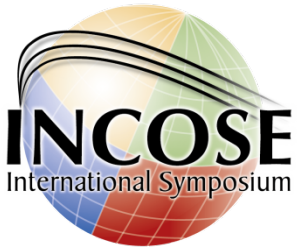

Assessing Uncertain Benefits: a Valuation Approach for Strategic Changeability (VASC)

Matthew Fitzgerald, **Adam M. Ross**, and Donna H. Rhodes

INCOSE 2012, Rome, Italy

11 July 2012

Motivation

> **"Complex DoD systems tend to be designed to deliver optimal performance within a narrow set of initial requirements and operating conditions at the time of design. This usually results in the delivery of point-solution systems that fail to meet emergent requirements throughout their lifecycles, that cannot easily adapt to new threats, that too rapidly become technologically obsolete, or that cannot provide quick responses to changes in mission and operating conditions."**
>
> **- Office of the Secretary of Defense (RT-18 Task Description)**

Optimization is weak to uncertainty…

Exploring *robustness* and *changeability* is of critical importance for complex systems

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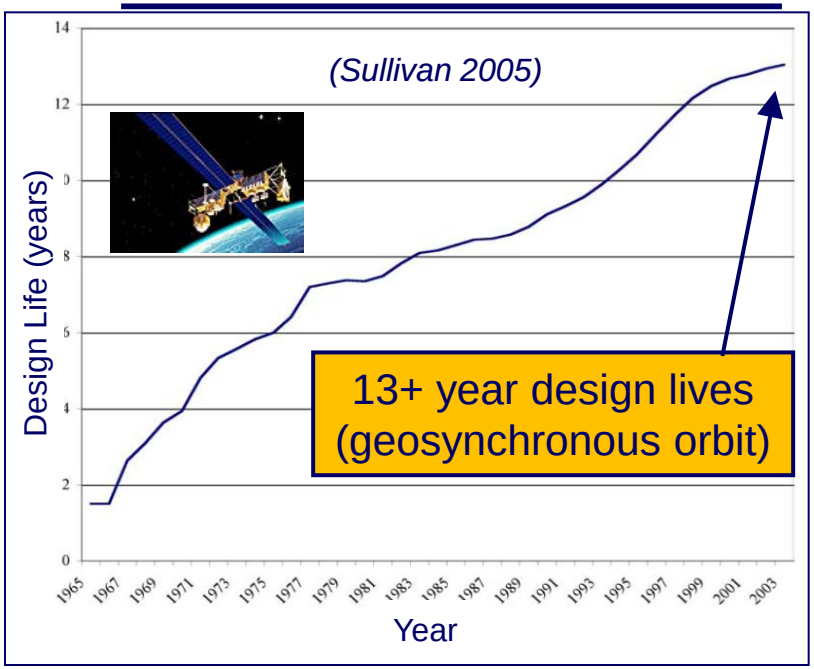
Mismatch of Design with Context

1960's Paradigm

- CORONA: 30-45 day missions
- 144 spacecraft launched between 1959-1972 *(Wheelon 1997)*

Evolution to Current State



- Inability to adapt to uncertain future environments, including disturbances

"Our spacecraft, which take 5 to 10 years to build, and then last up to 20 in a static hardware condition, will be configured to solve tomorrow's problems using yesterday's technologies." *(Dr. Owen Brown, DARPA Program Manager, 2007)*

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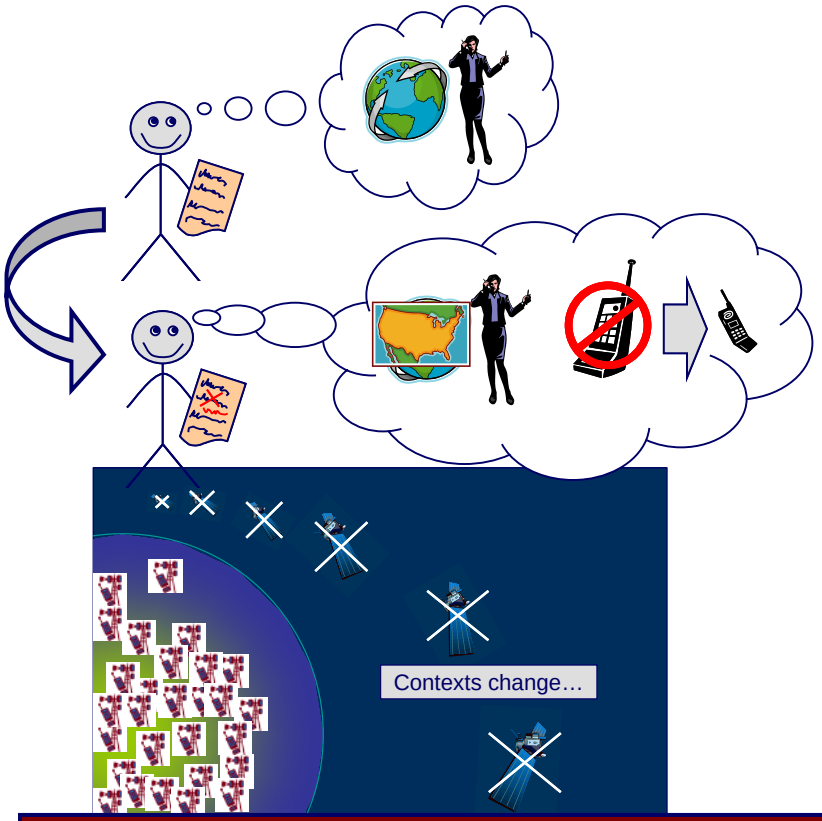
More than Missed Opportunities: Failures from Context Changes

New competitor/technology changes needs before system completed



Changing contexts can lead a technically sound system to fail

Adversary timescale shorter than "system" lifecycle

Cat and Mouse: A Case Study

When insurgent bombmakers come up with a new way to trigger a weapon, the US military devises a countermeasure. Insurgents figure out how to get around it, and the cycle continues. Here's how that played out with a device called an explosively formed penetrator.

1/Jammer-proof bombs
Summer 2004
Insurgents start using EFPs — lengths of pipe packed with explosives that launch a molten slug of copper. Because they're tripped by the engine heat of passing vehicles, coalition electronic jammers prove useless.

2/Bomb-proof decoys
May 2006
Individual soldiers improvise heat decoys, like a toaster hung on a pole in front of a truck, which inspires a countermeasure: the Rhino. It consists of a heating element housed in a steel box and extended on a 10-foot boom.

3/Decoy-proof targeting
Summer 2006
Insurgents recalibrate the aim of the EFPs, angling them backward to account for the decoy. EFPs comprise just a small percentage of roadside bombs, but they soon account for hundreds of fatalities.

4/Bomb-proof adjustments
Fall 2006
The Rhino II, which costs less than $2,000 and has an adjustable-length boom, changes the position of the decoy. More than 16,000 Rhino IIs are deployed overseas in just 30 months.

5/Jammer-triggered bombs
Early 2010
New EFPs ignore heat signatures and are triggered by the high-power radio waves emitted by coalition jammers. In other words, the latest bomb is set off by the countermeasure that defeated its predecessors.

Illustrations: Nook

Source: Wired Magazine, August 2010

Changing contexts can have high consequences if systems fail…

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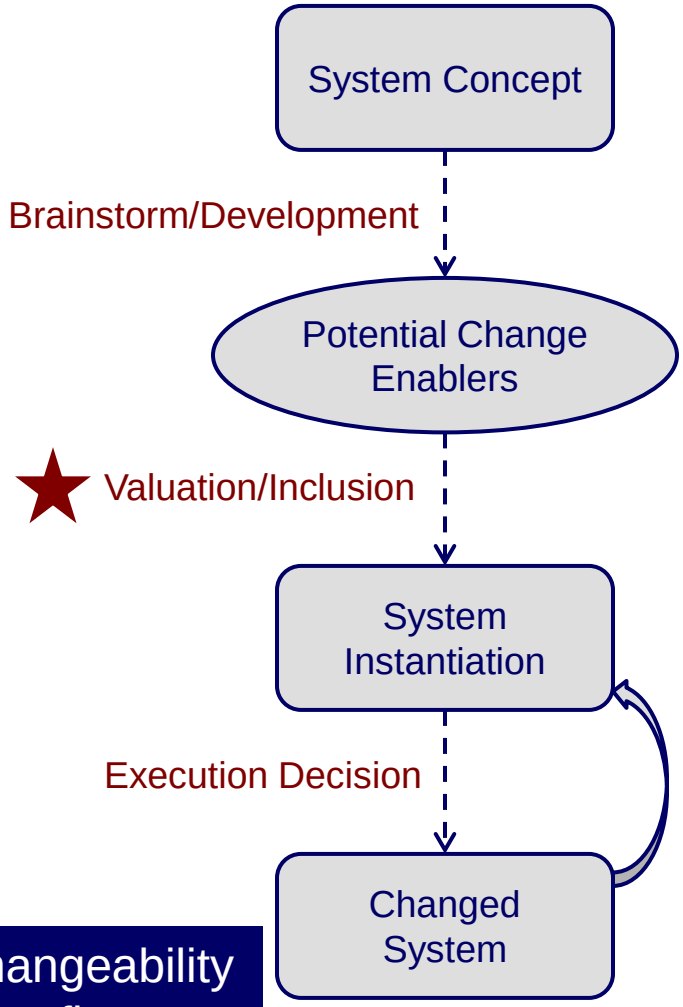
Changeability Introduction + Literature

Why we want changeability is clear, but what will it cost?

