A Method for Tradespace Exploration of Systems of Systems

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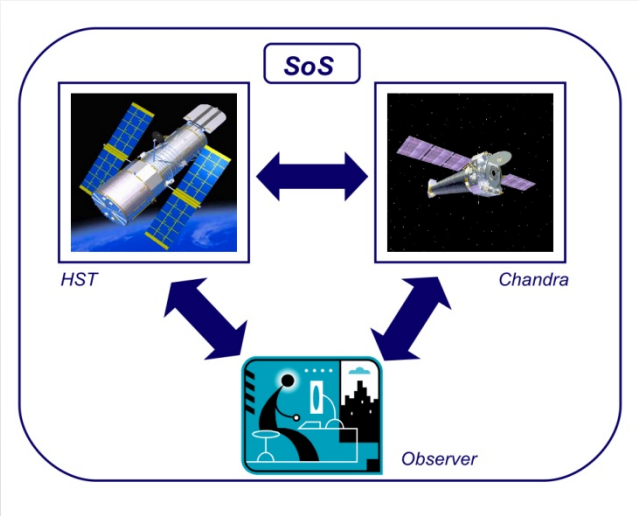
Systems of Systems (SoS)

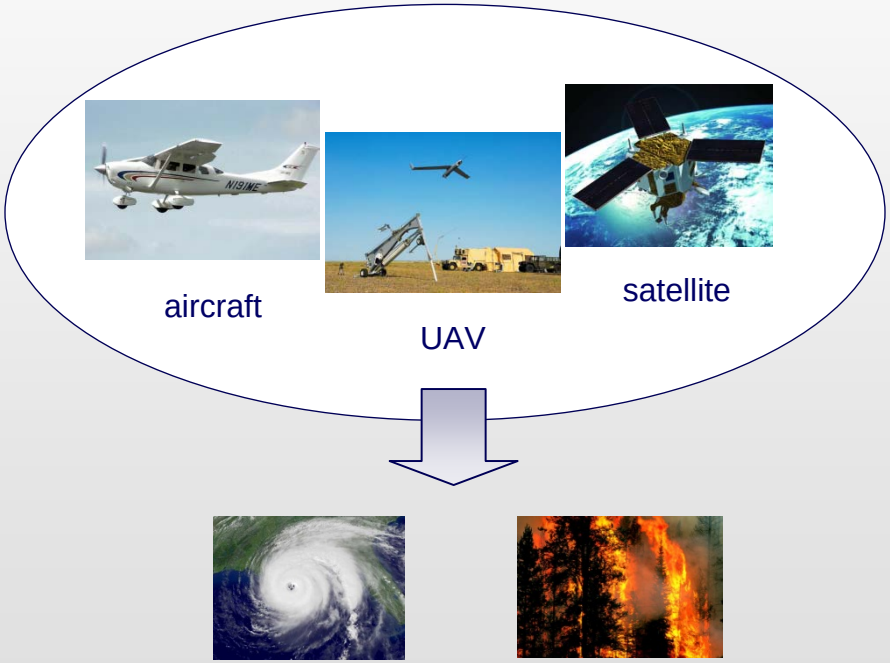
Systems of Systems (SoS) are dynamic higher order systems composed of other *independently managed systems* that together provide some emergent value.

A system-of-systems is a set of *collaboratively integrated systems* that possess two additional properties: *operational independence* of the components and *managerial independence* of the components. (Maier, 1998)



Coordinating Observatories

Components: HST, Chandra and the Observer/User



Multi Concept Disaster Surveillance System

Components: Aircraft, UAV, Satellite

Reference: Maier, M.W., "Architecting Principles for Systems-of-Systems", *Systems Engineering*, 1, 4, pp 267-84, 1998

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Motivation for SoS Tradespace Exploration Method

- SoS are different from traditional systems
  - Operational independence
  - Managerial independence
  - Emergent behavior
  - Varying composition over time, etc.
- SoS engineering requires new methods
- Heuristics and qualitative guidelines in the literature
  - Stable intermediate forms
  - Leverage at interfaces, etc.

Need for quantitative method for comparing SoS designs in order to assist decision makers in the conceptual design phase

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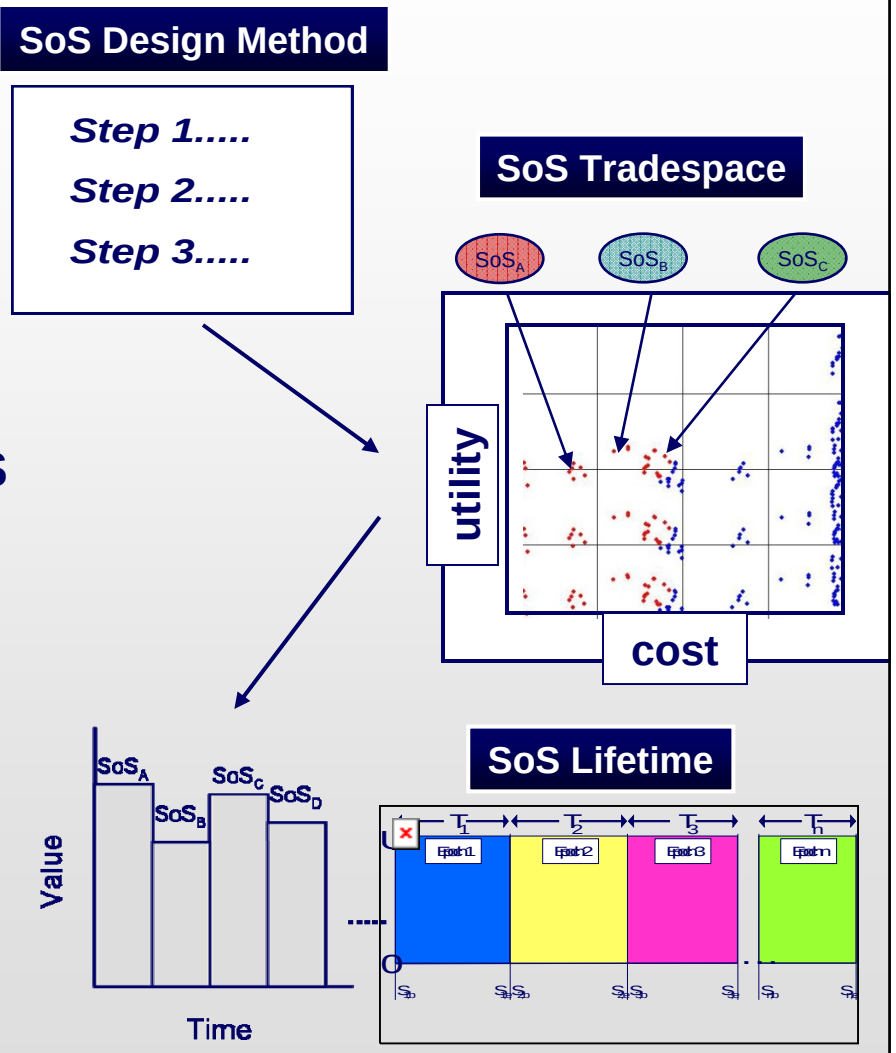
Research Questions

