Metric of Adaptability for Cyber-physical Systems

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Demonstration: VASC for SpaceTug

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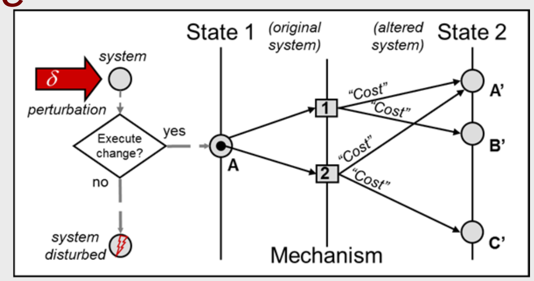
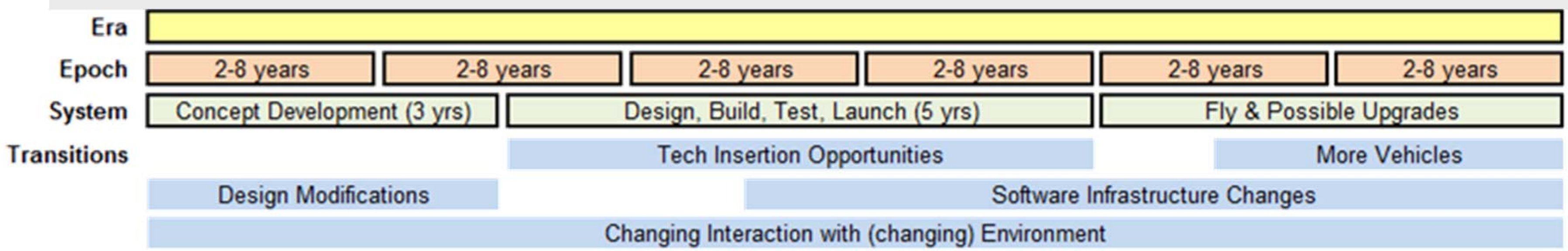
Designing for a Dynamic World

- Build on decade of foundational research for designing "value robust" systems
- Specifically target the high leverage *early concept phase*
- Metrics inform selection of promising adaptable concept designs for further analysis
- Uses exogenous uncertainties to frame adaptability* metric assessment





Systems developed in dynamic world and must accommodate shifts in context and needs (epoch) across their lifespan (era)

*For consistency with our past research, we use the name "changeability," which corresponds to DARPA "adaptability"

Success for modern systems is strongly determined by being able to respond to perturbations on appropriate timescales

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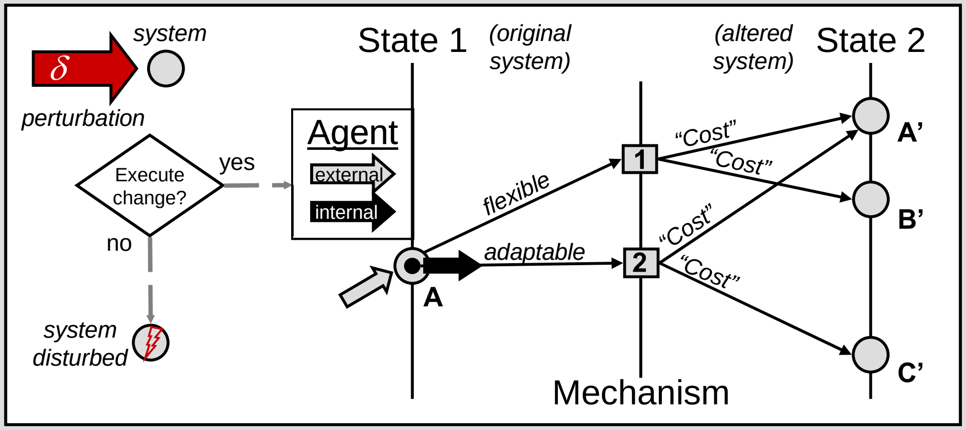
Framework to Enable Assessing and Designing for Changeability



Change Pathway:

Perturbation-Agent-Mechanism-Effect

At least two questions can be asked regarding degree of changeability

1. ***Can a system change itself or be changed?***

   Capability question; pursue structural and operational strategies

   - Can measure: number of destination end states, time/cost to achieve change

2. ***Does the change result in a "better" system?***

   Value question; analyze context-dependent performance and perceptions

   - Can measure: utility loss/gain over time, aggregate value delivery/availability

Changeability for the sake of changeability may result in unreturned carrying costs; cost-effective utility sustainment is where changeability can be a game-changer

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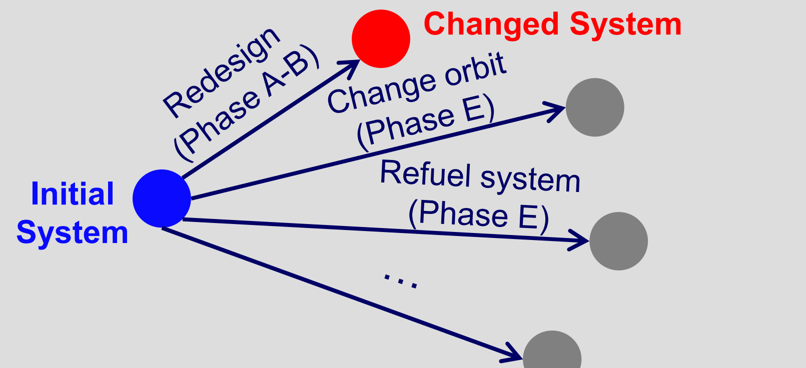
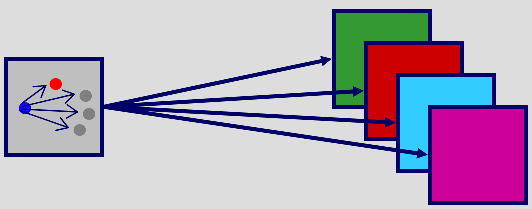
Interim Goal: Identifying when Changeability is Valuable



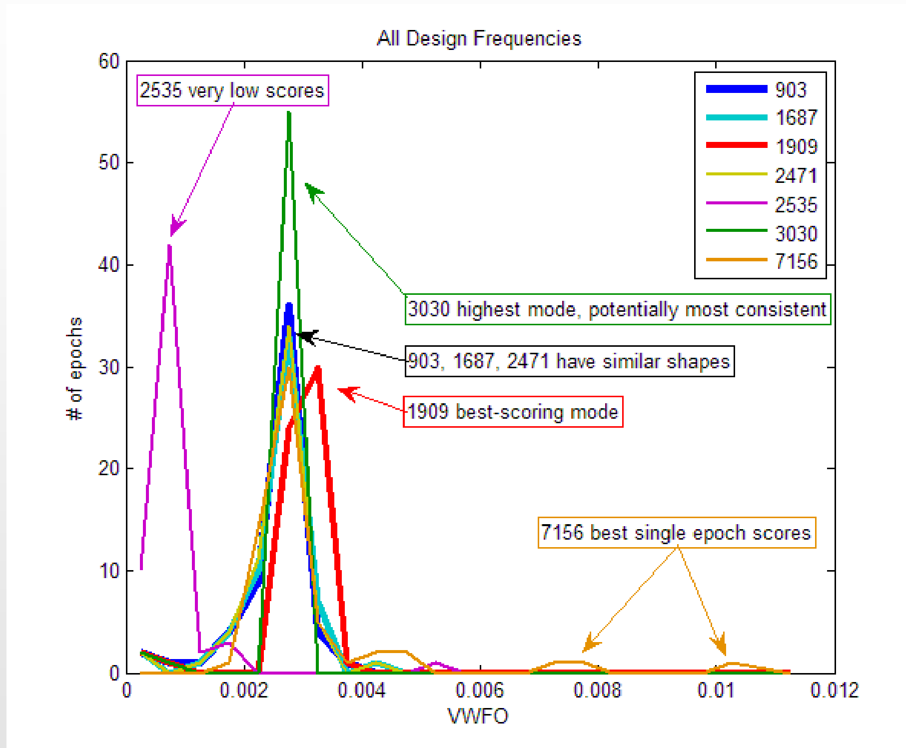
A system is *changeable* if it has transition options (*mechanisms)* available, which may depend on lifecycle phase



Today

Possible futures (epochs)

Not all changeability is worthwhile!
The *value of changeability* will depend on the future use and context



Quickly identify designs with valuable changeability

Design #	903	1687	1909	2471	2535	3030	7156
Min	0	0	0	0	1.3E-4	3.8E-4	19.1E-4
1st Quart.	24.2E-4	24.2E-4	28.1E-4	21.7E-4	6.4E-4	25.5E-4	24.2E-4
Median	25.5E-4	28.1E-4	30.6E-4	26.8E-4	7.7E-4	25.5E-4	25.5E-4
3rd Quart.	28.1E-4	29.3E-4	30.6E-4	28.1E-4	7.7E-4	25.5E-4	29.3E-4
Max	39.6E-4	42.1E-4	35.7E-4	40.8E-4	54.9E-4	28.1E-4	179.9E-4

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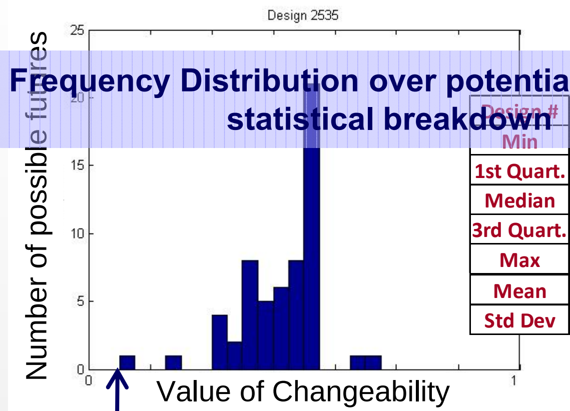
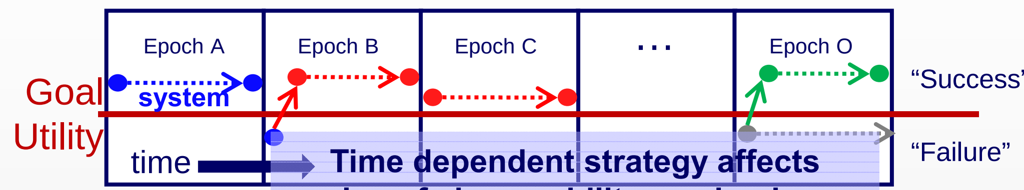
Final Goal: Valuable Changeability Profile of a Design



