Framing Energy and Environmental Planning Problems Using Many Objective Robust Decision Making

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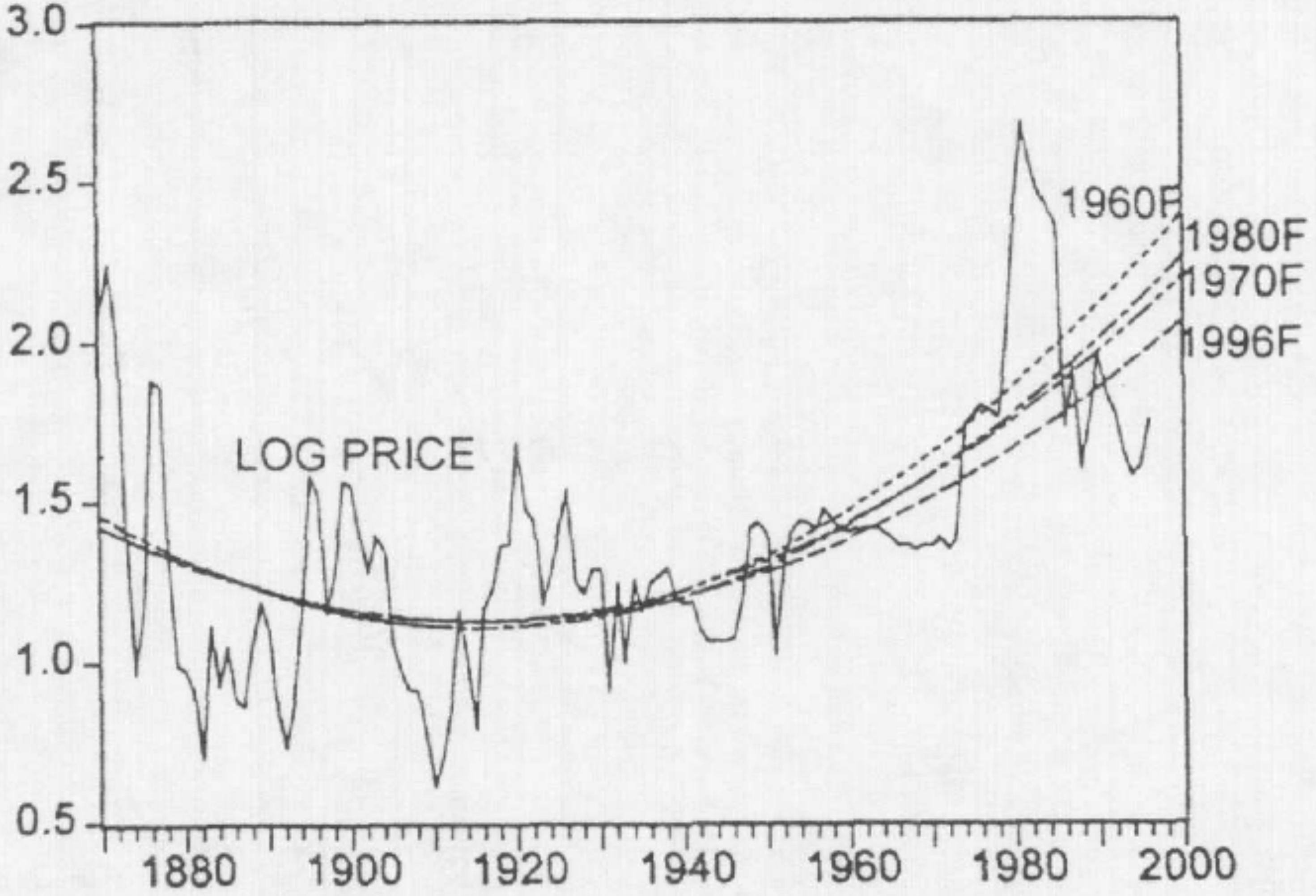
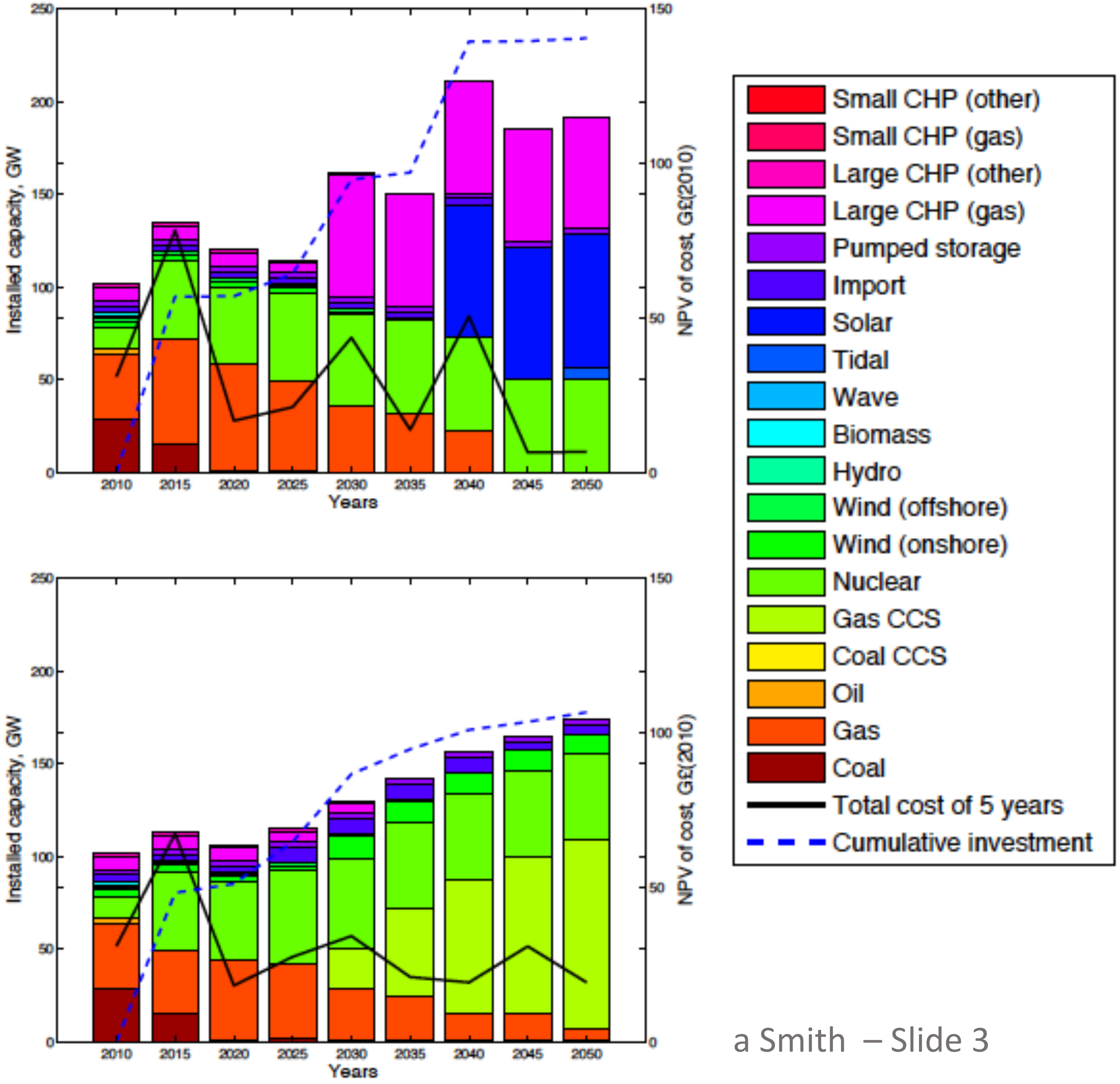
Planning requires estimates of future values of deeply uncertain **exogenous "input" data**.

Figure 1. Log Price of Crude Oil and Quadratic Trend Lines



[Pindyck, 1999, *Energy Journal*]

We also need the ability to **design** portfolios of stakeholder actions.