- **What are the characteristics that distinguish SoS design from traditional system design?**
  - local and global stakeholders
  - dynamic composition of system
  - legacy and new components
- **What is a practical framework for SoS tradespace exploration?**
  - Step-by-step method utilizing Dynamic Multi-Attribute Tradespace Exploration
- **How can the developed tradespace exploration framework be used to select SoS designs that are value robust through the SoS lifetime?**
  - Epoch-Era Analysis
  - Pareto Analysis



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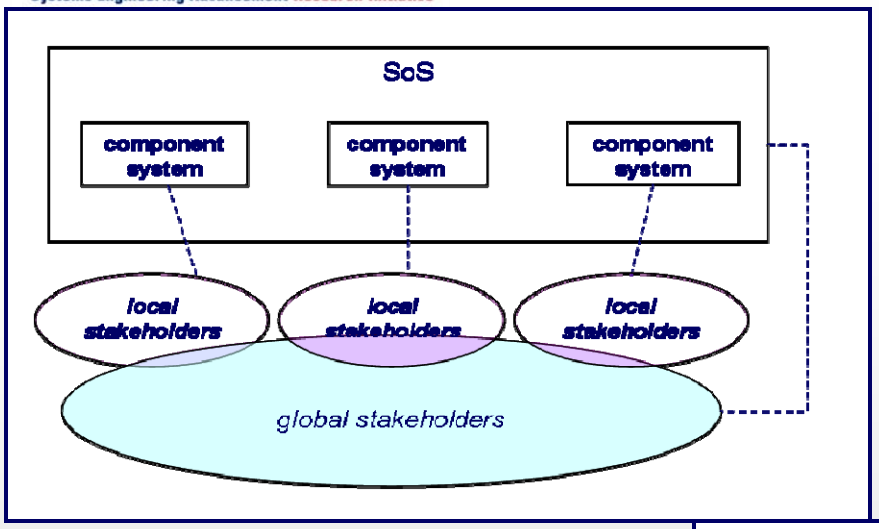
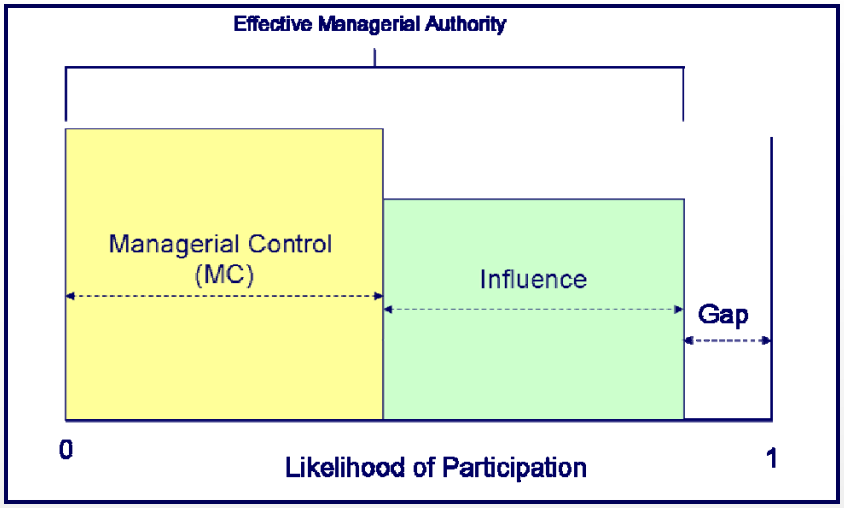
SoS - Specific Design Considerations

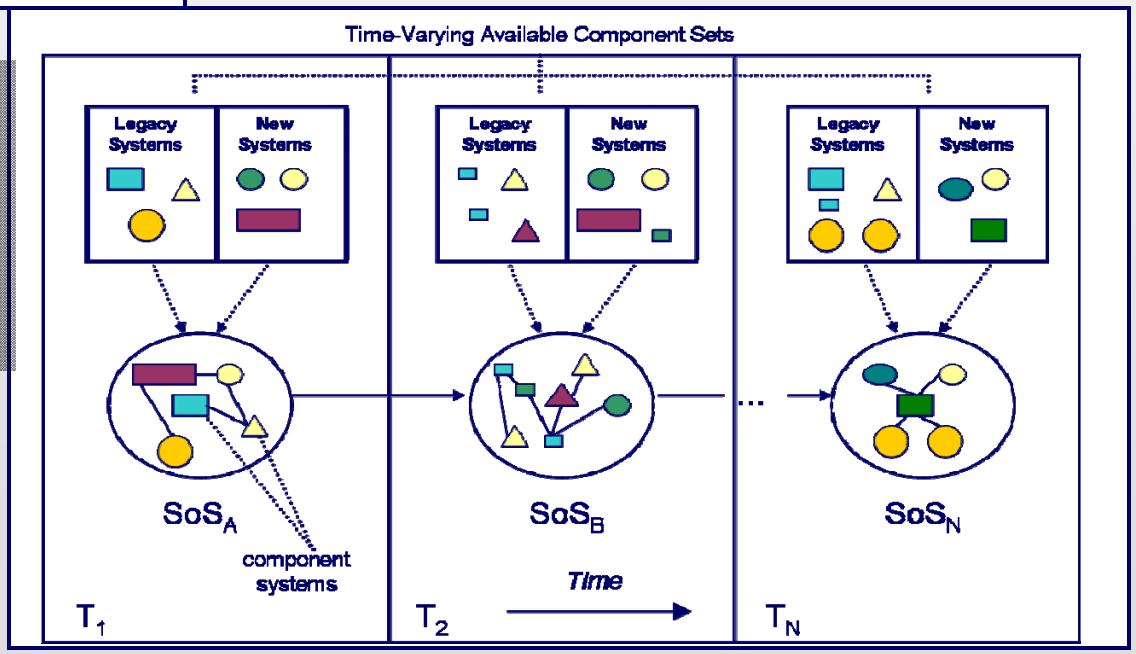




Local and Global Stakeholder Sets

Legacy and New Systems

Dynamic Composition



Chattopadhyay, D., Ross, A.M., and Rhodes, D.H., "A Framework for Tradespace Exploration of Systems of Systems", 6th Conference on Systems Engineering Research, Los Angeles, CA, April 2008.

