Mitigating Contextual Uncertainties with Valuable Changeability Analysis in the Multi-Epoch Domain

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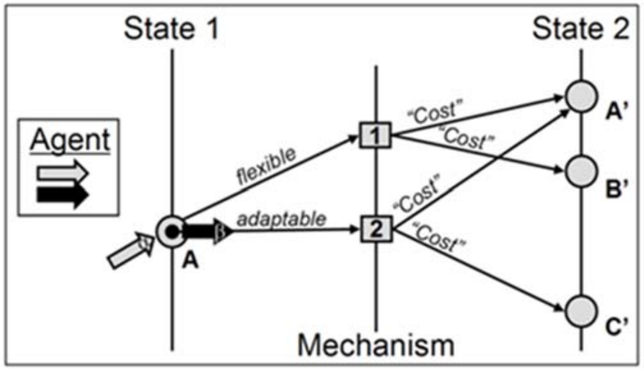
Outline

- Changeability Overview
- Challenges in Valuing Changeability
- Epoch-Era Analysis Summary
- Changeability Usage Strategy
- Multi-Epoch Analysis Metrics
- Space Tug Case Study

What is Changeability?

- Changeability: *the ability of a system to change its form or behavior at some point in its lifecycle*
  - Related words: flexibility, adaptability, etc.
- Agent-Mechanism-Effect framework
  - Agent: instigator
  - Mechanism: enabler
  - Effect: ΔState



Ross et al, 2008

Why Changeability?

- Benefits
  - Ability to avoid risk and seize opportunity as context changes over time

In the absence of changeability, exogenous disturbances / stakeholder preference modifications can compromise system value!

- Costs
  - Development, build, execution costs both in money and time

But how do we value changeability?

Challenges arising from the nature of changeability have complicated the process of appropriately quantifying it: a necessary step to justify the costs!

Previous Methods

Much previous research has been devoted to this problem, a sampling is shown here:

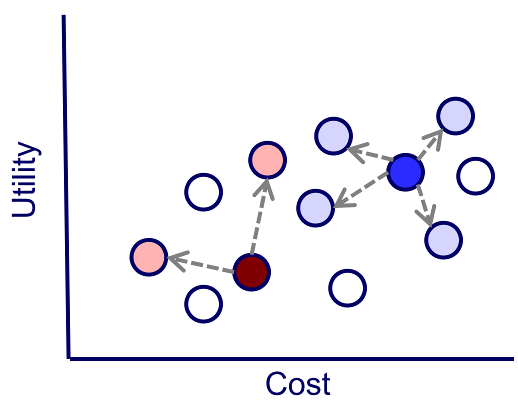
Metric / Method	Description / Measure	
Filtered Outdegree	# Outgoing change paths	Ross, Hastings 2006
Normalized F-O	Above, considering stakeholder "acceptable" threshold	Ross et al, 2009
Value-Weighted F-O	Above, counting only utility beneficial paths	Viscito, Ross, 2009
Available Rank Increase	# Designs able to surpass in utility	Fitzgerald, 2010
Real Options (financial)	Monte Carlo + Black-Scholes	Mathews, Datar, 2007
Real Options (decision)	Binomial Lattice + Decision point	De Neufville et al, 2006

These measure different things: can we compare their ability to address the challenges inherent in valuing changeability?

Valuation Challenges (1)

Magnitude vs. **Counting** value

- Two sources – targeted alternatively by many previous metrics/methods
  - Magnitude: **amount** of value increase
  - Counting: **number** of options



Red: largest value increase (as measured by utility)
Blue: twice as many paths → redundancy in event of breakages, potentially useful in more contexts

How can we account for both of these types of value in analysis?