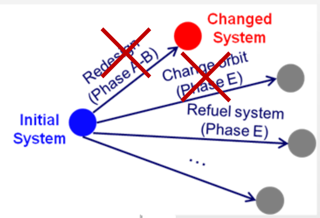
Frequency Distribution over potential futures with statistical breakdown

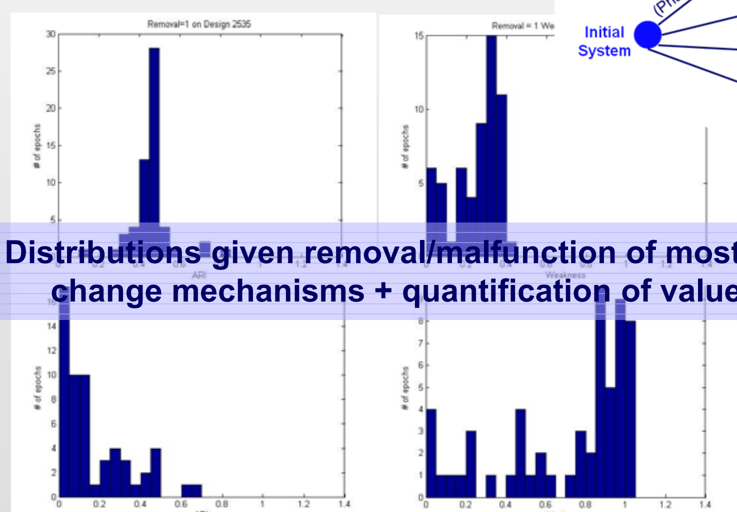
Design #	2535
Min	1.3E-4
1st Quart.	6.4E-4
Median	7.7E-4
3rd Quart.	7.7E-4
Max	54.9E-4
Mean	8.0E-4
Std Dev	6.9E-4

Always has some value for being changeable



Time dependent strategy affects value of changeability mechanisms





Distributions given removal/malfunction of most critical change mechanisms + quantification of value lost

Era analysis statistics / most common design transitions, strategy difficulty

Design #2535	Strategy:	Maximize Value	Maintain Value	Survive	Overall (Equal Wt)
Strategy Success Rate					59.7%
Avg $ cost ($M)		11	0	0.1	3.7
Avg time cost (days)		84	0	0.4	28.1
Avg # transitions		1.2	0	0.7	0.6

Summary of usage of change mechanisms given different change strategies

Rule \ Strategy	Likelihood of executing for strategy: Maximize Value	Maintain Value	Survive	Overall Rule Attractiveness
R1: Plane Change	5%	0%	0%	2%
R2: Apogee Burn	20%	10%	40%	23%
R3: Perigee Burn	5%	[illegible]	20%	10%
R4: Plane Tug	0%	0%	0%	0%
R5: Apogee Tug	20%	0%	0%	7%
R6: Perigee Tug	10%	0%	0%	3%
R7: Space Refuel	5%	0%	0%	2%
R8: Add Sat	30%	1%	5%	12%
Do nothing	5%	85%	35%	42%

Along with any other useful data or visualizations we develop, this "design profile" will highlight the sources and value of changeability in a given design, contexts where most useful, give suggestions on how to improve changeability, and allow for standardized comparison with other candidate designs

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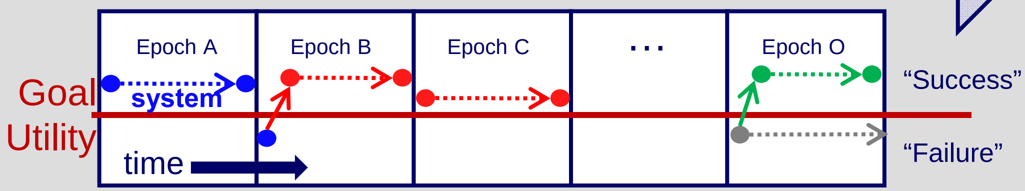
Current Focus Area: Era-level Strategies

Time dependent strategy will effect value of changeability mechanisms



Epoch strategy: $Z=U \geq U_{th}$ $Z=U \geq 0$ $Z=U \geq U_{th}$ $Z=\max(U)$ $Z=U \geq U_{th}$

Vision

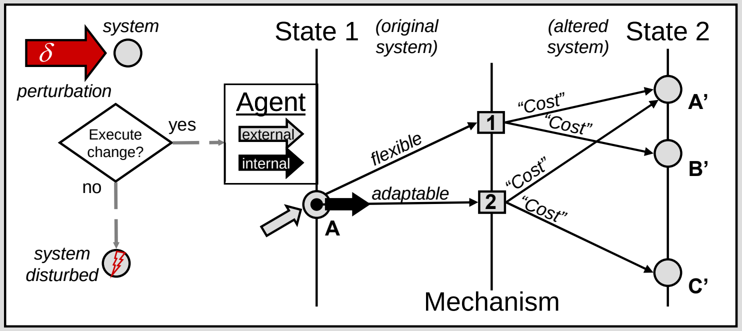
Be able to explore strategies and evaluate value-enhancing changeability (which change mechanisms to add to design)

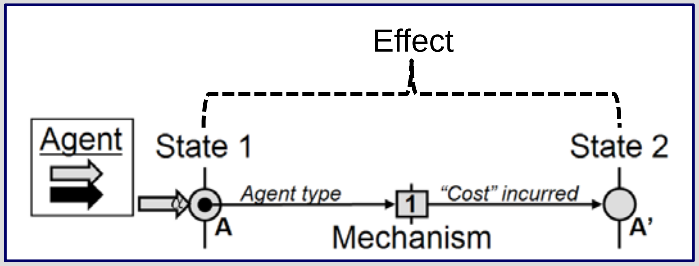
- Overall goal of "value sustainment" can be pursued with different strategies
- Strategies are a specification of long term or short term objectives
  - Period over which objective is measured
  - Objective function formulation (e.g. cost, utility, etc.)
- Examples of strategies
  - Maximize utility in each epoch
  - "Survive in each epoch
  - Maximize "aggregate" performance over the era
- Long term strategy can be constructed from short run strategies and evaluated

Changeability, specifically the presence of *change mechanisms*, gives the path options to allow for goal satisfaction across lifespan (epochs and eras)

Change Mechanisms and “Rules”

Change pathway: Perturbation-Agent-Mechanism-Effect





Change Mechanism: a method by which the system is changed

- “Burn on board fuel” results in change in satellite orbit, costing “extra ops cost” for executing the maneuver (system “state” includes operating orbit)

Change Rule: an algorithm that determines whether two proposed “states” are connected through a particular change mechanism

- “Compare two ‘states’ and if difference is only fuel and orbit location, then if fuel difference is equal to amount burned to achieve orbit difference, then states have directed accessibility via change mechanism for cost determined by that mechanism

The change rule is an operationalization of the concept of change mechanism in order to allow for computationally generated and evaluated alternative “paths”

Change mechanisms are “design features” that enable changeability
Change rules are algorithms to help evaluate changeability

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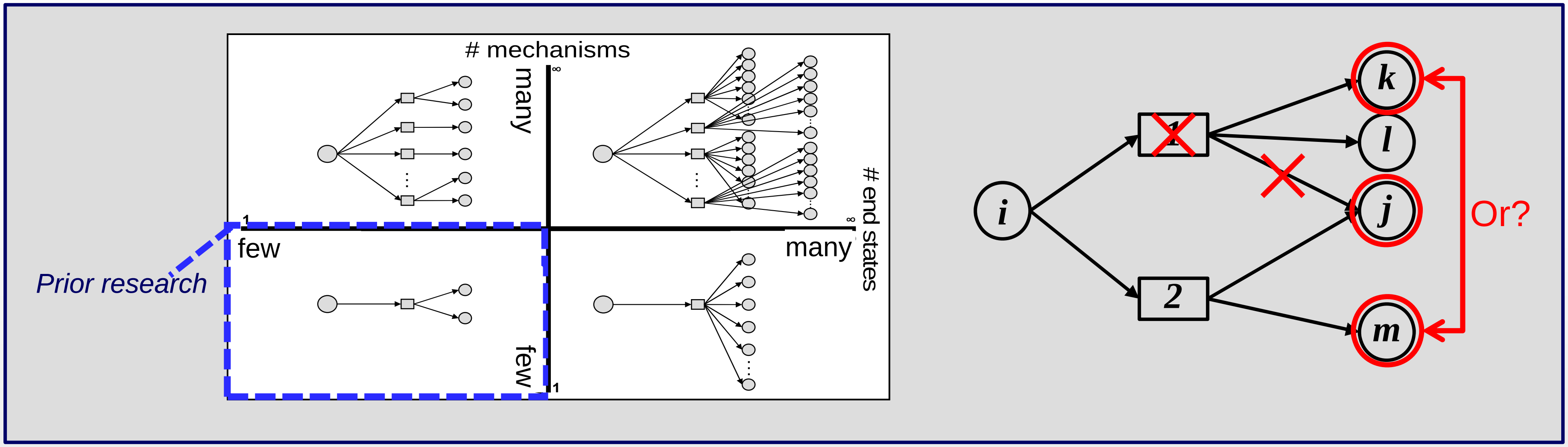
Addressing "Degree of" Change

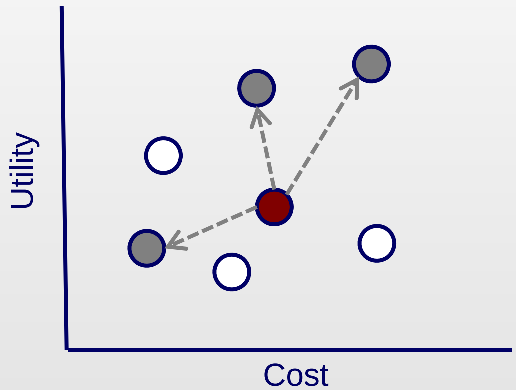


- In some sense, having more options is "good"
- Why does number of paths to end state matter?
  - Mechanism blocking
  - Mechanism paring
  - Uncertainty in desired goal end state
- Metrics aim to incorporate this "path counting" aspect
- Dilemma: *how to account for uncountable number of end states?* or re-phrased: *why should we care about all of these end states?*

End states matter insofar as the usefulness of those end states (i.e. "value")

How is Value Derived from Changeability?

- "Counting" vs "Magnitude" tension
  - Counting → number of available changes carries value
  - Magnitude → value derived from those changes must be considered
- Unfortunately, most metrics are unable to compare both of these sources



3 potential targets provides options
BUT
Can only execute 1

How do we account for this?