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SoS - Specific Design Considerations: Control-Influence Structure

Influence Ability of SoS designer to increase the perceived net benefit gain of a component system – could be incentive, or change in SoS framework to increase locally-perceived value

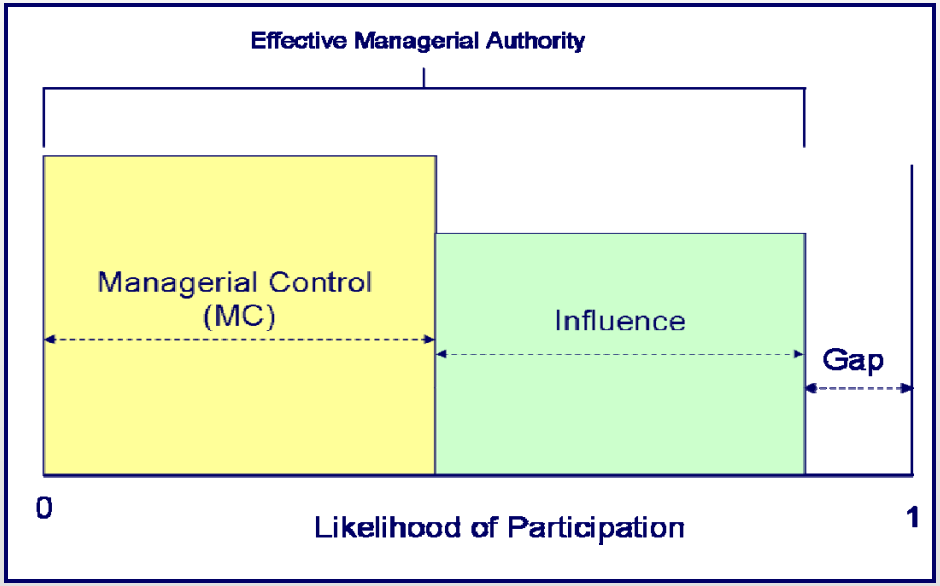
Effective Managerial Authority Combination of Control and Influence employed by SoS designer

Participation Risk Uncertainty in component system participation in SoS

Directed : MC=1, no uncertainty in component participation

Collaborative: 0<MC<1, component participation likelihood increased by increasing influence

Virtual: MC =0, component participation likelihood increased by increasing influence



SoS Designer can use these values to make decisions – Managerial Control and Influence are knobs the designer can potentially turn to reduce Participation Risk

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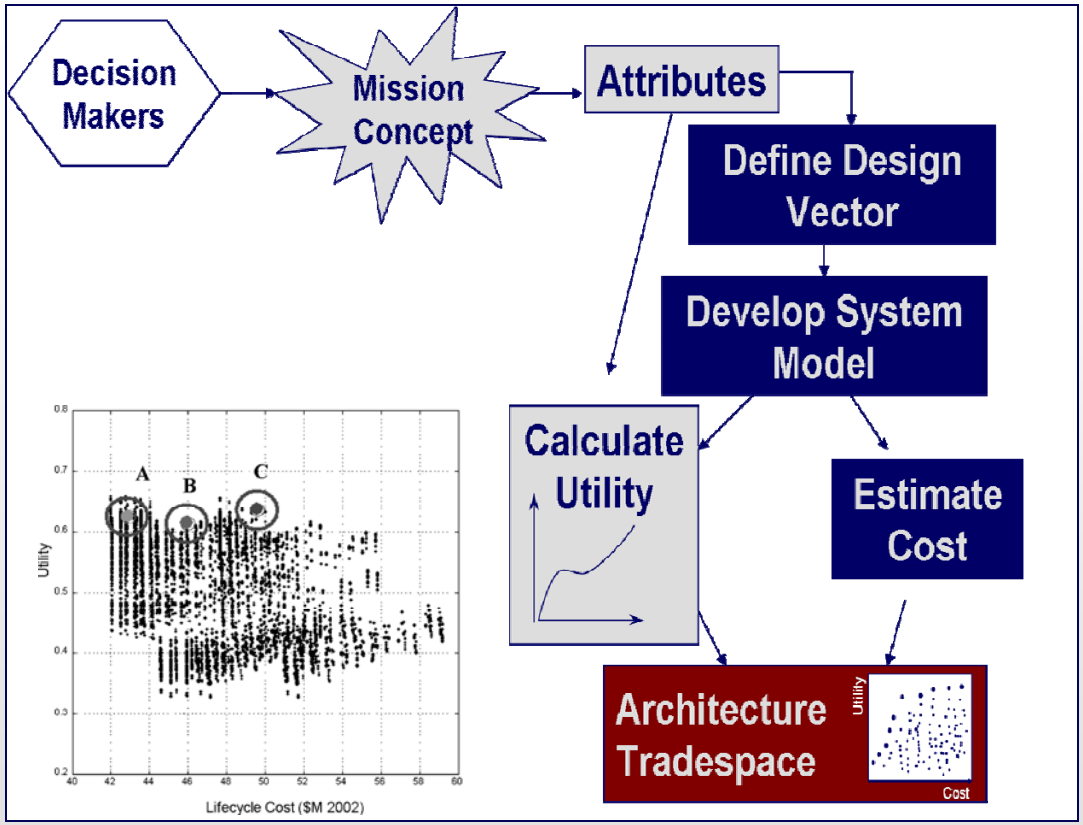
Framework for Exploring SoS Tradespace:
Based on Multi-Attribute Tradespace Exploration (MATE) Method

1. **Determine Stakeholders**
2. **Specify value proposition**
   - **Interview stakeholder**
   - **Determine attribute list**
   - **Elicit utility curves**
3. **Enumerate design vector**
4. **Develop system model linking design variables to attributes**
5. **Compare candidate architectures on same cost-utility basis in tradespace**



Application of decision analysis and utility theory to modelling and simulation based design

Reference: Ross, A.M., Hastings, D.E., Warmkessel, J.M., and Diller, N.P., "Multi-Attribute Tradespace Exploration as a Front-End for Effective Space System Design," *AIAA Journal of Spacecraft and Rockets*, Jan/Feb 2004.

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Framework for Exploring SoS Tradespace:
Uses Epoch-Era Analysis to Generate Future Scenarios

Compare Alternatives

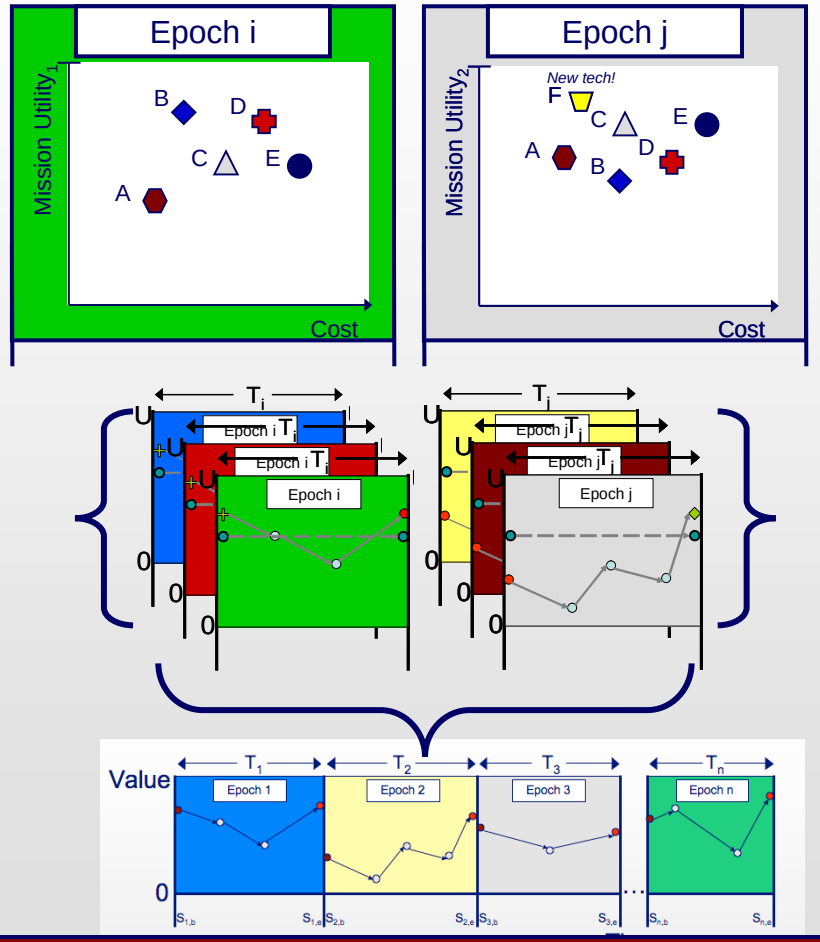
Static tradespaces compare alternatives for fixed context and needs (per Epoch)

