Systems Engineering Advancement Research Initiative

Using Dynamic Multi-Attribute Tradespace Exploration to Develop Value Robust Systems

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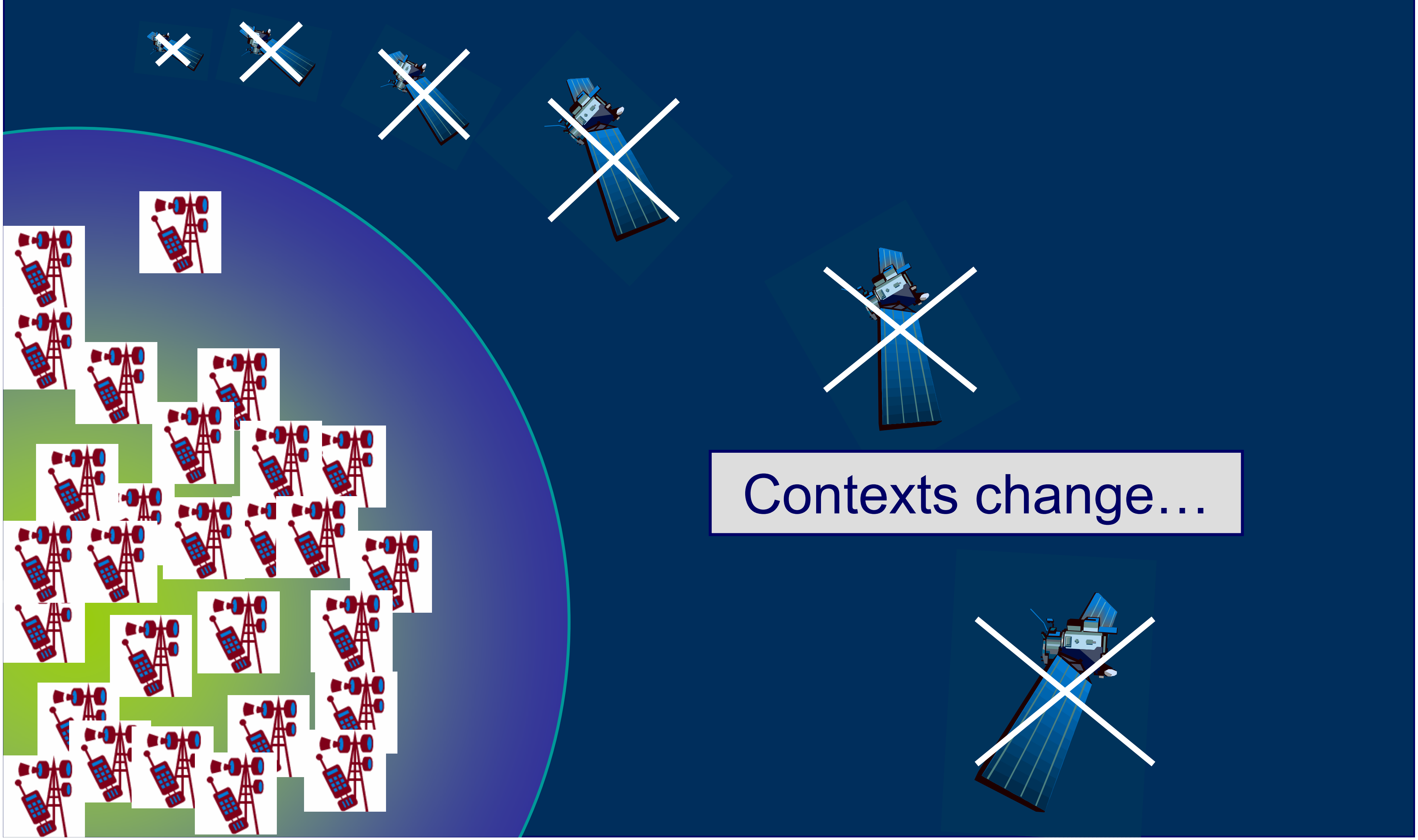
Meeting Customer Needs

- Goal of design is to create value (profits, usefulness, voice of the customer, etc…)
- Requirements capture a mapping of needs to specifications to guide design

Deploying a "Valuable" System…



Contexts change…

Meeting Customer Needs (cont.)

- Goal of design is to create value (profits, usefulness, voice of the customer, etc…)

- People change their minds…
- To continue to deliver value, systems must change as well…

What is System Success?

Success is defined across multiple perspectives and multiple time periods

System success, Ψ, across N decision makers at time t

Net "experience" Net "expectations"

