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Integrate life-cycle assessment and risk analysis results, not methods

Igor Linkov[1]*, Benjamin D. Trump[1,2], Ben A. Wender[3,4], Thomas P. Seager[4], Alan J. Kennedy[1] and Jeffrey M. Keisler[5]

Two analytic perspectives on environmental assessment dominate environmental policy and decision-making: risk analysis (RA) and life-cycle assessment (LCA). RA focuses on management of a toxicological hazard in a specific exposure scenario, while LCA seeks a holistic estimation of impacts of thousands of substances across multiple media, including non-toxicological and non-chemically deleterious effects. While recommendations to integrate the two approaches have remained a consistent feature of environmental scholarship for at least 15 years, the current perception is that progress is slow largely because of practical obstacles, such as a lack of data, rather than insurmountable theoretical difficulties. Nonetheless, the emergence of nanotechnology presents a serious challenge to both perspectives. Because the pace of nanomaterial innovation far outstrips acquisition of environmentally relevant data, it is now clear that a further integration of RA and LCA based on dataset completion will remain futile. In fact, the two approaches are suited for different purposes and answer different questions. A more pragmatic approach to providing better guidance to decision-makers is to apply the two methods in parallel, integrating only after obtaining separate results.

Environmental risk analysis (RA) and life-cycle assessment (LCA) are the predominant methods for characterization of the systemic environmental and toxicological impacts of processes, products, and their concomitant chemical releases[1]. RA quantifies both the potential exposure and hazard associated with a specific material in specific release scenarios to generate an absolute estimate of risk, and typically reports results relative to external thresholds, such as maximum contaminant level[2]. In contrast, LCA estimates potential impacts in diverse impact categories by aggregating emissions from all processes from the cradle to the grave of a product, and reports these impacts relative to the function or service provided[3]. Seeking to take advantage of the strengths of each method, several prominent research organizations recommend integrating elements from both RA and LCA for proactive assessment of emerging technologies, such as nanotechnology[4,5].

Efforts to integrate RA and LCA at the methodological level appeared in scholarly literature at least 15 years ago[6,7], while reviews provide a typology of the burgeoning literature[8] and methodological advancements continue to be published[9–11]. Lack of data is a recurring concern, although most scholars express optimism that further integration is achievable so long as toxicological data accumulates and rapid assay tools advance. Nonetheless, it is now clear that engineered nanomaterials (ENMs) present a serious challenge to this view. The rapid pace of nanotechnology development, high uncertainty in environmentally relevant parameters, and unique properties and behaviour of nanomaterials compared with the conventional chemicals for which RA and LCA methods were developed present serious obstacles to application of both LCA and RA to nanotechnologies. For example, nanomaterials typically violate the equilibrium assumptions employed in multi-media box models used widely in RA and LCA[12]. Although testing methods continue to evolve for nanomaterials, it remains unclear in what forms nanomaterials are present in the environment or even how nanotoxicological dosages should be determined[13].

Pushing the limits of RA and LCA

Partly because of these practical difficulties, methodological integration of RA and LCA has remained limited to largely two points of connectivity: (1) use of LCA to guide a comprehensive identification of sources terms relevant to RA, and (2) use of risk models from RA in the development of characterization factors for LCA—both of which are important drivers of regulatory decision-making and policy framing. Beyond these two points, it has long been clear that RA and LCA have different objectives, create different boundaries for analysis, and consider different environmental and human health end points[1]. Figure 1 shows a schematic representation of RA and LCA and emphasizes the two principal connections and differences between them. For example, RA (left side) is reported relative to the identification of a specific hazard, whereas LCA (right side) is reported relative to a functional unit. The principal differences are found at the bottom of the figure, in their contrasting applications. RA is motivated by hazard reduction, whereas LCA is motivated by gaining an understanding of the systemic environmental consequences of a product, process or service that fulfils a valuable economic or social function. LCA seeks to elucidate a broader assessment of environmental impacts relative to the benefits quantified in the functional unit.

The two perspectives are joined in what LCA practice refers to as a characterization factor, which expresses the potential deleterious effects of a chemical release to the environment in terms of a specific impact category—such as magnitude of human or ecological effects or interacting factors, such as global warming. In relation to ENMs, LCA requires thousands of characterization factors that relate mass quantities of chemical releases to human and ecotoxicological

[1]US Army Engineer Research and Development Center, Concord, Massachusetts 01742, USA. [2]University of Michigan School of Public Health, 1415 Washington Heights, Ann Arbor, Michigan 48109, USA. [3]National Academies of Sciences, Engineering, and Medicine, 500 5th Street NW, Washington DC 20001, USA. [4]660 College Avenue, School of Sustainable Engineering, Arizona State University, Tempe, Arizona 85287, USA. [5]100 Morrissey Boulevard, University of Massachusetts, Boston, Massachusetts 02125, USA. *e-mail: igor.linkov@usace.army.mil

impact categories, whereas RA has historically focused on one class of chemical at a time. Models used to establish characterization factors in LCA (such as relative toxicity) are derived from RA[14], and require similar physiochemical and toxicological data.