Define Epochs

Epoch set represents potential fixed contexts and needs

Construct Eras

Eras represent ordered epoch series for analyzing system evolution strategies



Parametrizing future contexts allows generation of large number of future scenarios

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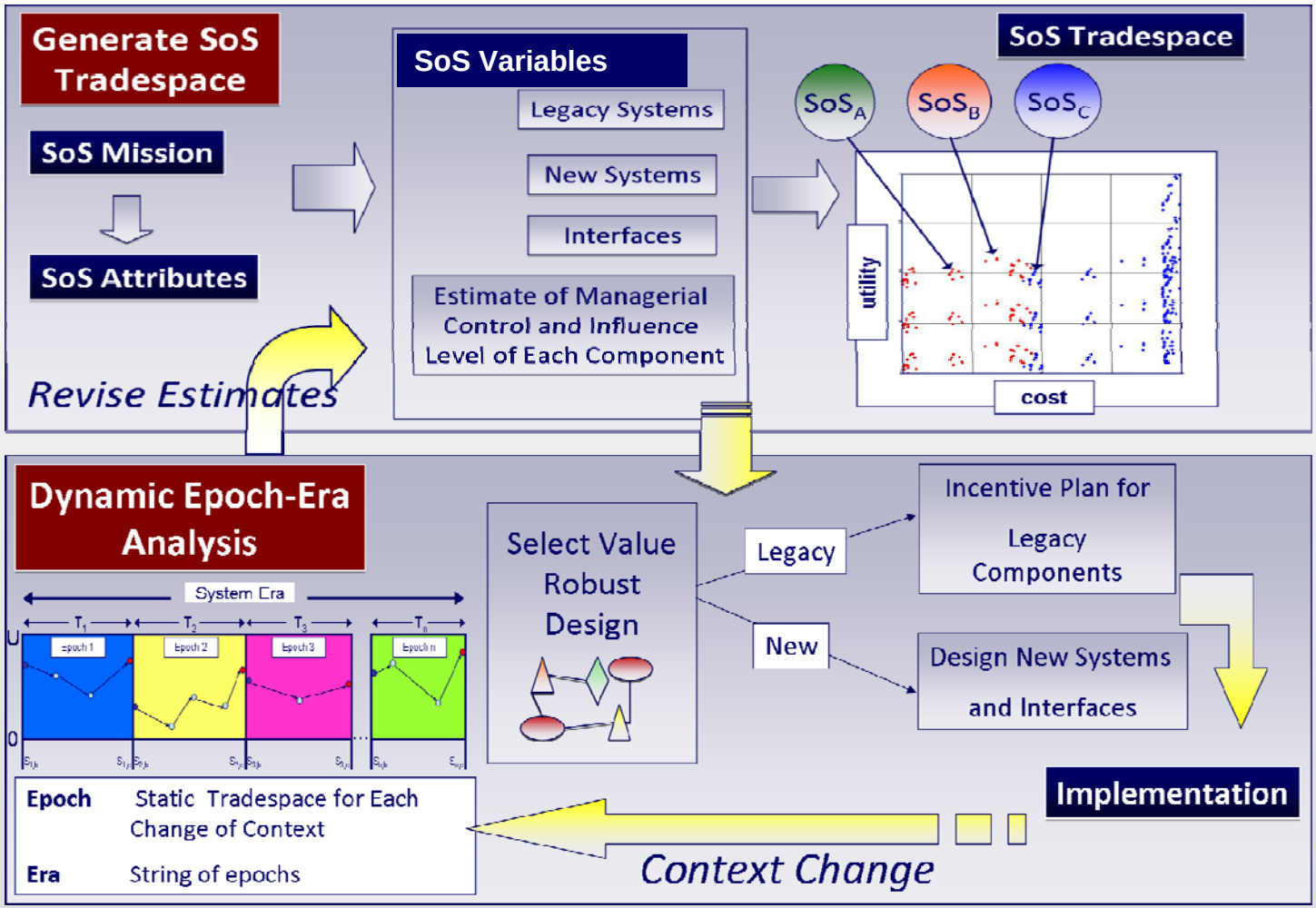
SoS Tradespace Exploration Method (SoSTEM)



Enhancing Dynamic MATE with SoS-specific considerations

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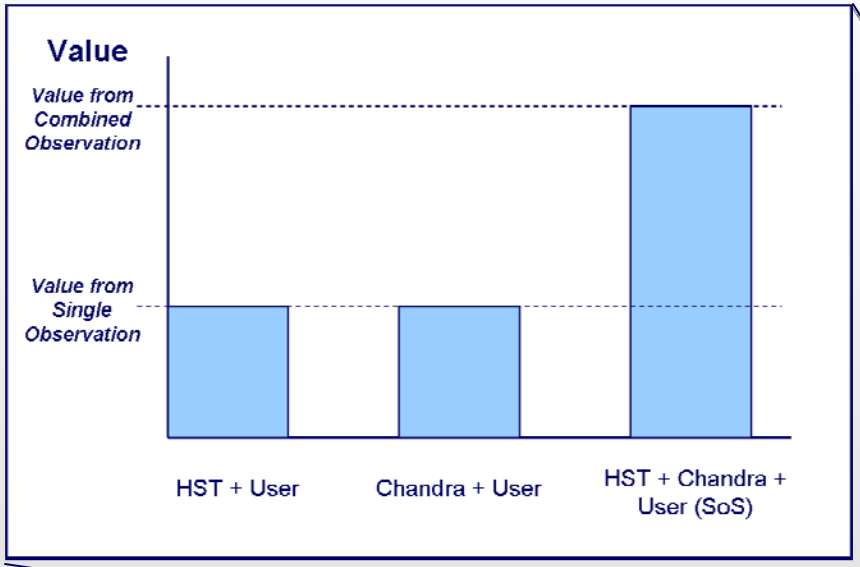
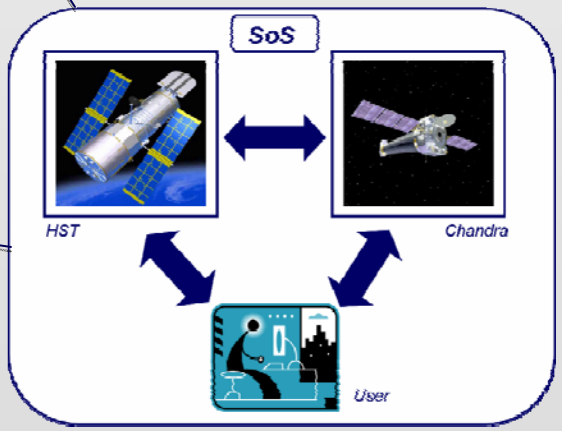
Selecting Value Robust Designs: SoS Value Delivery

