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Coupling Multi-Criteria Decision Analysis, Life-Cycle Assessment, and Risk Assessment for Emerging Threats

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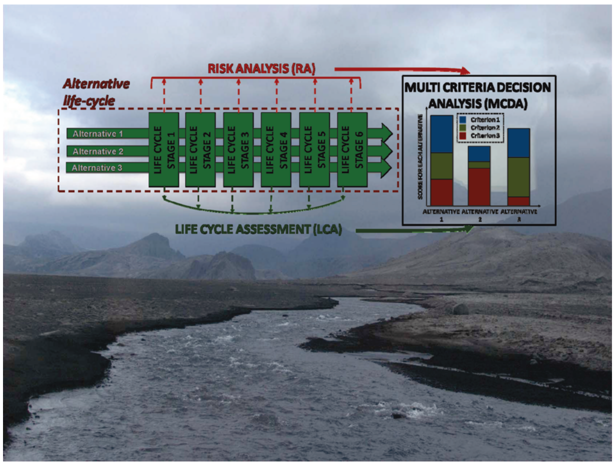

The recent emergence of new materials, technologies, and other environmental stressors in both the marketplace and the public consciousness coincides with increased recognition of the importance of an integrated systems approach to environmental health and safety that includes life-cycle thinking, public participation, and adaptive management of risks associated with emerging threats. While the fields of risk assessment and risk management have always operated in situations of uncertainty, emerging threats greatly increase the challenge to risk analysts already hard-pressed to elucidate the potential hazards of traditional chemicals.[1] A recent report from the National Research Council (NRC) recognizes that ten years or more is typically required to complete risk assessments for environmentally important chemicals.[2] Given the extraordinarily high levels of variability and uncertainty intrinsic to emerging materials (such as nanomaterials), the data and experimental resources required to complete technical analyses can be expected to be even greater than for traditional materials. Consequently, it seems highly unlikely that the classic risk analytic framework of hazard identification, source term characterization, environmental fate and transport modeling, exposure assessment, and dose−response assessment could be sufficient in practice to keep pace with the rate of technical innovation in emerging technologies.[3]

A series of NRC committees dating back to at least 1989[4] have reiterated the importance of a "decision-directed" approach to risk management that allocates analytic resources to discovering new information that is most informative in a specific decision context. Given the consistency of these recommendations over the last two decades, it may seem remarkable that a *structured* decision analytic framework has yet to be adopted by risk management agencies, such as the Environmental Protection Agency (EPA) and Department of Homeland Security (DHS). Although the recent NRC report includes "a framework for risk-based decision-making,"[2] the framework structures *only the risk-analytic aspects of risk management, not the decision-analytic*—which may illustrate the persistence of the ideal vision of detached scientific objectivity in risk analysis. By contrast, a recent NRC report with regard to public participation[5] emphasizes the importance of deliberative processes for bringing together disparate public and stakeholder views to help generate decision criteria, rank-order alternatives, deal with uncertainty in regard to competing objectives, and formulate management trade-offs between objectives in the context of risk.

Such deliberative processes can be incorporated in a multi-criteria decision-analytic approach (MCDA), as has been proposed for remediation of contaminated sites,[6] life-cycle impact assessment,[7] sustainability,[8] environmental policy,[9] or integrated risk assessment and life-cycle assessment.[10] MCDA refers to a collection of methods used to impart structure to decision processes that invoke incommensurate or irreducible objectives, multiple and divergent stakeholders, and (in many cases) incomplete information. This paper presents an approach for using MCDA to integrate uncertain information collected from risk analysis and life-cycle assessment in the context of emerging environmental threats. The objective of this approach is to establish an analytic basis for prioritizing research needs that are most informative to decision-makers such as product developers, regulators, or end-users.

DECISION ANALYSIS, RISK ASSESSMENT, AND LIFE-CYCLE ASSESSMENT

MCDA refers to a group of methods used to improve understanding of a complicated or uncertain decision-making process. Generally, the MCDA process consists of four steps:

(1) structuring the problem by identifying criteria through stakeholder elicitation and assessment of the different criteria that are relevant to the given decision;

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(2) eliciting the parameters of the model, such as alternatives, decision criteria, relative weights, and preference thresholds, and evaluating the performance of each alternative on each criterion;
(3) applying a decision algorithm that ranks each alternative from most to least preferred;
(4) interpreting results of the model and reiterating the process from step 1 or 2 by re-evaluating the model.

