Adaptive and Resilient Space Systems Panel

Dr. Adam M. Ross*, Research Scientist
Massachusetts Institute of Technology

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*Incorporating work from Matthew Fitzgerald, Dr. Matthew Richards, Dr. Donna Rhodes, Prof. Daniel Hastings, and Prof. Olivier de Weck

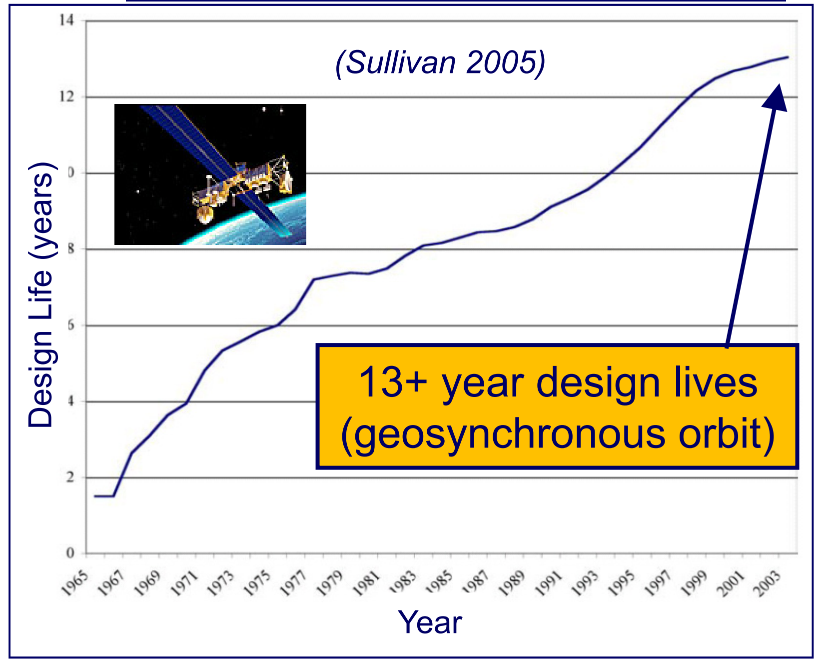
Mismatch of Design with Context

1960's Paradigm

- CORONA: 30-45 day missions
- 144 spacecraft launched between 1959-1972

(Wheelon 1997)

Evolution to Current State

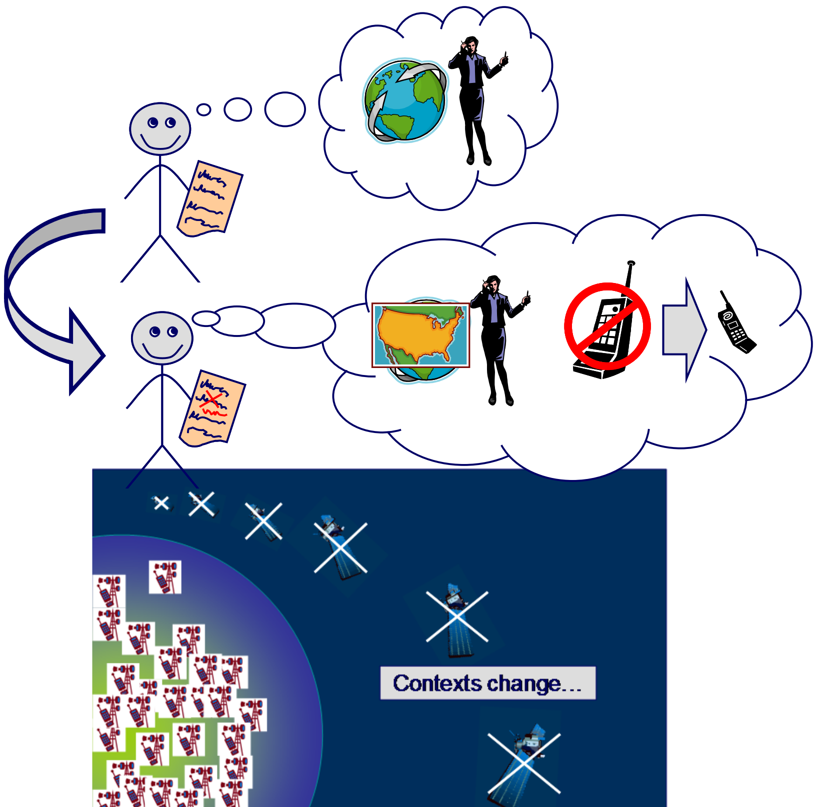


- Inability to adapt to uncertain future environments, including disturbances

"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)*

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.

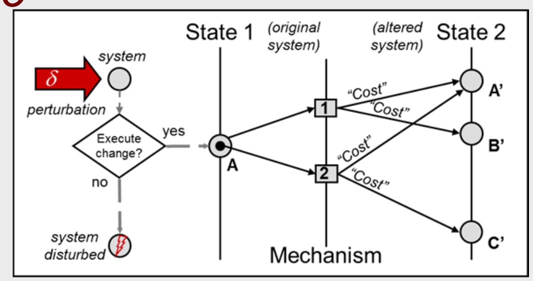
Illustrations: Nook

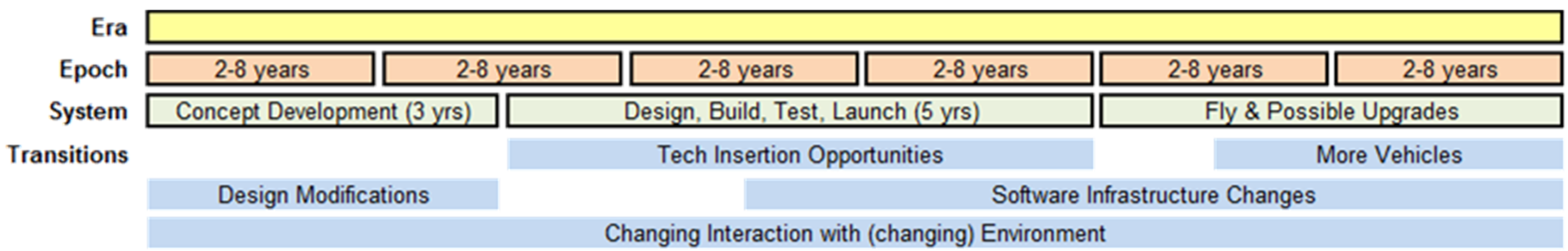
Source: Wired Magazine, August 2010

Changing contexts can have high consequences if systems fail…

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 need for system adaptability*