SoS 'Value' ~= sum of component value

SoS value> Components greater functionality in SoS
SoS value <Components interactions reduce combined capability



Coordinating Observatories, Chandra and HST



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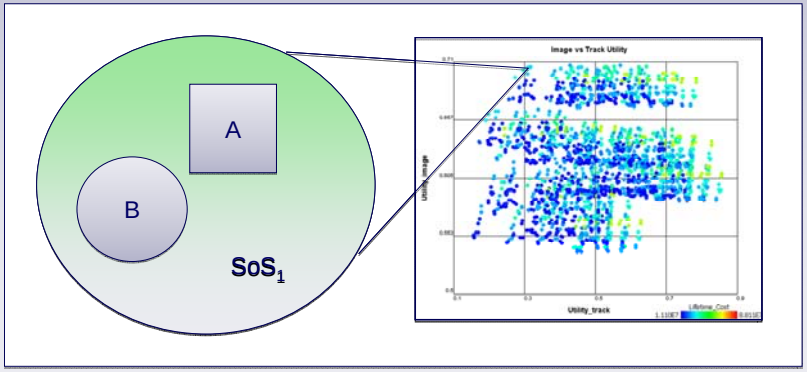
Selecting Value Robust Designs: SoS Value Delivery

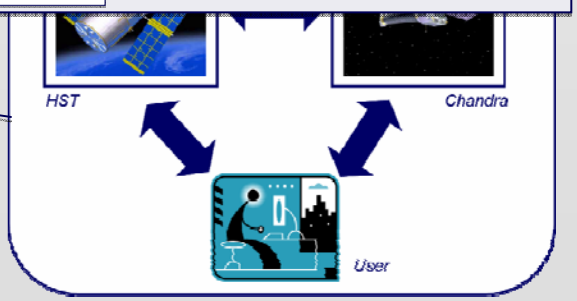
SoS 'Value' ~= sum of component value

SoS value> Components greater functionality in SoS

How is SoS value determined/modeled so that designs can be compared on a tradespace?



Coordinating Observatories, Chandra and HST



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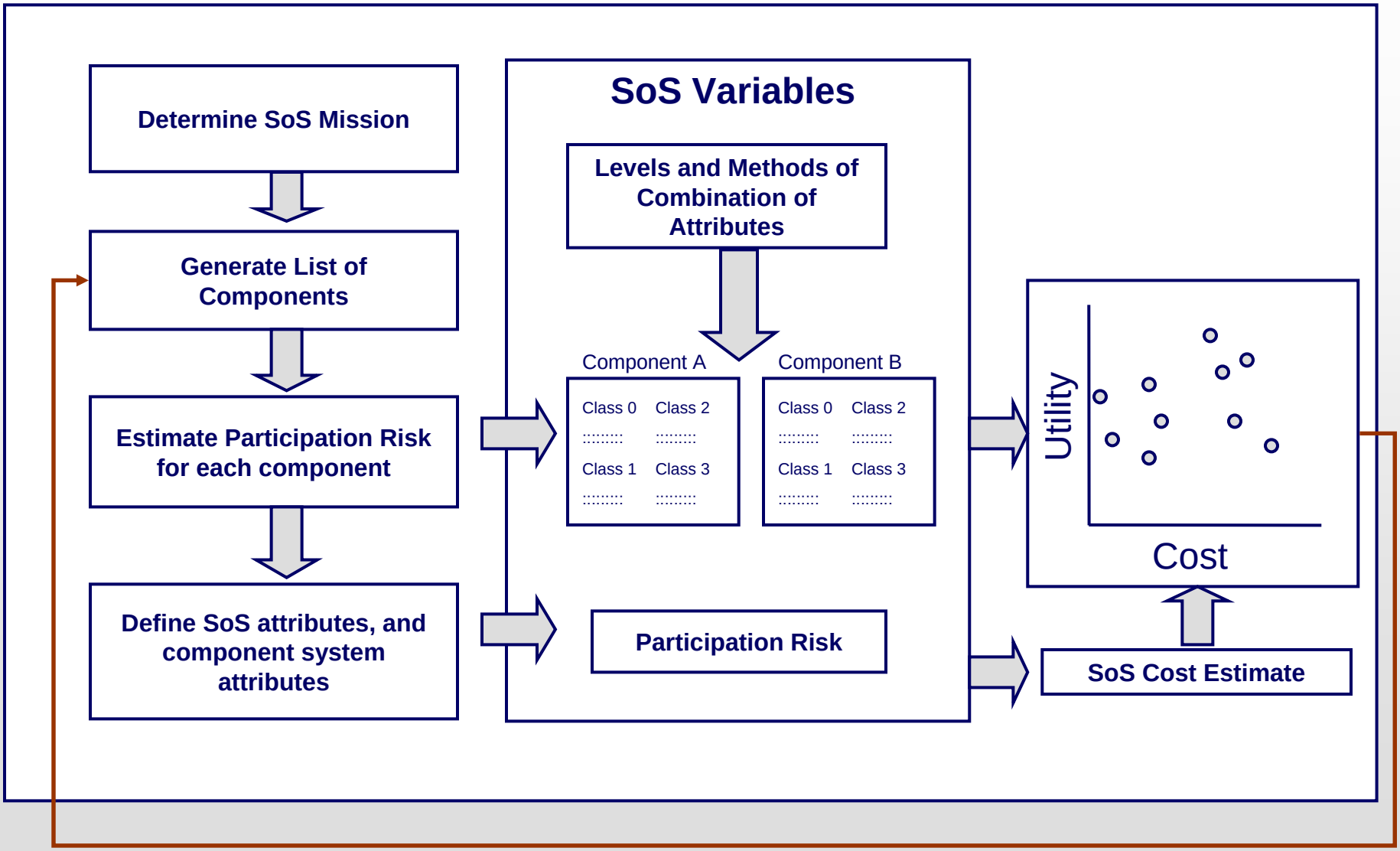
Steps To Generate SoS Tradespace in SoSTEM



