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Horses for courses: risk information and decision making in the regulation of nanomaterials

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Abstract Despite the widespread commercial use of nanomaterials, regulators currently have a limited ability to characterize and manage risks. There is a paucity of data available on the current production and use of nanomaterials and extreme scientific uncertainty on most aspects of the risk assessment "causal chain." Regulatory decisions will need to be made in the near-term in the absence formal quantitative risk assessments. The article draws on examples from three different regulatory contexts—baseline data monitoring efforts of the U.S. Environmental Protection Agency and California Department of Toxic Substances Control, prioritization of risk information in the context of environmental releases, and mitigation of occupational risks—to argue for the use of decision-analytic tools in lieu of formal risk assessment to help regulatory bodies. We advocate a "horses for courses" approach whereby existing analytical tools (such as risk ranking, multi-criteria decision analysis, and "control banding" approaches) might be adapted to regulators' goals in particular decision contexts. While efforts to build new and modify existing tools are underway, they need greater support from funding and regulatory agencies because innovative approaches are needed for the "extreme" uncertainty problems that nanomaterials pose.

Keywords Expert judgment · Nanotechnology risks · Regulation of nanotechnology · Risk ranking · Voluntary regulation · Governance

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Introduction

The growth of nanotechnologies in industry sectors ranging from pharmaceuticals and chemicals to energy and environment has been rapid. An ever-increasing number of unique nanomaterials are created every year, each engineered to take advantage of the properties that emerge when materials are manipulated at the nanoscale (Maynard 2007). Nanomaterials are already in use in scores of consumer products (Berube et al. 2010; PEN 2010), and hundreds of distinct types of nanomaterials are in production in the United States (Nanowerk 2010). With their growing prevalence, nanomaterials are expected to be released in occupational settings (Johnson et al. 2010), during product use (Colvin 2003; Felcher 2008), and into wastewater and landfills at the end of their useful life (Breggin and Pendergrass 2007; Benn and Westerhoff 2008). With these expected releases, human and

environmental health may be negatively impacted, and such impacts will have to be understood and managed if we are to safely enjoy the benefits of nanotechnology.

Despite the wide use of nanomaterials in commerce in the United States, regulators currently have limited access to information required for characterizing risks (Linkov et al. 2009a). This lack of information has hampered regulators' ability to asses and manage potential risks (Mittal 2010). In addition to a lack of information, there are at least three sets of barriers to the effective regulation of nanomaterial production, use, and release. The first set of barriers are institutional, particularly in the United States where environmental and non-occupational human health risks are primarily the responsibility the U.S. Environmental Protection Agency (EPA) and occupational risks are under the purview of the Occupational Safety and Health Administration (OSHA). In both cases, the regulatory agencies (EPA and OSHA) are under-resourced and are structurally unable to generate or acquire the rapidly expanding amount of risk information required to regulate nanomaterials and, more generally, chemicals (Bergeson et al. 2000; Powell et al. 2008). For instance, EPA can require testing of a new chemical, but it must first show the chemical could pose a risk—this puts the agency in a catch-22 since it does not have hazard data in the first place (Davies 2006; Choi et al. 2009). The burden of data collection and risk assessment is placed on these agencies that do not have budgetary means to carry out this mandate, while nanotechnology firms have little or no incentive to reveal or generate risk-relevant information under the existing regulatory regime (Choi and Ramachandran 2009; Choi et al. 2009).

Institutional difficulties are compounded by a second set of challenges—those posed by nanomaterials to existing methods for assessing and characterizing risks. For many environmental contaminants, there is a lack of sufficient information for analyzing multiple components of the risk assessment framework. In such cases, the use of default assumptions and extrapolations to fill in the data gaps is a common practice (Cooke 2010). Nanoparticles, however, pose an additional novel form of risk assessment challenge. As noted there is deep scientific uncertainty regarding every aspect of the risk assessment framework. These include uncertainties about particle characteristics that may affect toxicity, fate, and transport through the environment, routes of exposure and the metrics by which exposure ought to be measured, the mechanisms of translocation to different parts of the body, and the mechanisms of toxicity and disease (Kandlikar et al. 2007). In each case, there are multiple and competing models and hypotheses. Further compounding this risk assessment challenge is the emerging paradigm of life cycle risk assessment (Owens 1997; Sweet and Strohm 2006; Shatkin 2008; Beaudrie 2010), whereby regulators are expected to investigate potential impacts at every stage of a material or product's life. Consequently, uncertainties in estimating risks due to nanoparticle exposures are extreme and not yet easily amenable to the sorts of risk assessments that form the basis for current regulatory activities (Tsuji et al. 2006).