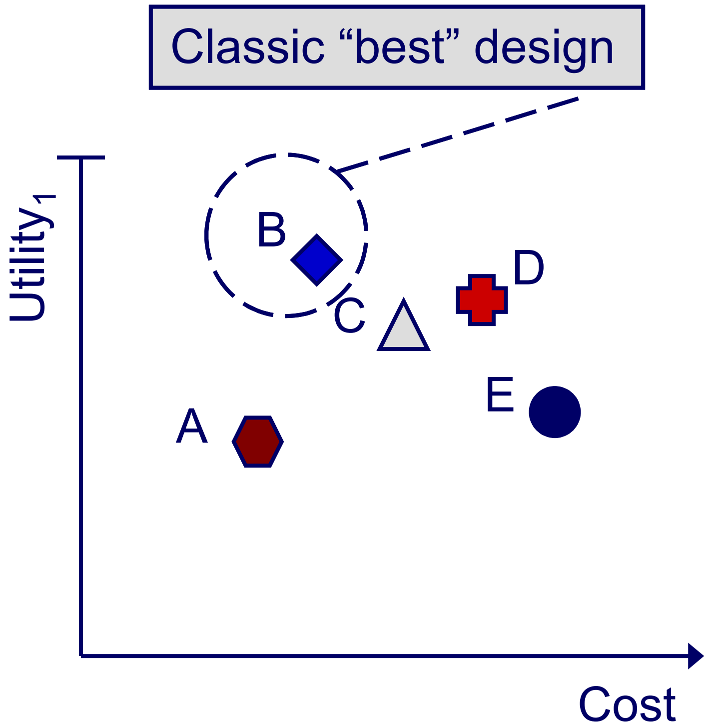


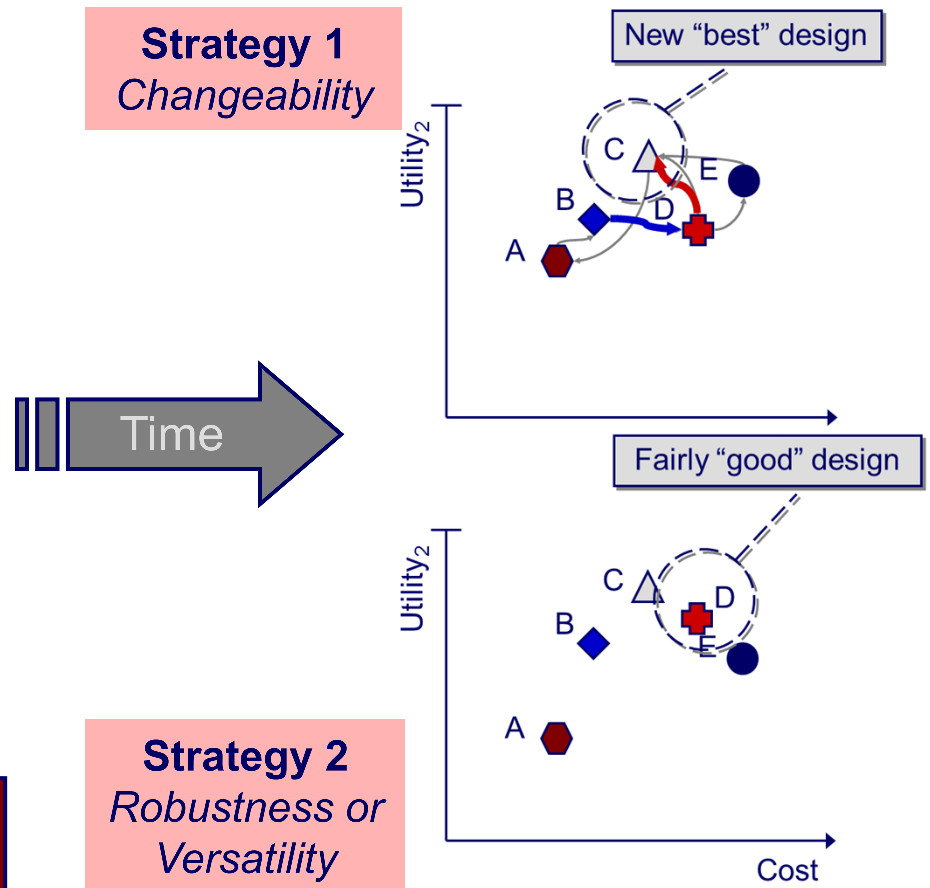
Systems developed in dynamic world and must accommodate shifts in context and needs (epoch) across their lifespan (era)

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

*For consistency with our past research, we use the term "changeability," which corresponds to "adaptability" and "flexibility"

Selecting “Best” Designs





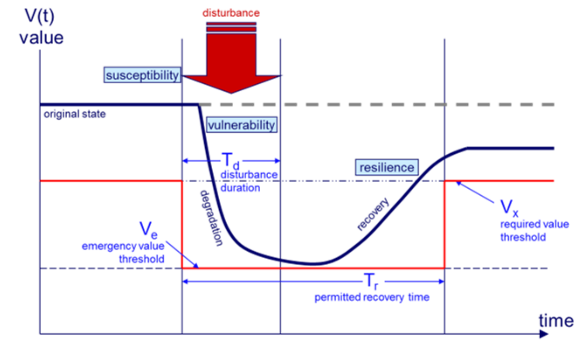
If the “best” design changes over time, how does one select the “best” design?

Changeable designs are *actively value robust*

Robust and Versatile designs are *passively value robust*

Changeability: Acceptable switch costs to new “designs”
Robustness: Insensitive to perturbations
Versatility: Inherent multiple “solutions” to perturbations

Related "ilities": Adaptability and Resilience



value robustness	ability of a system to maintain value delivery in spite of changes in needs or context
changeability	ability of a system to be intentionally altered in form or operations, and consequently possibly in function, at an acceptable level of "cost"
flexibility	ability of a system to be altered by a system-external change agent
adaptability	ability of a system to be altered by a system-internal change agent
survivability	ability of a system to minimize the impact of finite-duration disturbances on value delivery
susceptibility	reduction of the likelihood or magnitude of a disturbance
vulnerability	satisfaction of minimally acceptable value level during and after disturbance
resilience	timely recovery to an acceptable value level after a disturbance

A ***valuably changeable*** system is one that can be intentionally altered, typically in response to a perturbation (such as a change in context), in order to improve its value

Accounting for Valuable "ilities"

- Benefits of "ilities":
  - Systems can continue to produce value in uncertain future
  - Robust or versatile systems create greater expected value (Net Present Value or NPV) in the presence of uncertainty
  - ***Options*** *enable* changeable systems
- Costs of "ilities":
  - Direct cost (cost of robustness / cost to exercise options)
  - Cost of hooks (cost to purchase option)
  - Lost utility or added cost when compared to "optimized" solution
- Example valuation methods for "ilities"
  - Real Options Analysis
  - Tradespace Networks
  - Outdegree Assessments

There is a difference between whether something is "changeable" or "valuably changeable"

Conflicting Tensions to Account for Valuable Changeability

- Justifying investment in changeable (adaptable) systems is difficult because "valuable changeability" requires considering and trading off multiple dimensions
- Existing design approaches and metrics tend to account for a subset of these dimensions
- A set of metrics should be used to evaluate valuable changeability, determined by intended value sustainment strategy, context, and availability of data