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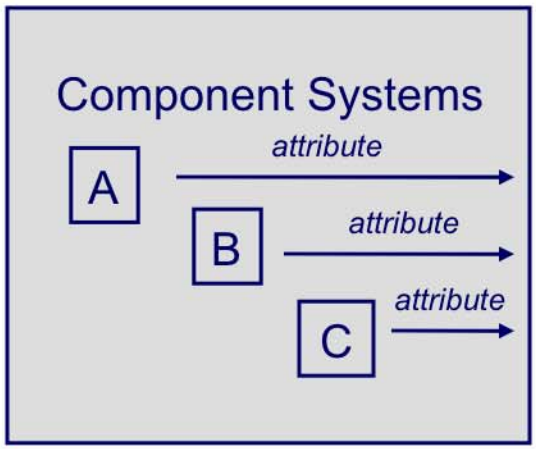
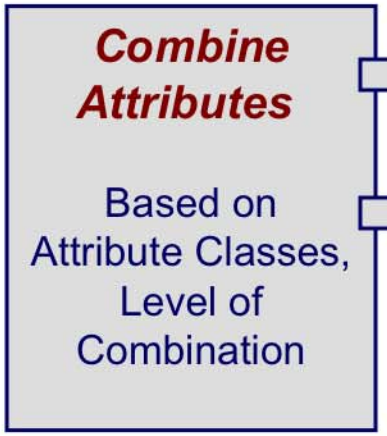
Combining Component System Attributes to Generate SoS Value

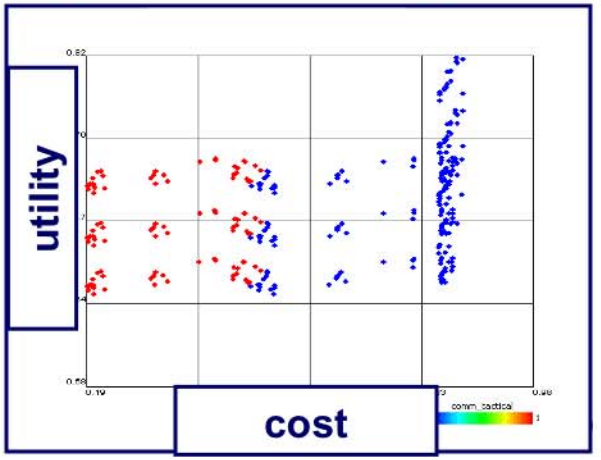




SoS Attribute

SoS Multi-Attribute Utility

SoS Cost



System attributes are decision maker perceived metrics that are used to measure the system value delivery

Component system attributes are combined to generate the SoS utility. Attribute combination has an impact on SoS costs.

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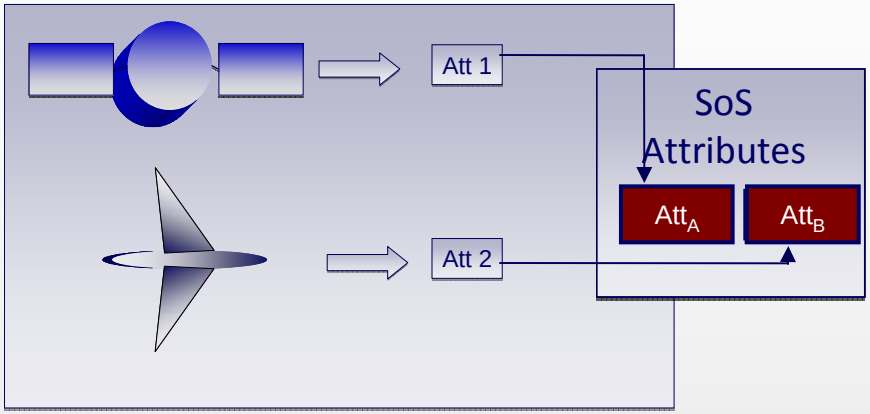
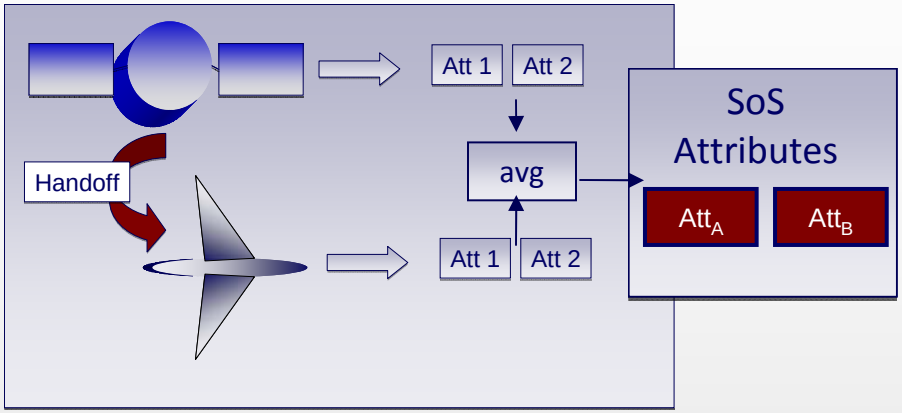
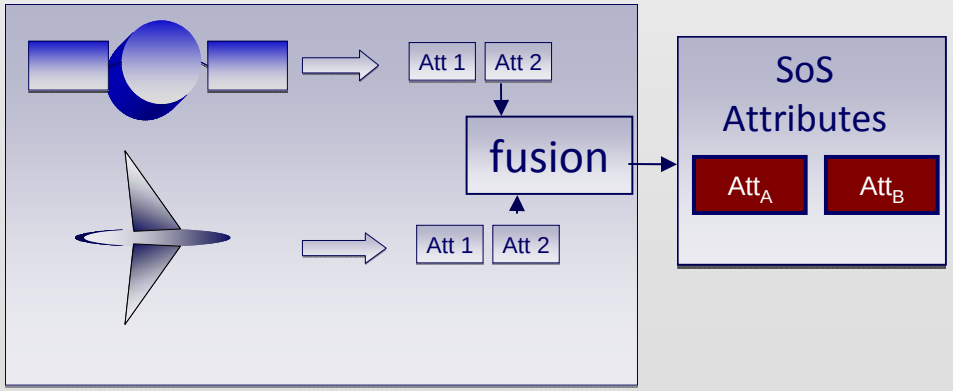
Level of Attribute Combination Complexity



'Low' Level Combination



'Medium' Level Combination



'High' Level Combination

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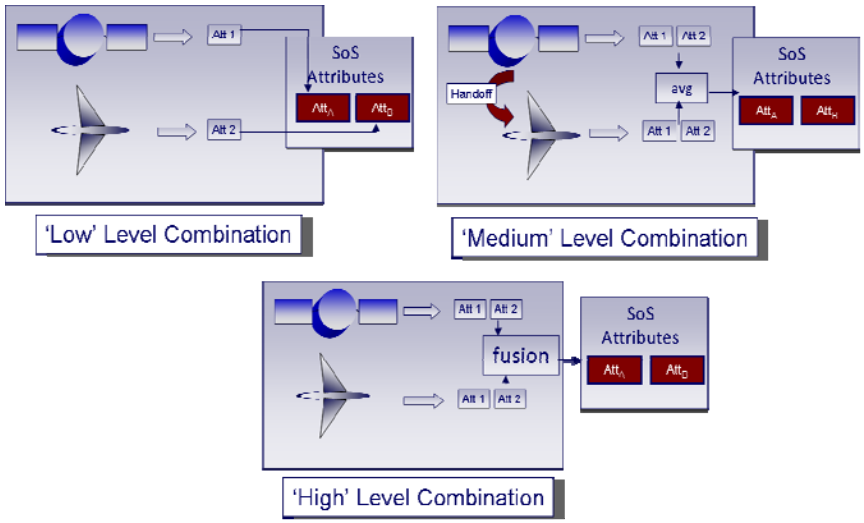
Combining Attributes to Quantify SoS Value Delivery

