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SEA RI
Systems Engineering Advancement Research Initiative

Affordability and Tradespace Exploration

Presentation to 2012 MORS Symposium
by Donna H. Rhodes

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MIT Systems Engineering Advancement Research Initiative

Systems Engineering Advancement Research Initiative (SEAri)

SEAri is positioned within the Engineering Systems Division at MIT

Mission

Advance the theories, methods, and effective practice of systems engineering applied to complex socio-technical systems through collaborative research

2010-2012 Sponsors

DARPA, US Air Force, US Gov't Agencies, NAVSUP/NPS, Singapore DSTA

PAST PERFORMANCE

- More than decade of research in value-driven design and tradespace exploration
- Successful research transfer of methods
- Collaborative engagements with defense organizations

LEADERSHIP

Dr. Donna Rhodes
- Director, Principal Investigator

Dr. Adam Ross
- Lead Research Scientist

Prof. Daniel Hastings
- Faculty Strategic Advisor

TECHNICAL TEAM

- Graduate Research Assistants
- Affiliated Graduate Students
- Undergraduate Students
- Affiliated Researchers
- Affiliated and visiting faculty

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Affordability …

- What if my mission or my operating environment changes? What if this happens multiple times?
- Is my affordable solution also survivable (and/or evolvable, adaptable, etc.)?
  - Does it make sense to invest in change options?
- How can I satisfy multiple stakeholders with diverse needs?

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Designing for a Dynamic World

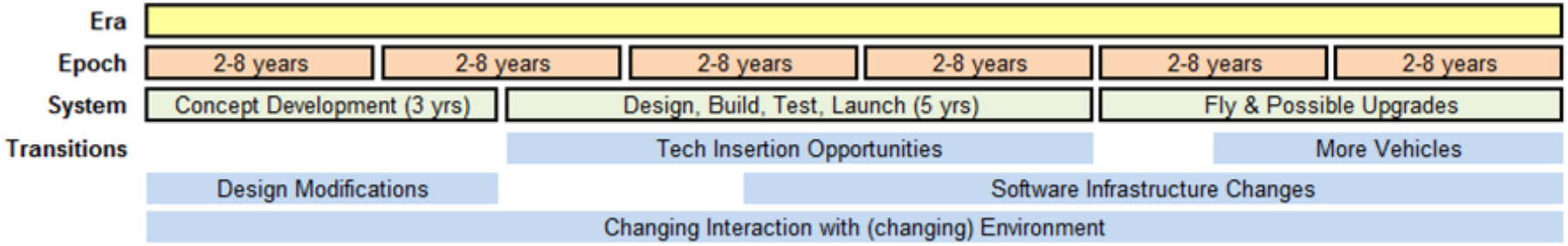
Ross, A.M., and Rhodes, D.H., "Using Natural Value-centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis," INCOSE International Symposium 2008, Utrecht, Netherlands, June 2008

Specifically targets the high leverage *early concept phase*

Methods/metrics inform selection of promising concept designs for further analysis

Uses exogenous uncertainties to frame the need for the ability of a system to respond to *perturbations*

Methods/metrics for affordable changeability and robustness



Systems developed in a dynamic world 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 and emergent needs on appropriate timescales

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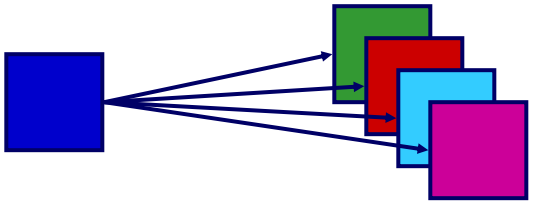
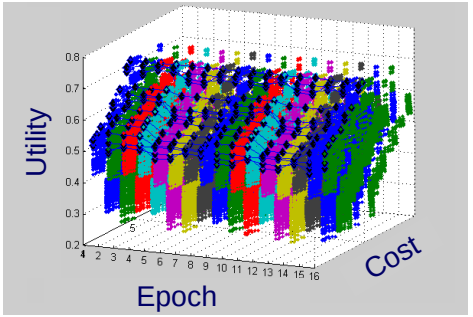
Encapsulating Uncertainties
Epochs

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 resources
- Availability of new technology
- Emergence of significant new or changed stakeholder need(s)
- Policy mandate impacting product line, services or operations
- New threat environment with non-state actors using improvised attacks

