A Method Using Epoch-Era Analysis to Identify Valuable Changeability in System Design

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Agenda

- Changeability
- Epoch-Era Analysis
- Description of Methodology
- X-TOS Case Study
- Conversion of Other Studies
- Further Research

Changeability

- Considered here as *the ability of a system to undergo physical or operational changes after deployment*
  - Design/build/test phase changeability similar, but typically with different effects

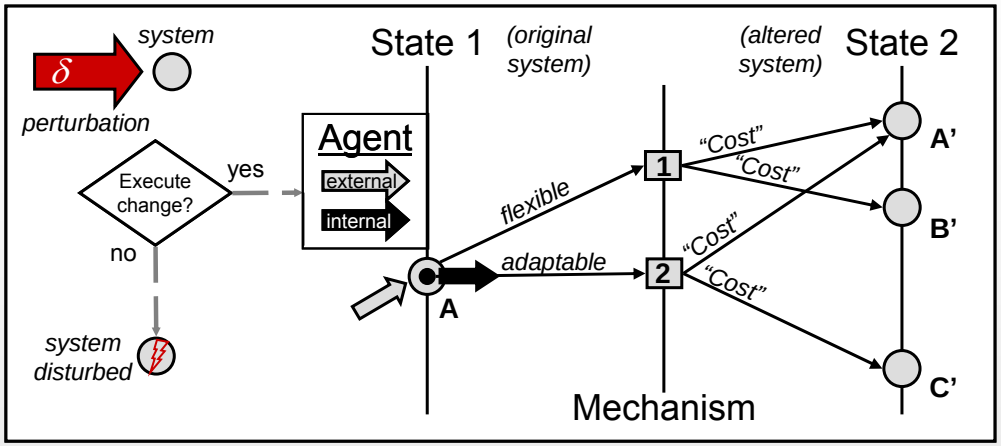
- Why changeability?
- Of real interest: valuable changeability

A design that can change to a worse design might as well not change

- Strength of epoch-era analysis: compatible with many metrics of changeability value
  - The most appropriate or desired metric can be chosen for each application
  - Potential to provide effective means of comparing design options and trading off changeability with other design considerations

Framework for Assessing and Designing for Changeability

Change pathway: Perturbation-Agent-Mechanism-Effect

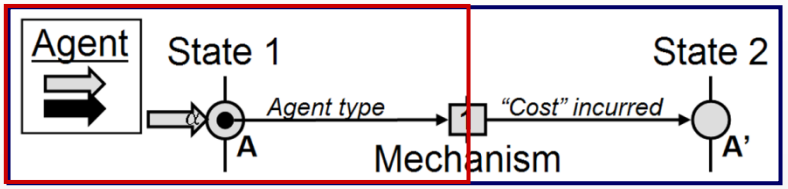


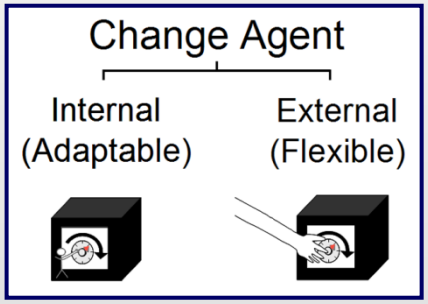
Two questions fundamental to accounting for changeability:

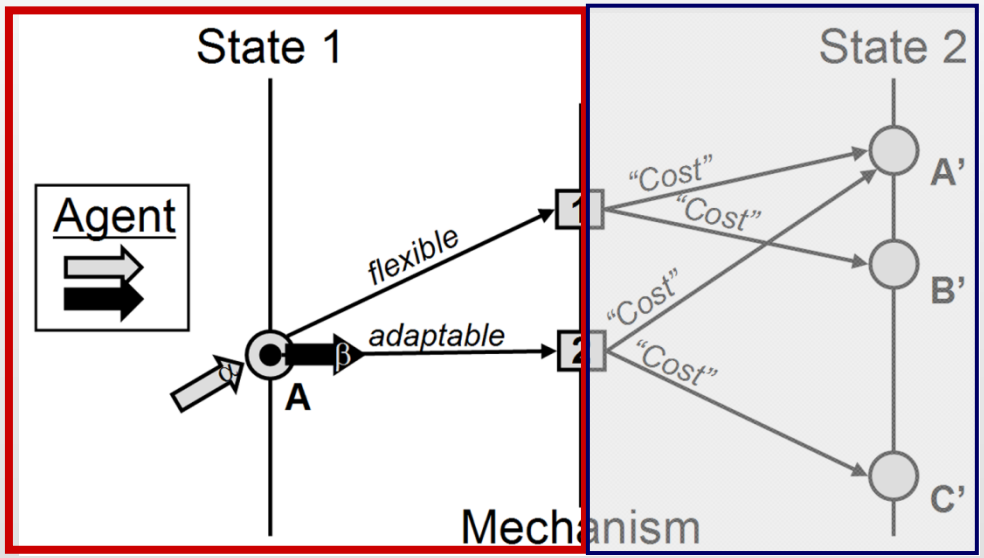
1. Can a system change itself or be changed?
   - Capability question; pursue structural and operational strategies
   - Key metrics: number of destination end states, time/cost to achieve change
2. Does the change result in a "better" system?
   - Value question; analyze context-dependent performance and perceptions
   - Key metrics: utility loss/gain over time, aggregate value delivery/availability

