Decision Analysis and Value of Information Analysis for Toxicology and Environmental Science

Igor Linkov and Matthew Bates

Risk & Decision Science Focus Area
US Army Corps of Engineers
igor.linkov@usace.army.mil

SOT
12 November 2014
Outline

• ERDC and Team Background
• Challenges in Applying Risk Assessment
• What is Decision Analysis and Why do we Do it
• Enhancing Risk Assessment with Decision-Analytic Tools
  ► MCDA Intro and State of Applications
  ► VOI Intro and State of Applications
• Detailed Case Study for MCDA: Exposure-based Chemical Prioritization
• Detailed Case Study for VoI: Nanotechnology
• How MCDA and VoI Can help toxicologists?
  • Weight of Evidence for Adverse Outcome Pathways
• Conclusion
Summary: Why Use Decision Analytic Techniques?

- Some benefits of implementing formal decision analysis:
  - **Transparent** – always clear how and why each item is scored.
  - **Replicable** – anybody will receive the same answer.
  - **Generalizable** – methods are easily ported between contexts.
  - **Robust** – there is a science behind this that we can leverage.
  - **Tractable** – break large problems down to focus on like parts.
  - **Scalable** – decision framework can be applied to large data.
  - **Quantitative** – easier to justify outcomes to ‘higher-ups’.
  - Helps you identify the **full set of objectives** for the analysis.
  - Allows **exploration of trade-offs** between these objectives.
  - Separates **subjective** (weights) from **objective** (scores) data.
  - Can **integrate values** across a group with diverse views.
  - Enables **scenario & sensitivity analyses**.
US Army / US Army Corps of Engineers, Engineer Research and Development Center

2500 Employees
Over 1000 engineers and scientists
28% PhDs; 43% MS degrees

Research Laboratories of the Corps of Engineers

Laboratories
Field Offices

Cold Regions Research Engineering Laboratory (Hanover, NH)
Topographic Engineering Center (Alexandria, VA)
Construction Engineering Research Laboratory (Champaign, IL)
Headquarters (Vicksburg, MS)
Coastal & Hydraulics Laboratory
Environmental Laboratory
Geotechnical & Structures Laboratory
Information Technology Laboratory
ERDC Research Business Areas

Civil Works/Water Resources

Military Engineering

Geospatial Research & Engineering

Environmental Quality/Installations
Risk and Decision Science Team

Capabilities
- Over 15 risk, decision and environmental scientists developing solutions that support decisions across a broad spectrum of military and civilian needs
- State-of-the-science models and tools for structuring and conducting risk assessment, stakeholder engagement, resource prioritization, planning, and other emerging issues relevant to USACE, DoD, and Nation

Current Programs
- Cutting edge R&D for DoD as well as for DHS, DHHS, EPA, CPSC and others
- Applying Decision-Analytic tools to evaluate alternatives, integrate stakeholder values in product development, and prioritize research for a variety of technologies & industries.
Top-Down Decision Analysis

Goal Identification and Problem Framing
- What are the goals, alternatives, and constraints?

Decision Model
- What are the criteria and metrics, How do we measure decision-maker values

Metrics Generation and Alternative Scoring
- How does each alternative score along our identified criteria and metrics?

Bottom-Up Risk Assessment

Risk Characterization
- What are the risks relative to a threshold? How do they compare to other alternatives?

Physical/Statistical Model
- What is the hazard? What is exposure?

Data Collection
- What are fundamental properties/mechanisms associated with each alternative?
Risk Assessment Formulation

What can happen (go wrong)?

How likely is it?

What are the consequences?
Risk Quantification

Benchmarks – Reflection of “Acceptable” Risk

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

Hazard Quotient
(Chemical-Specific)

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

Hazard Index
(Cumulative)

But what do we do when benchmarks are unknown?
Challenge 1: Emergence of New Technologies and Delays in Generated Risk Data

Emerging Technologies

Generated risk data

Gap

Risk data analyzed by regulatory agencies

Volume

Time

from Linkov and Satterstrom, 2008
Challenge 2: Needs for Real Time Decisions

What Can Be Done to Help in Decision Making?

Increased information availability may result in information overload.

Need for Revolutionary Changes:
Fusion of information and decisions reflecting stakeholder values.

After Roman, 1996
What is Decision Analysis? Why Do We Use It?
Typical Decision Making Challenges

- “Humans are quite bad at making complex, unaided decisions” (Slovic et al., 1977).

- A variety of psychological biases tend to skew our rationality.

- We can only keep a few factors in ‘working memory’ at a time, so are liable to miss considerations without decision aids.

- Individuals respond to complex challenges by using intuition and/or personal experience to find the easiest solution.

