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



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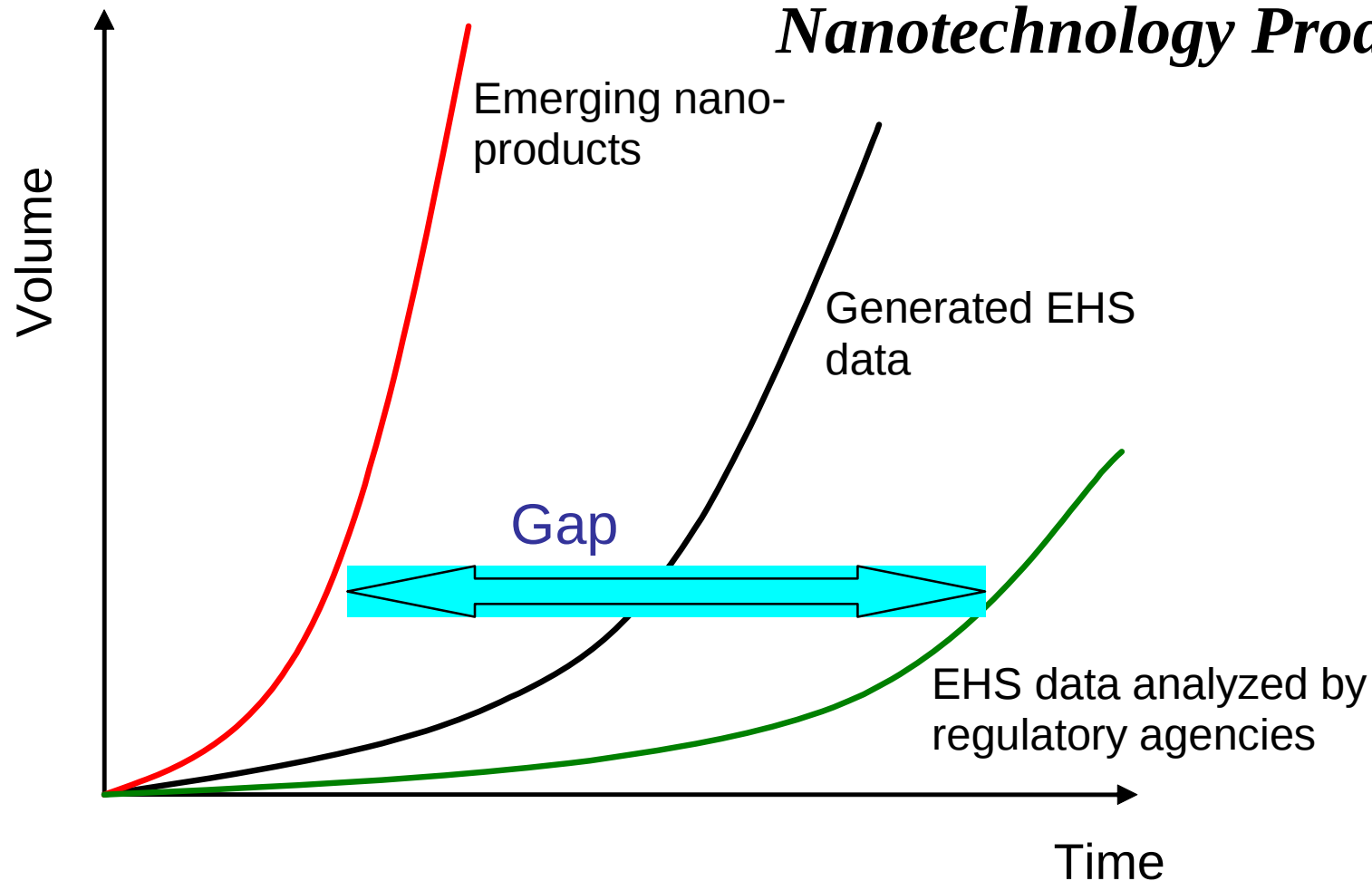
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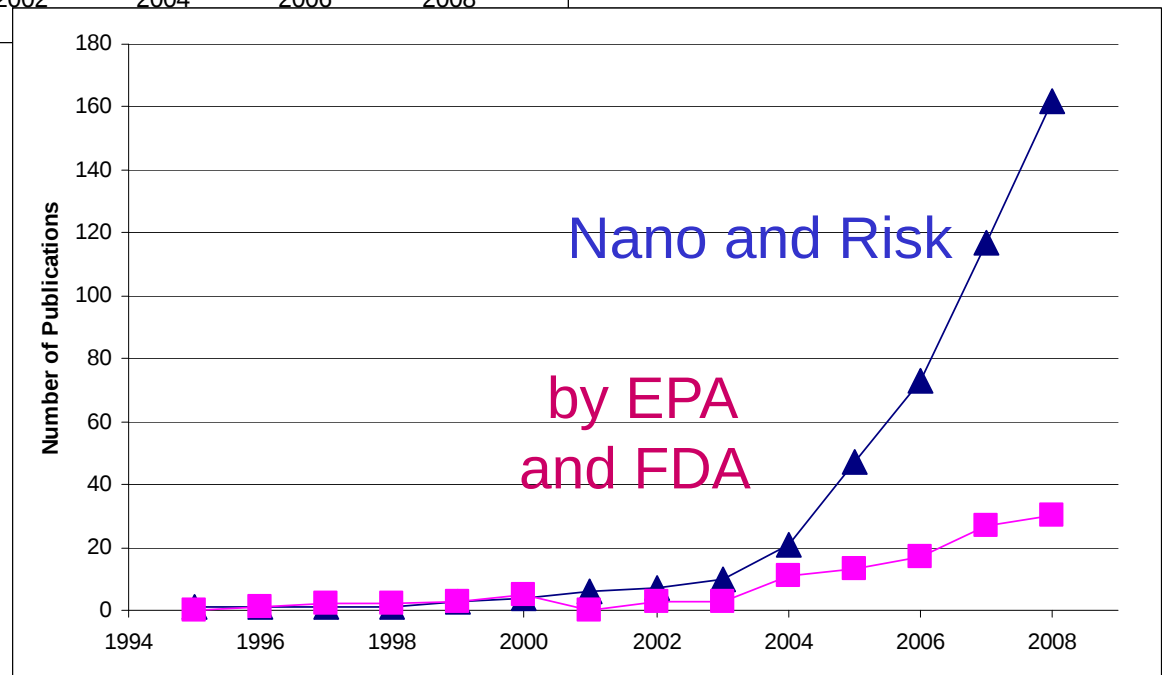
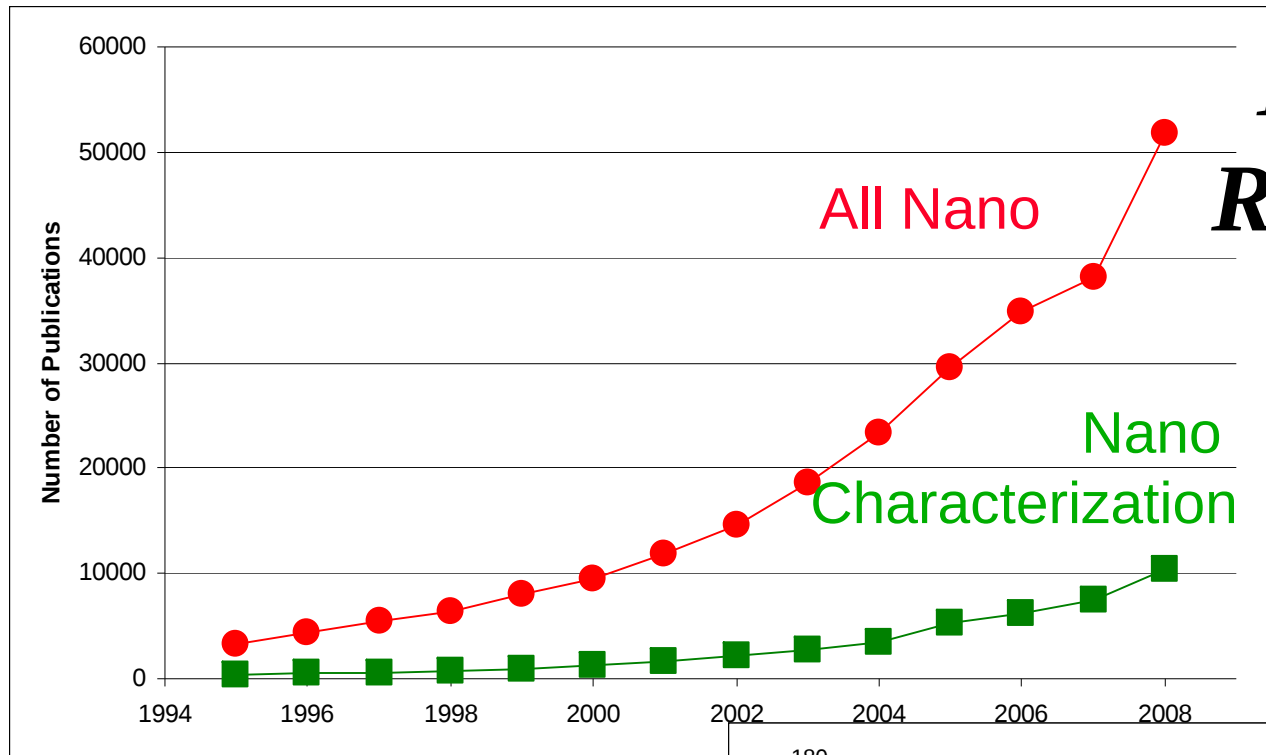
Problem: Nano EHS Data for Risk Assessment is Insufficient Because of Fast Emergence of Nanotechnology Products