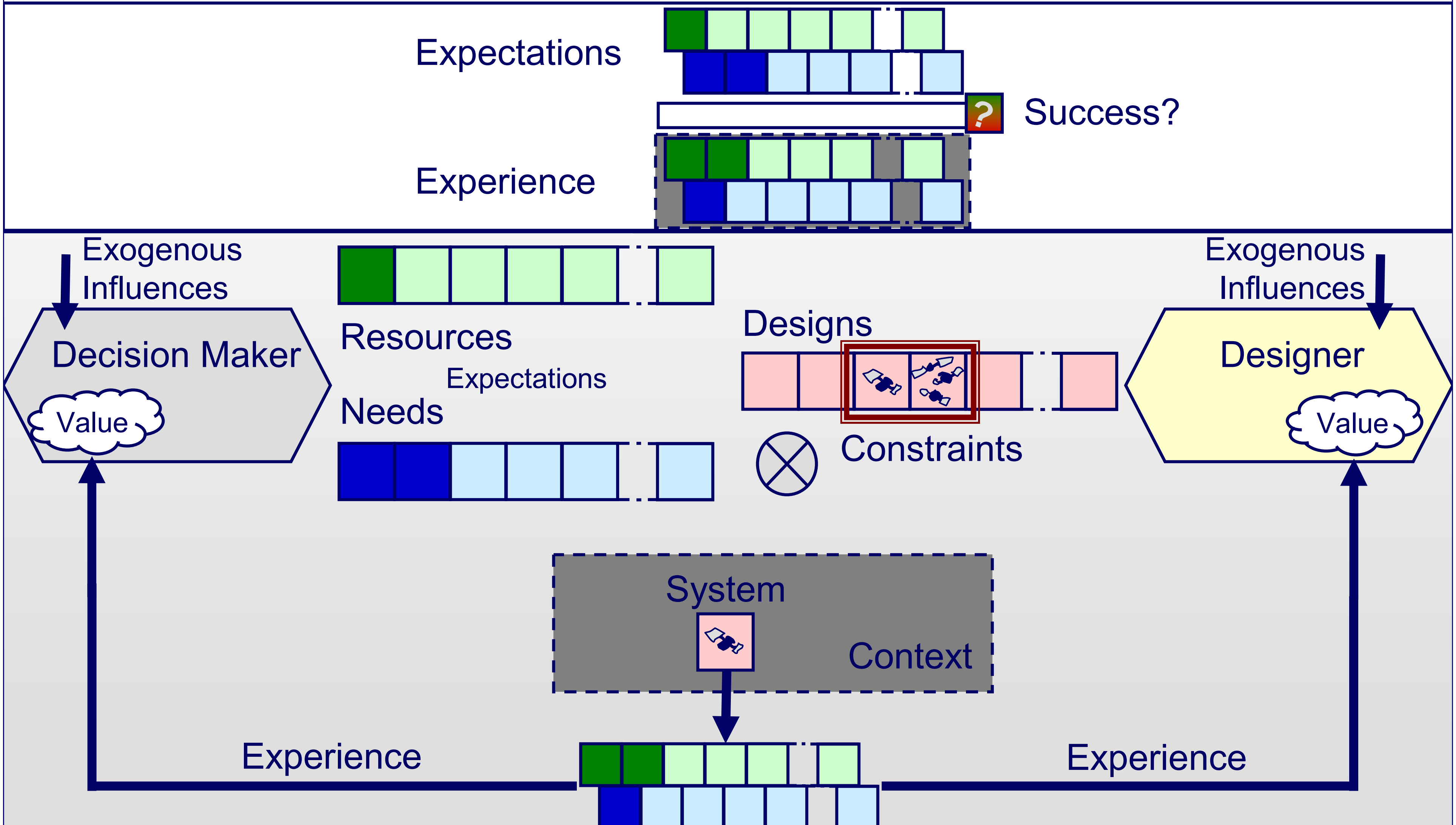
$$\Psi(t) = \sum_{i=1}^{N} \left[X_{DMi}(t) + \varepsilon_C^{X_{DMi}}(t) \geq Y_{DMi}(t) + \varepsilon_C^{Y_{DMi}}(t) \right]$$

$$0 \leq \Psi(t) \leq N$$

$X_{DMi}(t)$	Decision maker i unaffected system "experience" at time t	$\varepsilon_C^{X_{DMi}}(t)$	Context effect on decision maker i "experience" at time t
$Y_{DMi}(t)$	Decision maker i unaffected system "expectation" at time t	$\varepsilon_C^{Y_{DMi}}(t)$	Context effect on decision maker i "expectation" at time t

System Success: Net "experience" must meet or exceed net "expectations"

Characterizing the System Design Opportunity



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Types of Changes

- Δ Designs (including technology)
- Δ Context (including operating environment, competition)
- Δ Constraints (including "laws")
  - Physical (e.g. nature)
  - Human-made (e.g. policy, schedule)
  - Resources (e.g. capital)
  - Scoping (e.g. self-imposed)
- Δ Needs (including attributes)
- Δ DMs (including individuals and groups)
- Δ Resources (including dollars and time)

How can System Designers cope with these types of changes during design?

Aspects of Dynamic MATE

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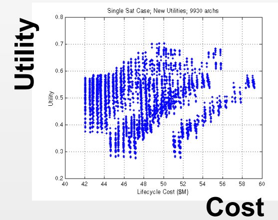
How can System Designers cope with these types of changes during design?

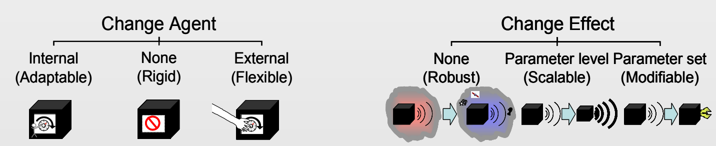
Experience(t) Exceeding Expectation(t)

$$\Psi(t)=\sum_{i=1}^{N}\left[X_{DMi}(t)+\varepsilon_C^{X_{DMi}}(t)\geq Y_{DMi}(t)+\varepsilon_C^{Y_{DMi}}(t)\right]$$

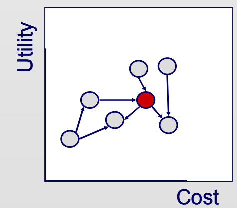
- System Success criteria
  - Expanding scope of system "value"
- Tradespace exploration
  - Understanding success possibilities across a large number of designs



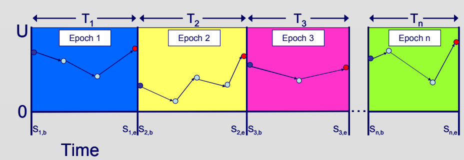
- Change taxonomy
  - Specifying and identifying change types