- Development
- Build
- Execution

All **3** processes are potentially rich research avenues, but ***valuation*** has received the most initial attention, as estimating future benefits is critical for justifying the costs

Key challenge: cost of changeability is more apparent than benefit



Previous Valuation Methods

Real Options Analysis
- Myers (1984)
- de Neufville, Scholtes, Wang (2006)
- Datar-Mathews (2007)

"Parameter Space"
- Swaney and Grossman (1985)

"Performance Space"
- Olewnik et al. (2006)

Variable Expiration
- Pierce (2010)

DSMs and ESMs
- Kalligeros et al. (2006)
- Bartolomei (2007), Mikaelian (2009)
- Danilovic and Browning (2007)

TDNs
- Silver and de Weck (2007)

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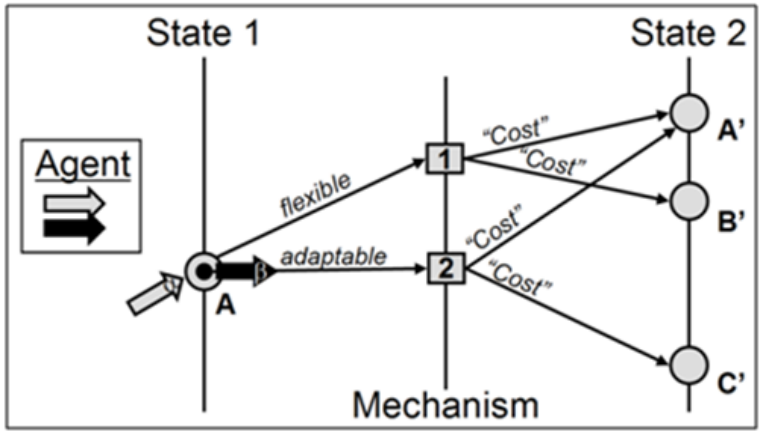
Changes as Paths

- Conceptually, it can be helpful to think of change events as “paths” between design points
- Agent-Mechanism-Effect framework
  - Agent: instigator
  - Mechanism: enabler
  - Effect: ΔState



Ross et al, 2008

Can we use this concept to create an approach for valuing changeability (the ability to access these paths), and to assist in the design process?

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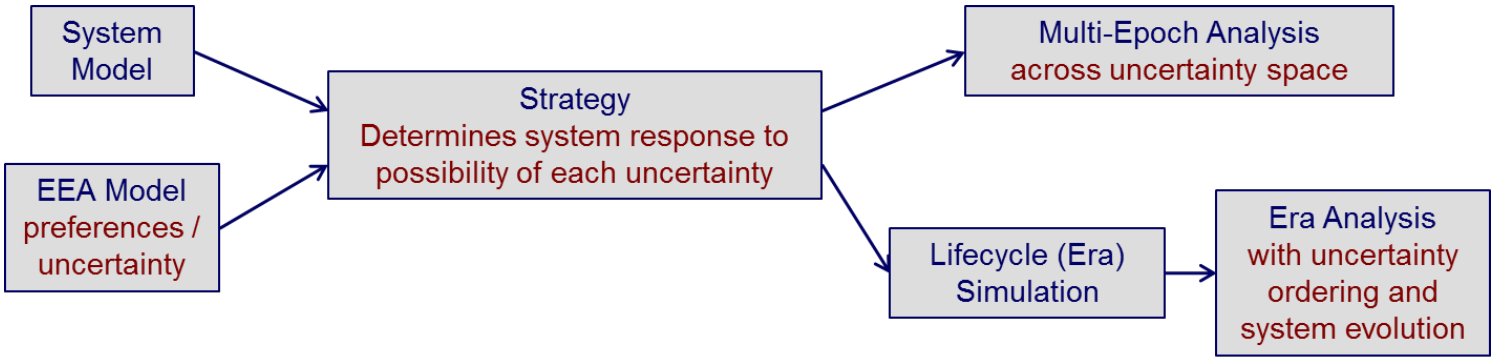
Valuating Changeability

Valuation Approach for Strategic Changeability (VASC)

- Extension of Epoch-Era Analysis (Ross, Rhodes, 2008)
- Key goal: reduce upfront assumptions to promote applicability to a wide range of problems and cases in technical design



Five Steps

1. Set up Epoch-Era Analysis (EEA)
2. Select Designs of Interest
3. Define Changeability Usage Strategies
4. Multi-Epoch Analysis
5. Era Simulation and Analysis

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Intro to the Space Tug System

- 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.

McManus and Schuman, 2003

In this case, the system decision-maker is attempting to design a system that best serves different sets of preferences corresponding to users (other people).

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Illustrating Changeability: Space Tug

- This problem is simple from a physics perspective, but nontrivial
  - Wide potential design space
  - Uncertainty in technology development
  - Uncertainty in user preferences
- It appears unlikely that a single design will prove to be optimal or near-optimal across the entire range of uncertainty

Can we utilize changeability to actively improve system value in the face of this uncertain future?

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Space Tug – Design Space

4 design variables → 384 designs

- Prop type (biprop, cryo, electric, nuclear)
- Fuel mass
- Capability level
- Design For Changeability (DFC) level

Of particular interest: DFC level *(Fricke and Schulz, 2005)*

- Discrete, ordinal variable representing effort to design for ease of redesign/change
- Varies from 0→1→2; higher is more reward, more penalty
- Reward: additional and/or cheaper change mechanisms
- Penalty: additional dry mass (higher costs + lower ΔV)

Change Mechanisms

#	Description	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

The costs of changeability are much more easily quantified than its benefits: we must value the benefits in order to justify inclusion.

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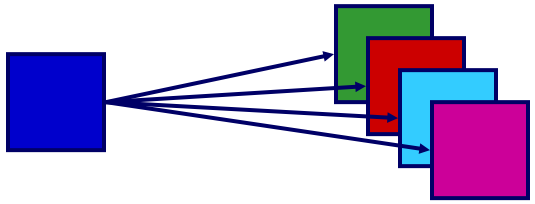
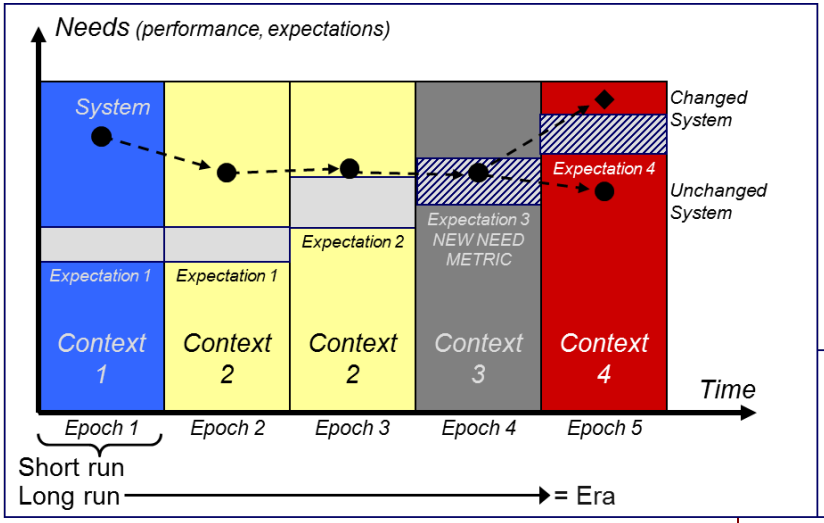
Step 1 – Set up Epoch-Era Analysis (EEA)

Conceptualizes the effects of time and changing contexts and needs on a system success

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





Ross, Rhodes, 2008

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(1) Space Tug Uncertainties

8 prefs x 2 contexts → 16 epochs

8 preference sets
- Delta-V potential
- Mass able to be manipulated
- Speed

2 contexts
- Present vs. future technology level

16 epochs
(defined as preference-context pairs)

Different ***preference sets*** correspond to missions with different needs
- Multi-attribute utility functions vary for each preference (e.g. rescue mission cares more about speed than debris collector)

Potential Missions
1. baseline,
2. technology demonstration,
3. GEO rescue,
4. deployment assistance,
5. refueling and maintenance,
6. debris collector,
7. all-purpose military, and
8. satellite saboteur

Different ***context variables*** determine underlying parameters in the models used to calculate the attributes/utility of designs
- Present / Future technology level: affects transition costs, fuel efficiencies, mass fractions, etc.

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Step 2 – Select Designs of Interest

- Results of VASC are easier to understand when a smaller subset of designs is considered
- Utilize EEA metrics to screen for interesting designs up front
  - Normalized Pareto Trace (NPT): find designs that are Pareto efficient in a large fraction of the epochs (passively robust). Also comes in a "fuzzy" variant (fNPT) to allow for uncertainty in modeling
  - Filtered Outdegree (FOD): find designs with a large number of outgoing change paths below an acceptable cost threshold, heuristically "more changeable" leads to more valuable changeability
- Can also encompass expert opinion (favored designs of technical experts, senior decision makers, etc.)