Increasing gap requires innovative risk management



Nanotech and Risk Assessment Published Papers



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.





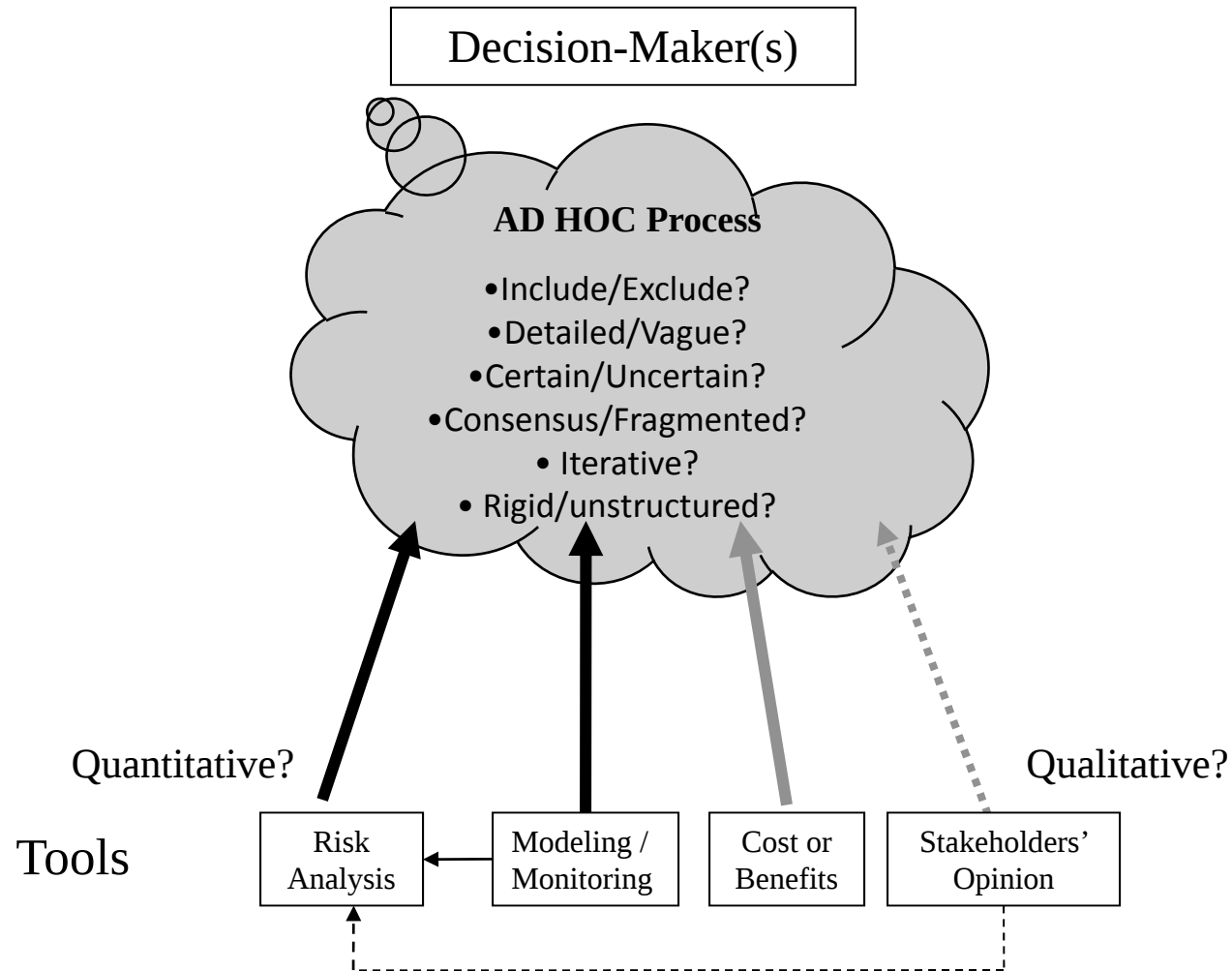
Overview

- 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



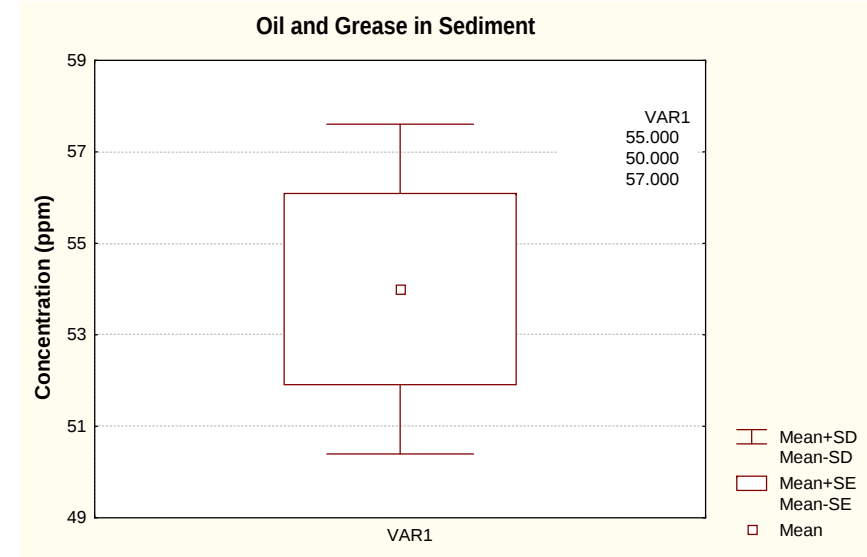
Challenge: Multiple & Uncertain Criteria