Changeability: Flexibility and Adaptability

- Distinguished by the location of the change agent (external vs. internal)
- Dependent on the scope of the problem, so the two are closely related



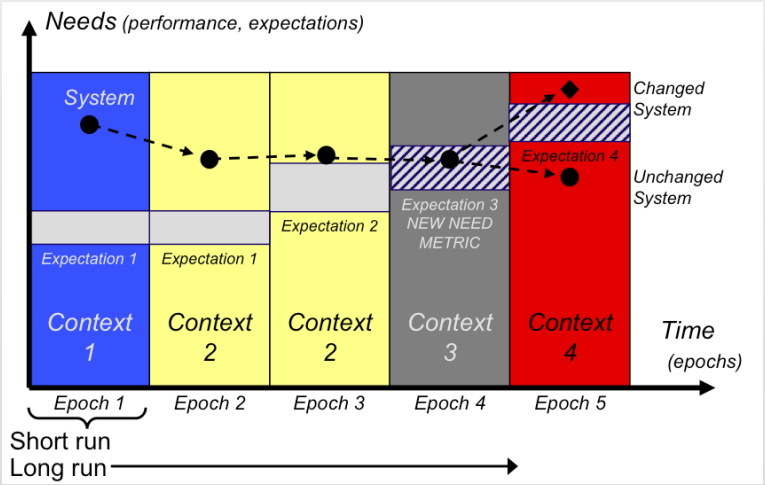




Changeability encompasses both of the more common terms Flexibility and Adaptability, allowing the two to be considered simultaneously

Epoch-Era Analysis

- Epoch-Era Analysis (EEA)
  - A method to investigate value-over-time behavior of systems, by modeling lifetimes as eras, sequences of fixed conceptual value statements
- Epochs - sets of fixed context variables
  - define potential future scenarios affecting perception of system value
- Eras - sequences of epochs
  - model changes in perception of value over time



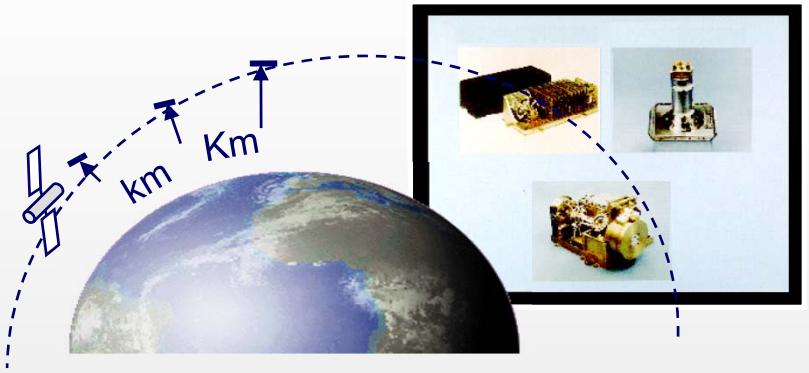
Changeability can provide a means to extend the duration of value-delivery of a system as needs and perceptions vary over time