- Tradespace networks
  - Analyzing changeability of designs



- System Epoch/Era analysis
  - Quantifying effects of changing contexts on system success



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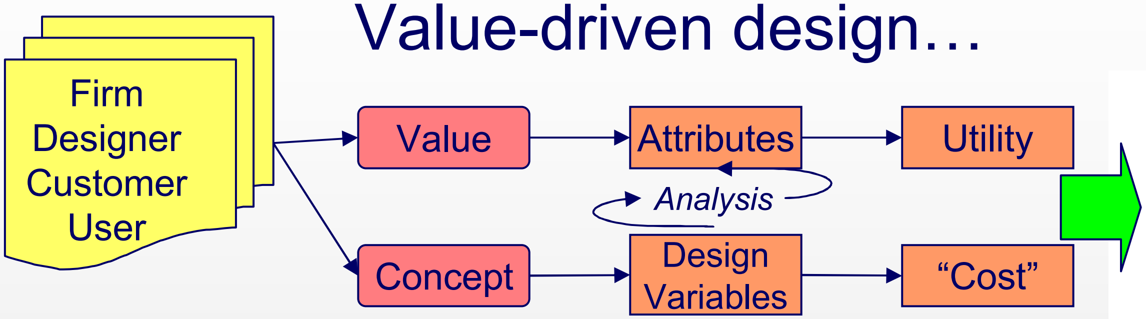
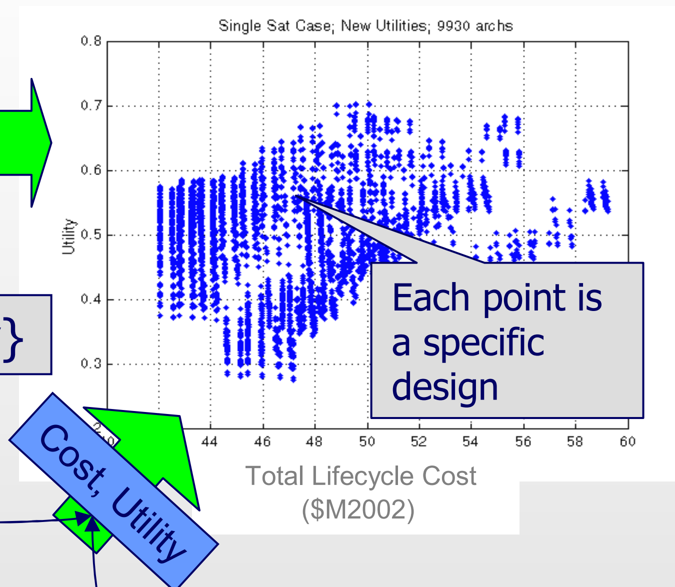
Tradespace Exploration

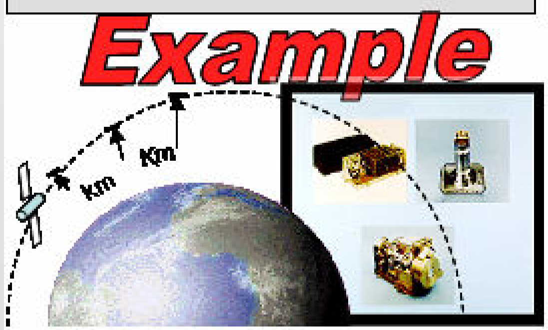
Value-driven design…



Tradespace: {Design,Attributes} ←→ {Cost,Utility}



X-TOS
Small low-altitude science mission



DESIGN VARIABLES:
Design trade parameters

Orbital Parameters
- Apogee Altitude (km)
- Perigee Altitude (km)
- Orbit Inclination (deg)

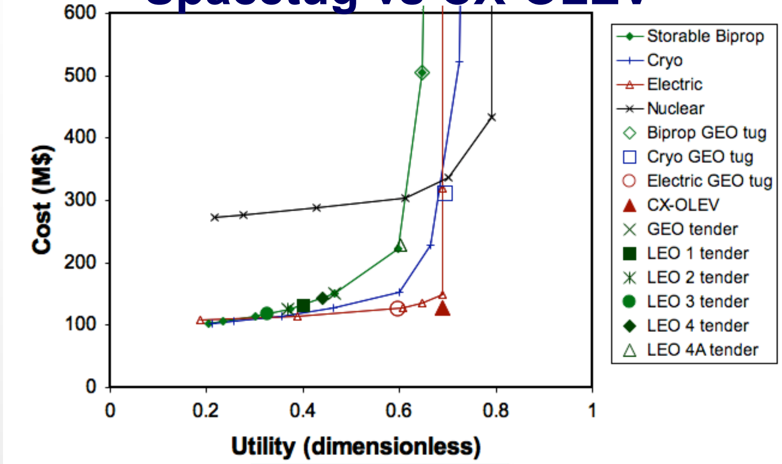
Spacecraft Parameters
- Antenna Gain
- Communication Architecture
- Propulsion Type
- Power Type
- Total Delta V

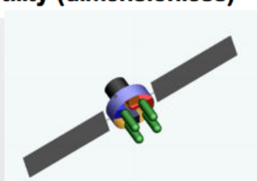
ATTRIBUTES:
Design decision metrics
- Data Lifespan (yrs)
- Equatorial Time (hrs/day)
- Latency (hrs)
- Latitude Diversity (deg)
- Sample Altitude (km)

Assessment of cost and utility of large space of possible system designs

Example “Real Systems”