Categories of uncertainties can aid in thinking about key changing factors

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

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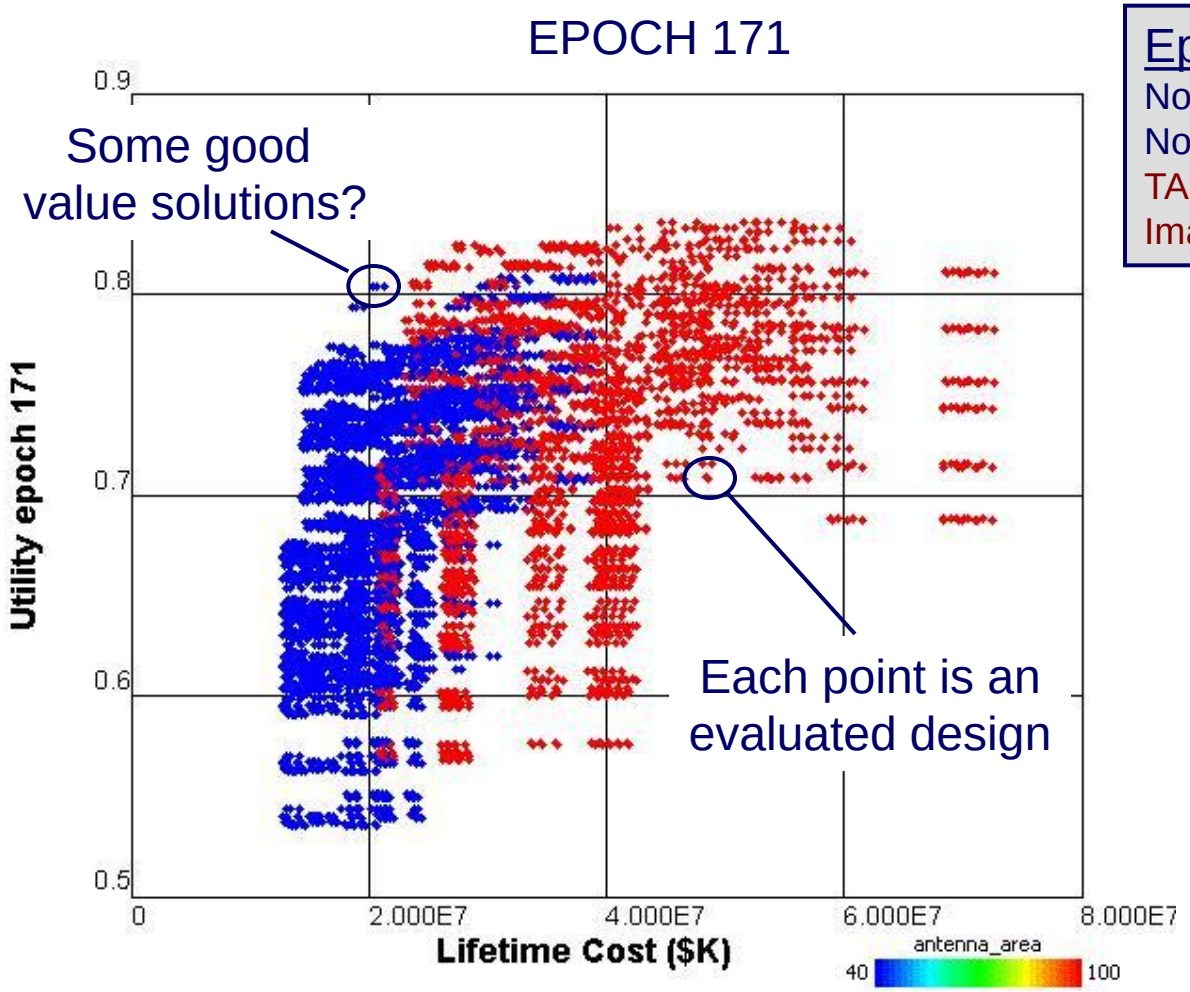
Typical Tradespace: Utility vs. Cost for a Given Epoch

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



Epoch 171

No AISR avail, WGS avail
No jamming, TRL 9 tech
TARGETS: Mid East, Asia
Imaging mission (primary)

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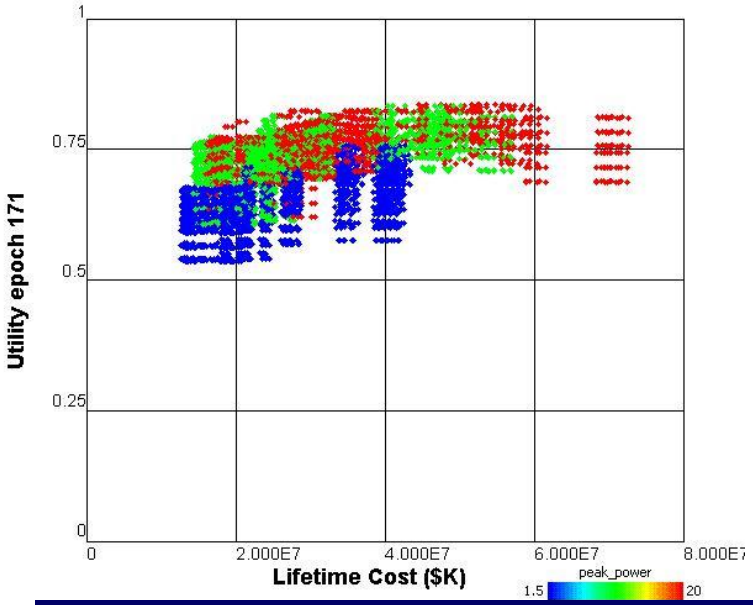
Understanding Changing Contexts

Epoch 171

No AISR avail, WGS avail, No jamming, TRL 9 tech

TARGETS: CountryX med, Country Y large

Imaging mission (primary)

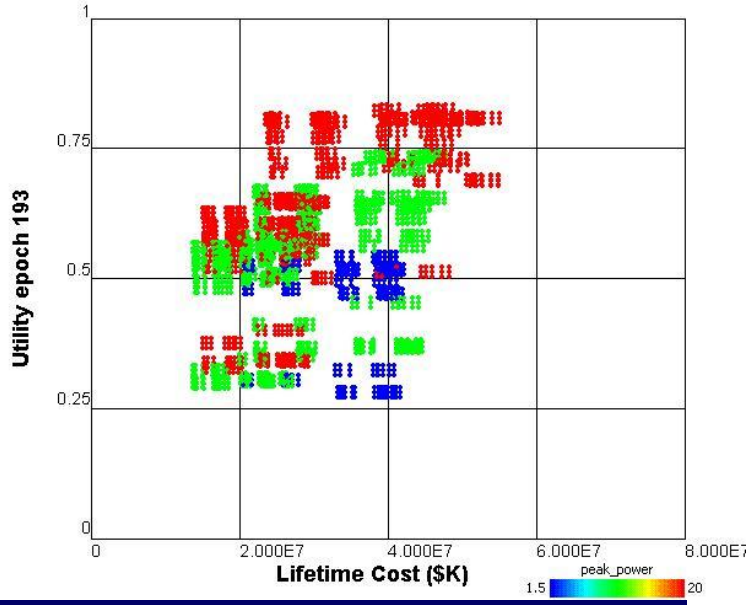


Epoch 193

No AISR avail, WGS avail, No jamming, TRL 9 tech

TARGETS: Country Z small, Country Y med

Tracking mission (primary)