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(2) Space Tug Interesting Designs

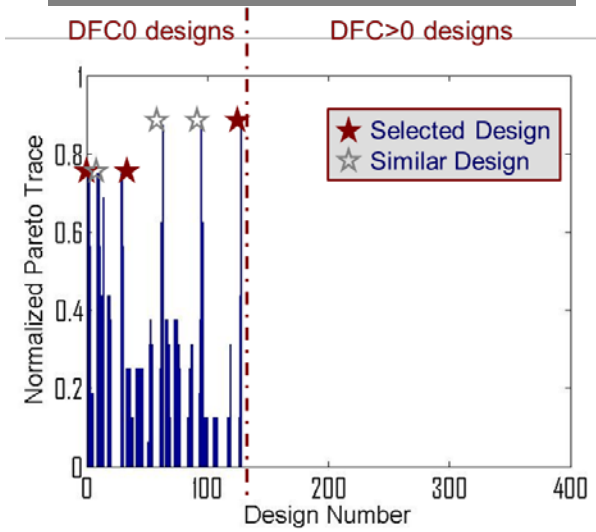
7 designs of interest identified

- Variety in design variables promotes exploration of design space

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

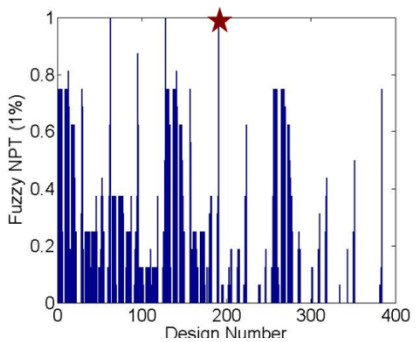
Design variables | Design attributes (present context)

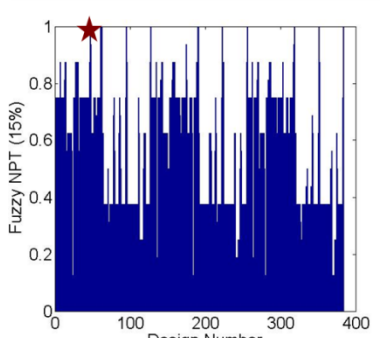
NPT



fNPT

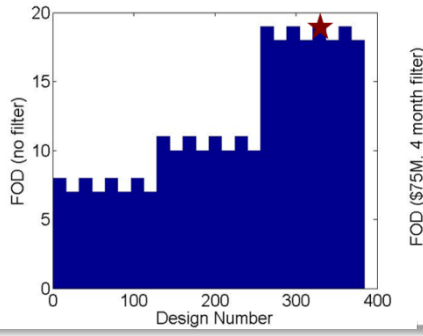
1% and 5% fuzziness

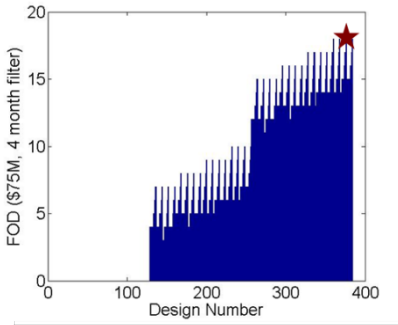




FOD

2 different thresholds





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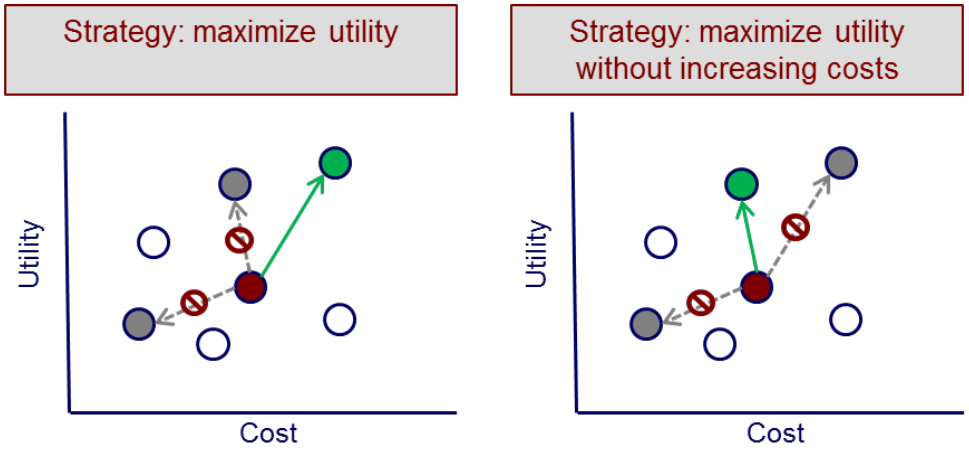
Step 3 – Define Changeability Usage Strategies

Changeability usage strategy – a statement of intended use of changeability

- Ex) "Maximize utility" or "Maximize efficiency for less than X cost when in Y,Z epochs because they are low stress"
- Assists valuing changeability by selecting single change path in each epoch
- Analysis is performed on each strategy separately and then compared
- Change mechanism usage and value will depend on the strategy and design being considered



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

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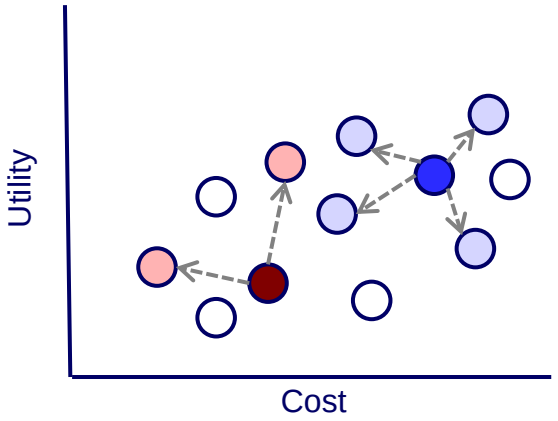
Strategies for Executing Changes

When combined with EEA, allows us to consider both ***magnitude*** and ***counting*** value of changeability

- Selected path is scored for its magnitude: the amount of value increase
- Counting value manifests in increased magnitude across epochs due to more options → higher likelihood of high-magnitude option



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

Strategy encapsulates truism:
"value achieved only by executed changes"

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(3) Space Tug Change Strategies

4 Strategies Identified

- Maximize Utility
  - A common first-order strategy (make system as good at its job as possible)
- Maximize Efficiency
  - Similar to above, but with a desire to be as cost efficient as possible while fielding a good system
- Survive
  - Change is executed only if system is invalid (including running out of fuel)
- Maximize Profit (short-run)
  - You develop a revenue model based on utility, using design changes to maximize revenues less costs in each epoch
  - Enabled by knowledge of epoch length: era-level strategy only

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Step 4 – Multi-Epoch Analysis

Multi-Epoch Analysis considers the performance effects of changes selected by strategies across the epoch space

Conceptually: "how does this system perform, using changeability, when exposed to the full range of uncertainty?"

- Computationally inexpensive: does not require simulation / sampling
- Explored via a suite of metrics (shown here)

	Acronym	Stands For	Definition
Robustness via "no change"	NPT	Normalized Pareto Trace	% epochs for which design is Pareto efficient in utility/cost
	fNPT	Fuzzy Normalized Pareto Trace	Above, with margin from Pareto front allowed
Robustness via "change"	eNPT, efNPT	Effective (fuzzy) Normalized Pareto Trace	Above, considering the design's end state after transitioning
"Value" gap	FPN	Fuzzy Pareto Number	% margin needed to include design in the fuzzy Pareto front
"Value" of a change	FPS	Fuzzy Pareto Shift	Difference in FPN before and after transition

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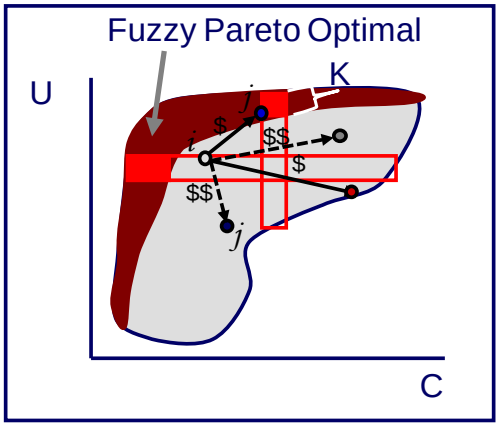
Metric: Fuzzy Pareto Number (FPN)

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

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

What does it measure?

FPN is calculated for each design in each epoch, and is used as a base utility-cost efficiency metric

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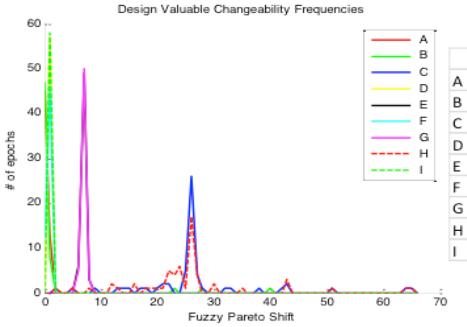
Metric: Fuzzy Pareto Shift (FPS)

With FPN calculated, FPS is simply the difference in FPN between the original and changed state of each design in each epoch



	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 the strategically-selected changes on the system

