Risk Assessment for Nanomaterials: Emerging Tools and Value of Information Analysis

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Risk Assessment for Nanomaterials: Emerging Tools and Value of Information Analysis
Problem: Nano EHS Data for Risk Assessment is Insufficient Because of Fast Emergence of Nanotechnology Products

Increasing gap requires innovative risk management

from Linkov and Satterstrom, 2008
After Linkov et al., 2009
Hypothesis and Main Point

- Relation of pattern, structure-activity and physico-chemical properties of nanoparticles on toxicity and life-cycle risk is widely unknown and available information is fragmented.

- Challenges of risk assessment and management for situations with a limited knowledge base and high uncertainty and variability require coupling traditional risk assessment with multi-criteria decision analysis (MCDA) and Life Cycle Assessment (LCA) to support sustainable nanomanufacturing and regulatory decision making.

- Entities engaged in nanotech must consider practical and innovative steps to develop sustainable nanomaterials minimizing identified life-cycle product risk while keeping costs down.
Overview

- Intro to Multi-Criteria Decision Analysis
- Nano and Traditional Risk Assessment
- Integration of RA/MCDA/LCA for Nano: Carbon Nanotubes Manufacturing Case Study
  - Problem
  - LCA assessment
  - Integrated RA/MCDA
  - Incorporation of Stakeholder Preferences
  - Value of Perfect Information Analysis
  - Value of Imperfect Information Analysis
- Conclusions
**Current RA/Decision-Making Processes**

**Decision-Maker(s)**

**AD HOC Process**
- Include/Exclude?
- Detailed/Vague?
- Certain/Uncertain?
- Consensus/Fragmented?
- Iterative?
- Rigid/unstructured?

**Tools**
- Risk Analysis
- Modeling / Monitoring
- Cost or Benefits
- Stakeholders’ Opinion

**Challenge:** Multiple & Uncertain Criteria
Problem: Parameter Uncertainty

- Parameter Uncertainty
- Uncertainty and variability in model parameters resulting from:
  - data availability
  - expert judgment
  - empirical distributions
- Can be addressed by:
  - Probabilistic Simulations (Monte-Carlo)
  - Analytical techniques (uncertainty propagation)
  - Expert estimates

Many parameters and factors important for risk assessment are not well known, reported ranges are large and often unquantifiable.
Problem: Model Uncertainty

- Model Uncertainty
  - Differences in model structure resulting from:
    - model objectives
    - computational capabilities
    - data availability
    - knowledge and technical expertise of the group
  - Can be addressed by
    - considering alternative model structures
    - weighting and combining models
    - Eliciting expert judgment

Mechanistic models for environmental risk assessment are very uncertain and expert judgment is required
subjective interpretation of the problem at hand

WHAT DO YOU SEE?

A HAT
OR
A BOA CONSTRICTOR
DIGESTING AN ELEPHANT

What is the relative influence of modeler perception on model predictions?
Multi-Criteria Decision Analysis

- Refers to a group of methods used to impart structure to the decision-making process.
- Generally consists of four steps:
  - Creating a hierarchy of criteria relevant to the decision at hand, for use in evaluating the decision alternatives.
  - Weighting the relative importance of the criteria.
  - Scoring how well each alternative performs on each criteria.
  - Combining scores across criteria to produce an aggregate score for each alternative.
Multi-Criteria Decision Analysis and Tools

• Multi-Criteria Decision Analysis (MCDA) methods:
  – Evolved as a response to the observed inability of people to effectively analyze multiple streams of dissimilar information
  – Many different MCDA approaches based on different theoretical foundations (or combinations)

• MCDA methods provide a means of integrating various inputs with stakeholder/technical expert values

• MCDA methods provide a means of communicating model/monitoring outputs for regulation, planning and stakeholder understanding

• Risk-based MCDA offers an approach for organizing and integrating varied types of information to perform rankings and to better inform decisions
Evolving Decision-Making Processes

Decision-Maker(s)

Decision Analytical Frameworks
- Agency-relevant/Stakeholder-selected
  - Currently available software
- Variety of structuring techniques
- Iteration/reflection encouraged
- Identify areas for discussion/compromise

Tool Integration
- Risk Analysis
- Modeling / Monitoring
- Cost
- Stakeholders’ Opinion