Two maximally different energy portfolios that provide near-optimal performance in a simple energy model of the UK [Trutnevyte and Strachan, 2013, International Energy Workshop]

Many Objective Robust Decision Making (MORDM)

- The approach combines methods for generating new policy alternatives and evaluating them under deeply uncertain input ensembles
- Collaboration between RAND Corporation and research groups of Prof. Patrick Reed and my own
- Methods
  - Multiobjective Evolutionary Algorithm (MOEA) optimization
  - Robust Decision Making

MORDM: Kasprzyk, Nataraj, Reed, Lempert [2013], Env. Mod. Soft

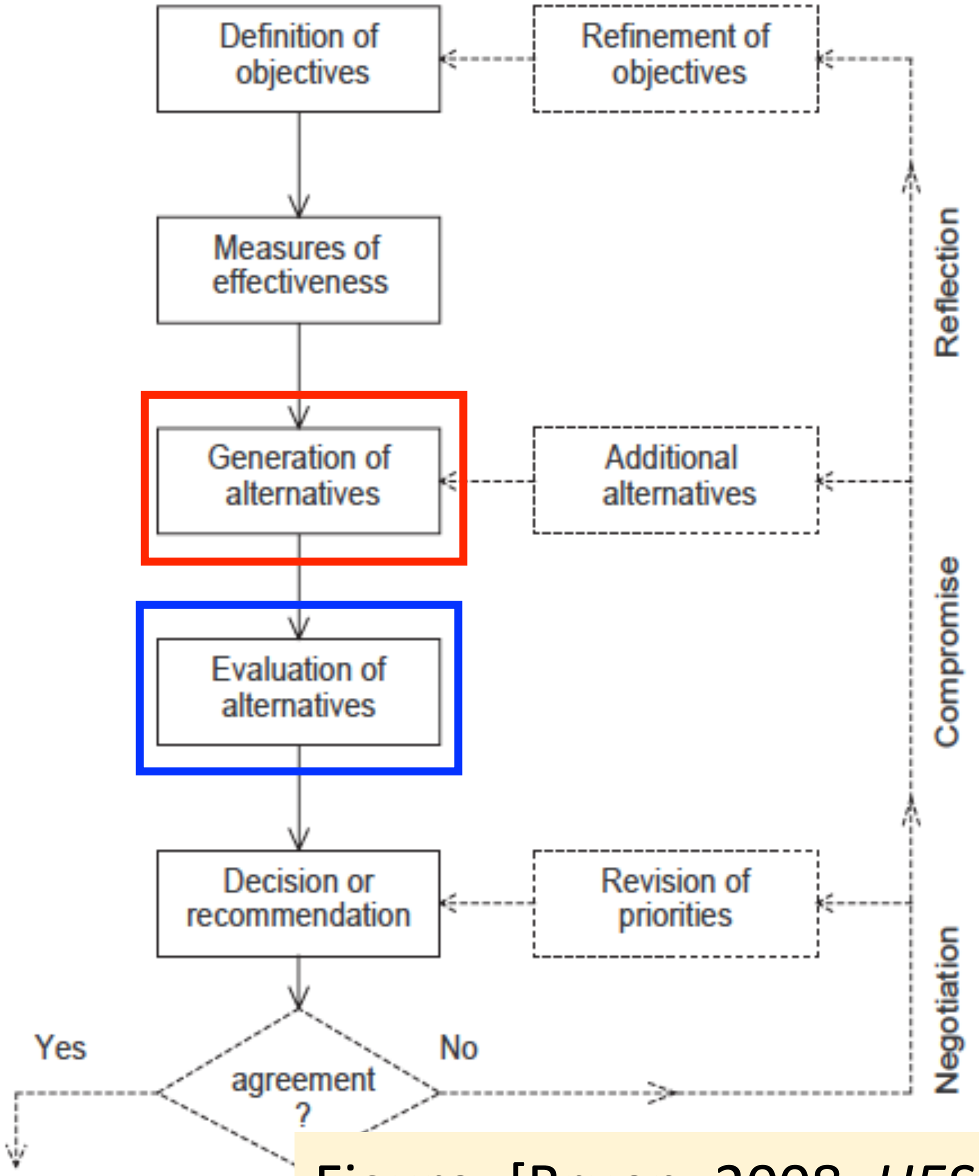
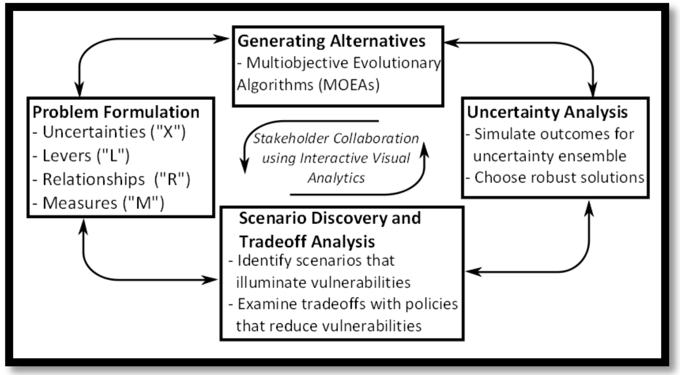