A final consideration in the regulation of nanomaterial risks is the regulatory impact on innovation in an emerging sector. Like other new technological domains, nanotechnology innovations are often made by small companies and startups. These firms have neither the expertise nor the resources to adequately assess the health and environmental risks of nanomaterials. Consequently, regulations that do not recognize this run the risk of slowing down the pace of innovation or increasing costs. This results in a "regulator's dilemma" (Weinberg 1986) where the uncertain costs of doing too much (chilling effects on innovation, increasing product costs) need to be weighed against the costs of doing too little (eroding trust in regulatory institutions, causing undue harm) to manage emerging risks.

The early U.S. regulatory response to nanomaterials in the face of institutional barriers and uncertain science was one based on voluntary measures. In early 2007, the EPA implemented a voluntary Nanomaterial Stewardship Program (NMSP). Like prior voluntary programs under Toxic Substances Control Act (TSCA) aimed at persuading chemical manufacturers to reveal screening level data, the NMSP has also been limited in its ability to generate risk information (Breggin et al. 2009). The scantiness of data gathered makes it evident that a compulsory reporting regime might be required (Brown 2009). Other North American jurisdictions have begun to mandate reporting through information "call-ins," such as the one issued by the California Department of Toxic Substances Control (DTSC), formally requesting "information regarding analytical test methods, fate and transport in

the environment, and other relevant information from manufacturers of carbon nanotubes" (Wong 2009). Similarly, Environment Canada (EC) decided in 2007 to treat nanomaterials as "new substances" under the Canadian Environmental Protection Act; this requires manufacturers and importers to submit risk related information to regulators (Environment Canada 2007).

Data requests can provide much needed baseline information on nanomaterial manufacture and use activities. However, baseline data is just one of many pieces of information that regulators might need. As nanomaterial use continues apace, regulators will face various decision contexts when dealing with the regulation of potential environmental pollutants. Agencies are responsible for, among other things, developing an understanding of the scope of a regulatory challenge, investigating and managing potential risks, and providing guidance for the safe production, use, and disposal of materials or technologies. In each of these contexts, regulators face decision-making and data challenges that are complicated by limitations in existing risk assessment tools. Until the science of nanomaterial risk assessment matures, regulators will need to explore the use of alternative approaches to aid in near-term decision-making (Kandlikar et al. 2007; Grieger et al. 2010). This article focuses on such challenges and explores some possible solutions.

The remainder of the article is structured as follows: in "Nanomaterial risks and regulatory decisions" section we focus on how the decision context can determine data needs; in "Baseline information and nanomaterial data collection" section we examine, based on recent experiences of U.S. regulators, what data/information can actually be obtained from firms; in "Risk information and decision making" section we examine how available information- and expert judgment-based decision support tools (both existing and novel) might help regulatory bodies manage nanomaterial risks. We conclude in "Conclusion" section with a discussion of data needs for supporting near-term regulatory decision making.

Nanomaterial risks and regulatory decisions

Quantitative risk assessment for environmental pollutants relies on mathematical models with input parameters relating to concentrations of pollutants in the environment, extent and duration of exposure, and toxicological effects from exposure. In conventional chemical-based risk assessment models, uncertainties in the values of each of these model parameters are parametric and analyzed using Monte Carlo simulations. In the case of nanomaterials, assessing and quantifying health risks is further complicated by lack of data and deep scientific uncertainty regarding every aspect of the risk assessment framework: (a) particle characteristics that may affect toxicity; (b) the persistence of manufactured nanoparticles in the environment which, in turn, influences the probability of exposure; (c) the routes of exposure and the metrics by which exposure ought to be measured; (d) the mechanisms of translocation to different parts of the body; and (e) the mechanisms of toxicity and disease. These are not merely uncertainties in the value of model parameters but rather uncertainties about the choice of the causal mechanisms themselves and the proper model variables to be used. Consequently, uncertainties in estimating risks due to nanoparticle exposures may be characterized as "extreme." The central challenge in quantifying nanoparticle risks is the presence of extreme uncertainty as manifested in difficulties of choosing appropriate model variables and the presence of multiple and competing models (Kandlikar et al. 2007).