Sharing Data, Concepts and Opinions

Decision Integration
**Simplified Decision Matrix**

<table>
<thead>
<tr>
<th>Plan</th>
<th>Cost</th>
<th>Eco Health</th>
<th>Human Health</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>100</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>B</td>
<td>100</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>C</td>
<td>150</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>D</td>
<td>150</td>
<td>10</td>
<td>15</td>
</tr>
</tbody>
</table>
### Example Decision Matrix

**How to combine these criteria?**

<table>
<thead>
<tr>
<th></th>
<th>Criteria 1</th>
<th>Criteria 2</th>
<th>Criteria 3</th>
<th>Criteria 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alt. 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alt. 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alt. 3</td>
<td>Monitoring Results</td>
<td>Stakeholder Preference</td>
<td>Economic Cost</td>
<td>Non-monetary benefit</td>
</tr>
<tr>
<td>Alt. 4</td>
<td>Monitoring Results</td>
<td>Stakeholder Preference</td>
<td>Economic Cost</td>
<td>Non-monetary benefit</td>
</tr>
</tbody>
</table>

**How to interpret these results?**

**How to compare these alternatives?**
Risk Assessment Formulation

What can happen (go wrong)?

How likely is it?

What are the consequences?

Kaplan & Garrick 1981
Traditional Risk Assessment

- **Goal:** Will exposure to a contaminant cause adverse health effects?
- Based on data (often limited and imprecise) regarding toxic effects of materials on people and animals
- State-of-the-science risk assessment is not very far advanced
  - Two general bodies of data
    - Toxicity studies in animals
    - Epidemiologic studies in humans
  - Uncertainties can be tremendously large
- Often handled as a “bright line” approach, but typically plagued with uncertainties
Risk Quantification

Benchmarks – Reflection of “Acceptable” Risk

\[ HQ = \frac{\text{Media Concentration}}{\text{Benchmark}} \]

\[ HI = \sum_{i} HQ_i \]

Hazard Quotient (Chemical-Specific)

Hazard Index (Cumulative)

No benchmarks for nano!
Example: Linking RA, MCDA and Life-Cycle Analysis for Nanomaterials

- Problem: find optimal manufacturing process for SWCNT (Single Wall Carbon Nano Tubes)
- Consideration of 4 manufacturing process alternatives: HiPco, Arc, Laser, CVD
- Combined MCDA (stochastic version of PROMETHEE II) on energy and material efficiency, life cycle score, health risk and cost

After Seager and Linkov, 2008, and Canis, Seager, Linkov, 2010
Linking RA, LCA and MCDA

Based on Canis, Seager & Linkov (2010)
A SCWNT-specific LCA: Manufacturing

Purposes of LCA:
• improvement assessment
• comparative decision-making

SWCNT photos provided by Brian Landi, Nanopower Research Labs (Ryne Raffelle, Director), Rochester Institute of Technology.
Heath risks: persistence, mobility, bioaccumulation, toxicity (not included in this analysis – lack of information)
LCA Components: Material Yield and Ecoindicators

Material yield

Table 1: Key yield parameters for production of single-walled nanotubes (SWNTs)

<table>
<thead>
<tr>
<th>Process Parameter</th>
<th>Arc (%)</th>
<th>CVD (%)</th>
<th>HiPco (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synthesis reaction yield (SRY)</td>
<td>4.50</td>
<td>2.95</td>
<td>0.08</td>
</tr>
<tr>
<td>Purification yield</td>
<td>70</td>
<td>90</td>
<td>90</td>
</tr>
</tbody>
</table>

Note: CVD = chemical vapor deposition; HiPco = high-pressure carbon monoxide.

LCIA score
Criteria Distributions

Literature Data represented as probability distributions or H, M, L

<table>
<thead>
<tr>
<th>Alternative/Criterion</th>
<th>Energy consumption (GWh/kg)</th>
<th>Material efficiency (% in mass)</th>
<th>LCIA Score (EcoPoints)</th>
<th>Cost ($/g)</th>
<th>Health risks</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOAL</td>
<td>Minimize</td>
<td>Maximize</td>
<td>Minimize</td>
<td>Minimize</td>
<td>Minimize</td>
</tr>
<tr>
<td>HiPco</td>
<td>0.05 0.21 0.36</td>
<td>0.00 0.23 0.45</td>
<td>1.48 20.69 39.90</td>
<td>242.50 1550.75 2859.00</td>
<td>L M H</td>
</tr>
<tr>
<td>CVD</td>
<td>0.05 0.21 0.36</td>
<td>0.00 0.23 0.45</td>
<td>1.48 20.69 39.90</td>
<td>242.50 1550.75 2859.00</td>
<td>L M H</td>
</tr>
<tr>
<td>Arc</td>
<td>0.05 0.21 0.36</td>
<td>0.00 0.23 0.45</td>
<td>1.48 20.69 39.90</td>
<td>242.50 1550.75 2859.00</td>
<td>L M H</td>
</tr>
<tr>
<td>Laser</td>
<td>0.05 0.21 0.36</td>
<td>0.00 0.23 0.45</td>
<td>1.48 20.69 39.90</td>
<td>242.50 1550.75 2859.00</td>
<td>L M H</td>
</tr>
</tbody>
</table>
Ranking of alternatives (equal criteria weights)
Accounting for Stakeholder Preferences