- Groups can devolve into entrenched positions resistant to compromise

- “There is a temptation to think that honesty and common sense will suffice” (USACE IWR-Drought Study p.vi)
Decision Making Involves Tradeoffs

- There are often more considerations than just money
  - Health
  - Environment

- Explicit tradeoffs
  - Spending $100K on Food vs Medical aid in disaster response
  - More of one means less of the other

- Implicit tradeoffs
  - “Providing maximum shelter” vs “preserving human dignity”
  - Terms of trade are not following physical laws

- Value tradeoffs
  - 100 acres of woodland vs 100 acres of wetland
  - Choice may depend on what each person “values”

- Good trade-off analysis turns “implicit” things into “explicit” things
Approaches to Evaluation

• **Subjective Prioritization (“Gut Feeling”)**
  – **Pros:** easy to do
  – **Cons:** no rigor, potential mistakes, poor transparency/reliability, susceptible to gaming, suboptimal (potentially inefficient and/or ineffective)

• **Ad hoc weighting using Excel Spreadsheets**
  – **Pros:** everybody can use Excel, relative ease of implementing
  – **Cons:** requires arbitrary weighting for multiple criteria, ad hoc metrics, etc.

• **Multi-Criteria Decision Analysis**
  – **Pros:** transparent, state-of-the-art methods, can be tailored/modified in real time, records and visualizes differences among commands and individual opinions
  – **Cons:** time and resource intensive, potentially costly, expertise required
Multi-Criteria Decision Analysis

• MCDA:
  – Evolved as a response to the observed inability of people to effectively analyze multiple streams of dissimilar information
  – Has many different technical approaches based on similar theoretical foundations

• MCDA integrates various technical inputs & evaluations with stakeholder & decision maker preferences/values.

• MCDA allows you to ask the right people for right info.

• MCDA methods show why a particular alternative is most valued.

• MCDA allows you to explore impact of scenario/data uncertainty and value of reducing it.
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
- Screen/eliminate clearly inferior alternatives
- Determine performance of alternatives for criteria
- Rank/Select final alternative(s)
- Gather value judgments on relative importance of the criteria

**Tools:**
- Environmental Assessment/Modeling (Hydro/Risk/Ecological/Environmental Assessment & Simulation models, etc.)
- Decision Analysis (Group Decision Making Techniques/Decision Methodologies & Software)
Example MCDA Decision Matrix

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

How to interpret these data/results? (normalized scores)

How to combine these criteria? (weights)

How to compare these alternatives? (MCDA evaluations)
Decision Analysis and Decision Tools

Similar Between Decision Analysis Techniques

Multicriteria Decision Support Framework

Different Between Decision Analysis Techniques

After Yoe (2002)
MCDA Process

(1) Identify objectives

Purchase a safe and reasonably priced vehicle.

(2) Identify criteria

- Cost
- Resale Value
- Repair Cost
- Fuel Efficiency
- Passenger Space
- Style and Comfort
- Safety

(3) Identify metrics

- Cost: $K
- Resale Value: $K in 3 yrs
- Repair Cost: $/yr per 10 yrs
- Fuel Efficiency: EPA mpg est
- Passenger Space: # seats
- Style and Comfort: 1-5 rating
- Safety: NHTSA rating

(4) Develop value f(x)

(5) Elicit weights

\[
\sum_{m=1}^{M} w_m = 1
\]

(6) Generate alternatives

- Honda
- BMW
- Audi
- Volvo
- Toyota

(7) Score alternatives

<table>
<thead>
<tr>
<th></th>
<th>Alt1</th>
<th>Alt2</th>
<th>Alt3</th>
<th>Alt4</th>
<th>Alt5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>0.136</td>
<td>0.23</td>
<td>0.114</td>
<td>0.076</td>
<td>0.25</td>
</tr>
<tr>
<td>Resale Value</td>
<td>0.023</td>
<td>0.048</td>
<td>0.05</td>
<td>0.033</td>
<td>0</td>
</tr>
<tr>
<td>Maintenance</td>
<td>0.05</td>
<td>0.028</td>
<td>0.05</td>
<td>0.042</td>
<td>0.028</td>
</tr>
<tr>
<td>Fuel Efficiency</td>
<td>0.038</td>
<td>0.038</td>
<td>0.15</td>
<td>0.015</td>
<td>0.053</td>
</tr>
<tr>
<td>Passenger Space</td>
<td>0.03</td>
<td>0.15</td>
<td>0.12</td>
<td>0.09</td>
<td>0</td>
</tr>
<tr>
<td>Style and comfort</td>
<td>0.05</td>
<td>0.05</td>
<td>0.025</td>
<td>0.025</td>
<td>0</td>
</tr>
<tr>
<td>Safety</td>
<td>0</td>
<td>0.1</td>
<td>0.1</td>
<td>0.3</td>
<td>0</td>
</tr>
</tbody>
</table>

(8) Calculate MCDA

(9) Analyze sensitivity

- Evaluate score and weight parameters that most influence our preferences for alternative x over y
- Vary scores/weights within a plausible range (e.g., +/- 10%)
Specifying Decision Criteria & Performance Measures

- A coherent set of criteria set is (Roy, 1985):
  - Exhaustive (nothing important left out)
  - Consistent (no secret preferences)
  - Non-redundant (no double counting)

- Effective criteria are (Yoe, 2002):
  - Directional (maximum, minimum or optimum)
  - Concise (smallest number of measures)
  - Complete (no significant impact left out)
  - Clear (understandable to others)