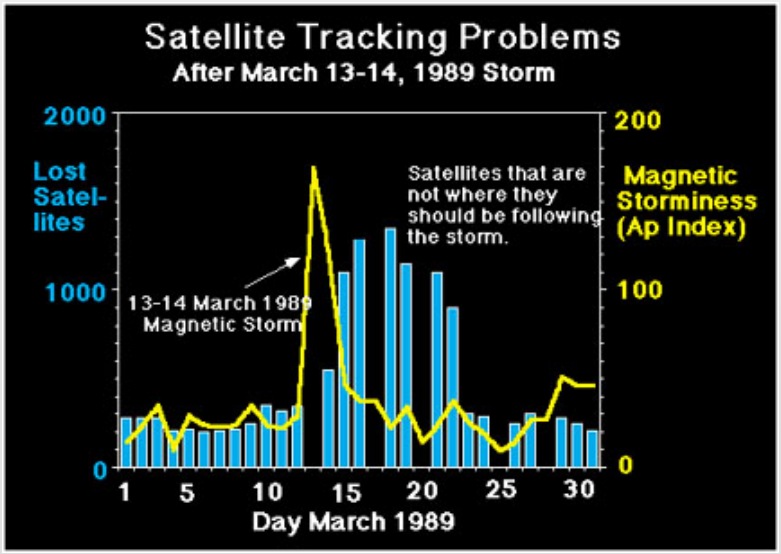
Ross, A.M., and Rhodes, D.H., "Using Natural Value-centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis," INCOSE International Symposium 2008, Utrecht, the Netherlands, June 2008.

Case Study: X-TOS

Single-Vehicle *in-situ* density measurements

- **Problem**: Inadequate drag models cause low-orbit objects to become "lost"
- **Need**: Better information on atmospheric drag
- **Concept**: In-situ vehicle carrying known instrument suite





X-TOS Case Study
Design and Value Attributes

- Proposed particle-collecting satellite in low orbit to sample atmospheric density
- Full MATE study conducted in 2002
- 8 design variables (7840 total designs), 5 value-generating attributes

Design Variable	Directly Associated Attributes
Apogee	Lifetime, Altitude
Perigee	Lifetime, Altitude
Inclination	Lifetime, Altitude, Max Latitude, Time at Equator
Antenna Gain	Latency
Comm. Architecture	Latency
Propulsion Type	Lifetime
Power Type	Lifetime
ΔV Capability	Lifetime

- Two-satellite configurations, in series and parallel, resulted in negligible utility gains for significant extra cost *(left out of this study)*

Changeability was noted to be highly desirable due to the effect of the uncertain atmospheric density (*intent of mission!*) on system performance

X-TOS Case Study
Transition Rules

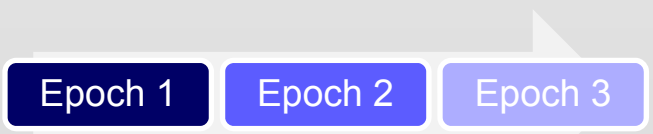
- In 2006, X-TOS revived for quantifying design changeability
- 8 transition rules designated for changing from one design point to another
- "Tugable" and "refuelable" designations created as binary "extra" design variables included for an added cost

Design Requirement	Effect	
Sufficient ΔV	Change inclination, decrease ΔV	} Burn fuel to change orbit
Sufficient ΔV	Change apogee, decrease ΔV	
Sufficient ΔV	Change perigee, decrease ΔV	
Tugable	Change inclination	} Change orbit via spacecraft tug
Tugable	Change apogee	
Tugable	Change perigee	
Refuelable	Increase ΔV	} Add fuel via space delivery
(none)	Change all orbit parameters and ΔV	} Add/insert new satellite

Costs for design transitions could include dollars, time, or other "currencies"
No transition is free (usually!)

Steps in Epoch-Era Changeability Analysis Approach

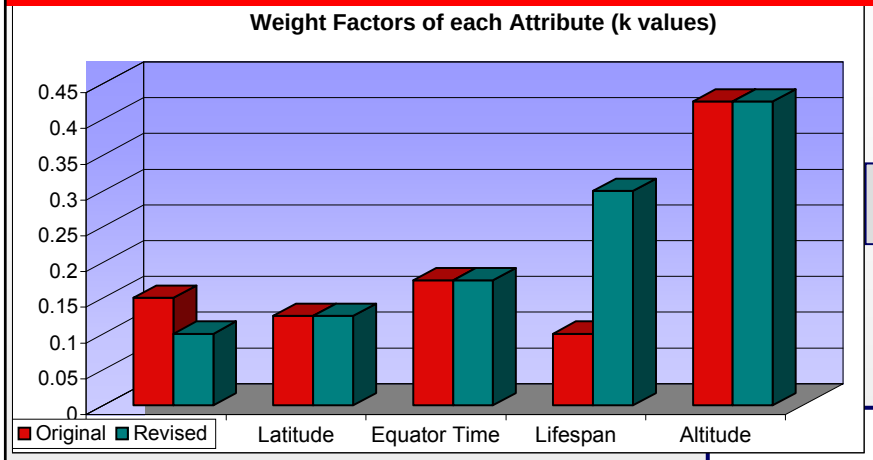
0. Construct epoch set using value-affecting parameters
1. Select concept designs
2. For each design in each epoch, calculate *valuable changeability* using chosen metric
3. Aggregate into frequency distributions for both individual designs and epochs
4. Statistical breakdown of valuable changeability distributions
5. Perform stochastic analysis of eras (epoch sequence) for additional value-over-time information