Figure: [Bruen, 2008, *HESS]*

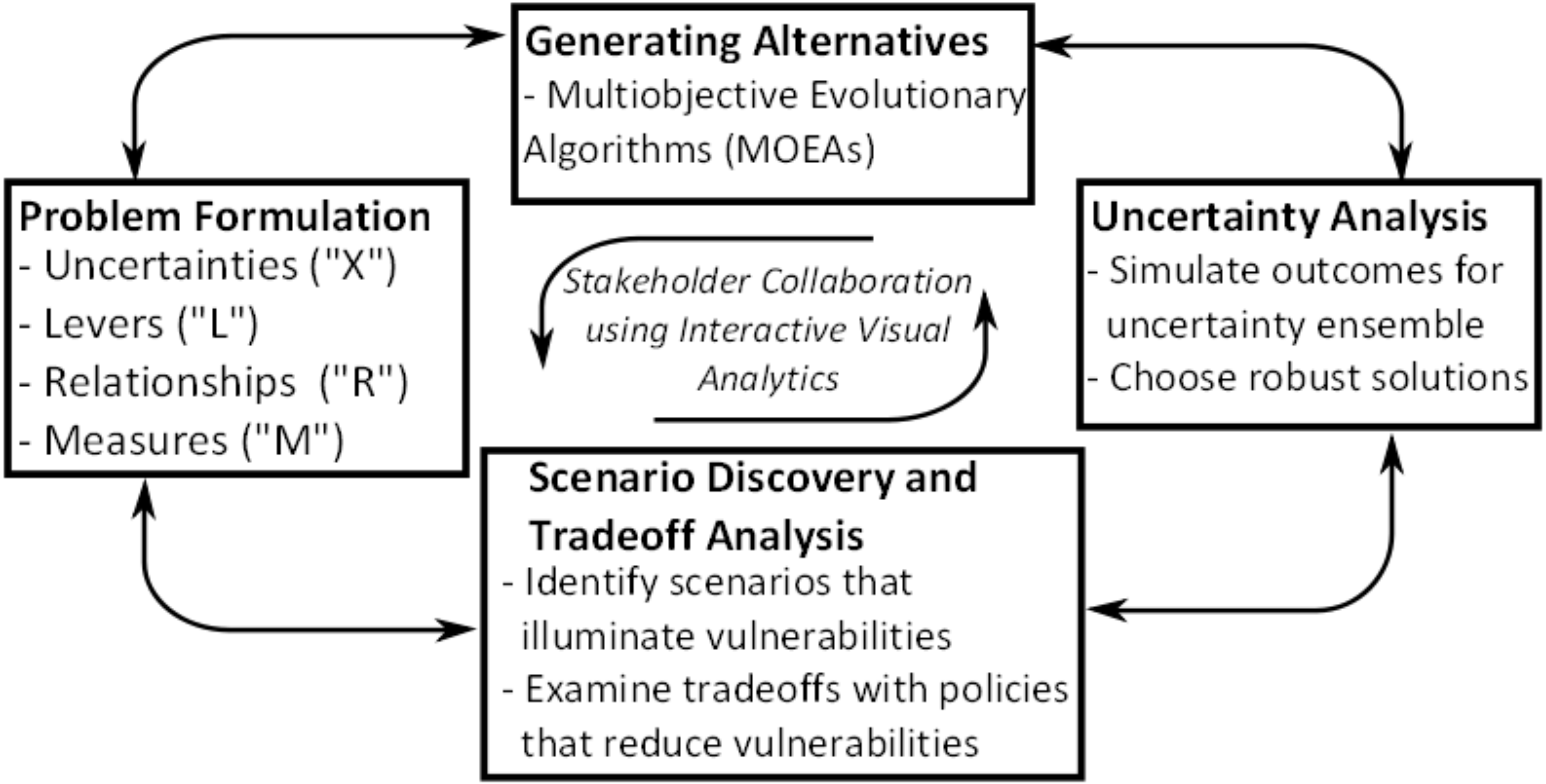
Outline



1. Introduce MORDM framework

2. Show water planning case study

3. Suggest future research

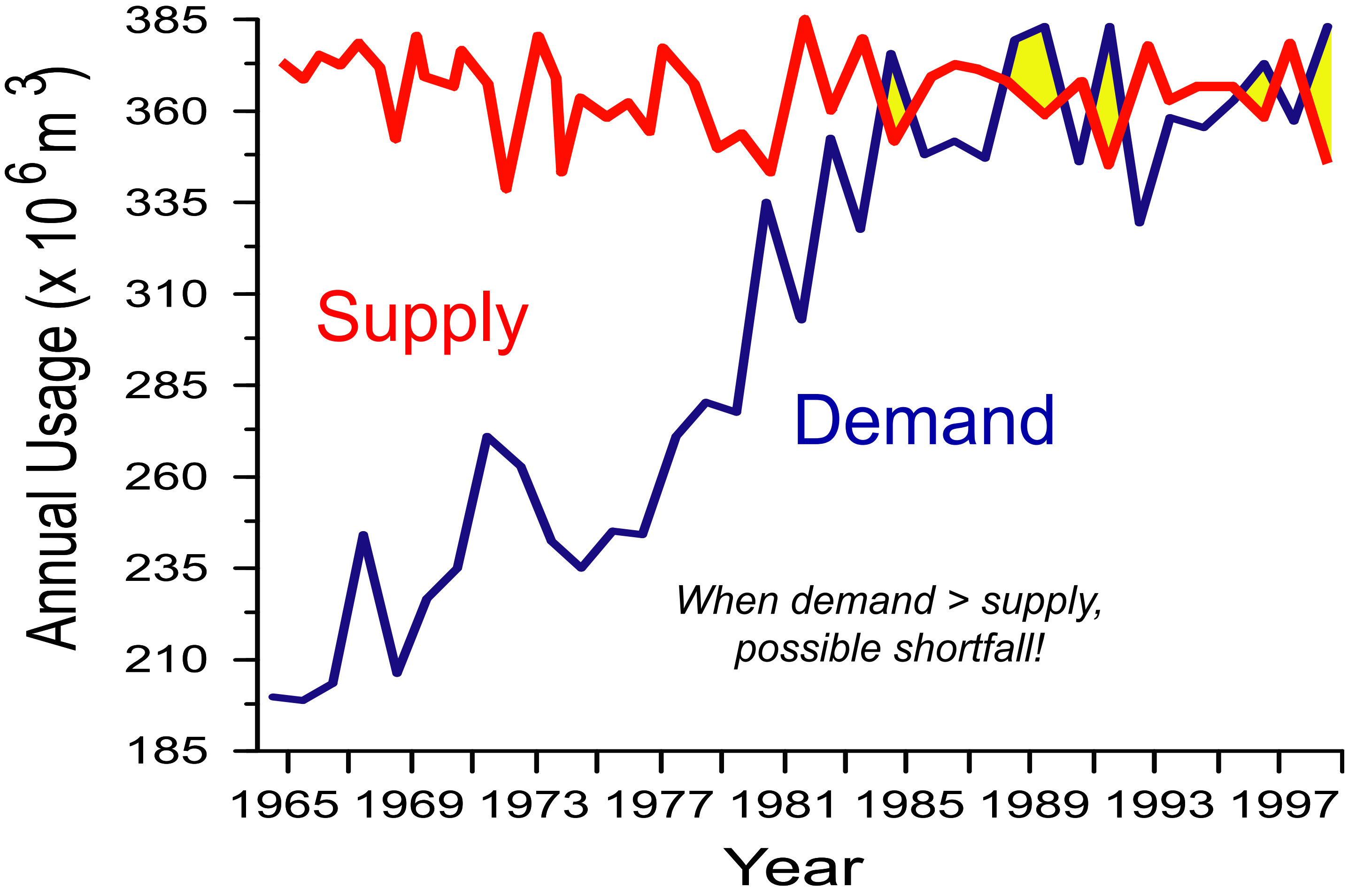

Generating Alternatives
- Multiobjective Evolutionary Algorithms (MOEAs)
Problem Formulation
- Uncertainties ("X")
- Levers ("L")
- Relationships ("R")
- Measures ("M")
Stakeholder Collaboration using Interactive Visual Analytics
Uncertainty Analysis
- Simulate outcomes for uncertainty ensemble
- Choose robust solutions
Scenario Discovery and Tradeoff Analysis
- Identify scenarios that illuminate vulnerabilities
- Examine tradeoffs with policies that reduce vulnerabilities

Which solutions do well under a large number of deeply uncertain trajectories?

How do we **characterize values of the uncertainties** that cause vulnerabilities for those robust solutions?

Lower Rio Grande Valley (LRGV) faces rising demands with variable supply.

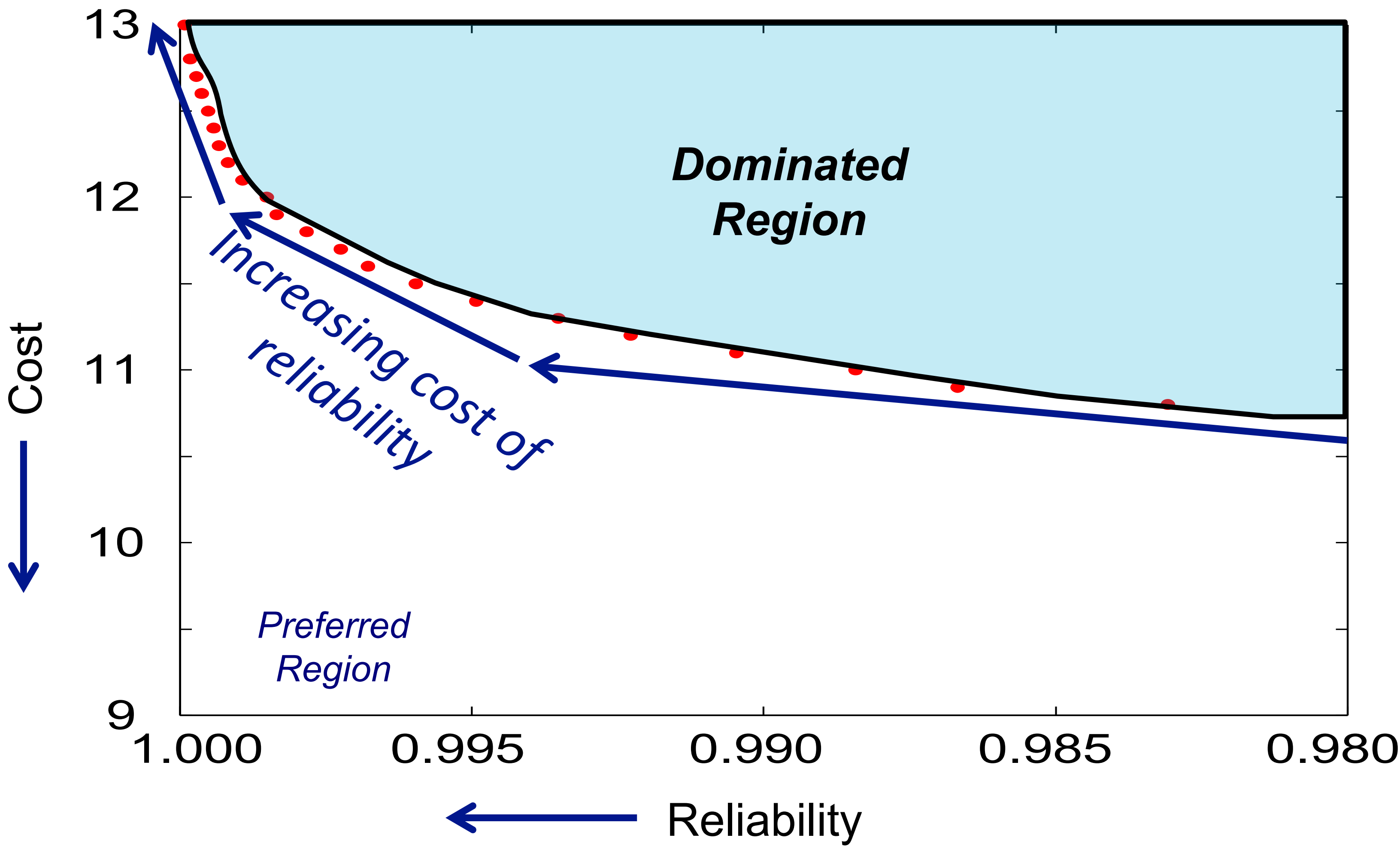
- Rapid population growth and high irrigation water use
- Existing water market with transfers from ag to urban
- How can a single city use a **water market** to increase the reliability of its water supply?