- Criteria are often correlated but can still be acceptable
- Criteria should be tested throughout the decision process
MCDA Use in Environmental Science

After Huang, Linkov 2011
MCDA Case Study

A Decision Analytic Approach to Exposure-Based Chemical Prioritization

Exposure-Based Chemical Prioritization

- Chemicals must be screened, evaluated, and classified based on their potential for human exposure.
- Different Tiers of Screening:
  - 100,000 → 10,000
  - 10,000 → 2,000
  - ...
- Little information on chemicals and their potential human health risks:
  - Minimal Data Sets?
- Screening results will be used to prioritize chemicals for further data gathering and toxicological analysis.
Approaches to Prioritization

Simple, Not Data Intensive, Arbitrary weights
- PBT Profiler
- Design for Environment Alternative Assessment
- ACC Model

Expert- or data-driven weights
- Decision Analysis

Complex Data Intensive
- USETox
- SHEDS
- E-FAST
- RAIDAR/FHX
- GExFRAME
- PRoTEGE
MCDA Framework for EPA

Exposure Potential

Chemical Properties
- Physical Hazard Potential
- Persistence
- Bioaccumulation Potential
- ADME

Life Cycle Properties
- Production
- Consumer Use
- Disposal
MCDA Framework for EPA

Evenly Weighted Criteria

- **Chemical Properties**
  - Physical Hazard Potential: $W_{1.1} = 0.25$
  - Persistence: $W_{1.2} = 0.25$
  - Bioaccumulation Potential: $W_{1.3} = 0.25$
  - ADME: $W_{1.4} = 0.25$

- **Life Cycle Properties**
  - Production: $W_{2.1} = 0.33$
  - Consumer Use: $W_{2.2} = 0.33$
  - Disposal: $W_{2.3} = 0.33$

**Weighting**
- $W_1 = 0.5$
- $W_2 = 0.5$
Physical Hazard Potential

- Assessed in terms of **flammability** and **reactivity**
- Thresholds as established by *NFPA 0-7: Code requirements for Identification of Fire Hazards of Materials*
Persistence

- Assessed in terms of chemical half lives in soil, sediment, and water
- Thresholds as established by (1) EPA: Design for the Environment Program Alternatives Assessment Criteria for Hazard Evaluation, and (2) Clean Production Action: The Green Screen for Safer Chemicals Version 1.0
Bioaccumulation

- Assessed in terms of Bioaccumulation Factor (BAF) / Bioconcentration Factor (BCF), Kow, Koa, and/or molecular weight
- Thresholds as established by (1) EPA: Design for the Environment Program Alternatives Assessment Criteria for Hazard Evaluation, (2) Clean Production Action: The Green Screen for Safer Chemicals Version 1.0, and (3) Euro Chlor: Bioaccumulation: Definitions and Implications
ADME

- Assessed in terms of the human body’s ability to absorb (A), distribute (D), metabolize (M), and eliminate (E) the chemical
- Thresholds under development
### Chemical Properties Data Values