Epoch: time period with fixed context and needs

X-TOS Case Study
Step 0 - Epoch Creation

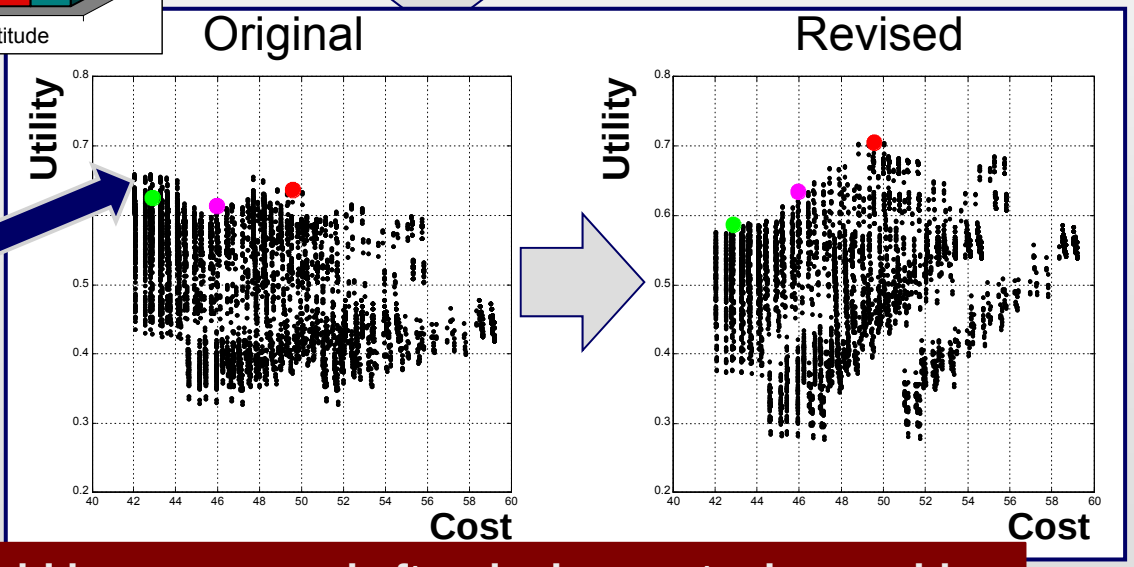
Science User Changes Preferences During Design Review



User changed preference "weighting" for lifespan

Evaluate new expectations

"Optimal" design had short, but acceptable lifespan (6 mos), after seeing proposed design, changed his preferences to reflect higher utility contribution from lifespan



Preference change could have occurred after deployment; changeable system more likely to be able to valuably respond

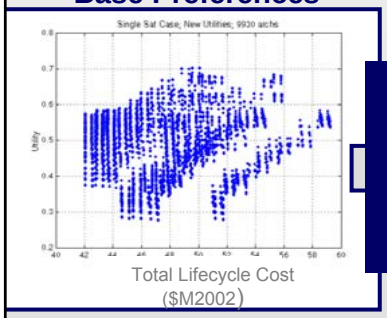
X-TOS Case Study
Step 0 - Epoch Creation (con't)

X-TOS epochs represent anticipatory exploration of possible preferences, helping to answer "what if" questions

What if you don't elicit the "right" requirements/preferences (attributes)?
What if you don't elicit the "right" attribute priorities?
What if you don't elicit the "right" utility curve shape?

- 58 total epochs are considered
  - Differentiated by varying stakeholder preferences in four ways
  - Enumerated one at a time as perturbations from the base case (i.e., 1 and 3 are never applied simultaneously)

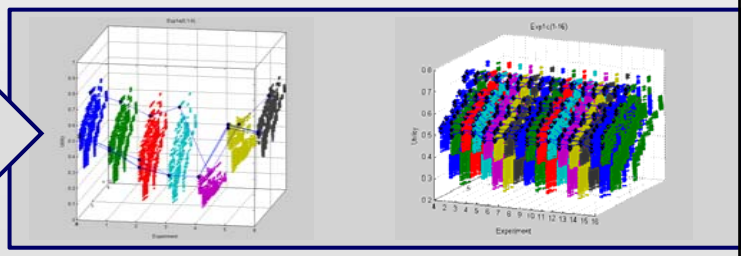
Base Preferences



Perturbation

1. Change value-delivering attribute set
2. Change attribute weightings in multi-attribute utility function
3. Linearize attribute utility curves
4. Different utility aggregating functions