However, LCA quantifies the potential impacts associated with marginal increases in emissions[15]. The broad scope of LCA requires generalized models and assumptions that lack the specificity typical of RA[16,17]. For example: (1) contaminant fate and transport models in LCA represent average landscape conditions of whole regions or the globe, and (2) human populations are modelled generically and do not include variations in potential exposure for different groups. Whereas LCA researchers have long sought to increase the spatial and temporal resolution of toxicity impact assessment models, even advanced methods, such as those using geographic information system tools to specify emission locations, will never match the level of detail provided by on-site measurements used in RA to verify regulatory compliance. This is particularly problematic in the context of ENMs, where even small differences in the local environmental conditions can have significant impacts on the fate, transport, and toxic properties of ENMs. Thus, despite sharing common modelling structures (for example, simplified box models, routine exposure pathways), life-cycle impact assessment differs substantially in practice and results from RA. While it has been argued that, in theory, the specificity of RA could be applied generally to the broad boundaries of LCA if only sufficient datasets could be generated, this Perspective argues against this and proposes instead that RA and LCA methods be maintained separately, only to be integrated as results feeding into a structured environmental decision-making process.

Methodological integration strategies

At the core of the differences between RA and LCA is a matter of perspective. Whereas RA focuses principally on receptors, LCA focuses principally on emitters. The two dominant strategies used to integrate RA and LCA on a methodological level are: (1) life-cycle risk analysis (LCRA), which seeks to apply RA across the different life-cycle stages of a product containing nanomaterials[18], and (2) including near-field exposure pathways and impacts as an additional impact category in LCA[9,11,19]. The first strategy aims to complement the relative precision of RA with the broad life-cycle boundaries inherent to LCA. The second strategy seeks to elevate in LCA the visibility of the occupational and consumer outcomes that have historically been the domain of RA.

LCRA requires quantification of the dominant nanomaterial emissions (or other hazardous releases of concern) and exposure pathways associated with each life-cycle phase[18] (for example, potential inhalation during a coating process in manufacturing or dermal exposure during consumer use) as well as the toxicological response to this exposure. True to its roots in RA, LCRA is exclusively focused on toxic impacts and thereby considerably narrower in scope than LCA, but nonetheless adopts broader boundaries than traditional RA. This life-cycle-extended approach to RA is applauded, as significant potential for exposure to hazardous substances exists along the life cycle. However, the practical difficulties of fulfilling the broader boundaries of LCA, including a complete chemical inventory and impact points that include non-toxicological considerations, in the case of ENMs, are rarely acknowledged.

At the opposite end of the spectrum from LCRA are attempts to incorporate near-field emissions and associated impacts into LCA[9,11], which at present quantifies impact potentials from only far-field sources. Proponents of this approach recognize that indoor and occupational exposure typically exceeds that from far-field sources[19] and posit that omission of near-field impacts may result in shifting burdens from the general population to workers. Unfortunately, this strategy faces both theoretical and practical barriers. In practice,

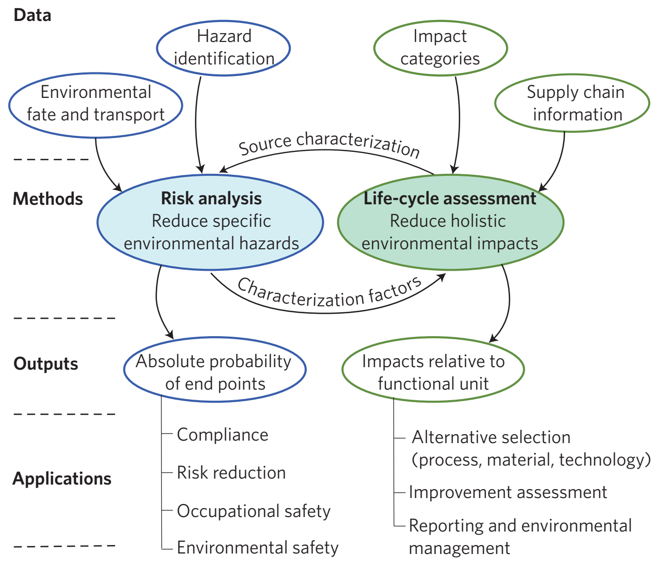

Figure 1 | Schematic representation of RA and LCA connections in the context of nanotechnology applications.

indoor environments differ greatly in size, ventilation rates, background concentrations, and implemented risk management controls in various regulatory contexts. Overlooking this variability and attempting to model a generic indoor environment may yield grossly misleading results and undermines the measurements and precision that motivates RA.