<table>
<thead>
<tr>
<th>Chemical Name</th>
<th>CAS #</th>
<th>ADME</th>
<th>Bioaccumulation</th>
<th>Chemical Properties Data</th>
<th>Persistence</th>
<th>Physical Hazard</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>50000</td>
<td>3</td>
<td>1</td>
<td>3.20E+00</td>
<td>No Data</td>
<td>No Data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DDT</td>
<td>50283</td>
<td>3</td>
<td>3</td>
<td>1.70E+04</td>
<td>No Data</td>
<td>No Data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parathion</td>
<td>56382</td>
<td>2</td>
<td>2</td>
<td>1.60E+02</td>
<td>No Data</td>
<td>3.00E+01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>gamma-Hexachlorocyclohexane</td>
<td>58889</td>
<td>2</td>
<td>2</td>
<td>2.50E+02</td>
<td>No Data</td>
<td>No Data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbaryl</td>
<td>63252</td>
<td>1</td>
<td>1</td>
<td>1.70E+01</td>
<td>No Data</td>
<td>No Data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methoxychlor</td>
<td>72435</td>
<td>2</td>
<td>3</td>
<td>1.90E+03</td>
<td>No Data</td>
<td>No Data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vinyl Chloride</td>
<td>75014</td>
<td>1</td>
<td>1</td>
<td>1.50E+00</td>
<td>No Data</td>
<td>No Data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,1,2,2-tetrachloroethane</td>
<td>75945</td>
<td>1</td>
<td>1</td>
<td>1.80E+01</td>
<td>No Data</td>
<td>No Data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pentachlorophenol A</td>
<td>79947</td>
<td>1</td>
<td>2</td>
<td>1.60E+04</td>
<td>No Data</td>
<td>3.90E+00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Siphonil-8</td>
<td>80567</td>
<td>2</td>
<td>3</td>
<td>7.30E+01</td>
<td>No Data</td>
<td>No Data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>p-lter-Parathion</td>
<td>80486</td>
<td>1</td>
<td>1</td>
<td>1.80E+02</td>
<td>No Data</td>
<td>No Data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diethyl phthalate</td>
<td>84862</td>
<td>1</td>
<td>1</td>
<td>1.80E+01</td>
<td>No Data</td>
<td>No Data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Di-n-butyl phthalate</td>
<td>84942</td>
<td>1</td>
<td>1</td>
<td>4.30E+02</td>
<td>No Data</td>
<td>No Data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,2,3 Tri chlorobenzene</td>
<td>87010</td>
<td>1</td>
<td>1</td>
<td>2.00E+02</td>
<td>No Data</td>
<td>1.20E+04</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pentachlorophenol</td>
<td>87685</td>
<td>1</td>
<td>2</td>
<td>1.10E+01</td>
<td>No Data</td>
<td>No Data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2,4,5-Tri chlorophenoxy phosphonic acid</td>
<td>93765</td>
<td>1</td>
<td>2</td>
<td>3.20E+00</td>
<td>No Data</td>
<td>1.35E+03</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2,4-D</td>
<td>94757</td>
<td>1</td>
<td>1</td>
<td>3.60E+00</td>
<td>No Data</td>
<td>2.90E+02</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ethylene bisulfate</td>
<td>96457</td>
<td>1</td>
<td>1</td>
<td>1.60E+01</td>
<td>No Data</td>
<td>No Data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methylparaben</td>
<td>95763</td>
<td>1</td>
<td>1</td>
<td>1.90E+00</td>
<td>No Data</td>
<td>No Data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Styrene</td>
<td>130425</td>
<td>1</td>
<td>1</td>
<td>3.00E+03</td>
<td>No Data</td>
<td>No Data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n-Hexane</td>
<td>11043</td>
<td>2</td>
<td>1</td>
<td>1.70E+02</td>
<td>No Data</td>
<td>1.30E+01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tri (2-chloroethyl)phosphate</td>
<td>11596</td>
<td>1</td>
<td>1</td>
<td>3.00E+01</td>
<td>No Data</td>
<td>1.10E+01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aldicarb</td>
<td>11506</td>
<td>1</td>
<td>1</td>
<td>4.20E+00</td>
<td>No Data</td>
<td>1.10E+01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DEHP, Di (2-ethylhexyl) phthalate</td>
<td>117817</td>
<td>1</td>
<td>1</td>
<td>2.00E+02</td>
<td>No Data</td>
<td>1.10E+01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>octaBEE</td>
<td>120722165</td>
<td>3</td>
<td>3</td>
<td>4.00E+02</td>
<td>No Data</td>
<td>3.00E+07</td>
</tr>
</tbody>
</table>

Chemical Properties Data Table

<table>
<thead>
<tr>
<th>Chemical Name</th>
<th>CAS #</th>
<th>ADME</th>
<th>Bioaccumulation</th>
<th>Chemical Properties Data</th>
<th>Persistence</th>
<th>Physical Hazard</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Flash Point (Fusibility) | Explosivity (Ractivit)
Compounds with both chemical properties and life cycle properties that are conducive to high exposure potential will be ranked the highest, indicating compounds which require the most attention.
### Ranked table of MCDA results for the assessment of 51 chemicals (9 with insufficient data to complete analysis)