Epoch Space (58)



More specific epochs can be created by actually re-deriving utility curves with the stakeholder for different hypothetical situations (mission goal change, wartime, etc)

Changeability Analysis Approach

Design Selection and Value of Changeability

1. Selecting Designs

- Selecting designs can take different forms
  - Full-factorial design vector enumeration
  - Only predetermined designs of interest
  - Single point design from technical study
- Choice should be made based on available time, data, and interest in detail for the study

2. Calculating Changeability Value

- Choose changeability value metric
  - Choice depends on parameters defining both system and epoch
- Value of each design's changeability within each epoch is calculated and stored

X-TOS Case Study
Step 1 – Select Designs

- We select seven designs, identified as designs of interest in the 2006 study, for further investigation

Ross, A. M. and D. E. Hastings, "Assessing Changeability in Aerospace Systems Architecting and Design Using Dynamic Multi-Attribute Tradespace Exploration", *AIAA Space 2006*

DV	2471	903	1687	2535	1909	3030	7156
Inclination	90	30	70	90	70	90	90
Apogee	460	460	460	460	1075	2000	770
Perigee	150	150	150	290	150	150	350
Com Arch	TDRSS	TDRSS	TDRSS	TDRSS	TDRSS	TDRSS	TDRSS
Delta V	1200	1200	1200	1200	1200	1200	1000
Prop Type	Chem	Chem	Chem	Chem	Elec	Elec	Chem
Pwr Type	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Solar Array	Solar Array
Ant Gain	Low	Low	Low	Low	Low	Low	Low
Data Life	0.51	0.51	0.51	10.05	0.52	0.61	11
Lat Div	180	60	140	180	140	180	180
Eq Time	5	11	6	5	2	2	5
Latency	2.27	2.27	2.27	2.30	2.42	2.67	2.40
Sample Alt	150	150	150	290	150	150	350
Cost ($10M)	4.21	4.21	4.21	4.88	4.52	4.99	4.15
Legend (ascending number order)	**D**	**A**	**B**	**E**	**C**	**F**	**G**

Could analyze ALL of the enumerated designs (limited only by computation time), but there are likely many uninteresting designs regardless of changeability.

An intelligent pre-processing method saves time and makes the results of the method more concise

X-TOS Case Study
Step 2 – Calculate Changeability Value

Value-Weighted Filtered Outdegree (VWFO) is used

- Uses X-TOS specified transition rules
- A new metric is currently in development to replace it, due to concerns over comparing utility between epochs

$$VWFO_i^m = \frac{1}{N-1}\sum_{j=1}^{N-1}[H(u_j^m - u_i^m) * Arc_{i,j}^m]$$

H	= Heaviside step function
N	= number of designs
i	= origin design
j	= destination design
Arc	= transition allowed
m	= current time (context)
u	= utility of design

VWFO counts only changes beneath a time/money cost threshold which result in a positive effect on utility

X-TOS Case Study

Step 2 – Calculate Changeability Value

- VWFO is calculated for each design in each epoch
  - the filter is set to maximum → no changes are eliminated

Design

Epoch Number	A	B	C	D	E	F	G
1	2.55	2.81	3.06	2.68	0.77	2.55	2.55
2	2.68	2.81	2.93	2.93	0.89	2.81	3.32
3	2.68	2.68	2.81	2.68	0.64	2.55	2.55
4	0	0	0	0	1.53	0.38	7.78
5	0	0.26	0.26	0.13	1.66	0.38	7.40
6	3.06	3.32	3.06	3.19	0.77	2.55	1.91
7	1.66	1.91	2.68	1.79	0.13	2.55	4.47
…	…	…	…	…	…	…	…

$x10^{-3}$

This is raw data: effectively using it is the tricky part!