Decision algorithms are the centerpiece of MCDA with many different types to select from, including utility-based methods (such as multiattribute utility theory, MAUT) or outranking methods that focus on comparative assessment of alternatives. MCDA helps organize information for decisions that engage multiple points of view (i.e., disagreement between different decision-makers or stakeholders), or require assessment of tradeoffs among several criteria that are not reducible to one optimal result. Although MCDA can proceed when uncertainty is high, it requires that alternatives and decision criteria be identified at the outset.

Typically, decision criteria and relative weights are elicited from decision-makers and stakeholders or public groups that are engaged in the decision process. To this extent, MCDA is consistent with shared governance ideals and mechanisms of public participation in the context of risk. However, where weight sets are highly variable or uncertain, stochastic sampling can be used instead of extensive value elicitation, especially in screening stages of an analysis.[11] As stakeholders inevitably learn more about the decision problem, new alternatives or priorities may emerge, allowing for reformulation of the decision problem. By iterating between elicitation and analysis, greater confidence in criteria preferences is likely to emerge. However, there is little assurance that different stakeholders will reach consensus. MCDA allows representation of multiple and competing views in the form of different criteria weight sets, thereby allowing identification of important conflicts or opportunities for compromise.[6]

Risk analysis (including risk assessment and risk management) has been the basis for regulatory decision-making for chemicals for at least two decades and is quickly becoming the analytic foundation for managing emerging threats. Risk assessment and risk management have been separated in many regulatory and planning applications. In general, risk assessment is associated with a set of quantitative tools and models, while risk management uses a less formal set of practices and processes, including tacit decision heuristics that may be used with or without risk assessment. Given the practical limitations of risk assessment and the necessity of adopting a quantitative risk management approach, the best way forward in setting strategic directions for emerging threats such as innovative materials and industrial chemicals includes a highly integrated approach that structures both risk assessment and risk management processes.

However, the boundaries of a risk analysis can be too narrow. Traditionally, risk assessment is concerned with a single material, population, or end-point (such as achieving a chemical concentration standard or maximum allowable excess cancer risk). Given that the goal of risk management for chemicals is typically reducing exposures to the subject chemical within a specific target population, risk analysis may result in mitigating one risk, but only at the expense of exacerbating other problems outside the boundaries of study.

Life-cycle assessment (LCA) is a more recent analytic approach to study the systemic environmental consequences of human activities. The important distinction between LCA and more narrowly focused analytic approaches is the studied effort to include the broadest possible accounting of emissions and/or resource consumption such as extraction and benefaction of raw materials, assembly, distribution, use of finished products, and the disposition of wastes. For example, a recent LCA of remediation options for a trichloroethene (TCE) contaminated site shows significant differences in off-site environmental impacts, such as respiratory illness, global warming, and eutrophication, resulting from the emissions associated with the *remediation technologies themselves*, rather than the original TCE contamination.[12]

Unlike RA, the focus of an LCA is an economic functional unit representing a marginal increase in final demand. The overall approach begins by establishing an inventory of all chemicals released to the environment throughout the supply chain (including disposal) required to meet a marginal increase in a final demand called the *functional unit*. Selection of the functional unit is a critically important aspect of establishing the scope and goals of the study. For example, an LCA study that focuses on comparison or improvement of electricity generation technologies may report inventory results relative to one kWh of electricity delivered to a home or business consumer. However, the electricity itself may also be viewed as an intermediary product, whereas *final* demand is whatever the consumer uses the electricity *for*. Should the functional unit be represented as lighting, or heating, or computing, the results of the LCA might be very different. In the case of emerging materials, it may be unclear how to best represent the functional unit if new applications for the materials are evolving rapidly.

An emissions inventory may consist of thousands of chemical species released to multiple environmental media, including water, soil, and air. To facilitate interpretation, the inventory data are *characterized* by aggregation into several impact categories expressed in units of chemical equivalents that are representative of an environmental impact. For example, global warming impacts are expressed in terms of equivalent mass of carbon dioxide. Eutrophication is typically expressed in terms of nitrogen equivalents, and cancer is expressed in benzene equivalents. The characterization of inventory data proceeds by multiplying the mass of the chemical emission in the inventory by the standardized relative potency, or *characterization factor*, of that chemical. Typically, characterization factors lack information specific to a location, time, or other contextual environmental factors to the same extent that RA studies do. Therefore, characterized LCA data are subject to considerable uncertainties. However, decisions informed by LCA are more likely to result in an overall reduction of environmental impacts rather than displacement of impacts from one life-cycle stage to another. Therefore, it is now recognized within the EPA that the material life-cycle is the preferred perspective from which to examine problems of environmental pollution.[13]