- **Strategy** attempts to clarify this distinction with a simple guiding statement:

Value is derived from changeability only with *executed* changes

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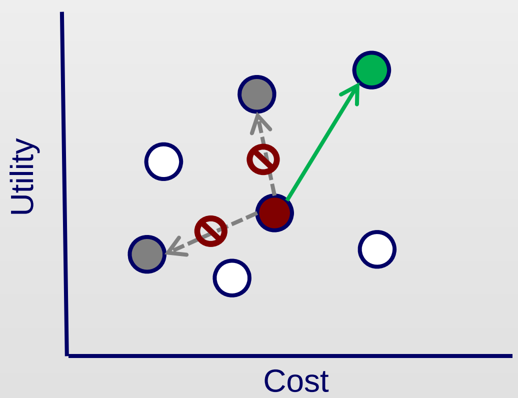
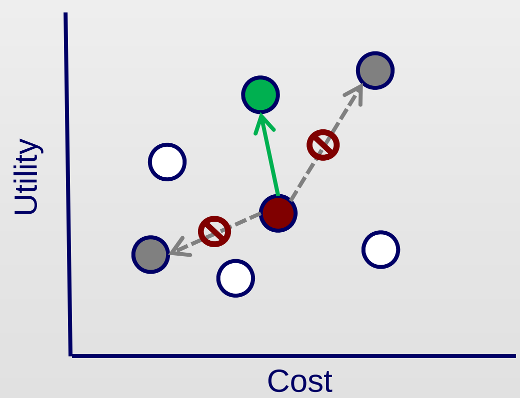
Changeability Strategies

- A ***strategy*** is a statement of how/when the stakeholder plans to execute any changeability options present in the system
  - Examples: maximize utility, exercise for survival only, etc.
- Given a defined tradespace network and epoch, a strategy will select the "best" transition (if any) that should be utilized from each design point

Strategy: maximize utility

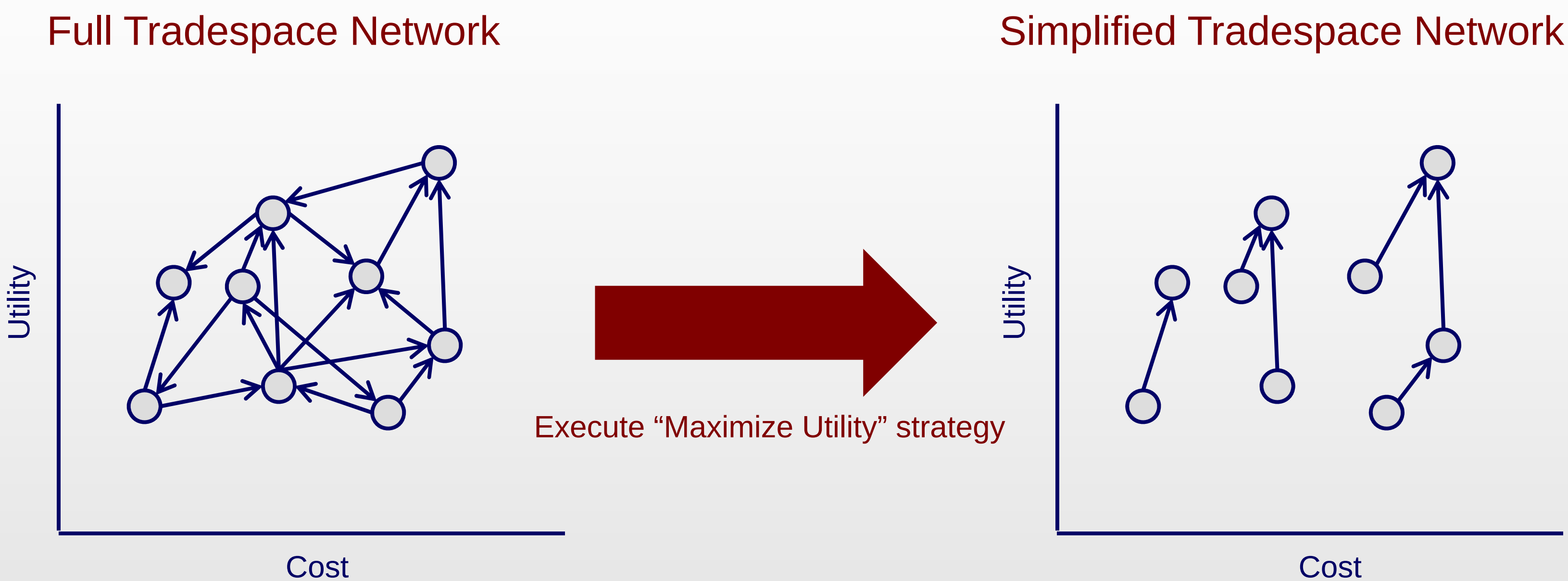


Strategy: maximize utility without increasing costs



Filtering out unused transitions enables more mathematically frugal analysis by eliminating the need to use a metric that lumps "magnitude" and "counting" value together

Simplified Tradespace Network



- Applying a strategy to a tradespace network reduces the problem to a maximum of one arc exiting each design point.
- Capturing the value of that arc will result in the design-epoch *valuable changeability* score that feeds into our previously described method (March PI meeting)

Addressing "Counting" Value

- Given the foregoing formulation, the problem is simplified, but it removes explicit value from "counting" possible change paths to alternative end states
- Number of available end states will still have an impact in the following areas:
  - More likely to have a high value transition under a given strategy (the standard "more is better" heuristic)
  - More likely to be valuable across multiple alternative strategies
  - More likely to retain valuable changeability when subject to unforeseen disturbances (i.e., less dependent on a single change mechanism, captured in previously shown "removal weakness" plots)

Counting value is accounted for when multiple strategies / conditions are considered: a single epoch snapshot is concerned only with the magnitude

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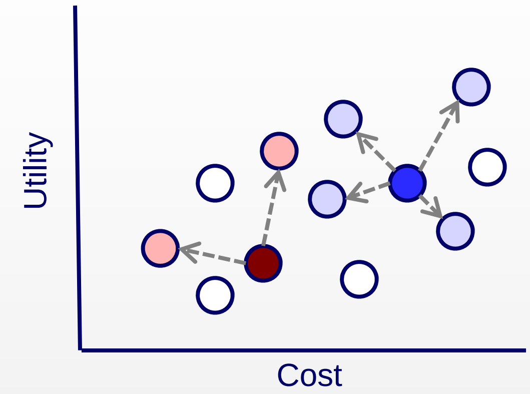
Revisiting Counting vs. Magnitude

Tension between "Counting" and "Magnitude"

- Older metrics "count" change paths as a heuristic for changeability value in the absence of a meaningful value statement consistent across multiple epochs
- Have to account for "magnitude" of the executed change, rather than assume all are equally used and equally valuable



If a DFC2 design has twice as many path options as a DFC0 design, is it twice as valuable?

NOT NECESSARILY

The combination of strategies and Fuzzy Pareto Shift was created for this purpose

But the number of paths is still important information!

- The number provides more options, potentially leading to more value across multiple epochs and strategies, or robustness against loss of change mechanisms

This value is recaptured across considering multiple strategies and with Removal Weakness

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Generating Insights into Change Mechanism Rules

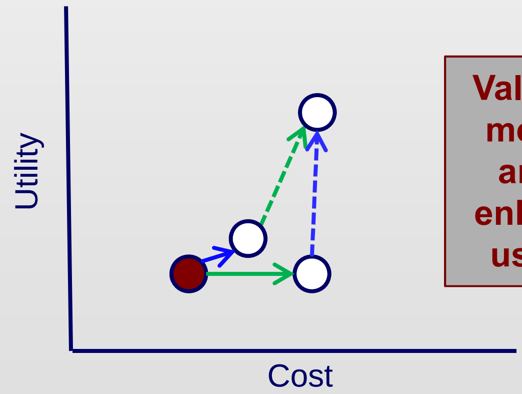
Rule-centric analysis

- This method can be approached in such a way as to investigate potential development of change mechanisms (in addition to the standard design selection) by finding their supplied value to the design space (in entirety or subset)

Removal Weakness and ARI supplied by individual rules can get at this concept

Rule coupling

- Transition matrices were collapsed to allow for potential uncovering of additional value via combining execution of mechanisms



Value of change mechanisms 1 and 2 greatly enhanced when used together

Can also perform Removal Weakness and ARI investigations on <u>sets</u> of mechanisms to explicitly find and value these coupling effects

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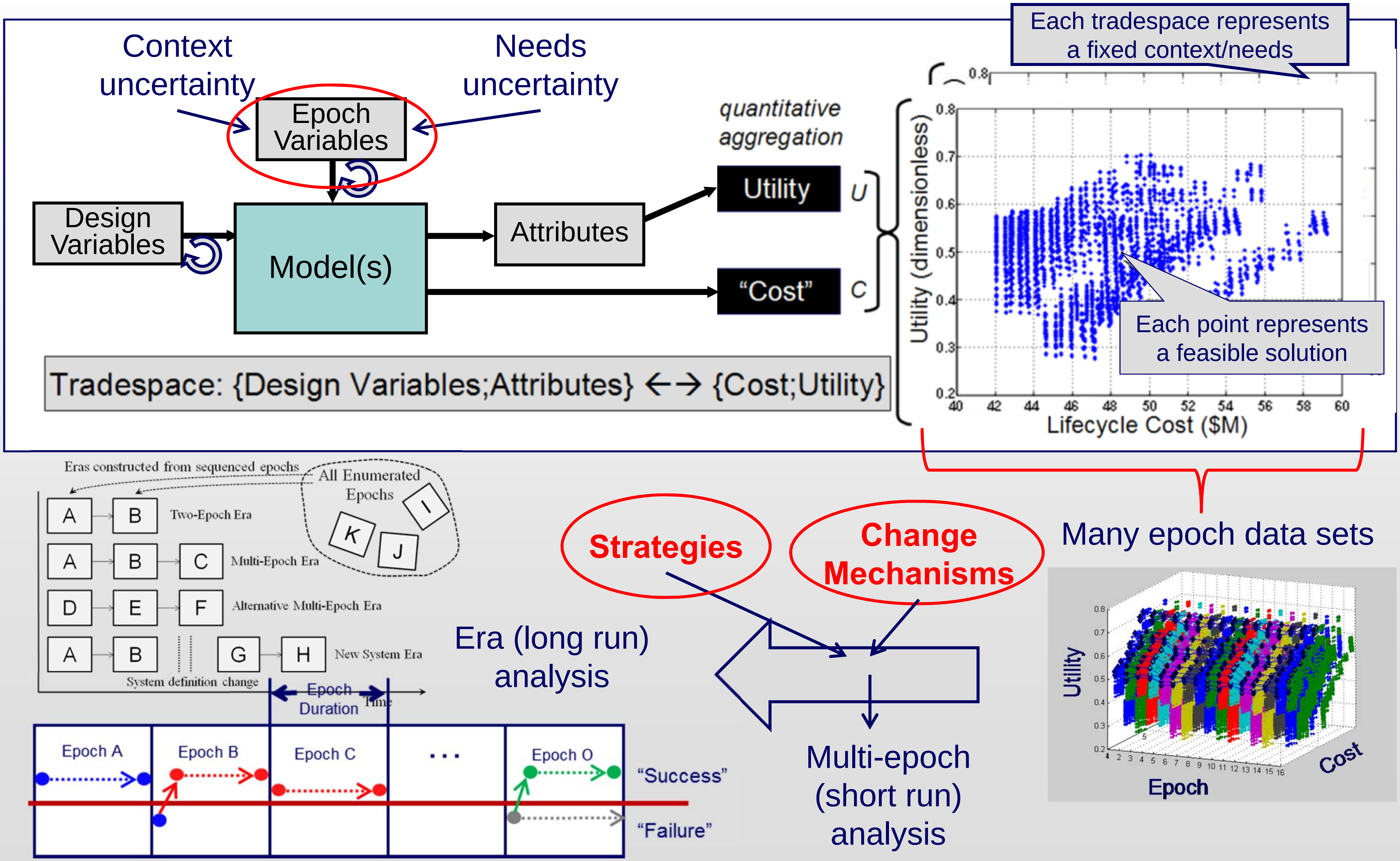
Data Flow for VASC Metrics



