Exploring Near-Equilibrium Solutions:
The MARKAL-MGA Algorithm and Use

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Presentation Outline

- Optimization: Tools in the Toolbox
- Characteristics of Real-World Problems
- Arguments for Exploring Near-Equilibrium Solutions
- Modeling to Generate Alternatives Algorithm
- Application in Energy System Modeling and Illustrative Results
- Current Implementation
- MARKAL-MGA Critique
- Expected Future Developments

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Optimization: Tools in the Toolbox

- Least cost (LC) optimization
  Prescriptive modeling: What should I do?
- Sensitivity analysis
  Shadow prices, reduced costs from LC solution
- Multiobjective optimization
  Optimal tradeoff among objectives
- Chance-constrained optimization
  Development of robust solutions considering uncertainties

Modeling to Generate Alternatives (MGA)?
Exploration of near-equilibrium solutions

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Motivation: Characteristics of Real-World Problems

- Modeling is a learning process
- Simplifications are made in modeling
  - Linearization, discretization, etc.
- Uncertainty exists in:
  - model structure, parameters, and inputs
- Unmodeled issues, such as:
  - Unknown objectives and constraints
    - External influences
    - Currently unknown health issues
    - Implications of future policies
  - Qualitative factors
    - Political & public pressure
    - Human behavior

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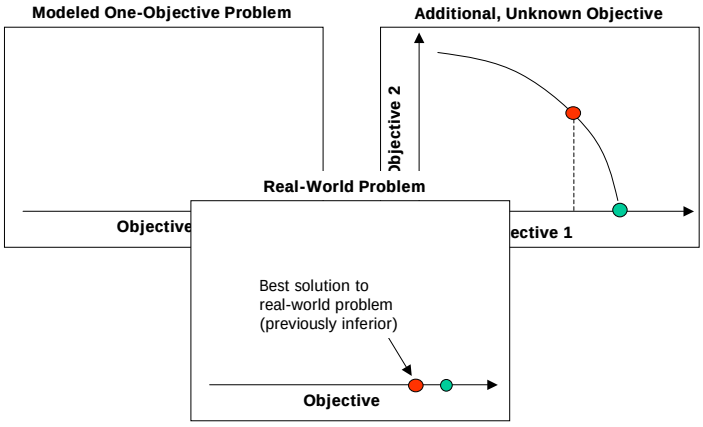
Arguments for Exploring Near-Equilibrium Solutions

The best solutions to real-world problems are often inferior solutions to the modeled problem



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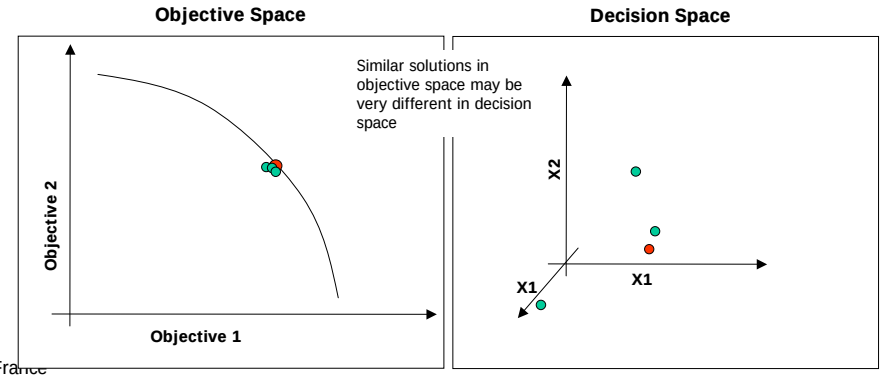
Arguments for Exploring Near-Equilibrium Solutions

There may be a variety of near-optimal solutions to the problem.



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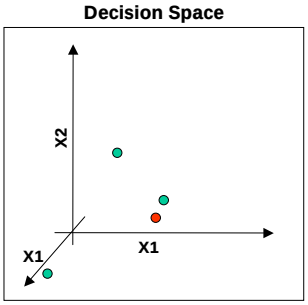
Arguments for Exploring Near-Equilibrium Solutions

Alternatives very different in decision space may perform very differently with respect to unmodeled issues.