[Example data courtesy G. Characklis]

What is the outcome of adding reservoir rights to meet supply?

- Each point: a volume of **reservoir rights**
- Non-domination (i.e., highest reliability at each cost level)
- Shows increasing cost of providing reliability

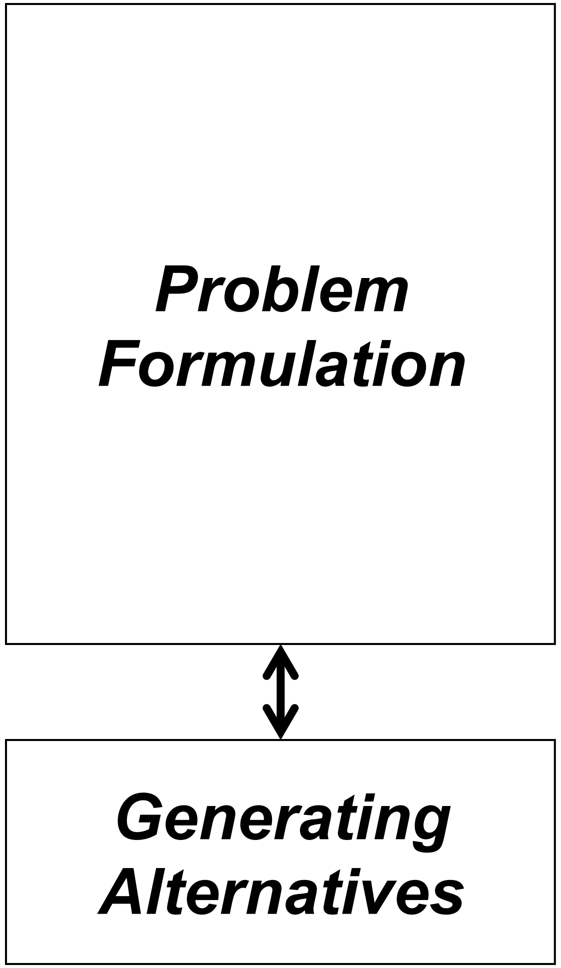


[Kasprzyk et al., 2009, WRR]

Can the market help lower costs?
What other objectives are important for planning?

A **many-objective** approach to the LRGV helps answer these questions.

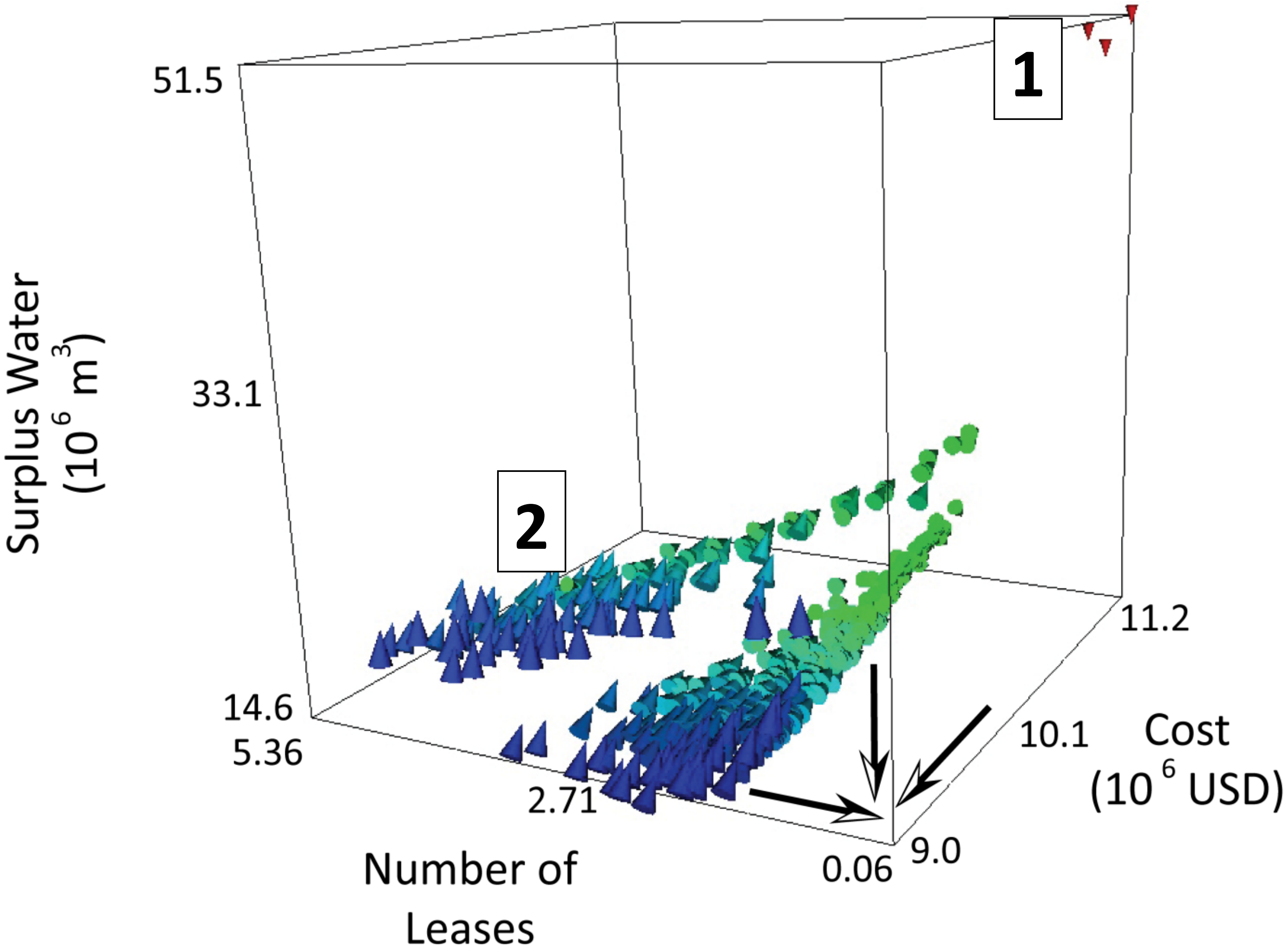
- Portfolio of 3 instruments
  - **Permanent rights**: non-market supply, % of reservoir inflows
  - **Spot leases**: immediate transfers of water, variable price
  - **Adaptive options contract**: reduces lease-price volatility
- Monte Carlo simulation model considers natural variability
  - Sampling of historical data for hydrology, demands, lease pricing
- Use a Multiobjective Evolutionary Algorithm to generate alternatives
  - Up to 6 objectives calculated using expected values under 10-year planning horizon