- Epoch 193 has smaller targets and more emphasis on tracking users' needs
- Color shows Radar peak power
- Tradespace sparser: more systems do not meet minimum requirements
- Delighting user harder: note utility scale
- Power trade (and others) different; low power (blue) designs not on Pareto Front

Changing context and mission effects on alternatives' utility becomes readily apparent

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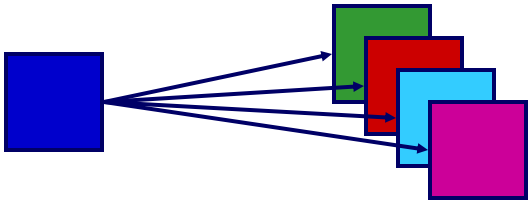
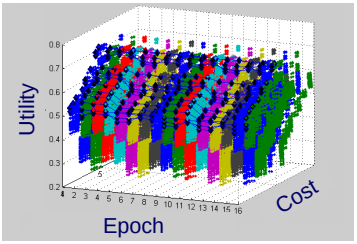
Multi-Epoch Tradespace Exploration

Ross, A.M., McManus, H.L., Rhodes, D.H., and Hastings, D.E., "Revisiting the Tradespace Exploration Paradigm: Structuring the Exploration Process," AIAA Space 2010, Anaheim, CA, September 2010



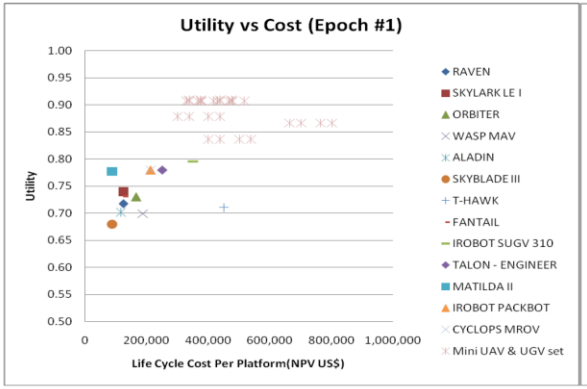
Today Possible futures (epochs)

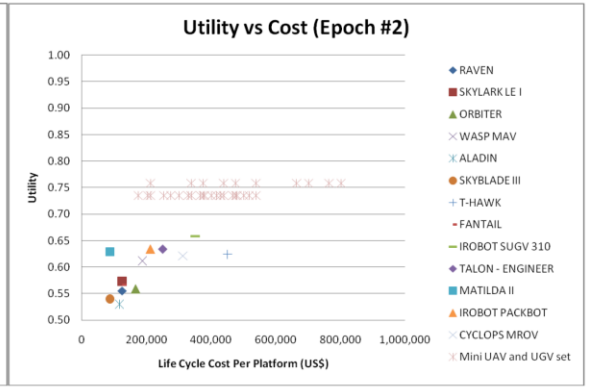
Koo, C.K.K., "Investigating Army Systems and Systems of Systems for Value Robustness," Master of Science in Engineering Management, *System Design and Management Program*, MIT, Cambridge, MA, February 2010.

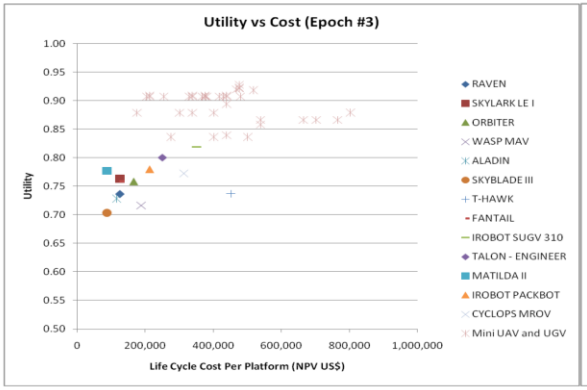


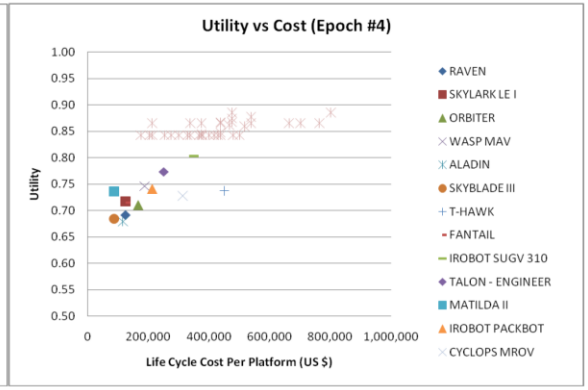
Demonstrations

- Diverse set of "point designs" compared on common basis
- Many tradespaces evaluated over changing contexts (e.g., technology levels) and needs (e.g., missions and utilities)
- Allows for identification of alternatives robust against uncertainties revealed over time









