Coupling Multicriteria Decision Analysis and Life Cycle Assessment for Nanomaterials

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It is now nearly universally accepted that the product life cycle is the proper perspective for thinking about materials, including nanomaterials (Davis 2007; USEPA 2008). The principal advantage of conducting formal life cycle assessment (LCA) is that it quantifies environmental impact at different product life cycle stages and avoids shifting potential environmental problems from one stage to another. However, nanomaterials present at least three significant challenges to existing LCA techniques.

LCA models that fail to complete the impact assessment stage leave designers, decision- or policy makers vulnerable to biases such as prematurely anchoring on first impressions, placing undue emphasis on narrow – albeit salient – aspects of a choice, or judging on the basis of stigma.

Material Variability

One of the obstacles to understanding the environmental implications of nanomaterials is characterization of the materials themselves. Even within a seemingly narrow class of nanomaterials—for example, single-walled carbon nanotubes (SWCNTs)—it is essential to understand the purity (e.g., metals and soot content) and uniformity (e.g., length, diameter, conductivity, and chirality) as well as the relationship between these characteristics and their functionality in the end-use application. At present, there is no standard specification among nanomaterial suppliers. Therefore, even "high-purity" nanomaterials may contain environmentally significant concentrations of metal catalyst or other material (e.g., SWCNT may contain as little as 10% by mass of actual nanotubes, with the balance being simpler forms of carbon). The experimental procedures for characterization of nanomaterials are still evolving.

Uncertainty in Toxicity and Risk

Nanomaterials are especially problematic with regard to toxicity and risk. Typical LCAs include one or more midpoints that relate to human or ecotoxicological health. Characterization of toxicological midpoints depends on the relation of source terms (as embodied in the life cycle inventory) to health midpoints, relative to selected benchmarks. Characterization factors depend on the fate and transport of the chemical in the environment as well as the relationship between a biological dose and a health response. However, selection of standard LCA midpoint equivalencies predated the explosion of interest in nanomanufacturing. Whereas with conventional chemicals, it is usually appropriate to represent dose in mass terms (e.g., milligram body burden per kilogram body mass), it is not yet

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clear that mass concentration drives toxicity at the nanoscale. Surface properties, functionalization, interaction with environmental media, and microbial activation may all play roles in nanomaterial toxicity that cannot be captured in terms of mass (or volume) concentration.

Although toxicological studies will improve understanding, it is highly unlikely that all the possible nanomaterial permutations or combinations (including functionalization) can be tested or modeled with standard methods and tools developed in the field. Conventional chemicals are often stable in the environment or, in the case of organics, may involve hundreds of different formulations, whereas even a single class of nanomaterial, such as SWCNT, may entail thousands or tens of thousands of different varieties with distinctive dose–response relationships. Empirical testing, which is limited with regard to conventional chemical classes, will never be sufficiently informative of the range of possibilities in regard to nanomaterials. It may be impossible to determine "allowable" concentrations, loadings, or exposures. Consequently, the idea of benchmarking nanomaterial toxicity in terms of characterization factors relating to existing LCA midpoint equivalencies may be unrealistic.

Uncertainty in Performance

All LCA data must be referenced to an appropriate functional unit representing the demand, activity, or product that is the purpose of the production system. However, the extraordinary level of experimentation with nanomaterials has resulted in a rapid expansion of potential end-use applications. Nonetheless, nanomaterials are rarely used in the pure phase. More typically, they are additives or substitutes in composite materials. In many cases, the type and quantity of nanomaterials have not been optimized, and the mechanisms of functionality may not be entirely understood. In other cases, laboratory-scale processes have not yet been sufficiently scaled up to understand the potential environmental implications of high-yield manufacturing. Because the synthesis, purification, and separation processes employed in manufacture of nanomaterials can result in important changes in the nanotube characteristics, these processes cannot be assessed independently of the end-use application.

Continuing with the example of SWCNT, we find that flame, arc, or chemical vapor deposition synthesis techniques result in tubes with different distributions of length, diameter, purity, or catalytic metal content.[1] Depending on the end-use application, they may require different levels of purification effort to remove metals or surface coatings (e.g., of adsorbed carbon). Additionally, the relationship between SWCNT content and functionality in the final application may be dependent on the synthesis methods and purification techniques employed. Consequently, it may not be proper to express life cycle inventories simply in terms of mass of nanotube material—even if the purity and type of material are well characterized and entirely transparent. (This approach would more properly be termed a process assessment, rather than *life cycle* assessment.) The relationship between the life cycle inventory and the functional unit can likely only be established in the context of a specific application.