[Kasprzyk et al., 2009, WRR]

Many-Objective Results

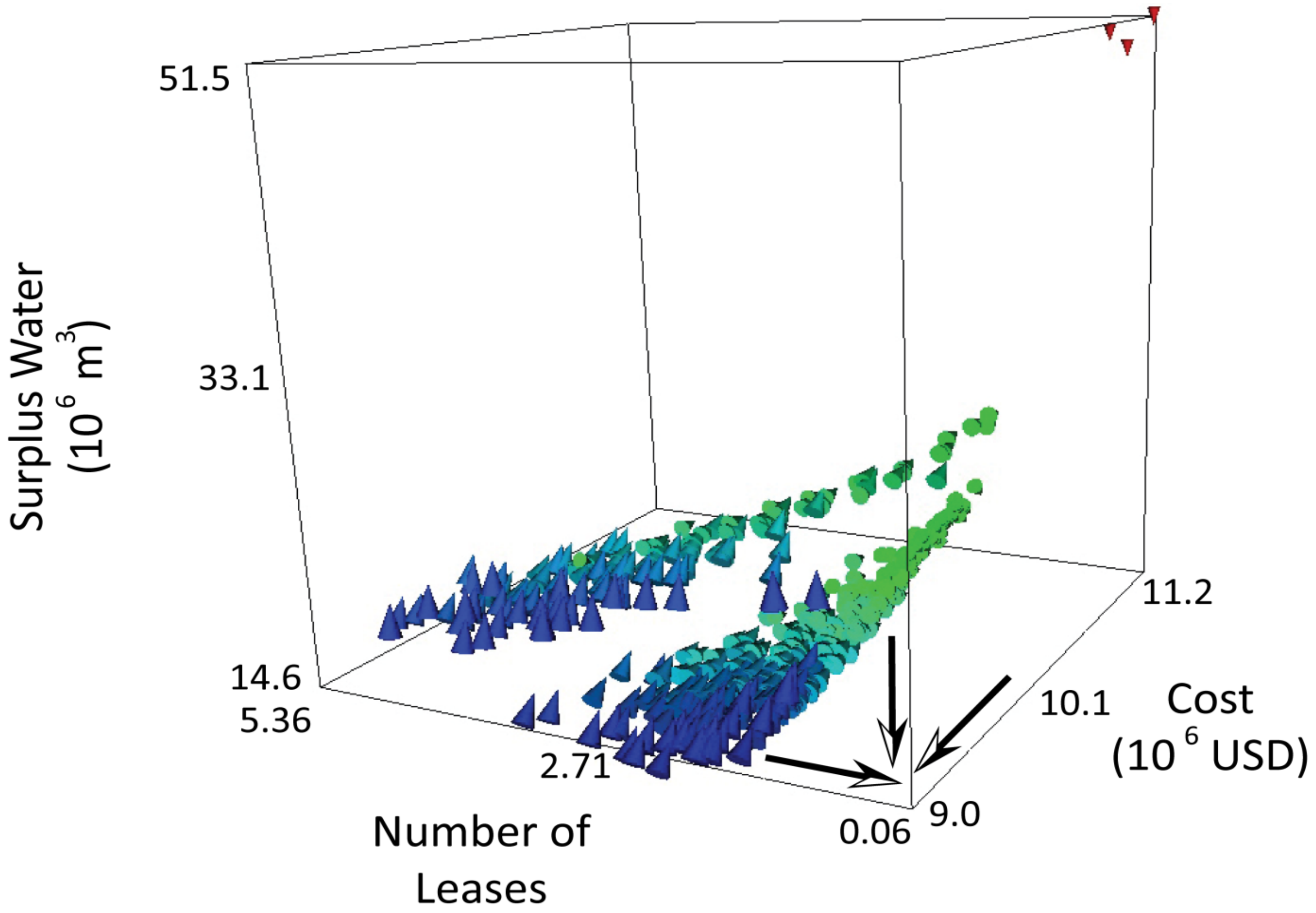
- Visualize rights (color), leases (orientation), options (size)
- Two distinct groups of solutions:
    1. rights-dominated
    2. market use
- Over-reliance on traditional water supply raised costs and surplus water volumes!



[Kasprzyk et al., 2012, Env. Mod. Soft.]

Our selected solutions were based on **expected-value** objective calculations.

- All objectives used a **single distribution** of input data to calculate expectation
- Issue: Is our choice of solution **biased** by assumptions of input data?
- Challenge: **Deep Uncertainty**, where decision makers can't characterize full set of events or probabilities