Due to these extreme uncertainties, developing the information base needed to support regulatory action for nanomaterials using traditional risk assessment techniques is more challenging than it is for conventional chemicals. It is unlikely that traditional risk assessment tools can be used in the near future (IRGC 2007, 2009; Marchant et al. 2008), and regulators will be faced with understanding and managing the growing field of nanomaterials by utilizing alternative assessment tools and approaches (Owen and Handy 2007). Professional or expert judgment can be useful in identifying relevant variables, assessing the strengths of competing mechanisms and models, and in estimating uncertainties in parameters (Morgan and Henrion 1990). Expert judgment also lends itself naturally to the development of tools for decision making under uncertainty (Cooke and Probst 2006; Knol et al. 2010).

In what follows, we will explore three regulatory scenarios that highlight the difficulty of collecting

risk-relevant information and that demonstrate how decision-support methods can aid in regulatory decision making while the science of nanomaterial risk assessment is developed further. The scenarios include:

- developing baseline information for production and releases of nanomaterials;
- establishing priorities for risk related research; and
- managing occupational risks in the workplace.

Figure 1 illustrates these three scenarios and highlights the relationship between the increasing specificity of the decision context and the different tools and data needs required to meet regulatory goals. As a decision context becomes more specific (moving from left-to-right), the data needs become more apparent, and the requirements for decision support methodologies become clear (i.e., selecting control methods for a specific nano-process). For less specific contexts in which decisions are broad based (moving from right-to-left), greater clarity in decision goals is needed to improve selection from a menu of support tools. These following sections will investigate this spectrum of regulatory decision contexts in greater detail.

Baseline information and nanomaterial data collection

Since many nanomaterials are largely unregulated (Beaudrie 2010), information about risks from their current use is scarce. Publicly available information can be accessed primarily through two sources—the Nanowerk database (Nanowerk 2010) and the Project on Emerging Nanotechnologies' Consumer Products Inventory (PEN 2010). The Nanowerk database contains information on nanoscale *materials* that are available for commercial and research sale. While a useful tool, the database does not distinguish between research and commercial use, nor does it have the means to check the accuracy of information provided. The PEN database catalogs *consumer products* on the basis of producer claims about the presence of nanomaterials. The PEN database also suffers similar shortcomings related to verification of the presence of nanomaterials and their molecular identity (Berube et al. 2010). The paucity of reliable data on nanomaterial production and use is one motivation for data collection efforts of regulatory agencies such as EPA, DTSC, and Environment Canada. In what follows, we will summarize the goals behind the EPA and DTSC efforts for baseline data monitoring and will briefly comment on the outcomes and their implications for managing and regulating nanomaterials.

EPA's NMSP

The NMSP's data collection efforts are part of an ambitious voluntary plan to promote environmental stewardship of nanomaterials. Of the four explicitly stated goals of NMSP only one is aimed at collecting data about existing nanoscale materials from manufacturers and is the focus of this section. The other goals pertain to identification and promotion of risk management practices, development of test data, and encouragement of "responsible development" and are not examined here. Under the "Basic" program of the NMSP,[1] the EPA developed a data submission form modeled after TSCA's Pre-Manufacture Notification (PMN). Firms were encouraged (but not required) to use this form in responding to the program. In addition to general identification information about the substance (i.e., chemical name, molecular formula, CAS number), the form also asks for data on amounts, chemical and physical properties in the standard PMN format, properties specific to nanomaterials (e.g., size-dependent properties) not included in the PMN, and hazard information such as health and environmental effects, bioaccumulation, and biodegradation.

The data collection phase of NMSP lasted for 6 months, and EPA issued an interim report in July 2008 (EPA 2009). While the Nanowerk database had over 1800 distinct entries for nanoscale materials and the PEN database over 600, the NMSP reported 106 distinct nanoscale materials, which is a relatively low yield rate. Of these almost two-thirds of the nanomaterials (63) were reported by a single company, and one-sixth of nanomaterials were not named due to claims of confidentiality (Chatterjee 2008). While the agency had relative success in collecting information on basic physical and material characteristics (this type of information was obtained for between 60%

[1] An advanced program was also envisaged, but as of December 2009 only four companies had signed on.