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Roberts, C.J., Richards, M.G., Ross, A.M., Rhodes, D.H., and Hastings, D.E., "Scenario Planning in Dynamic Multi-Attribute Tradespace Exploration," 3rd Annual IEEE Systems Conference, Vancouver, Canada, March 2009

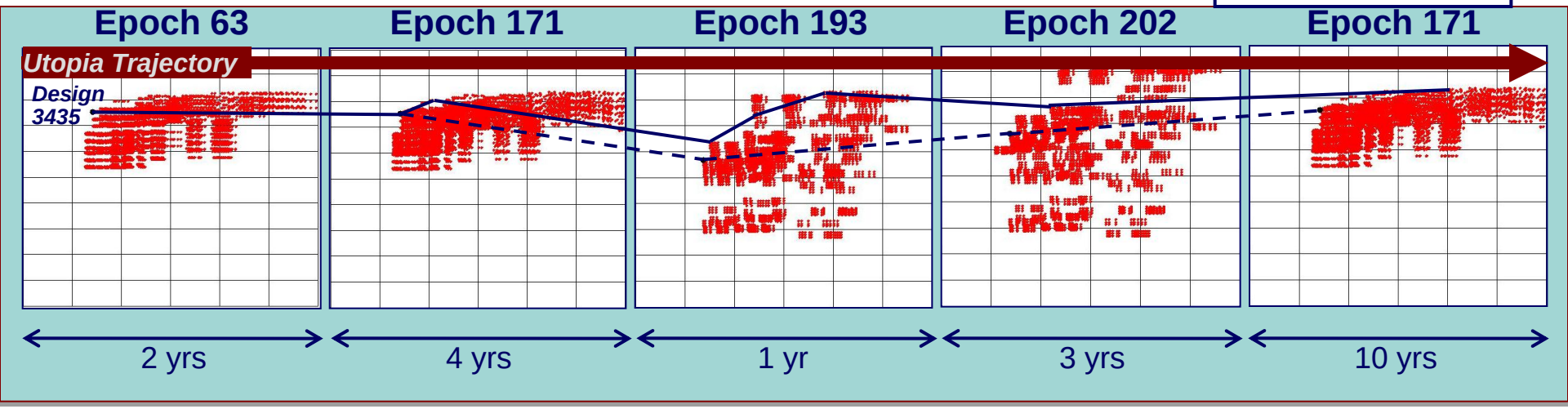
Evaluate System Evolution Strategies

Utilize optimization approaches to derive time-based system evolution strategies that sustain / maximize stakeholder value delivery

Example strategies include:

- Maintain minimum distance from utopia trajectory
- Maximize delivered system value given a fixed budget

Evolution strategy: Maximize value delivery over the Era at least cost



Challenge is to find system design and transition strategy that delivers the highest value over the entire system lifecycle or within a particular context

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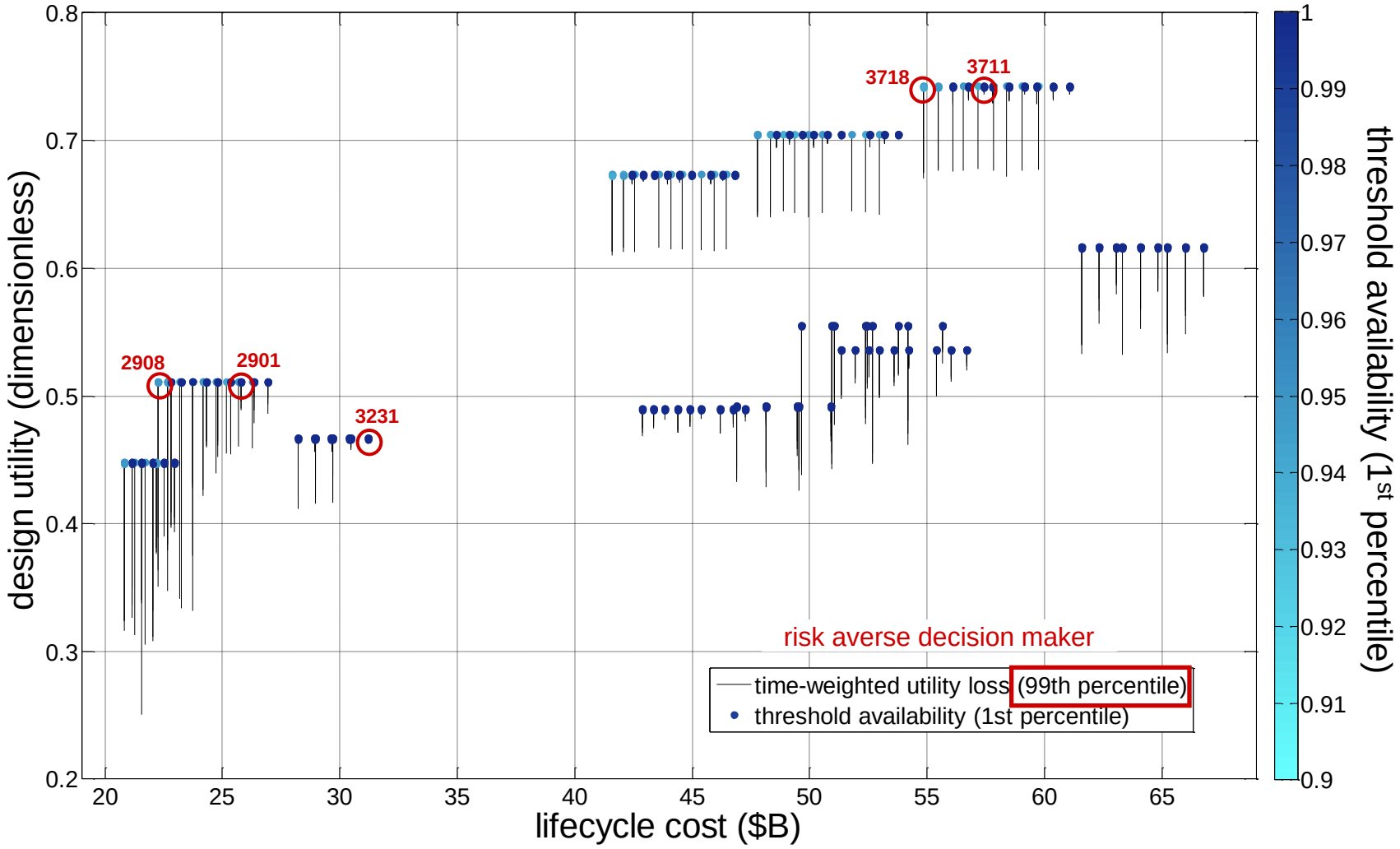
TSE for Survivability