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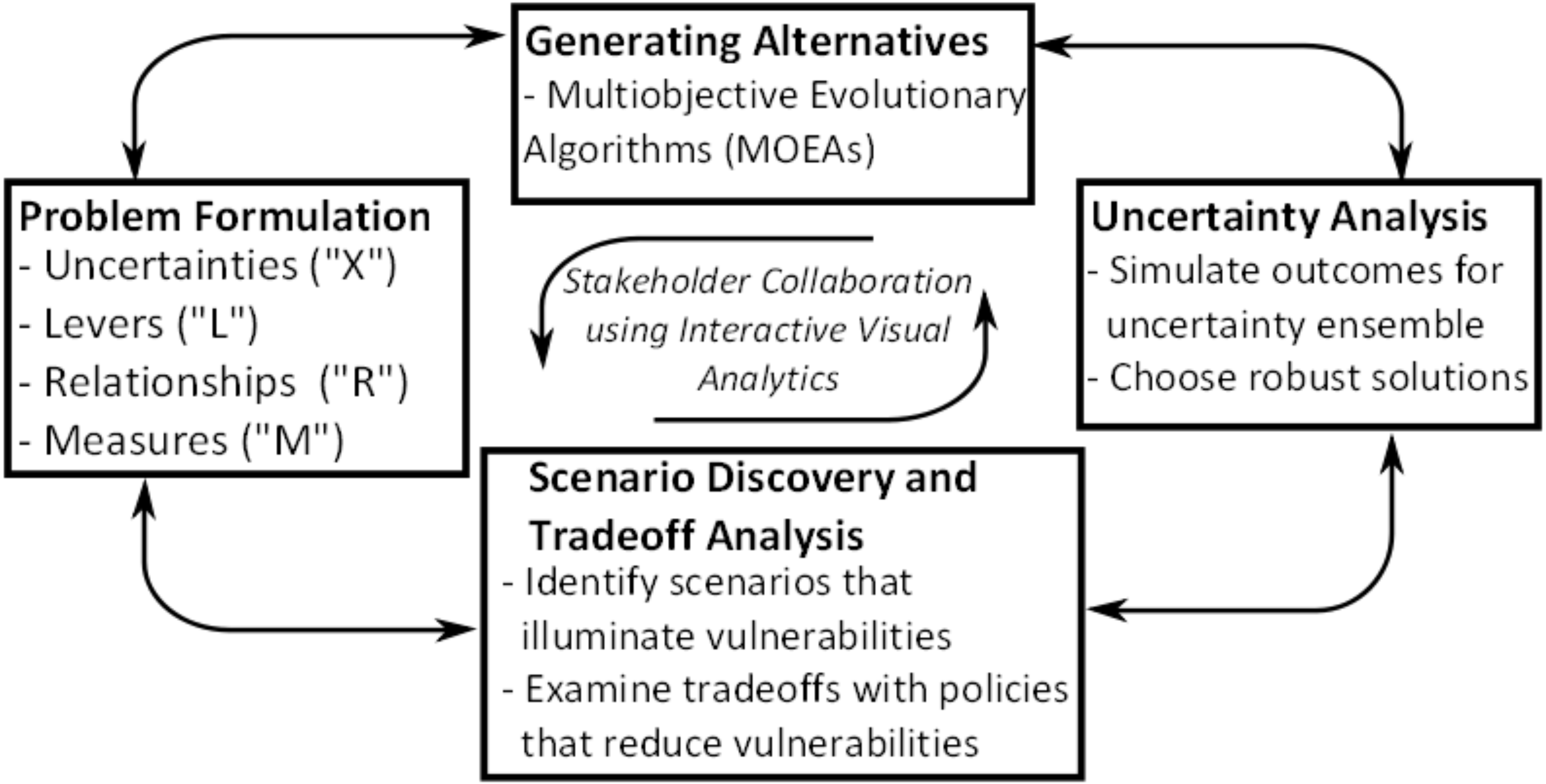
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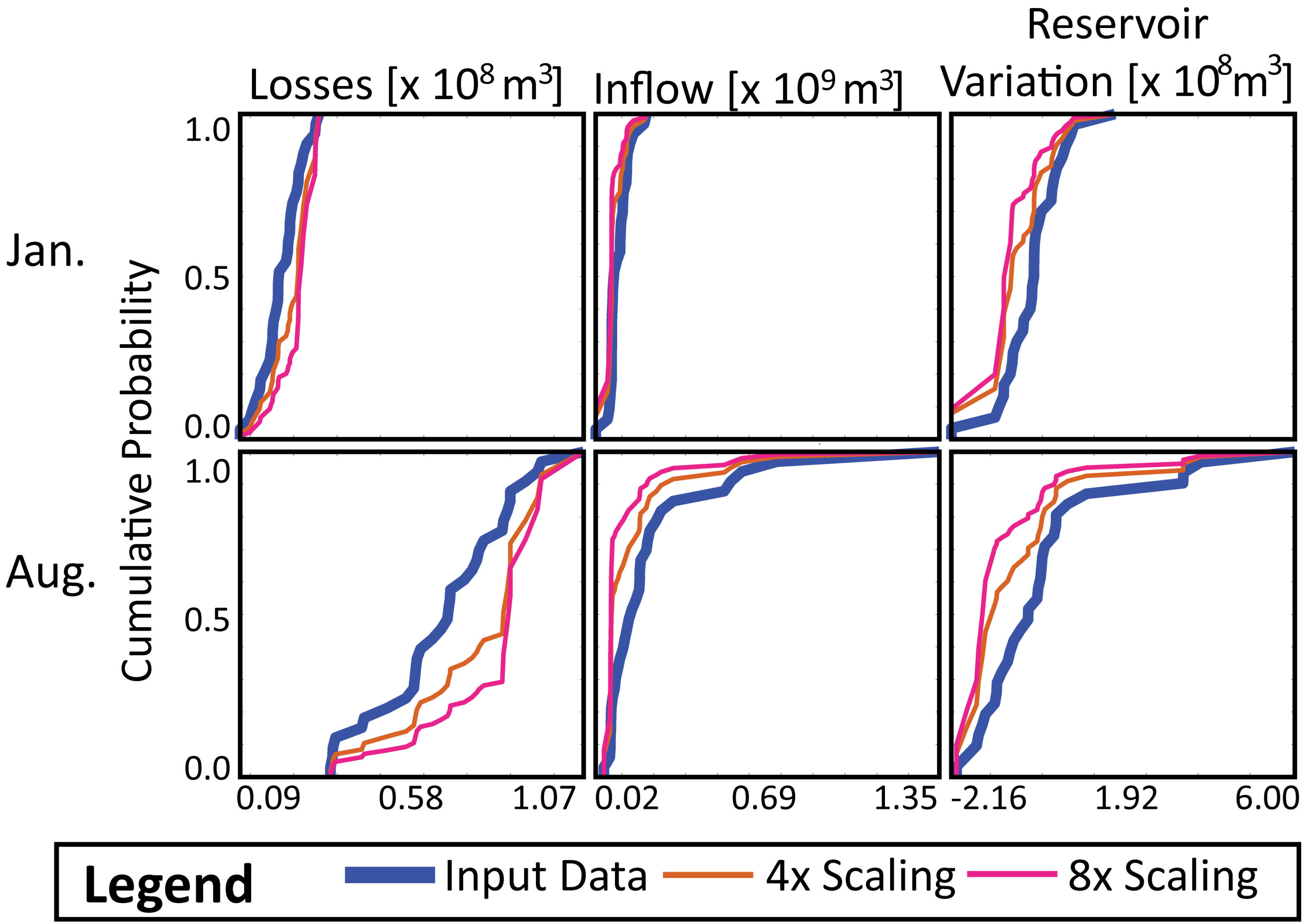
Scaling factors modify input data.

- Baseline historical data
- Values exceeding highest/lowest 25% of data scaled N times likelier
- Scaling factors unique to each variable, sampled as point values
- How wrong do we have to be to cause performance failures?



Uncertainty ensemble

- State of the world (SOW): a value for each of these dimensions
- A SOW controls **how** input data is sampled within the Monte Carlo simulation

Table 1: Scaling Factors

Parameter	Lower Bound	Upper Bound
Low Inflows	1	10
High Losses	1	10
High Demands	1	10
High Lease Prices	1	10
Losses in Storage	1	10

Table 2: Scalar Model Parameters

Parameter	Lower Bound	Upper Bound
Initial Rights	0.0	0.4
Demand Growth Rate	1.1%	2.3%
Initial Reservoir Volume	987 mill. m^3	2714 mill. m^3

Evaluating robustness

- Apply ensemble of 10,000 LHS samples of uncertainties (SOWs) to each solution
- Sort values and calculate:
  - 10th percentile (for measures to be maximized)
  - 90th percentile (for measures to be minimized)
- **Percent deviation** :

$$\frac{c_{90} - c_{base}}{c_{base}} x100 = \frac{51-37}{37} x100 = 37.8\%$$

Cost Distribution for Solution N:
36
37
39
40
44
45
48
50
51
55

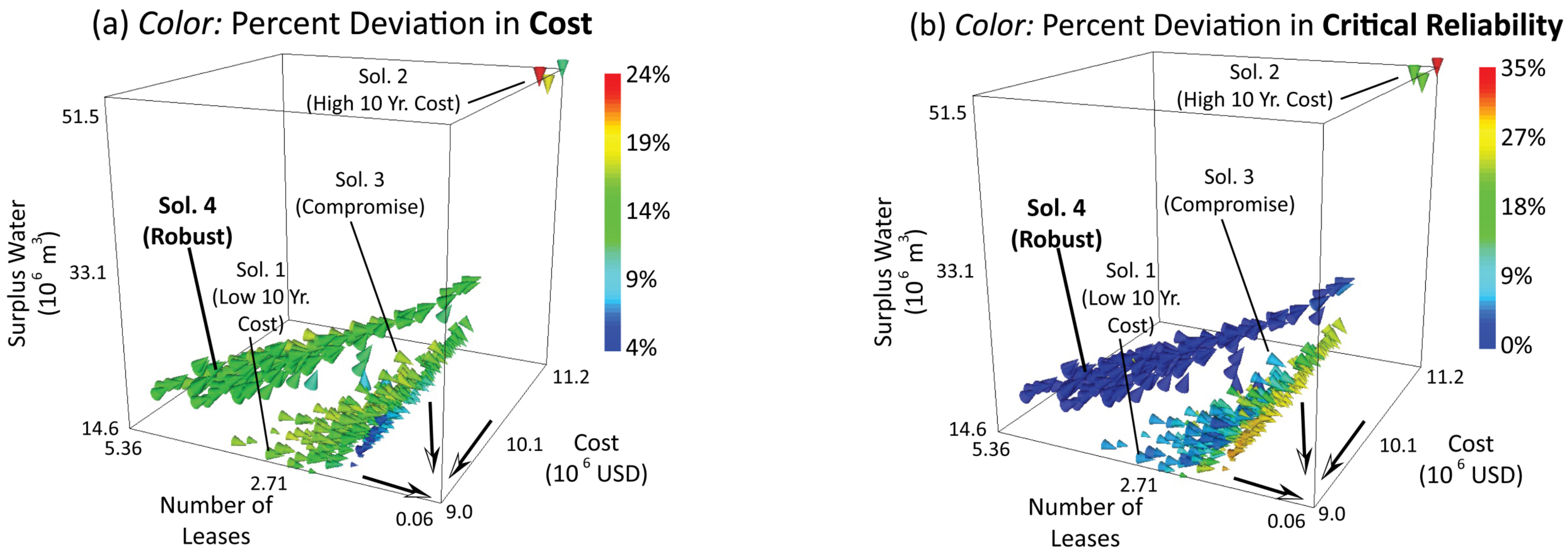
Cost in baseline SOW ← (37)

Cost in 90th percentile SOW ← (51)

Solution X costs 37.8% more in the 90th percentile of the ensemble than it did under the baseline SOW.

