Finding common ground when experts and models disagree:

Belief dominance and Climate Change R&D Policy

Erin Baker, University of Massachusetts
Valentina Bosetti, Bocconi University and FEEM
Ahti Salo, Aalto University

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Deep Uncertainty

- Conflicting experts or models
Deep Uncertainty - Approaches

- **Aggregate beliefs:**
  Clemen & Winkler; Cooke; Lichtendahl et al

- **Dynamic Decision making under uncertainty and learning:** (Kolstad, Baker, Lemoine, Pyndyck)

- **Criticism:**
  - “lacking externally consistency”
  - Mathematically resolve disagreement resulting in a single best recommendation
Deep Uncertainty - Approaches

- Retain individual beliefs
  - Ambiguity Aversion, robust optimization
    - Lacking internal consistency
    - Mathematically resolve disagreement resulting in a single best recommendation

- Synthesize in the context of a decision
- Robust Decision Making
  - Evaluates a small number of alternatives
  - Iterates to develop alternatives
Our approach: Robust Portfolio Decision Analysis

- Considers portfolios of alternatives (technologies, policies)
  - \{high R&D into nuclear; solar subsides; 450ppm; cap&trade\}
  - \{low R&D into nuclear; solar subsidies; carbon tax\}

- Results in a set of “good” alternatives
  - \{portfolio 1, portfolio 7, portfolio 10, …\}

- Provides insights about good individual projects
  - core projects = \{solar subsidies, …\}

All sets on this slide are purely illustrative; these are not results.
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May help to open up the dialogue on climate change. “Emphasize solutions and benefits”.

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All sets on this slide are purely illustrative; these are not results.

RPDA: theoretical framework

- Belief dominance
- From non-dominated portfolios to robust individual alternatives
Belief Dominance

An alternative* \( \mathbf{x} \) dominates an alternative \( \mathbf{x}' \) over a set \( \Phi \) of probability distributions if:

\[
\int U(x; z) f(z; x) \, dz \geq \int U(x'; z) f(z; x') \, dz \quad \forall f \in \Phi
\]

\( \mathbf{x} \) is a vector of decision variables
\( Z \) is a random variable with probability distribution \( f \)
\( U \) is an objective function

*An “alternative” may be a portfolio.
Belief Dominance (example)

An alternative* $\mathbf{x}$ dominates an alternative $\mathbf{x}'$ over a set $\Phi$ of probability distributions if:

\[
\int U(\mathbf{x}; z)f(z; \mathbf{x}) \, dz \leq \int U(\mathbf{x}'; z)f(z; \mathbf{x}') \quad \forall f \in \Phi
\]

$x$ is a vector of decision variables (investments into technology R&D, solar, nuclear,...)

$Z$ is a random variable with probability distribution $f$ (outcomes of technical change, such as cost; distribution depends on investment)

$U$ is an objective function (The total cost of abatement, derived from an IAM)

*An “alternative” may be a portfolio.
Dominance Concepts

- **Belief**: alternative $x$ dominates alternative $x'$
  \[
  \int U(x; z)f(z; x)\,dz \geq \int U(x'; z)f(z; x')\,dz \quad \forall f \in \Phi
  \]

- **Stochastic**: distribution $f$ dominates distribution $g$
  \[
  \int U(x; z)f(z)\,dz \geq \int U(x; z)g(z)\,dz \quad \forall U \in V
  \]

- **Pareto**: alternative $x$ dominates alternative $x'$
  \[
  \int U_i(x; z)f(z)\,dz \geq \int U_i(x; z)f(z)\,dz \quad \forall U_i
  \]
From portfolios to individual alternatives

- Each portfolio is made up of individual projects $i=1..I$
- Define $x_i=1$ if project $i$ is funded and 0 otherwise
- Define a portfolio $\bar{x} \equiv (x_1, ..., x_N)$
- Let $\text{ND} = \{\text{non-dominated portfolios}\}$

$\text{core} \equiv \{i \mid x_i = 1 \ \forall \bar{x} \in \text{ND}\}$

$\text{ext} \equiv \{i \mid x_i = 0 \ \forall \bar{x} \in \text{ND}\}$

$\text{bord} \equiv \{i \mid i \notin \text{core} \text{ and } i \notin \text{ext}\}$

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project $b$ is in exterior; project $d$ is in core
Proof of concept: Public energy technology R&D portfolios
Proof of concept: Energy Technology R&D Portfolio in Response to Climate Change.

