Acknowledging Local Realities When Evaluating Regional Water Resources: Innovations, Challenges, & Uncertainties

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Case Study

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Both Case Studies

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Roanoke Case Study

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Roanoke Case Study

THE UNIVERSITY
of NORTH CAROLINA
at CHAPEL HILL

Preview of Key Points

- **East versus Southwest examples**
  - Roanoke River Basin: hydropower, PJM, & wind power
  - Lower Rio Grande Valley: water supply portfolio planning

- **Droughts: dependencies & uncertainties**
  - Roanoke: droughts yield severe wind power vs. eco tradeoffs
  - LRGV: traditional planning leads to a "myopic view"

- **Many-objective *a posteriori* decision aiding**
  - Creates a framework for "problem conceptions" to compete
  - New tools for optimization under uncertainty
  - Visual analytics support discovery & negotiation

Roanoke Case Study

Kerr Dam provides energy, flood control, recreation, "ecosystem services" to support the hardwood forest.

Roanoke River Basin
Kerr Dam ⭐
Hardwood Bottomland Forest
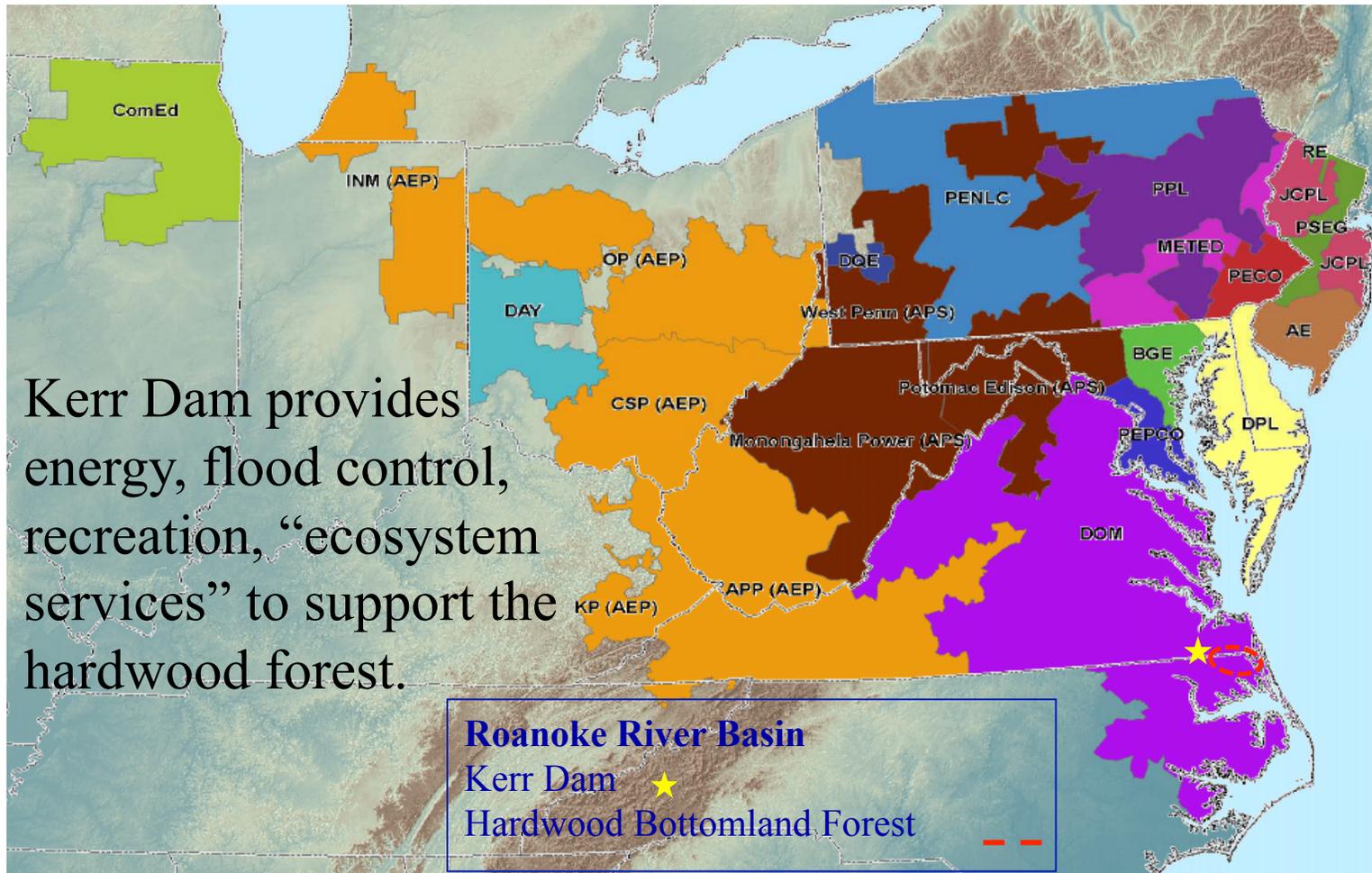
[1]Source: PJM Load Forecast Report 2009

Renewable investments in Pennsylvania-New Jersey-Maryland Interconnection (PJM)

- Eleven of 13 states + DC in PJM territory have renewable goals

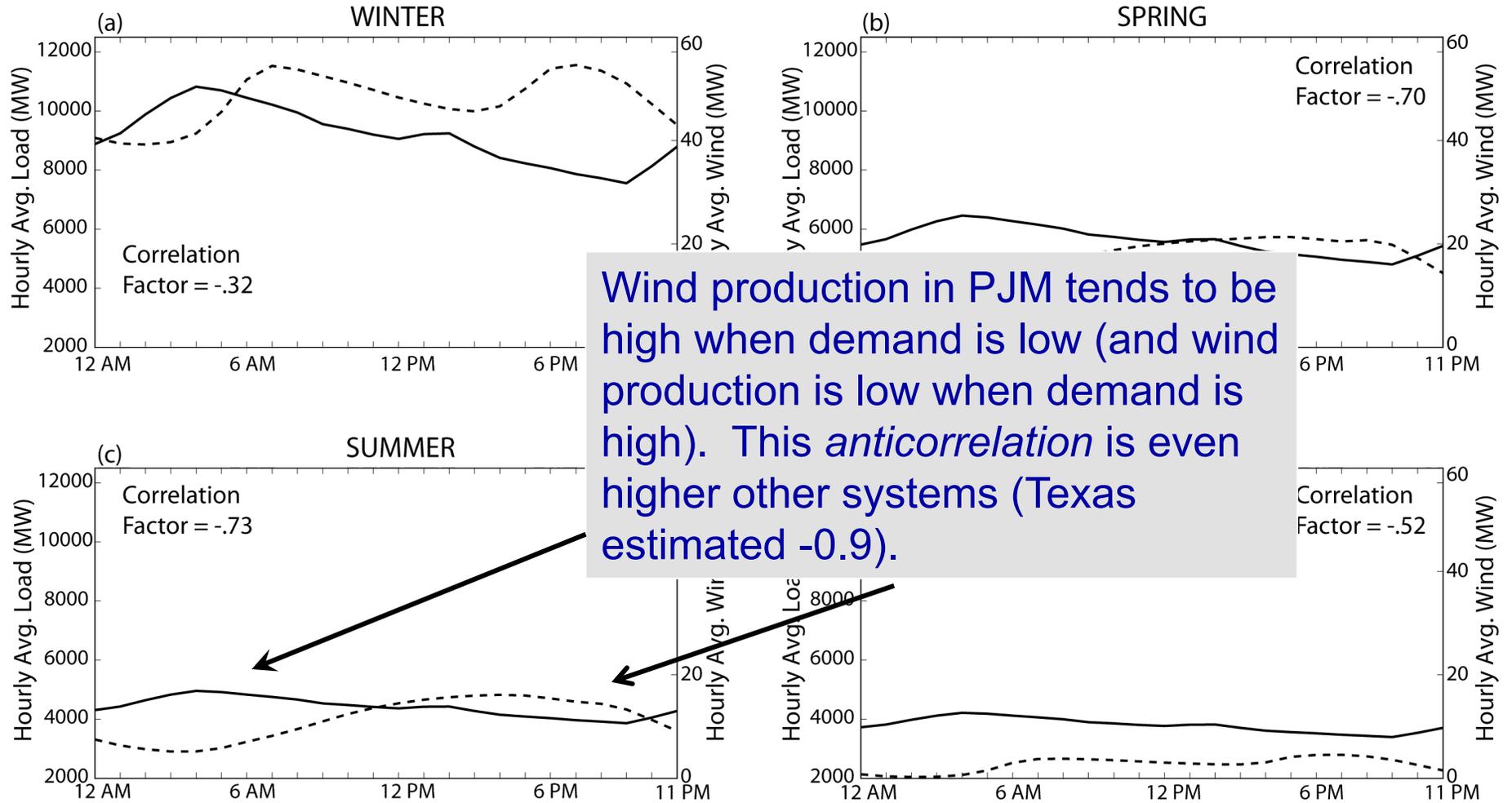- Wind generation includes 40% of planned investments in PJM

Allegheny Ridge Wind Farm, PA 2009

The good, the bad, the ugly of wind

- **Question:** What are the social and private costs with large-scale wind installation?

- **Goal:** Evaluate the decision of a hydroelectric generator to provide a service to PJM that buffers intermittent output from wind turbines

- **Outcome:** Regulatory adjustments to entice generators to provide wind-following services

Seasonal wind and load daily cycle

(a) WINTER — Correlation Factor = -.32

(b) SPRING — Correlation Factor = -.70

(c) SUMMER — Correlation Factor = -.73

Correlation Factor = -.52

Wind production in PJM tends to be high when demand is low (and wind production is low when demand is high). This *anticorrelation* is even higher other systems (Texas estimated -0.9).

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Model data from 2006-2008

- ## PJM
  - Day-ahead and ancillary (reserves) services markets hourly prices
  - Hourly load data from the Dominion Zone (Virginia and north/central North Carolina)
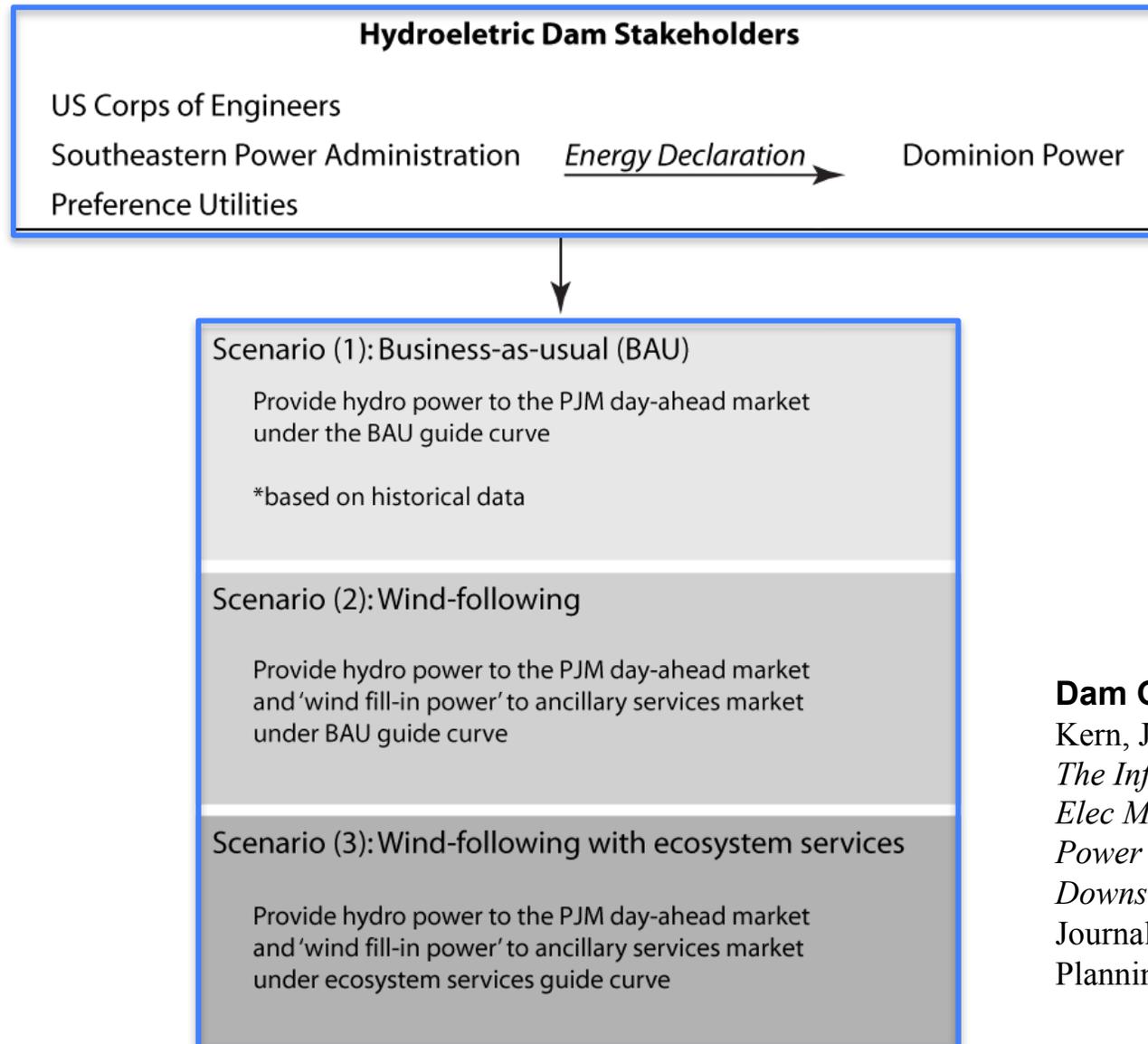- ## Hydro-Climate
  - Wind power output from NREL Eastern Wind Dataset (West Virginia/Virginia) hourly avg.
  - Hydrological data from U.S. Geological Survey and U.S. Army Corps of Engineers