Valuation Challenges (2)

Dataset Independence

- Desirable to use metrics that score designs without reliance on alternatives
  - Reduces burden of proof on design team
  - Stabilizes results even if design space changes in the middle of analysis

Universal Context

- Desire metrics that are consistent across contexts
  - ie, want a score of X in one context to be identical to a score of X in another
  - Possible for more conclusions to be drawn about relative value across contexts and between designs

Many value metrics that are independent are NOT universal, because value is inherently subjective and thus can change with context

Previous Methods - Comparison

Using those criteria to compare:

	Independent	Universal	Magnitude	Counting	
Filtered Outdegree	✗	✗	✗	✓	Ross, Hastings 2006
Normalized F-O	~	✓	✗	✓	Ross et al, 2009
Value-Weighted F-O	✗	✗	~	✓	Viscito, Ross, 2009
Available Rank Increase	✗	✓	✓	✗	Fitzgerald, 2010
Real Options (financial)	✓	✗	✓	✗	Mathews, Datar, 2007
Real Options (decision)	✓	✗	✓	~	De Neufville et al, 2006

Obviously, none of these metrics are completely sufficient on their own, as each is missing at least one of these four desirable traits

Can we create a method that will span all four columns here?

Solving the Problem

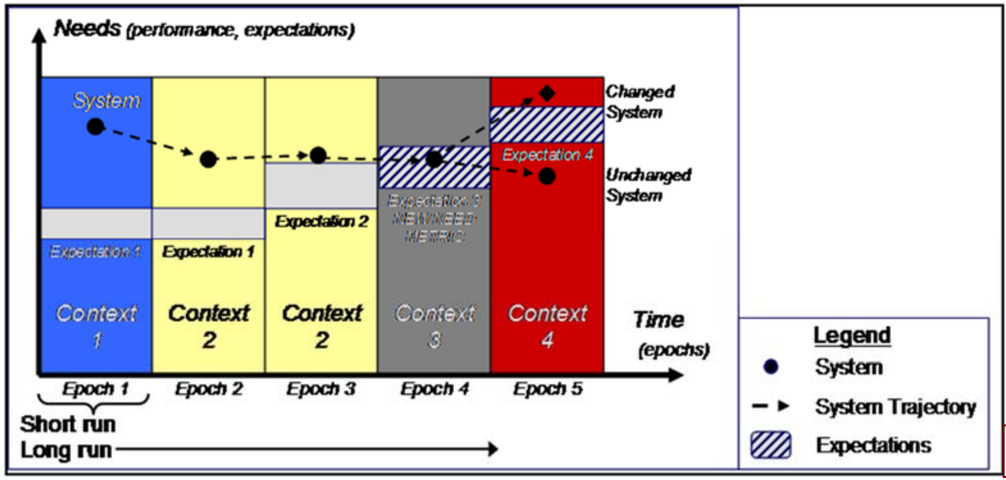
Leverage two techniques to address the biggest components of changeability analysis

- Modeling passage of time
  - Epoch-Era Analysis (EEA)
- Modeling system change
  - Changeability usage strategy

Combined, these two will allow for a fundamental modeling and understanding of changeability in design and operation

Epoch-Era Analysis (EEA)

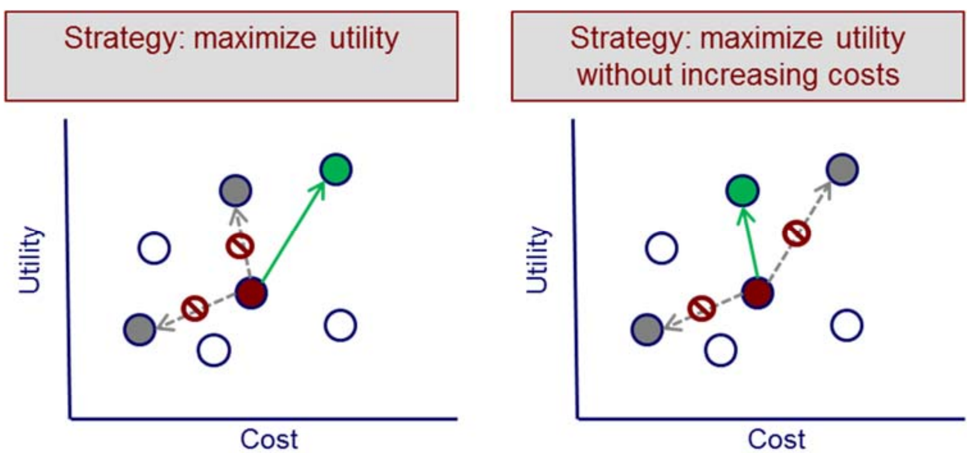
- Conceptualizes the effects of time and changing context on a system
  - Epochs: periods of fixed context (short run)
  - Eras: sequences of epochs simulating a potential future experienced by the system (long run)