Given a Representative Concentration Pathway (RCP) of $2.6 \text{ w/m}^2$ ($\sim 450\text{ ppm}$):

- R&D Investment
- Technology Performance
- IAM chooses Implementation
- Value (Cost)

3 sets of elicitations on 5 technologies plus combined
The general model

$$\min_x \int \left\{ TAC(z, s) + \kappa B(x) \right\} f_\tau(z; x) dz$$

For $$s = 2.6 (~450\text{ppm})$$

$$\sum_j x_{ij} = 1 \ \forall i$$

$$x_{ij} = 1$$ if technology $$i$$ is invested in at the $$j$$th funding level; 0 otherwise

$$i = \text{solar, nuclear, CCS, bio-elec, bio-fuel}$$

$$j = \text{low, mid, high}$$

$$TAC(z, s) = \text{total abatement cost for stabilization } s, \text{ tech outcome } z$$

$$B(x) = \text{total R&D investment for portfolio } x$$

$$\kappa = \text{opportunity cost of investment}$$

$$f_\tau(z; x) = \text{pdf of } z \text{ from team } \tau \text{ given investment portfolio } x$$
The computational model

\[ H(x, \tau) \equiv \sum_{l=1}^{1000} p_\tau(z_l; x) TAC(z_l, s) + \kappa B(x) \]

s.t. \( \sum_j x_{ij} = 1 \ \forall i \)

- \( x \) belief dominates \( x' \) if \( H(x, \tau) \leq H(x', \tau) \ \forall \tau \)

\( x_{ij} = 1 \) if technology \( i \) is invested in at the \( j \)th funding level; 0 otherwise

\( i = \) solar, nuclear, CCS, bio-elec, bio-fuel

\( j = \) low, mid, high

\( TAC(z, s) = \) total abatement cost for stabilization \( s \), tech outcome \( z \)

\( B(x) = \) total R&D investment for portfolio \( x \)

\( \kappa = \) opportunity cost of investment

\( p_\tau \) is the discrete probability of outcome \( z_l \) given investment \( x \). We use importance sampling to estimate \( p_\tau \).
# Results: non-dominated portfolios

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<th>Technologies</th>
<th>Objectives ENPV (cost in billions of $2005)</th>
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10 out of 243 total are non-dominated
## Results: core and exterior projects

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BE high is in core; Nuc low is in exterior
Normalized ENPV of TAC by team

Combined Harvard FEEM UMass
Normalized ENPV of TAC by team: some are less robust
Results: core and exterior of “robust” non-dominated

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core = {BE high; CCS mid}

exterior = {Solar high; nuclear low; BF low}
Future work – When Models Disagree

- Model uncertainty and parametric uncertainty

\[ H(x; \tau, m) = \sum_{i=1}^{1000} p_{\tau x}(z_i) \left[ TAC_m(z_i; s) \right] + \kappa B_x \]

- \( \tau \) is beliefs over parametric uncertainty; \( m \) represents individual models

- portfolio \( x \) belief dominates \( x' \) if: \( H(x; \tau, m) \leq H(x'; \tau, m) \) \( \forall \tau, m \)
Conclusions

- Belief Dominance is a new concept that allows analysts to derive a set of good alternatives under conflicting beliefs.
  - Synthesizes beliefs in a decision context
  - Avoids worst-case analysis
- RPDA leads to implications about individual alternatives
  - Example: A high investment into bio-electricity was robust across all beliefs
- By focusing on a set of good alternatives, RPDA uses the best available knowledge to support decision making in a way that preserves flexibility for decision makers.
A structured process for eliciting subjective probability distributions from experts about items of interest to decision makers.
## TEaM Results

### Solar LCOE

<table>
<thead>
<tr>
<th>Solar LCOE</th>
<th>Nuclear capital cost</th>
<th>Biofuels combined</th>
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Covering Distributions with Importance Sampling

Nominal (elicited) distributions $q_{ij}(x_i)$

Covering (importance) distribution $p_i(x_i)$ chosen to span the range of nominal distributions and sample from the area of interest.

Sampling distribution is multiplied by the likelihood ratio $q_i/p_i$ to remove sampling bias.