Decision to offer wind-following and ecosystem services

- **Wind-Following:**
  - Kerr Dam provides some amount of fill-in power for a group of wind turbines along the Allegheny Mountains
  - Diverting capacity from the traditional energy markets to deal with periods of low wind energy

- **Bottomland Forest Ecosystem Issues:**
  - Kerr Dam tasked with supporting downstream river conditions or "ecosystem services"
  - The "opportunity cost" for Kerr Dam is the change in revenues as compared to a "business as usual case" where the dam participates in the day-ahead market
  - Reflecting "shadow price" of offering an incremental unit of capacity for wind-following
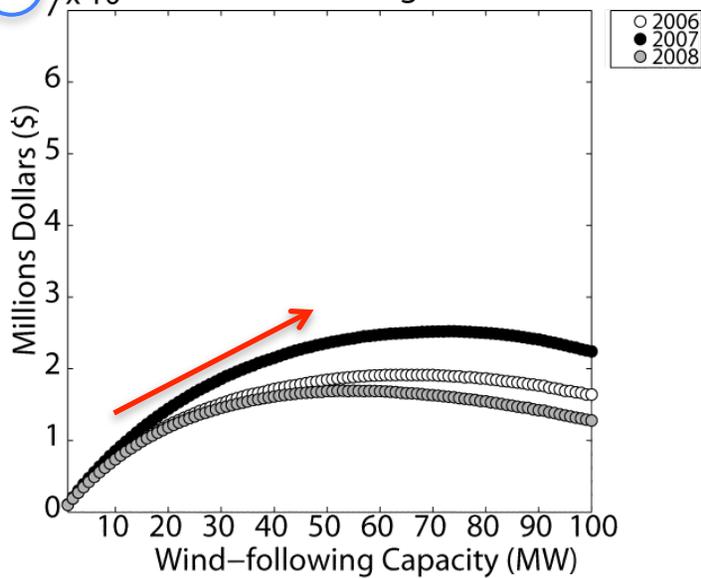
Model description

Hydroeletric Dam Stakeholders

US Corps of Engineers

Southeastern Power Administration   *Energy Declaration* →   Dominion Power

Preference Utilities

Scenario (1): Business-as-usual (BAU)

Provide hydro power to the PJM day-ahead market under the BAU guide curve

*based on historical data

Scenario (2): Wind-following

Provide hydro power to the PJM day-ahead market and 'wind fill-in power' to ancillary services market under BAU guide curve

Scenario (3): Wind-following with ecosystem services

Provide hydro power to the PJM day-ahead market and 'wind fill-in power' to ancillary services market under ecosystem services guide curve

Dam Guide Curves:
Kern, J. et al. (In-Press), *The Influence of De-Reg Elec Markets on Hydro-Power Generation and Downstream Flow Regime*, Journal Water Resources Planning & Mgmt.

Performance Across Hydro-Climate Gradient

- We compare simulated wind-following operations to historical data over 2006-2008
  - 2006: typical wet year (Palmer Drought Index, PDI 0 to > 4)
  - 2007: transition to severe drought (PDI < -3 Aug-Dec)
  - 2008: sustained drought (PDI -6 in Jan to -1 Dec)
- The drought we model would be considered a 1-in-100 year event, but increased population and pressures on water supplies make these events more likely
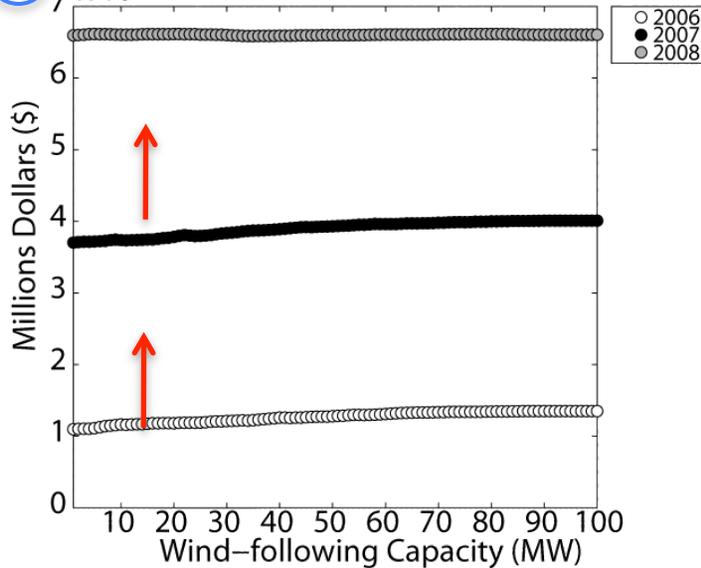
Annual Opportunity Cost (Millions $)

(a) Wind-following

(b) Wind-following with Ecosystem Services

Annual Opportunity Cost ($/MWh)

(c) Wind-following

(d) Wind-following with Ecosystem Services
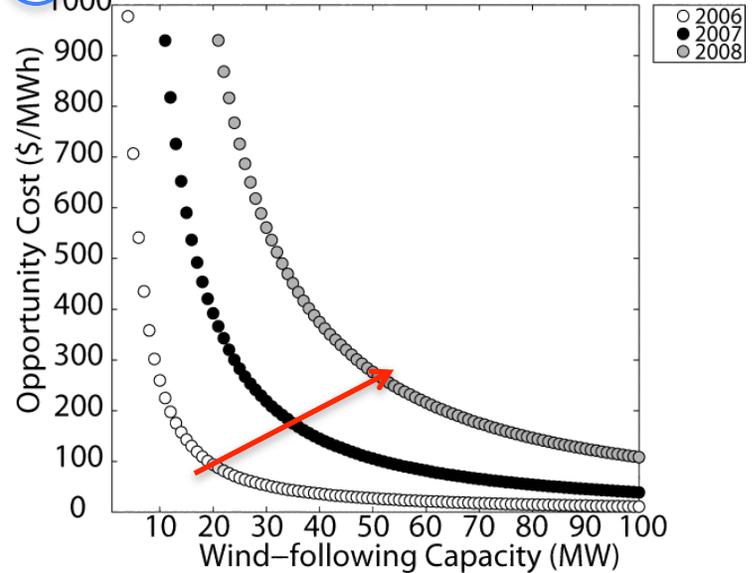
Average Monthly Reserve Payment and Opportunity Cost ($/MWh)

Wind-following is profitable for Dominion under drought conditions if unconstrained by other demands. Smoothing wind intermittency becomes a challenge in 'dry' years with environmental demands.
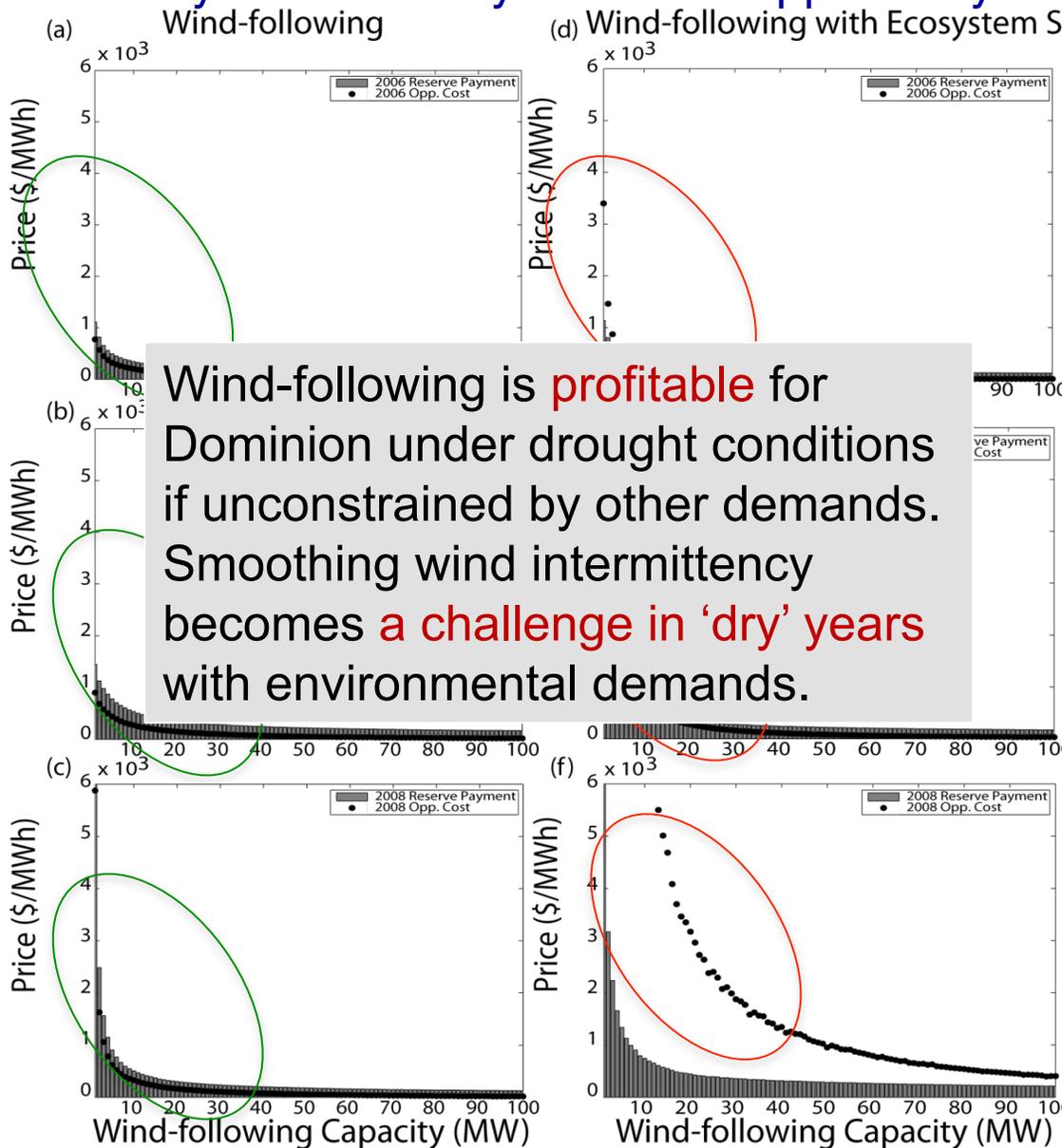
Roanoke Case Study Conclusions

- The system costs of integrating intermittent generation resources (wind and solar) are substantially driven by private and social opportunity costs:

  - *Private costs: Lost revenue from diverting capacity away from energy markets*

  - *Social costs: Conflicts with environmental river management goals*

- Market prices for wind-following services will need to reflect opportunity costs

  - *Failing to account for operational constraints such as ecosystem services may lead to under-estimation of these costs, by significant margins*