Class	Name	Property of Class	Cost to Display
0	Articulated Value	Exist and assessed	0
1	Free Latent Value	Exist, but not assessed	0
2	Combinatorial Latent Value	Can exist by recombining Class 0 and 1 Attributes	Small
3	Accessible Value	Can be added through changing the design variable set (scale or modify)	Small -> Large

Attribute Classes from [1]



SoS Attribute

SoS attribute = fn(component A attribute, component B attribute…)

Impact on Cost

Class	Cost Added (% Component Cost)
0,1	Small (10)
2	Medium(20)
3	Large (30)

Multiplier (1,2,3) on cost added for level of attribute combination complexity

[1]Ross, A.M. and Rhodes, D.H. Using Attribute Classes To Uncover Latent Value During Conceptual Systems Design, IEEE International Systems Conference, Montreal CA, April 2008.

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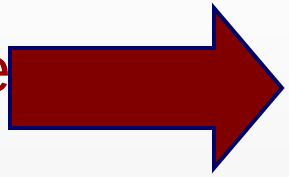
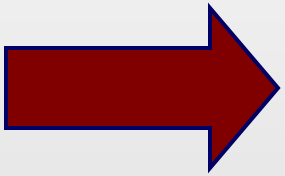
Two Case Studies

- Operationally Responsive Disaster Surveillance System



Illustrate key aspects of SoSTEM

- Satellite Radar System



System of Systems Tradespace Exploration Method (SoSTEM application)

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Selected Goals of the Case Study

- **Stakeholder analysis**
  - Incorporation of considerations for the independence of component system management
  - **Multiple stakeholders at the SoS level**
- **Legacy and New Component Systems**
  - **Comparison of both legacy and new designs on a single tradespace**
  - **Comparison of multi-concept SoS on a single tradespace**
- **Dynamics of SoS Composition and Context**
  - **Epoch-Era Analysis to study system performance over changing future contexts, identification of value robust designs**
  - Develop strategies for graceful degradation to robust or stable intermediate designs

Illustrate selected aspects of the SoS Tradespace Exploration Method

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Multi-Concept Operationally Responsive Disaster Surveillance

Design Concepts

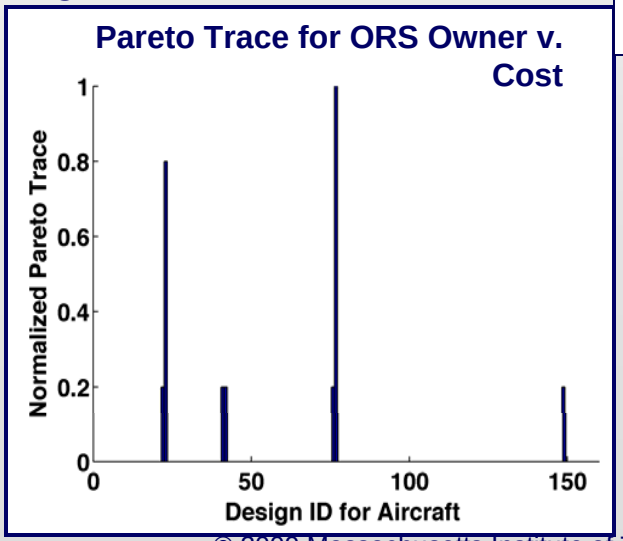
- Aircraft
- Satellite
- Sensor Swarm
- **SoS designs** consisting of any two of above

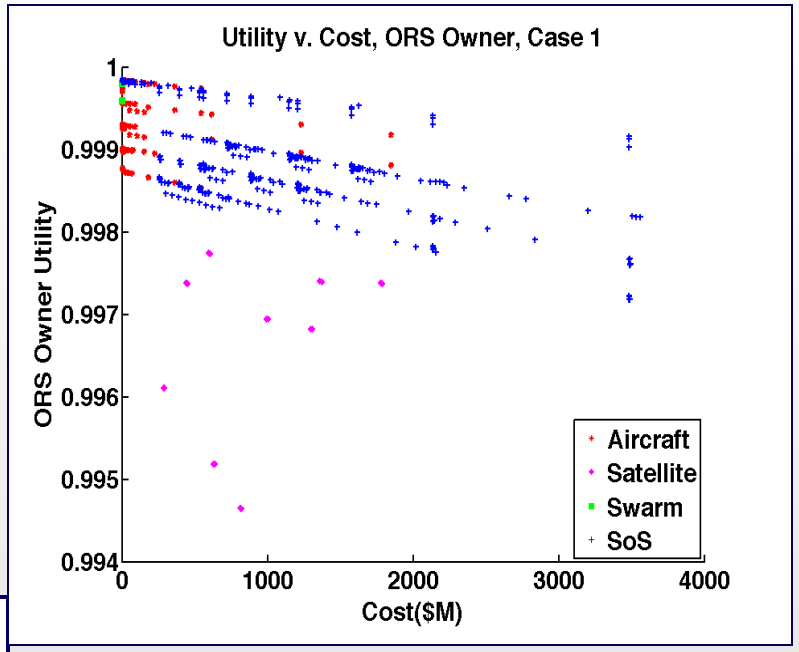
Stakeholders

Firefighter

ORS Owner

- **Epoch Analysis**
- **Pareto Trace**





Attributes (Firefighter/ORS Owner)

Acquisition Cost	Time Between AOI
Price/Day	Max % of AOI Covered
Cost/Day	Time to Max Coverage
Responsiveness	Imaging Capability
Time to IOC	Data Latency

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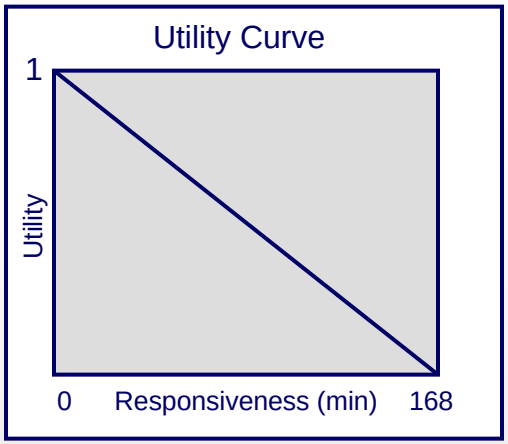
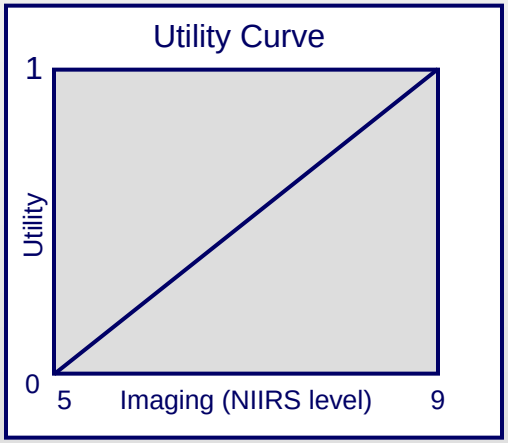
Attributes for Selected Stakeholders