Ross, Rhodes, 2008

Strategy

- ***Changeability usage strategy*** – a stakeholder or decision-maker's statement of intended use of changeability
  – Assists in valuing changeability by selecting a single change path in each epoch (as defined by the mechanism-effect framework), from design **d → d***

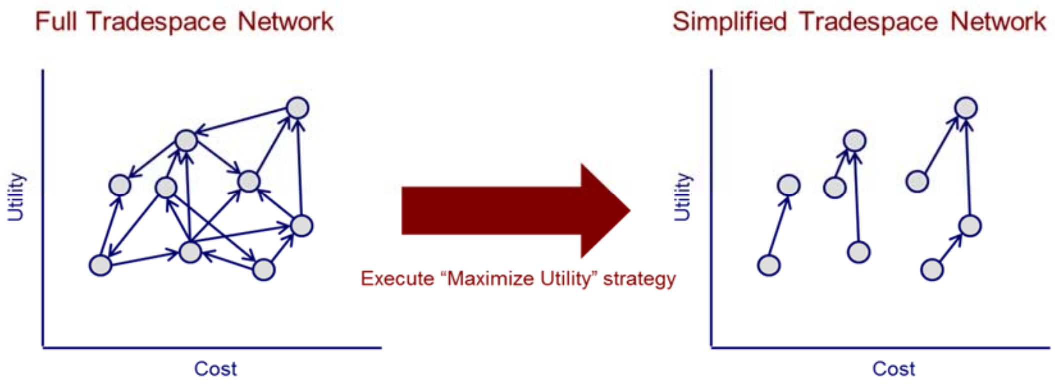


Strategy statement represents logic used to select amongst available change paths

Strategies can vary in metrics used or complexity of logic depending on stakeholder desires

Strategy in EEA

- Allows EEA to appropriately combine magnitude and counting value
  - Selected path is scored for its magnitude
  - Counting value manifests in increased magnitude across epochs due to better options



Selected paths simplify tradespace network: only remaining paths are valued

Strategy encapsulates "value achieved only by executed changes" truism

Metrics to Support Multi-Epoch Analysis

Context shifts + changeability responses decided via EEA / Strategy → **Metrics then interrogate results for the value of the changeability across epoch space**

Metrics:

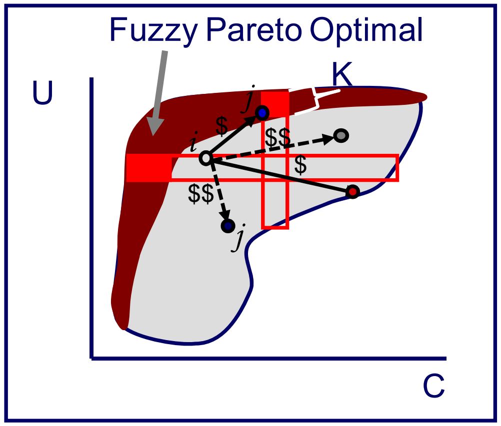
- Fuzzy Pareto Number / Shift (FPN / FPS)
- Effective (fuzzy) Normalized Pareto Trace (eNPT / efNPT)
- Available Rank Improvement (ARI)

Fuzzy Pareto Number (FPN)

Pareto Optimality = non-dominated in cost and utility

Fuzzy Pareto Optimality = within K% (of total U and C range) of Pareto Optimality