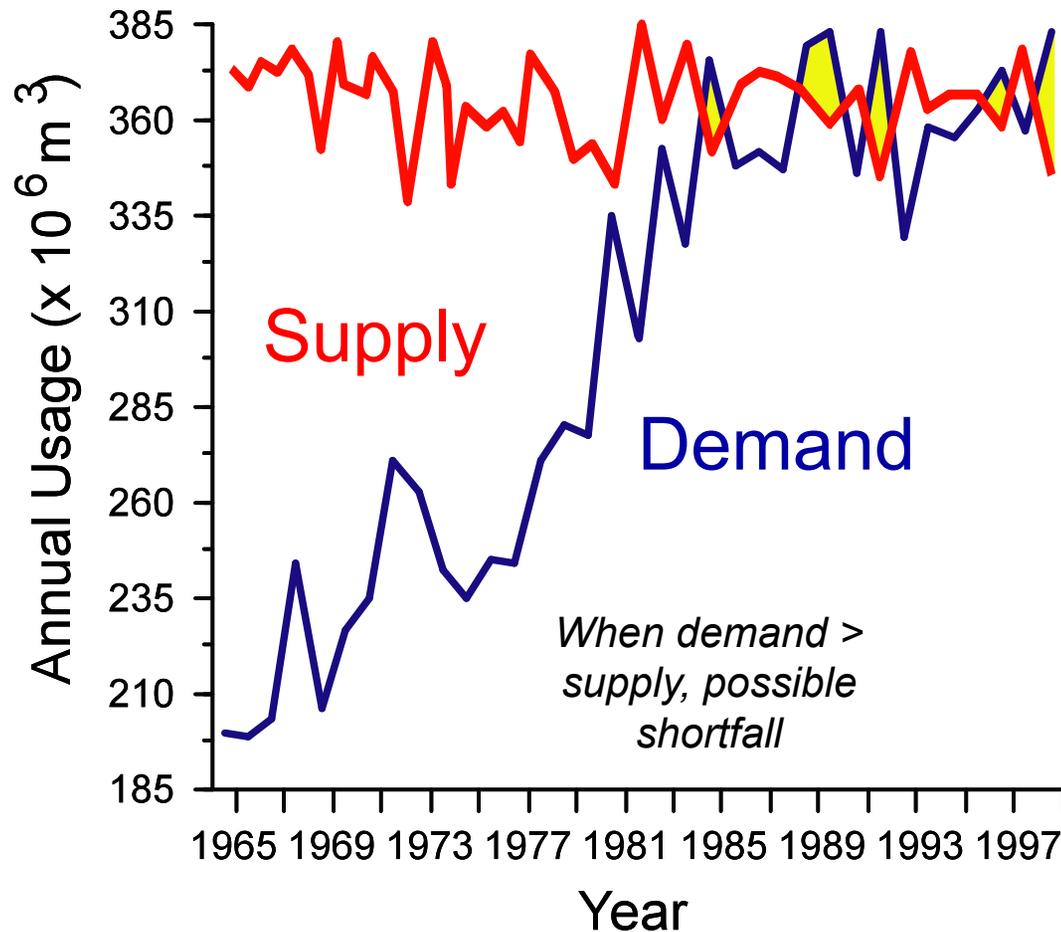 - *This will also create new challenges for energy market monitoring*

LRGV Case Study

- Water portfolio planning: Lower Rio Grande, TX

(MS work J. Kasprzyk; Collaborators: Greg Characklis and Brian Kirsch, UNC)

(From Characklis 2007)

Water Marketing in Texas, USA

When demand > supply, possible shortfall

- Lower Rio Grande Valley
- Rapid urban population growth and high irrigation water use
- Existing water market with transfers from ag. to urban
- Research goal: help a **single city** use the water market more effectively

Water Marketing in Texas, USA

- Three water supply instruments:
  - **<u>Permanent rights</u>**: traditional non-market supply (% of reservoir inflows)
  - **<u>Spot leases</u>**: immediate transfers of water, variable price
  - **<u>Adaptive options contract</u>**: reduces lease-price volatility (similar to European call stock option)

- Monte Carlo simulation with monthly timestep for 10-year horizon and extreme drought scenario, sampling uncertain historical data:
  - Reservoir inflows (allocations to rights)
  - Changes in reservoir level
  - Water demands
  - Lease pricing

Decisions for Supply Instruments

- Permanent rights
  - N_R = Volume of rights
  - Allocated pro rata based on reservoir inflows
- Adaptive Options Contract
  - $N_{O,low}$ = Low-volume alternative options volume
  - $N_{O,high}$ = High-volume alternative options volume
  - ξ = Threshold for deciding between high/low
- Anticipatory Thresholds
  - $(\alpha, \beta)_{May-Dec}$ = "When", "How Much" for May-Dec
  - $(\alpha, \beta)_{Jan-Apr}$ = "When", "How Much" for Jan-Apr

Thresholds (% of dem.):

Transfers

Current Supply

$\alpha = 1.5$ $\beta = 1.8$

Multi-Objective Tradeoffs
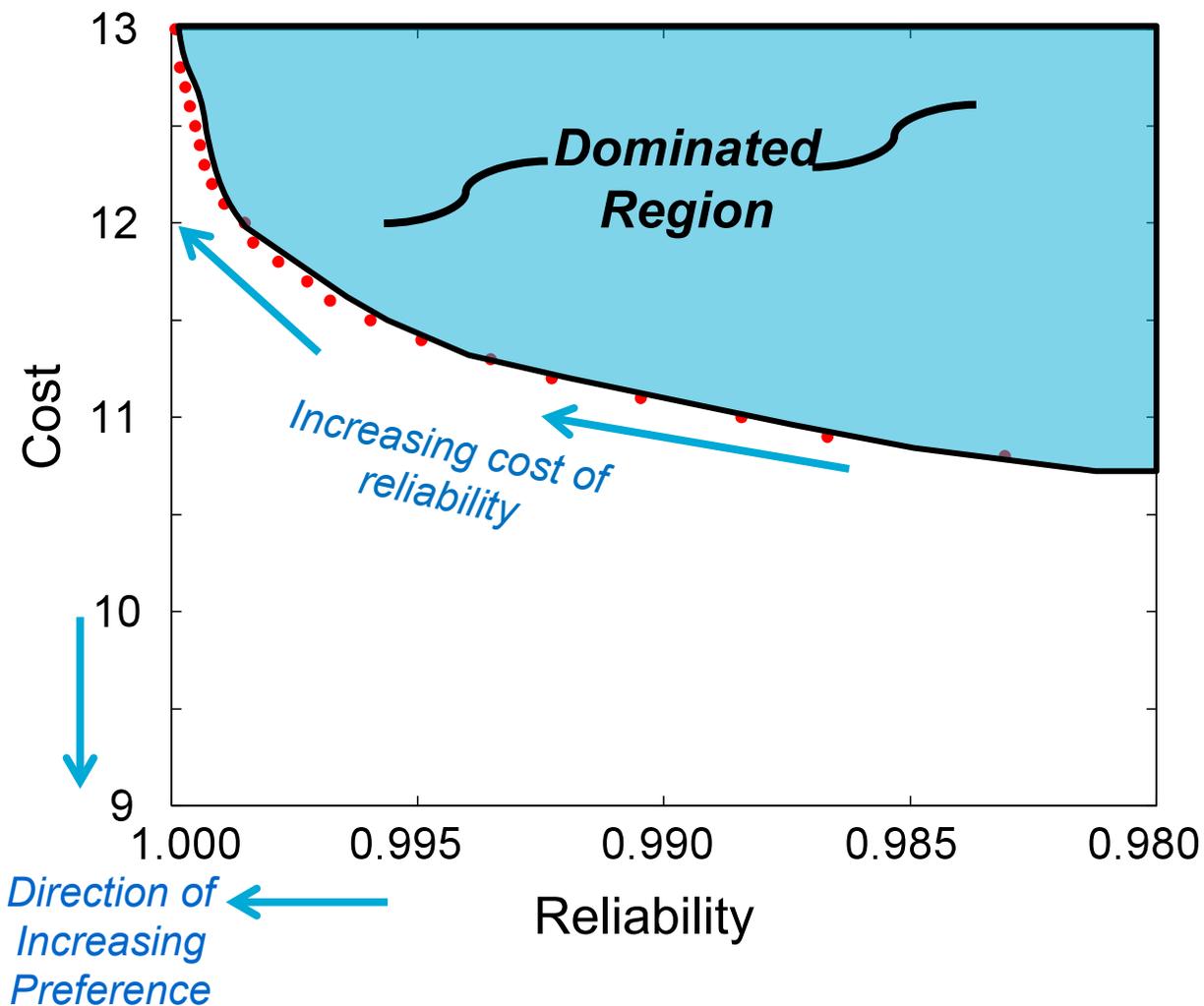
- Each point is a different water supply portfolio
- Non-dominated or Pareto set
- Shows increasing cost of added reliability
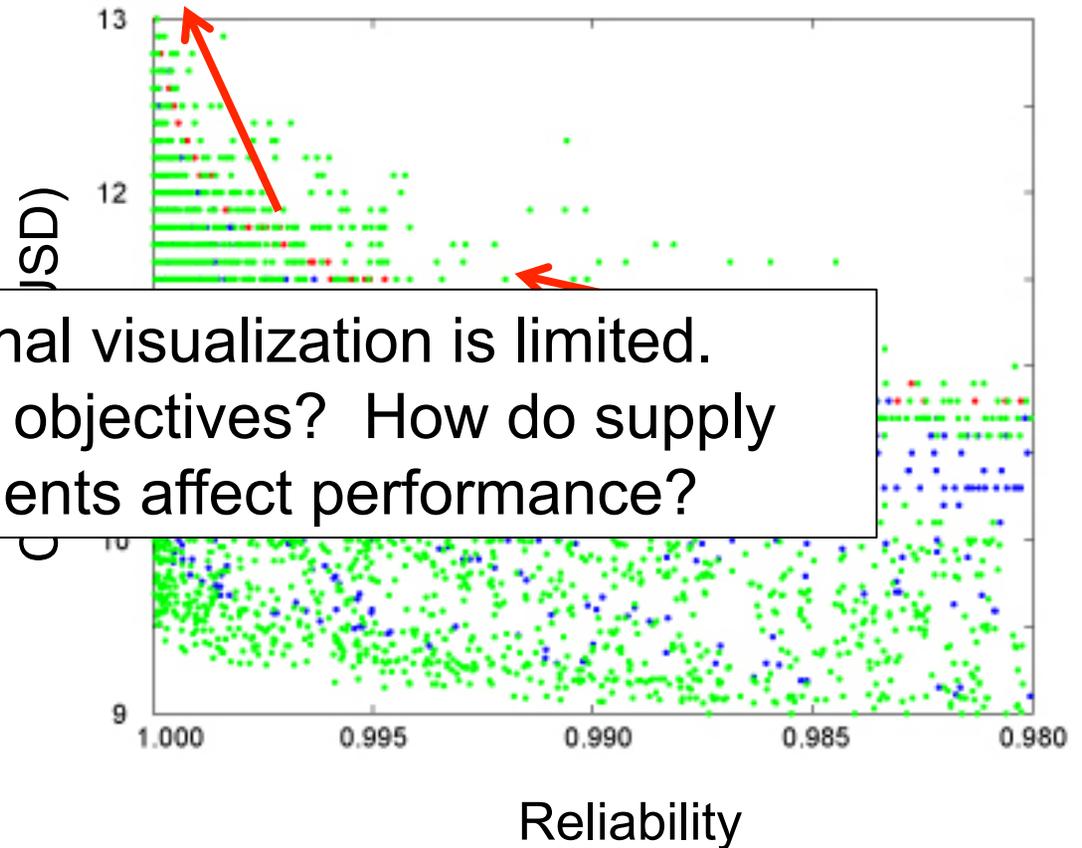
Many-Objective Search Illustration

Three-objective Test Problem

MOEA Search (Blue)

Notice how it not only finds the solution, but also distributes itself across the solution.