- Sets of weights (or weight ranges) corresponding to different stakeholders can be established e.g., LCIA score is likely to be less important to manufacturers.
- For each fixed set of weights, analysis can be run again.
- For each stakeholder, we can obtain a relative ranking of manufacturing alternatives.
 Preference Analysis

The "Manufacturer"

The "End User"

The "Environmentalist"

The "Regulator"

Energy consumption

Health risks

Material efficiency

Costs

LCIA Score

Rank 4

Rank 3

Rank 2

Rank 1
Risk Assessment: Framing the Problem

- 5 risk categories
- 5 nanomaterials:
  1. C60
  2. MWCNT
  3. CdSe
  4. Ag NP
  5. Al NP

After Tervonen et al., 2009
# Criteria Measurements

<table>
<thead>
<tr>
<th></th>
<th>Agglomeration</th>
<th>Reactivity /charge</th>
<th>Crit. Function groups</th>
<th>Contaminant Dissociation</th>
<th>Bioavailability pot. (±10)</th>
<th>Bioaccumulation pot. (±10)</th>
<th>Toxic pot. (±10)</th>
<th>Size (±10%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C60</td>
<td>4</td>
<td>2, 3</td>
<td>3</td>
<td>2</td>
<td>25</td>
<td>50</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>MWCNT</td>
<td>4</td>
<td>2, 3</td>
<td>4</td>
<td>3</td>
<td>25</td>
<td>50</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>CdSe</td>
<td>4</td>
<td>4, 5</td>
<td>1</td>
<td>4</td>
<td>50</td>
<td>75</td>
<td>75</td>
<td>20</td>
</tr>
<tr>
<td>Ag NP</td>
<td>3</td>
<td>4, 5</td>
<td>1</td>
<td>4</td>
<td>50</td>
<td>75</td>
<td>75</td>
<td>50</td>
</tr>
<tr>
<td>Al NP</td>
<td>5</td>
<td>1, 2</td>
<td>1</td>
<td>1</td>
<td>25</td>
<td>75</td>
<td>10</td>
<td>50</td>
</tr>
</tbody>
</table>

## Risk Profiles

<table>
<thead>
<tr>
<th>Profile</th>
<th>Agglomeration</th>
<th>Reactivity /charge</th>
<th>Crit. Function groups</th>
<th>Contaminant Dissociation</th>
<th>Bioavailability potential</th>
<th>Bioaccumulation pot.</th>
<th>Toxic pot.</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme-high</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>5</td>
</tr>
<tr>
<td>High-medium</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>50</td>
</tr>
<tr>
<td>Medium-low</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>100</td>
</tr>
<tr>
<td>Low-very low</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>200</td>
</tr>
</tbody>
</table>

After Tervonen et al., 2009
Risk Classes

After Tervonen et al., 2009
### Risk Assessment: Results

After Tervonen et al., 2009

<table>
<thead>
<tr>
<th></th>
<th>Extreme risk</th>
<th>High risk</th>
<th>Medium risk</th>
<th>Low risk</th>
<th>Very low risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>C60</td>
<td>0</td>
<td>0</td>
<td>51</td>
<td>49</td>
<td>0</td>
</tr>
<tr>
<td>MWCNT</td>
<td>0</td>
<td>26</td>
<td>73</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>CdSe</td>
<td>0</td>
<td>98</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Ag NP</td>
<td>0</td>
<td>29</td>
<td>71</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>AI NP</td>
<td>0</td>
<td>0</td>
<td>33</td>
<td>34</td>
<td>34</td>
</tr>
</tbody>
</table>

Direction of preference:
- Very high risk
- High risk
- Medium risk
- Low risk
- Very low risk

After Tervonen et al., 2009
Research is only useful if it helps support and influence future decisions.