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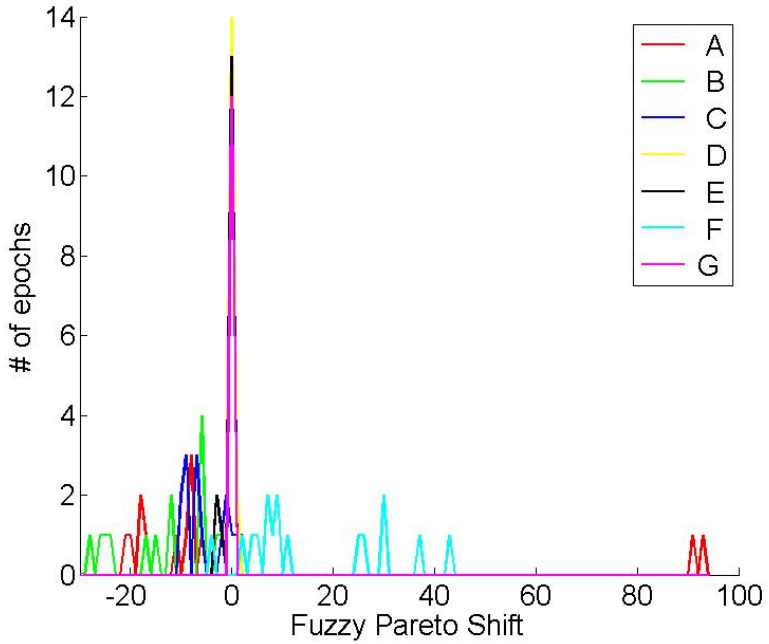
(4) Space Tug – FPS (Max Utility)



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

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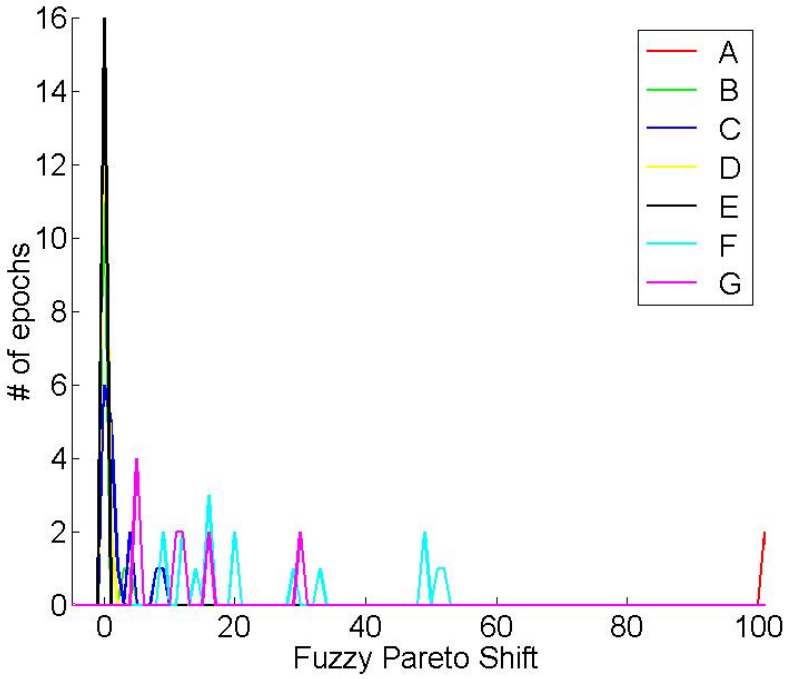
(4) Space Tug – FPS (Max Efficiency)



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

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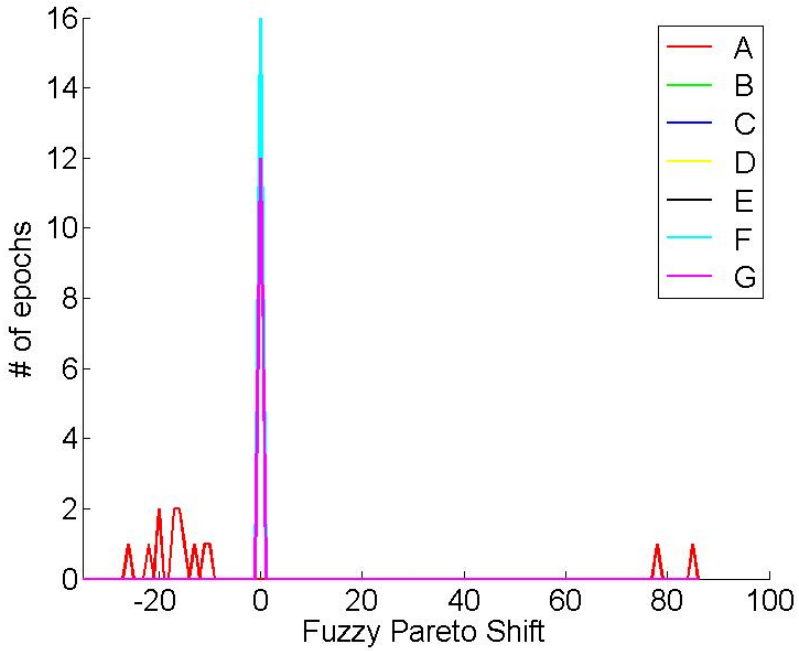
(4) Space Tug – FPS (Survive)



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

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Metric: 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

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

What does it measure?

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

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(4) Space Tug – eNPT / efNPT

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

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

eNPT 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)

5% efNPT

(green == improvement over 0%)

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 best way to think about this is that “designs D and E are efficient when considering changeability across a range of usage strategies”

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Step 5 – Era Simulation and Analysis

Era Analysis uncovers additional information, emergent only when considering time-ordered effects of uncertainty across the system's lifetime

Conceptually: "how does this system perform, using changeability, when uncertainty evolves over time?"

- Simulation of sample eras (constructed by sequencing epochs according to some model) allows collection of more data
  - Change mechanism usage
  - Cost/benefit "going rates" for adding/removing changeability
  - Lifetime cost/utility/revenue/efficiency statistics (not included here)

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(5) Space Tug Era Characteristics

As mentioned, we can implement a basic revenue model in order to use the Maximize Profit strategy in this step:

$$\text{Rev}_{\text{Per-epoch}} = \begin{cases} \$200M + \$1000M * \text{Utility} * \text{MonthsServed} & \textit{If viable} \\ 0 & \textit{If inviable} \end{cases}$$

Designs are rewarded for viability/utility and availability

The Max Profit strategy will weigh the monetary cost AND downtime associated with executing a change against the benefits of higher utility

For each design and strategy, the following simulation was performed:

- 5000 eras of 10 years
- Future technology arrives at a random time after 5 years
- Each potential contract (epoch) has a random duration from 1 to 12 months

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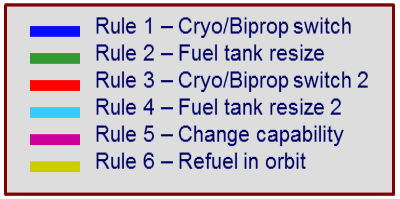
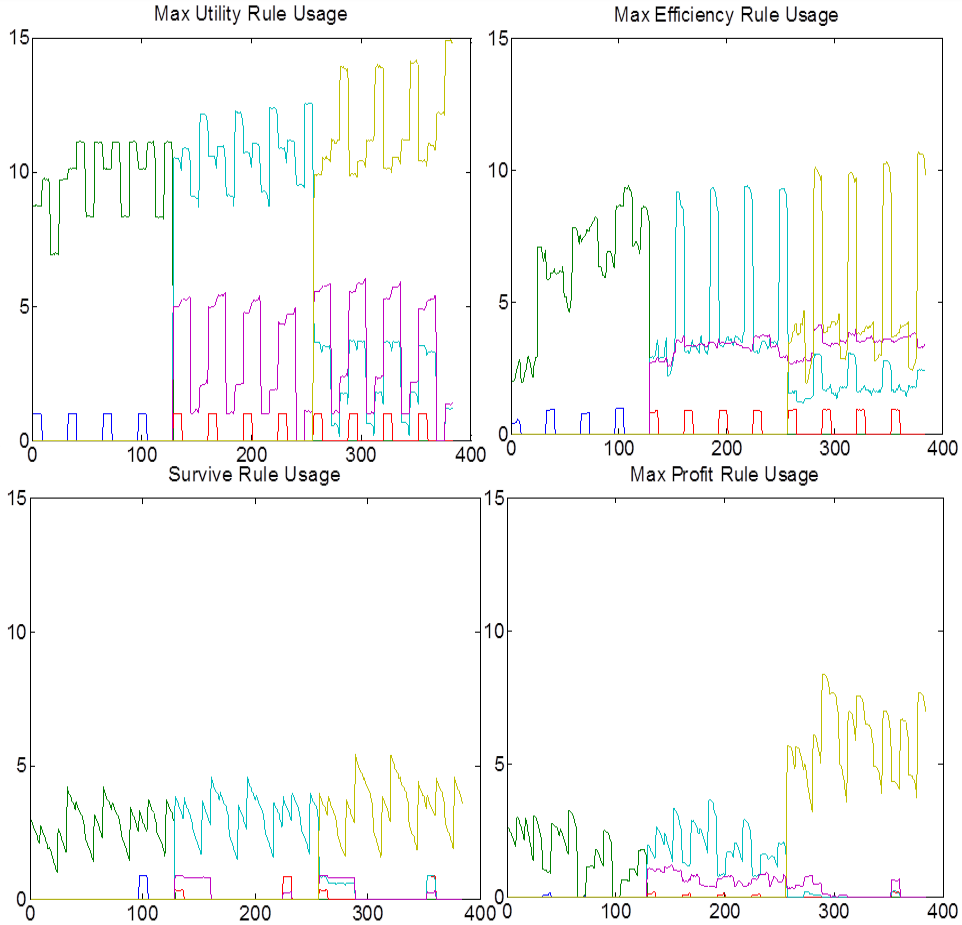
(5) Space Tug Rule Usage

X axis == design number
Y axis == average rule executions per era





We count the number of executions for each change mechanism (transition "rule") in an *average era*: revealing their relative frequency of use