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



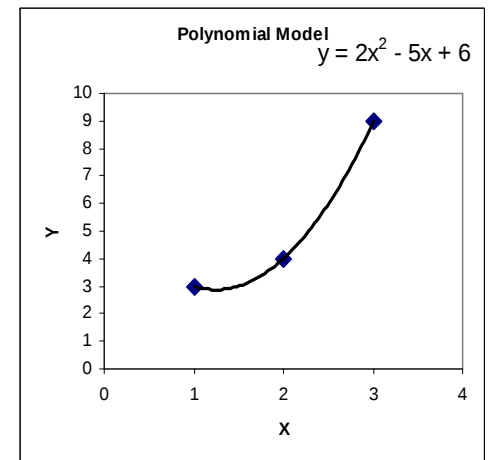
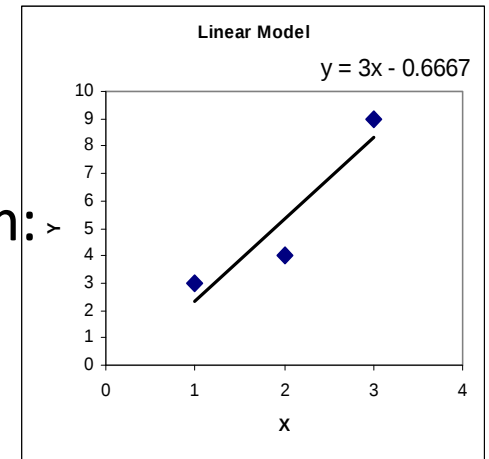
Many parameters and factors important for risk assessment are not well known, reported ranges are large and often unquantifiable





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





Problem: “Modeler/Scenario Uncertainty”

**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





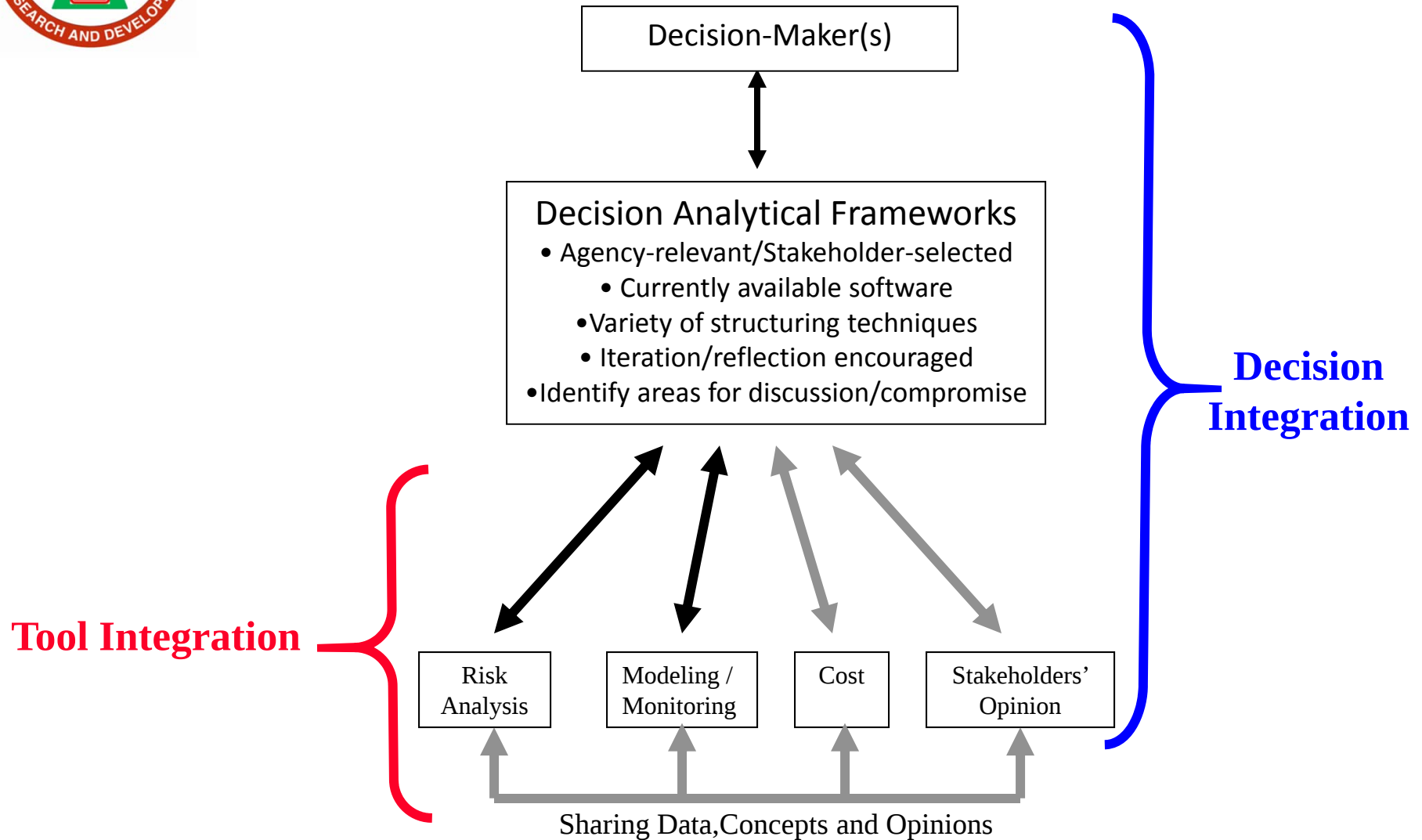
Multi-Criteria Decision Analysis and Tools

- 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





Simplified Decision Matrix

Plan	Cost	Eco Health	Human Health
A	100	10	5
B	100	5	10
C	150	10	10
D	150	10	15





Example Decision Matrix

How to combine these criteria?

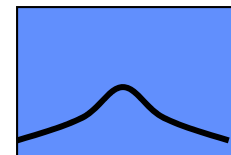
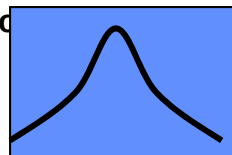
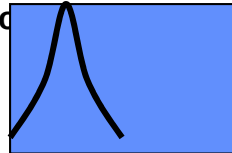


How to compare these alternatives?



	Criteria 1	Criteria 2	Criteria 3	Criteria 4
Alt. 1	How to interpret these results?			
Alt. 2	Monitoring Results	Stakeholder Preference	Economic Cost	Non-monetary benefit
Alt. 3	Monitoring Results	Stakeholder Preference	Economic Cost	Non-monetary benefit
Alt. 4	Monitoring Results	Stakeholder Preference	Economic Cost	Non-monetary benefit

How to interpret these results?



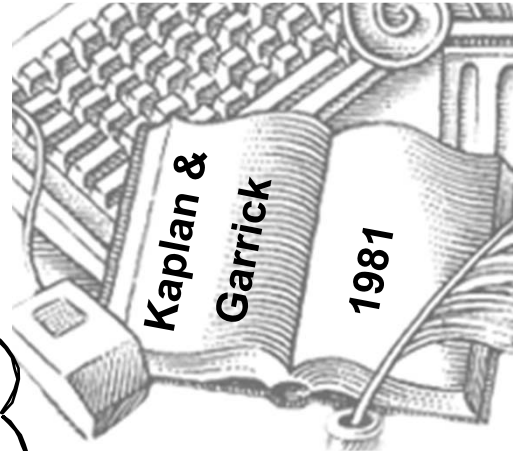


Risk Assessment Formulation

What can happen
(go wrong)?

How likely is it?

What are the
consequences?





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

$$HQ = \frac{MediaConcentration}{Benchmark}$$

Hazard Quotient
(Chemical-Specific)

$$HI = \sum_i HQ_i$$

Hazard Index
(Cumulative)

No benchmarks for nano!