Is more precise information on health criteria useful? And on manufacturing criteria?

What must be the quality of information for it to be useful?

Are the benefits of additional information worth the costs?
What is Value of Information (VoI)?

- A measure of the value that information can bring in a decision context
  - Without information: the outcome of decisions are uncertain; the optimal decision yields a prior expected value
  - With information, the optimal decision can be made depending on the results; uncertainty is reduced; for each result, the optimal decision yields a posterior expected value; the total posterior expected value is their average
  - VoI: the difference between posterior expected value and prior expected value
- Computing VoI requires a decision model that can make the link between information and decisions
- Information is valuable if and only if it might switch the decision
### VoI Results and Discussion

<table>
<thead>
<tr>
<th>Net Flow of Best Alternative</th>
<th>No New Information</th>
<th>Manufacturing only</th>
<th>Health only</th>
<th>Full, Perfect Information</th>
<th>% of VoI from M Only</th>
<th>% of VoI from H Only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>63%</td>
<td>66%</td>
<td>63%</td>
<td>66%</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>Consumer</td>
<td>58%</td>
<td>58%</td>
<td>62%</td>
<td>63%</td>
<td>18%</td>
<td>84%</td>
</tr>
<tr>
<td>Regulator</td>
<td>38%</td>
<td>40%</td>
<td>56%</td>
<td>58%</td>
<td>9%</td>
<td>90%</td>
</tr>
<tr>
<td>Environmentalist</td>
<td>16%</td>
<td>16%</td>
<td>35%</td>
<td>35%</td>
<td>4%</td>
<td>99%</td>
</tr>
<tr>
<td>Balanced Weights</td>
<td>38%</td>
<td>39%</td>
<td>39%</td>
<td>41%</td>
<td>27%</td>
<td>48%</td>
</tr>
</tbody>
</table>

### Cumulative Added Net Flow with New Info

- **Manufacturing only**
- **Health only**
- **Manufacturing & Health**

### Total Average Net Flow with New Information

- **Manufacturing & Health**
- **Health only**
- **Manufacturing only**
- **None**
**VoI Results and Discussion**

- Manufacturer & Consumer will be confident with their decisions
- Environmentalist & Regulator cannot decide with confidence

- Perhaps decision makers can make concessions to wary stakeholders
- Investing in health research will have the most impact
Linking RA, AM and MCDA

Adaptive Management

MCDA Feeds RA
RA Feeds MCDA

MCDA

Decision Matrix
Weights
Synthesis
Decision

Evaluation
Criteria
Alternatives
Problems

RA Feeds MCDA
Summary: Essential Decision Ingredients

People:
- Policy Decision Maker(s)
- Scientists and Engineers
- Stakeholders (Public, Business, Interest groups)

Process:
- Define Problem & Generate Alternatives
- Identify criteria to compare alternatives
- Gather value judgments on relative importance of the criteria
- Screen/eliminate clearly inferior alternatives
- Determine performance of alternatives for criteria
- Rank/Select final alternative(s)

Tools:
- Environmental Assessment/Modeling (Risk/Ecological/Environmental Assessment and Simulation Models)
- Decision Analysis (Group Decision Making Techniques/Decision Methodologies and Software)
There are clear benefits to be gained by advancing the use of formal risk and decision analysis methods:

- Opportunities to explore trade-offs among diverse objectives
- The ability to distinguish science and engineering inputs to a decision from values associated with objectives
- Means for exploring the implications of uncertainty and the value of reducing it
- Providing a quantitative framework to implement adaptive management
However, efforts to apply these approaches will confront a number of practical issues related to the following:

- Under-estimating the level of effort required to accomplish effective deliberation through the use of decision analysis
- Determining who can/should be involved in value/preference elicitation
- Intolerance for transparency in decision-making
- The misconception that decision analysis is a substitute for an actual decision
Conclusions

- Decision models and Value of Information analyses can prove useful tools to:
  - Help making decisions under uncertainty
  - Assess whether information gathering has value in this context
- To help assess nanomaterials research options:
  - Several decision situations should be identified where information obtained from the research might be useful
  - A Vol analysis applied to these decision models coupled with an estimation of the costs of the research and the cost of delaying the decisions would help assess whether research proposals are worth the investment/ which ones are most worthy
References

References