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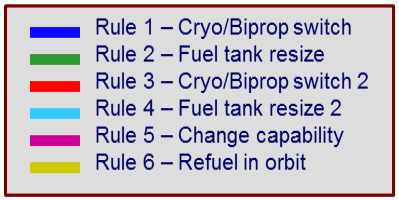
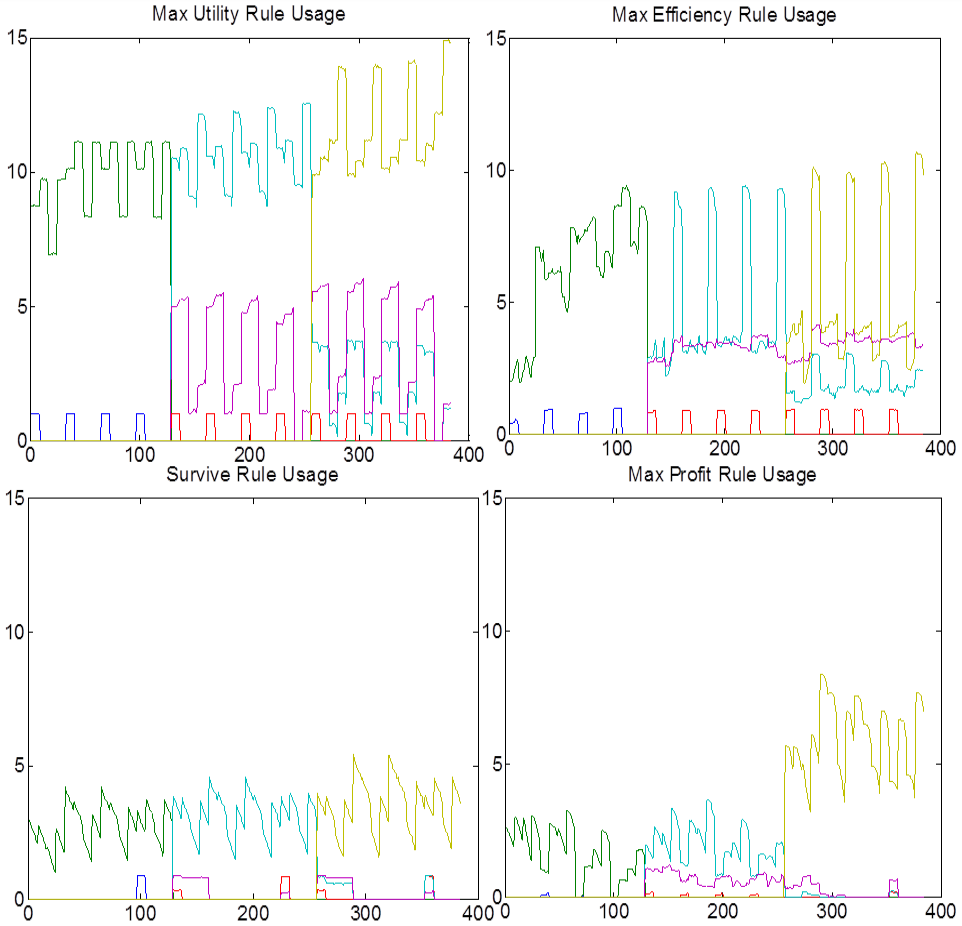
(5) Space Tug Rule Usage

~10 total for DFC0,
~15 for others

X axis == design number
Y axis == average rule executions per era





~10 total for all

<5 total for all

~5 total for DFC2,
<5 for others

Insight #1: Max Utility and Max Efficiency strategies have significantly more transitions than the others

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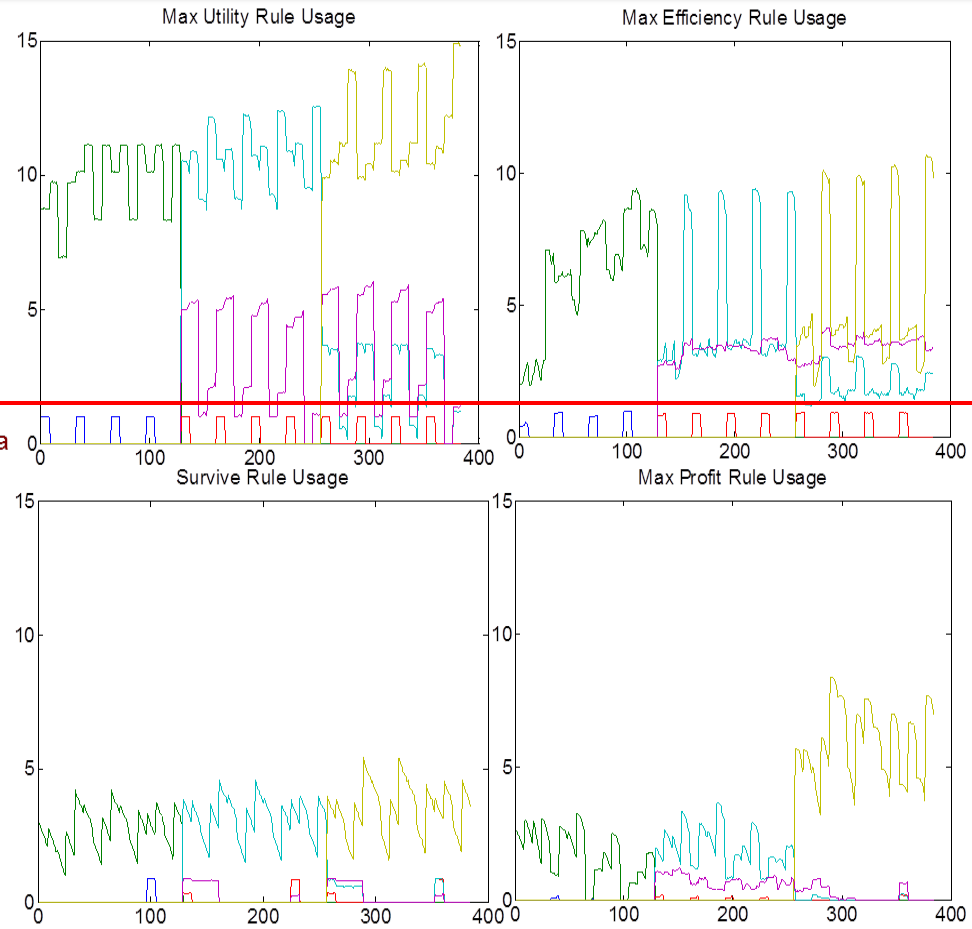
(5) Space Tug Rule Usage

Rule removal could also be performed here to investigate the performance effects of eliminating those few transitions



X axis == design number
Y axis == average rule executions per era

- 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

Never averages more than once per era

Insight #2: Rules 1,3 are rarely used, could possibly save money by choosing not to invest in development **(also true of Rule 5 under Survive/Profit strategies)**

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(5) Space Tug Cost/Benefit

D is not changeable… what if we added changeability?

DFC1 counterpart: Design 256
DFC2 counterpart: Design 384

→ Let's investigate these briefly

Assume for now that Profit is our biggest goal in design selection, we want to decide what the cost/benefits to profit of increasing changeability are under the Maximize Profit strategy

Maximize Profit
Avg 10-year Era

Design	Revenue (10^4 $M)	Cost (10^4 $M)	Profit (10^4 $M)
D	7.7	0.7	7
256	7.4	0.8	6.6
384	10.7	0.3	10.4

So maybe we are interested in Design 384, but that changeability comes at an increased Base Cost, which could present a challenge if funds are limited

Base Cost D → 384 = 3020 → 3564 = +544 $M

Thus the decision is between $544M up front and $34B over ten years

This "going rate" between changeability and some goal can be calculated for any design with any metric deemed critically important: perhaps Met Contracts or Avg FPN

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(5) Space Tug "Going Rates"

-DFC tradeoff	Design	+DFC tradeoff
N/A	**D**	+$544M initial cost, +$34B profit over 10 years
-$80M initial cost, -$4B profit over 10 years	**E**	+$80M initial cost, +$21B profit over 10 years
-$384M initial cost, -$20B profit over 10 years	**F**	N/A

- Thus, the final decision will be made with a small set of designs of interest, selected for varying abilities to be valuable (rarely inviable, high utility across many epochs, very changeable, etc)
- Robust and changeable designs should be identified, with "going rates" for changeability established to consider small variations which may prove valuable

Initial vs. delayed costs and benefits of changeability can be traded using this approach

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Summary of VASC

VASC is a five-step approach that guides system designers/analysts in the process of understanding the usage and value of changeability in their system

1. Set up Epoch-Era Analysis (EEA)
2. Select Designs of Interest
3. Define Changeability Usage Strategies
4. Multi-Epoch Analysis
5. Era Simulation and Analysis

- Decision strategy interpreted over short and long time scales
- Explicitly values/compares changeability-enabling design decisions (mechanisms)
- Scalable with available information and man/computer power
- Wide set of metrics designed to reveal multi-dimensional insight on the effects of changeability on utility and efficiency

With a better understanding of changeability and its value, more effective decisions can be made decisions regarding its inclusion in systems

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Thank You!

Questions?