We now visualize "percent deviation" across all solutions and measures.

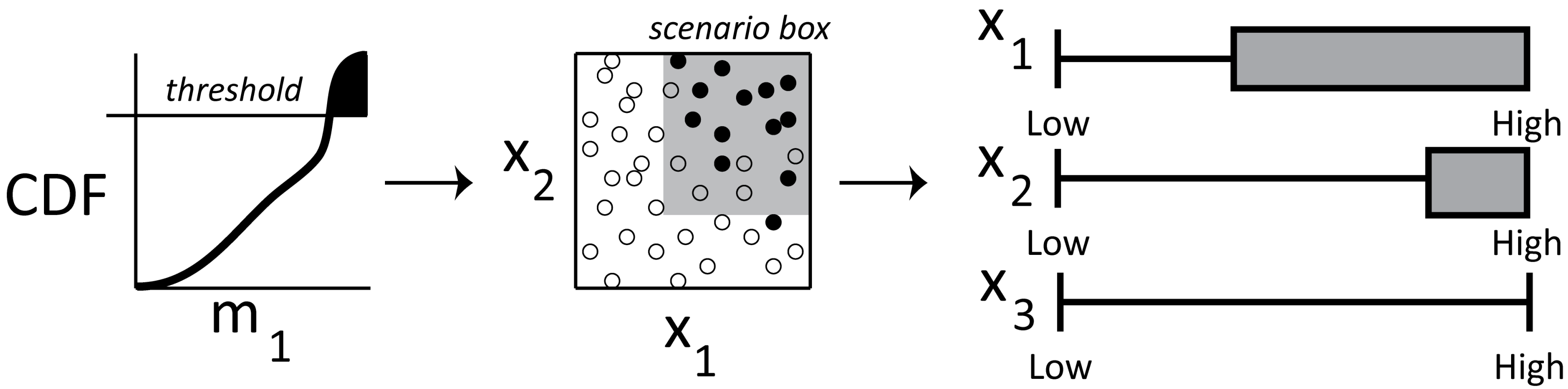
Percent deviation shows us **robustness** of the tradeoff space.



- Solution 4 exhibits low deviation in critical reliability and cost.
- It comes from a different tradeoff region than Solution 1-3.

Legend
Size: Critical Reliability
Orientation: Dropped Transfers
Axes: Measures in **baseline** SOW
Color: % Deviation

Scenario Discovery



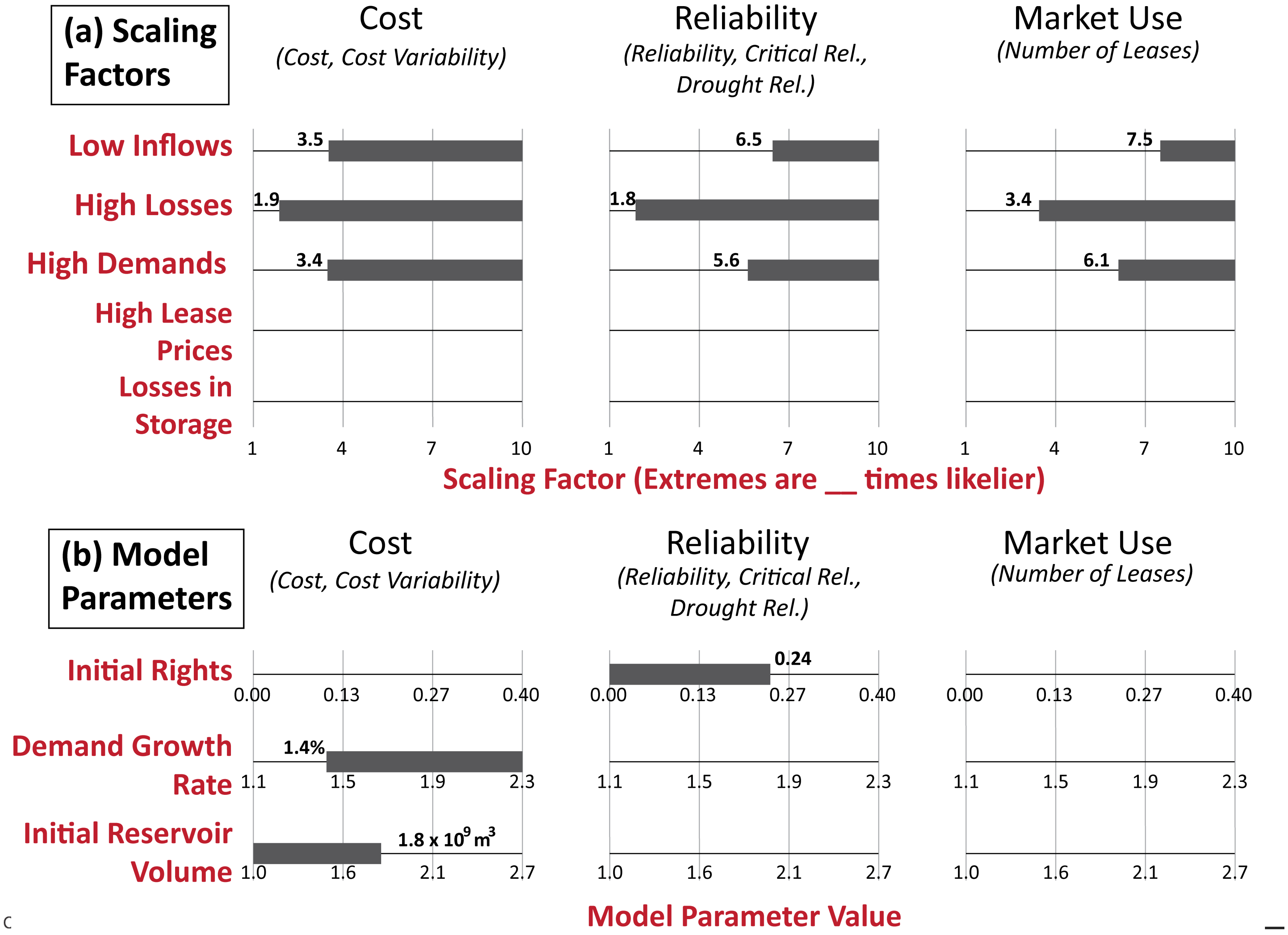
Step 1: Set percentile performance threshold using one or more measures, (m)

Step 2: PRIM creates "boxes" describing values that cause violations of thresholds

Step 3: Results show important values for uncertainties (x)

- Patient Rule Induction Method (PRIM) is an interactive algorithm for **discovering** scenarios
  - Instead of specifying scenario values *a priori*, the discovered ranges are clearly linked to policy vulnerabilities.