Popsize: 400
Archive: 35

Target Solution Set (Red)
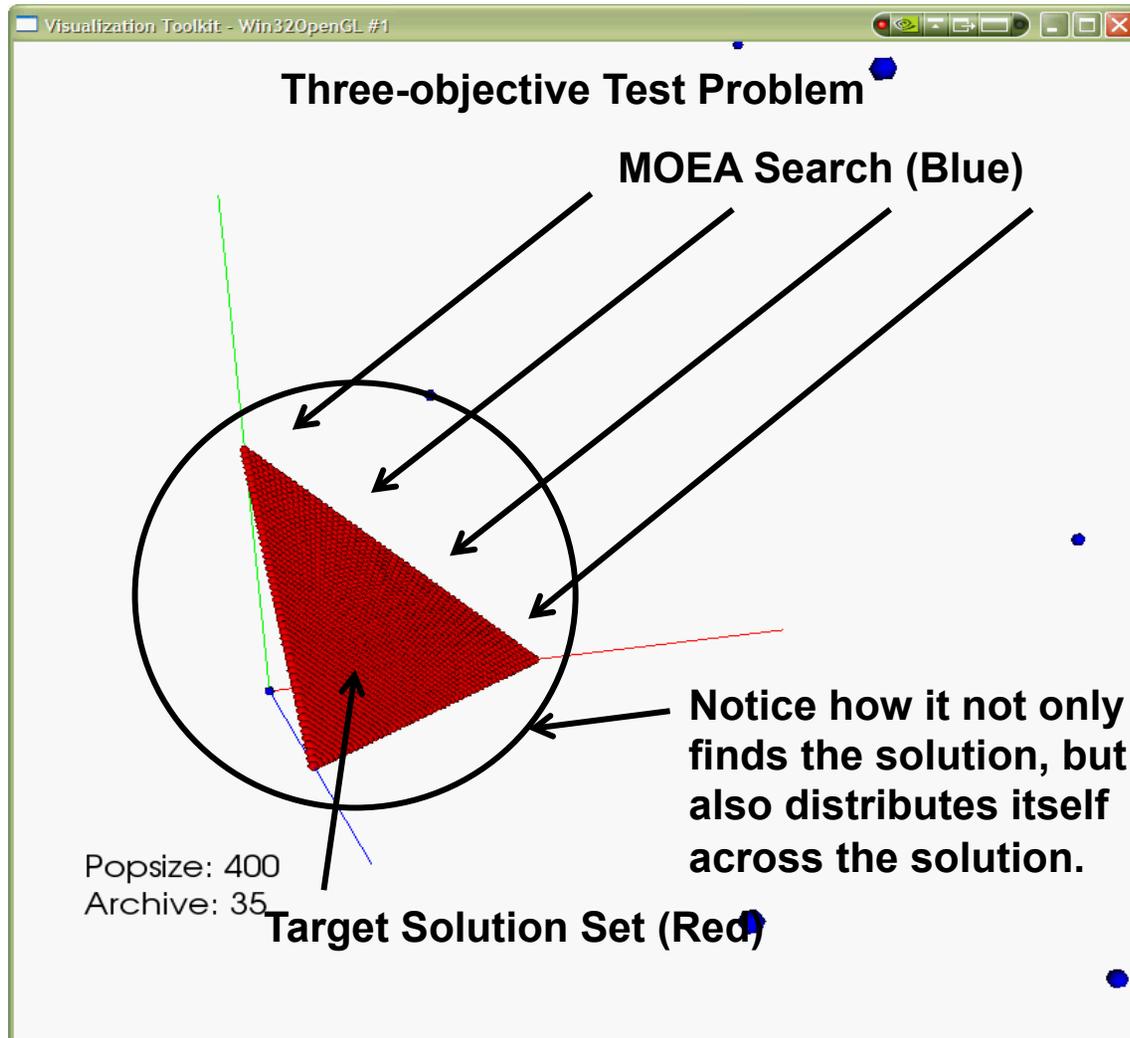
- Multi-Objective Evolutionary Algorithms (MOEAs)
  - Heuristic search
  - Effective where other search techniques fail
- ε-NSGAII
  - Highly adaptable
  - Can be used with supercomputers or desktop computing

Constructive Analysis of Supply Instruments

	Decisions	Planning Objectives	Constraints
Case A: *Rights Only*	● **Permanent Rights Volume**	● **Cost** ● **Reliability** ● **Surplus Water**	● **Reliability > 98%**
Case B: *Rights, Options*	● **Options Contract** ● **Planning thresholds: Options**	● **Cost Variability** ● **Dropped Transfers**	● **Cost Variability < 1.1**
Case C: *Rights, Options Leases*	●**Planning thresholds: options and leases**	● **Number of Leases**	
Case D: *Critical Constraint*			● **No critical failures**

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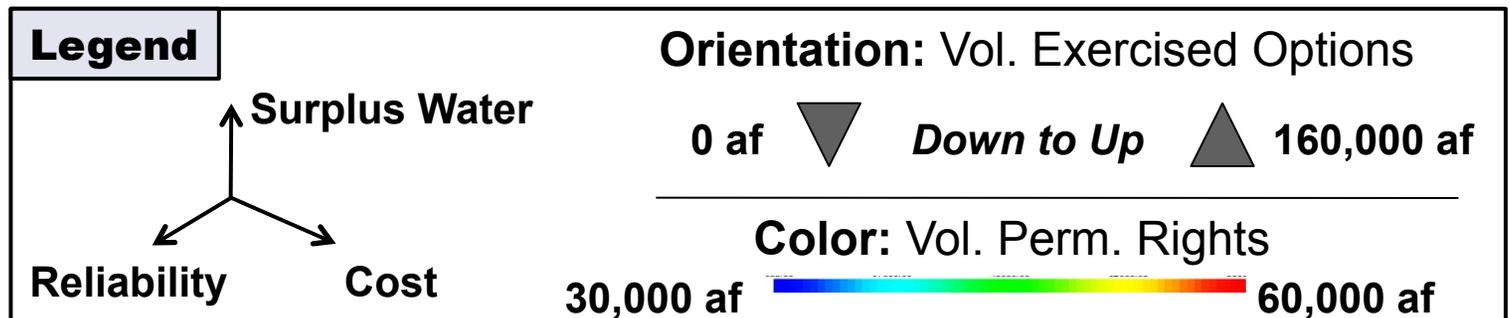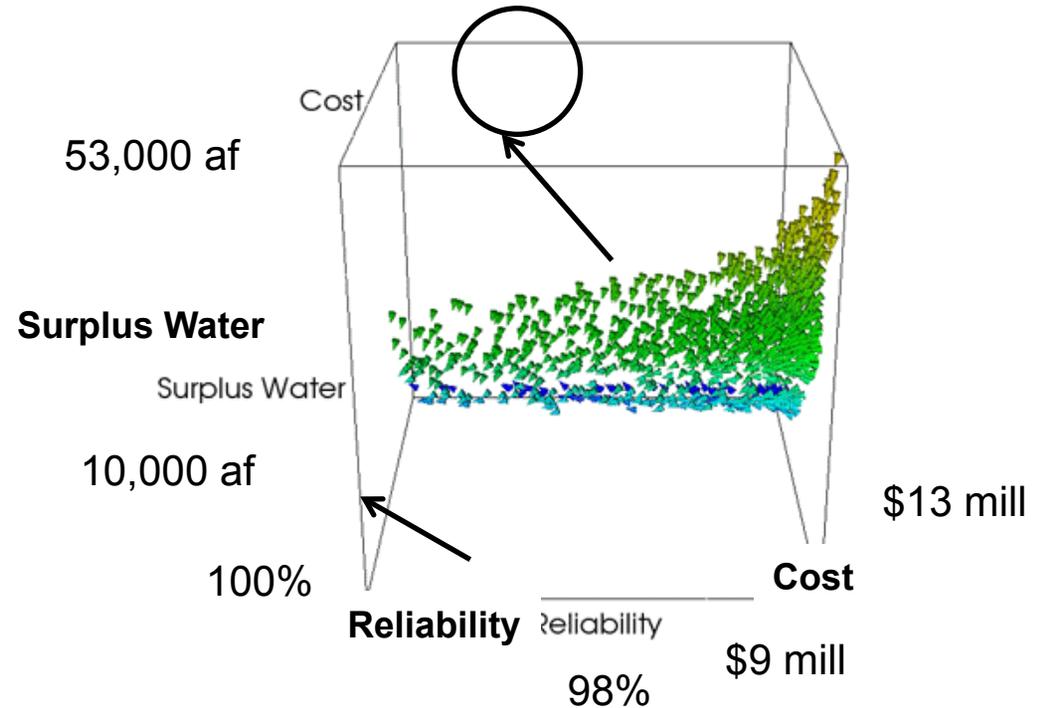# Results: Cost / Reliability Tradeoffs

- **Case A :**
  - Limited flexibility
  - Increasing marginal cost of reliability

- **Case B:**
  - Cost S
  - Dampe

- **Case C**
  - Adding leases provides a large number of alternatives.
  - Greatest cost savings **at each level** of reliability

Traditional visualization is limited. Additional objectives? How do supply instruments affect performance?

Reliability

Results: Case B

- Highly reliable solutions:
  - Lower permanent rights cost (changing **color**)
  - Decreased surplus water
  - Lower marginal cost

- These portfolios have increasing volumes of exercised options (**orientation** pointing up).
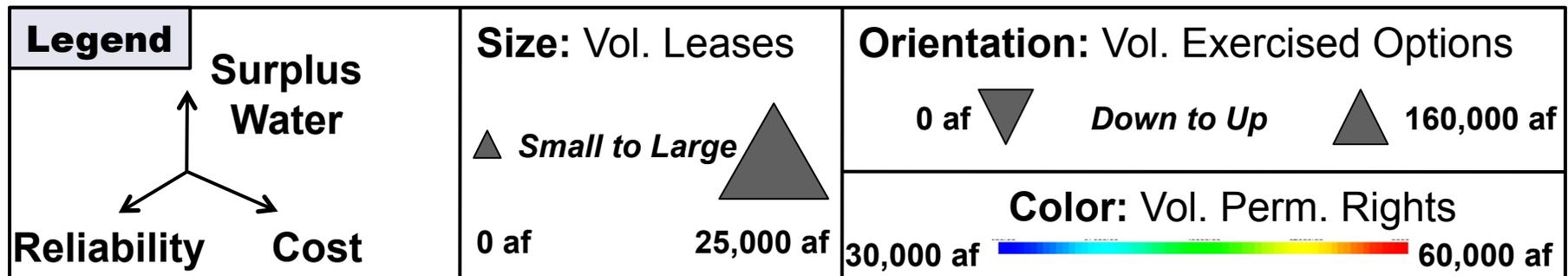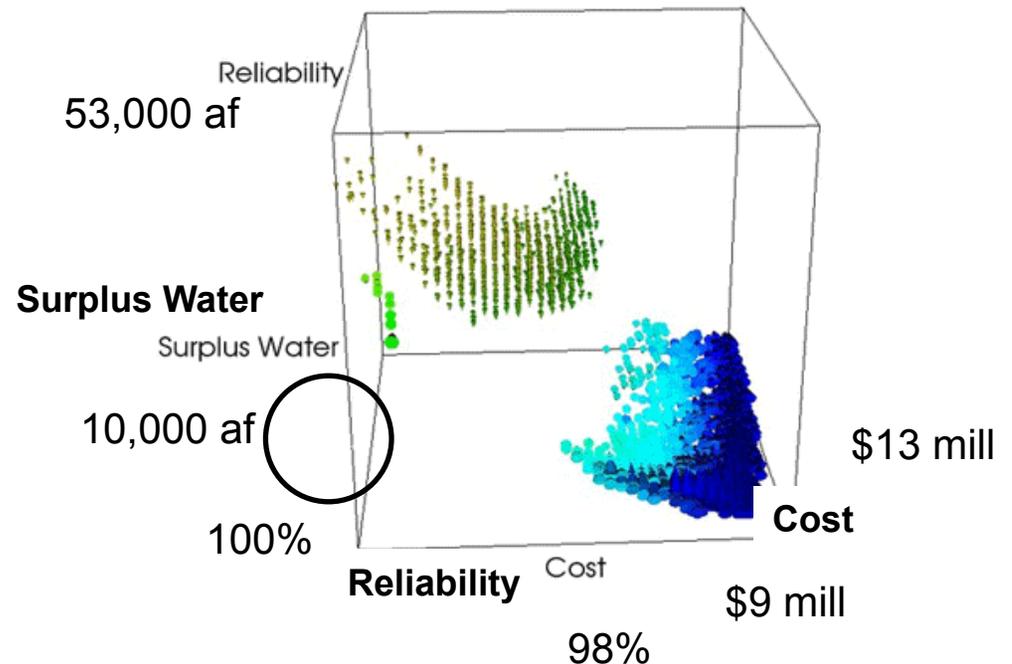