Example: Linking RA, MCDA and Life-Cycle Analysis for Nanomaterials

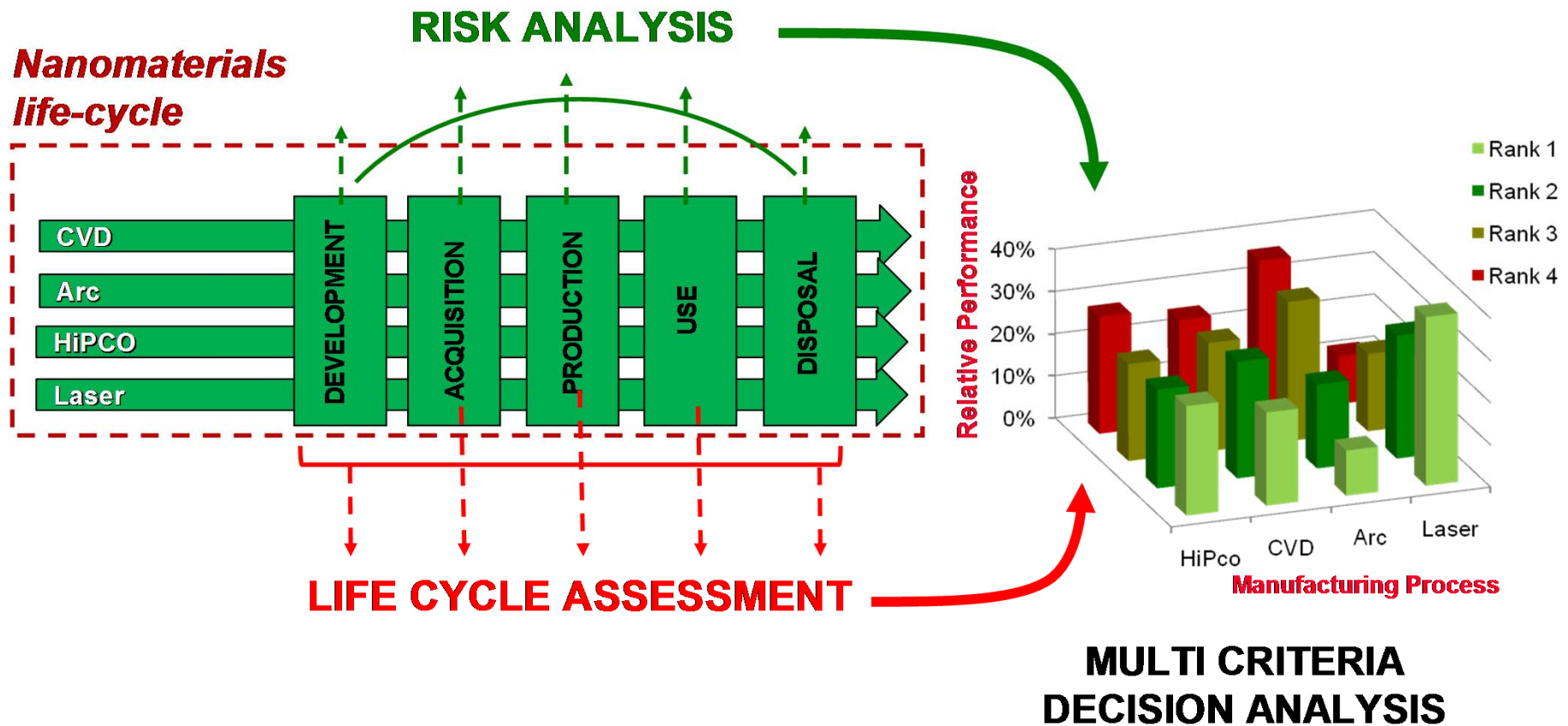
- Problem: find optimal manufacturing process for SWCNT (Single Wall Carbon Nano Tubes)
- Consideration of 4 manufacturing process alternatives: HiPco, Arc, Laser, CVD
- Combined MCDA (stochastic version of PROMETHEE II) on energy and material efficiency, life cycle score, health risk and cost

After Seager and Linkov, 2008, and
Canis, Seager, Linkov, 2010





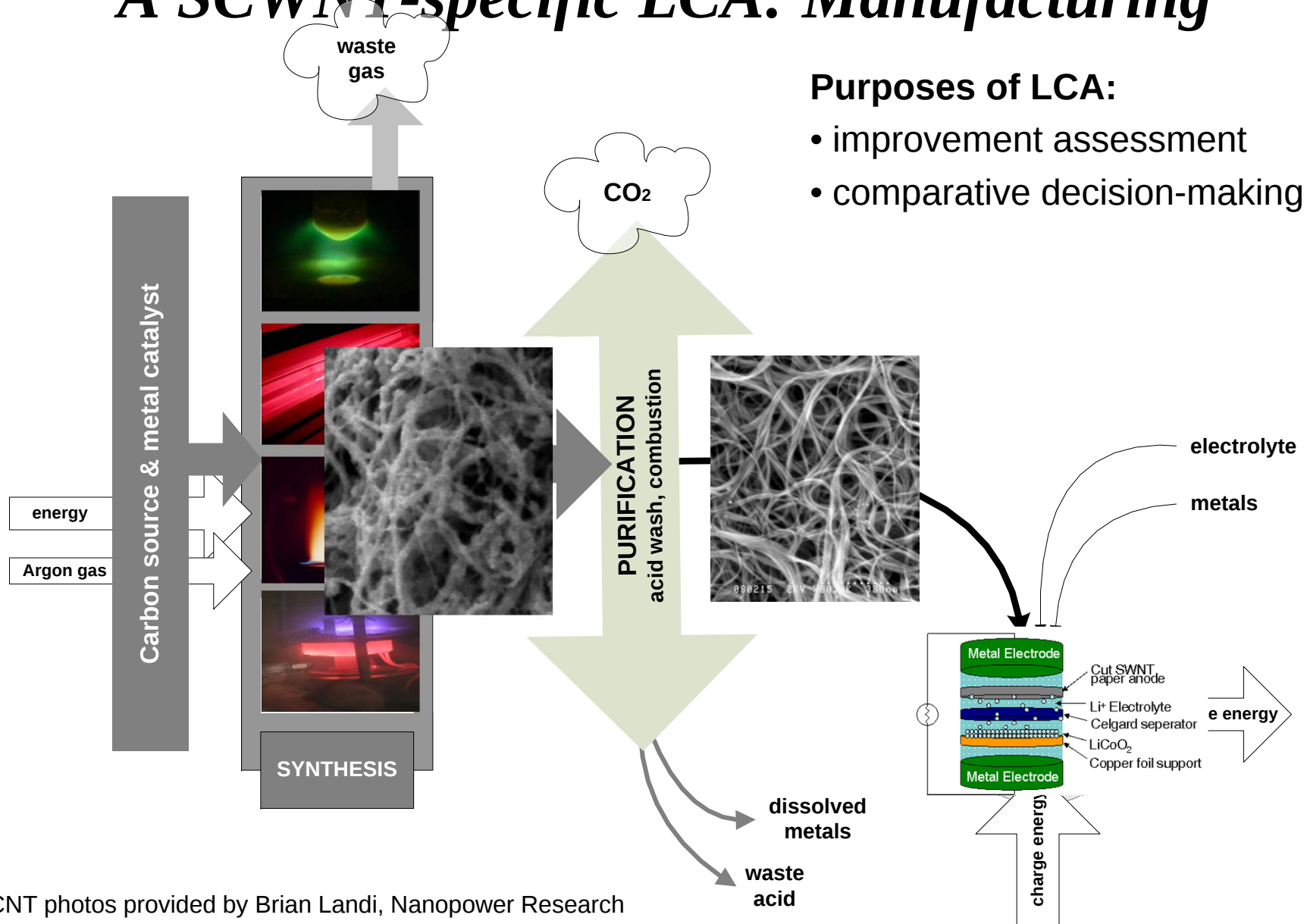
Linking RA, LCA and MCDA



Based on Canis, Seager & Linkov (2010)



A SCWNT-specific LCA: Manufacturing



SWCNT photos provided by Brian Landi, Nanopower Research Labs (Ryne Raffelle, Director) , Rochester Institute of Technology.