Scenarios Where the "Robust" Solution Performs Poorly



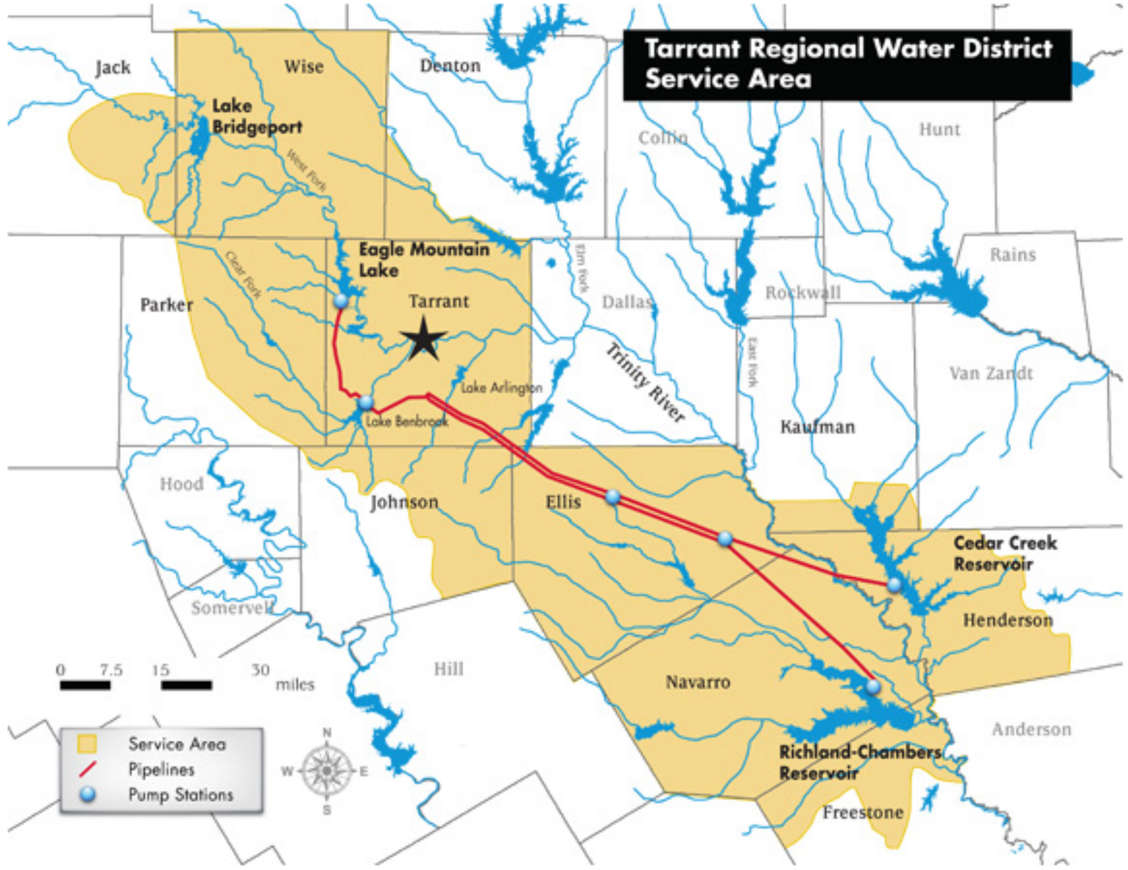
Conclusions

- Adding multiple objectives helps confront **cognitive myopia**
  - Aggregated, low dimensional formulations make decision makers ignore critical aspects (such as reducing surplus water)
- *Ex post* monitoring and adaptation: Decision makers can use scenario discovery to determine most important uncertainties for future planning
- MORDM can be applied across a wide array of problems, using simulation models of varying size
  - Screening models, regional planning, agent-based modeling

Future Research: Water planning considering energy

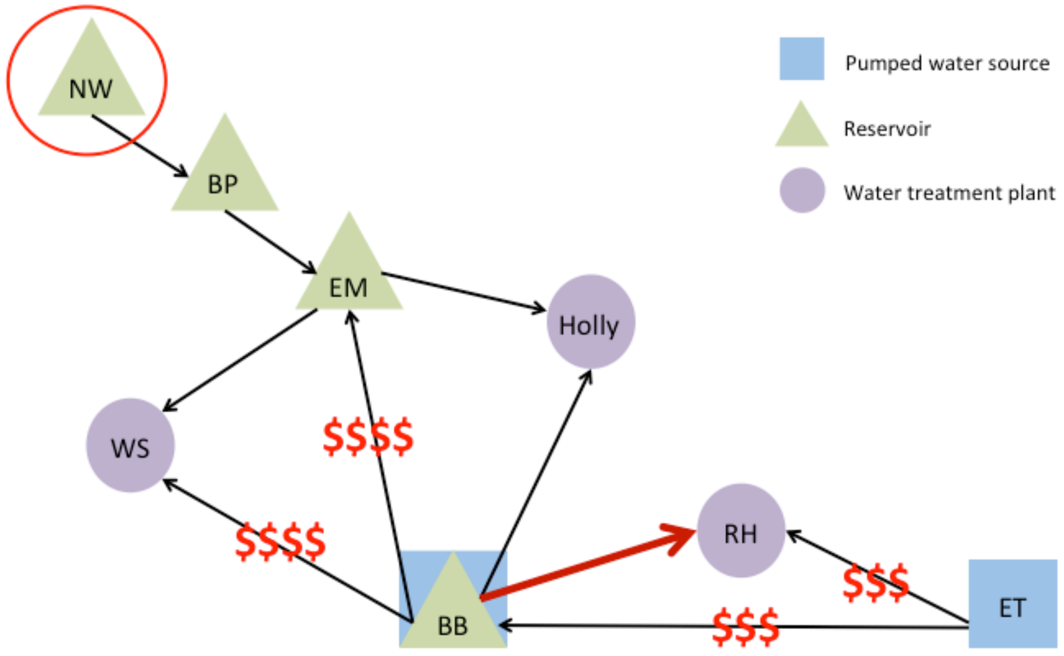
- Tarrant Regional Water District (TRDW) serves more than 1.7 million people
  - Cities of Fort Worth and Arlington
  - Raw water supplier
  - 7 reservoirs, over 150 miles of pipeline
- High energy costs
  - Pumping up 400 feet of elevation
  - In 2012, $17.6 million in energy costs

TRWD Service Area



Challenges

- Complex modeling
  - GUI simulation models not often made to be run 1000s of times
  - Node-link topology requires spatially disaggregated input data
- Integrated planning
  - TRWD buys energy in advance, not directly linked to water issues
  - In water planning, providing reliability often trumps efficiency or cost savings



Future Research: Energy planning

- Open to new collaborations!
- Use a "screening" level energy planning model to determine candidate portfolios of renewable technologies
- Optimize and evaluate portfolios using **multiple** objectives in addition to cost, including [Trutnevyte and Strachan 2013]:
  - Separate consideration of fixed and operating costs
  - Maximizing total installed capacity or produced energy
  - Explicit minimization of greenhouse gas emissions
  - Integration with other sectors

Thanks! Any questions?

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References

- Characklis, G., B. R. Kirsch, J. Ramsey, K. Dillard, and C. T. Kelley (2006) "Developing portfolios of water supply transfers," Water Resources Research, 42, W05403.
- Kasprzyk, JR, PM Reed, GW Characklis, BR Kirsch (2009) "Managing Population and Drought Risks Using Many-Objective Water Supply Portfolio Planning Under Uncertainty" Wat. Resour. Res., 45.
- Kasprzyk, J. R., Reed, P. M., Kirsch, B. R., and Characklis, G. W., "Many-Objective de Novo Water Supply Portfolio Planning Under Deep Uncertainty." Environmental Modelling & Software, 34: 87-104, 2012.
- Kasprzyk, JR, S Nataraj, PM Reed, RJ Lempert (2013) "Many-Objective Robust Decision Making for Complex Environmental Systems Undergoing Change" Env. Mod. Soft., 42
- Pindyck, RS (1999) "The long-run evolution of energy prices," The Energy Journal, vol. 20, 1-27.
- Trutnevyte, E., Strachan, N. (2013) "Nearly perfect and poles apart: investment strategies into the UK power system until 2050" Paper for the Interational Energy Workshop 2013.