Smaling, 2005



FPN = minimum K for a design to be considered fuzzy Pareto optimal in a given epoch

$$FPN(d) = \min\{K \mid d \subset P_K\}$$

FPN is Universal and becomes Independent with one assumption

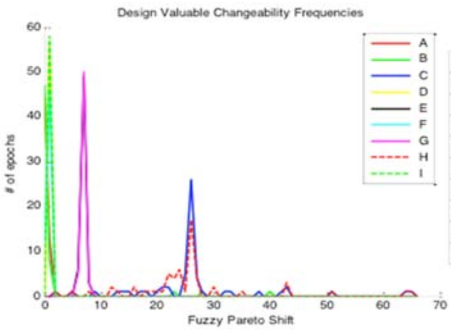
If Pareto Front is fully defined (no unconsidered designs will be Pareto Optimal):

Independent: Pareto front / reasonable data range are functions of design space, not considered designs

Universal: FPN = X implies design is within X% of cost efficiency regardless of context

Fuzzy Pareto Shift (FPS)

- FPN is calculated for each design in each epoch
- Exploit its good properties, and strategy-selected change decisions, to quantify change value



	Min	1st Q	Med	3rd Q	Max
A	0	0	0	0	1
B	0	0	0	0	40
C	2	25	26	26	65
D	0	1	1	1	1
E	6	7	7	7	8
F	0	1	1	1	1
G	6	7	7	7	8
H	2	22	26	26	65
I	1	1	1	1	1

FPS = FPN(d) – FPN(d*)

Distribution / table views display both magnitude and counting value (magnitude on x-axis, counting via weights)

What does it measure?

FPS explicitly calculates the cost-efficiency effect of a change on the system, in a means that retains the independent and universal properties of FPN

Desirable Property Check-up

Where do we stand with these concepts?

	Independent	Universal	Magnitude	Counting
FPN	✔★	✔	✖	✖
FPN + Strategy = FPS	✔★	✔	✔	✖
FPS + EEA	✔★	✔	✔	✔

★= Well-defined design space assumption: if mistaken and the design space changes dramatically, simply must recalculate

On at least this level, we are getting a more complete picture of changeability value than any of the previous methods!

But we can exploit the changeability strategy to generate more insights of a slightly different type than simply the value of the changeability alone

Effective (fuzzy) Normalized Pareto Trace

Previous EEA robustness metrics:

NPT = fraction of epochs in which a design is on the Pareto Front

fNPT = also counts epochs with a given level of fuzziness or less

But why grade designs on their own performance when they may change as epochs vary?

eNPT and efNPT = match corollaries but uses the performance of the strategy-determined end state (d*) rather than the initial state

$$fNPT(d,K) = \frac{\sum_{epochs} 1(FPN(d) \le K)}{\# epochs} \Rightarrow efNPT(d,K) = \frac{\sum_{epochs} 1(FPN(d^*) \le K)}{\# epochs}$$

What does it measure?

Quantifies "changeability-enabled robustness" for a given design/strategy combination

Available Rank Increase

Available Rank Increase (ARI) - approximates value as the number of designs (rank) a design can surpass in utility via change mechanisms

$$ARI(r,d) = Rank(d) - \min\{Rank(d^r)\}$$

- Imperfect metric (no accounting for costs, affected heavily by design enumeration)
- Does not require strategy end states (in fact, it essentially presupposes a Max Utility strategy), but can be applied to just a strategy's specified transitions as well

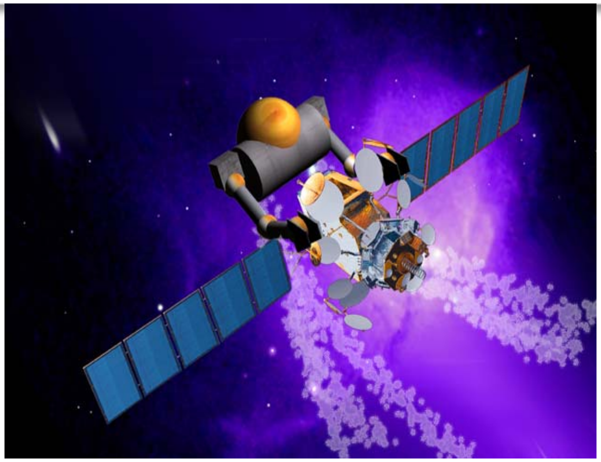
What does it measure?