There have been several previous efforts to integrate RA and LCA (e.g., refs 14, 15). Nevertheless, in the context of decision-making, previous analyses rarely advance beyond the rudimentary aspects of impact assessment in LCA recommended by the International Organization for Standardization (ISO).[16] In this approach, risk assessment is used to establish the proper characterization factors that relate inventory data to the selected impact mid- or end-points. However, the multiple, incommensurate data resulting from characterization do not readily lend themselves to cross-comparison to establish which impacts are most worthy of further analytical attention. One approach is to extend RA to reduce all characterized data into a common metric,

Table 1. Comparison of Risk Assessment, Life-Cycle Assessment, and Decision Analysis

	Strengths	Weaknesses
Risk Assessment	• Enables analysis despite incomplete information/uncertainty • Elucidates causal mechanisms resulting in adverse health end points • Results in quantitative comparisons on absolute basis	• Insufficiently linked to decision context • Emphasis on expert knowledge detaches process from stakeholder concerns • Extraordinarily high data requirements
Decision Analysis	• Data needs bounded by specific decision problem • Incorporates multiple stakeholder concerns through elicitation of decision criteria • Operates with quantitative and qualitative information • Incorporates uncertainty for exploring sensitivity of decision-maker choices to new information	• Insufficient to generate data • Results depend on selection of decision-analytic method, such as analytic hierarchy, outranking, or multiattribute utility theory • Additional expertise in social or cognitive sciences is required to construct mental models and determine the values of the decision-makers
Life-Cycle Assessment	• Holistic view avoids new problems • Focused on specific functional unit representing end-use demand • Facilitates prioritization or comparison of different life-cycle stages for improvement assessment • Allows comparative assessment of multiple production pathways to equivalent end use	• Paucity of inventory data regarding emerging technologies • Current standards for impact assessment lack explicit decision-analytic framework • Treatment of variability and uncertainty is inconsistent, if present at all

such as disability-adjusted-life-years (DALYs), with the implication that alternatives that present the lowest DALY impacts are the most preferred—although experts caution against oversimplification of results in terms that disguise underlying value judgments, such as weighting coefficients used to aggregate data.[17] Alternatively, ISO describes an optional normalization process in which characterized data are normalized by dividing by total regional, industry-, or nation-wide characterized emissions. The result is expressed in terms of a dimensionless fraction representing the total characterized emissions that are attributable solely to the function unit. An overall environmental impact score can be estimated by computing the linear-weighted sum of all normalized impact categories.

There are at least two difficulties with these existing approaches in the context of emerging technologies or threats. First, toxicity data for proper estimation of characterization factors are unlikely to be available for novel materials. Second, normalization by broad data sets may mask aspects of the decision that are relevant in the context of the specific decision, but have yet to manifest on a nation- or industry-wide scale.[11] Advanced techniques in multicriteria decision analysis (MCDA) can at least partially overcome these difficulties, although application of MCDA in the context of LCA and risk is still rare. (One exception is ref 18).

Table 1 identifies and compares several practical strengths and weaknesses of RA, LCA, and MCDA. RA and LCA are methods for generating primary data, while MCDA complements these methods by providing a framework for interpreting data and relating it to a specific decision problem. Without an explicit decision-analytic framework, both risk analysis and LCA can leave decision-makers or managers facing complex, multicriteria, multistakeholder problems unaided and vulnerable to bias or cognitive limitations. Ultimately, the consequences of unaided decision processes may differ from those that might, upon further reflection, be preferred by decision-makers.[19] Whereas MCDA results in a *relative* characterization of decision problem, such as a rank-ordering of alternatives from most to least preferred, RA and LCA typically result in *absolute* characterizations of risk or impact in terms of human health and/or environmental endpoints. Consequently, MCDA has previously been criticized as vulnerable to subjective biases, at least compared to RA and LCA, which strive for objectivism. Each of the three analytic approaches is individually insufficient to properly inform decision-makers of risks under uncertainty. However, these methods collectively offer improvements over a singular approach to risk analysis, which traditionally is not adept at tackling high levels of uncertainty and variability when assessing emerging materials and associated threats.