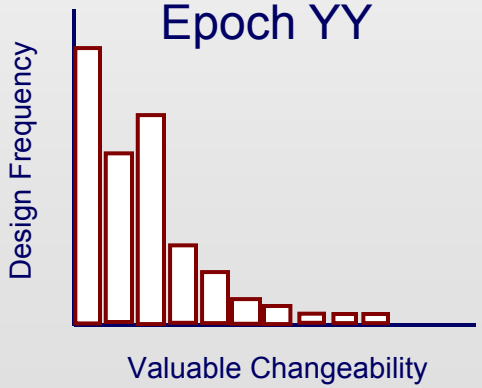
Changeability Analysis Approach
Frequency Distribution

3. Aggregating Frequency Distributions

The calculated valuable changeability data can be aggregated and presented as distributions

- distribution of one design over all epochs
- distribution of one epoch over all designs

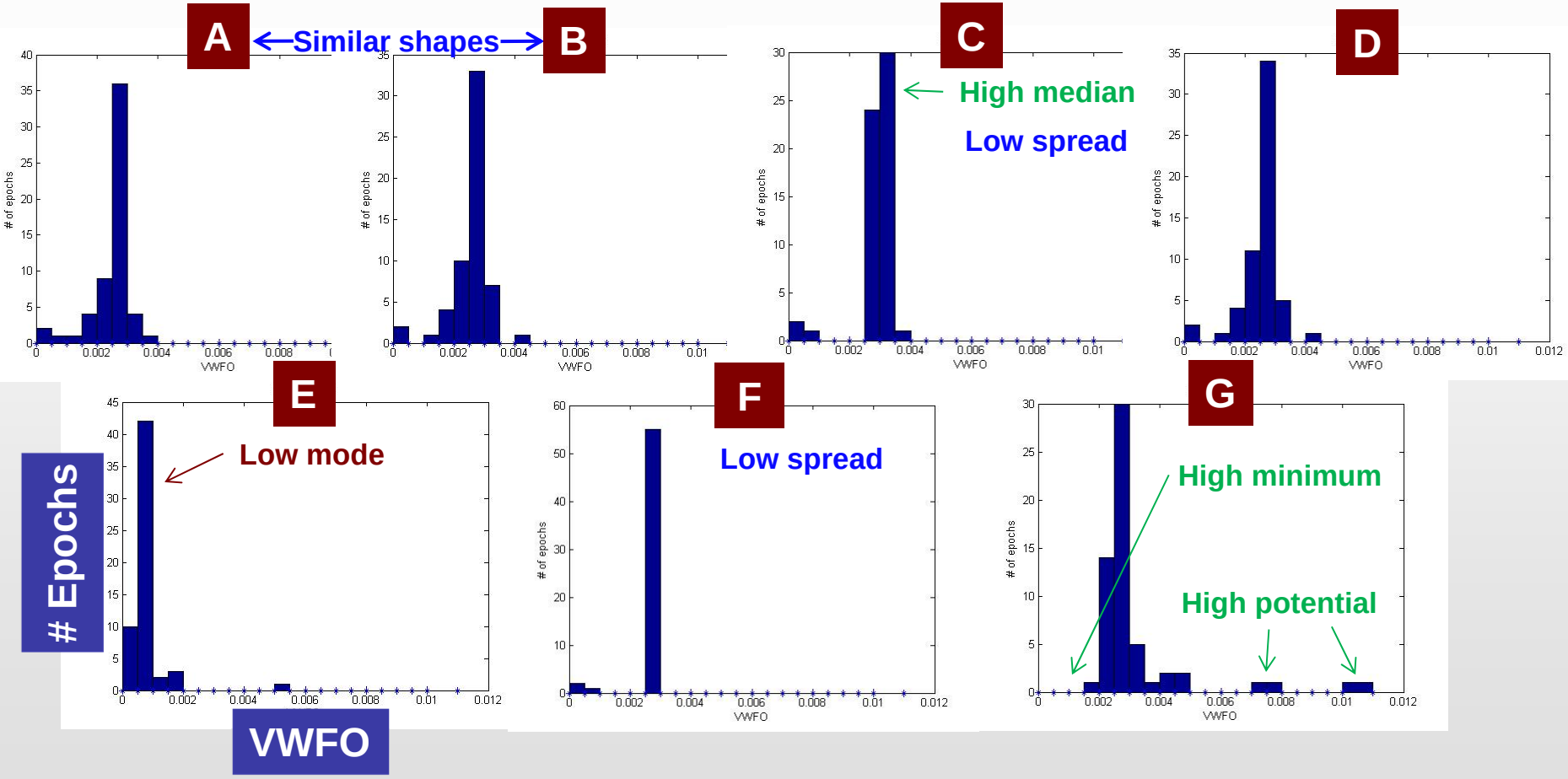
Glimpse into Design XX's valuable changeability within epochs