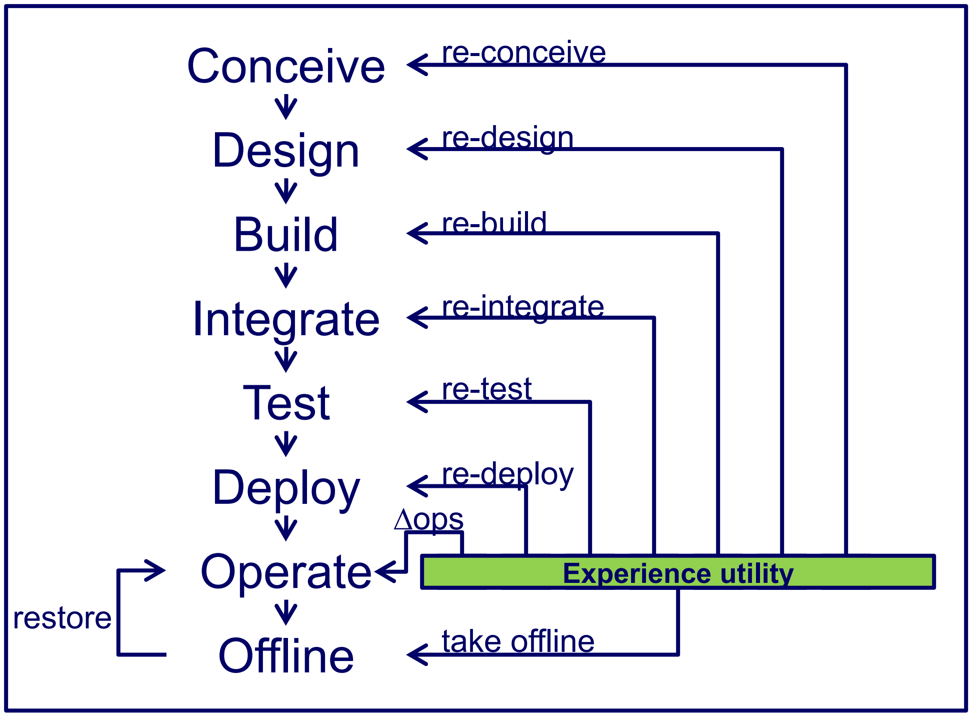
Dimensions of key aspects to accounting for valuable changeability

Design vs. Value		Short run vs. Long run		Context specific vs. General	
f(design-only)	f(value-only)	f(per epoch)	f(per era)	$f(epoch_i)$, i=M	$f(epoch_i)$, $\forall i$
Examples:					
Number of spares	*Excess capacity*	*Number of options during fabrication*	*Number of options across lifecycle*	*Sensitivity to specific available technology*	*Sensitivity to changes in budget*

Recent research, Valuation Approach for Strategic Changeability (VASC), guides selection of appropriate metrics for a given valuable changeability assessment

When to Change the System: Lifecycle Phase Impacts

The time in a lifecycle when a system change occurs is an important consideration for changeability and tradeoffs



Adversary timescale shorter than "system" lifecycle

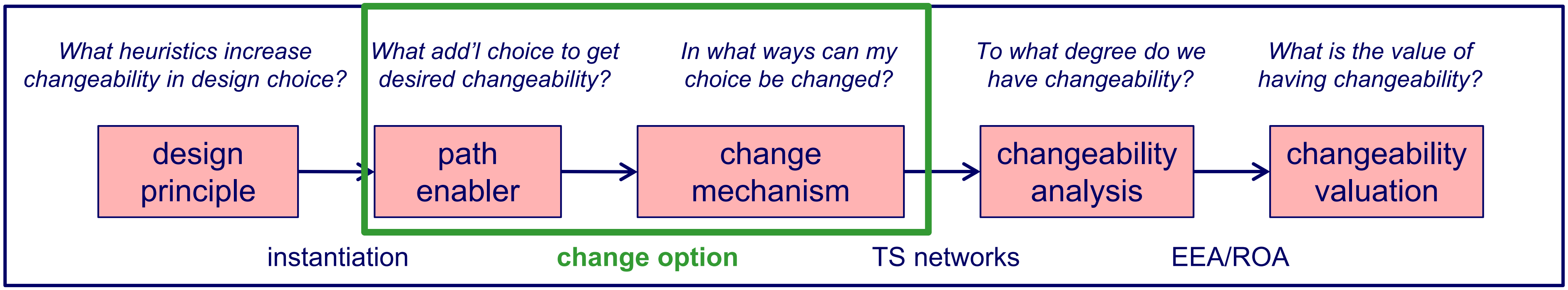
Source: *Wired Magazine, August 2010*

The farther a change goes back into the lifecycle, the longer (usually) it takes before utility is experienced again

Choices can be made to give an option to change later in lifecycle, or to reduce the time and cost for getting back to operations

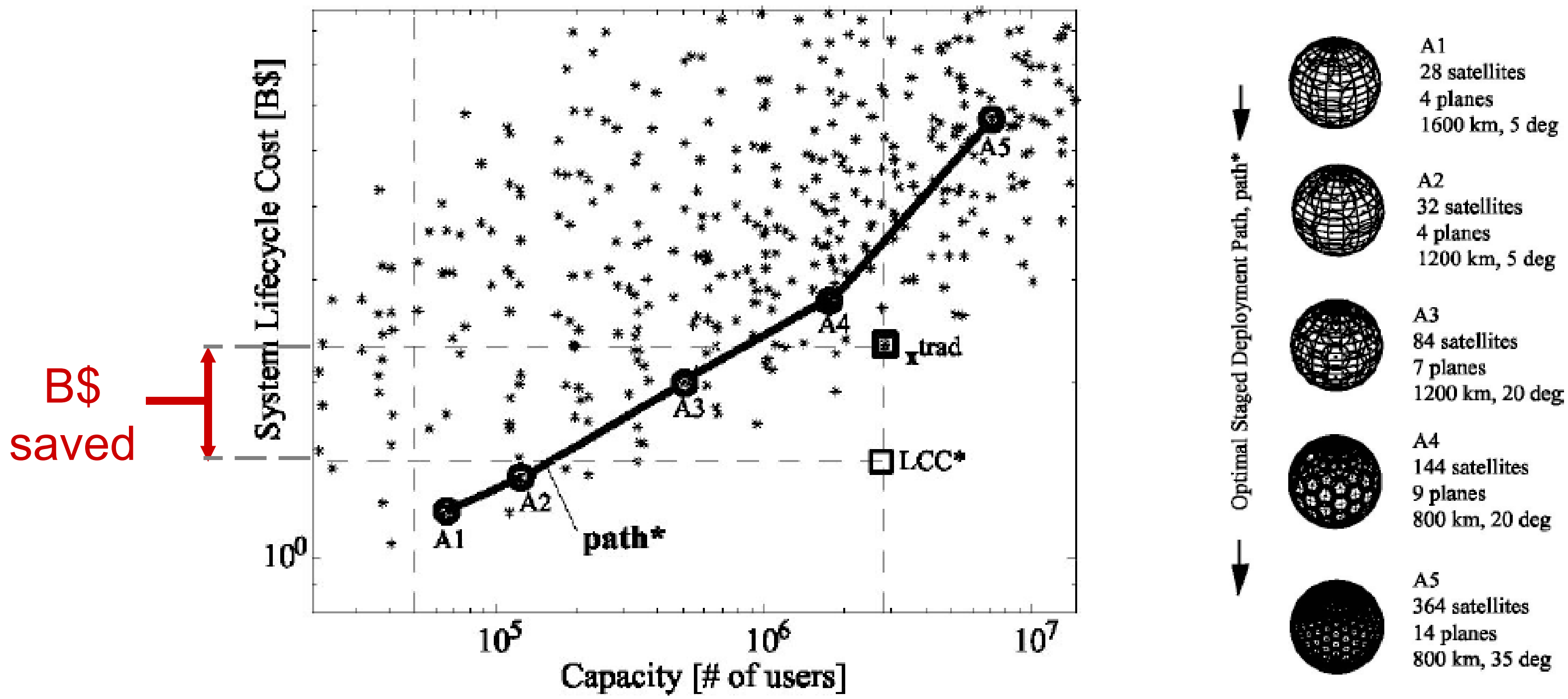
"Success" determined by matching response time and cost to the perturbation