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Backup Slides

- Contributions
- Additional Metrics
- Future work
- Additional Era Analysis techniques (not shown in paper)

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Development of Valuation Approach for Strategic Changeability

Primary goal for method development

- Uncover difficult-to-extract information on valuable changeability for a design space and present it in an accessible way to assist in decision making

Other important goals

- Identify designs which deliver high amounts of value in different ways (robustness, changeability), and the operational strategies that maximize value
- Assess what change mechanisms deliver the most value or are the most critical for some designs to function well
- Establish cost/benefit tradeoff for adding/removing changeability from a design

Research Contributions

- Expanded set of screening and valuation metrics (*eNPT, efNPT, FPN, FPS*)
- Explicit method for accounting for value of changeability over short and long time scales (*strategy-interpreted*)
- Linked explicit design decisions with changeability (*change rule comparison*)
- Incremental analysis approach that can scale with available information and effort
- An approach that is mostly automated, but also encourages focused value-elicitation and interpretation discussions between decision makers and analysts

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Metric: Available Rank Increase (ARI)

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

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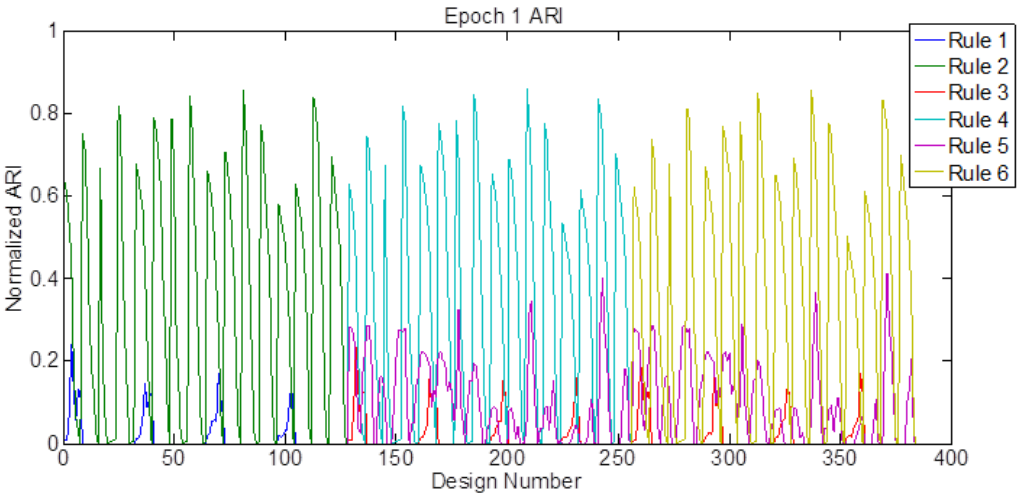
(4) Space Tug – ARI

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")



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

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Set of Metrics for Value Sustainment

	Acronym	Stands For	Definition
Robustness via "no change"	NPT	Normalized Pareto Trace	% epochs for which design is Pareto efficient in utility/cost
	fNPT	Fuzzy Normalized Pareto Trace	Above, with margin from Pareto front allowed
Robustness via "change"	eNPT, efNPT	Effective (fuzzy) Normalized Pareto Trace	Above, considering the design's end state after transitioning
"Value" gap	FPN	Fuzzy Pareto Number	% margin needed to include design in the fuzzy Pareto front
"Value" of a change	FPS	Fuzzy Pareto Shift	Difference in FPN before and after transition
	ARI	Available Rank Increase	# of designs able to be passed in utility via best possible change
Degree of changeability	OD	Outdegree	# outgoing transition arcs from a design
	FOD	Filtered Outdegree	Above, considering only arcs below a chosen cost threshold

Each of these address different aspects of value sustainment (via changeability or robustness)

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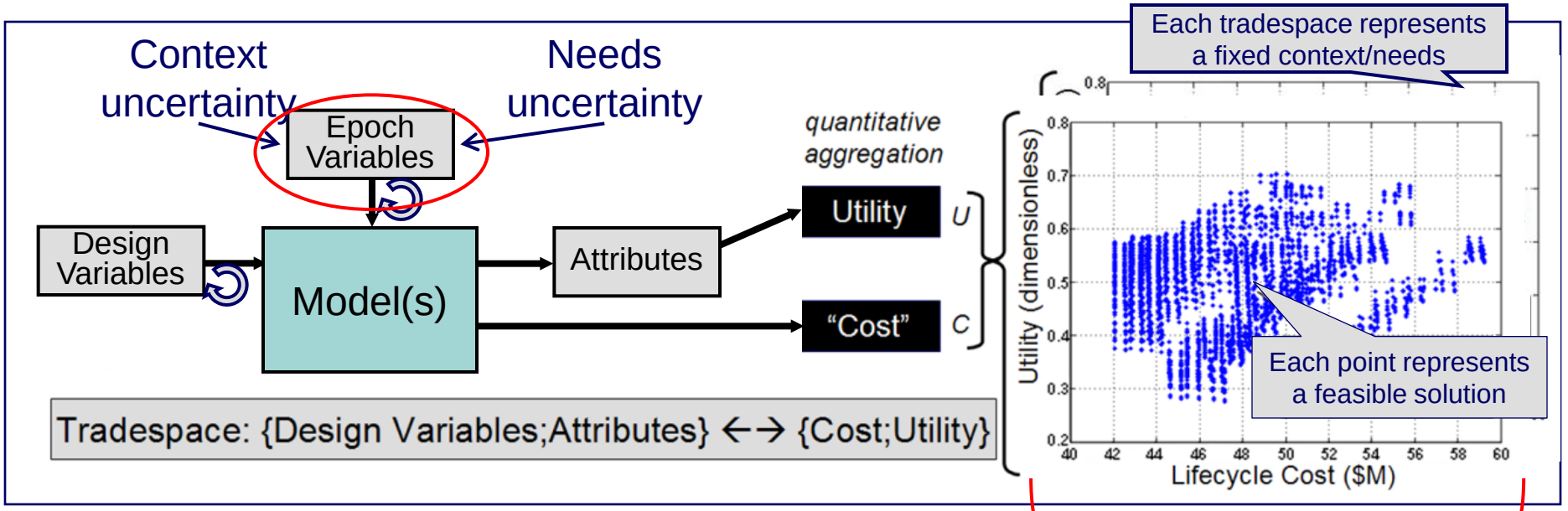
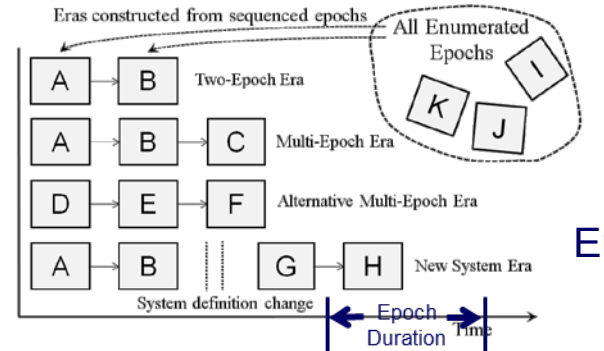
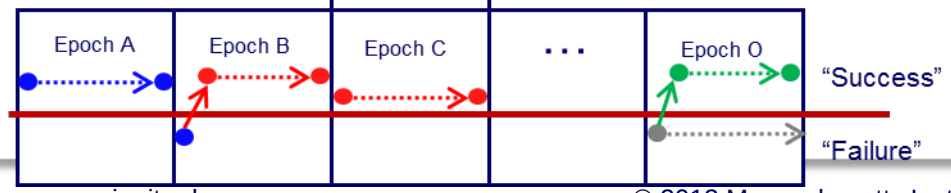
Data Flow for VASC Metrics







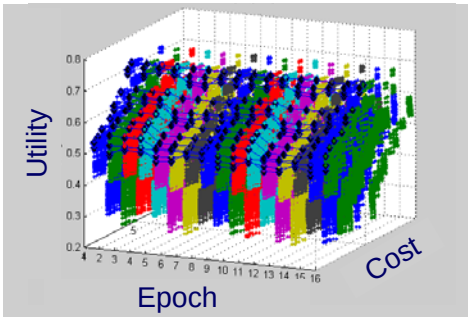
Era (long run) analysis

Strategies

Change Mechanisms

Multi-epoch (short run) analysis

Many epoch data



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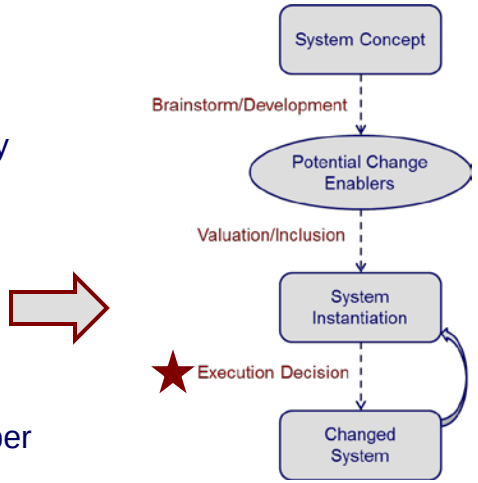
Future Directions

- Non-tradespace studies
  - Would change process, but key features (strategies, Epoch-Era) are not dependent on tradespaces
  - Strategy step would become a multivariable optimization algorithm, with the strategy statement represented in the objective function and the degrees of freedom determined by available mechanisms
- Techniques for finding value- and goal-maximizing strategies
  - Addressing the last part of the changeability "lifecycle"
- Study of design "families"
  - With a fixed strategy, steady-state behavior involves rotating between a small number of designs in different epochs: better descriptor of lifecycle value than original/transitory designs?