While more data may hypothetically provide the bridge between the emitter (LCA) and receptor (RA) perspectives, the differences in boundaries, purpose, and emphases that contrast the two methods means that they suggest different, incompatible strategies for managing data gaps, simplifying data requirements and reporting uncertainty. Thus, methodological integration is only possible in the case of fully complete datasets—now understood to be a practical impossibility. As a consequence, integration of RA and LCA must proceed at later stages of analysis.

Decision analysis integrates results

Reconciling the fundamental differences between RA and LCA limits integration at the methodological level. Furthermore, integration potentially undermines the strengths that make each approach unique: LCA generates a systemic understanding of potential impacts in numerous categories, and RA develops specific toxics management strategies based on measurements and models with greater precision. An alternative to integration of LCA and RA on the methodological level is to apply each method in parallel—which is already done in practice—and then devote greater resources to developing decision support methods capable of combining disparate types of data inputs[20]. Incorporation of results at the decision-level takes advantage of the strengths that make each approach valuable.

Multi-criteria decision analysis (MCDA) is a family of methods designed to reveal the complicated tradeoffs or compromises inherent in complicated problems[21]. The results of RA and LCA form decision criteria that can be compared alongside non-environmental criteria, such as cost and material performance. Examples already exist in emerging technologies, environmental management, and occupational health and safety, where qualitative and semi-quantitative data, such as with subject expert assessment, can inform properties and characteristics that are otherwise difficult to quantify at present[22–24]. Use of MCDA in environmental application is growing both in government[25] and in academic literature[26]. Orienting RA and LCA towards informing a specific decision can reduce data needs for both RA and LCA by blending qualitative and quantitative measures[22–24]. Furthermore, such an integrative process allows us to utilize both RA and LCA, which methodologically answer different questions, and ultimately generate information and decision support for ENMs that uses results from RA and LCA to inform ENM policy[27].

Decision-driven approaches

Integration of LCA and RA results for ENMs conceptually follows a three-step process[20]:

(1) Elicitation of criteria, values, and boundaries from stakeholder groups.
(2) Generation and assessment of alternatives relative to these criteria by subject experts.
(3) Ranking of preferred alternatives by decision analysts.

The integration of results starts in the first step, which demands effort to structure criteria for which LCA and RA can produce measures, and about which stakeholders can provide judgements. It is LCA and RA that populate the assessment matrices essential in the second step[20,21]. MCDA utilizes data using natural (quantitative) and constructed (qualitative) scales, probabilistic and point estimates, or mixed methods[20]. When data is missing or highly uncertain, of particular importance is the need to select a robust and representative sample of subject experts, where it is necessary to account for (1) those experts that may or may not be directly affected by the decision at hand, and (2) the various disciplinary and experiential backgrounds from which these experts draw their opinions, beliefs and advice. For many iterations of MCDA, robust decision support depends largely on whether appropriate and knowledgeable subject experts are chosen for inclusion. Special attention should be placed on selecting appropriate methods for weight elicitation[28–29].

This structure gives decision analysts in the third step the comparatively simple cognitive task of considering tradeoffs among alternatives in a given decision context separately from considering the complex drivers of the technical measures used. Alternatives are typically rank-ordered from most preferred to least preferred based on tradeoff-weighted aggregation of normalized criteria performance scores. These scores support more complex analyses, such as sensitivity analysis showing under which weights conditions rankings may change, and graphical representations for comparing and ranking alternatives[20–22]. This is particularly important in an environment of high scientific uncertainty insofar as stochastic exploration of uncertainty relative to decision confidence can prioritize new data needs in a way that improves the decision applicability of new research[23]. Although aligning environmental research strategy with decision imperatives has been a high priority at least since publication of *Understanding Risk*[30], more recent reviews still bemoan the lack of decision applicability in nano-specific environmental research[4,31]. Provided the rate of innovation in nanotechnology can be expected to outstrip the rate of usable, high-quality environmental data generation, methodological integration of RA and LCA, which places additional data requirements on analysts and decision-makers, is at best impractical. Rather, integration of RA and LCA results (not methods) in the context of MCDA is a more promising route to mitigating environmental impacts and satisfying the long-standing recommendations of the National Research Council.

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