Select Interesting Point Designs

Richards, M.G., Ross, A.M., Hastings, D.E., and Rhodes, D.H., "Multi-Attribute Tradespace Exploration for Survivability," 7th Conference on Systems Engineering Research, Loughborough University, UK, April 2009

Pareto Efficient Set for Cost, Utility, Utility Loss, and Threshold Availability (magnified)



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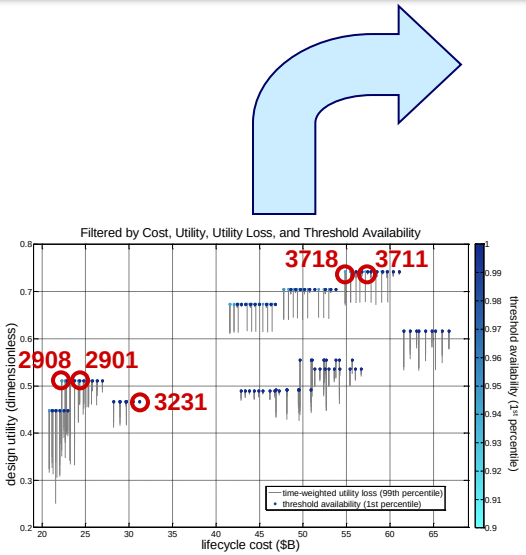
Extract Survivability Insights from Selected Point Designs

Richards, M.G., Ross, A.M., Stein, D., and Hastings, D.E., "Multi-Attribute Tradespace Exploration for Survivability: Application to Satellite Radar," AIAA Space 2009, Pasadena, CA, September 2009



Design Vector ID	2908	2901	3231	3718	3711
orbit altitude (km)	1500			1500	
Walker constellation	9/3/2	9/3/2	27/3/1	66/6/5	66/6/5
transmit frequency (GHz)	10			10	
antenna area (m^2)	100	100	40	40	
antenna type	AESA			AESA	
radar bandwidth (MHz)	2000			2000	
peak transmit power (kW)	20			20	
tugable	no			no	
comm. architecture	direct	relay	relay	direct	relay
tactical link	yes			yes	
shield thickness (mm)	1	1	10	1	
satellite spares	0	2	2	0	2
lifecycle cost ($B)	22.3	25.8	31.2	54.8	57.4
utility	0.51	0.51	0.47	0.74	0.74
utility loss (95th)	0.09	0.01	0.00	0.06	0.00
utility loss (99th)	0.12	0.02	0.00	0.07	0.01
threshold availability (1st)	0.95	1.00	1.00	0.95	1.00

- Survivability insights from selected point designs
  - Relay backbone critical for achieving continuous threshold availability
  - Investing in spare satellite(s) minimizes utility losses
  - Satellite shielding has limited impact in nominal debris environment
  - Distributed constellation mitigates worst-case risks

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What changeability options should I invest in?

Fitzgerald, M.E. and Ross, A.M., "Mitigating Contextual Uncertainties with Valuable Changeability Analysis in the Multi-Epoch Domain," 6th Annual IEEE Systems Conference, Vancouver, Canada, March 2012