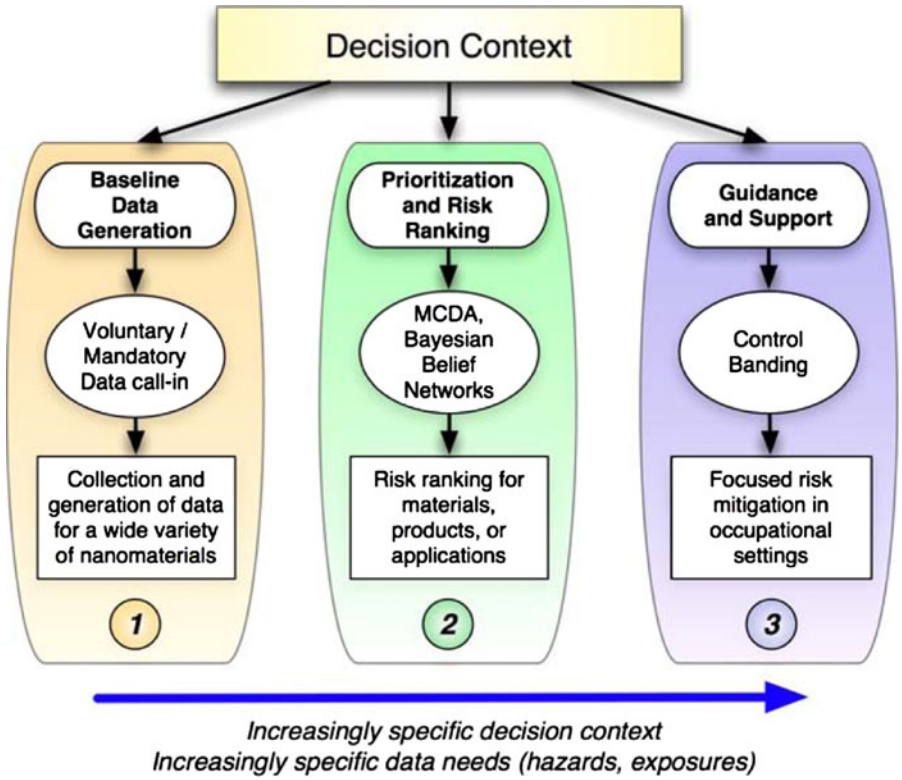

Fig. 1 Decision contexts and available decision support tools. Decision contexts (*rounded rectangles*) become increasingly specific from left-to-right influencing the choice of support tools (*ovals*) to aid in regulatory decision making. Data requirements similarly become more specific with increasing specificity of the decision context

and 80% of nanomaterials), risk information was largely missing from the submission. Data for acute toxicity was provided for about 20% of the materials, while chronic toxicity was provided for less than 5% of materials. Data collection under the NMSP was ambitious, and the categories of data requested went beyond those expected of other new chemicals. However, the voluntary nature of the program meant that the yield rate was low, as was the quality of risk information obtained. It is possible that the companies with little experience working collaboratively with EPA might have had concerns about the implications of voluntary disclosures, including those related to confidentiality, and refrained from complying with the NMSP request (Lockard 2010). Clearly, there was a mismatch between the expectations and goals of EPA and the eventual outcome of the NMSP data collection effort.

California DTSC carbon nanotube information "call-in"

In January 2009, the California DTSC issued a letter "requiring information regarding analytical test methods, fate and transport in the environment, and other relevant information from manufacturers of carbon nanotubes" from all California-based producers and importers carbon nanotubes (CNTs) (Wong 2009). DTSC used its authority under the California Health and Safety Code in issuing a mandatory "call-in." The six call-in questions were general in nature and asked each firm about its position in the value chain, sampling and monitoring methods used in the workplace, knowledge about the firm's product in the environment, knowledge about CNT risks, and methods used to protect workers. Questions were aimed more at discovering the types of work in which the firms engaged and less about technical details related to material properties and risk.