Cost

53,000 af

Surplus Water

Surplus Water

10,000 af

$13 mill

100%

Cost

Reliability   Reliability

$9 mill

98%

Legend

Surplus Water

Reliability   Cost

Orientation: Vol. Exercised Options

0 af ▽ *Down to Up* △ 160,000 af

Color: Vol. Perm. Rights

30,000 af   60,000 af

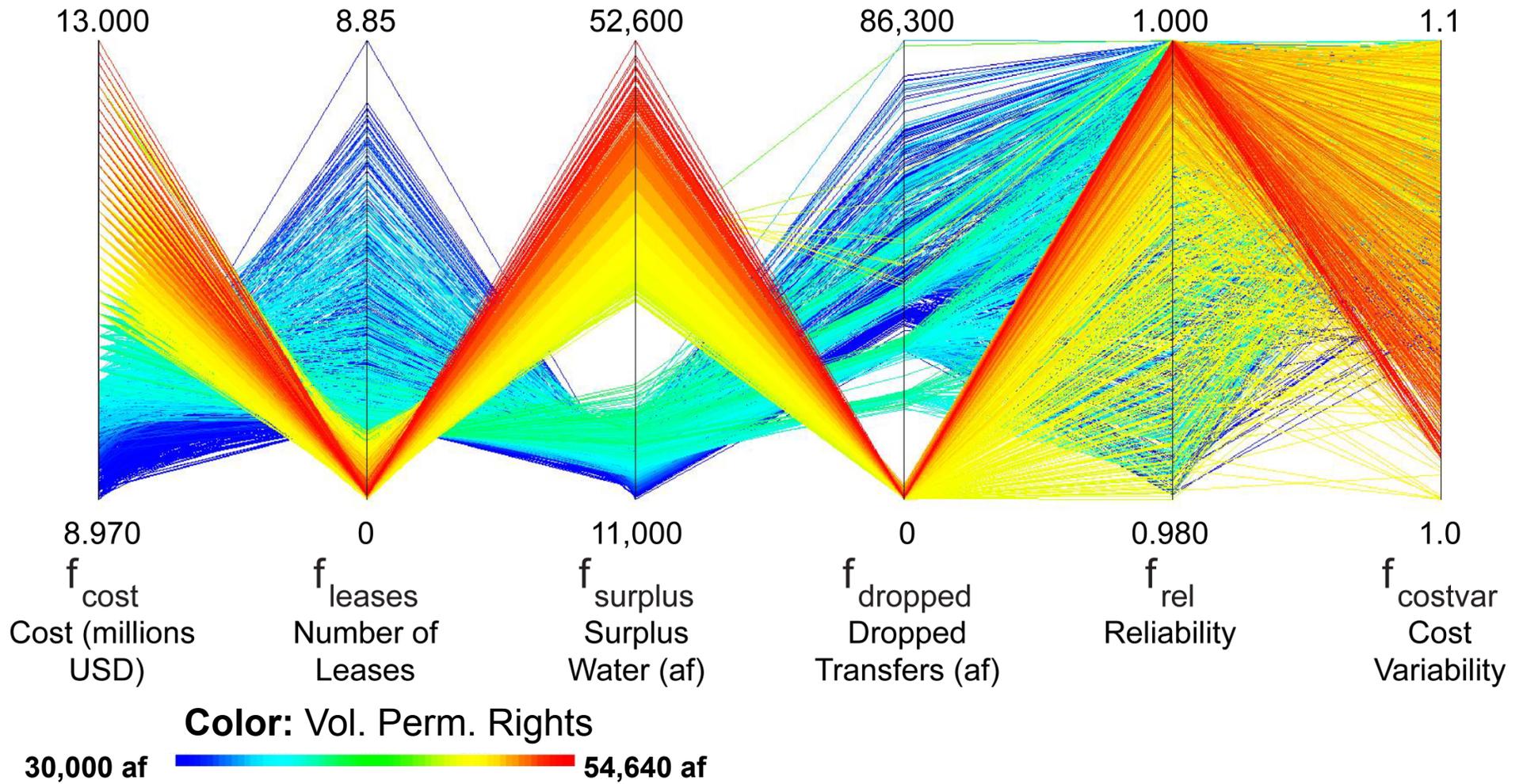# Results: Case C

- Complex surface with discontinuities

  - Distinct portfolio strategies (high rights, low rights)

  - Monthly flexibility of options vs. discrete rights/options

- High reliability, low surplus solutions **blend** both leases and options

Reliability
53,000 af

Surplus Water

Surplus Water

10,000 af

100%

Reliability

Cost

98%

$13 mill

Cost

$9 mill

Legend	Size: Vol. Leases	Orientation: Vol. Exercised Options	
Surplus Water ↑ ← Reliability → Cost	▲ *Small to Large* 0 af 25,000 af	0 af ▽ *Down to Up* ▲ 160,000 af	
		Color: Vol. Perm. Rights	
		30,000 af	60,000 af

Results: Case C

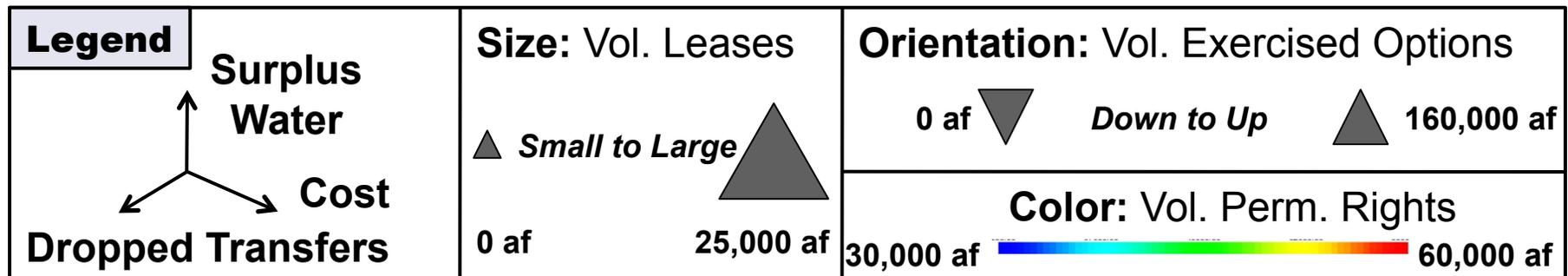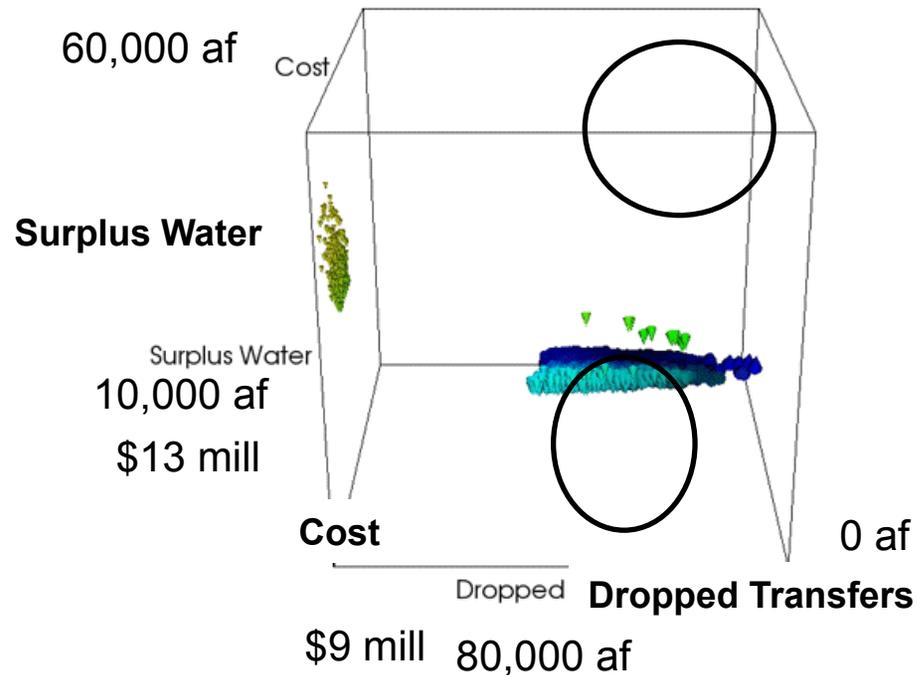Rights - Options - Leases

Lessons from Cases A - C

- We found **distinct portfolio types** and surprising objective interactions
  - Flexibility was critical to preventing failures (highest-performing alternatives mixed all supply instruments)
  - The analysis promoted a better understanding of planning rules and objective interactions
- Can we modify our formulation to more accurately capture **risk-aversion** and **rigorously test** the results?

Case D Constraint: **No month** in
any realization has
Supply < 60% of Demand.

Results: Case D

- **Islands of feasible solutions**
  - Only reliability > 99.5% (some failures in A – C were critical)
  - Long-term risks difficult to identify
  - Are optimal solutions "standing on a needle"?
- **Diverse range of portfolios**
  - Higher dropped transfers for options/leases portfolios
  - Perm. Rights portfolios: high cost, surplus

60,000 af

Cost

Surplus Water

Surplus Water

10,000 af

$13 mill

Cost

0 af

Dropped

Dropped Transfers

$9 mill   80,000 af

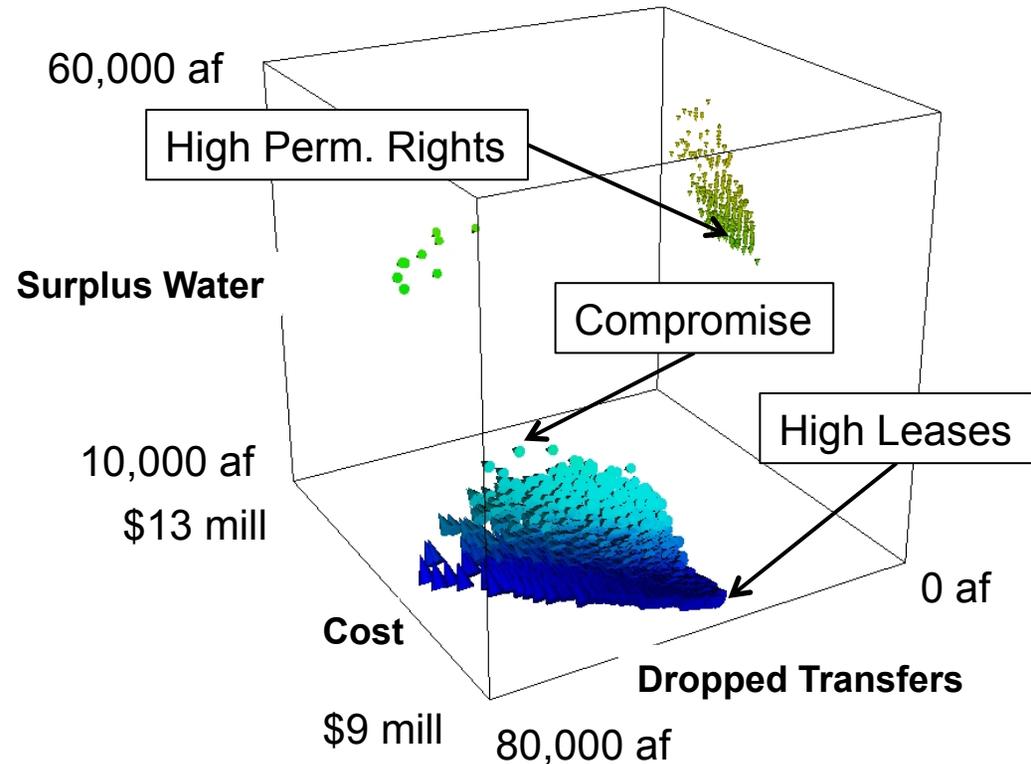| **Legend**	**Size:** Vol. Leases	**Orientation:** Vol. Exercised Options
Surplus Water ↑ ↗ **Cost** ↙ **Dropped Transfers**	▲ *Small to Large* — 0 af to 25,000 af	0 af ▽ *Down to Up* △ 160,000 af
		Color: Vol. Perm. Rights — 30,000 af to 60,000 af

Drought Scenario

Test solutions in a single-year:

Highest projected monthly demand

Driest year on record

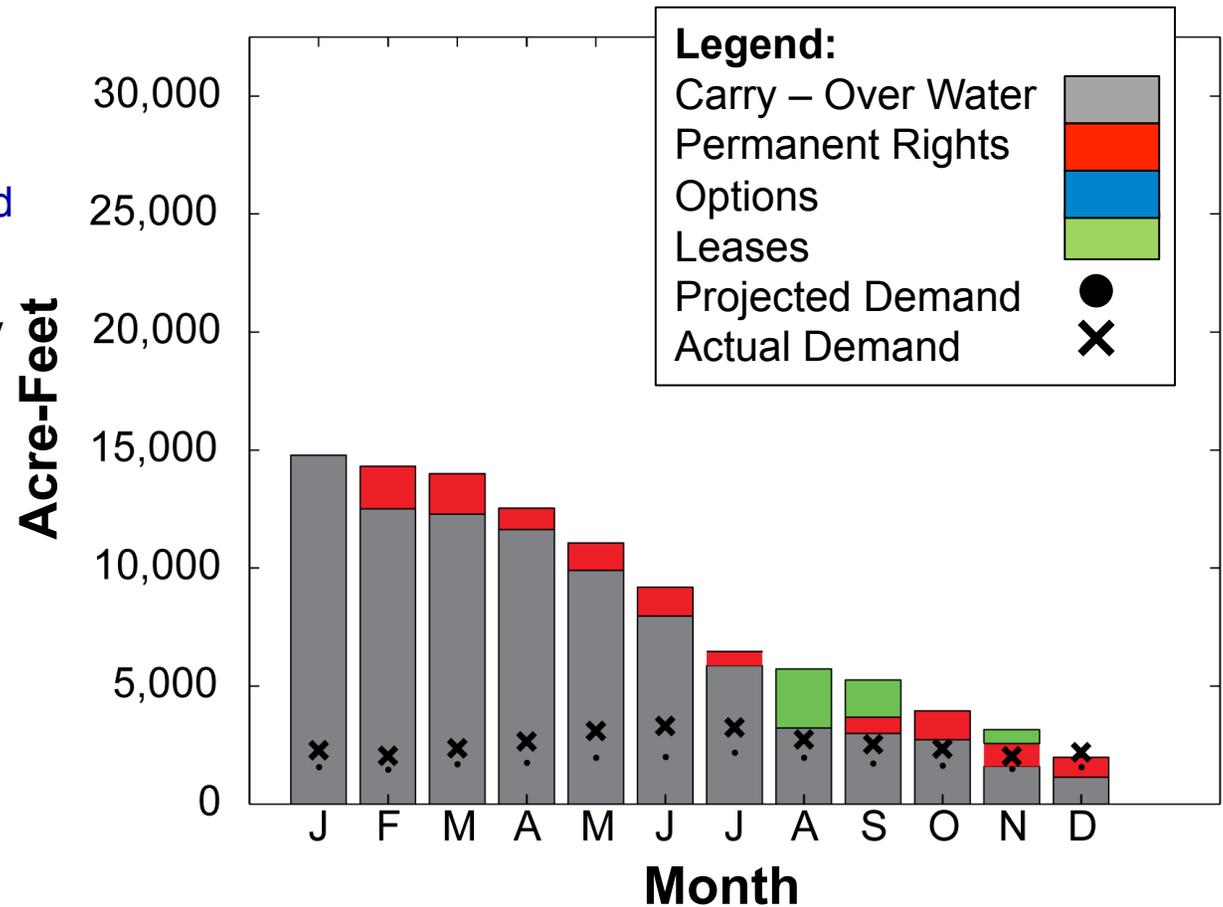How will the selected solutions perform in this modest test?

Drought Scenario

- **Solution 1: High Permanent Rights**
  - $11.5 mil., 49k af rights, 600 af dropped transfers
  - Number of leases – 0.5

- **Solution 2: High Leases**
  - $9.2 mil, 30k af rights, 37k af dropped transfers
  - Number of leases – 4.8

- **Solution 3: Compromise**
  - $11.0 mil, 40k af rights, 54k af dropped transfers
  - Number of leases – 1.1

60,000 af

High Perm. Rights

Surplus Water

Compromise

High Leases

10,000 af
$13 mill

0 af

Cost

Dropped Transfers

$9 mill   80,000 af

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Solution 1 (Permanent Rights Dominate)

- **Effect of surplus water**
  - Carry-over supply decreases with low inflow (drought) and high demand
  - Minor failure in December

- **Drought year caused city to rely on leases** (much more than in 10-year scenario)
  - Low inflows and high demands are unexpected
  - Lease acquisitions not sufficient to avoid December failure

Legend:
- Carry – Over Water (grey)
- Permanent Rights (red)
- Options (blue)
- Leases (green)
- Projected Demand ●
- Actual Demand ✕

Y-axis: **Acre-Feet** (0, 5,000, 10,000, 15,000, 20,000, 25,000, 30,000)
X-axis: **Month** (J F M A M J J A S O N D)

Solution 1 (10-year): Cost $11.5 mil, Surplus 37k af, Dropped Transfers 0 af, Leases 0.5
Solution 2 (10-year): Cost $9.2 mil, Surplus 12k af, Dropped Transfers 37k af, Leases 4.8
Solution 3 (10-year): Cost $11.0 mil, Surplus 21k af, Dropped Tranfsers 54k af, Leases 1.1

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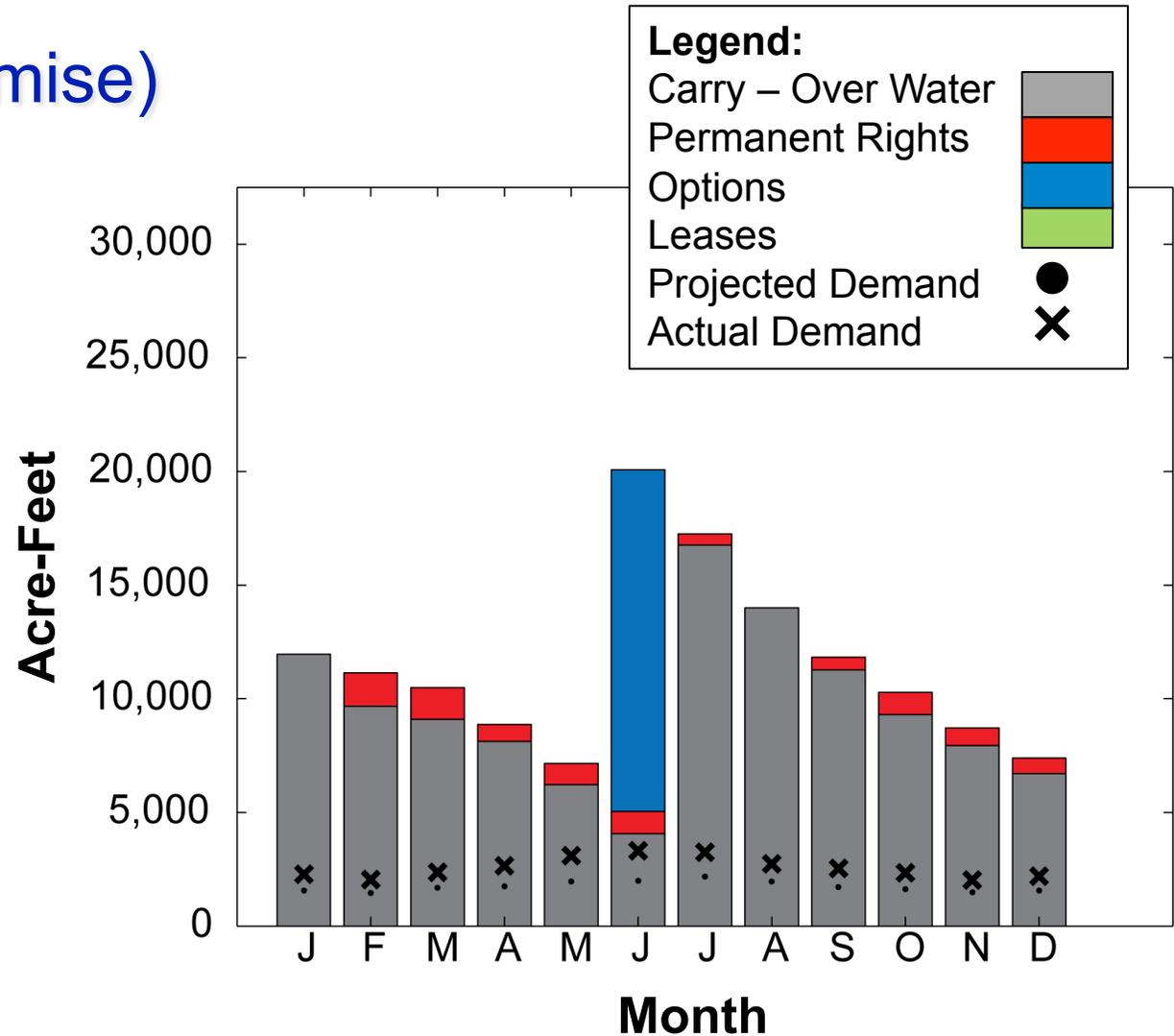
Solution 2 (Leases Dominate)

- **More flexible strategy**
  - Ironically, same number of leases as Solution 1
  - Strategy is more robust to drought
- **Minor failure in May**
  - Options contract provides significant **drought relief**, leases provide security
  - **Resiliency** – response to failure event
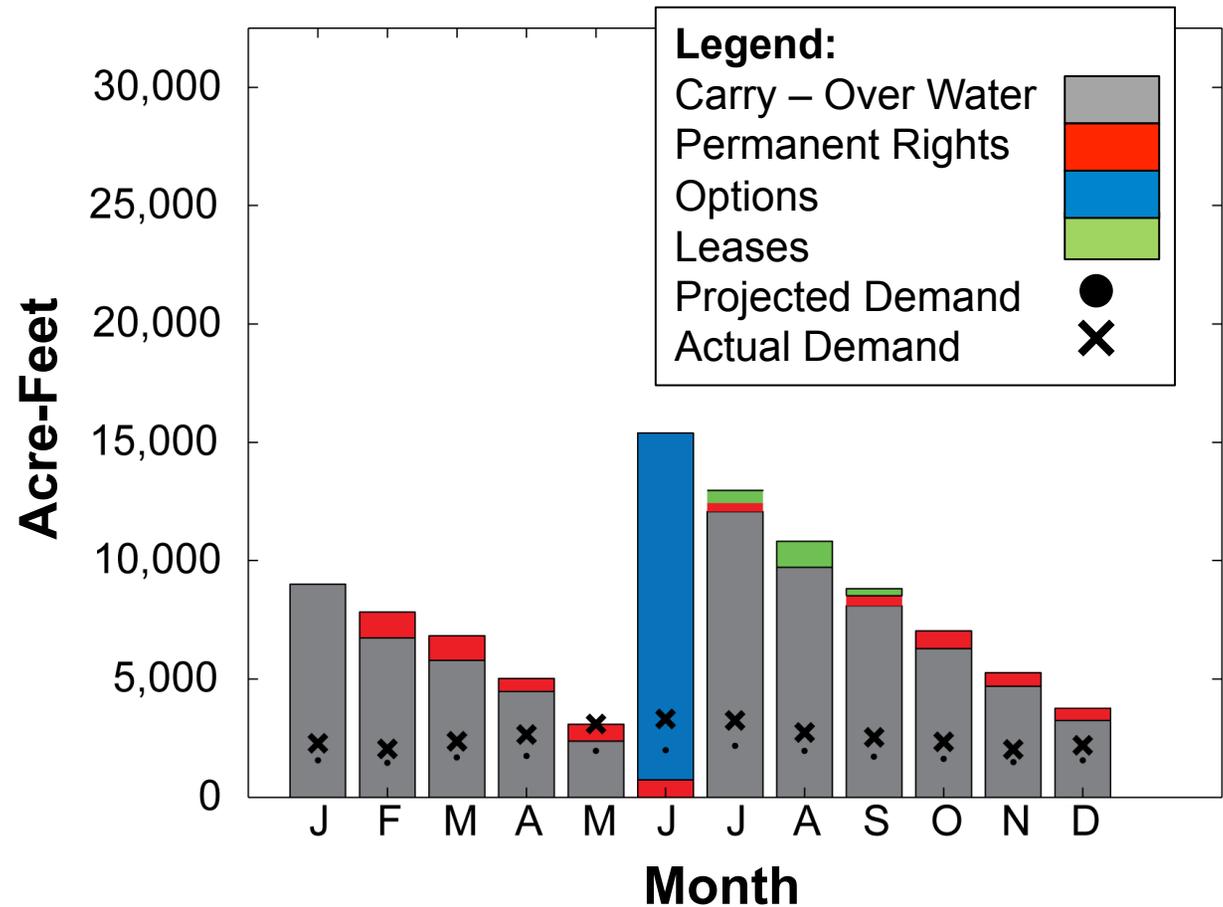
Legend:
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Solution 3 (Compromise)

- **Effective combination of rights and options**
  - More conservative options contract
  - Exercised options provide large supply, but city still ends year with less water than in Jan.