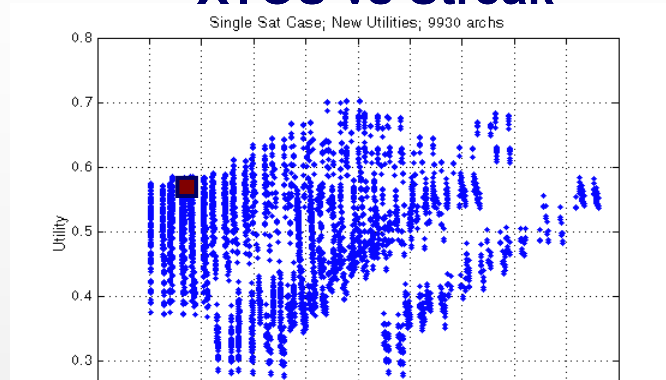
Spacetug vs CX-OLEV

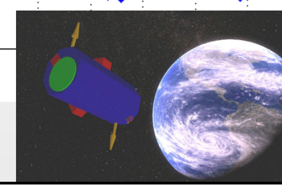




	Electric Cruiser (2002 study)	CX-OLEV (2009 launch)
Wet Mass kg	1405	1400
Dry Mass kg	805	670*
Propellant kg	600	730*
Equipment kg	300	213*
DV m/s	12000 – 16500***	15900**
Utility	0.69	0.69
Cost	148	130*

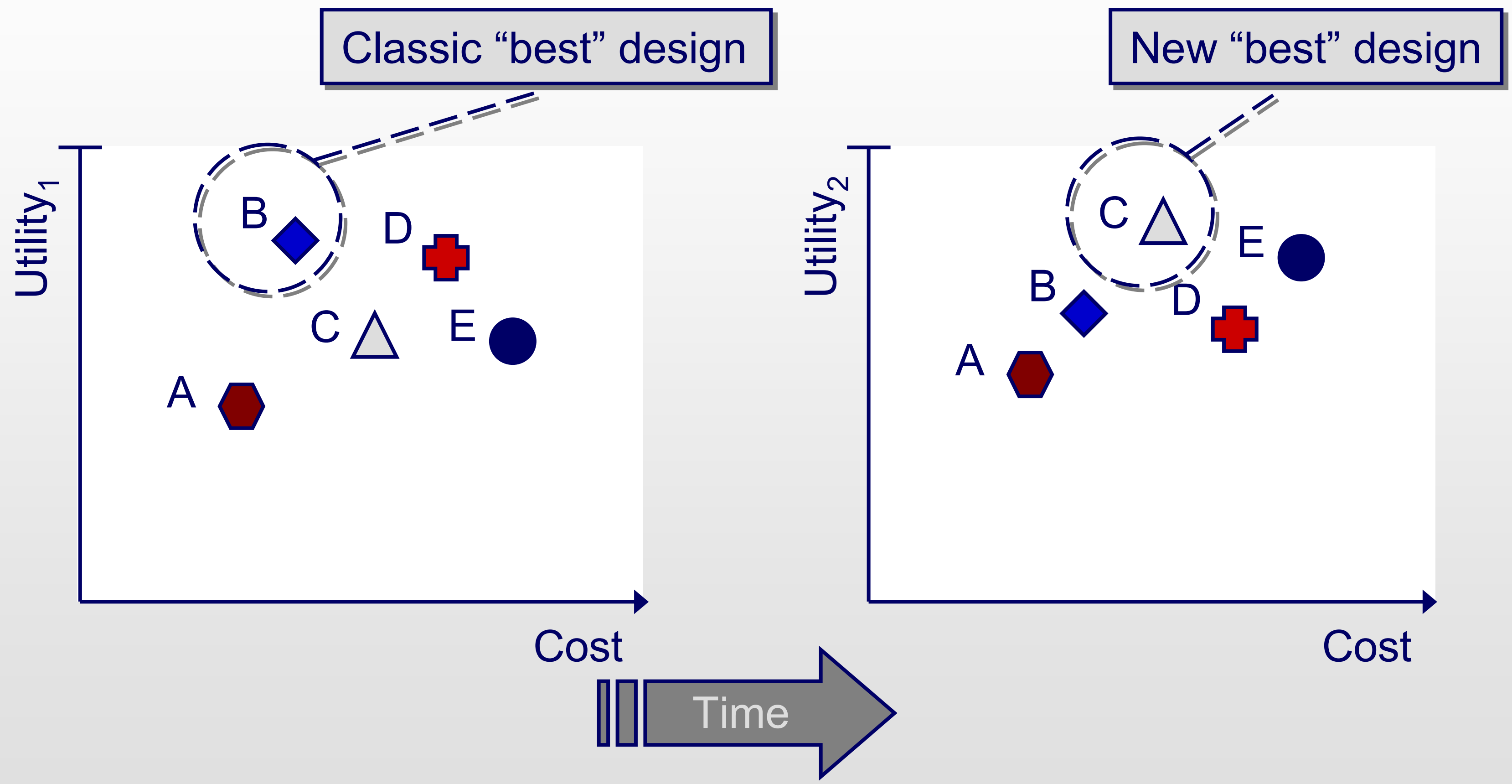
XTOS vs Streak





	XTOS (2002 study)	Streak (Oct 2005 launch)
Wet Mass kg	325 - 450	420
Lifetime (yrs)	2.3 - 0.5	1
Orbit	300 -185 km @ 20°	321a-296p -> 200 @ 96°
LV	Minotaur	Minotaur
Utility	0.61 - 0.55	0.57 - 0.54*
Modified Utility**	0.56 - 0.50	0.59
Cost $M	75 - 72	75***
Instruments	Three (?)	Ion gauge and atomic oxygen sensor