Example Change Options



System	Path Enabler	Change Mechanism	Potential End States
ARAMIS satellite architecture	Modular tile components	Reconfiguring/adding/substituting tiles	Many
iPhone	Mobile App Store and extensible software architecture	Adding new function	Many
Space station w/shuttle	Docking w/ extra fuel and thrusters	Increasing ISS altitude by shuttle firing thrusters	Many
F-14	Mechanical hinged wings	Changing wing sweep angle	Few
Atlas V	Strap-on solid rocket motors	Scaling up or down lift capability	Few
US ISR SoS	Reprogrammable Global Hawk flight-path waypoints	Changing surveillance area, as needed, by combatant commander	Infinite

Example: Staged Deployment of Satellite Constellation



Embedding the *real option* to deploy system in stages allows for mitigation of demand uncertainty

Source: de Weck, O.L., de Neufville R. and Chaize M., "Staged Deployment of Communications Satellite Constellations in Low Earth Orbit", *Journal of Aerospace Computing, Information, and Communication*, **1** (3), 119-136, March 2004.

Example Choices that Enhance Changeability in Space Systems

Here are some example design and operations choices that could improve the valuable changeability or versatility of space systems

- Allow more capabilities of the system to be software addressable (i.e., remote change enabled)
- Allow the systems to be serviced on orbit (i.e., design it that way, in-situ change enabled)
- Consider splitting functions across architectures (of which fractionation is an extreme example)
- Launch often with short lived systems
- Build spares (on ground or in-orbit)
- Develop scalable architectures (e.g., allow for staged deployment of constellation)
- Pursue standardized platform architectures (e.g., standard bus)
- Develop reconfigurable systems (i.e., those with very low switch costs between a finite set of states)
- Leverage less capable, more mature technologies, possibly available from multiple suppliers
- Pursue modularized payloads (i.e., allow for swapping of payloads on-ground or in orbit)
- Consider infrastructure development to offload functions from given mission-specific systems (i.e., lowers incremental mission costs)
- Consider augmenting capabilities with airborne platforms (i.e., allows for incremental and responsive performance enhancement)
- Develop data integration and interoperability capabilities to enable ad-hoc “SoS” across systems

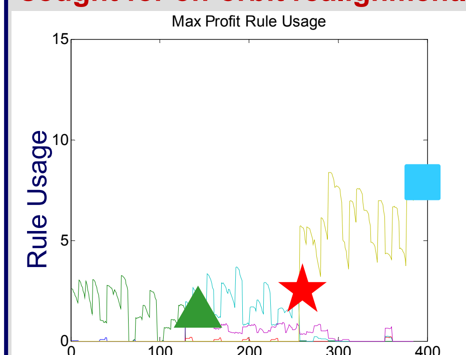
Keep in mind that for given expectations on perturbation time scales, the cost of system changes, and expected needs, different design/operation strategies may be “best”

Systems Engineering Advancement Research Initiative

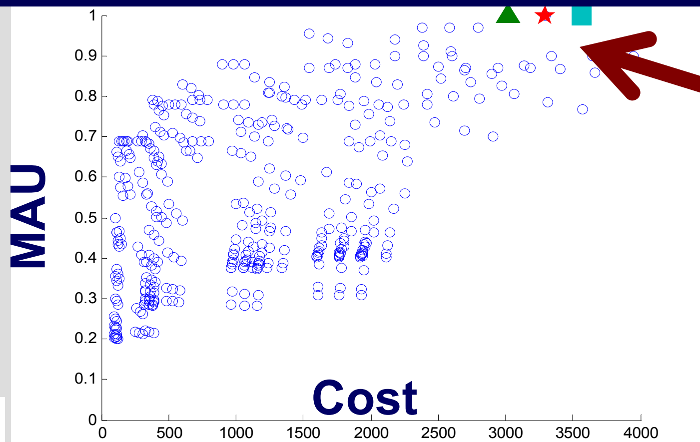
Goal: Adaptability Investment Tradeoff for an Orbital Transfer Vehicle

More complete accounting of benefits of adaptability for investment and design decisions

Orbit transfer vehicle scenario simulates future missions sought for on-orbit realignment.



Adaptability shown to be more available and utilized by the higher cost designs



Static tradespace shows apparent excessive cost for red or cyan designs

VASC era analysis quantifies the cost tradeoff for additional lifetime value

Design:	128 ▲	256 ★	384 ■
# of adaptability features	0	2	3
Initial cost for adaptability	$0M	$272M	$544M
Average # missions completed	14.6	15.3	17.9
Avg. % deviation from cost efficiency	38.8	33.6	20.1
Avg. anticipated lifetime net benefit	$70B	$66B	$104B

N= 5000 alternative futures (per design)

Quantification of Adaptability Decision Options

Additional initial investment can result in increases in missions completed, efficiency, and net benefit

Example Related Publications

de Weck, O.L., de Neufville R. and Chaize M., "Staged Deployment of Communications Satellite Constellations in Low Earth Orbit", *Journal of Aerospace Computing, Information, and Communication*, **1** (3), 119-136, March 2004.

Fitzgerald, M.E., Ross, A.M., and Rhodes, D.H., "A Method Using Epoch-Era Analysis to Identify Valuable Changeability in System Design," 9th Conference on Systems Engineering Research, Los Angeles, CA, April 2011.

Richards, M.G., Ross, A.M., Hastings, D.E., and Rhodes, D.H., "Survivability Design Principles for Enhanced Concept Generation and Evaluation," INCOSE International Symposium 2009, Singapore, July 2009.

Richards, M.G., Ross, A.M., Shah, N.B., and Hastings, D.E., "Metrics for Evaluating Survivability in Dynamic Multi-Attribute Tradespace Exploration," *Journal of Spacecraft and Rockets*, Vol. 46, No. 5, September-October 2009.

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.

Ross, A.M., Rhodes, D.H., and Hastings, D.E., "Defining Changeability: Reconciling Flexibility, Adaptability, Scalability, Modifiability, and Robustness for Maintaining Lifecycle Value," *Systems Engineering*, Vol. 11, No. 3, pp. 246-262, Fall 2008.