While a comprehensive assessment of the response to DTSC is beyond the scope of this article, the overall response to the call-in was mixed. Of the 22 respondents to the DTSC call-in, 11 research organizations (universities and national research labs) and six private firms provided substantive responses. In addition, two firms were out of business and three other respondents stated that their work did not involve CNTs. Strikingly, half of the six private firms

provided very brief responses—these are likely small venture-capital based companies lacking resources to respond fully to questions. Among the universities and research organizations, there was substantial variation. Some groups (such as the California State University system) reported no CNT usage, while others provided detailed responses. The specific responses to questions might (at least at the current stage) be less useful than the process and dialog in which DTSC has begun to engage manufacturers of nanomaterials. DTSC is signaling to users and producers of nanomaterials that there is need for information disclosure and is thereby raising awareness about the potential health and safety consequences. The DTSC is also engaging in dialog via site visits[2] and information sessions.

The DTSC call-in and EPA NMSP provide interesting contrasts. EPA's program was voluntary, while DTSC's call-in was mandatory and required firms to respond. EPA's data collection efforts were comprehensive and based on a standardized data collection form; they also went beyond what is required for new chemicals under TSCA. DTSC's call-in, on the other hand, included open-ended questions that accommodated a range of qualitative responses. In particular, it appears that an explicit decision was made by DTSC to avoid asking for risk information that needed expensive (and potentially mandatory) bioassays (Lockard 2010). The response to both initiatives was mixed, suggesting that improvements could be made. There may also be inherent limits to obtaining useful information from such efforts in the face of confidentiality claims. Neither of these approaches has been successful in acquiring the full range of nanomaterial property and toxicology data required to permit a full risk assessment in the near-term. However, at this early stage, the collected data can help regulators to better understand the scope of the challenge and to assess their needs for future calls for information.

Baseline information call-ins provide regulators and risk managers with preliminary data on the types and amounts of nanomaterials being created, used, and released. As the EPA and DTSC experience shows, this data will initially be scant, and procedures for collection will need to be improved. However, as more complete data becomes available, regulators will be faced with the greater challenge of assessing the implications of a variety of nanomaterials used in a wide range of applications. We turn to this challenge in the next section.

Risk information and decision making

As more risk information becomes available for nanomaterials, regulators will face a challenge in deciding how to utilize limited resources to best manage potential risks. Nanomaterials, nano-applications, and nano-products will have to be analyzed to determine which may pose the greatest harm (if any) along its lifecycle, and regulators will have to prioritize them accordingly for further scrutiny. In addition, regulators will be required to provide guidance and advice to manufacturers of nanomaterials so they may protect workers and make products that are safe. It is unlikely, however, that traditional risk assessment tools can guide this decision-making process in the near-term (Kuempel et al. 2007; Grieger et al. 2010). While research continues on developing nano-specific risk assessment models (Tsuji et al. 2006; Warheit et al. 2008), regulators will be required to make complex risk–benefit tradeoffs. This task will require tools that allow regulators to make best judgments given available information. In contexts where complexity is endemic, uncertainties are large, and optimal decisions are not obvious, formal decision-analytic methods can help (Kuempel et al. 2007; Kuzma et al. 2008; Linkov and Satterstrom 2009; Linkov et al. 2009b; Grieger et al. 2010).

Decision-analytic methods can synthesize both available information and expert judgment into an integrated framework (Tervonen et al. 2009). Rather than providing an absolute measure of risk, decision-analytic methods can be used to provide a measure that allows regulators to rank the relative risks of nanomaterials (Hansen et al. 1999). Organizing a multitude of potential risk sources into a ranked list might help regulators focus their attention on those with the greatest potential for harm. Similarly, risk-ranking tools can be used to provide guidance on the selection of safety measures to limit exposure or to anticipate and plan for risk events (Hansen et al. 1999; Fauss et al. 2009; Owen et al. 2009).

[2] Survey questionnaires administered to CEOs during the site visits also provided DTSC with additional information about activities of ten companies.

There are numerous decision contexts for which regulators must begin to investigate potential harm from nanomaterials, and each context brings with it a specific set of data needs and support tools. Below we provide two examples to illustrate the information and assessment challenge that regulators are likely to face as nanomaterials proliferate.