Tradespace Analysis: Selecting "best" designs



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

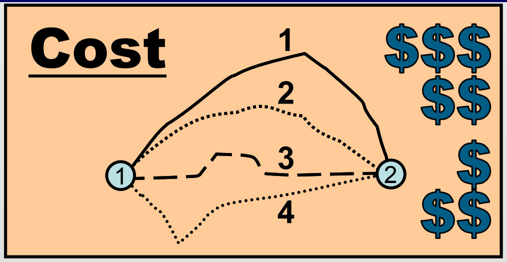
Tradespace Networks

Example: X-TOS Transition Rules

Rule	Description	Change agent origin
R1: Plane Change	Increase/decrease inclination, decrease ΔV	Internal (Adaptable)
R2: Apogee Burn	Increase/decrease apogee, decrease ΔV	Internal (Adaptable)
R3: Perigee Burn	Increase/decrease perigee, decrease ΔV	Internal (Adaptable)
R4: Plane Tug	Increase/decrease inclination, requires "tugable"	External (Flexible)
R5: Apogee Tug	Increase/decrease apogee, requires "tugable"	External (Flexible)
R6: Perigee Tug	Increase/decrease perigee, requires "tugable"	External (Flexible)
R7: Space Refuel	Increase ΔV, requires "refuelable"	External (Flexible)
R8: Add Sat	Change all orbit, ΔV	External (Flexible)

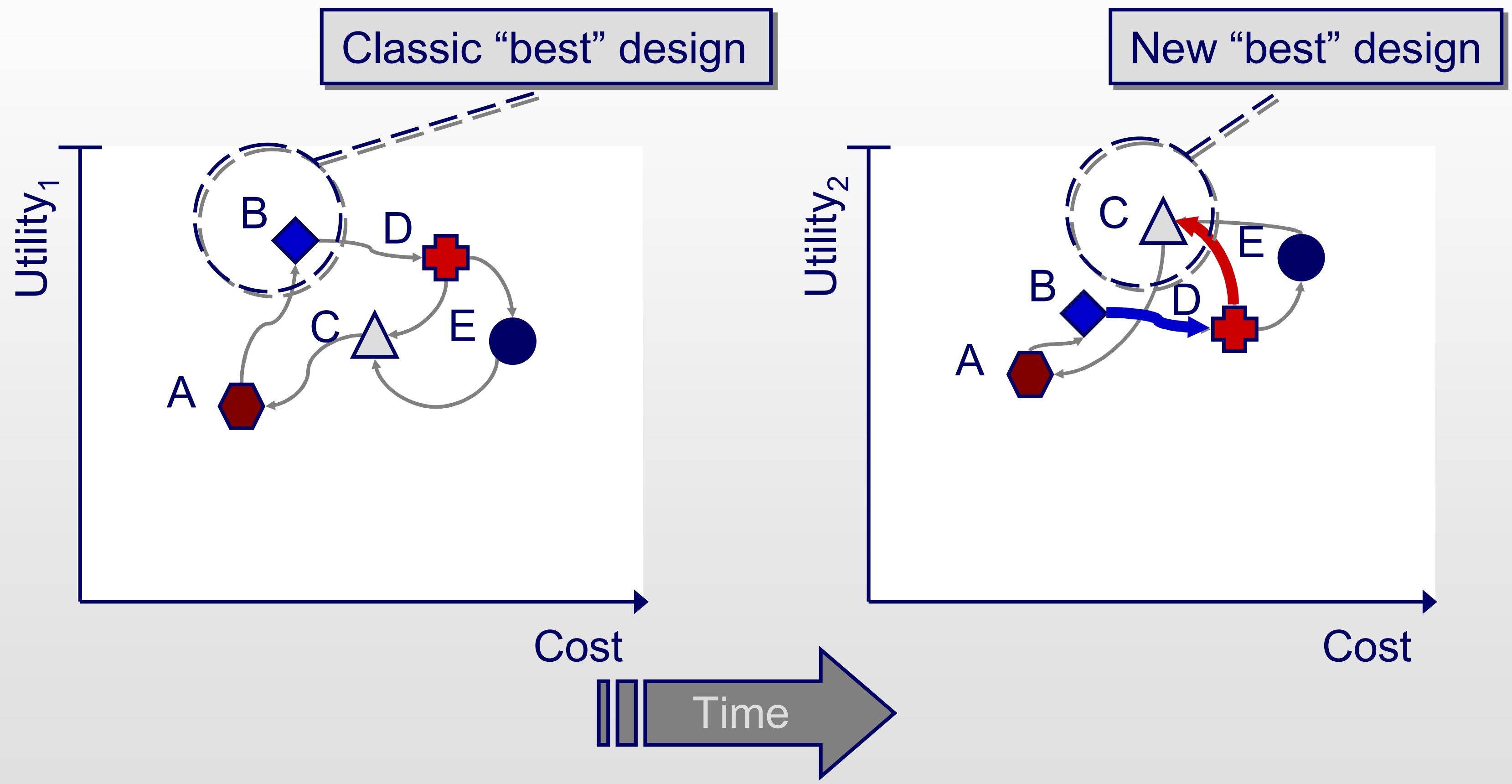
Tradespace designs = nodes

Applied transition rules = arcs



Transition rules are mechanisms to change one design into another
The more outgoing arcs, the more potential change mechanisms