- Application outside of traditional systems engineering
  - Move past physical design variable modification, include CONOPS change options
  - Integration with portfolio concepts, change manifests as acquisition/retirement of assets and "designs" are portfolios of these assets: a new means of quantifying portfolio risk?
- Modification to consider "disturbance" protection
  - Change mechanisms represent undesirable (uncontrollable) disturbances which affect the system, arising with epoch shifts
  - Benefits / tradeoffs involved with "deactivating" these change mechanisms (robustness, hardness, avoidance enablers)

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Space Tug – Era-level Profit

	MAX UTILITY			MAX EFFICIENCY		
Design	Avg Rev	Avg Cost	Avg Profit	Avg Rev	Avg Cost	Avg Profit
A	3.3	1.7	1.6	2.4	0.1	2.3
B	4.0	2.6	1.4	4.4	0.4	4.0
C	4.3	2.3	2	4.4	0.6	3.8
D	6.9	4.6	2.3	7.9	3.6	4.3
E	6.6	5.7	0.9	6.7	3.7	3.0
F	5.7	2.7	3	3.0	0.8	2.2
G	6.5	0.4	6.1	2.2	0.9	1.3
	SURVIVE			**MAX PROFIT**		
Design	Avg Rev	Avg Cost	Avg Profit	Avg Rev	Avg Cost	Avg Profit
A	3.6	0.6	3.0	3.0	0.2	2.8
B	4.9	0.6	4.3	4.3	0.2	4.1
C	5.3	0.7	4.6	4.7	0.3	4.4
D	8.6	1.6	7.0	7.7	0.7	7.0
E	6.9	1.0	5.9	6.5	0.6	5.9
F	7.1	0.3	6.8	7.5	0.3	7.2
G	6.7	0.4	6.3	7.4	0.4	7.0

All numbers are x10⁴$M

Backgrounds are for BEST and WORST designs in that category for that strategy

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Space Tug – Era-level Profit

	MAX UTILITY			MAX EFFICIENCY		
Design	Avg Rev	Avg Cost	Avg Profit	Avg Rev	Avg Cost	Avg Profit
A	3.3	1.7	1.6	2.4	0.1	2.3
B	4.0	2.6	1.4	4.4	0.4	4.0
C	4.3	2.3	2	4.4	0.6	3.8
D	6.9	4.6	2.3	7.9	3.6	4.3
E	6.6	5.7	0.9	6.7	3.7	3.0
F	5.7	2.7	3	3.0	0.8	2.2
G	6.5	0.4	6.1	2.2	0.9	1.3

D

G

	SURVIVE			MAX PROFIT		
Design	Avg Rev	Avg Cost	Avg Profit	Avg Rev	Avg Cost	Avg Profit
A	3.6	0.6	3.0	3.0	0.2	2.8
B	4.9	0.6	4.3	4.3	0.2	4.1
C	5.3	0.7	4.6	4.7	0.3	4.4
D	8.6	1.6	7.0	7.7	0.7	7.0
E	6.9	1.0	5.9	6.5	0.6	5.9
F	7.1	0.3	6.8	7.5	0.3	7.2
G	6.7	0.4	6.3	7.4	0.4	7.0

D

F

All numbers are x10⁴$M

Backgrounds are for BEST and WORST designs in that category for that strategy

Insight #1: 3 different designs have highest profits for the 4 strategies

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Space Tug – Era-level Profit

	MAX UTILITY			MAX EFFICIENCY		
Design	Avg Rev	Avg Cost	Avg Profit	Avg Rev	Avg Cost	Avg Profit
A	3.3	1.7	1.6	2.4	0.1	2.3
B	4.0	2.6	1.4	4.4	0.4	4.0
C	4.3	2.3	2	4.4	0.6	3.8
D	6.9 D	4.6	2.3	7.9 D	3.6	4.3
E	6.6	5.7	0.9	6.7	3.7	3.0
F	5.7	2.7	3	3.0	0.8	2.2
G	6.5	0.4	6.1	2.2	0.9	1.3

	SURVIVE			MAX PROFIT		
Design	Avg Rev	Avg Cost	Avg Profit	Avg Rev	Avg Cost	Avg Profit
A	3.6	0.6	3.0	3.0	0.2	2.8
B	4.9	0.6	4.3	4.3	0.2	4.1
C	5.3	0.7	4.6	4.7	0.3	4.4
D	8.6 D	1.6	7.0	7.7 D	0.7	7.0
E	6.9	1.0	5.9	6.5	0.6	5.9
F	7.1	0.3	6.8	7.5	0.3	7.2
G	6.7	0.4	6.3	7.4	0.4	7.0

All numbers are x10⁴$M

Backgrounds are for BEST and WORST designs in that category for that strategy

Insight #2: Design D has highest revenues for each

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Space Tug – Era-level Profit

	MAX UTILITY			MAX EFFICIENCY		
Design	Avg Rev	Avg Cost	Avg Profit	Avg Rev	Avg Cost	Avg Profit
A	3.3	1.7	1.6	2.4	0.1	2.3
B	4.0	2.6	1.4	4.4	0.4	4.0
C	4.3	2.3	2	4.4	0.6	3.8
D	6.9	4.6	2.3	7.9	3.6	4.3
E	6.6	5.7	0.9	6.7	3.7	3.0
F	5.7	2.7	3	3.0	0.8	2.2
G	6.5	0.4	6.1	2.2	0.9	1.3
	SURVIVE			MAX PROFIT		
Design	Avg Rev	Avg Cost	Avg Profit	Avg Rev	Avg Cost	Avg Profit
A	3.6	0.6	3.0	3.0	0.2	2.8
B	4.9	0.6	4.3	4.3	0.2	4.1
C	5.3	0.7	4.6	4.7	0.3	4.4
D	8.6	1.6	7.0	7.7	0.7	7.0
E	6.9	1.0	5.9	6.5	0.6	5.9
F	7.1	0.3	6.8	7.5	0.3	7.2
G	6.7	0.4	6.3	7.4	0.4	7.0

ranks 1,2,3,5

All numbers are x10⁴$M

Backgrounds are for BEST and WORST designs in that category for that strategy

Insight #3: Cheap DFC0 designs dominate the Max Efficiency strategy (but not the others)

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Space Tug – Era-level Profit

	MAX UTILITY			MAX EFFICIENCY		
Design	Avg Rev	Avg Cost	Avg Profit	Avg Rev	Avg Cost	Avg Profit
A	3.3	1.7	1.6	2.4	0.1	2.3
B	4.0	2.6	1.4	4.4	0.4	4.0
C	4.3	2.3	2	4.4	0.6	3.8
D	6.9	4.6	2.3	7.9	3.6	4.3
E	6.6	5.7	0.9	6.7	3.7	3.0
F	5.7	2.7	3	3.0	0.8	2.2
G	6.5	0.4	6.1	2.2	0.9	1.3

	SURVIVE			MAX PROFIT		
Design	Avg Rev	Avg Cost	Avg Profit	Avg Rev	Avg Cost	Avg Profit
A	3.6	0.6	3.0	3.0	0.2	2.8
B	4.9	0.6	4.3	4.3	0.2	4.1
C	5.3	0.7	4.6	4.7	0.3	4.4
D	8.6	1.6	7.0	7.7	0.7	7.0
E	6.9	1.0	5.9	6.5	0.6	5.9
F	7.1	0.3	6.8	7.5	0.3	7.2
G	6.7	0.4	6.3	7.4	0.4	7.0

Higher

Tie

DFC2

All numbers are x10⁴$M

Backgrounds are for BEST and WORST designs in that category for that strategy

Insight #4: Survive strategy has higher projected long-term profits for non-DFC2 designs than the short-term profit maximization strategy

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Space Tug – Era-level Profit

	MAX UTILITY			MAX EFFICIENCY		
Design	Avg Rev	Avg Cost	Avg Profit	Avg Rev	Avg Cost	Avg Profit
A	3.3	1.7	1.6	2.4	0.1	2.3
B	4.0	2.6	1.4	4.4	0.4	4.0
C	4.3	2.3	2	4.4	0.6	3.8
D	6.9	4.6	2.3	7.9	3.6	4.3
E	6.6	5.7	0.9	6.7	3.7	3.0
F	5.7	2.7	3	3.0	0.8	2.2
G	6.5	0.4	6.1	2.2	0.9	1.3
	SURVIVE			**MAX PROFIT**		
Design	Avg Rev	Avg Cost	Avg Profit	Avg Rev	Avg Cost	Avg Profit
A	3.6	0.6	3.0	3.0	0.2	2.8
B	4.9	0.6	4.3	4.3	0.2	4.1
C	5.3	0.7	4.6	4.7	0.3	4.4
D	8.6	1.6	7.0	7.7	0.7	7.0
E	6.9	1.0	5.9	6.5	0.6	5.9
F	7.1	0.3	6.8	7.5	0.3	7.2
G	6.7	0.4	6.3	7.4	0.4	7.0

All numbers are x10^4$M

Backgrounds are for BEST and WORST designs in that category for that strategy

Insight #5: Designs D and F have best average performance

D: rank 3,1,1,2
F: rank 2,6,2,1

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Space Tug – Era-level Profit

	MAX UTILITY			MAX EFFICIENCY		
Design	Avg Rev	Avg Cost	Avg Profit	Avg Rev	Avg Cost	Avg Profit
A	3.3	1.7	1.6	2.4	0.1	2.3
B	4.0	2.6	1.4	4.4	0.4	4.0
C	4.3	2.3	2	4.4	0.6	3.8
D	6.9	4.6	2.3	7.9	3.6	4.3
E	6.6	5.7	0.9	6.7	3.7	3.0
F	5.7	2.7	3	3.0	0.8	2.2
G	6.5	0.4	6.1	2.2	0.9	1.3
	SURVIVE			MAX PROFIT		
Design	Avg Rev	Avg Cost	Avg Profit	Avg Rev	Avg Cost	Avg Profit
A	3.6	0.6	3.0	3.0	0.2	2.8
B	4.9	0.6	4.3	4.3	0.2	4.1
C	5.3	0.7	4.6	4.7	0.3	4.4
D	8.6	1.6	7.0	7.7	0.7	7.0
E	6.9	1.0	5.9	6.5	0.6	5.9
F	7.1	0.3	6.8	7.5	0.3	7.2
G	6.7	0.4	6.3	7.4	0.4	7.0

All numbers are x10⁴$M

Backgrounds are for BEST and WORST designs in that category for that strategy

But overall:

Strategy selection has a large effect on performance for every design!