<table>
<thead>
<tr>
<th>Rank</th>
<th>Chemical Name</th>
<th>CAS #</th>
<th>Chemical Property Score</th>
<th>Life Cycle Score</th>
<th>Aggregate Exposure Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Toluene</td>
<td>108-88-3</td>
<td>0.97</td>
<td>0.96</td>
<td>1.93</td>
</tr>
<tr>
<td>2</td>
<td>Sineure</td>
<td>100425</td>
<td>0.95</td>
<td>0.89</td>
<td>1.84</td>
</tr>
<tr>
<td>3</td>
<td>Xylidone</td>
<td>116915</td>
<td>0.97</td>
<td>0.76</td>
<td>1.73</td>
</tr>
<tr>
<td>4</td>
<td>Acetaminophen</td>
<td>62-49-2</td>
<td>0.97</td>
<td>0.86</td>
<td>1.83</td>
</tr>
<tr>
<td>5</td>
<td>Ethylene Glycol</td>
<td>107-21-1</td>
<td>0.97</td>
<td>0.90</td>
<td>1.87</td>
</tr>
<tr>
<td>6</td>
<td>Acetone</td>
<td>67-64-1</td>
<td>0.97</td>
<td>0.78</td>
<td>1.75</td>
</tr>
<tr>
<td>7</td>
<td>Terbutaline</td>
<td>79947</td>
<td>0.95</td>
<td>0.90</td>
<td>1.85</td>
</tr>
<tr>
<td>8</td>
<td>Phenolphthalein</td>
<td>87855</td>
<td>0.95</td>
<td>0.92</td>
<td>1.87</td>
</tr>
<tr>
<td>9</td>
<td>Di-n-butylphthalate</td>
<td>94442</td>
<td>0.97</td>
<td>0.90</td>
<td>1.87</td>
</tr>
<tr>
<td>10</td>
<td>Diethyl phthalate</td>
<td>84662</td>
<td>0.93</td>
<td>0.90</td>
<td>1.83</td>
</tr>
<tr>
<td>11</td>
<td>Hexamethyidyldisiloxane (HMDI)</td>
<td>26637984</td>
<td>0.96</td>
<td>0.93</td>
<td>1.90</td>
</tr>
<tr>
<td>12</td>
<td>2,4-Dinitrotoluene</td>
<td>10348019</td>
<td>0.97</td>
<td>0.87</td>
<td>1.84</td>
</tr>
<tr>
<td>13</td>
<td>Triton X-100</td>
<td>75568</td>
<td>0.95</td>
<td>0.90</td>
<td>1.85</td>
</tr>
<tr>
<td>14</td>
<td>Chloroprene</td>
<td>56910</td>
<td>0.95</td>
<td>0.90</td>
<td>1.85</td>
</tr>
<tr>
<td>15</td>
<td>2,4-Dichlorophenoxyacetic acid (2,4-D)</td>
<td>95177</td>
<td>0.97</td>
<td>0.90</td>
<td>1.87</td>
</tr>
<tr>
<td>16</td>
<td>Adipic Acid</td>
<td>110953</td>
<td>0.93</td>
<td>0.90</td>
<td>1.83</td>
</tr>
<tr>
<td>17</td>
<td>Vinyl Chloride</td>
<td>77274</td>
<td>0.97</td>
<td>0.90</td>
<td>1.87</td>
</tr>
<tr>
<td>18</td>
<td>p-Xylenol</td>
<td>95860</td>
<td>0.95</td>
<td>0.90</td>
<td>1.85</td>
</tr>
<tr>
<td>19</td>
<td>1,3-Butadiene</td>
<td>60380517</td>
<td>0.97</td>
<td>0.90</td>
<td>1.87</td>
</tr>
<tr>
<td>20</td>
<td>Ethylene Glycol</td>
<td>107-21-1</td>
<td>0.97</td>
<td>0.90</td>
<td>1.87</td>
</tr>
<tr>
<td>21</td>
<td>3,3-Dimethylglutaric acid</td>
<td>35963277</td>
<td>0.95</td>
<td>0.90</td>
<td>1.85</td>
</tr>
<tr>
<td>22</td>
<td>1,3,5-Triformylbenzene</td>
<td>79947</td>
<td>0.96</td>
<td>0.90</td>
<td>1.87</td>
</tr>
<tr>
<td>23</td>
<td>Vinyl esters</td>
<td>5041744</td>
<td>0.96</td>
<td>0.90</td>
<td>1.87</td>
</tr>
<tr>
<td>24</td>
<td>Melamine</td>
<td>95177</td>
<td>0.95</td>
<td>0.90</td>
<td>1.87</td>
</tr>
<tr>
<td>25</td>
<td>Polycarbonate</td>
<td>178365</td>
<td>0.95</td>
<td>0.90</td>
<td>1.87</td>
</tr>
<tr>
<td>26</td>
<td>Formaldehyde</td>
<td>50909</td>
<td>0.95</td>
<td>0.90</td>
<td>1.87</td>
</tr>
<tr>
<td>27</td>
<td>Azobenzene</td>
<td>77274</td>
<td>0.95</td>
<td>0.90</td>
<td>1.87</td>
</tr>
<tr>
<td>28</td>
<td>Hexachlorobenzene</td>
<td>77274</td>
<td>0.95</td>
<td>0.90</td>
<td>1.87</td>
</tr>
<tr>
<td>29</td>
<td>Halothane</td>
<td>77274</td>
<td>0.95</td>
<td>0.90</td>
<td>1.87</td>
</tr>
<tr>
<td>30</td>
<td>Ethylene glycol</td>
<td>107-21-1</td>
<td>0.95</td>
<td>0.90</td>
<td>1.87</td>
</tr>
<tr>
<td>31</td>
<td>DDT</td>
<td>50293</td>
<td>0.95</td>
<td>0.90</td>
<td>1.87</td>
</tr>
<tr>
<td>32</td>
<td>Perchloroethylene</td>
<td>127184</td>
<td>0.95</td>
<td>0.90</td>
<td>1.87</td>
</tr>
<tr>
<td>33</td>
<td>Perfluorooctane</td>
<td>52645511</td>
<td>0.95</td>
<td>0.90</td>
<td>1.87</td>
</tr>
<tr>
<td>34</td>
<td>1,3-Dichloro-1,2-propanediol</td>
<td>144070</td>
<td>0.95</td>
<td>0.90</td>
<td>1.87</td>
</tr>
<tr>
<td>35</td>
<td>Ethylene oxide</td>
<td>90457</td>
<td>0.95</td>
<td>0.90</td>
<td>1.87</td>
</tr>
<tr>
<td>36</td>
<td>Parathion</td>
<td>50293</td>
<td>0.95</td>
<td>0.90</td>
<td>1.87</td>
</tr>
<tr>
<td>37</td>
<td>Methoxyflurane</td>
<td>72833</td>
<td>0.95</td>
<td>0.90</td>
<td>1.87</td>
</tr>
<tr>
<td>38</td>
<td>Methanol</td>
<td>72833</td>
<td>0.95</td>
<td>0.90</td>
<td>1.87</td>
</tr>
<tr>
<td>39</td>
<td>2,4,6-Trihaloanilines</td>
<td>72833</td>
<td>0.95</td>
<td>0.90</td>
<td>1.87</td>
</tr>
<tr>
<td>40</td>
<td>Lead</td>
<td>7439921</td>
<td>m/a</td>
<td>m/a</td>
<td>Insufficient Data</td>
</tr>
<tr>
<td>41</td>
<td>Manganese</td>
<td>7439921</td>
<td>m/a</td>
<td>m/a</td>
<td>Insufficient Data</td>
</tr>
<tr>
<td>42</td>
<td>Cadmium</td>
<td>7439921</td>
<td>m/a</td>
<td>m/a</td>
<td>Insufficient Data</td>
</tr>
<tr>
<td>43</td>
<td>Polyurethane</td>
<td>7439921</td>
<td>m/a</td>
<td>m/a</td>
<td>Insufficient Data</td>
</tr>
<tr>
<td>44</td>
<td>Polychlorinated biphenyls (PCB)</td>
<td>7439921</td>
<td>m/a</td>
<td>m/a</td>
<td>Insufficient Data</td>
</tr>
<tr>
<td>45</td>
<td>Benzene</td>
<td>7439921</td>
<td>m/a</td>
<td>m/a</td>
<td>Insufficient Data</td>
</tr>
<tr>
<td>46</td>
<td>Chloroform</td>
<td>7439921</td>
<td>m/a</td>
<td>m/a</td>
<td>Insufficient Data</td>
</tr>
<tr>
<td>47</td>
<td>Dichloromethane</td>
<td>7439921</td>
<td>m/a</td>
<td>m/a</td>
<td>Insufficient Data</td>
</tr>
</tbody>
</table>