Tradespace Networks: Changing designs over time



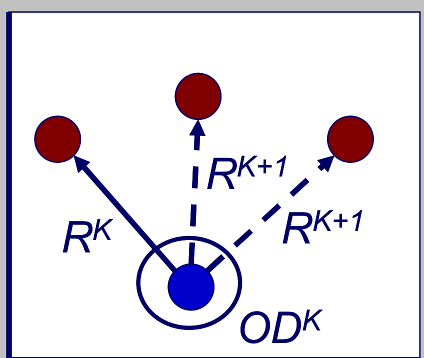
Select changeable designs that can approximate "best" designs in new contexts

Changeability Metric: Filtered Outdegree

objective

Outdegree

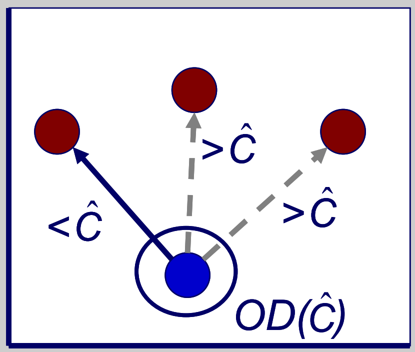
outgoing arcs from a given node



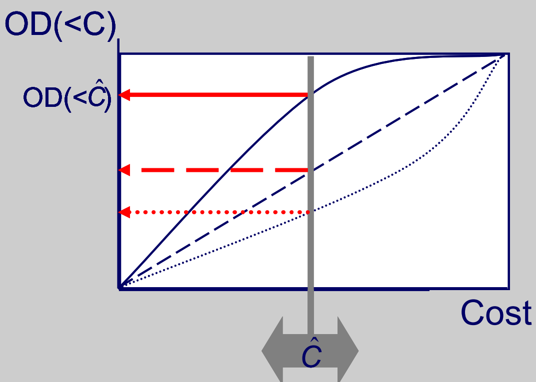
subjective

Filtered Outdegree

outgoing arcs from design at acceptable "cost"
(measure of changeability)



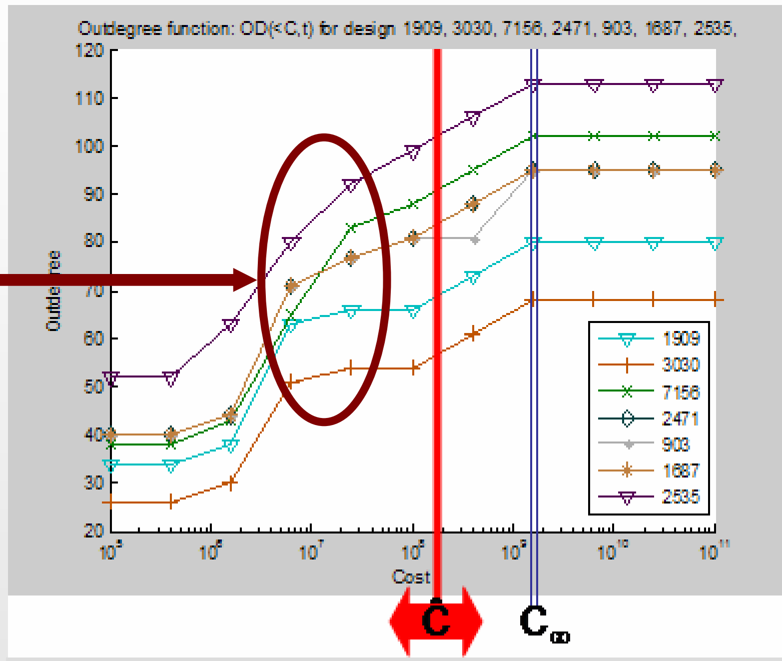
Outdegree



Subjective Filter

Filtered outdegree is a measure of the apparent changeability of a design

Ex: X-TOS Outdegree function



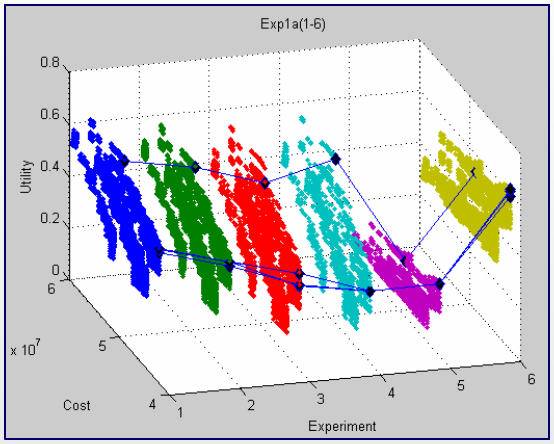
DV	2471	903	1687	2535	1909	3030	7156
Inclination	90	30	70	90	70	90	90
Apogee	460	460	460	460	1075	2000	770
Perigee	150	150	150	290	150	150	350
Com Arch	TDRSS	TDRSS	TDRSS	TDRSS	TDRSS	TDRSS	TDRSS
Delta V	1200	1200	1200	1200	1200	1200	1000
Prop Type	Chem	Chem	Chem	Chem	Elec	Elec	Chem
Pwr Type	Fuel Cell	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

- Pareto Set designs (903, 1687, 2535, 2471) are not the most changeable
- Design 7156 becomes relatively more changeable as cost threshold increases

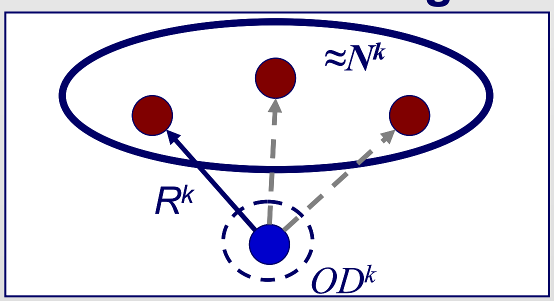
Outdegree functions reveal differential nature of apparent changeability