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Space Tug – FPN Tracking

MAX UTILITY					MAX EFFICIENCY			
Design	Best	Worst	Avg	Avg (no fail)	Best	Worst	Avg	Avg (no fail)
A	0.0	96.0	17.4	2.2	0.0	100.4	24.7	0.0
B	0.0	94.1	15.8	3.0	0.0	96.4	17.7	2.1
C	0.1	84.2	13.1	4.8	0.0	100.5	27.9	3.7
D	0.0	91.0	16.8	7.9	0.0	95.1	19.7	8.6
E	1.0	85.4	15.6	8.8	1.0	80.6	13.3	7.2
F	2.1	82.1	18.1	12.7	1.0	100.4	24.1	2.3
G	3.1	100.6	33.6	10.6	1.0	100.9	33.3	4.5

SURVIVE					MAX PROFIT			
Design	Best	Worst	Avg	Avg (no fail)	Best	Worst	Avg	Avg (no fail)
A	0.0	99.3	20.1	1.4	0.0	100.5	25.6	0.3
B	0.0	97.5	19.3	2.9	0.1	97.9	20.1	3.2
C	0.0	93.8	16.5	4.3	0.0	99.9	25.5	4.1
D	0.1	96.1	26.8	16.2	0.7	100.4	38.5	19.9
E	1.0	87.3	14.4	5.5	1.4	97.0	22.9	8.5
F	3.2	100.8	38.2	16.9	3.2	100.7	38.3	17.3
G	3.7	100.9	44.0	21.2	2.9	100.7	38.2	15.5

Remember that FPN is a pseudo-distance from the Pareto Front, so lower is better!

We can also track the designs' Fuzzy Pareto Number over the eras to get a sense of their continuing efficiency as they use fuel and execute design transitions

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Space Tug – FPN Tracking

	MAX UTILITY				MAX EFFICIENCY			
Design	Best	Worst	Avg	Avg (no fail)	Best	Worst	Avg	Avg (no fail)
A	0.0	96.0	17.4	2.2	0.0	100.4	24.7	0.0
B	0.0	94.1	15.8	3.0	0.0	96.4	17.7	2.1
C	0.1	84.2	13.1	4.8	0.0	100.5	27.9	3.7
D	0.0	91.0	16.8	7.9	0.0	95.1	19.7	8.6
E	1.0	85.4	15.6	8.8	1.0	80.6	13.3	7.2
F	2.1	82.1	18.1	12.7	1.0	100.4	24.1	2.3
G	3.1	100.6	33.6	10.6	1.0	100.9	33.3	4.5

	SURVIVE				MAX PROFIT			
Design	Best	Worst	Avg	Avg (no fail)	Best	Worst	Avg	Avg (no fail)
A	0.0	99.3	20.1	1.4	0.0	100.5	25.6	0.3
B	0.0	97.5	19.3	2.9	0.1	97.9	20.1	3.2
C	0.0	93.8	16.5	4.3	0.0	99.9	25.5	4.1
D	0.1	96.1	26.8	16.2	0.7	100.4	38.5	19.9
E	1.0	87.3	14.4	5.5	1.4	97.0	22.9	8.5
F	3.2	100.8	38.2	16.9	3.2	100.7	38.3	17.3
G	3.7	100.9	44.0	21.2	2.9	100.7	38.2	15.5

DFC0 designs tend to have better *best* FPNs

but higher DFCs have better *worst* FPNs

Insight #1: Changeability is avoiding worst case scenarios more than switching between optima

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Space Tug – FPN Tracking

MAX UTILITY					MAX EFFICIENCY			
Design	Best	Worst	Avg	Avg (no fail)	Best	Worst	Avg	Avg (no fail)
A	0.0	96.0	17.4	2.2	0.0	100.4	24.7	0.0
B	0.0	94.1	15.8	3.0	0.0	96.4	17.7	2.1
C	0.1	84.2	13.1	4.8	0.0	100.5	27.9	3.7
D	0.0	91.0	16.8	7.9	0.0	95.1	19.7	8.6
E	1.0	85.4	15.6	8.8	1.0	80.6	13.3	7.2
F	2.1	82.1	18.1	12.7	1.0	100.4	24.1	2.3
G	3.1	100.6	33.6	10.6	1.0	100.9	33.3	4.5

SURVIVE					MAX PROFIT			
Design	Best	Worst	Avg	Avg (no fail)	Best	Worst	Avg	Avg (no fail)
A	0.0	99.3	20.1	1.4	0.0	100.5	25.6	0.3
B	0.0	97.5	19.3	2.9	0.1	97.9	20.1	3.2
C	0.0	93.8	16.5	4.3	0.0	99.9	25.5	4.1
D	0.1	96.1	26.8	16.2	0.7	100.4	38.5	19.9
E	1.0	87.3	14.4	5.5	1.4	97.0	22.9	8.5
F	3.2	100.8	38.2	16.9	3.2	100.7	38.3	17.3
G	3.7	100.9	44.0	21.2	2.9	100.7	38.2	15.5

no-fail = A
with-fail = not A

Insight #2: Design **A** always has the best average when not considering inviable epochs, but is inviable too often to have the best overall average

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Space Tug – FPN Tracking

MAX UTILITY					MAX EFFICIENCY			
Design	Best	Worst	Avg	Avg (no fail)	Best	Worst	Avg	Avg (no fail)
A	0.0	96.0	17.4	2.2	0.0	100.4	24.7	0.0
B	0.0	94.1	15.8	3.0	0.0	96.4	17.7	2.1
C	0.1	84.2	13.1	4.8	0.0	100.5	27.9	3.7
D	0.0	91.0	16.8	7.9	0.0	95.1	19.7	8.6
E	1.0	85.4	15.6	8.8	1.0	80.6	13.3	7.2
F	2.1	82.1	18.1	12.7	1.0	100.4	24.1	2.3
G	3.1	100.6	33.6	10.6	1.0	100.9	33.3	4.5

SURVIVE					MAX PROFIT			
Design	Best	Worst	Avg	Avg (no fail)	Best	Worst	Avg	Avg (no fail)
A	0.0	99.3	20.1	1.4	0.0	100.5	25.6	0.3
B	0.0	97.5	19.3	2.9	0.1	97.9	20.1	3.2
C	0.0	93.8	16.5	4.3	0.0	99.9	25.5	4.1
D	0.1	96.1	26.8	16.2	0.7	100.4	38.5	19.9
E	1.0	87.3	14.4	5.5	1.4	97.0	22.9	8.5
F	3.2	100.8	38.2	16.9	3.2	100.7	38.3	17.3
G	3.7	100.9	44.0	21.2	2.9	100.7	38.2	15.5

When G is ranked last

Insight #3: Design **G** is regularly among the worst due to its high failure rate and high cost exceeding its marginal utility gains

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MAX UTILITY					MAX EFFICIENCY			
Design	Best	Worst	Avg	Avg (no fail)	Best	Worst	Avg	Avg (no fail)
A	0.0	96.0	17.4	2.2	0.0	100.4	24.7	0.0
B	0.0	94.1	15.8	3.0	0.0	96.4	17.7	2.1
C	0.1	84.2	13.1	4.8	0.0	100.5	27.9	3.7
D	0.0	91.0	16.8	7.9	0.0	95.1	19.7	8.6
E	1.0	85.4	15.6	8.8	1.0	80.6	13.3	7.2
F	2.1	82.1	18.1	12.7	1.0	100.4	24.1	2.3
G	3.1	100.6	33.6	10.6	1.0	100.9	33.3	4.5

SURVIVE					MAX PROFIT			
Design	Best	Worst	Avg	Avg (no fail)	Best	Worst	Avg	Avg (no fail)
A	0.0	99.3	20.1	1.4	0.0	100.5	25.6	0.3
B	0.0	97.5	19.3	2.9	0.1	97.9	20.1	3.2
C	0.0	93.8	16.5	4.3	0.0	99.9	25.5	4.1
D	0.1	96.1	26.8	16.2	0.7	100.4	38.5	19.9
E	1.0	87.3	14.4	5.5	1.4	97.0	22.9	8.5
F	3.2	100.8	38.2	16.9	3.2	100.7	38.3	17.3
G	3.7	100.9	44.0	21.2	2.9	100.7	38.2	15.5

Ranks 3,1,1,1 in “worst” FPN
Ranks 2,1,1,2 in “avg” FPN

Robust in efficiency of changeability

Insight #4: Design E appears to be the best compromise between the strategies (potentially valuable if strategy will change over time)

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