Solution	Objective 1 Cost	Objective 2 Emissions	Objective 3 Robustness
LC	121	834	75
Alt1	123	822	**92**
Alt2	122	832	65
Alt3	122	833	**13**

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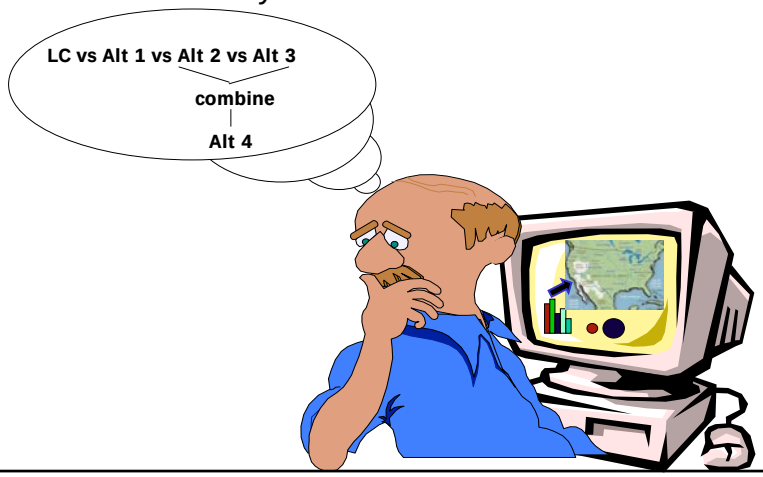
Arguments for Exploring Near-Equilibrium Solutions

Decision-makers often perform better given a small set of very different alternatives.



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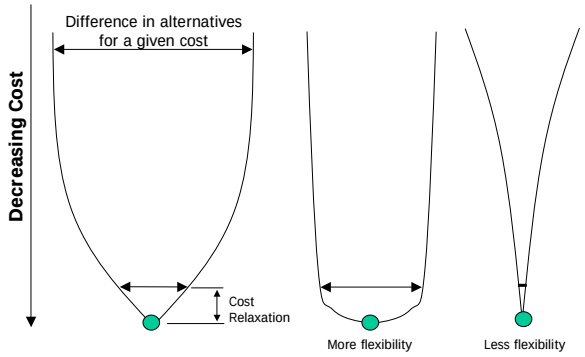
Arguments for Exploring Near-Equilibrium Solutions

The similarity (or difference) among alternatives can yield valuable information about the flexibility available in solving the problem.



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MGA Algorithm

Goal:

Generate a small number of very different alternatives

- Solve the least cost (LC) formulation
- Set total system cost <= (1 + δ) * LC
- Set the objective to maximize some metric of distance from the LC solution
  - For example, minimize the occurrence of all technologies from the LC solution
- Generate MGA alternative 1
- Repeat iterative, each time maximizing the difference from the LC & all previous MGA solutions
- Terminate when a target number of MGA solutions have been reached or where difference is small

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MARKAL-MGA Implementation

- Define difference metric:
  - Minimize capacity (or investment) of individual technologies (or sets) that have appeared in prior alternatives
- Specify number of alternatives to generate
- Set system-wide cost relaxation

Additions to GEN file:

```
* Activate MGA

$SET MGA 'MIN'

SET MY_MGA(TCH) / TLS01*TLS61, TLC01*TLC63,
TLF01*TLF61, TLM01*TLM61, TLP01*TLP59/;

$SET MGA_Filter(MY_MGA(TCH))

SET MGA_Runs / MGA_X00*MGA_X25 /;

MGA_MRKSlk = 0.015;
```

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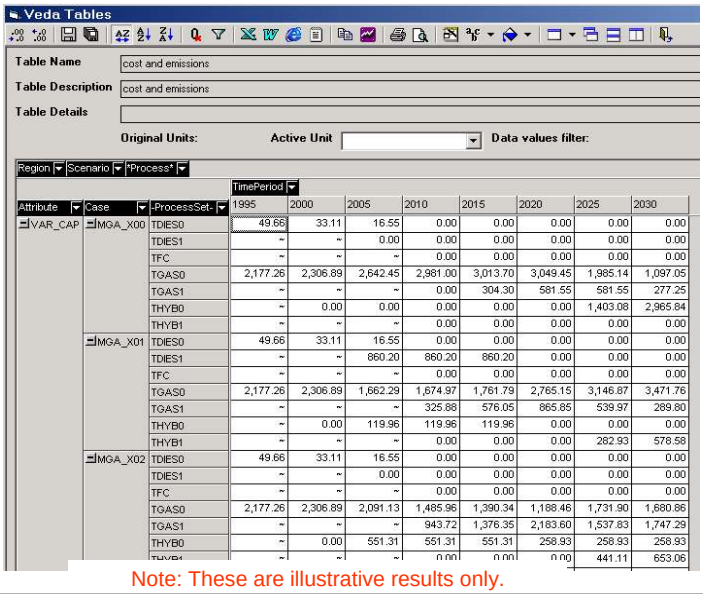
Analysis of Results with VEDA