Ross, A.M., McManus, H.L., Rhodes, D.H., Hastings, D.E., and Long, A.M., "Responsive Systems Comparison Method: Dynamic Insights into Designing a Satellite Radar System," AIAA Space 2009, Pasadena, CA, September 2009.

Siddiqi A., de Weck O., Iagnemma K., "Reconfigurability in Planetary Surface Vehicles: Modeling Approaches and Case Study", *Journal of the British Interplanetary Society (JBIS),* 59, 2006.

Silver M., de Weck O. "Time-Expanded Decision Networks: A Framework for Designing Evolvable Complex Systems", *Systems Engineering*, 10 (2), 167-186, 2007

Suh E.S., de Weck O.L., and Chang D., "Flexible product platforms: framework and case study", *Research in Engineering Design*, 18 (2), 67-89, 2007.

Websites with more information: http://seari.mit.edu http://strategic.mit.edu

BACKUP SLIDES

Panel Questions

- What do Adaptability and Resilience mean in space systems?
- What are the characteristics of an Adaptable space system?
- How can we justify implementation of Adaptability in a space system, since it often incorporates additional cost to the system?
- How can we build and operate Adaptive Space Systems?

SEAri Working Definitions for Selected "ilities"

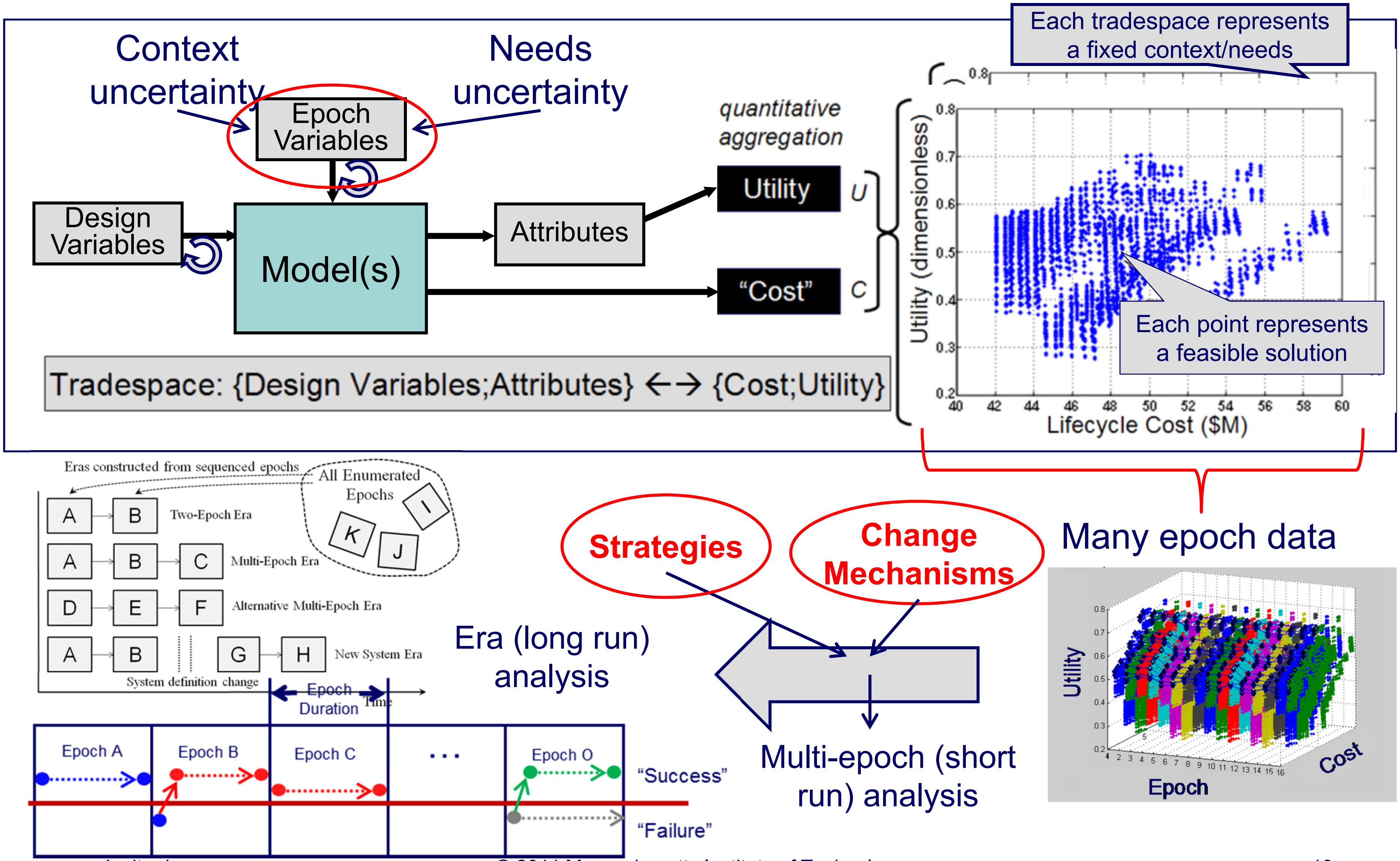
robustness	ability of a system to maintain its level and set of specified parameters in the context of changing system external and internal forces
versatility	ability of a system to satisfy diverse needs for the system without having to change form (measure of latent value)
changeability	ability of a system to alter its form—and consequently possibly its function—at an acceptable level of resource expenditure
flexibility	ability of a system to be changed by a system-external change agent with intent
adaptability	ability of a system to be changed by a system-internal change agent with intent
scalability	ability of a system to change the current level of a specified system parameter
modifiability	ability of a system to change the current set of specified system parameters
survivability	ability of a system to minimize the impact, or potential impact, of a finite duration disturbance on value delivery
evolvability	ability of a design to be inherited and changed across generations (over time)
reconfigurability	ability of a system to between a finite set of states at low switch costs
extensibility	ability of a system to accommodate new features after design
value robustness	ability of a system to maintain value delivery in spite of changes in needs or context

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

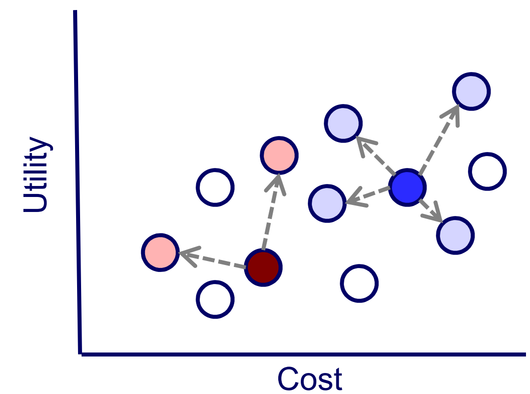
Each of these address different aspects of value sustainment (via changeability or robustness)

Data Flow for VASC Metrics



Counting vs. Magnitude of Change

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

Considerations for Evaluating and Valuating Changeability

How do we achieve desirable (i.e. "valuable") changeability?
How do we know when we have it?

1. Can system change itself (adaptable) or be changed (flexible), reacting to perturbation?

- Can system or external 'agent' detect, assess, and decide on appropriate responses to a perturbation?
- Does system have possible new 'states' or 'operation modes'?
- Can the system alter itself, or be altered to one of these new 'states' or 'modes'?
- Can a change be accomplished through a structural and/or operational strategy?
- What will be the timescale and costs for making the change?