Useful as an interesting basis for comparison of change mechanisms as utility-enablers

Space Tug Data Set - Intro

- Scenario: You are the owner of a space tug rental company, providing the services of your system to customers with varying preferences.

- Goals: Meet customer demands as well as possible, for as long as possible – satisfied contracts provide revenue based on duration and utility.



In this case, the system decision-maker (you) is attempting to satisfy different sets of preferences corresponding to other people.

7 designs of interest (out of 384) identified for further analysis across 4 strategies and 16 epochs, defined by 8 "mission" preferences and 2 technology levels

		Design Variables			Performance Attributes			
Design Number	**Ref**	**Prop Type**	**DFC Level**	**Fuel Mass (kg)**	**Capability (kg)**	**Fast?**	**DeltaV (m/s)**	**Base Cost ($M)**
1	A	Biprop	0	30	300	Y	143	97
29	B	Nuke	0	1200	300	Y	7381	306
47	C	Cryo	0	10000	1000	Y	6147	628
128	D	Nuke	0	30000	5000	Y	14949	3020
191	E	Nuke	1	10000	1000	Y	16150	980
328	F	Biprop	2	50000	3000	Y	4828	2804
376	G	Elec	2	30000	5000	N	27829	3952

Space Tug – DFC Level

Key design variable: Design for Changeability (DFC) level

- Levels: 0, 1, 2 where higher = more investment
- Investment modeled as both a mass and cost penalty on satellite
- Higher level → improved or new change mechanisms

#	Rule	Effect	DFC level
1	Engine Swap	Biprop←→cryo	0
2	Fuel Tank Swap	Change propellant mass	0
3	Engine Swap (reduced cost)	Biprop←→cryo	1 or 2
4	Fuel Tank Swap (reduced cost)	Change propellant mass	1 or 2
5	Change capability	Change capability	1 or 2
6	Refuel in orbit	Change propellant mass (no redesign)	2

Space Tug - eNPT

Remember: captures both robustness and changeability by considering executed change mechanisms across all epochs

Design	Do Nothing (NPT)	Max U	Max Eff	Survive
A	0.75	0	0.875	0
B	0.75	0	0.813	0.75
C	0	0	0.25	0
D	0.875	1	1	0.875
E	0	0	0	0
F	0	0	0	0
G	0	0	0	0

Insights:

- Maximizing utility *reduces* Pareto trace, sacrificing efficiency for utility
- Maximizing efficiency results in the *highest* eNPT scores
- Designs with money/mass invested in DFC are *not on the Pareto front* (score zero)

Space Tug - efNPT

Applying the fuzzy factor to effective NPT ***(efNPT)***:

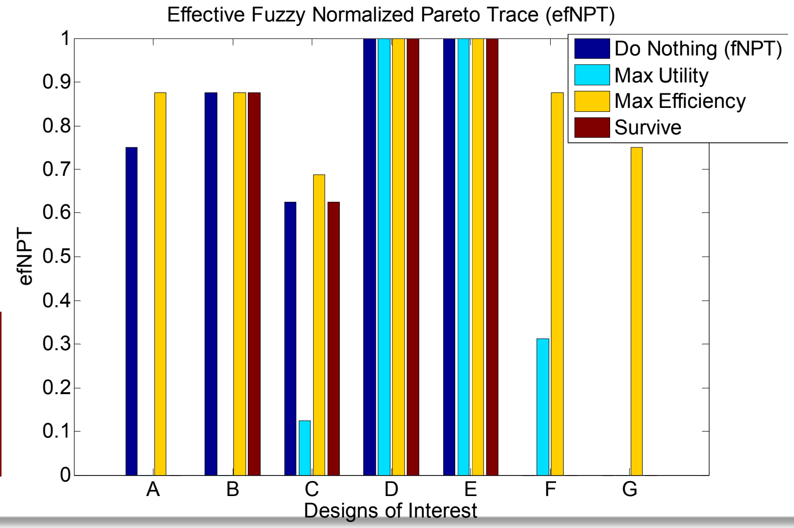
effective 5% fuzzy NPT
(green == improvement over 0%)