**Key:**
- I: Industrial/occupational additives and byproducts.
- P: Pesticides and herbicides.
- M: Mixtures.
- A: Additives in food and commercial products.

**Note:**
- “Insufficient Data” indicates that the data is not available.

*doii10.1371/journal.pone.0079711.s001*
Plot of MCDA Results (42 Chemicals)

Exposure Screening Results:

- Low Risk
- Medium Risk
- High Risk
Value of Information Analysis (VOI)

Analysis of the benefit gained from reducing uncertainty through research
Managing Uncertainty: Value of Information Analysis

- Vol systematically explores uncertainty in the MCDA results.
- Vol shows the potential impact of new information on decision outcomes.
- It is useful for prioritizing research & establishing cutoffs for data gathering.
- Vol research prioritization steps:
  1. Estimate uncertainty of parameters in the MCDA model.
  2. Monte Carlo simulations repeatedly sample those parameters from the uncertain decision space & reassess MCDA decision recommendations.
  3. Measure changes from base-case expectation when sampling/not-sampling all combinations of parameters.
  4. Find criteria for which simulated additional information most change our base-case expectation or prevent losses associated with poor decisions.
  5. Compare research benefits with costs to calculate Vol.
Monte Carlo Vol: Summary of Approach

1. Estimate uncertainty of parameters in the MCDA model

2. Monte Carlo simulations draw from distributions + mean values many times to generate distributions of total scores with and without simulated information

3. Each research strategy (i.e. combinations of parameters for which information is simulated) will result in an output distribution. Compare mean of distributions to base MCDA score to see expected impact of each research portfolio

4. With all combinations of parameters tested, find criteria for which simulated additional information most change base-case decision expectations

5. Finally, research benefits can be compared to the cost of generating the information

<table>
<thead>
<tr>
<th>Output Change</th>
<th>Parameters Tested</th>
<th>Cost to Perform</th>
<th>Change Per MM</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>P1, P2, P3</td>
<td>$10 MM</td>
<td>0.35</td>
</tr>
<tr>
<td>3.2</td>
<td>P1, P2</td>
<td>$8.9 MM</td>
<td>0.36</td>
</tr>
<tr>
<td>2.9</td>
<td>P1, P3</td>
<td>$5 MM</td>
<td>0.58</td>
</tr>
<tr>
<td>0.1</td>
<td>P3</td>
<td>$1.1 MM</td>
<td>0.09</td>
</tr>
</tbody>
</table>

### Diagram

- MCDA
- Simulate
- P1 Distribution
- P2 Distribution
- ... Pn Distribution
- Total Score Distribution
Value of Information Analysis
Case Study

A decision-directed approach for prioritizing research into the impact of nanomaterials on the environment and human health.

Problems in Assessing Nanomaterials

- Nanomaterials exhibit a high degree of uncertainty about the Environmental, Health and Safety risks in addition to the cost and effectiveness of materials.