- **Demonstrating distinct portfolio types**
  - Interaction between rights, options, leases
  - Finding portfolios that are adaptive under drought conditions

Legend:
Carry – Over Water
Permanent Rights
Options
Leases
Projected Demand ●
Actual Demand ✕

Y-axis: **Acre-Feet** — 0, 5,000, 10,000, 15,000, 20,000, 25,000, 30,000

X-axis: **Month** — J F M A M J J A S O N D

Solution 1 (10-year): Cost $11.5 mil, Surplus 37k af, Dropped Transfers 0 af, Leases 0.5
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Solution 3 (10-year): Cost $11.0 mil, Surplus 21k af, Dropped Tranfers 54k af, Leases 1.1

LRGV Test Case Conclusions

- A many-objective analysis with evolving problem formulations showed **distinct portfolio types** and **tradeoffs** between planning objectives

- A drought analysis exhibited that **risk aversion** and **uncertainties** represent mathematical challenges, aided by optimization, visualization, and solution exploration

- The approach used in this work has potential for **confronting cognitive challenges** for decision making under uncertainty, facilitating discovery and negotiation

Questions?

Dominion offers wind-following

Dominion offers wind-following with ecosystem services
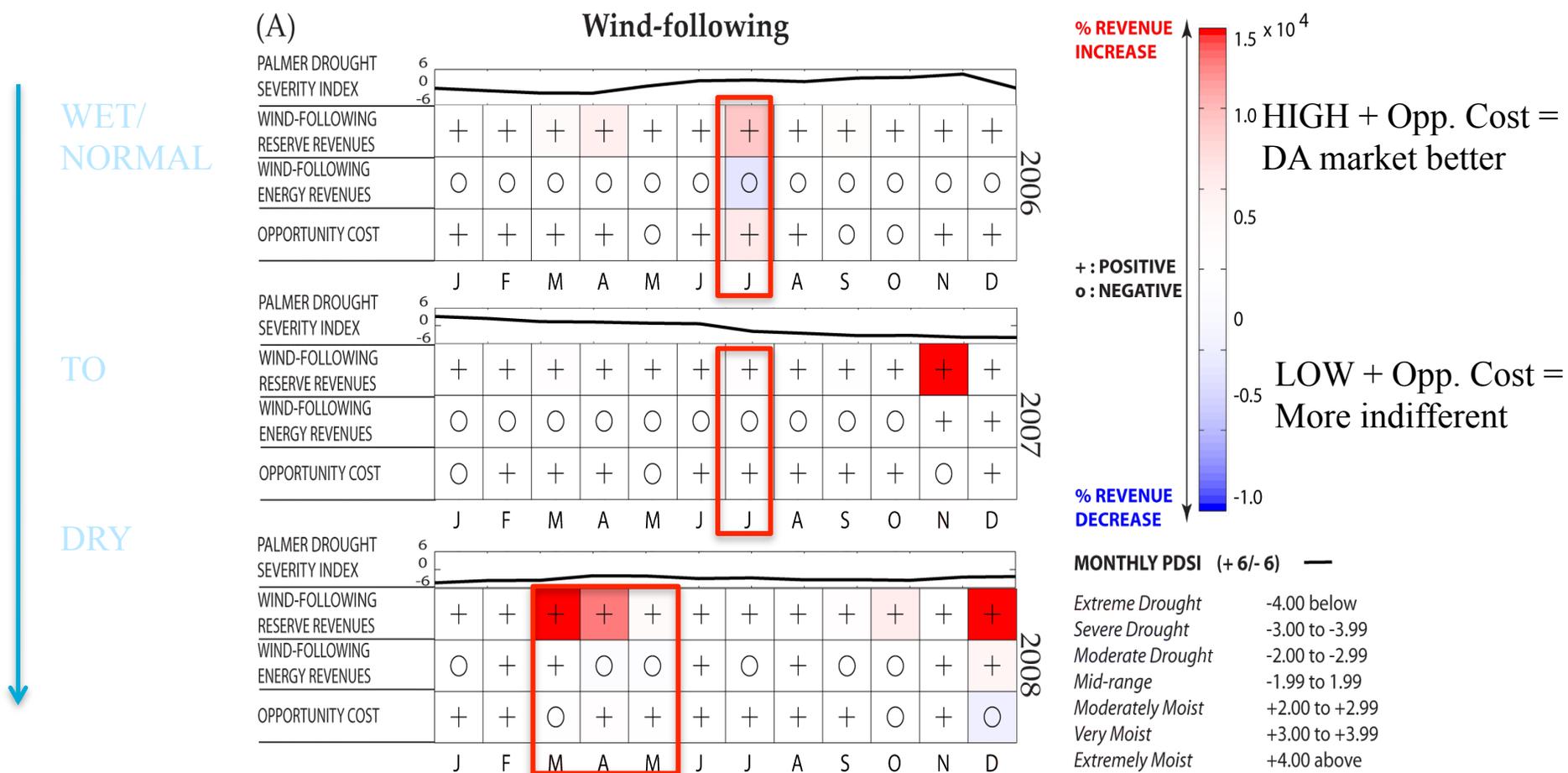
LOW (+) to HIGH (+) Opp. Cost = sell MORE wind to sell LESS wind (MORE spilling)

Measuring policy conflicts

Measure percent deviations from the BAU revenues (acts as the 'baseline' revenue)

- Wind-following reserves
  - Revenues (Millions $), Payments ($/MWh)
- Wind-following energy
  - Revenues (Millions $), Payments ($/MWh)
- Opportunity cost
  - Cost (Millions $), ($/MWh)

Defining revenue parameters

- ## Wind-following revenues

$$\max_{y_{PJM,t}, y_{WIND,t}} WF\ Rev_t = \sum_{t=1}^{T} (p_{PJM,t} \times y_{PJM,t}) + (p_{PJM,t} \times y_{WIND,t}) - \alpha \times (y_{PJM,t} + y_{WIND,t}\ ^{*}$$
$$- Hourly\ BAU\ Declaration_t) + (p_{S,t} - p_{PJM,t}) \times y_{SEPA,t}$$

- ## Wind-following ecosystem services revenues

$$\max_{y_{PJM,t}, y_{WIND,t}} WF\ Eco\ Rev_t = \sum_{t=1}^{T} (p_{PJM,t} \times y_{PJM,t}) + (p_{PJM,t} \times y_{WIND,t}) - \alpha \times (y_{PJM,t} + y_{WIND,t}\ ^{*}$$
$$- Hourly\ Ecosystem\ Services\ Declaration_t) + (p_{S,t} - p_{PJM,t}) \times y_{SEPA,t} - (p_{PJM,t}$$
$$* spilling_t)$$

*Hetzer, J., Yu, D., and Bhattarai, K.,(2008). *An Economic Dispatch Model Incorporating Wind Power*. IEEE Transactions on Energy Conversion, Vol. 23, No. 2,. pp. 603-611.
*Pattanariyankool, S. and Lave, L.B., 2010). *Optimizing transmission from distant wind farms*. Energy Policy, Vol. 38, pp. 2806–2815.

Defining payment parameters

- ## Wind-following reserves payments ($/MWh)

$$WF\ reserves\ payments = \sum_{t=1}^{T} WF\ Reserves\ price\ \left(\frac{\$}{MW}\right) * y_{CAP\ WIND}(MW) * \frac{1}{y_{WIND}(MWh)}$$

- $$WF\ energy\ payments = \sum_{t=1}^{T} \frac{WF\ Energy\ Revenues\ (\$)}{y_{WIND}(MWh)}$$

$$Opportunity\ Cost\ \left(\frac{\$}{MWh}\right) = \sum_{t=1}^{T} \frac{Opportunity\ Cost\ (\$)}{y_{WIND}(MWh)} = \frac{(BAU\ Rev_t - WF\ Rev_t)(\$)}{y_{WIND}(MWh)}$$

Many-Objective Design Analytics: Bridging Astrodynamics & Earth Science

Stakeholder Interviews

Identify Design Parameters

Identify Key Objectives

Identify Constraints

Variables
Assumptions
Constants
…

Requirements
Goals

…

Explore, Visualize, Communicate

Watch architectures "evolve" and identify key interactions between design parameters, objectives, and constraints

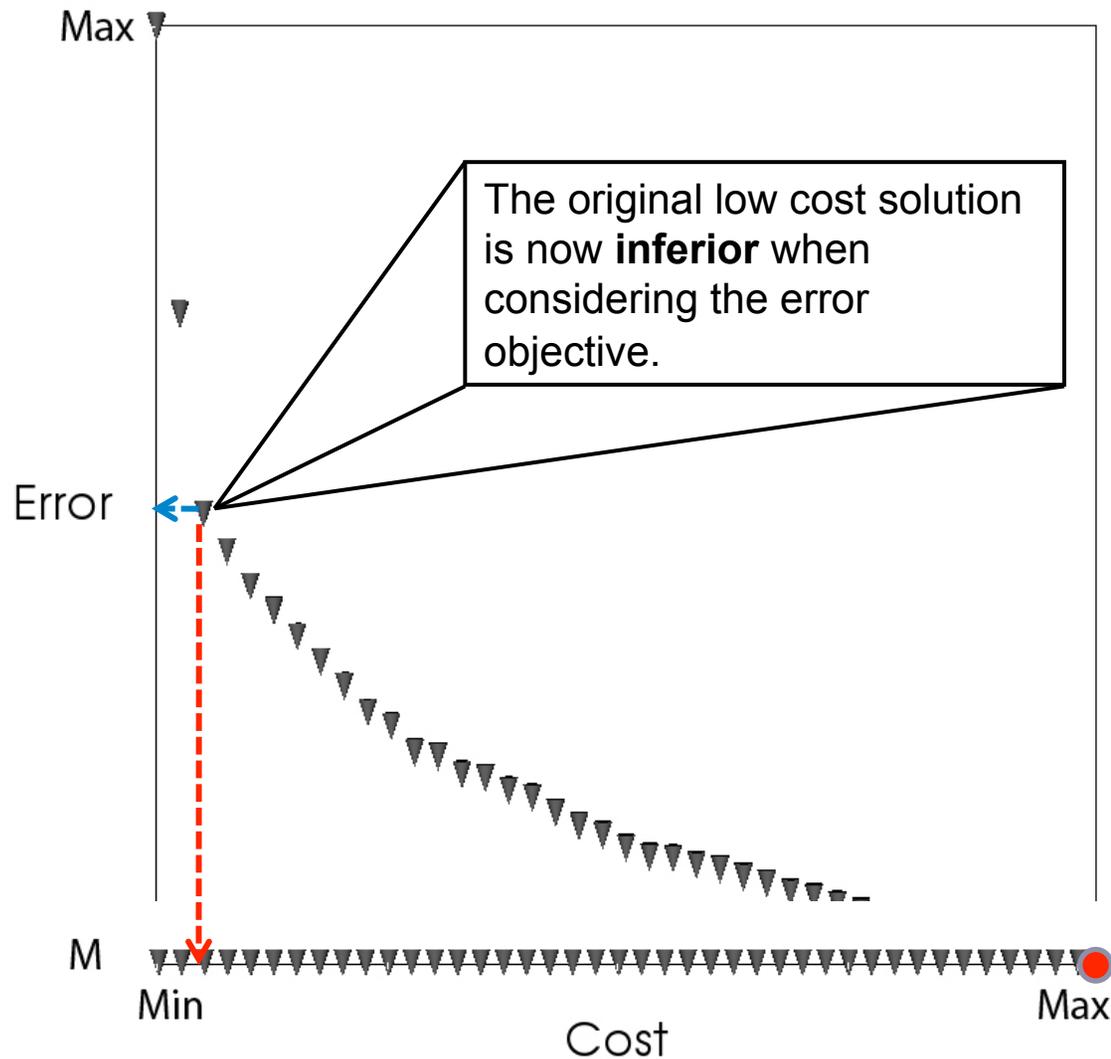Provide an accessible visualization roadmap of key tradeoffs to Decision Maker

Application Program Interfacing (API)

Identify existing Aerospace tools that model:

Assess feasibility for GRIPS integration via the API

Build new models if necessary

Wrap models into GRIPS via API

Design Parameters

Key Objectives

Constraints
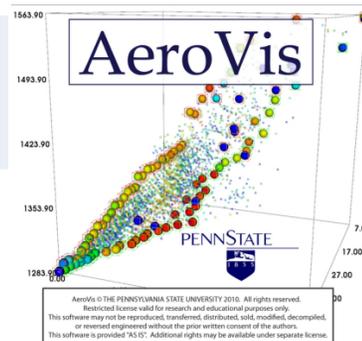
Multi-objective optimization

Massively parallel search
using Multi-objective Evolutionary Algorithms (MOEAs)

The benefit of adding multiple objectives

- Single Objective Design Problem…
- Two Objective Design Problem…
- Many-Objective Design Problem…
  - Discovery of key interactions/tradeoffs
  - Considers many subproblems
    - 2, 3, 4, 5…objective interactions
    - Facilitate negotiation

The original low cost solution is now **inferior** when considering the error objective.