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 VASC 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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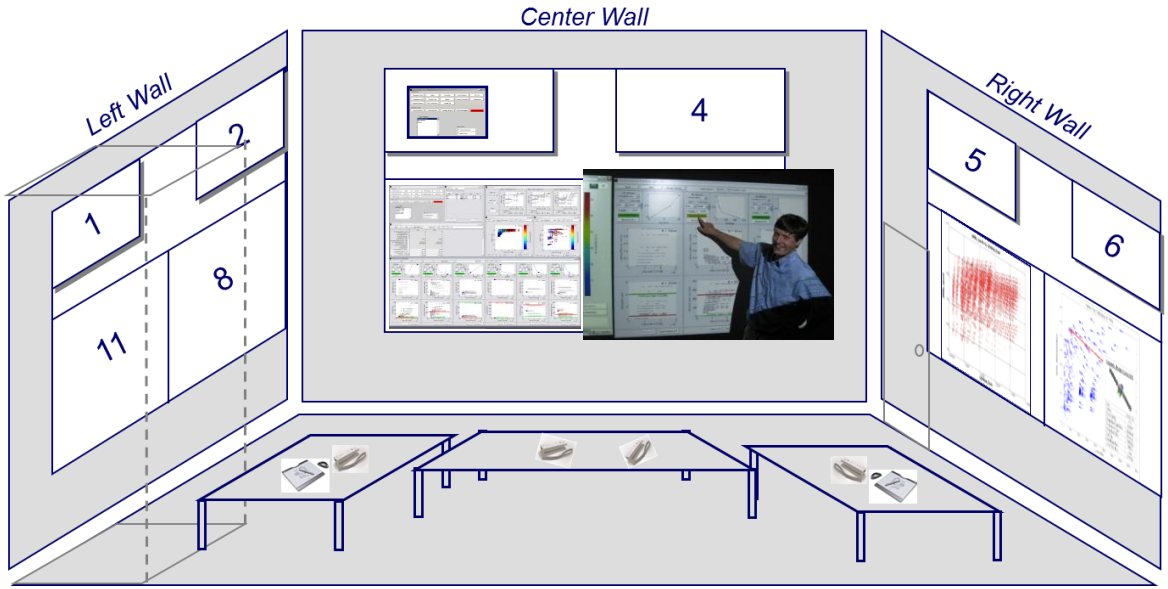
SEAri Tradespace Exploration Lab

Moving beyond a technique used only by expert tradespace analysts, can we develop…

A concept of operations for creating, using and sharing tradespace data with multiple, diverse decision makers

Development of a multi-sensory tradespace exploration lab

To address the shortcomings in sense-making of large dynamic tradespace data sets (VisLab)



Rich data sets can be explored to reveal complex relationships between design-space and value-space for generating intuition into problems

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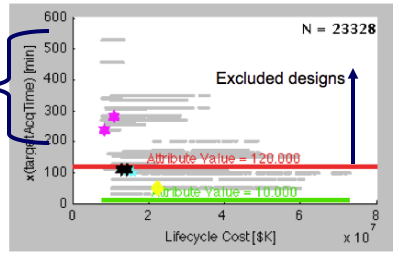
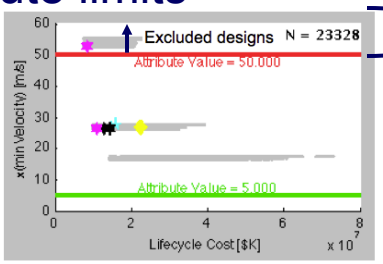
Multi-Stakeholder Negotiation

Ross, A.M., McManus, H.L., Rhodes, D.H., and Hastings, D.E., "A Role for Interactive Tradespace Exploration in Multi-Stakeholder Negotiations," AIAA Space 2010, Anaheim, CA, September 2010

N's attribute limits

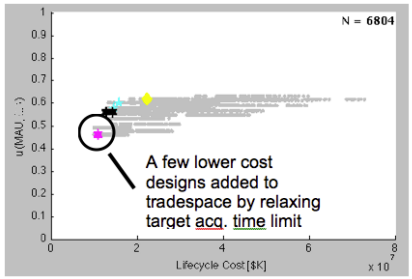
N's *target acquisition time* attribute range excludes lower cost alternatives from compromise set

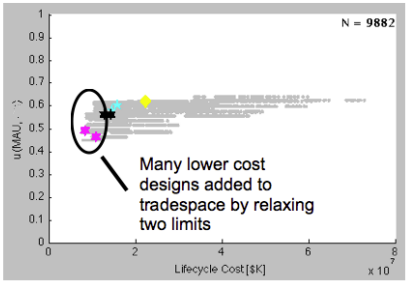




N's *target min detectable velocity* attribute range excludes lower cost alternatives from compromise set

Relaxing one attribute range allows for lower cost alternatives





Relaxing both attribute ranges allows for even more lower cost alternatives

Relaxing these limits is not trivial and requires negotiation among DMs, especially since *TAT* was important to N

Negotiated compromises

Symbol	Design ID	Design Variables: Altitude (km)	Num. Sats	Ant. Area (m^2)	Bandwidth (GHz)	Power (kw)	Tac Comm	"E" MAU	"N" MAU	"R" MAU	Cost B$
Black Star	3423	1500	10	40	2	1.5	yes	**0.75**	0.56	0.63	12.8
	3435	1500	10	40	2	10	yes	**0.81**	0.56	**0.92**	14.3
Blue 5pt star	6027	1200	10	40	2	10	yes	**0.80**	0.58	**0.92**	14.6
	519	800	10	40	2	10	yes	0.68	0.60	0.88	15.8
Diamond	6349	1500	20	40	2	10	yes	**0.87**	**0.62**	**0.92**	22.3
Pink Star	2679	1500	5	10	2	10	yes	**0.56**	**0.49**	**0.60**	8.3
	2787	1500	5	40	2	10	yes	0.60	0.46	**0.85**	10.9

Stake-holder	Design ID	Design Variables: Altitude (km)	Num. Sats	Ant. Area (m^2)	Bandwidth (GHz)	Power (kw)	Tac Comm	"E" MAU	"N" MAU	"R" MAU	Cost B$
All	3423	1500	10	40	2	1.5	yes	**0.75**	**0.47**	0.63	12.8
	3435	1500	10	40	2	10	yes	**0.81**	0.47	**0.92**	14.3
	*6027	1200	10	40	2	10	yes	**0.80**	0.50	**0.92**	14.6
	*519	800	10	40	2	10	yes	0.68	**0.53**	0.88	15.8
	**6349	1500	20	40	2	10	yes	**0.87**	**0.57**	**0.92**	22.3
E+R	2679	1500	5	10	2	10	yes	**0.56**	X	0.60	8.3
	2787	1500	5	40	2	10	yes	0.60	X	**0.85**	10.9