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

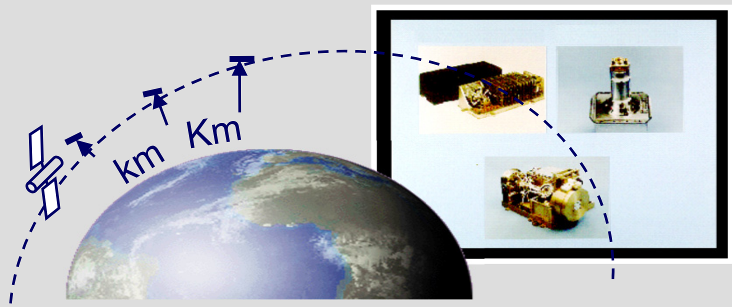
- What is the value (benefit at cost) of the change in a given epoch (context) for a given stakeholder? (i.e., are the costs appropriate and sufficient for the benefit?)
- What is the accumulated value across the entire era (lifecycle) and how does changeability support or impede this value?
- Are stakeholders willing to sacrifice value in one epoch (short run) in order to achieve higher value in the era (long run)?
- How many change pathways are possible for making valuable changes?

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

Identified Adaptability-Enhancing Design Features in a Satellite System

For given system, defined possible change mechanisms that allow system to adapt to new missions

From "X-TOS" satellite system analysis



Rule	Description	Change Enablers
R1: Plane Change	Increase/decrease inclination, decrease DV	Extra fuel
R2: Apogee Burn	Increase/decrease apogee, decrease DV	Extra fuel
R3: Perigee Burn	Increase/decrease perigee, decrease DV	Extra fuel
R4: Plane Tug	Increase/decrease inclination, requires "tugable"	Grappling point
R5: Apogee Tug	Increase/decrease apogee, requires "tugable"	Grappling point
R6: Perigee Tug	Increase/decrease perigee, requires "tugable"	Grappling point
R7: Space Refuel	Increase DV, requires "refuelable"	Refuelable tank
R8: Add Sat	Change all orbit, DV	Satellite spares

For a selected strategy "*maintain greater than 40% mission utility over 15 years*", identified features

software-based automated analysis

Design Number:	903	1687	1909	2471	2535	3030	7156
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	0.65	0.85	2.0	0.65	0	1.9	0
Rule(s) Executed	1-3	1-3	4-6	1-3	n/a	4-6	n/a

Adaptability-Enhancing Design Features

Add grappling points to allow for space tug

Carry extra fuel to allow for re-maneuvering

None needed

N= 1000 alternative futures (per design)

Potential Exists for "Design for Adaptability" Design Principles

Degree of adaptability can be assessed if
- Perturbations and end states can be quantified (e.g., filtered outdegree)

Value of adaptability can be assessed if
- Future contexts/expectations can be quantified (e.g., value-weighted filtered outdegree)
- For real options, probabilities must be known as well

Given a rigorous definition and metrics for adaptability, theoretically and empirically proposed "design for adaptability" principles can be developed; see Richards (2009)

Foundational research indicates architecting principles, metrics, and strategies for adaptability are achievable, but still of low maturity

Theoretically and empirically derived survivability design principles (Richards 2009)

Type I (Reduce Susceptibility)
prevention
mobility
concealment
deterrence
preemption
avoidance
Type II (Reduce Vulnerability)
hardness
redundancy
margin
heterogeneity
distribution
failure mode reduction
fail-safe
evolution
containment
Type III (Enhance Resilience)
replacement
repair

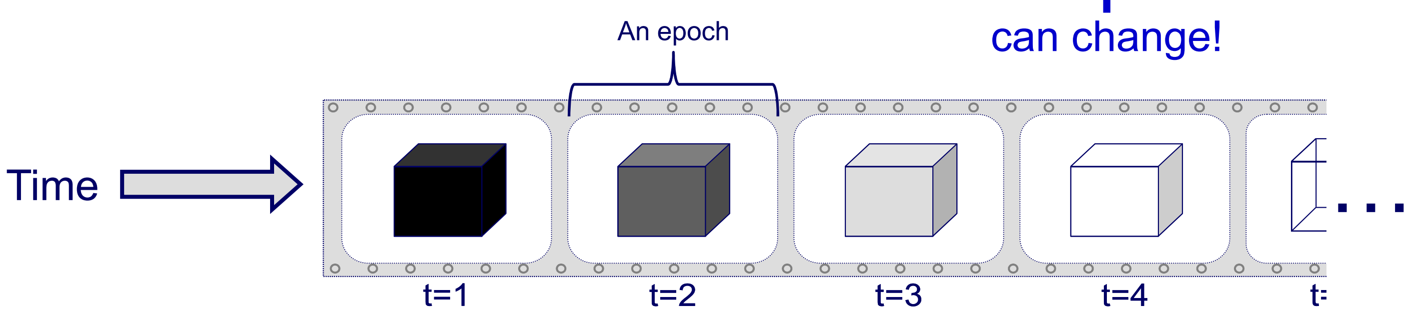
An “Epoch” as a Snippet of Time

Definition of Epoch

Time period with a fixed context and needs; characterized by static constraints, concepts, available technologies, and articulated expectations

System success depends on the system meeting *expectations* within a given *context*

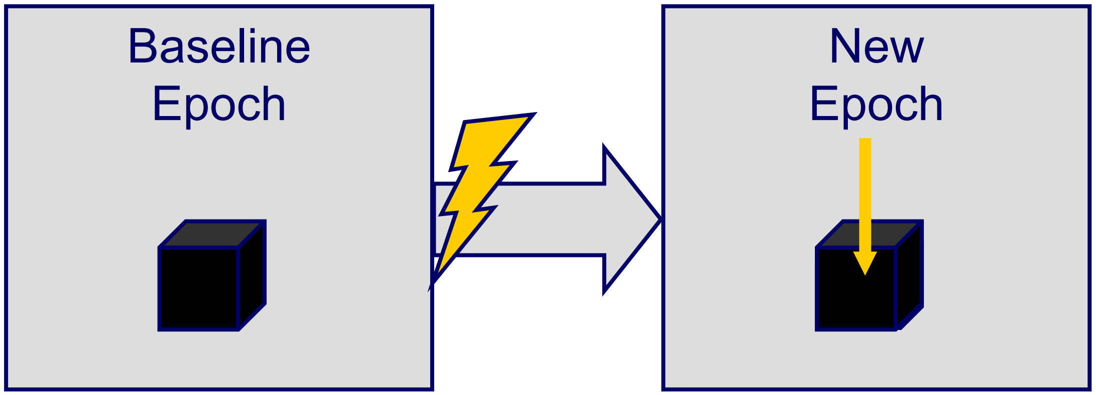
can change! can change!