Criteria for the Comparison of Manufacturing Alternatives

Manufacturing:
energy
efficiency,
material yield

LCIA score

Health risks:
persistence,
mobility,
bioaccumulation,
toxicity
(not included in
this analysis – lack
of information)

Cost





LCA Components: Material Yield and Ecoindicators

RESEARCH AND ANALYSIS

Environmental Assessment of Single-Walled Carbon Nanotube Processes

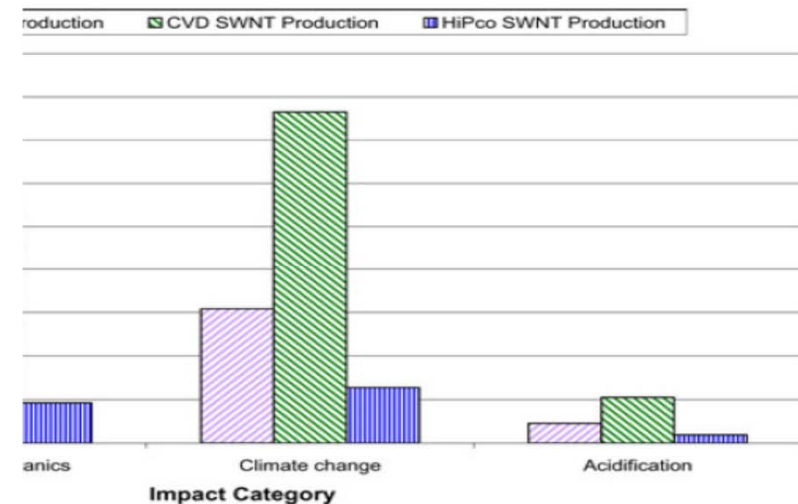
Meagan L. Healy, Lindsay J. Dahlben, and Jacqueline A. Isaacs

Material yield

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

Process Parameter	Arc (%)	CVD (%)	HiPco (%)
Synthesis reaction yield (SRY)	4.50	2.95	0.08
Purification yield	70	90	90

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



position (CVD), and high-pressure carbon monoxide (HiPco) base case = single-walled nanotube; Pt = normalized impact per gram of product.

LCIA score





Criteria Distributions

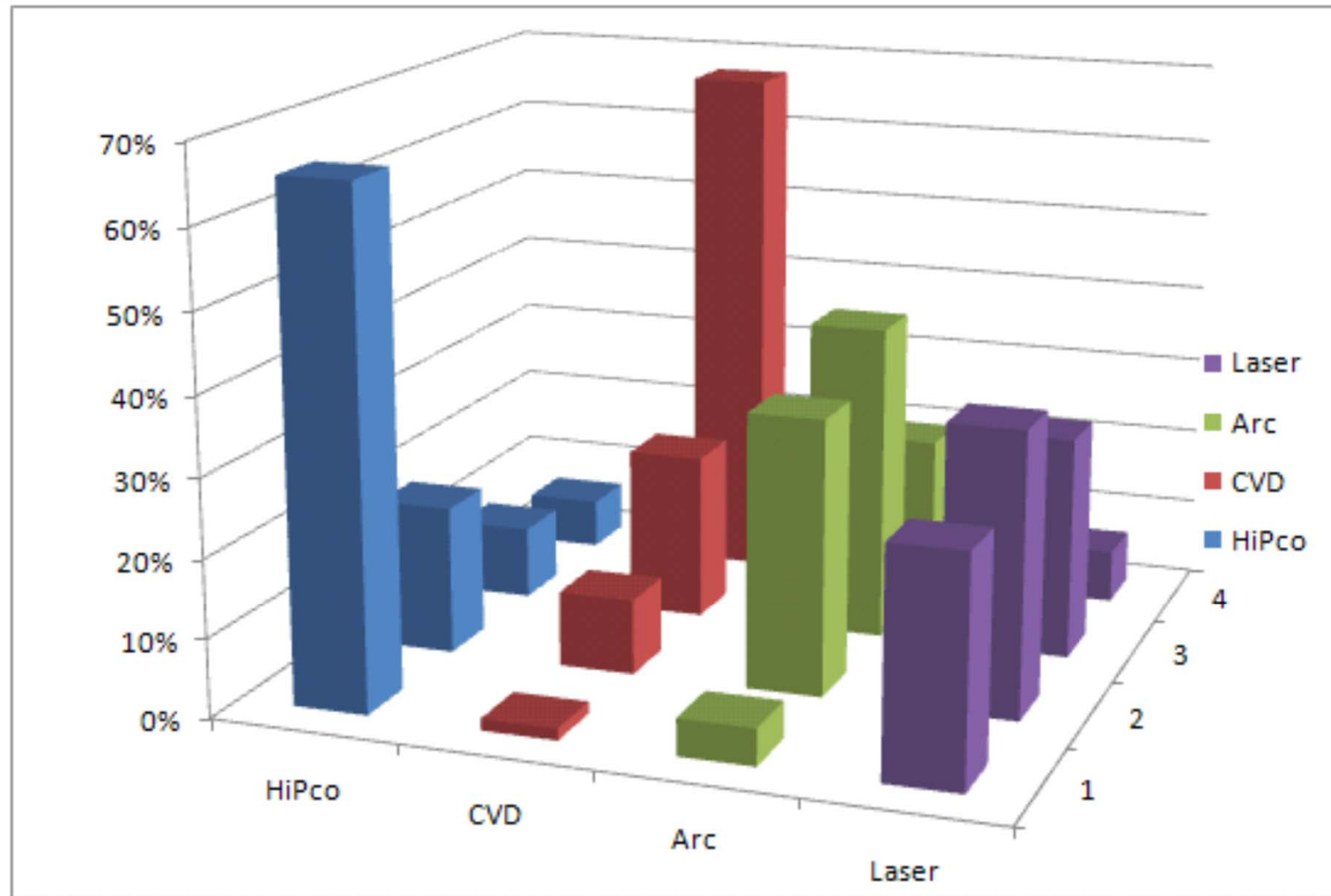
Literature Data represented as probability distributions or H, M, L

Alternative/ Criterion	Energy consumption (GWh/kg)	Material efficiency (% in mass)	LCIA Score (EcoPoints)	Cost (\$/g)	Health risks
GOAL	Minimize	Maximize	Minimize	Minimize	Minimize
HiPco					
CVD					
Arc					
Laser					





Ranking of alternatives (equal criteria weights)





