology performance on selected criteria and stakeholder values [9,10]. In this case, the model utilized criteria rankings for typical ENM manufacturers', consumers' and regulators' preference profiles for selecting among three nano-manufacturing alternatives: baseline, low-end and high-end technologies.

Environmental protection is the mandate of regulators, entities who are not likely to prefer innovations that are accompanied by uncertainty and potential risk to humans and the environment. On the other hand, manufacturers and consumers tend to embrace innovation that has potential economic and societal benefits. Results of the model showed manufacturers' and consumers' typical preference for the high-end alternatives that provide significant societal benefits but are associated with higher risks, as well as regulators' preference for low-risk, low-end alternatives

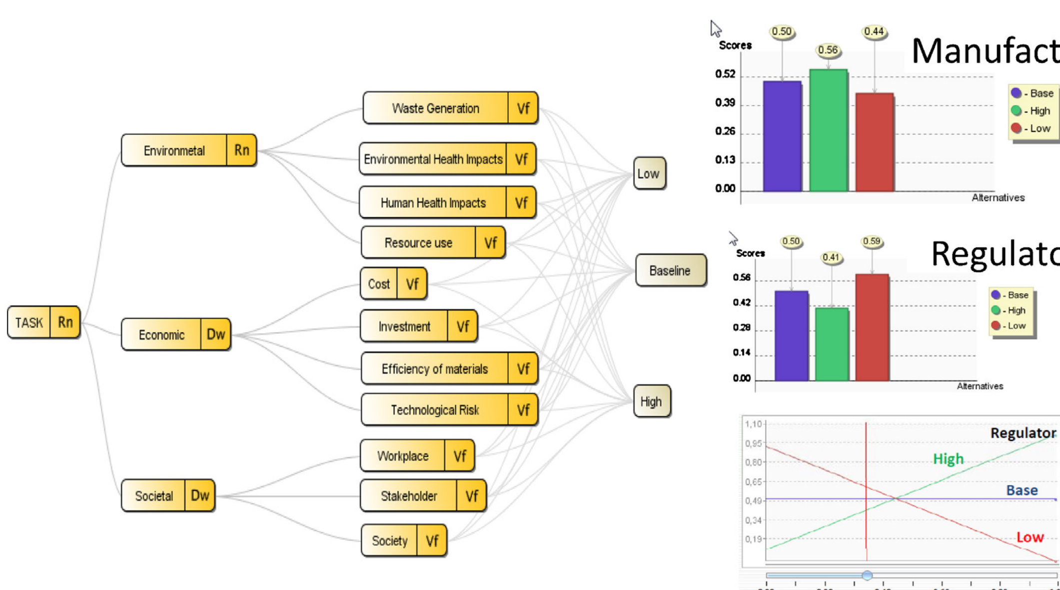

Figure 1 Decision Model for selecting nanomanufacturing alternatives. The Triple Bottom Line approach is used to prioritize Baseline, Low-end and High-end manufacturing technologies based on typical weighting schemes for Manufacturers and Regulators. High-end alternative is preferred for Manufacturers, while Low-end alternative ranks higher for Regulators. Sensitivity analysis shows that small increase in Societal Values for regulators can change their preferences from Low to High technology alternatives. DECERNS software package (10) was used for modeling.