These now delivery utility to N with relaxed preferences

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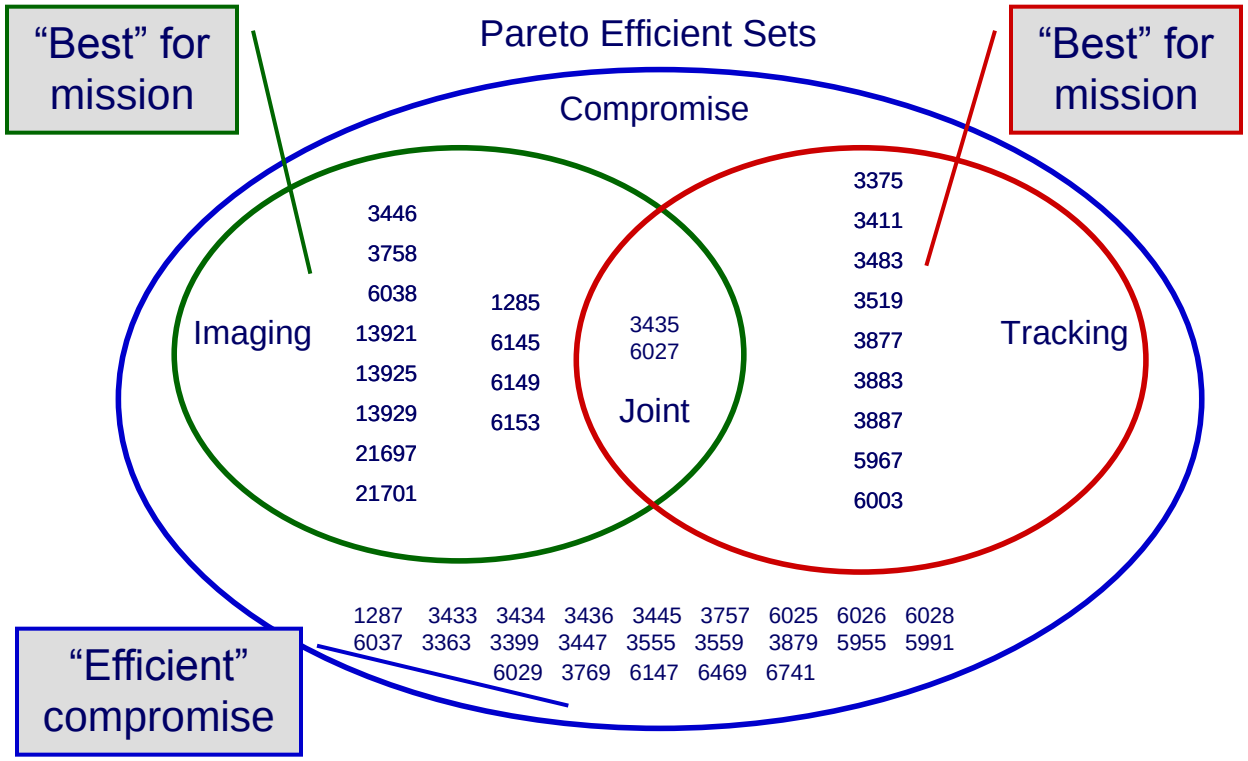
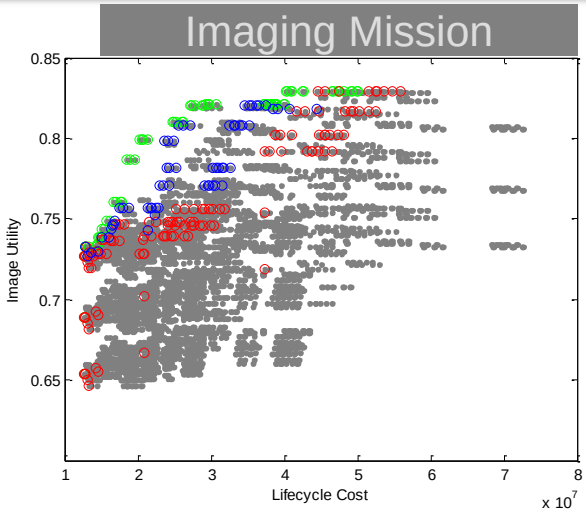
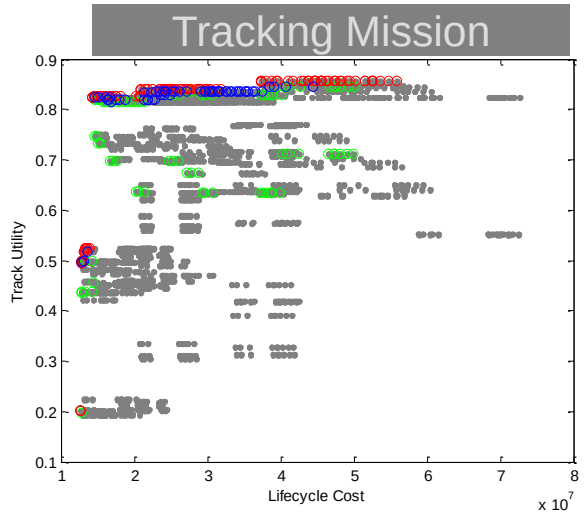
Finding "Compromises" Across Missions and Stakeholders