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Application to Space Tug

Space Tug Data Set - Intro

Scenario: You are the owner of a space tug rental company, providing 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 potential customers.

Steps in Valuation Approach for Strategic Changeability (VASC)

1. Set up data for epoch-era analysis
2. Identify designs of interest
3. Define rule usage strategies
4. Multi-epoch changeability analysis
5. Era simulation and analysis

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1. Set up Data for Epoch-Era Analysis

Activities

- Identify input data:
  - design variables,
  - change mechanisms
  - stakeholder preferences, desired attributes
  - context variables

Outputs

- Design/epoch lists, transition matrices
- Fuzzy Pareto Number for each design/epoch pair

4 design variables → 384 designs

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

8 prefs x 2 contexts → 16 epochs

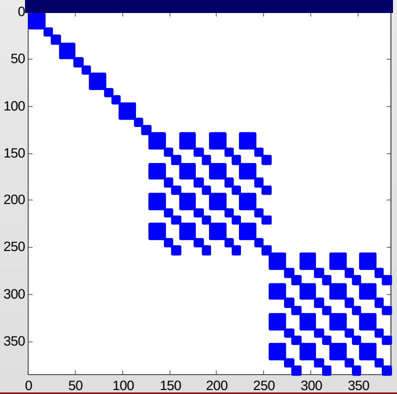
8 preference sets

- Delta-V potential
- Mass able to be manipulated
- Speed

2 contexts

- Present vs. future technology level

Collapsing Mech. Transition Matrices



#	Change Mechanism	DFC lvl
1	Engine Swap	0
2	Fuel Tank Swap	0
3	Engine Swap (reduced cost)	1 or 2
4	Fuel Tank Swap (reduced cost)	1 or 2
5	Change capability	1 or 2
6	Refuel in orbit	2

Step 1 puts the case in question into the epoch-era framework, allowing for piecewise consideration of time in sequences of constant-context sections

Space Tug Data Set Designs

4 design variables → 384 designs

- Propulsion type (bipropellant, cryogenic, electric, nuclear)
- Fuel mass
- Capability level
- Design For Changeability (DFC) level

DFC level is a switch intended to model a conscious effort to design for ease of redesign/change

- Varies from 0→1→2
- Reward: additional and/or cheaper change mechanisms
- Penalty: additional dry mass, resulting in higher costs and lower deltaV

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Space Tug Data Set Epochs

- 8 user preference sets
- 2 contexts

} 16 epochs (defined as preference-context pairs)

3 attributes valued in each preference set

- Delta-V potential
- Mass able to be manipulated (equal to capability level design variable)
- Speed (electric == slow, others are fast)

Contexts (not varied in the X-TOS data) are sets of variables that 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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Space Tug Data Set Change Rules

6 change mechanism rules

#	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

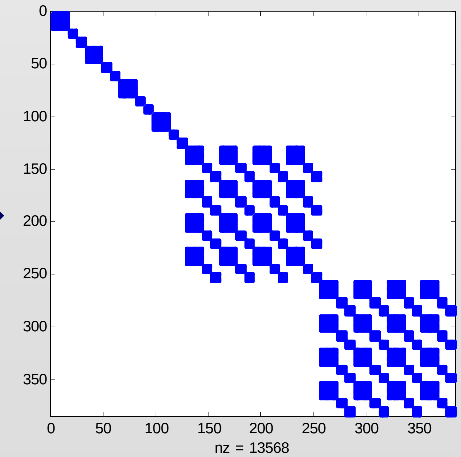
Rules 1-5 are "redesign" rules – require decommissioning and relaunching a space tug (with the associated costs)

Rule 6 is an "in action" rule, and does not require a new space tug

Multi-arc Transitions

- Previously: only single-mechanism transitions allowed (computational limits)
- Now: new method to ***combine and collapse separate mechanism transition matrices***
  - Mechanism paths established, all possible end states / total transition costs found one at a time and saved if non-dominated by another mechanism path
  - Allows for more robust era analysis by considering full set of path options

Collapsing the mechanisms into multi-arc transitions allows for the use of a full accessibility matrix when assessing potential end states



2. Identify Designs of Interest

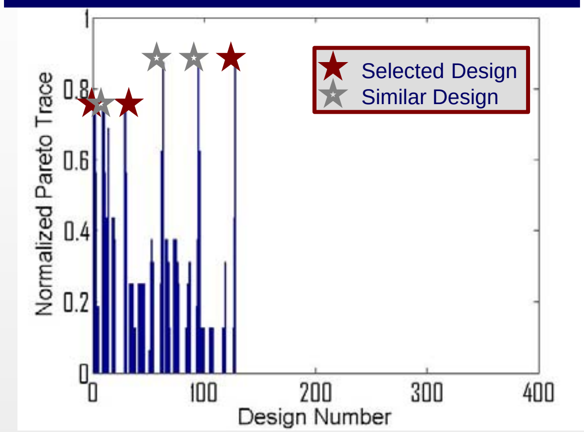
Activities

- Calculate changeability screening metrics:
  - Normalized Pareto Trace (and fuzzy NPT)
  - Filtered Outdegree
- Any other desired design identification techniques

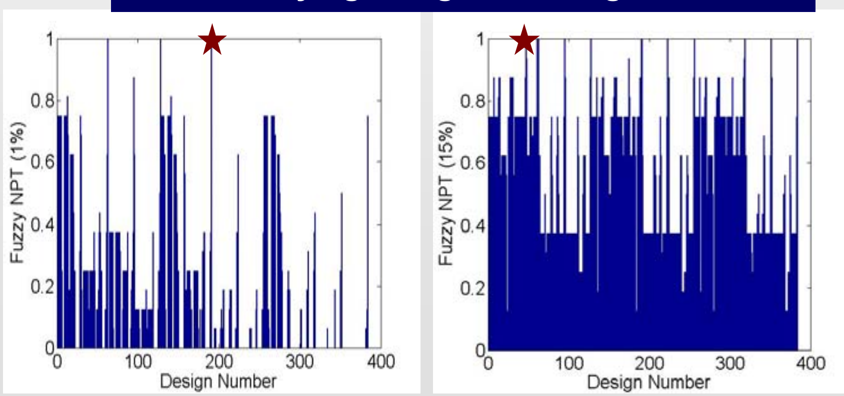
Outputs

- Subset of designs (~5-7) for further exploration

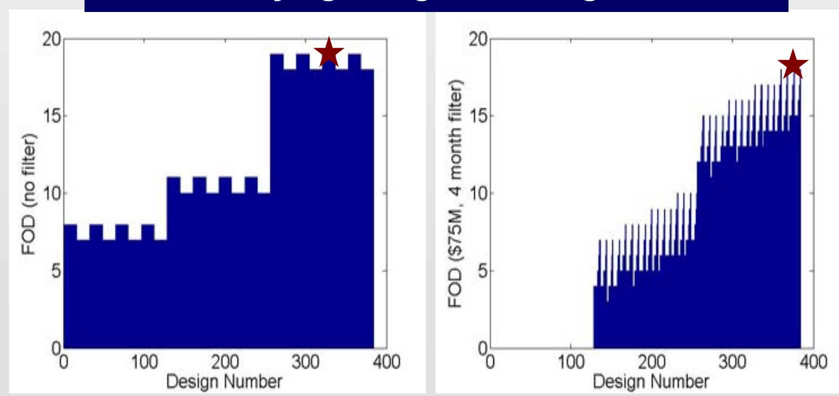
Identifying designs with high NPT



Identifying designs with high fNPT



Identifying designs with high FOD



Step 2 is necessary to reduce both the computation time and the difficulty of synthesizing and grasping the results of the method by reducing the scope of our full attention

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Designs of Interest: Summary

Summary: identified potential designs based on NPT/fNPT (passively robust) and FOD (changeable)

Reference Table for future plots

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 (Prop Type, DFC Level, Fuel Mass, Capability) — **Design attributes** (present context) (Fast?, DeltaV, Base Cost)

This selection process can take many forms, whatever is desired by the engineers using the method. It can also be repeated later to narrow down design choices in subgroups.