Risk ranking and prioritization

Risk managers and regulators are currently faced with a growing problem. If conventional risk assessment is to be used as the standard for making decisions, then many questions about nanomaterial risk management could go unanswered until adequate information becomes available. As noted above, however, decision-analytic tools and expert judgment can be used to enable a preliminary assessment and ranking of risks, and several examples of such methodologies have been demonstrated for nanomaterials in recent years (Robichaud et al. 2005; Hansen et al. 2008; Wardak et al. 2008).

Risk-ranking methodologies can involve qualitative or quantitative estimations of hazards and/or exposures and can be applied to materials, products, applications, or lifecycle stages. As the examples below indicate, these methodologies are flexible and can be useful in many different decision contexts. Hansen et al. (2008) conducted a risk-ranking analysis by utilizing scenarios for exposure from consumer products containing nanomaterials. Exposure was rated from "expected exposure" to "possible exposure" or "no exposure" based on the location of nanomaterials and product use, and the researchers were able to identify classes of nanomaterials and products currently on the market that are likely to pose the highest exposure. Robichaud et al. (2005) investigated a similar problem involving a qualitative assessment of risks from the production of nanomaterials. Their analysis involved expert judgment on five factors related to both hazard and exposure potential: emissions, flammability, log K_{OW} (bioaccumulation), water solubility, and toxicity. While the analysis investigated comparative risks from the chemicals used in the production process, and not risks from nanomaterials per se, their study illustrates how comparative estimates of risk might be made. Wardak et al. (2008) similarly used expert judgment as input to the "probability" and "severity" estimates of possible "risk triggers" (inherent nanoparticle properties that trigger a higher level of risk) for a variety of nanomaterials across their lifecycle. Risk triggers were identified for two lifecycle stages (use and disposal) and three exposure pathways (inhalation, ingestion, and skin absorption). Expert judgment was used to determine subjective scores (scale of 1 to 5) for each risk trigger, and the scores were combined to map the relative risks of different nanomaterials for each combination of life cycle stage and exposure pathway. These three approaches have many similarities in methodology that can be formalized using multi-criteria decision analysis (MCDA), which we turn to next.

MCDA is a widely discussed approach to nanomaterial risk assessment with a long history of use in various decision contexts (Linkov et al. 2007). The first stage of MCDA typically involves the development of criteria by which the "utility" of each nanomaterial under consideration is characterized. Each of these criteria is then given weight based on its importance for the decision maker. Several tools are available to help the decision maker in this weighting task (Linkov et al. 2007; Tervonen et al. 2009). In a final step, nanomaterial performance can be compared across decision criteria and a weighted aggregate performance measure defined. As MCDA is an inherently subjective process, it requires the use of judgment at every step of the analysis. Consequently, experts are able to weigh available evidence and make best judgments when data are not available. As such, the MCDA framework is well suited to analysis under high uncertainty (Kiker et al. 2005; Tervonen and Lahdelma 2007; Seager and Linkov 2008).

Tervonen et al. (2009) use MCDA-type analysis called SMAA-TRI that classifies five nanomaterials into five different risk categories: extreme risk, high risk, medium risk, low risk, and very low risk. The analysis is based on a set of performance metrics that measure both the toxicity and physicochemical characteristics of nanomaterials, along with expected environmental impacts through the lifecycle. The approach can incorporate available data (i.e., particle size) as well as subjective probabilities for variables that are not available from the literature (i.e., measures for bioavailability). The result is the assignment of each nanomaterial to different risk classes along with an associated measure of confidence in the assignment.

A benefit of MCDA is its adaptability to various decision contexts. Whether the goal is risk ranking, prioritization, or identification of high-risk life cycle stages, the MCDA approach can be applied. Further, MCDA can draw input from various groups of experts and members of the public, and analyses can be made even with limited data. The MCDA framework is flexible enough to incorporate criteria such as "social importance" and "stakeholder preference" in addition to traditional risk measures, allowing a much broader analysis of the benefits and risks of emerging nanomaterials. MCDA is also adaptive because it enables the implementation of near-term solutions. Subsequent management modifications can be made as new scientific data becomes available or regulatory policy evolves (Linkov et al. 2007).