INTEGRATED FRAMEWORK

As shown in Figure 1, MCDA structures data generated by RA and LCA relative to decision criteria for the purpose of prioritizing technological (such as different materials or chemical processes) or management (such as response to climate change) alternatives. Because MCDA is directly informed by stakeholders or decision-makers who define the salient criteria and the weight sets that represent their willingness to make trade-offs among these criteria, MCDA represents an approach to risk governance and management that is inclusive of democratic ideals regarding public participation. Specific methods of public engagement have been detailed by others.[20] Generally speaking, effective risk management is understood to require integration of both analytic and deliberative processes that encompass three essential steps: (1) elicitation of values and criteria from stakeholder groups, (2) generation and assessment of alternatives relative to these criteria by experts, (3) and prioritization or selection of preferred alternatives.[21] Whereas RA and LCA are essential to step 2, it is MCDA that provides sufficient structure to step 3 to overcome the human cognitive limitations associated with reasoning under high levels of uncertainty and juggling multiple decision criteria and alternatives simultaneously.

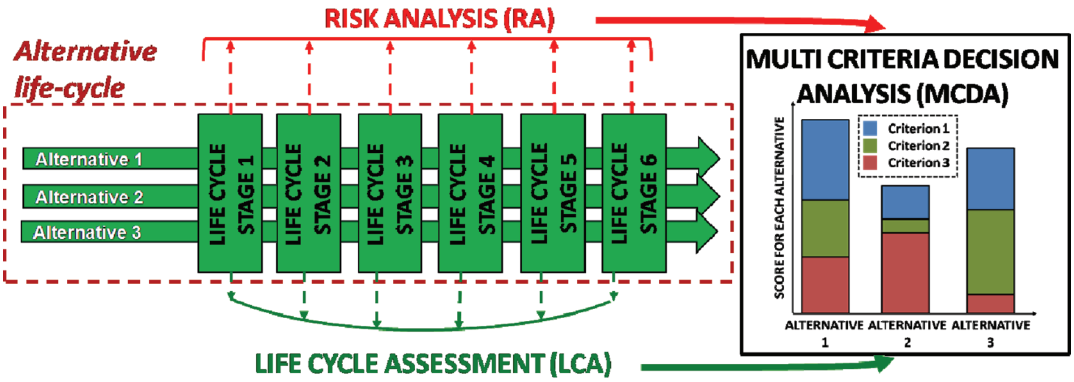

Figure 1. Combined RA, LCA, and MCDA framework for making decisions about emerging risks.

INTEGRATED PROCESS

We propose an expansion of previous frameworks in risk governance that focus primarily on discourse-based approaches to prioritizing among alternatives that explicitly incorporates decision analysis. In the case of emerging threats, where uncertainty is high due to a paucity of information, and research is ongoing, a decision-analytic approach that investigates the sensitivity of the preferred rank-ordering of alternatives to *new* information may be especially helpful in guiding the further development of novel technologies. Specific steps are detailed below.

1. Define Problem and Decision Context. In RA and LCA, framing focuses on defining the problem, the boundaries of analysis, the relevant effect end-points, and in the case of LCA, a functional unit of economic activity that represents the demand driver necessitating the subject activity. These remain essential here. However, additional aspects are required by the MCDA aspects, that may include identification of experts and construction of cognitive maps or influence diagrams that help decode the complexity of the problem.[22]

2. Identify Stakeholders, Decision-Makers, Assessment Criteria, and Weight Estimates. The necessity of public and stakeholder participation in risk management processes is already well recognized (e.g., ref 23). However, MCDA requires a formal elicitation of decision criteria or objectives from multiple decision-makers, stakeholders, or public groups engaged in the problem. It is not necessary for all decision-makers to agree on the criteria set, as any decision-maker who wishes to ignore a criterion proposed by others can choose their weight set appropriately. Contrasting weights sets should never be averaged or aggregated, as MCDA allows representation of individual views. Criteria should represent the most important goals, constraints, or other measurable consequences of the decision. Life-cycle criteria may include energy intensity and materials and aggregated life-cycle impact assessment scores. Risk-based criteria could include human health and ecological risks.

3. Define and Assess Management Alternatives. Whereas subjective decision criteria are elicited from decision-makers or stakeholders, understanding of the system and management alternatives typically resides with science experts, who must assess the performance of each alternative relative to each criterion. At this stage, uncertainty is likely to be high. However, MCDA allows quantitative, probabilistic, or even semiquantitative and qualitative assessment, so long as stakeholders can express a preference for one alternative over another with respect to each criteria (e.g., more or less, preferred or not preferred). Performance assessments can be obtained through detailed RA and LCA, or based upon expert judgment, depending upon the level of information available.