- There are multiple stakeholders who have conflicting objectives and concerns.
Case Study: Selecting a Nanomanufacturing Technology for Single-Wall Carbon Nanotubes

Single-Wall Carbon Nanotubes (SWCNT)

- Useful in industry: High strength, stiffness, & thermal/electrical conductivity; useful for sports, transportation, industrial, & technology equipment

- Four alternative manufacturing techniques: High pressure carbon monoxide (HiPCO), arc discharge (Arc), chemical vapor deposition (CVD), and laser vaporization (Laser)

- Uncertainty on five criteria: Health risks, environmental impacts, manufacturing costs, material efficiency, and energy consumption
Framework of Integrated Decision Analytic Tools

Organize Components into Structured Framework

- Each alternative (blue) is evaluated across all criteria (orange) in order to get a comparative assessment

- This acts as a framework that can be populated with values and importance weights by the user (i.e. the actual decision maker)
Incorporate Stakeholder Criteria Weights

- In this example, we created 4 hypothetical stakeholders as well as a balanced view.

- The balanced view puts an equal importance on each of the five decision factors (criteria).

- The manufacturer’s major concern is Cost.

- Consumers focus on Cost & Safety.

- Environmentalists focus on Health Risks & Life-Cycle Impacts.
Determine the Value of Criteria for Each Alternative

Below we see a summary of the value of each alternative across each criteria.

<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</td>
<td>1550.75 2859.00</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</td>
<td>1550.75 2859.00</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</td>
<td>1550.75 2859.00</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</td>
<td>1550.75 2859.00</td>
</tr>
</tbody>
</table>

Note that these values are independent of the stakeholder preferences.
Determine the Value of Criteria for Each Alternative

Below we see a summary of the value of each alternative across each criterion.

<table>
<thead>
<tr>
<th>Alternative</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></td>
<td>Minimize</td>
<td>Maximize</td>
<td>Minimize</td>
<td>Minimize</td>
<td>Minimize</td>
</tr>
<tr>
<td>HiPro</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CVD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arc</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laser</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note that these values are independent of the stakeholder preferences.
Simulate Results for Neutral Stakeholder (Equal Weighting)

- MCDA allows the transparent and structured evaluation of each alternative across all of the criteria.

- Without incorporating stakeholder preference we can run analysis with equal weighting of criteria.

- Using simulation to account for uncertainty, we see that different outcomes are possible but that HiPCO is ranked first the majority of the time – i.e. it is likely the best choice under these circumstances.
Simulate Stakeholder Specific Results

- Here we can see how the simulations perform under each stakeholder preference structure

- The Consumer, Manufacturer, and Regulator are most likely to prefer the HiPCO method

- The Environmentalist prefers the Laser method but only slightly more than that of HiPCO
# Nano Vol Results

<table>
<thead>
<tr>
<th></th>
<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 Vol from M Only</th>
<th>% of Vol from H Only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td></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></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></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></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></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**

**Total Average Net Flow with New Information**
Weight of Evidence (WoE) and Adverse Outcome Pathways (AoP)
Predicting physical properties of emerging compounds with limited physical and chemical data: QSAR model uncertainty and applicability to military munitions

Erin R. Bennett, Jay Clausen, Eugene Linkov, Igor Linkov

Goal: Predict Kow

Chemicals: RDX-like and Altrazine-like Compounds

Methods: Multiple QSAR models

<table>
<thead>
<tr>
<th>Method</th>
<th>ACD/log P v10.2</th>
<th>ALOGP v2.1</th>
<th>ClogP v4.9</th>
<th>KOWWIN v1.67</th>
<th>MarvinSketch/log P v4.1.8</th>
<th>SPARC v4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Training set</td>
<td>&gt;10 000</td>
<td>&gt;10 000</td>
<td>&gt;10 000</td>
<td>2464</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Validation set</td>
<td>&gt;13 000</td>
<td>n/a</td>
<td>n/a</td>
<td>&gt;10 000</td>
<td>120 atoms from 893 cpds</td>
<td>n/a</td>
</tr>
<tr>
<td>Availability</td>
<td>Download</td>
<td>Online</td>
<td>Online</td>
<td>Download</td>
<td>Online</td>
<td>Online</td>
</tr>
</tbody>
</table>

1912-24-9 Atrazine

121-82-4 RDX
QSAR Modeling Uncertainty

$C_{12}H_4Cl_6$ like Compounds

$C_3H_6N_6O_6$ like Compounds

RDX
Problem: “Modeler/Scenario Uncertainty”

subjective interpretation of the problem at hand

WHAT DO YOU SEE?