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







Method provides quantitative approach for discovering "best" mission-specific designs, as well as "efficient" (benefit at cost) compromises across missions and stakeholders

Discover "best" alternatives for individual missions, as well as "efficient" compromises

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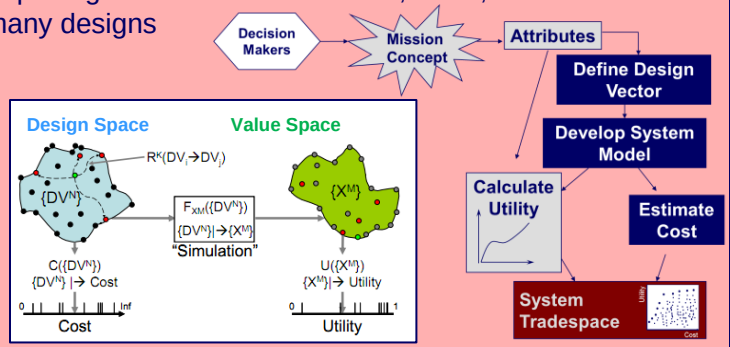
SEAri Tradespace Exploration and Evaluation Methods

Multi-Attribute Tradespace Exploration (MATE)

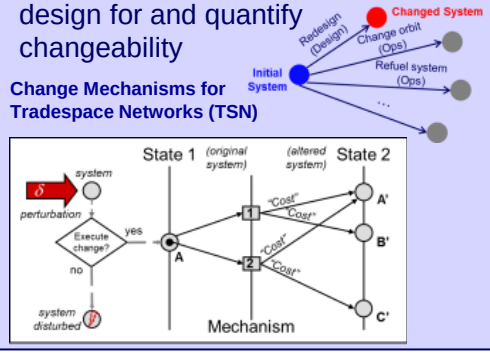
Exploring distribution of attributes, costs, and utilities across many designs



Dynamic MATE

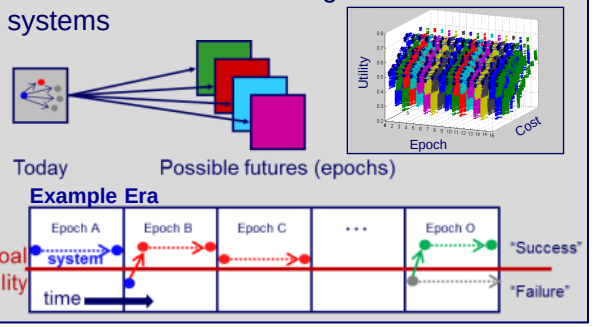
Using tradespace networks to design for and quantify changeability

Change Mechanisms for Tradespace Networks (TSN)



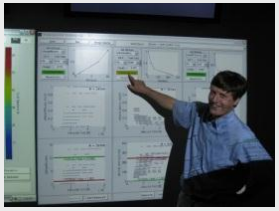
Epoch-Era Analysis (EEA)

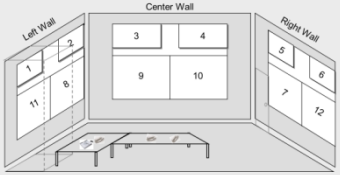
Considering the impact of short run and long run context and needs changes on the success of systems

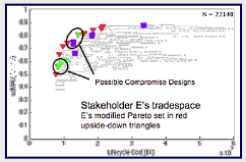


Tradespace Exploration Lab (TSELab) with VisLab (software)

Interactive tradespace exploration environment



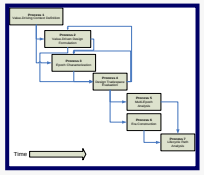




Responsive Systems Comparison Method (RSC)

Using MATE, EEA, and other approaches, RSC is a set of seven processes for gaining insights into developing value robust systems

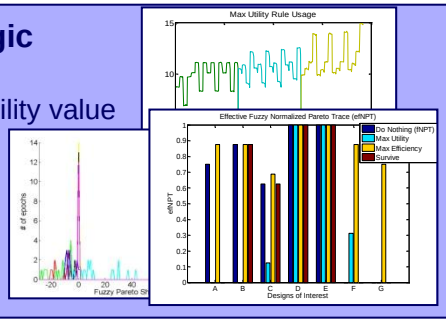
1. Value-Driving Context Definition
2. Value-Driven Design Formulation
3. Epoch Characterization
4. Design Tradespace Evaluation
5. Multi-Epoch Analysis
6. Era Construction
7. Lifecycle Path Analysis



Valuation Approach for Strategic Changeability (VASC)

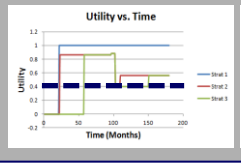
Framework and metrics for changeability value in both multi-epoch and era domains

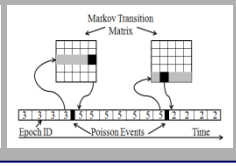
1. Set up data for epoch-era analysis
2. Identify designs of interest
3. Define rule usage strategies
4. Multi-epoch changeability analysis
5. Era simulation and analysis

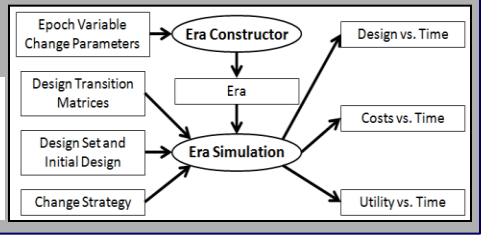


Epoch Syncopation Framework (ESF)

Investigating how epoch ordering and change strategies affect timing of design change decisions







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