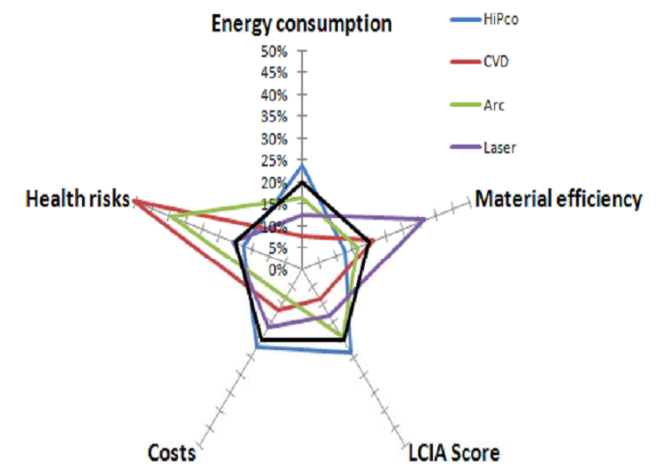
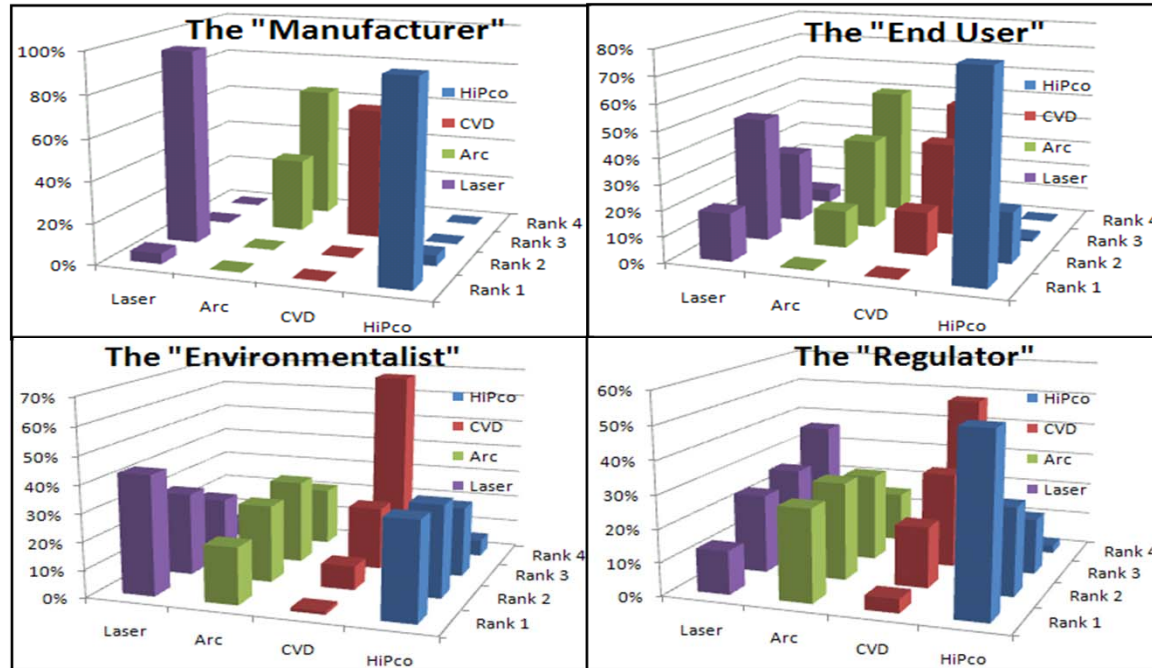
Accounting for Stakeholder Preferences

- 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

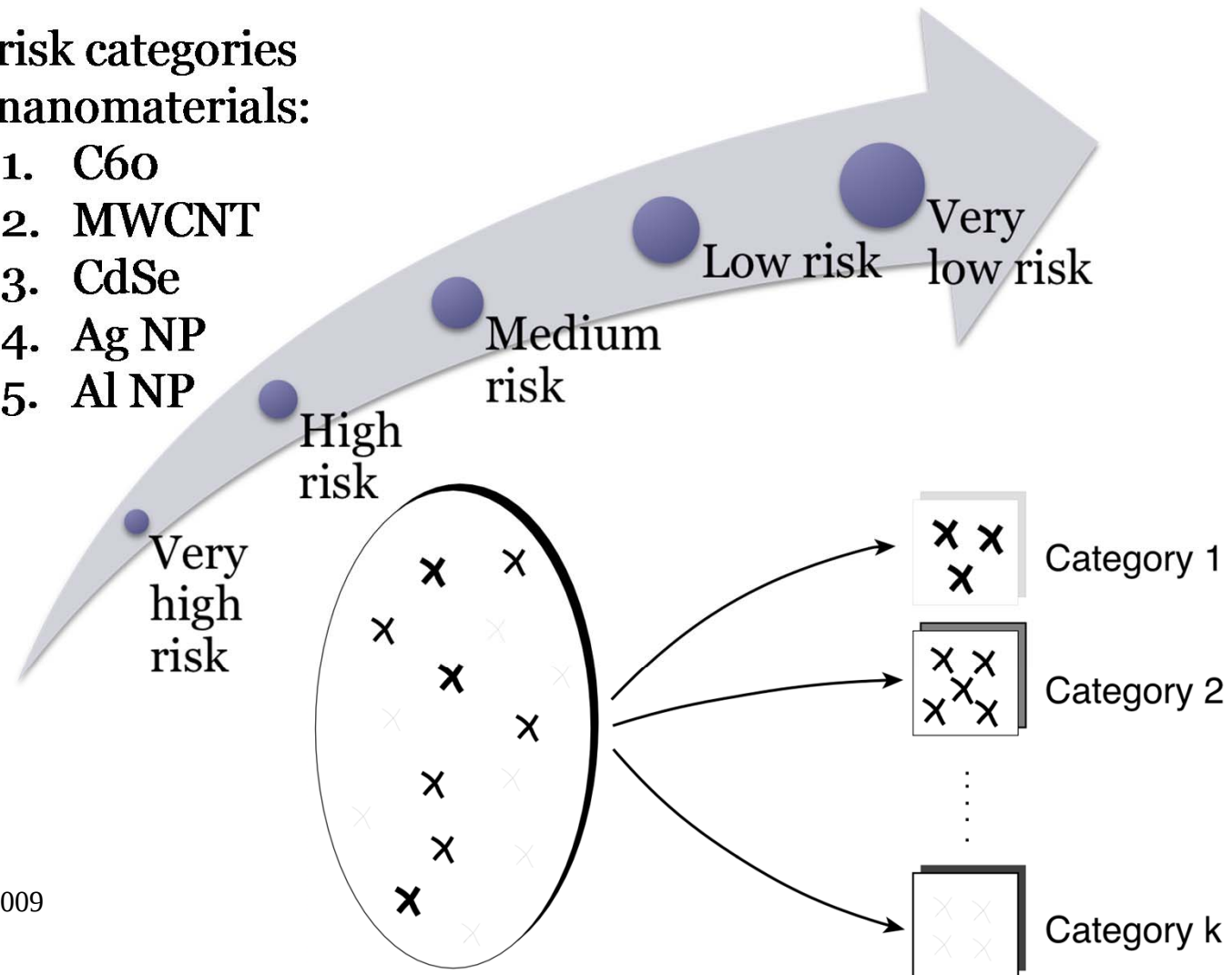




Risk Assessment: Framing the Problem

- 5 risk categories
- 5 nanomaterials:

1. C60
2. MWCNT
3. CdSe
4. Ag NP
5. Al NP



After Tervonen et al., 2009





Criteria Measurements

	Agglomeration	Reactivity /charge	Crit. Function groups	Contaminant Dissociation	Bioavailability pot. (± 10)	Bioaccumulation pot. (± 10)	Toxic pot. (± 10)	Size ($\pm 10\%$)
C60	4	2, 3	3	2	25	50	10	100
MWCNT	4	2, 3	4	3	25	50	25	50
CdSe	4	4, 5	1	4	50	75	75	20
Ag NP	3	4, 5	1	4	50	75	75	50
Al NP	5	1, 2	1	1	25	75	10	50