4. Apply MCDA Under Uncertainty. Aggregation of incommensurate decision criteria requires normalization of data into uniform or dimensionless units that can subsequently be compared based on minimization or maximization preferences. Because there may be little or no public information on appropriate weight sets, it is reasonable to explore all feasible weights sets stochastically.[11,24] Each alternative must be scored by computing a weighted average of relative performance on each decision criteria. Lastly, the weighted scores result in a probabilistic rank ordering of the different alternatives for each distinct stakeholder or decision-maker group. Such an approach can be used to screen underperforming alternatives, prioritize high-ranking alternatives for further research, or to facilitate further value-elicitation from decision-makers and stakeholders.

APPLICATIONS

The framework presented for synthesizing information from both RA and LCA in a decision-directed structure is flexible enough to be applied in a variety of settings. Table 2 introduces two examples where this approach is currently being applied. Where multiple decision-makers or stakeholder groups have bearing, MCDA can show where and why the preferences of different stakeholder groups are either aligned or in conflict, and express a quantitative measure of confidence in the results. Moreover, the results can be tested for sensitivity to new information, such as a change in criteria uncertainties resulting from additional research. Each case study exemplifies certain aspects of the ideal framework, with the exception of testing the sensitivity of eventual decision-maker preferences with respect to new hypotheses or information for the purpose of guiding future research. Wider adoption of this framework would aid in the prioritization of research programs and the subsequent interpretation of their results.

Nanomanufacturing. The first case study relates to nanoengineered product development. At the current state of nanotechnology, a number of systhesis pathways for nanomaterials may be available, and considerable uncertainty may exist regarding the preferred pathway—e.g., top-down or bottom-up.[30] Agents acting at different life-cycle stages may have legitimate disagreements about materials selection or synthesis technologies. Therefore, nanotechnology presents several characteristics of an intractable environmental problem: a high degree of uncertainty, multiple or competing objectives, and complexity

Table 2. Framing the Case Studies with a Combined RA, LCA, MCDA Approach

	Nanomanufacturing[25]	Management of Contaminated Sediments[26−29]
Decision Context	Choose optimal process to manufacture single-wall carbon nanotubes (SWCNT)	Select a management alternative for contaminated sediments
Stakeholders/ Decision-Makers	Nanomanufacturers, consumers, regulators, environmentalists	Government, and private sector; agency officials, environmentalists, general public
Alternatives	High Pressure Carbon Monoxide (HiPCO), arc discharge (Arc), chemical vapor deposition (CVD), laser vaporization (Laser)	Natural recovery, capping, landfill, open water disposal
Life-Cycle Stages	Extraction, manufacturing and assembly, use, disposal	Alternative implementation, disposal facility use and operation, end-life stage
Criteria	Material efficiency, energy consumption, LCIA Score, cost, health risks	Contaminant transport and human exposure, societal impacts, cost, carbon footprint
Associated Risks	Human health and ecological risks	Human health and ecological risks

in the interaction of several system elements that may result in surprising consequences. Canis et al.[25] focus on assessment of synthesis pathways for production of single-wall carbon nanotubes (SWCNT). There is significant variety in approaches, including high pressure carbon monoxide (HiPCO), arc discharge (Arc), chemical vapor deposition (CVD), and laser vaporization (Laser). Each process produces SWCNT with different purities and properties that must be processed further (e.g., acid washing, purification, cutting) depending upon the final application, and therefore, engenders unique life-cycle environmental, economic, and health (such as worker or consumer safety) consequences.

Selection of an appropriate manufacturing alternative depends upon the values placed on the criteria chosen for impact evaluation including material efficiency, energy consumption, life-cycle impacts (of associated bulk chemical releases), production costs, and nanorelated health risks. Different stakeholders' views can be represented in the form of weight sets that represent the tradeoffs among these decision criteria. For example, manufacturers could place higher value on cost, material and energy process efficiency, and health risks—but not life-cycle considerations. End users may agree with manufacturers on cost, but place greater emphasis on health risks and life-cycle impacts, without separate consideration of process efficiency. Environmentalists and regulators might place more value on protection of natural resources and environmental quality without concern for costs. In the extreme, one group may chose to ignore one or more criteria altogether.