Design	Do Nothing (fNPT)	Max U	Max Eff	Survive
A	0.75	0	0.875	0
B	0.875	0	0.875	0.875
C	0.625	0.125	0.688	0.625
D	1	1	1	1
E	1	1	1	1
F	0	0.313	0.875	0
G	0	0	0.75	0

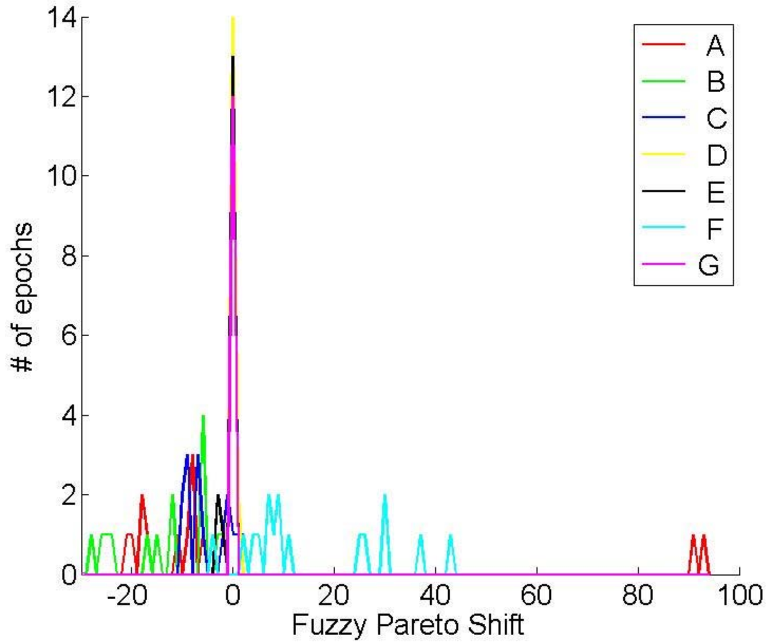
Now the DFC investments in E, F, and G look more viable, especially E which matches D at the maximum effective NPT under all strategies with a mere 5% fuzziness considered

The design/strategy paired data can also be plotted effectively in bar graph form for visual insight:

The best way to think about this is that "designs D and E are efficient across all contexts when considering changeability across a range of usage strategies"



Space Tug – FPS (Max Utility)



Epoch FPS Score Summary

Design	Min	1st Q	Med	3rd Q	Max
A	-101	-19	-13	-8	93
B	-101	-25.5	-13.5	-6	-2
C	-10	-9	-6.5	-1	2
D	0	0	0	0	1
E	-3	0	0	0	0
F	-4	6	9	28	43
G	-101	-50.5	0	0	0

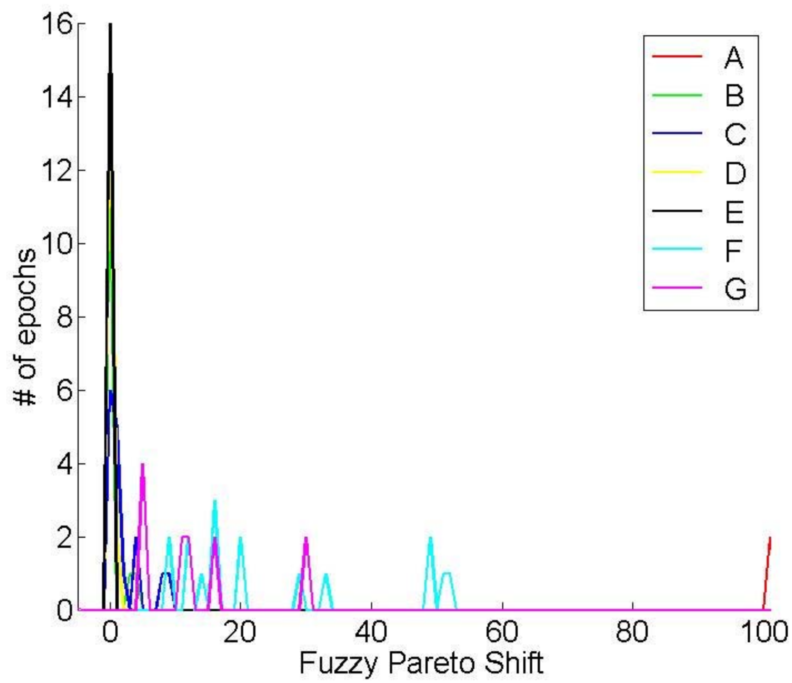
-101 FPS implies a switch from on the Pareto front (FPN=0) to invalid (FPN=101, utility undefined)