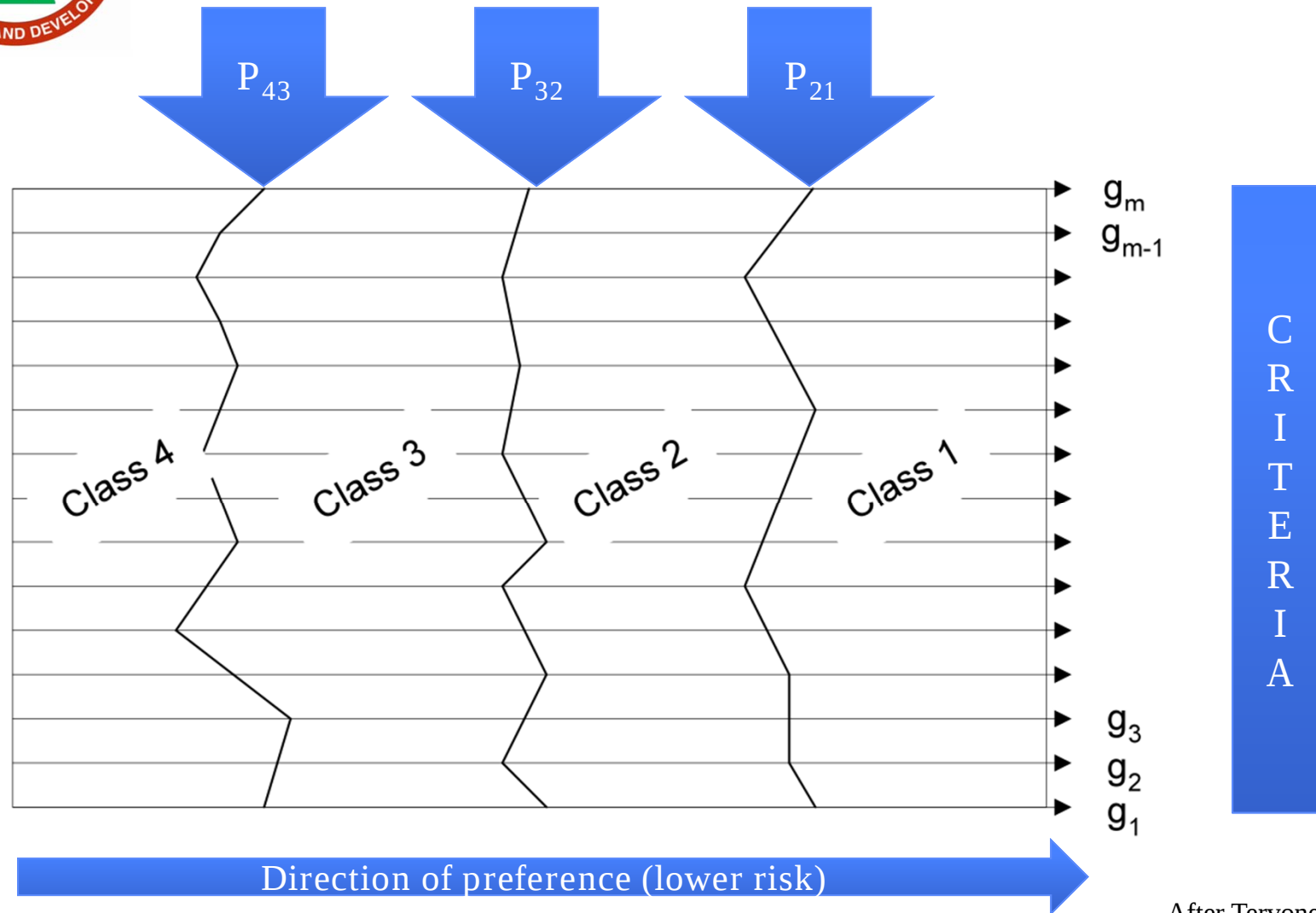
Risk Profiles

Profile	Agglomeration	Reactivity /charge	Crit. Function groups	Contaminant Dissociation	Bioavailab ility potential	Bioaccumul ation pot.	Toxic pot.	Size
Extreme-high	4	4	4	4	100	100	100	5
High-medium	3	3	3	3	80	80	80	50
Medium-low	2	2	2	2	70	70	70	100
Low-very low	1	1	1	1	60	60	60	200





Risk Classes



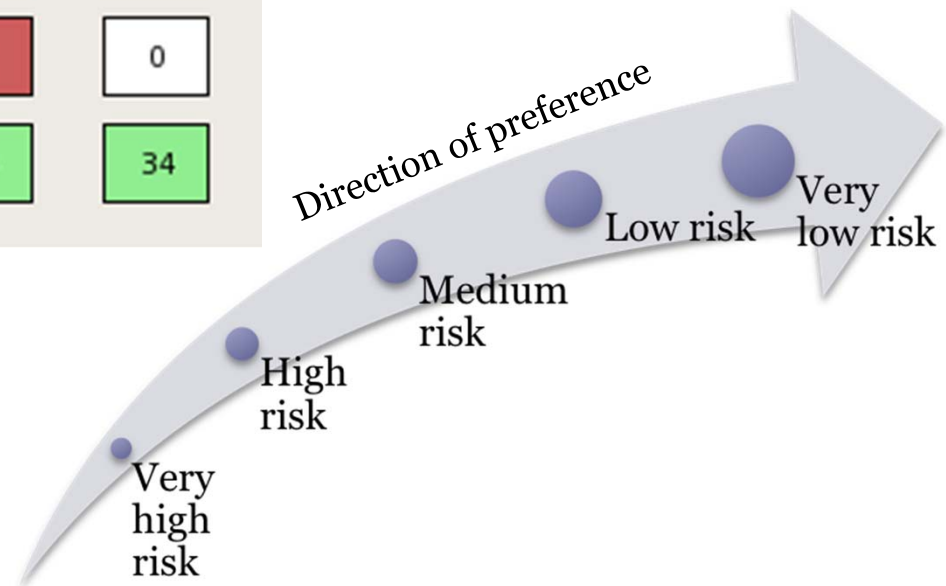
After Tervonen et al., 2009





Risk Assessment: Results

	Extreme risk	High risk	Medium risk	Low risk	Very low risk
C60	0	0	51	49	0
MWCNT	0	26	73	1	0
CdSe	0	98	1	1	0
Ag NP	0	29	71	1	0
Al NP	0	0	33	34	34



After Tervonen et al., 2009





How to Prioritize Research in the Context of This Specific Decision

- 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) ?

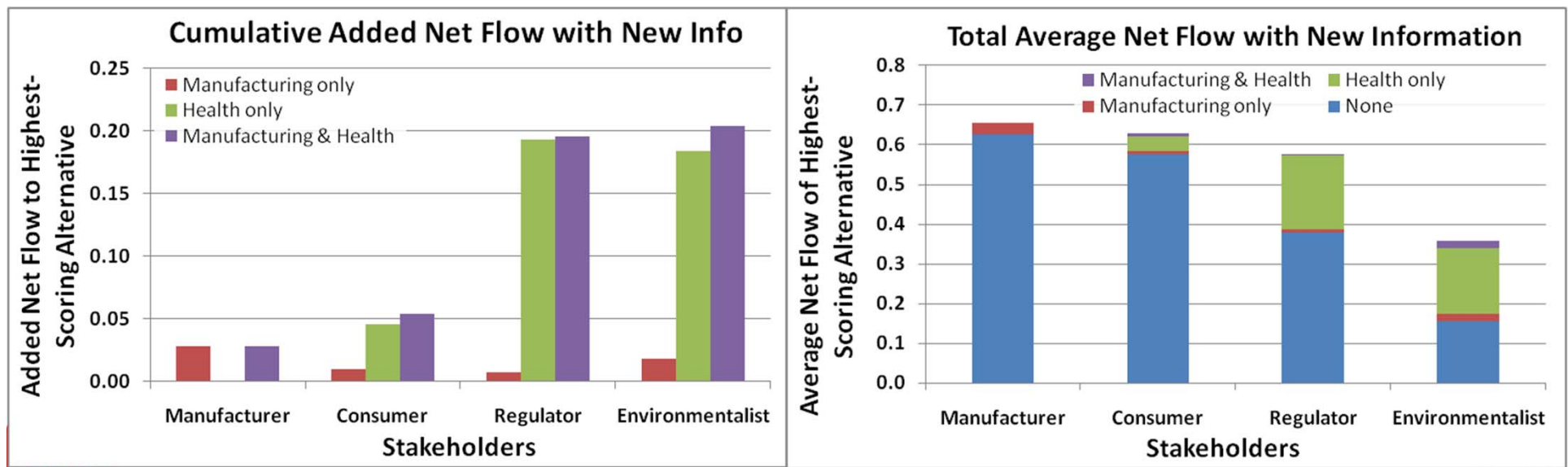
- A measure of the value that information can bring in a decision context
 - Without information: the outcome of decisions are uncertain; the optimal decision yields a prior expected value
 - With information, the optimal decision can be made depending on the results; uncertainty is reduced; for each result, the optimal decision yields a posterior expected value; the total posterior expected value is their average
 - Vol: the difference between posterior expected value and prior expected value
- Computing Vol 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