Max

Error

M

Min   Max

Cost

Many-Objective Analysis: Avoiding Myopia

- Single Objective Design Problem…
- Two Objective Design Problem…
- **Many-Objective Design Problem…**
  - More compromise solutions
  - Considers many subproblems
    - Discovery
    - Negotiation

2-objective Tradeoff

Compromise solutions found with many objective analysis

2

3

1

2-objective Tradeoff
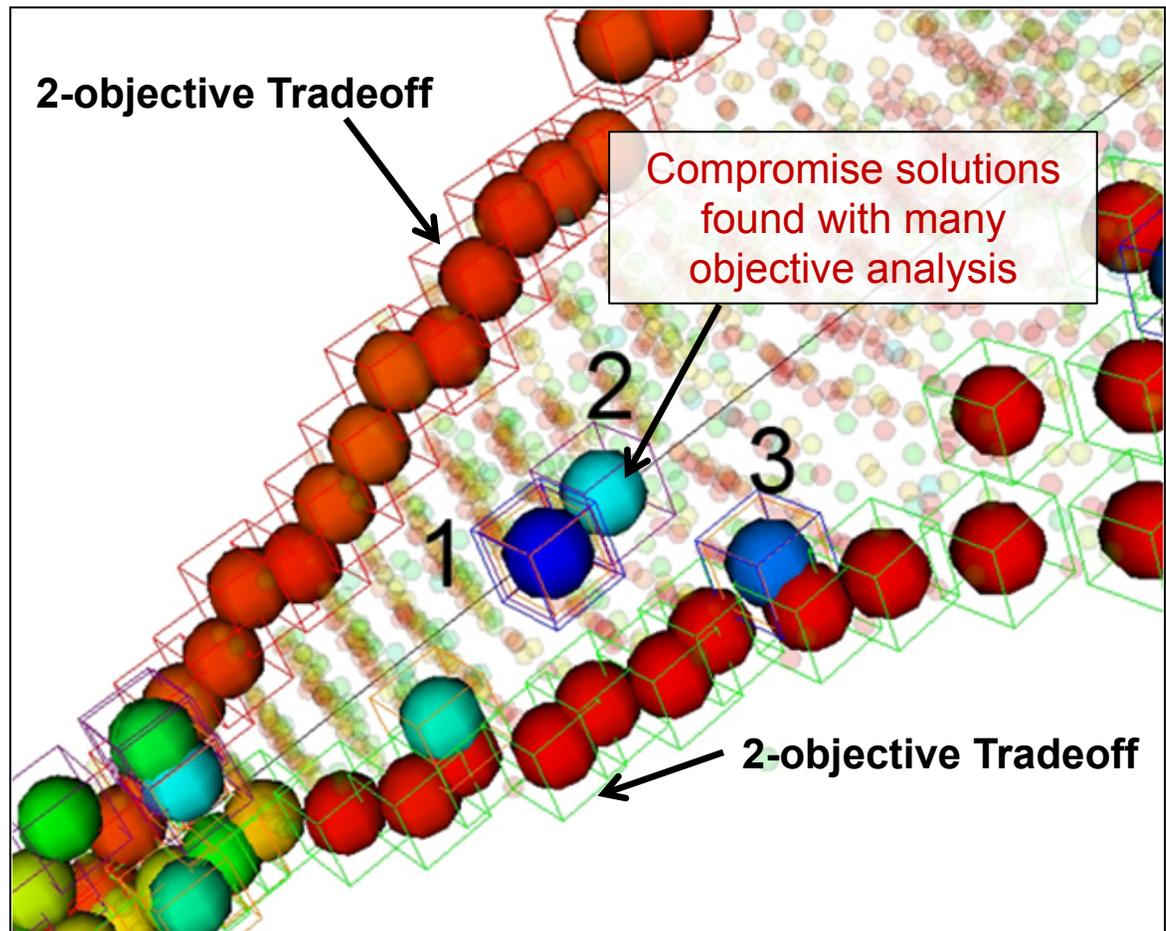
GRIPS for Satellite Constellation Reconfiguration

Ferringer et al. AIAA/AAS Astrodynamics Specialist Conf., Honolulu, HI, August 19, 2008

The propellant gage plots for two selected reconfiguration scenarios (recall 4 satellites were lost and 20 remain)

Key

- Mass depleted ●
- Mass used ●
- Mass remaining ●
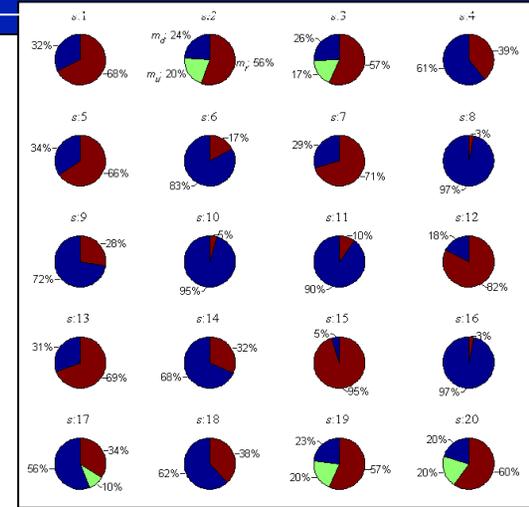
Design 2835

'Best Compromise'
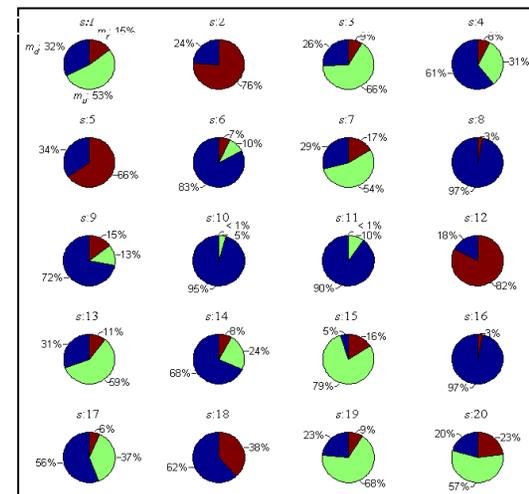
Design 2150

'Best Coverage'
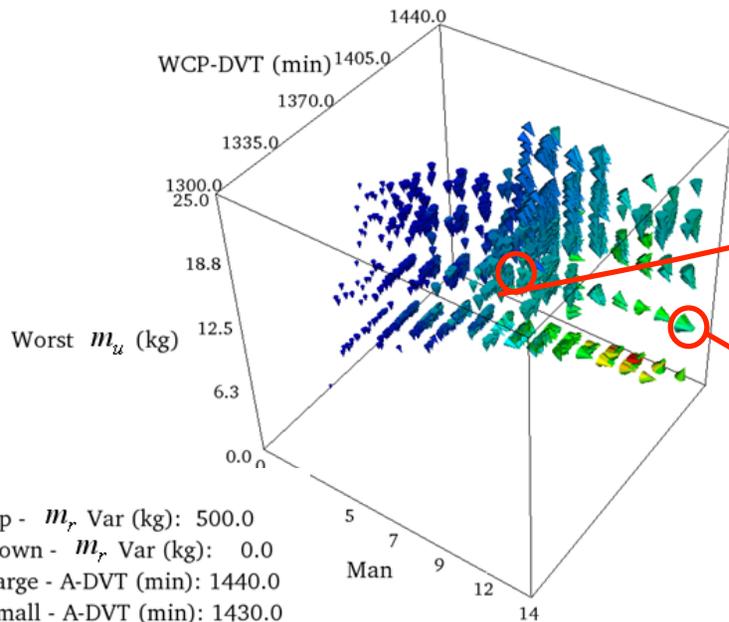
Found the reconfiguration options that minimize the time of flight, minimize propellant expended, extend constellation lifetime, and maximize performance

From The Aerospace Corporation 2009 Annual Report*

"While most applications to date have been based on optimizing the performance of space systems architectures, GRIPS permits the explicit trade of system-level parameters in diverse areas, such as orbits, sensor characteristics, and system costs. The GRIPS process provides a new tool to help decision makers understand the impact of system-level decisions."

"GRIPS is currently being used in support of several National Reconnaissance Office programs within imagery intelligence and signal intelligence. As a result of the insights developed through GRIPS results, system-level specifications are being modified, and decisions that were made decades ago are being reconsidered."

*Source: http://www.aero.org/corporation/AerospaceAR.pdf

GRIPS for Civil and Commercial, License to Start-up Apptimation LLC (2010)

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Apptimation Aviation LLC:
Flight Network Scheduling Result
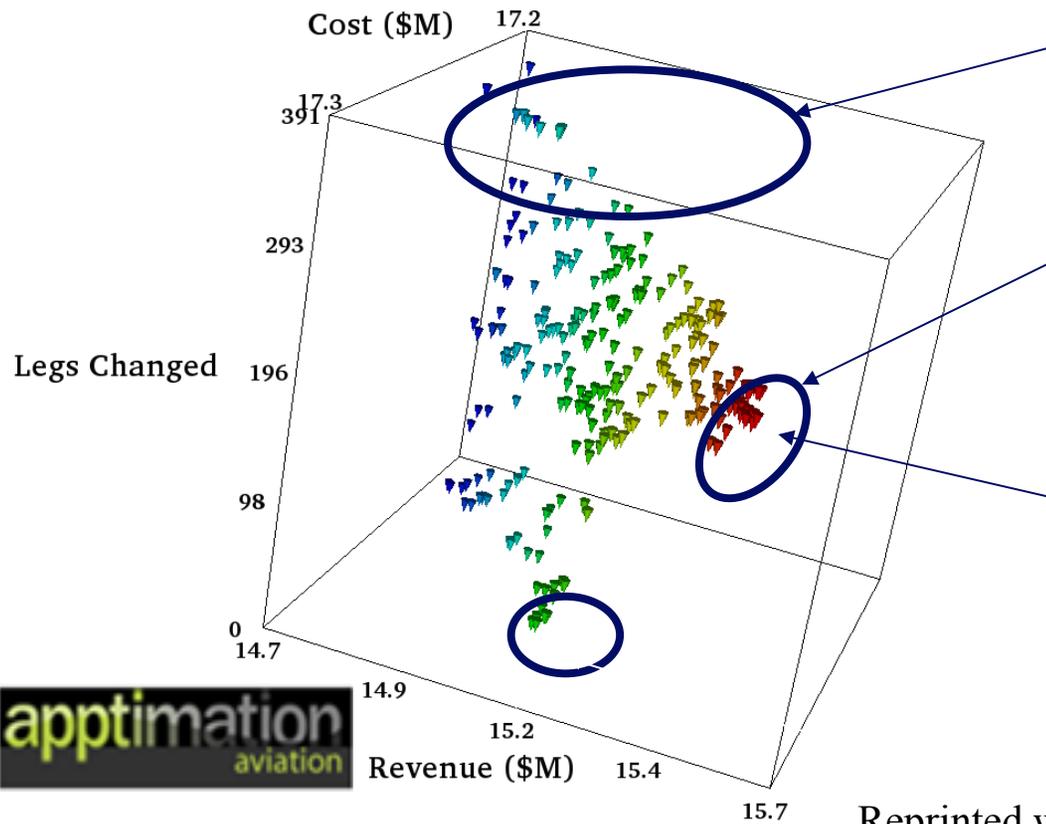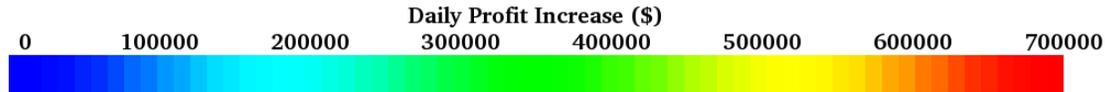
Note that the most disruptive schedule changes do not translate into greater profits for the airline.

The most profit to be had is between 220 and 270 legs changed

This design produces the greatest daily profit increase for the airline but also is very disruptive changing 270 out of the possible 391 legs

This design produces a $350,000 daily profit increase and the benefit of disrupting _only 18 flight legs_ out of the possible 391.

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