Attribute	Case	-ProcessSet-	1995	2000	2005	2010	2015	2020	2025	2030
VAR_CAP	MGA_X00	TDIES0	49.66	33.11	16.55	0.00	0.00	0.00	0.00	0.00
		TDIES1	"	"	0.00	0.00	0.00	0.00	0.00	0.00
		TFC	"	"	"	0.00	0.00	0.00	0.00	0.00
		TGAS0	2,177.26	2,306.89	2,642.45	2,981.00	3,013.70	3,049.45	1,985.14	1,097.05
		TGAS1	"	"	"	0.00	304.30	581.55	581.55	277.25
		THYB0	"	0.00	0.00	0.00	0.00	0.00	1,403.08	2,965.84
		THYB1	"	"	"	0.00	0.00	0.00	0.00	0.00
	MGA_X01	TDIES0	49.66	33.11	16.55	0.00	0.00	0.00	0.00	0.00
		TDIES1	"	"	860.20	860.20	860.20	0.00	0.00	0.00
		TFC	"	"	"	0.00	0.00	0.00	0.00	0.00
		TGAS0	2,177.26	2,306.89	1,862.29	1,874.97	1,761.79	2,765.15	3,146.87	3,471.76
		TGAS1	"	"	"	325.88	576.05	865.85	539.97	289.80
		THYB0	"	0.00	119.96	119.96	119.96	0.00	0.00	0.00
		THYB1	"	"	"	0.00	0.00	0.00	282.93	578.58
	MGA_X02	TDIES0	49.66	33.11	16.55	0.00	0.00	0.00	0.00	0.00
		TDIES1	"	"	0.00	0.00	0.00	0.00	0.00	0.00
		TFC	"	"	"	0.00	0.00	0.00	0.00	0.00
		TGAS0	2,177.26	2,306.89	2,091.13	1,485.96	1,390.34	1,188.46	1,731.90	1,680.86
		TGAS1	"	"	"	943.72	1,376.35	2,183.60	1,537.83	1,747.29
		THYB0	"	0.00	551.31	551.31	551.31	258.93	258.93	258.93
		THYB1	"	"	"	0.00	0.00	0.00	441.11	653.06

Note: These are illustrative results only.

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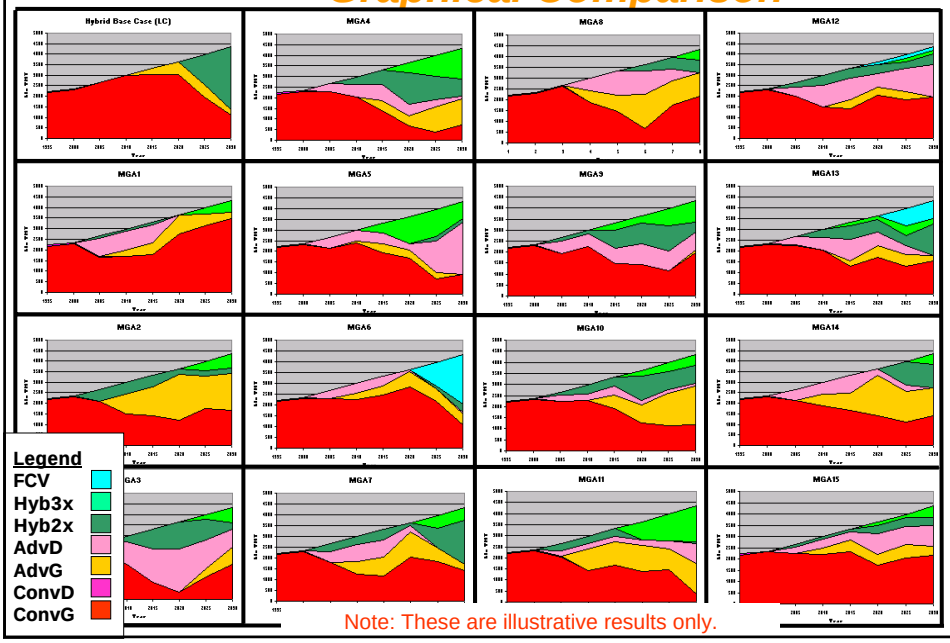
Graphical Comparison



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Critique of Experience

Advantages

- Easily integrated into MARKAL
- Readily applied
- Interesting results

Challenges and Issues

- What should cost relaxation be?
- How should results be interpreted?
- Is 'expected value' result meaningful?
- What are appropriate distance metrics?
- With overall cost relaxation, small players can behave oddly
- Reduced cost and shadow price have questionable meaning

Conclusion

- Valuable technique that complements, not replaces existing tools.

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Expected Future Developments

- Add demand-level cost constraints
- Investigate application to other interesting analyses:
  - Modeling suboptimal trading outcomes for emissions trading programs
- Develop approaches for analyzing and comparing the MGA outcomes
  - How are the alternatives similar or different?
  - Which outcomes are interesting and deserve further investigation?

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