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3. Define Rule Usage Strategies

Activities

- Determine set of possible rules-usage strategies
- Define strategies in terms of logic for change mechanism execution in each epoch
- For each design/epoch pair, determine most desirable end state (defined by the strategy), which is reachable via transition rules

Outputs

- Realized end states and transition costs for each combination of design/epoch/strategy

Example Strategies (used in Space Tug analysis)

Name	Description
Maximize Utility	Make system as good at its job as possible (highest reachable utility per epoch)
Maximize Efficiency	Desire to be as cost-utility efficient as possible
Survive	Execute change only if system risks becoming “invalid”
Maximize Profit	(given a revenue model) use design changes to maximize revenues less costs each epoch

In Step 3, the strategy is the unifying factor of the method: specifying the logic that interprets the system condition over time and identifies change options that should be executed

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4. Multi-epoch Changeability Analysis

Activities

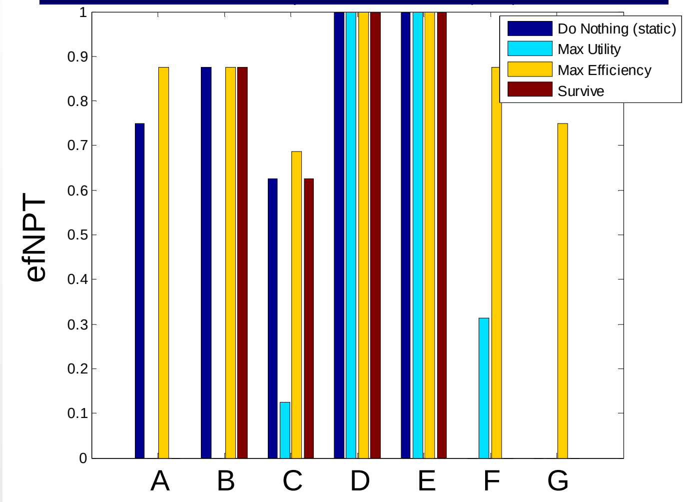
- Calculate multi-epoch metrics:
  - Effective NPT and Effective Fuzzy NPT
  - Fuzzy Pareto Shift
  - Removal Weakness
  - Available Rank Increase

Outputs

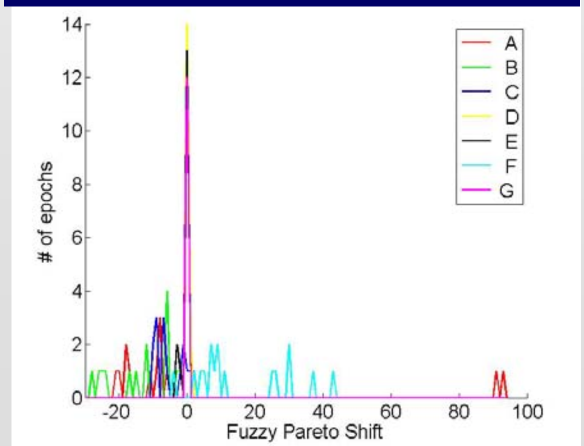
- Information on when, why, and how designs of interest are changing within epochs, and value of those changes
- Identification of particularly valuable change mechanisms and/or designs which rely on a single mechanism for a large portion of their value

In Step 4, multi-epoch changeability analysis considers possible situations the system could be used in, but without the complication of time ordering or time dependence

Exploring Effective Fuzzy Normalized Pareto Trace for each strategy



Exploring Fuzzy Pareto Shift of designs of interest for a strategy



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5. Era Simulation and Analysis

Activities

- Simulation of many randomly generated potential eras for each design of interest

Outputs

- Change mechanism usage frequency and likelihood
- Era-Level statistics on average/aggregate utility provided and design efficiency
- Comparison of strategies and change mechanism usage for each design

Tabulated revenue/cost statistics for an average era, with best and worst performances highlighted for each strategy under consideration

Design	MAX UTILITY Avg Rev	MAX UTILITY Avg Cost	MAX UTILITY Avg Profit	MAX EFFICIENCY Avg Rev	MAX EFFICIENCY Avg Cost	MAX EFFICIENCY 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

Design	SURVIVE Avg Rev	SURVIVE Avg Cost	SURVIVE Avg Profit	MAX PROFIT Avg Rev	MAX PROFIT Avg Cost	MAX PROFIT 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

Strategy: Max Profit

Likelihood of rules being utilized within 10 years

Design	Rule 1	Rule 2	Rule 3	Rule 4	Rule 5	Rule 6
A	2.1%	93.9%	0.0%	0.0%	0.0%	0.0%
B	0.0%	94.3%	0.0%	0.0%	0.0%	0.0%
C	0.0%	92.8%	0.0%	0.0%	0.0%	0.0%
D	0.0%	80.9%	0.0%	0.0%	0.0%	0.0%
E	0.0%	0.0%	0.0%	96.8%	31.5%	0.0%
F	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
G	0.0%	0.0%	0.0%	0.0%	0.0%	98.4%

Likelihood of Design E executing each transition rule across a 10 year era (per strategy)

Strategy	Rule 1	Rule 2	Rule 3	Rule 4	Rule 5	Rule 6
MaxU	N/A	N/A	N/A	100.0%	89.2%	N/A
MaxEff	N/A	N/A	N/A	100.0%	97.1%	N/A
Survive	N/A	N/A	N/A	94.9%	0.0%	N/A
MaxP	N/A	N/A	N/A	96.8%	31.5%	N/A

In Step 5, sample eras give important lifecycle information on the designs as they perform, change, and age over time, as well as help identify valuable change mechanisms

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Synthesis / Final Selection for Space Tug

After analyzing the data, the reduced set of designs are D, E, and F

- D had the highest NPT and represents a non-changeable but robust potential design
- E had highest fNPT and effective fNPT, and uses changeability to avoid failure to best effect
- F was the most valuably changeable design of interest according to FPS, similar to design A but with much fewer failures and unviable epochs

Designs D, E, and F are equally valid as "good" over time, but one must choose between robustness and changeability to decide which design is "best"

Evaluating the "going rate for changeability" for meeting a goal, by comparing changeable to non-changeable versions of a design, can give explicit upfront cost versus long run value tradeoffs

If we decide on design E, then we might consider investing in Rules 4 and 5

Rule 4: swap fuel tank
Rule 5: change capability

Likelihood of Design E executing each transition rule across a 10 year era (per strategy)

Strategy	Rule 1	Rule 2	Rule 3	Rule 4	Rule 5	Rule 6
MaxU	N/A	N/A	N/A	✓ 100.0%	✓ 89.2%	N/A
MaxEff	N/A	N/A	N/A	✓ 100.0%	✓ 97.1%	N/A
Survive	N/A	N/A	N/A	✓ 94.9%	✗ 0.0%	N/A
MaxP	N/A	N/A	N/A	✓ 96.8%	✗ 31.5%	N/A

Evaluating strategies and identifying change rules used lead to concrete design and change mechanism investment decisions

BACKUP

Steps in Valuation Approach for Strategic Changeability (VASC)

1. Set up data for epoch-era analysis
2. Identify designs of interest
3. Define rule usage strategies
4. Multi-epoch changeability analysis
5. Era simulation and analysis

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Multi-epoch Analysis (1)

Effective Normalized Pareto Trace (eNPT) – identical to NPT but for each epoch uses the Pareto performance of the end state determined by a strategy (rather than that of the design itself)

- Captures both robustness and changeability by considering executed change mechanisms across all epochs

Design	Do Nothing (NPT)	Max U	Max Eff	Survive	Max Prof
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	-

Unsurprisingly, Max Efficiency results in highest Pareto Traces, and the addition of DFC>0 (E,F,G) eliminates it

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Multi-epoch Analysis (2)

We can also apply a ***fuzzy*** factor to effective NPT ***(efNPT)***:

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

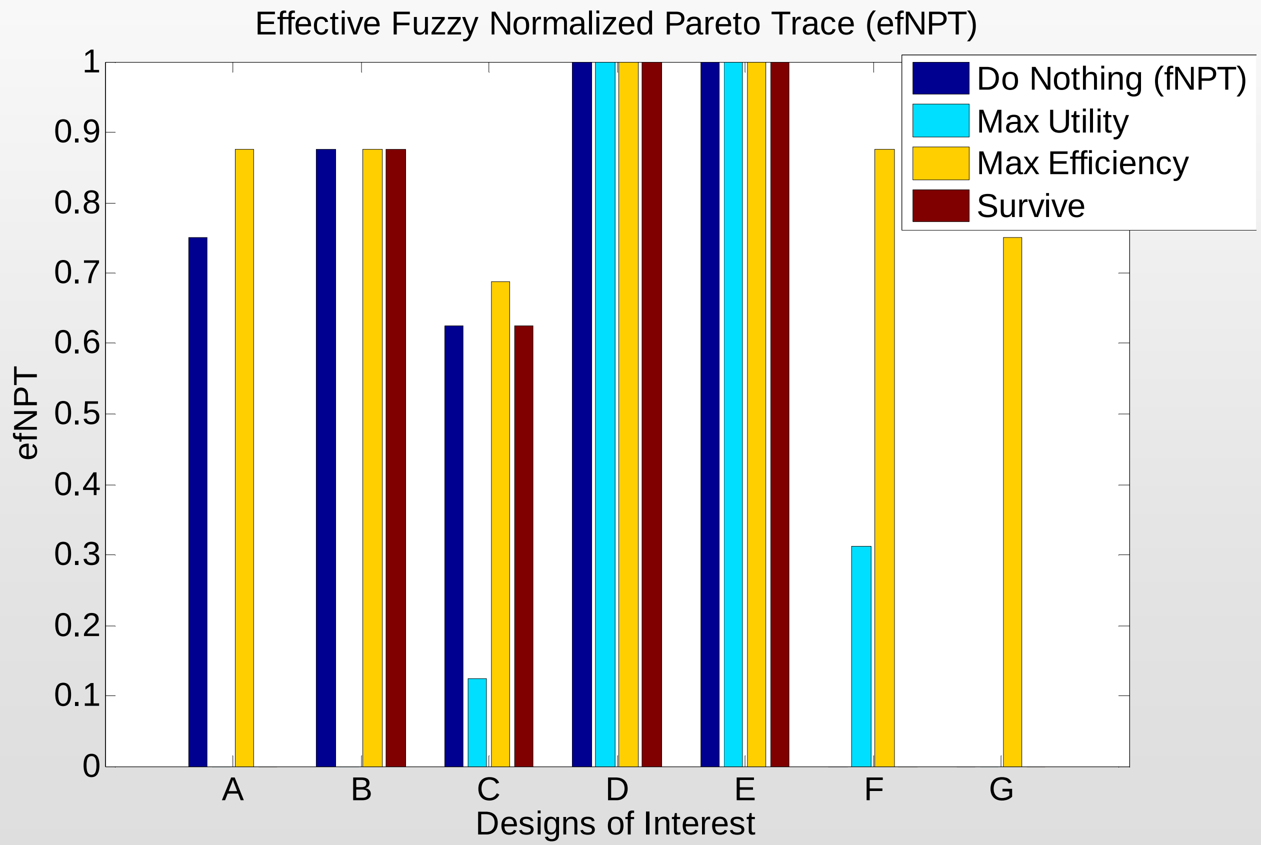
Design	Do Nothing (fNPT)	Max U	Max Eff	Survive	Max Prof
A	0.75	0	0.875	0	-
B	0.875	0	0.875	0.875	-
C	0.625	0.125	0.688	0.625	-
D	1	1	1	1	-
E	1	1	1	1	-
F	0	0.313	0.875	0	-
G	0	0	0.75	0	-