Epoch-based Thinking

Using the concept of “epoch” to generate and consider a large number of possible future contexts and needs facing a system, along with short term and long term strategies for maintaining a successful system across epochs

Basic Epoch Shift: System Impact-Response



System Definition

Baseline Epoch → **New Epoch**

↓

Response(?) ← **Effect**

↓

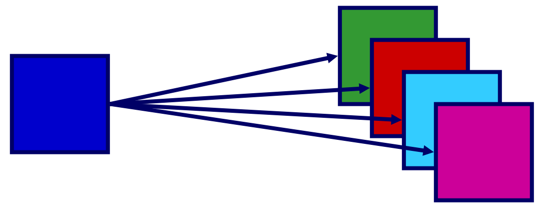
Success?

- What about analyzing across more than just pair-wise epoch shifts?
- How can the technique become generalized or even automated?

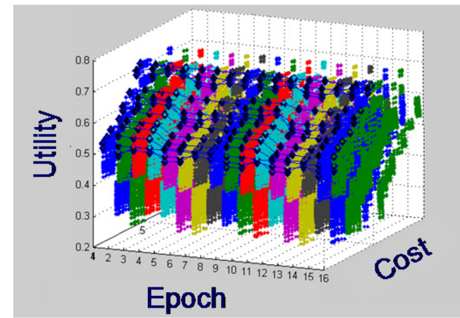
Generating Epochs

Many possible contexts and needs may unfold in the future, impacting actual and perceived system utility and cost

"Epoch-based thinking" can be used to structure anticipatory scenario analysis



Today Possible futures (epochs)



Example triggers for epoch shifts impacting a system

- Change in political environment
- Entrance of new competitor in market
- Emergence of significant new or changed stakeholder need(s)
- Policy mandate impacting product line, services or operations

Categories of epoch variables can aid in thinking about key changing factors

E.g., Resources, Policy, Infrastructure, Technology, End Uses ("Markets"), Competition, etc.

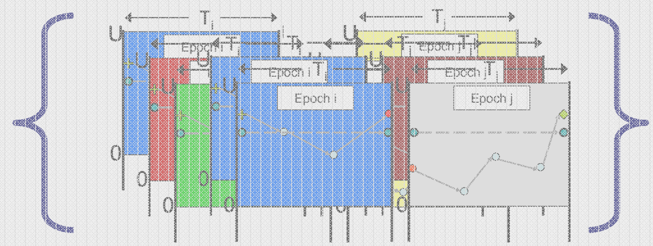
Multi-Epoch Analysis

RSC Processes

Process 3

Epoch Characterization

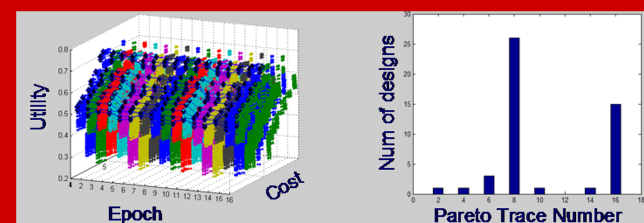
Epoch set represents potential fixed contexts and needs



Process 5

Multi-Epoch Analysis

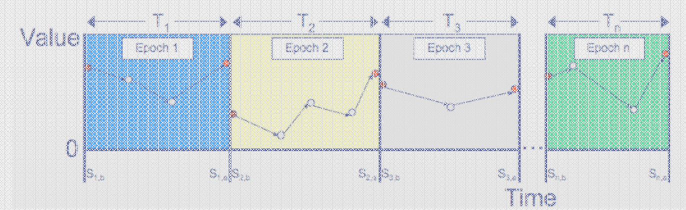
Analysis across large number of epochs reveals “good” designs



Process 6

Era Construction

Eras represent ordered epoch series for analyzing system evolution strategies



- Cross-epoch analysis
- Within-epoch analysis
- Identification of versatile and changeable designs

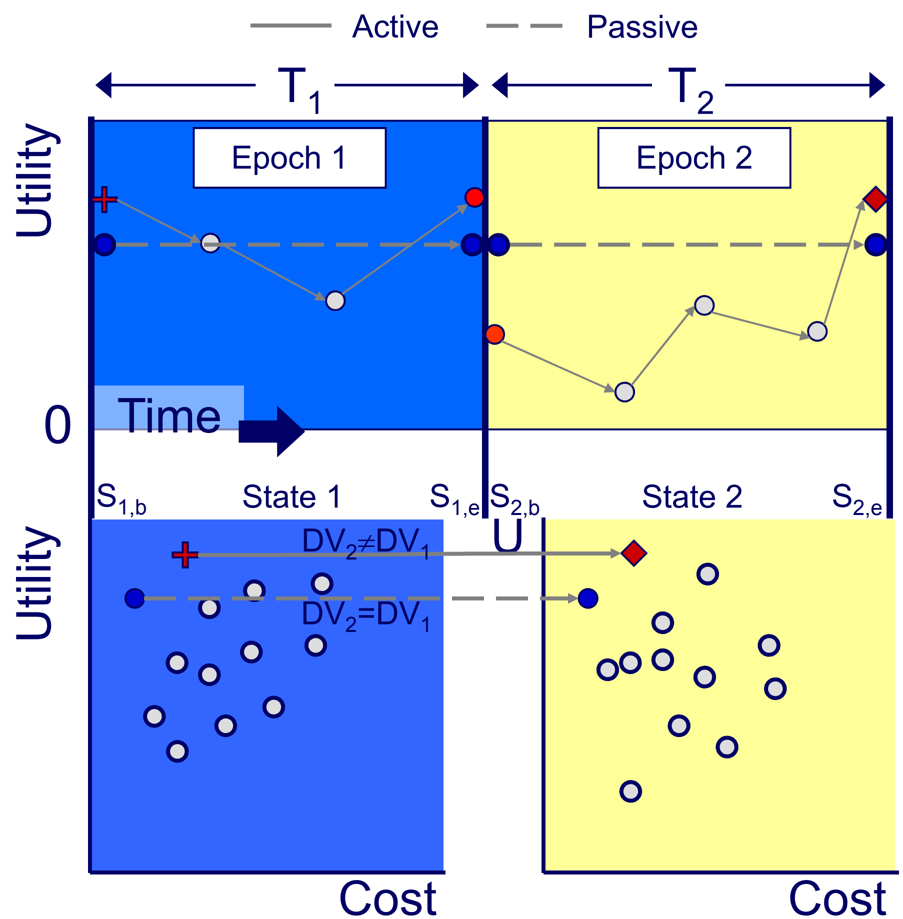
For large numbers of designs and epochs, this requires an automated ability to assess epoch shift impacts

Achieving Value Robustness

New Epoch Drivers
- External Constraints
- Design Technologies
- Value Expectations

Two strategies for "Value Robustness"

1. Active
   - Choose "changeable" designs that can deliver high value when needed
   - Metric: Filtered Outdegree
2. Passive
   - Choose "versatile" designs that remain high value
   - Metric: Normalized Pareto Trace



Value robust designs can deliver value in spite of inevitable epoch change

Space Tug Demo

End-to-end application of valuation approach for strategic changeability to an existing data set (Space Tug)