While MCDA is a useful tool, the simple modeling techniques that underlie it (linear, additive response models) can miss the actual complexity of the risk phenomena. Mechanism-based models that characterize the relevant physical and biological variables and their interactions provide more accurate representations and are, therefore, more scientifically defensible. A recent study by Morgan (2005) using influence diagrams demonstrates how physical and biological variables can be systematically mapped in an influence hierarchy that characterizes nano-toxicology. Influence diagrams are a generalized representation of probabilistic networks such as Bayes Belief Networks (BBNs) (Pearl 1986) that can be used to model variables and their influences in a probabilistic manner. BBNs have been used in myriad fields including ecology, resource management, and technology forecasting (Heckerman et al. 1995; Vans 1998). While there are currently no examples published in peer-reviewed literature of BBNs in the nanomaterial risk domain, the field is well suited for the use of this approach, particularly for calculating the value of different types of information and so suggesting directions for new research and data monitoring efforts.

Risk ranking and other decision-analytic tools are largely illustrative at this point; however the studies described above provide preliminary evidence that regulatory decisions could benefit from their use. Such tools could be utilized in the near-term to provide guidance for action, to prioritize for data collection and further research, or to limit the use of certain nanomaterials or applications. As more data and a better scientific understanding of the relationship between nanomaterial properties and toxicity/exposure become available, these methodologies can develop into more robust risk assessment tools.

Expert judgment will likely play a significant role both in the selection of variables and their weighting when developing or fine-tuning frameworks, as well as in estimating values when utilizing frameworks for specific decisions. In the case of occupational health, expert judgment is currently used to estimate both prospective risks in operational settings (Walker et al. 2001; Ramachandran et al. 2003), as well as retrospective exposures (Ramachandran 2001) in historical workplace settings. It is therefore not surprising that occupational exposure assessment has made the greatest progress toward developing risk management and mitigation tools for nanomaterials. We describe these efforts below.

Occupational hazards and control banding

Occupational health is at the forefront of concern for nanomaterial safety. However, recent research by Engeman et al. (2010) describes that only 45% of companies surveyed in North America, Europe, and Asia report having a nano-environment, health, and safety (EHS) program in place. The top three reasons for not developing a nano-EHS program include "a lack of information," "a lack of guidance/regulation," and "budget constraints" (Engeman et al. 2010). A similar survey of companies working with nanomaterials in Germany and Switzerland in 2008 indicated that 65% of companies did not conduct risk assessments on materials that they produce (Helland et al. 2008). These figures illustrate a significant gap in occupational safety programs that can protect workers from potential risks associated with nanomaterial production. Further, this gap signals a growing need for nanomaterial safety guidance for the workplace.

Occupational risks pose a different challenge than the risk-ranking scenarios described in the previous section. Given the very specific context of risk in a laboratory or production facility, it is likely that more information is available to a risk manager, especially in cases where nano-EHS programs are in place. First, the basic characteristics of materials such as composition and size distribution will likely be known. Other physical/chemical properties of materials may also be

known in some instances, and some assay or toxicological data may be available. It is also very likely that the exposure scenarios under consideration can be clearly defined, and a menu of mitigation options is available. In other words, in occupational settings the decision context is well mapped, and the decision problem is more manageable than the open-ended ranking exercise of the previous section. Decision making often boils down to a single question: how can particular hazard/exposure combinations linked to different workplace tasks be associated with specific measures for exposure control? In these instances, decision-support tools are useful (Maynard 2007; Zalk and Nelson 2008). In particular, a recent approach known as "control banding" can aid in choosing appropriate exposure control methods.

Control banding is a methodology that has served as a support tool for occupational safety for a number of years and has been used extensively by the pharmaceutical industry for categorizing exposure controls in the workplace (Maynard 2007; Zalk and Nelson 2008). The idea is to develop "control bands" that can be mapped to particular sets of exposure/hazard combinations so that health risks for workers involved in particular operational tasks are minimized. Each control band corresponds to a particular control technology or action that is suitable for the given hazard and exposure scenario.