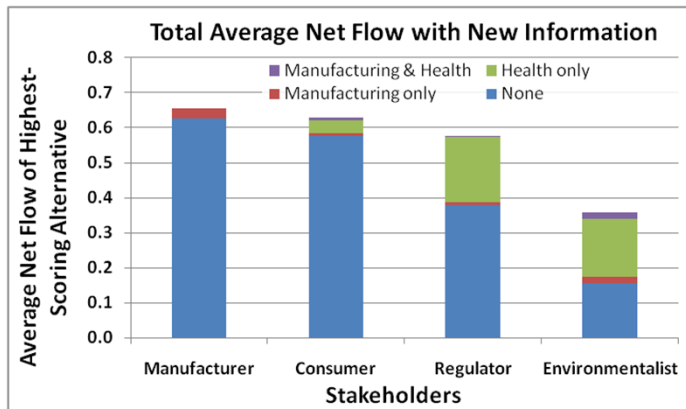
VoI Results and Discussion

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



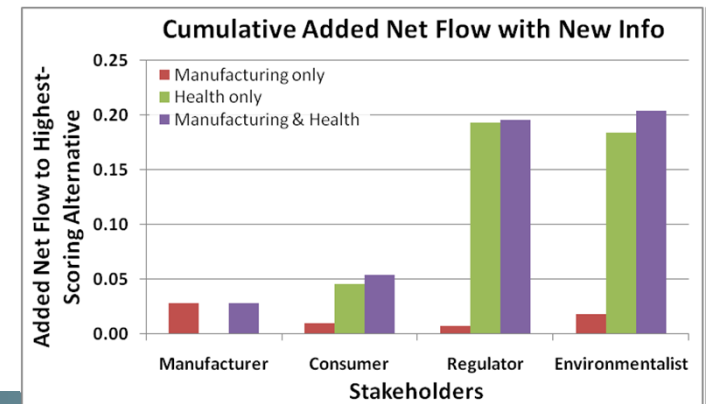


VoI Results and Discussion



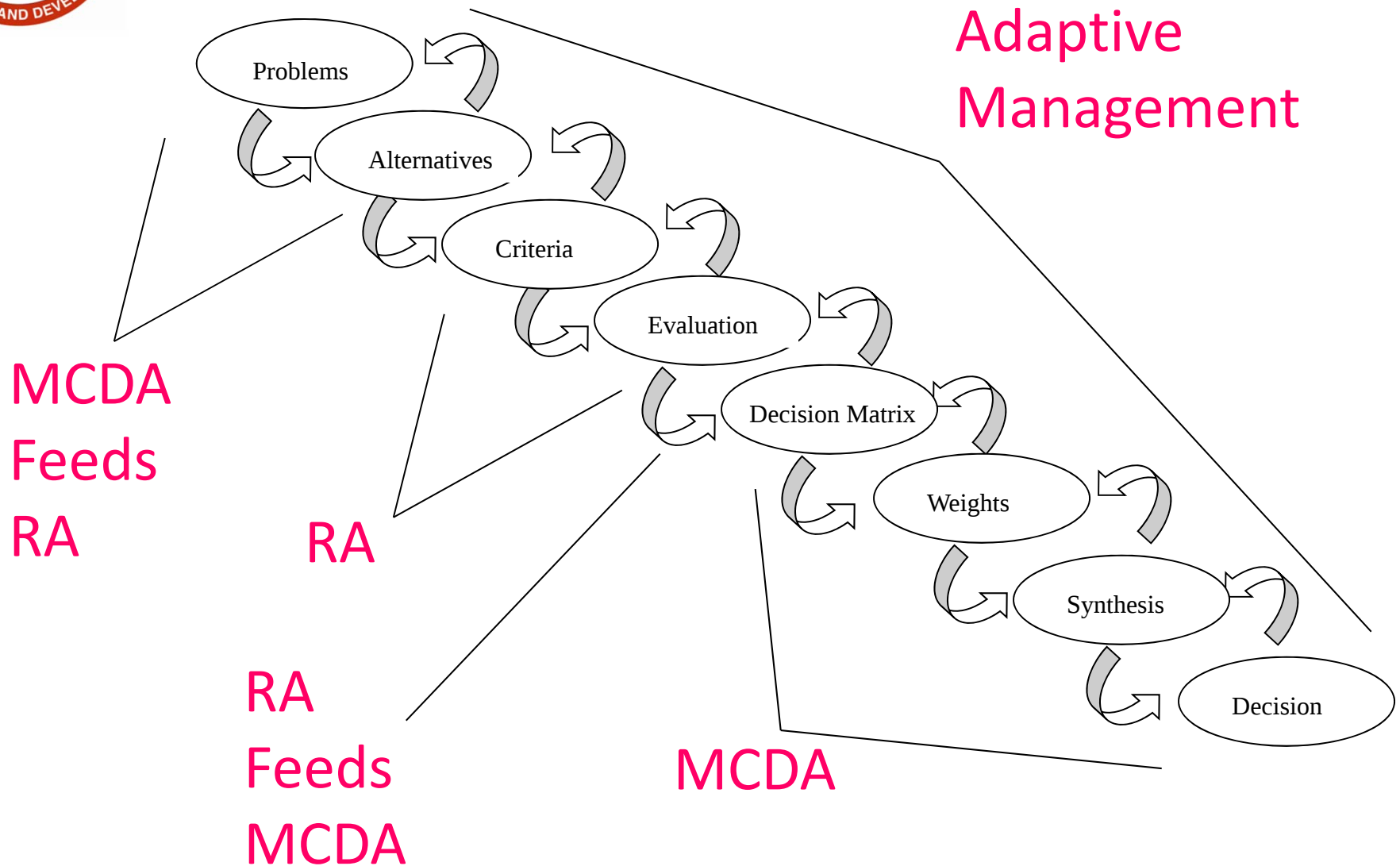
- Manufacturer & Consumer will be confident with their decisions
- Environmentalist & Regulator cannot decide with confidence

- Perhaps decision makers can make concessions to wary stakeholders
- Investing in health research will have the most impact





Linking RA, AM and MCDA





Summary: Essential Decision Ingredients

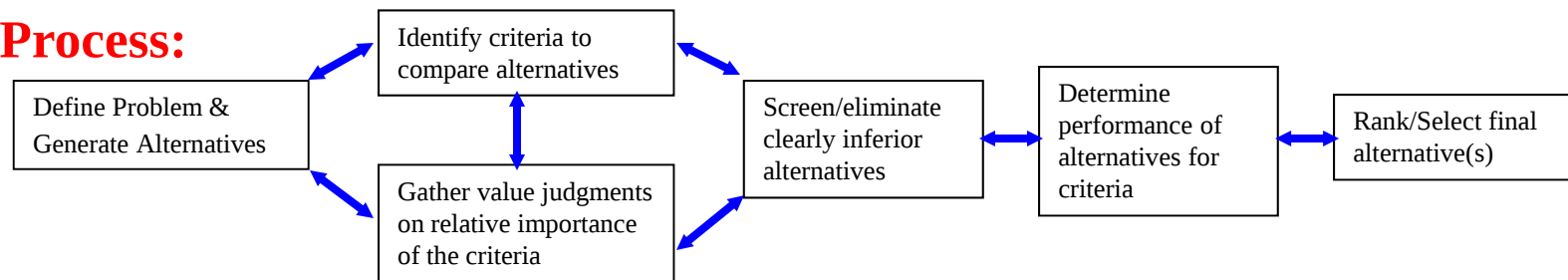
People:

Policy Decision Maker(s)

Scientists and Engineers

Stakeholders (Public, Business, Interest groups)

Process:



Tools:

Environmental Assessment/Modeling (Risk/Ecological/Environmental Assessment and Simulation Models)

Decision Analysis (Group Decision Making Techniques/Decision Methodologies and Software)





Main Points

- 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





Main Points

- 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





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