Special thanks to Matthew Fitzgerald who developed much of this work

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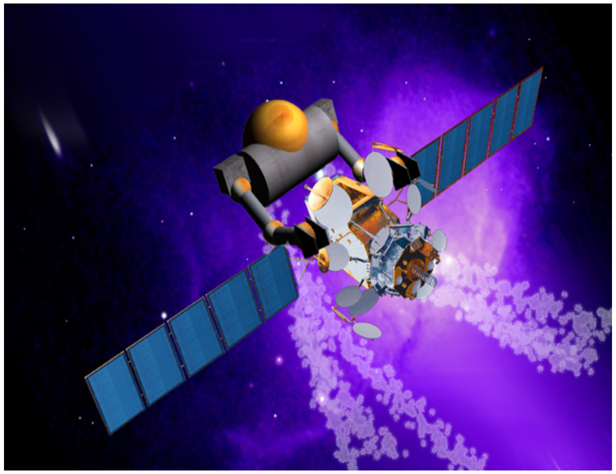
Space Tug Data Set - Intro

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

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

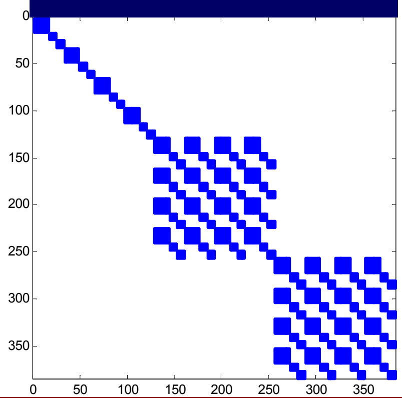
4 design variables → 384 designs
- Prop type (biprop, cryo, electric, nuclear)
- Fuel mass
- Capability level
- Design For Changeability (DFC) level

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

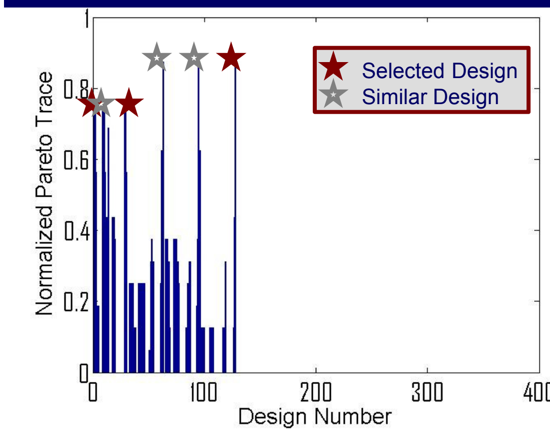
Step 1 puts the case in question into the epoch-era framework, allowing for piecewise consideration of time in sequences of constant-context sections

2. Identify Designs of Interest

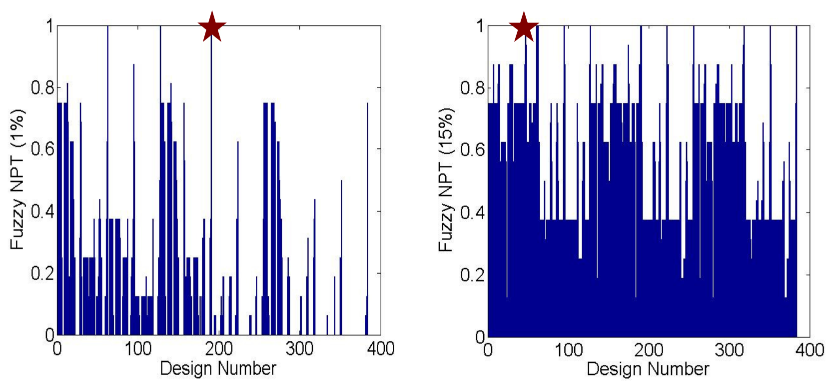
Activities
- Calculate changeability screening metrics:
  - Normalized Pareto Trace (and fuzzy NPT)
  - Filtered Outdegree
- Any other desired design identification techniques

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

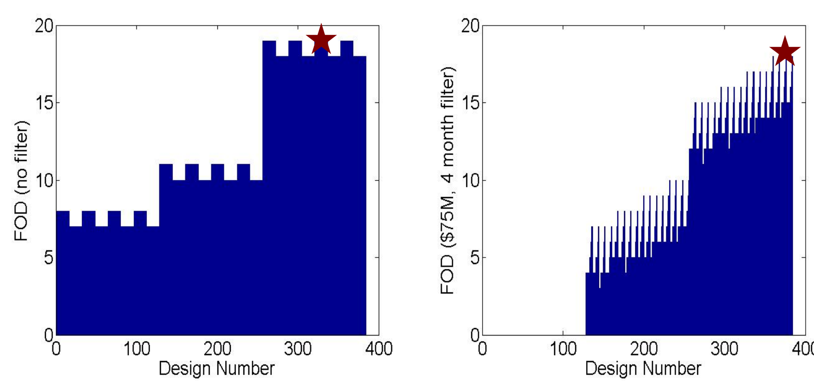
Identifying designs with high NPT



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

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

4. Multi-epoch Changeability Analysis

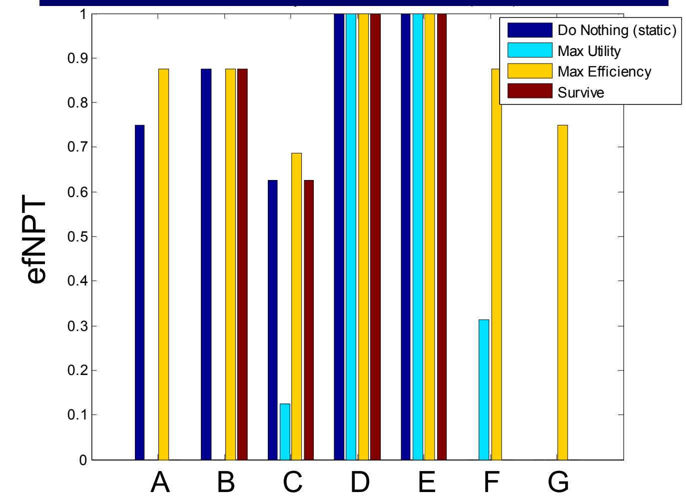
Activities

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

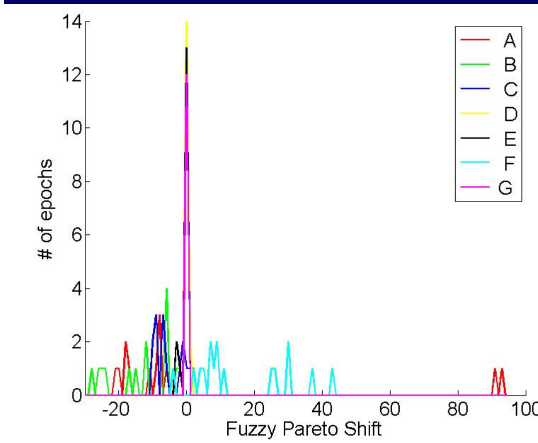
Outputs

- 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

Exploring Effective Fuzzy Normalized Pareto Trace for each strategy



Exploring Fuzzy Pareto Shift of designs of interest for a strategy



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

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

	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

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

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