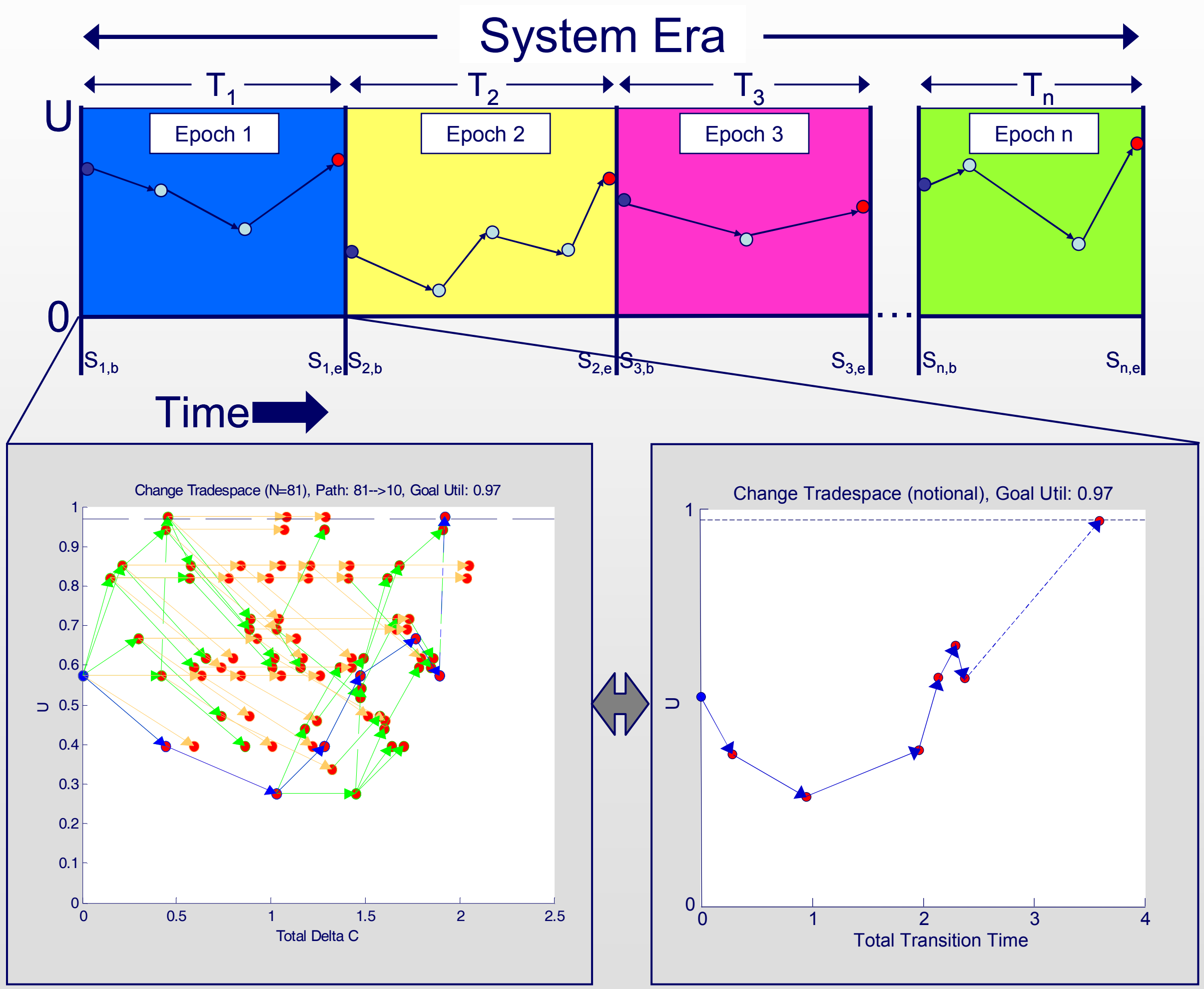
Tradespace Networks in the System Era

Pareto Tracing across Epochs



Changeability Quantified as Filtered Outdegree

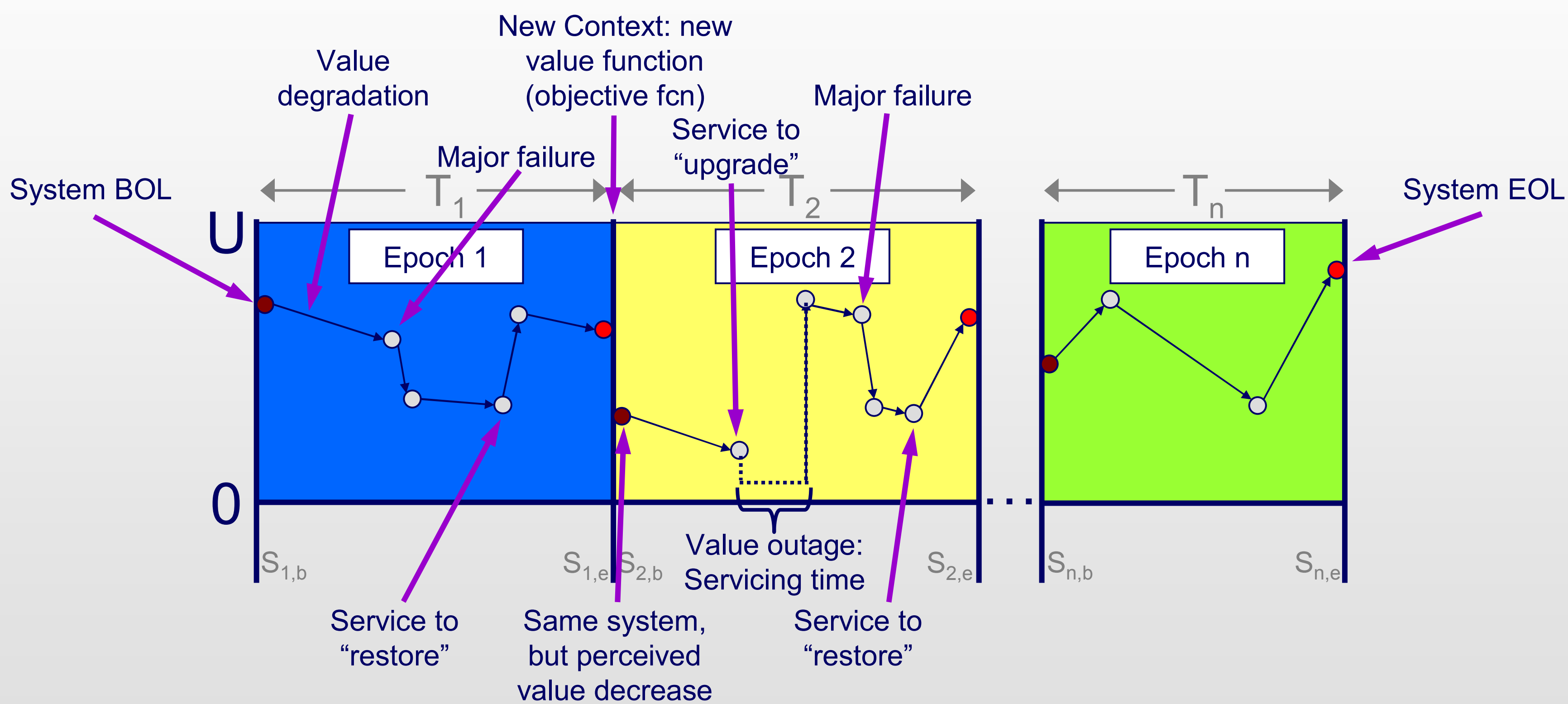




Temporal strategy can be developed across networked tradespace

Example System Timeline

Example system: Serviceable satellite



System timeline with "serviceability"-enabled paths allow value delivery

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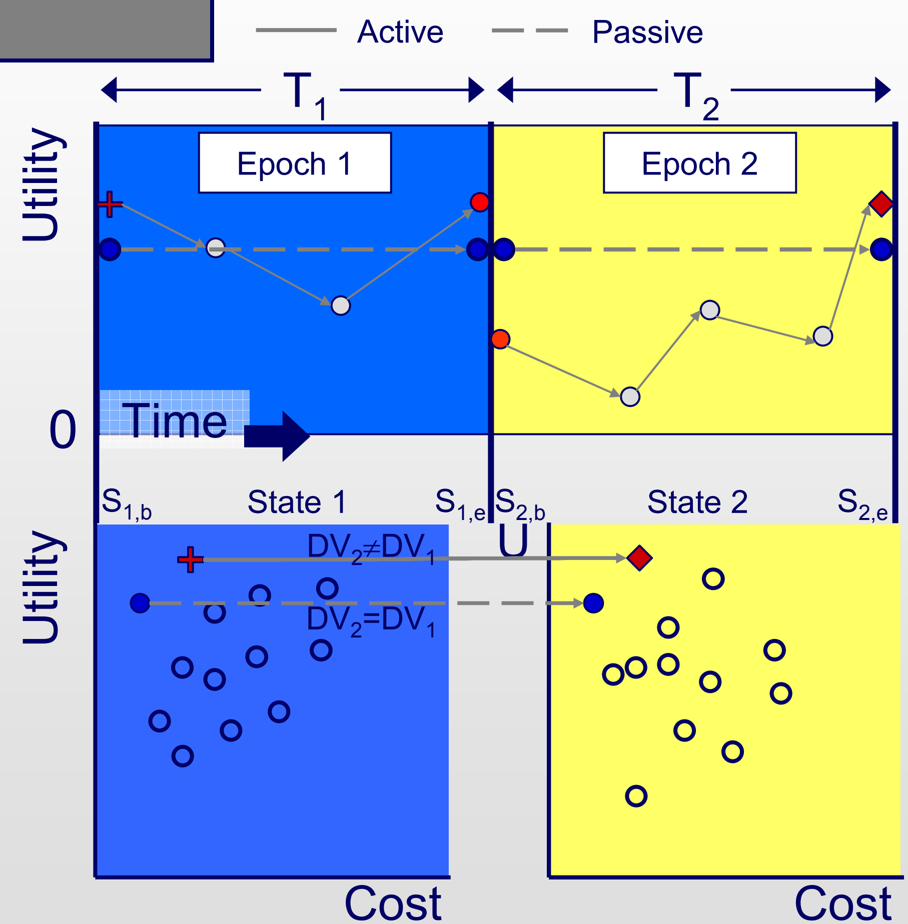
Achieving Value Robustness

Research suggests two strategies for "Value Robustness"

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

1. Passive
   - Choose "clever" designs that remain high value
   - Quantifiable: Pareto Trace number

2. Active
   - Choose changeable designs that can deliver high value when needed
   - Quantifiable: Filtered Outdegree



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

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Thank you for your attention!

Any questions?

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For further details on topic please see:

Ross, Adam M., Managing Unarticulated Value: Changeability in Multi-Attribute Tradespace Exploration. Cambridge, MA: MIT. PhD in Engineering Systems. 2006.