Glimpse into ease/difficulty of design changeability within Epoch YY

X-TOS Case Study

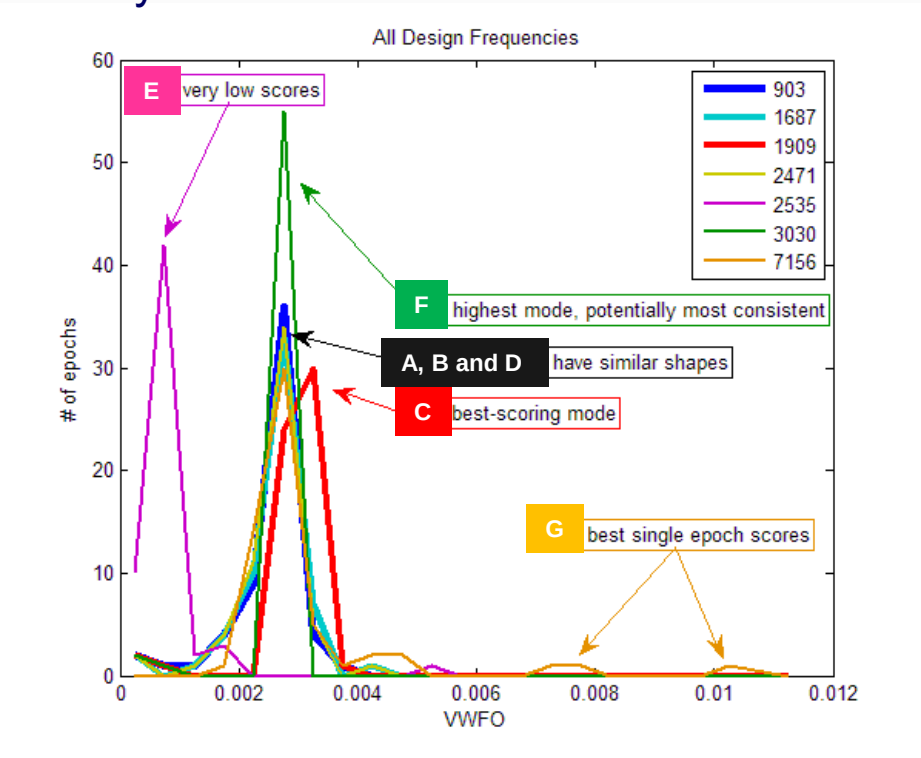
Step 3 – Frequency Distribution



A quick scan gives us an intuitive understanding of the differences in changeability between the designs over the varying epochs

X-TOS Case Study
Step 3 – Frequency Distribution

Frequency curve overlay view:



Too many or too similar designs will be crowded:

Remember that an intelligent preselection, reducing the number of designs in consideration, makes the data easier to visualize and draw conclusions from

Changeability Analysis Approach
Statistical Breakdown

4 . Statistical Breakdown of Distributions

- Distributions themselves provide good intuitive understanding, but a more quantitative statistical breakdown is needed to effectively compare large numbers of designs
- Of particular interest are the order statistics: minimum, maximum, median, percentiles
  - Can be easily calculated from data sets that form distributions
  - Averages/variances may also prove useful, but since distributions are not necessarily in a canonical form they have little physical significance

Depending on design philosophy or stakeholder risk preferences, designs may carry different levels of appeal. XX has highest potential changeability value, XY has highest minimum, and XZ has highest median.

Cross-epoch Valuable Changeability Summary

Design	Min	1st Quartile	Median	3rd Quartile	Max
XX	0	0.2	0.3	0.6	0.7
XY	0.1	0.2	0.25	0.3	0.4
XZ	0	0.1	0.4	0.5	0.6

X-TOS Case Study
Step 4 – Statistical Breakdown

- Distributions are mined for descriptive statistics
  - Can reaffirm visual conclusions of previous step and reveal new information
  - Mean and Standard Deviation shown to illustrate a point: the mean for Design G is pulled up by its outlier maximum; *the median is more trustworthy as a comparison of central tendency between designs!*

Design	A	B	C	D	E	F	G
Min	0	0	0	0	0.13	0.38	1.91
1st Quart.	2.42	2.42	2.81	2.17	0.64	2.55	2.42
Median	2.55	2.81	3.06	2.68	0.77	2.55	2.55
3rd Quart.	2.81	2.93	3.06	2.81	0.77	2.55	2.93
Max	3.96	4.21	3.57	4.08	5.49	2.81	17.99
Mean	2.46	2.61	2.83	2.49	0.80	2.45	3.13
Std Dev	0.65	0.67	0.63	0.66	0.69	0.48	2.27

$x10^{-3}$

This view allows for easy comparison between designs, especially for larger studies. We use it here to confirm the relative superiority of C and G, and the weakness of E.