In the case presented by Canis et al.,[25] HiPCO is most likely the preferred alternative for all stakeholders given the current state of information presented. Nevertheless, the strength of that preference varies among different groups. Manufacturers and end-user preferences are very strong, while the environmentalists and regulators are much more uncertain. The contrast results from different preferences for environmental impacts relative to cost. This distinction is very important in the context of planning a research strategy. For example, new information on health risks may change the preferred rank ordering of each alternative for some stakeholders, but not for others. This case emphasizes the role of LCA information and contrasting stakeholder views when nanomaterial-specific toxicological risk information is unknown.

Management of Contaminated Sediments. Management of contaminated sediments is typically driven by ecological risk assessments that consider risks associated with the contamination presence in the environment, but not impacts associated with remediation operation itself. Although the contamination in the sediments is not an *emerging* issue (contaminated sediments are typically the result of industrial-age practices that have long since been abandoned), the social and regulatory expectations with regard to sediment management are evolving rapidly. Practices that were previously legal and widespread may now incur enormous civil liabilities for the potentially responsible partners. Consequently, approaches to contaminated sediments management now incorporate a much deeper commitment to stakeholder and public participation than was previously the case —sometimes with surprising results.[31] An MCDA approach that is coupled with LCA may therefore be a valuable complement to risk assessment and overall sediment risk management.

For example, Sparrevik et al,[26−29] report an integrated framework for contaminated sediment management that incorporates life-cycle and risk data in a stakeholder-driven MCDA model. Traditional sediment management used in these studies includes alternatives such as natural recovery, capping, near shore disposal, landfill, and open water disposal. The general increased environmental concern and involvement of stakeholders in today's environmental issues may enhance the need to consider risk in a much broader social context rather than just as an estimate of ecological hazard. Risk perception and the constructs and images of risks held by stakeholders and society are therefore important items to address in the sediment management process. To overcome these problems, decision criteria such as social acceptance are incorporated into the MCDA model as decision criteria, along with ecological and human health risks and costs. The results favor remediation alternatives that are less resource intensive, such as the use of biochar as a substitute for activated carbon derived from petroleum or coal resources. However, the LCA results have to be balanced against other interests when selecting remedial strategy. LCA in combination with MCDA provides therefore a flexible strategy for the decision-maker to prioritize remedial strategies based on a holistic perspective. For stakeholders or residents to be able to embrace a complex decision such as selection of remediation alternatives, an involvement process with lateral learning using results derived from both LCA and RA process, combined with MCDA giving structure, robustness, and transparent documentation is preferable. This case study incorporates all three analytic elements, but stops short of testing whether new information might resolve disagreement.

DISCUSSION

There are several advantages to framing risk assessment and management in a decision-analytic context—especially in applications of high variability and uncertainty.[32] Whereas the objective of technical analysis is often an absolute characterization of intrinsic material properties, a decision-directed approach emphasizes comparative bases for relative assessment of alternatives (e.g., ref 33). Because the decision-directed approach is bounded by the available alternatives and decision criteria, data needs may be less intensive. Top-level goals focus the investigation on those factors that influence choices among the available alternatives.[34] Moreover, research efforts can be focused on reducing uncertainties that relate directly to the preferred alternatives, conserving investigative resources that are unlikely to result in a change in eventual decision-maker preferences. However, a decision-directed approach requires coupling risk analytic investigations with both value elicitation tools and structured decision aids, such as cost−benefit or multicriteria decision analysis.[21] This necessarily requires an expansion of knowledge expertise to include social and decision sciences (e.g., ref 19) in addition to the physical and toxicological sciences, so as to combine multiple objectives into a single total score or explore trade-offs among incommensurate objectives.

The need for a decision-directed approach to risk management of emerging threats is especially acute, due to the high levels of uncertainty associated with novel technologies, the complex systems in which they are embedded, and the divergent views of groups vested in the risk outcomes. For example, recent NRC reports regarding environmental health and safety research for nanomaterials[35] and bulk chemicals[2] are critical of the lack of connectivity between existing research programs and the needs of policy and product development decision-makers. It should be clear that developing appropriate risk- and life-cycle based decision frameworks that are operable in highly uncertain research domains should be a high policy priority. In fact, the draft National Nanotechnology Initiative *2011 Environmental, Health, and Safety Strategy*[36] emphasizes RA, LCA, and MCDA as appropriate methods for prioritizing research strategy in the physical sciences. Among the variety of MCDA methods that have been developed to inform decision-making in social and environmental contexts, several are amenable to application in areas of high uncertainty and/or emergent technology.

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