Impact Assessment in High-Uncertainty Applications

It is clear that application of LCA for nanomaterials will entail unprecedented levels of uncertainty that require careful treatment. However, it is also clear that nanotechnology applications will be moving forward rapidly. At present, the challenges presented by nanotechnology make impact assessment within LCA so difficult that the normalization and weighting steps are often simply ignored. Nonetheless, LCA techniques must continue to evolve to meet the needs of the nanotechnology community, which would otherwise be forced to confront multicriteria, multistakeholder problems unaided. LCA models that fail to complete the impact assessment stage leave designers, decision makers, and policy makers vulnerable to biases, such as prematurely anchoring on first impressions, placing undue emphasis on narrow—albeit salient—aspects of a choice, or judging on the basis of stigma or affectation. Ultimately, the consequences of the decision may differ from those that might, on further reflection, be preferred (e.g., Gregory and

McDaniels 2005). Accordingly, we make several recommendations.

Using Multicriteria Decision Analysis With LCA

LCA practitioners must explore alternatives to existing utility-based, normative decision life cycle impact assessment approaches and instead emphasize practical decision strategies. It is especially beneficial to couple LCA with multicriteria decision analytic (MCDA) techniques to facilitate understanding of trade-offs and multiple perspectives in the impact assessment. MCDA provides a clear and transparent methodology for making decisions and also offers a formal way for combining information from disparate sources (e.g., Tervonen and Lahdelma 2007). It has been recommended as one of the most promising nanotechnology risk governance tools (Roco 2008), and an example application to nanomaterials has been reported (Linkov et al. 2007; Tervonen et al. 2008). The U.S. Army Corps of Engineers is currently working on integrating risk assessment and MCDA in what is called a risk-informed decision framework. The general approach may be extendable to nanomaterial applications. In particular, outranking approaches[2] are especially suitable for problems where there are a large number of alternatives, strong heterogeneity exists between criteria (making aggregation difficult), and compensation of loss in a given criteria by gain in another is unacceptable.

Uncertainty in LCA for nanotechnology should be quantified in a hybrid approach that couples scenario modeling with probabilistic representation of results. Where multiple types of uncertainty are extraordinarily high—as in the case of nanomaterials—traditional approaches to quantifying uncertainty, such as Monte Carlo analysis (MCA), are inadequate. Probability distributions under conditions of model and boundary uncertainty lack meaning (at best) or may lead to overconfidence (at worst). In a scenario, certain parameters or boundaries are fixed by stakeholders or decision makers, whereas model outputs are represented probabilistically. This allows model users to explore sensitivities and possibilities while gaining a feel for trade-offs that may facilitate construction of preferences within the decision context.

Stakeholder preferences—as embodied in criteria weights—should be represented stochastically, rather than as point estimates. There remains considerable uncertainty with regard to value elicitation for the purposes of decision making in the context of LCA (e.g., Gloria et al. 2007). Explicit incorporation of uncertainty in the weighting and impact assessment stage of LCA would allow for a more accurate representation of how stakeholders actually perceive environmental trade-offs. Moreover, it would allow a rapid exploration of multiple views for screening or comparison of alternatives without extensive value function elicitation (Tervonen & Lahdelma 2007). The general approach, called stochastic multiattribute acceptability analysis (SMAA), is appropriate for situations in which the weights may be only partially or even completely unknown due to the number of decision makers (i.e., variability), are highly uncertain, or contain mixed qualitative and quantitative preference information. In these cases, which are typical of environmental decision-making problems involving nanomaterials, reducing uncertainty or describing variability may be prohibitively expensive. SMAA methods are capable of determining the sensitivity of ranking alternatives by exploring the weight space in which one alternative may be preferred over others.

In summary, in the context of the extraordinarily high uncertainty that is currently characteristic of nanotechnology, comparative approaches to LCA that emphasize analysis within a specific decision context may have greater utility than attempts to establish life cycle properties on an absolute basis. In particular, we stress the importance of carrying LCA forward through the impact assessment stage, rather than truncating the assessment at midpoint characterization (as is often the case). In particular, attention should be directed to further development of new tools for life cycle impact assessment that draw on a wide range of formal MCDA techniques. As a consequence, we can expect that LCA will become increasingly useful as a practical design, decision-making, and policy-making tool, even for nanomaterials and other emerging technologies.

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Notes

1. Editor's note: For a description of nanomanufacturing techniques and the possible associated environmental impacts, see the article by Şengül and colleagues (2008) in this issue.
2. Outranking approaches employ a pairwise comparison of alternatives on individual criteria, rather than on the basis of a linear-weighted aggregated sum. The result is a partially compensatory or noncompensatory MCDA approach in which overperformance on one criterion will not compensate for underperformance on others.

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