Now 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”

Multi-epoch Analysis (3)

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



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Multi-epoch Analysis (4)

Fuzzy Pareto Shift (FPS) calculates valuable changeability as the increase (or decrease) in efficiency resulting from executed changes in each epoch

$$\mathbf{FPS = FPN_{init} - FPN_{final}}$$

FPN = Fuzzy Pareto Number
= minimum fuzzy percentage required to place a design in the Fuzzy Pareto Front

- Viewed as a distribution, comparing shapes between designs, and also in a percentile summary
- Failure is typically recorded as -101 (worse than the worst possible decrease): we omit these designs from the distribution plots

FPS is calculating the *magnitude* of the value effects of the *selected* design transition in each epoch and can vary significantly between strategies as different rule execution logic and/or restrictions are imposed, changing chosen design end states

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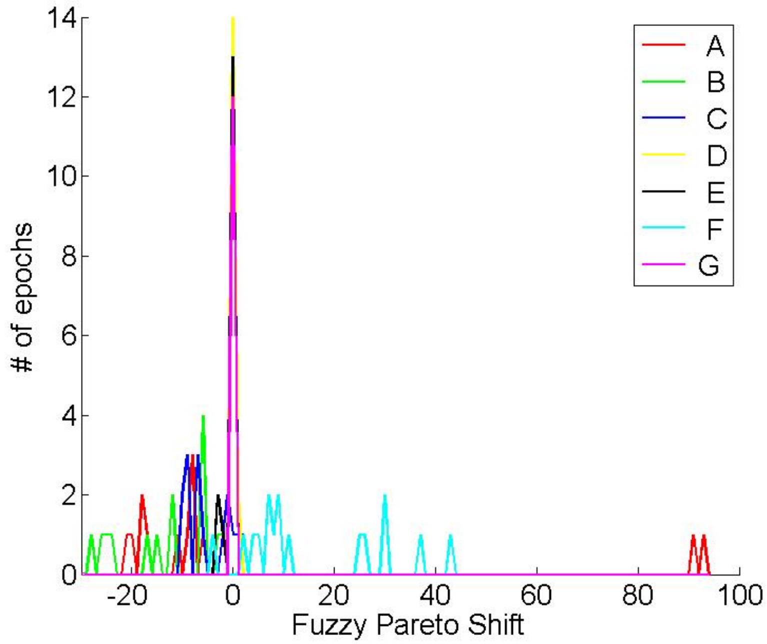
Multi-epoch Analysis (5)

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

- 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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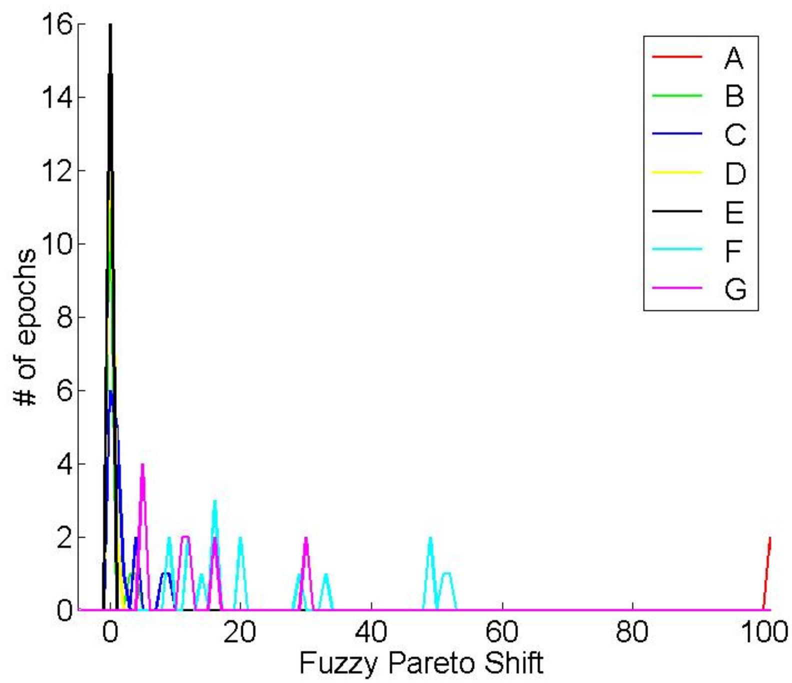
Multi-epoch Analysis (6)

Max Efficiency

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



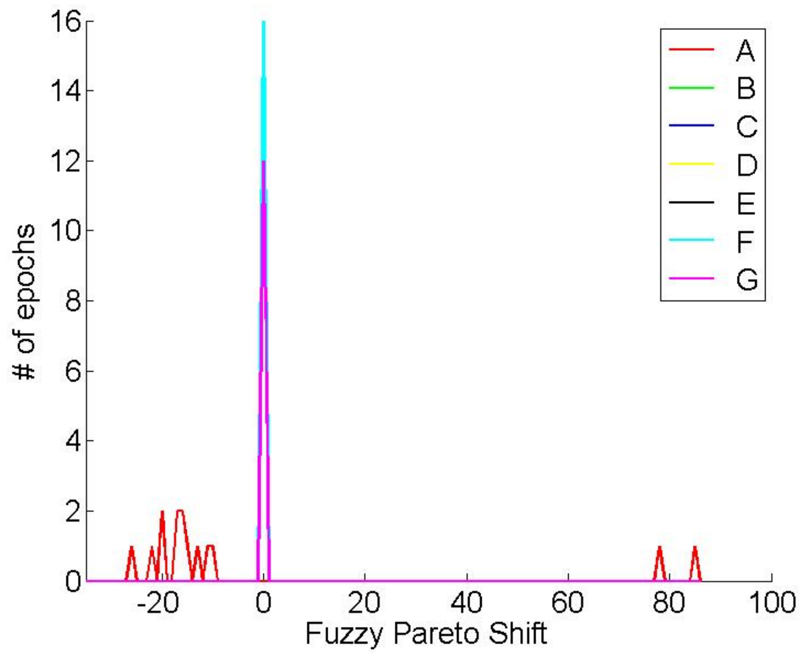
Epoch FPS Score Summary

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

- 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

Multi-epoch Analysis (7)

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)

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

Multi-epoch Analysis (8)

Removal Weakness quantifies the degree to which a design depends on a particular change mechanism for its valuable changeability

- This information is important for assessing the criticality of a change mechanism, showing how valuable a system would be if the mechanism failed
- For this system, most of the change mechanisms are redesign types, which don't suffer from potential breakdowns
- We can do a removal weakness investigation for Rule 6 – the in-service refuel – but the results are uninteresting:

Removing Rule 6 makes the DFC2 designs identical to the DFC1 designs, but still with their additional weight penalty. Plots and charts are omitted for conciseness.

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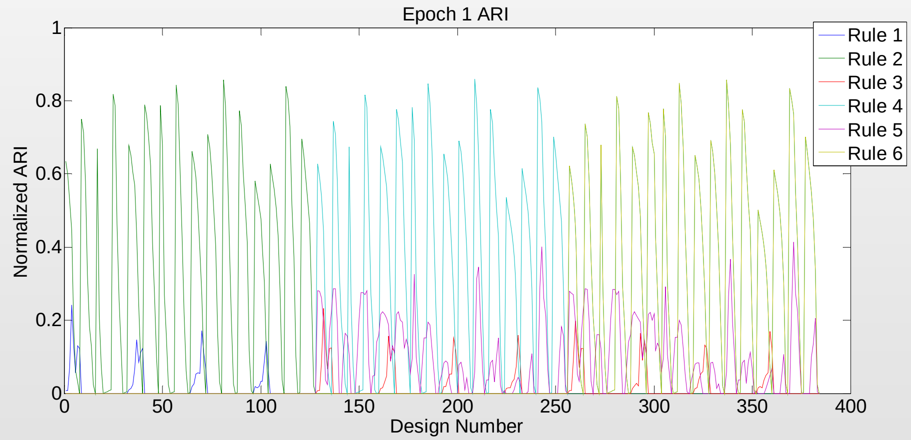
Multi-epoch Analysis (9)

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

- Imperfect metric (no accounting for costs, affected heavily by design enumeration) but can be an interesting basis for comparison of change mechanisms as utility-enablers

Here we see the most ARI is enabled in Epoch 1 by Rules 2,4,6 increasing the amount of fuel available for low fuel designs: they are large-value-adding mechanisms



- 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 if desired

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

Steps in VASC

1. Set up data for epoch-era analysis ✓
2. Identify designs of interest ✓
3. Define rule usage strategies ✓
4. Multi-epoch changeability analysis ✓
5. Era simulation and analysis ⬅

Era-Level Analysis

Era simulation is different for Space Tug than it was for X-TOS for a few reasons

- ***Time-ordered context variables*** – the epochs must be sampled intelligently so that the technology level starts at "present" and progresses to "future" and stays there
- ***Epoch length knowledge*** – the epochs are essentially space tug rental "contracts" from prospective customers, so unlike many exogenous variables we know how long each will last, affecting decision making

Need to implement a more sophisticated epoch sampler and also make sure to derive a new selected end state for any epoch in which the chosen transition takes longer than the epoch lasts

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Era-Level Analysis (2)

As mentioned, we also implement a basic revenue model:

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

Designs are rewarded for viability/utility and availability

This gives us another criteria to plan strategy on, leading to the Max Profit strategy

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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Strategy Impact on 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

Discussion of Strategy Impacts on Profits

Notable profit results

- 3 different designs have highest profits for the 4 strategies
- Design D has highest revenues for each
- Cheap DFC0 designs dominate the Max Efficiency strategy (but not the others)
- Survive strategy has higher projected long-term profits for some designs than the short-term profit maximization strategy
- Designs D and F have highest average performance