Changeability Analysis Approach
Era Analysis

5. Stochastic Analysis of Era

Other types of information can be extracted by creating *ordered sequences of epochs* (i.e., era) using a stochastic era construction model, and analyzing value effects on systems over time

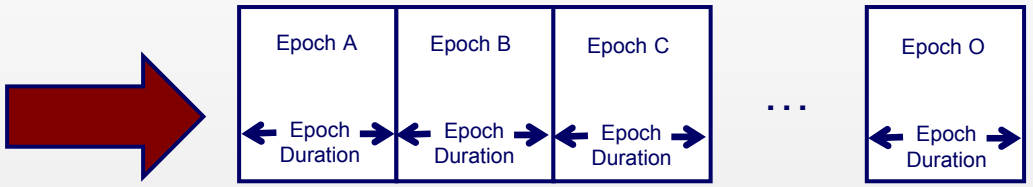
Can use different techniques depending on type of changeability analysis for system

- A full tradespace exploration study with defined change mechanisms between different designs permits creation of transition rules
- A point-design real option study on value of including a particular payload or package would allow for a higher-fidelity calculation of option value predicated on the changing parameters over time

X-TOS Case Study
Step 5 – Era Analysis

For this section, a simple era constructor and decision algorithm was created and applied to the epoch/design set

1. Random epoch selection
2. Geometric epoch duration
3. Acceptable MAU threshold = 0.4
   (if below 0.4, attempt to transition above for lowest cost)
4. Target lifetime = 15 years



Rader, A.A., Ross, A.M., and Rhodes, D.H., "A Methodological Comparison of Monte Carlo Methods and Epoch-Era Analysis for System Assessment in Uncertain Environments," 4th Annual IEEE Systems Conference, San Diego, CA, April 2010.

- 1000 randomly generated eras tested for each design
  - Recorded successes, dollar and time cost of transitions (for successful eras), and number of transitions in each era
- Other (unused) options
  - Penalty cost for failure to both dollars and time
  - More complex and realistic decision-making algorithms , such as “move as close to the Pareto Front as possible”

Era construction can be as simple or as complex as desired, but should remain realistic to the epoch definitions

X-TOS Case Study
Step 5 – Era Analysis (con't)

Design	A	B	C	D	E	F	G
Success %	75.3	75.8	75.0	75.2	73.6	75.6	78.0
Avg $ cost	0	2.49K	6.35M	0	0	3.15M	0
Avg time cost	13 min	17 min	4.27 mo.	14 min	0	4.97 mo.	0
Avg # transitions	.651	.846	2.008	.648	0	1.897	0

- Obvious similarities
  - A, B, D *again* – cheap transitions (fuel burns)
  - C and F – expensive transitions (space tugs)
  - E and G – changeability not utilized (passively robust)
    - Function of the decision algorithm

Constructing eras with defined transition logic allows for a better understanding of the effect of changeability "in action" and its relationship with system value delivery

Reminder:
Steps in Epoch-Era Changeability Analysis Approach

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Epoch: time period with fixed context and needs

Applying Approach Using Existing Data Sets

- 3 important steps to beginning this process when starting from an existing study
  - **Design selection:** limit to a reasonable amount (~10) for clarity, selecting the most interesting designs, unless time is not a concern and full detail is desired
  - **Value metric choice:** choose based on available information, assumptions deemed acceptable by stakeholders, and the particular system application being considered
  - **Epoch creation:** find any parameters in your value statements (both static and for changeability) that are assumed to be constant in one context and vary them over a reasonable range

There are no "right" choices for these steps: an intelligent decision maker who understands the system should select the methods he considers to be appropriate

Emerging Research Results

- EEA-based method for comparing candidate design changeability
  - Compatible with any changeability value metric
  - Enables diagrams and statistics which represent the frequently unintuitive nature of value-over-time in an intuitive, static form
  - Scalable, allowing for both in-depth design space studies and less computationally demanding design point analysis

Epoch Era Analysis provides a generalizable foundation on which to evaluate changeability and to assist the design process.

Further Research

- **New changeability value metric:** strong desire for a metric with general applicability, as opposed to the limiting assumptions on common techniques
- **Change mechanism value:** a concise method for assessing the value of including different change mechanisms
  - Would allow change mechanisms to be effectively traded off individually in the design process
- **Modular change:** methods for aggregating the value of change with infinite potential end states

Thank You