A nanomaterial-specific control banding methodology ("CB Nanotool") was developed by Paik et al. (2008) through extensive expert input, review, and testing. The CB Nanotool involves a basic matrix with "severity" (i.e., hazard) and "probability" (i.e., exposure) indices as the X and Y axes and utilizes nanomaterial physical/chemical properties (shape, size, surface area, and surface activity), available toxicology information (carcinogenicity, mutagenicity), and exposure availability (volume produced, dustiness) to link the indices to one of four control bands (Paik et al. 2008). The control bands correspond with increasingly stringent control methodologies from "general ventilation" up to "seek specialist advice." An example of the CB Nanotool control banding matrix can be seen in Fig. 2.

Analysts can input known "severity" factors for each nanomaterial in use and estimate "probability" factors based on specific exposure characteristics of each occupational task under consideration. The resulting combination of severity and exposure scores for each task relates to one of the four control bands that provide control advice for minimizing occupational risk.

One strength of such a tool lies in its ability to utilize basic data without the need for expensive testing. In addition, control banding offers the advantage of focusing on a small number of risk management/mitigation decisions to help in managing the "extreme uncertainty" problem. Furthermore, where nanomaterial-specific information on factors related to "severity" are unavailable, "unknown" values can be set to a default of "high" to enable a precautionary approach to the selection of exposure control measures. The tool is more risk averse at the start but can be modified to reflect new scientific findings as and when better risk information becomes available. Not surprisingly, the CB Nanotool was demonstrated to provide recommendations that were equal to or more conservative than industrial hygiene experts' opinions for adequate controls in 27 of 31 trials (Zalk et al. 2009). Since it can provide guidance

Probability Score

Severity Score	Extremely Unlikely (0 - 25)	Less Likely (26 - 50)	Likely (51 - 75)	Probable (76 - 100)
Very High (76 - 100)	RL 3	RL 3	RL 4	RL 4
High (51 - 75)	RL 2	RL 2	RL 3	RL 4
Medium (26 - 50)	RL 1	RL 1	RL 2	RL 3
Low (0 - 25)	RL 1	RL 1	RL 1	RL 2

Fig. 2 Control banding matrix with risk level (RL) indicators as a function of the combination of probability and severity scores. Control bands correspond to risk levels as follows: RL 1—General Ventilation; RL 2—Fume hoods or local exhaust ventilation; RL 3—Containment; RL 4—Seek specialist advice. (Adapted from Paik et al. 2008)

for selecting control measures in the workplace without extensive workplace specific research, the CB Nanotool has been adopted as part of the Lawrence Livermore National Laboratory Nanotechnology Safety Program (Zalk et al. 2009) and is under consideration for use by Safe Workplace Australia, which is the Australian regulatory body for worker health and safety (Occupational Health & Safety 2010).

Conclusions

The data and analysis challenges facing regulators of nanomaterials are extensive. Some of these challenges—particularly institutional ones–can only be fixed with changes to existing regulations. For instance, TSCA reform that is currently underway might make a big difference if it releases EPA from the informational catch-22 it currently faces when seeking to regulate new chemicals. Other challenges are more closely tied to nanomaterials and their properties and are common to regulatory bodies within most jurisdictions. In particular, gathering baseline information is proving to be challenging because of the regulators dilemma and confidentiality concerns. However, progress is being made on collection of baseline monitoring information and the quality and coverage of such information is likely to increase substantially.

In this article, we have argued for a "horses for courses" approach to how information about risks (including baseline information) and related decision-analytical tools can help regulators. In particular, until such time as formal risk assessments can be performed in scientifically defensible ways, regulators could use suitably designed decision-analytic tools such as those involving risk ranking (e.g., to prioritize for further research on nanomaterials) and control banding (for workplace risk mitigation) to help them manage complexity and uncertainty.

Decision-analytic tools are currently at a preliminary stage and much research needs to be done on how they might be tailored to suit regulatory goals. New methods development is also particularly appropriate in the case of nanomaterials where the uncertainty is extreme. Consequently, there needs to be a more concerted effort to build decision-analytic tools than is currently the case. There are several potentially fruitful areas of research including: the systematic use of subjective expert judgments, modeling using probabilistic networks and BBNs, and integrated assessment efforts that consider nanomaterial life cycles. Funding agencies and regulatory bodies should consider supporting such research in a targeted manner, because interdisciplinary research that combines the relevant sciences (physical sciences, biology/toxicology, and decision science) is unlikely to emerge organically and targeted funding can seed such collaborations.

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