Strategy selection has a large effect on performance for every design

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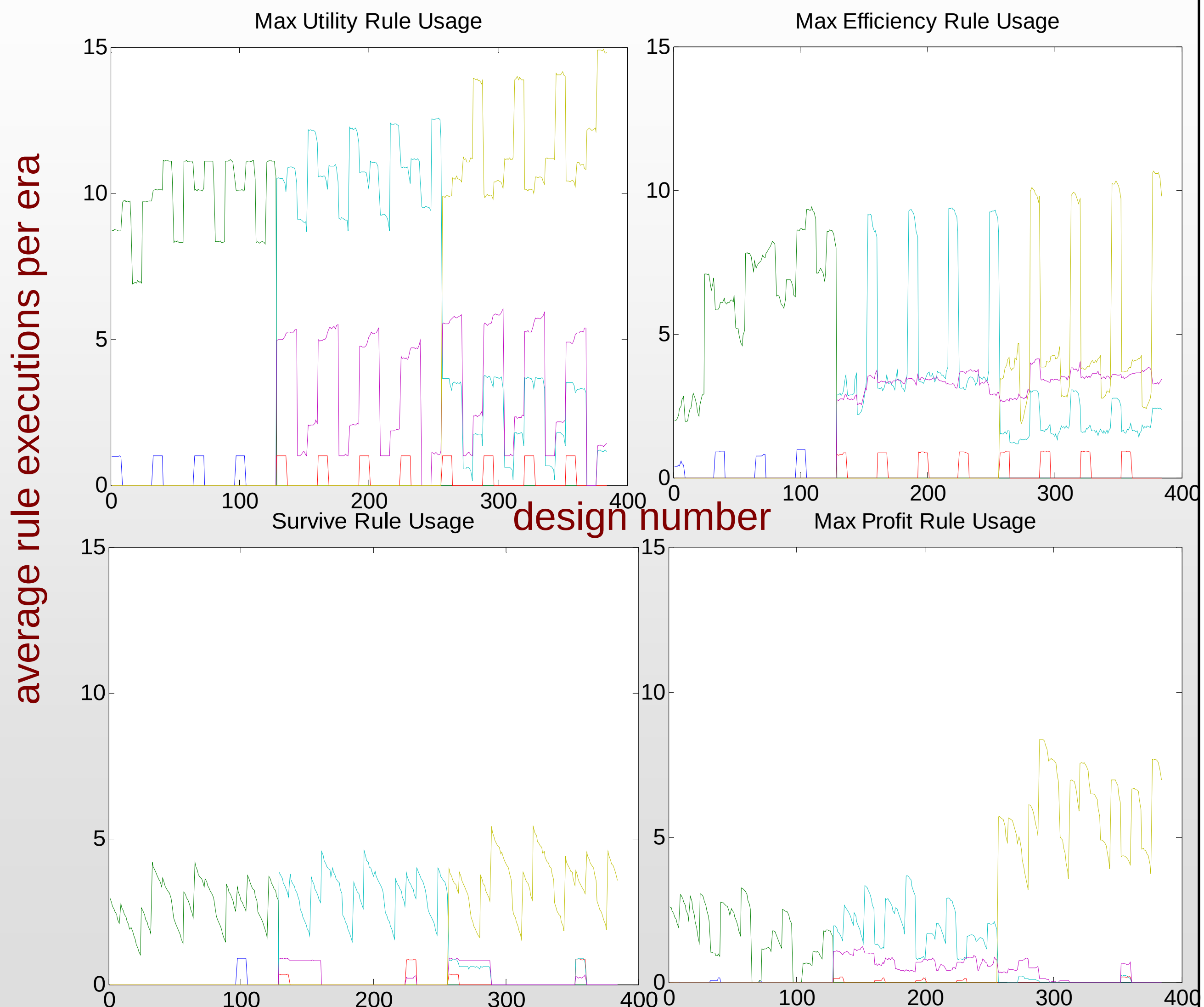
Rule Usage in Each Strategy

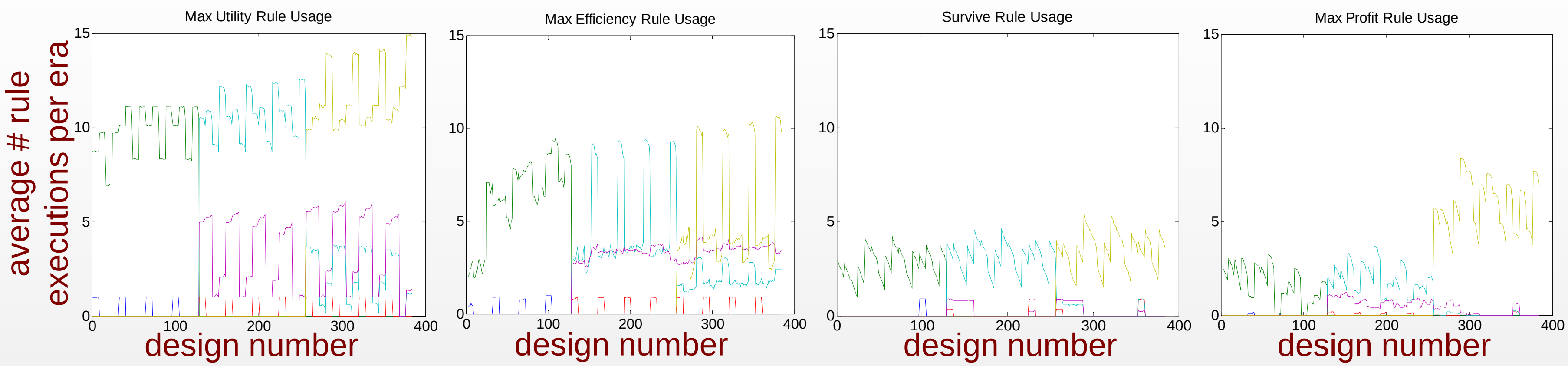
Rule usage varies by design number and by strategy



Rule Legend

- 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

Rule Usage in Each Strategy



Notable rule usage results

- Max Utility and Max Efficiency have significantly more transitions than others
- Rules 1,3 are rarely used, could possibly save money by choosing not to invest in its development
  - Same is true for rule 5 if using Survive or Max Profit strategies
  - Could investigate the utility/profit effects of this with a removal weakness study, or also could remodel reduced weight/cost effect

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Strategy Comparison: Rule Usage in Epoch Shift

Can frame rule usage as "likelihood of execution" for a single random epoch shift

Max Utility

Design	Rule 1	Rule 2	Rule 3	Rule 4	Rule 5	Rule 6
A	5%	46%	0%	0%	0%	0%
B	0%	51%	0%	0%	0%	0%
C	0%	58%	0%	0%	0%	0%
D	0%	56%	0%	0%	0%	0%
E	0%	0%	0%	64%	11%	0%
F	0%	0%	5%	17%	29%	53%
G	0%	0%	0%	0%	0%	64%

Max Efficiency

Design	Rule 1	Rule 2	Rule 3	Rule 4	Rule 5	Rule 6
A	2%	10%	0%	0%	0%	0%
B	0%	35%	0%	0%	0%	0%
C	0%	32%	0%	0%	0%	0%
D	0%	42%	0%	0%	0%	0%
E	0%	0%	0%	45%	17%	0%
F	0%	0%	5%	10%	18%	21%
G	0%	0%	0%	10%	20%	16%

Survive

Design	Rule 1	Rule 2	Rule 3	Rule 4	Rule 5	Rule 6
A	0%	16%	0%	0%	0%	0%
B	0%	11%	0%	0%	0%	0%
C	0%	15%	0%	0%	0%	0%
D	0%	15%	0%	0%	0%	0%
E	0%	0%	0%	15%	0%	0%
F	0%	0%	0%	0%	0%	24%
G	0%	0%	0%	0%	0%	10%

Max Profit

Design	Rule 1	Rule 2	Rule 3	Rule 4	Rule 5	Rule 6
A	0%	14%	0%	0%	0%	0%
B	0%	14%	0%	0%	0%	0%
C	0%	13%	0%	0%	0%	0%
D	0%	8%	0%	0%	0%	0%
E	0%	0%	0%	17%	2%	0%
F	0%	0%	0%	0%	0%	36%
G	0%	0%	0%	0%	0%	20%

This view reinforces the impression that rules 1,3,5 may be expendable for our designs of interest depending on our choice of strategy

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Rule Usage across an Era

Similarly, the data can be rephrased into a likelihood of execution (at least once) over an entire era

- For example, the Max Profit table transforms to:

Max Profit

Likelihood of rules being utilized within 10 years

Design	Rule 1	Rule 2	Rule 3	Rule 4	Rule 5	Rule 6
A	2.1%	93.9%	0.0%	0.0%	0.0%	0.0%
B	0.0%	94.3%	0.0%	0.0%	0.0%	0.0%
C	0.0%	92.8%	0.0%	0.0%	0.0%	0.0%
D	0.0%	80.9%	0.0%	0.0%	0.0%	0.0%
E	0.0%	0.0%	0.0%	96.8%	31.5%	0.0%
F	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
G	0.0%	0.0%	0.0%	0.0%	0.0%	98.4%

This is the same data as the previous slide, but presented in a format more conducive to evaluating lifecycle behavior

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Strategy Comparison: Example Metrics across Era

An example MOE comparison for Space Tug: *met contracts* and *utility-months served*

Max Utility

Design	Avg Contracts Met	Avg Utility-Months
A	16.1	29.5
B	16.5	36.7
C	17.3	39.4
D	17.1	65.0
E	17.6	62.2
F	17.8	53.5
G	14.2	61.7

Max Efficiency

Design	Avg Contracts Met	Avg Utility-Months
A	14.4	21.0
B	16.0	40.4
C	14.3	39.9
D	16.7	75.2
E	17.7	63.5
F	14.8	26.2
G	13.3	19.1

Survive

Design	Avg Contracts Met	Avg Utility-Months
A	15.5	32.4
B	15.8	45.3
C	16.6	49.0
D	16.7	81.6
E	17.2	64.1
F	14.2	66.6
G	13.6	63.1

Max Profit

Design	Avg Contracts Met	Avg Utility-Months
A	14.2	26.7
B	15.7	39.8
C	14.9	43.6
D	14.7	73.1
E	16.0	61.7
F	14.3	71.4
G	14.0	70.9

(The average number of total contracts is 19 for all strategies)

"Most Valuable" (MOE) across Era

	Max Utility			Max Efficiency			Survive			Max Profit	
Design	Avg Contracts Met	Avg Utility-Months	Design	Avg Contracts Met	Avg Utility-Months	Design	Avg Contracts Met	Avg Utility-Months	Design	Avg Contracts Met	Avg Utility-Months
A	16.1	29.5	A	14.4	21.0	A	15.5	32.4	A	14.2	26.7
B	16.5	36.7	B	16.0	40.4	B	15.8	45.3	B	15.7	39.8
C	17.3	39.4	C	14.3	39.9	C	16.6	49.0	C	14.9	43.6
D	17.1	65.0	D	16.7	75.2	D	16.7	81.6	D	14.7	73.1
E	17.6	62.2	E	17.7	63.5	E	17.2	64.1	E	16.0	61.7
F	17.8	53.5	F	14.8	26.2	F	14.2	66.6	F	14.3	71.4
G	14.2	61.7	G	13.3	19.1	G	13.6	63.1	G	14.0	70.9