Insights:

- C, D, E, and F are never invalid (when changeability is considered)
- Maximizing utility generally has a slight negative effect on efficiency, with the exception of F
- D, E, and G do not shift in a majority of epochs
- A and F have the most effective improvements in efficiency

Space Tug – FPS (Max Efficiency)

As -101 is failure, +101 means changing from an invalid design to one on the Pareto front



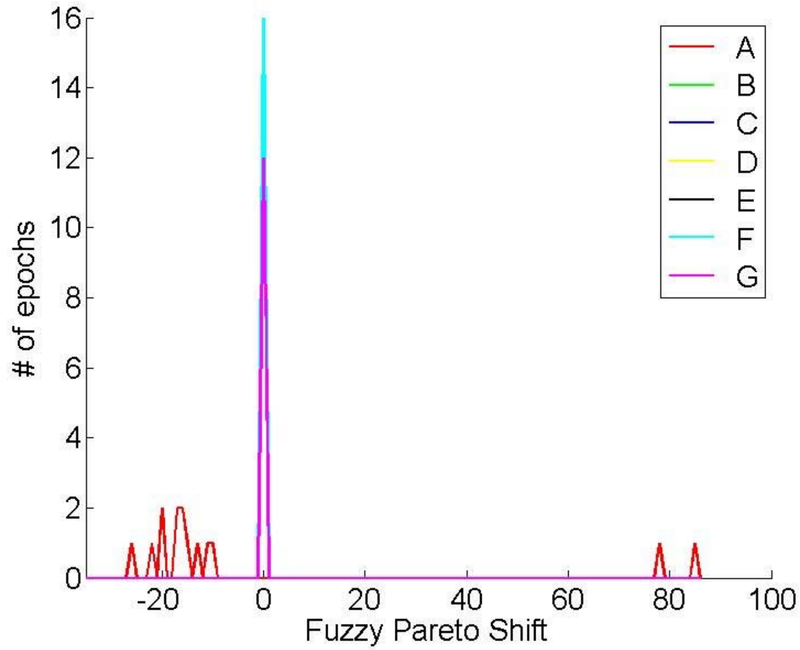
Epoch FPS Score Summary

Design	Min	1st Q	Med	3rd Q	Max
A	-101	0	0	0	101
B	-101	0	0	0	4
C	0	0	1	3	9
D	0	0	0	0	1
E	0	0	0	0	0
F	9	13	18	41	52
G	-101	-48	8	14	30

Insights:

- Maximizing efficiency does not allow for negative FPS changes, excepting unavoidable failure
- Many of the negative FPS changes from max utility are now ~0, via not changing
    - This is due in part to preselecting designs of interest, which are naturally efficient designs
- F is about the same, but the other DFC2 design (G) now also displays high FPS scores

Space Tug – FPS (Survive)



Epoch FPS Score Summary

Design	Min	1st Q	Med	3rd Q	Max
A	-101	-21	-16.5	-12	85
B	-101	0	0	0	0
C	0	0	0	0	0
D	0	0	0	0	0
E	0	0	0	0	0
F	0	0	0	0	0
G	-101	-50.5	0	0	0

This is a mathematical artifact (averaging -101 and 0 for the quartile)

Insights:

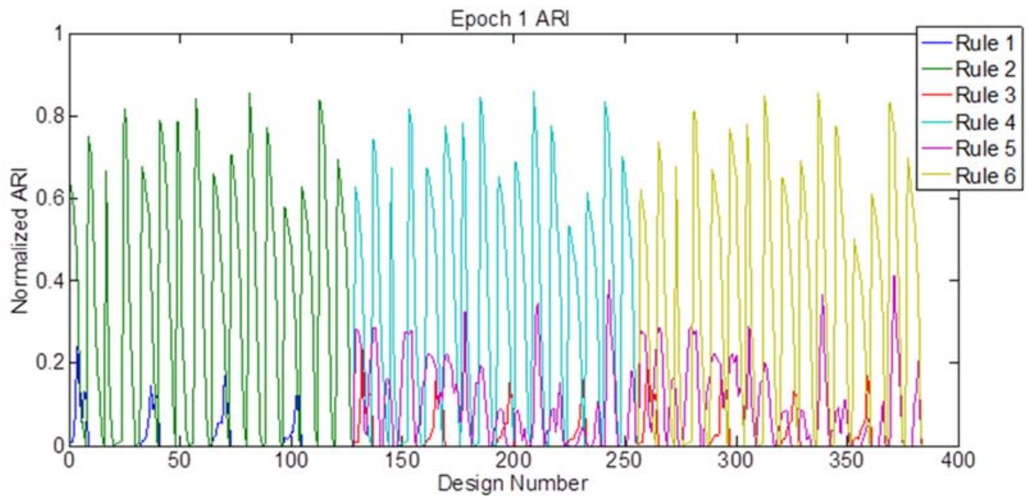
- The survive strategy is characterized by many fewer changes, with the exception of A
  - it must change always as it will run out of fuel if operated in consecutive epochs

Space Tug - ARI

Remember: goal is to compare effectiveness of various change mechanisms at improving design utility via surpassing other design points

Plotted: ARI for every design in Epoch 1 for every change mechanism ("rule")

- Rule 1 – Cryo/Biprop switch
- Rule 2 – Fuel tank resize
- Rule 3 – Cryo/Biprop switch 2
- Rule 4 – Fuel tank resize 2
- Rule 5 – Change capability
- Rule 6 – Refuel in orbit



Insights:

Rules 2,4,6 are the large-value-adding mechanisms, increasing the amount of fuel available for low fuel designs

Other mechanisms may be less critical (potentially save money/time in development by scrapping those options)

ARI can also be compiled across strategies and epochs to get a sense of average mechanism performance in different situations

Conclusions

- Investigate change mechanism value to assist inclusion/exclusion decisions
  - The "increase fuel" change mechanisms are the most valuable at improving utility
- Identify desirable designs under different criteria
  - Designs D and E are passively robust
  - Design F is valuably changeable
  - Not clear exactly on what grounds to compare these types of value

Expansion into era analysis can increase detail and allow for improved passive/active value comparison: see our other paper!

Thank you!

Questions?

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More about VASC

M.E. Fitzgerald, A.M. Ross, and D.H. Rhodes, "A Method Using Epoch-Era Analysis to Identify Valuable Changeability in System Design," *CSER 2011, 2011.*

Forthcoming

M.E. Fitzgerald and A.M. Ross, "Mitigating Contextual Uncertainties with Valuable Changeability Analysis in the Multi-Epoch Domain," *IEEE Syscon 2012, 2012.*

M.E. Fitzgerald and A.M. Ross, "Sustaining Lifecycle Value: Valuable Changeability Analysis with Era Simulation," *IEEE Syscon 2012, 2012.*

M.E. Fitzgerald, A.M. Ross, and D.H. Rhodes, "Assessing Uncertain Benefits: a Valuation Approach for Strategic Changeability (VASC)," *INCOSE International Symposium 2012, 2012.*

M.E. Fitzgerald, A.M. Ross, and D.H. Rhodes, "Quantifying the Effect of Changeability on Value, Cost, and Schedule for a Satellite Radar System," *AIAA Space 2012, 2012.*

Other related work

M.G. Richards, A.M. Ross, N.B. Shah, and D.E. Hastings, "Metrics for Evaluating Survivability in Dynamic Multi-Attribute Tradespace Exploration," *Journal of Spacecraft and Rockets, vol. 46, Sep. 2009, pp. 1049-1064.*

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