A HAT
OR
A BOA CONSTRICCTOR
DIGESTING AN ELEPHANT

What is the influence of modeler perception on model predictions?
IAEA Model Intercomparisons

1 year after deposition

- SCK-CEN
- FRUITPATH -95%
- FRUITPATH
- FRUITPATH +95%
- SPADE

Ratio to the Median Calculation

Model Ri

Radionuclide Concentration (Bq/kg)

- "Chernobyl" Scenario
- Waste Scenario

after Linkov et al., 2003 and 2005)
Emerging Issue: Adverse Outcome Pathways:

Aromatase inhibition leading to fish reproductive dysfunction

<table>
<thead>
<tr>
<th>Level of Organization</th>
<th>AOP Diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro-molecular</td>
<td><img src="image1" alt="Aromatase Inhibition" /></td>
</tr>
<tr>
<td>Cell/Tissue</td>
<td><img src="image2" alt="Granulosa cells, Reduced E2 synthesis" /> → <img src="image3" alt="Hepatocyte, Reduced VTG expression and production" /> → <img src="image4" alt="Oocytes, Reduced VTG uptake, impaired development" /></td>
</tr>
<tr>
<td>Organ/Organ System</td>
<td><img src="image5" alt="Circulation, Reduced E2 concentrations" /> → <img src="image6" alt="Circulation, Reduced VTG concentrations" /></td>
</tr>
<tr>
<td>Individual</td>
<td><img src="image7" alt="Female, Decreased spawning and cumulative fecundity" /></td>
</tr>
<tr>
<td>Population</td>
<td><img src="image8" alt="Population, Declining Trajectory" /></td>
</tr>
<tr>
<td>Community</td>
<td><img src="image9" alt="Community, Food-web alterations" /></td>
</tr>
</tbody>
</table>
How DA can help Toxicologists?

- Decison maker - Value
- Bayesian Expert - subjective
- Statistical - data
- Mechanistic - model

Reliance on empirical data

Rarely used methods

Used in most environmental areas

Judgment
Comparing WoE Approaches

From Linkov et al., 2009
## Logic Model Output

<table>
<thead>
<tr>
<th>Key Event (upstream)</th>
<th>Key Event (downstream)</th>
<th>Weight-of-evidence for link</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aromatase inhibition</td>
<td>Ovarian (granulosa cell) E2 synthesis (reduction)</td>
<td>Strong</td>
</tr>
<tr>
<td>Ovarian (granulosa cell) E2 synthesis (reduction)</td>
<td>Plasma 17β-estradiol concentrations (reduction)</td>
<td>Strong</td>
</tr>
<tr>
<td>Plasma 17β-estradiol concentrations (reduction)</td>
<td>Transcription and translation of vitellogenin (reduction)</td>
<td>Strong</td>
</tr>
<tr>
<td>Transcription and translation of vitellogenin (reduction)</td>
<td>Plasma vitellogenin concentrations (reduction)</td>
<td>Strong</td>
</tr>
<tr>
<td>Plasma vitellogenin concentrations (reduction)</td>
<td>Vitellogenin uptake, impaired oocyte development (reduction)</td>
<td>Moderate</td>
</tr>
<tr>
<td>Vitellogenin uptake, impaired oocyte development (reduction)</td>
<td>Spawning and cumulative fecundity (reduction)</td>
<td>Moderate</td>
</tr>
<tr>
<td>Spawning and cumulative fecundity (reduction)</td>
<td>Population trajectory (declining)</td>
<td>Moderate</td>
</tr>
</tbody>
</table>
Steps of MCDA Methodology

1. Define KERs as alternatives for which relative confidence is unknown and needs to be prioritized

2. Map out the criteria and metrics based on BH considerations and KERs as a value tree

3. Assign weights for importance of each of the criteria and metrics associated with each criterion.

4. Score each KER based on each metric (In this case, Strong=3, Moderate=2, Weak=1)

5. Integrate scores and weights for each KER to assess overall confidence level

6. Conduct sensitivity analysis
Criteria Weights and Key Event Scores
Confidence Assessment Scores

Overall scores

Scores

Alternatives

- 17B-estradiol to VTG trans.
- E2 to Plasma 17B-estradiol
- Fecundity to Pop. Decline
- Inhibition to E2 Synthesis
- Oocyte growth to fecundity
- VTG conc. to oocyte growth
- VTG trans to reduced conc.
Sensitivity Analysis

1. Inhibition to E2 Synthesis = 1.00
2. E2 to Plasma 17B-estradiol = 1.00
3. 17B-estradiol to VTG trans. = 0.85
4. VTG trans to reduced conc. = 0.60
5. Fecundity to Pop. Decline = 0.575
6. VTG conc. to oocyte growth = 0.55
7. Oocyte growth to fecundity = 0.30

Essentiality: 0.30
Empirical Data: 0.20
Certainty and Consistency: 0.10
Biological Plausibility: 0.40
Conclusions

- Quantitative WoE frameworks provide an objective and transparent mean to assess AOPs
- MCDA strengthens WoE logic by adding visual effect of a mapped decision structure as well as quantitative weighing of LOE
- Restricts expert inputs to weighing evidence
- Allows for incorporation of inputs from multiple experts
Conclusions

- Decision Analytic approaches represent the practical application of analytical tools to support complex decisions, allocation problems and planning processes.
- Benefits include transparency, flexibility, repeatability between decision makers, and responsiveness to multiple planning scenarios.
- Applications are diverse but all require decision maker / stakeholder consideration of multiple criteria/alternatives.
- This can 1) help with integration of methods in tools, and 2) implement some ‘default’ decision models for cases.
References