Notable contracts/utility-months results

- Design G always has the fewest met contracts, as the electric propulsion is inviable in some epochs
- Design D always has the most utility-months served
  - Selected as a high utility robust design
- Design E has the most contracts met under almost all strategies
  - changeability is the most accommodating to different preferences

These are simple yet telling measures, but may seem redundant after a profit model: we can follow these up with more sophisticated value metrics

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Strategy Comparison: FPN across Era

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

Max Utility

Design	Best	Worst	Avg	Avg (no fail)
A	0.0	96.0	17.4	2.2
B	0.0	94.1	15.8	3.0
C	0.1	84.2	13.1	4.8
D	0.0	91.0	16.8	7.9
E	1.0	85.4	15.6	8.8
F	2.1	82.1	18.1	12.7
G	3.1	100.6	33.6	10.6

Max Efficiency

Design	Best	Worst	Avg	Avg (no fail)
A	0.0	100.4	24.7	0.0
B	0.0	96.4	17.7	2.1
C	0.0	100.5	27.9	3.7
D	0.0	95.1	19.7	8.6
E	1.0	80.6	13.3	7.2
F	1.0	100.4	24.1	2.3
G	1.0	100.9	33.3	4.5

Survive

Design	Best	Worst	Avg	Avg (no fail)
A	0.0	99.3	20.1	1.4
B	0.0	97.5	19.3	2.9
C	0.0	93.8	16.5	4.3
D	0.1	96.1	26.8	16.2
E	1.0	87.3	14.4	5.5
F	3.2	100.8	38.2	16.9
G	3.7	100.9	44.0	21.2

Max Profit

Design	Best	Worst	Avg	Avg (no fail)
A	0.0	100.5	25.6	0.3
B	0.1	97.9	20.1	3.2
C	0.0	99.9	25.5	4.1
D	0.7	100.4	38.5	19.9
E	1.4	97.0	22.9	8.5
F	3.2	100.7	38.3	17.3
G	2.9	100.7	38.2	15.5

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

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“Most Valuable” (FPN) across Era

Max Utility

Design	Best	Worst	Avg	Avg (no fail)
A	0.0	96.0	17.4	2.2
B	0.0	94.1	15.8	3.0
C	0.1	84.2	13.1	4.8
D	0.0	91.0	16.8	7.9
E	1.0	85.4	15.6	8.8
F	2.1	82.1	18.1	12.7
G	3.1	100.6	33.6	10.6

Max Efficiency

Design	Best	Worst	Avg	Avg (no fail)
A	0.0	100.4	24.7	0.0
B	0.0	96.4	17.7	2.1
C	0.0	100.5	27.9	3.7
D	0.0	95.1	19.7	8.6
E	1.0	80.6	13.3	7.2
F	1.0	100.4	24.1	2.3
G	1.0	100.9	33.3	4.5

Survive

Design	Best	Worst	Avg	Avg (no fail)
A	0.0	99.3	20.1	1.4
B	0.0	97.5	19.3	2.9
C	0.0	93.8	16.5	4.3
D	0.1	96.1	26.8	16.2
E	1.0	87.3	14.4	5.5
F	3.2	100.8	38.2	16.9
G	3.7	100.9	44.0	21.2

Max Profit

Design	Best	Worst	Avg	Avg (no fail)
A	0.0	100.5	25.6	0.3
B	0.1	97.9	20.1	3.2
C	0.0	99.9	25.5	4.1
D	0.7	100.4	38.5	19.9
E	1.4	97.0	22.9	8.5
F	3.2	100.7	38.3	17.3
G	2.9	100.7	38.2	15.5

Notable FPN results

- DFC0 designs tend to have better *best* FPNs, but higher DFCs have better *worst* FPNs
  - Changeability is avoiding worst case scenarios more than switching between optima
- Design A always has the best average when not considering inviable epochs, but is inviable too often to have the best overall average
- Design G is regularly among the worst due to its high failure rate and high cost exceeding its marginal utility gains
- Design E appears to be the best compromise between the strategies other than Max Utility

This is a good time to create a “design profile” for each design, to help synthesize information and compare strategies: an example follows

Delivered to the Government in Accordance with Contract FA8650-10-C-7084

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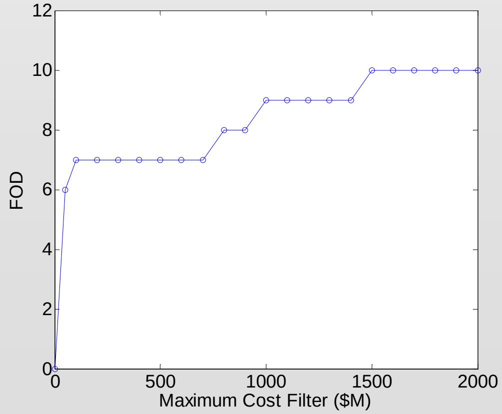
Design Profile – Design E

Design Vector (191)

Nuclear
Medium capability
10000kg fuel tank
DFC1

NPT/FOD

NPT	0
Fuzzy% to reach max fNPT	1%
Outdegree	10



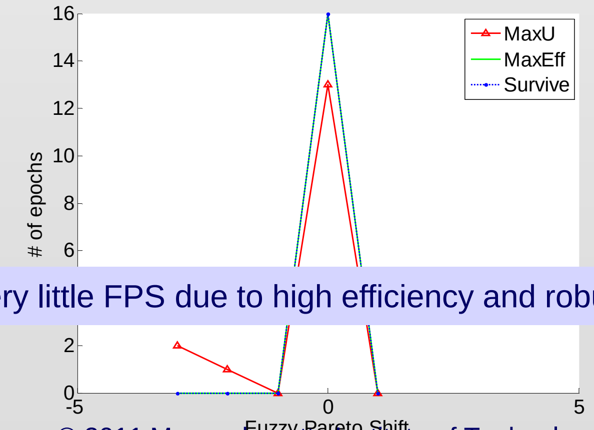
Avg 10-year Era Statistics

Strategy	Met Contracts	Utility-Months	Revenue (10^4 $M)	Cost (10^4 $M)	Profit (10^4 $M)	Avg FPN	Avg FPN no fails
MaxU	17.6	62.2	6.6	5.7	0.9	15.6	8.8
MaxEff	17.7	63.5	6.7	3.7	3.0	13.3	7.2
Survive	17.2	64.1	6.9	1.0	5.9	14.4	5.5
MaxP	16	61.7	6.5	0.6	7.2	22.9	8.5

Likelihood of at least one use of transition rule

Strategy	Rule 1	Rule 2	Rule 3	Rule 4	Rule 5	Rule 6
MaxU	N/A	N/A	N/A	100.0%	89.2%	N/A
MaxEff	N/A	N/A	N/A	100.0%	97.1%	N/A
Survive	N/A	N/A	N/A	94.9%	0.0%	N/A
MaxP	N/A	N/A	N/A	96.8%	31.5%	N/A

Multi-Epoch Data



Very little FPS due to high efficiency and robustness

Removal weakness plots/tables could also be included here

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Synthesis / Final Selection for Space Tug

After analyzing the data, the reduced set of designs are D, E, and F

- D had the highest NPT and represents a non-changeable but robust potential design
- E had highest fNPT and effective fNPT, and uses changeability to avoid failure to best effect
- F was the most valuably changeable design of interest according to FPS, similar to design A but with much fewer failures and unviable epochs

Designs D, E, and F are equally valid as "good" over time, but one must choose between robustness and changeability to decide which design is "best"

Evaluating the "going rate for changeability" for meeting a goal, by comparing changeable to non-changeable versions of a design, can give explicit upfront cost versus long run value tradeoffs

If we decide on design E, then we might consider investing in Rules 4 and 5

Rule 4: swap fuel tank

Rule 5: change capability

Likelihood of Design E executing each transition rule across a 10 year era (per strategy)

Strategy	Rule 1	Rule 2	Rule 3	Rule 4	Rule 5	Rule 6
MaxU	N/A	N/A	N/A	✓ 100.0%	✓ 89.2%	N/A
MaxEff	N/A	N/A	N/A	✓ 100.0%	✓ 97.1%	N/A
Survive	N/A	N/A	N/A	✓ 94.9%	✗ 0.0%	N/A
MaxP	N/A	N/A	N/A	✓ 96.8%	✗ 31.5%	N/A

Evaluating strategies and identifying change rules used lead to concrete design and change mechanism investment decisions

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Investigating Cost/Benefit of Adding Changeability

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

+34$B

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

Impact of Adding/Removing DFC: Initial vs. Delayed Costs/Benefits

-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

- A final decision can 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 vs. changeable designs should be identified, with "going rates" for changeability established to consider small variations which may prove valuable

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Discussion of Scalability

Activity	Worst Variable to Increase	Approximate Order
Transition Matrices Generation	# designs	**N^2** (worst case, depends on rule algorithm)
Rule Collapse	# change mechanisms	**Factorial**
FPN	# designs	Linear, but depends on shape of tradespace
NPT (fuzzy, effective)	# designs / epochs	Linear in both
Strategy End State Calculation	# designs	Linear, but time depends on complexity of strategy
FPS	# designs	Simple arithmetic, but depends on having FPN and Strategy calculated
Removal Weakness	# change mechanisms - 1	**Requires a repeat of Rule Collapse**
Era Simulation	# eras per design / strategy complexity	Linear, but dependent on strategy if some era information is known (like epoch length for Space Tug)

Approach is easily scalable to extremely large projects with the exception of collapsing multi-arc transitions, which scales poorly with number of change mechanisms.

However, speeding up current algorithm is certainly possible through additional research, and approach is valid (though less informative) when considering single-arc transitions.

Acronym Glossary

Acronym	Stands For	Definition
VASC	Valuation Approach for Strategic Changeability	Our method and accompanying metrics for changeability analysis
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
eNPT, efNPT	Effective (fuzzy) Normalized Pareto Trace	Above, considering the design's end state after transitioning
FPN	Fuzzy Pareto Number	% margin needed to include design in the fuzzy Pareto front
FPS	Fuzzy Pareto Shift	Difference in FPN before and after transition
DFC	Design For Changeability	A set of design principles designed to promote system changeability
OD	Outdegree	# outgoing transition arcs from a design
FOD	Filtered Outdegree	Above, considering only arcs below a chosen cost threshold
ARI	Available Rank Increase	# of designs able to be passed in utility via best possible change