Attribute Name	Attribute Definition	Firefighter Attribute Range	ORS Owner Attribute Range	Attribute Units
Acquisition Cost	Cost to acquire system	0-800	0-1000	$M
Price/day	Amortized price paid for operations per day	0-25	N/A	$K/day
Cost/day	Cost of operations per day	N/A	0-2500	$K/day
Time to IOC	Time between initial need for system and initial operating capability	0-180	0-180	days
Responsiveness	Time from request to initial observation of AOI	0-168	0-168	hours
Max % AOI Covered	Percentage of AOI imaged by system	5-100	5-100	percentage
Time to Max Coverage	Time to maximum coverage of AOI	0-1440	0-1440	minutes
Time between AOI	Time from AOI_1 to AOI_2	0-120	0-120	minutes
Imaging Capability	NIIRS level of images	5-9	5-9	NIIRS level
Data Latency	Time between start of imaging to reception of images by user	0-360	0-360	minutes





Attributes were generated by the design team by proxy for Firefighters and ORS Owner

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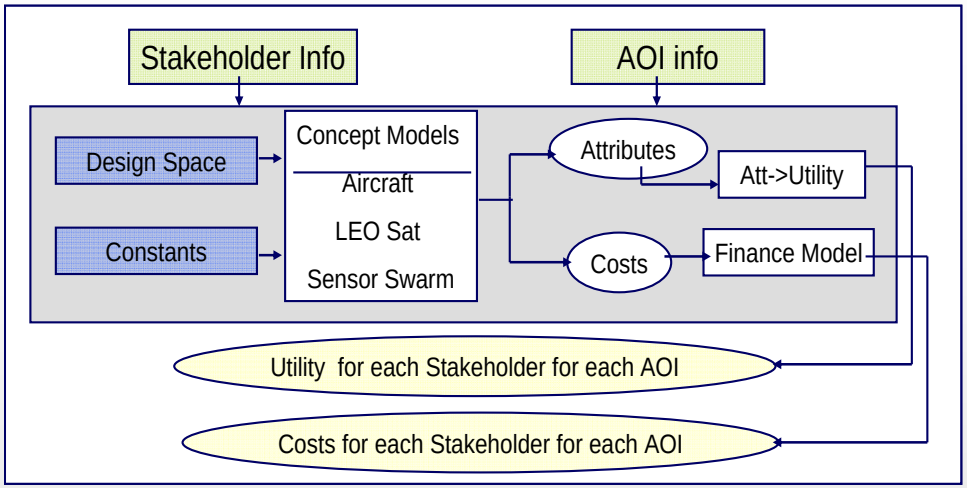
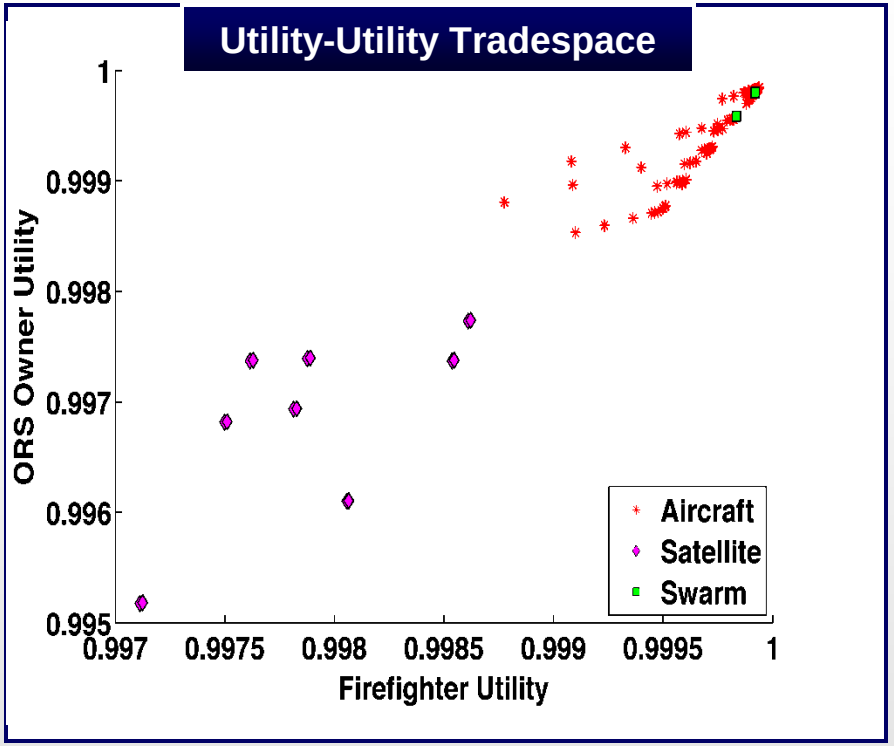
First-Pass Model
Single System Concepts



First-Pass Model Flow



Concept	Design	Number of Assets	Wavelength	Aperture Size (m)
Aircraft	ScanEagle	1	IR	0.04
Sensor Swa	Camera Swa	50	IR	0.04

Comparison of diverse concepts on tradespace
Pareto Set includes multiple concepts

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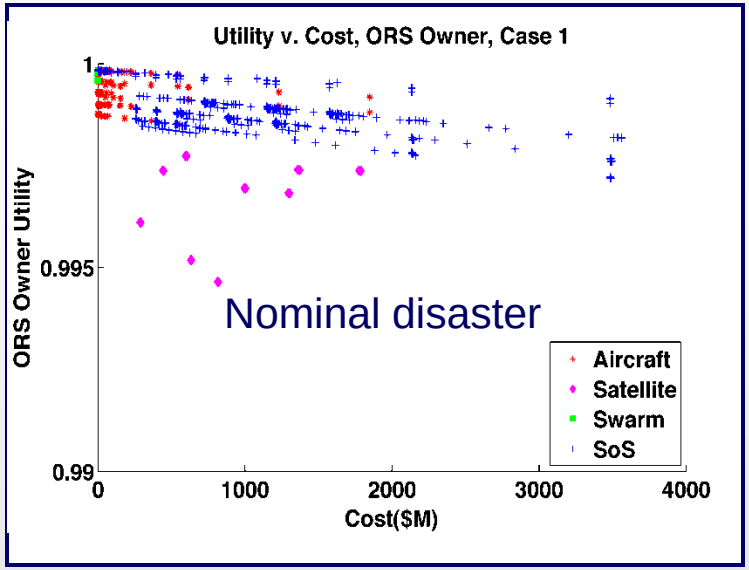
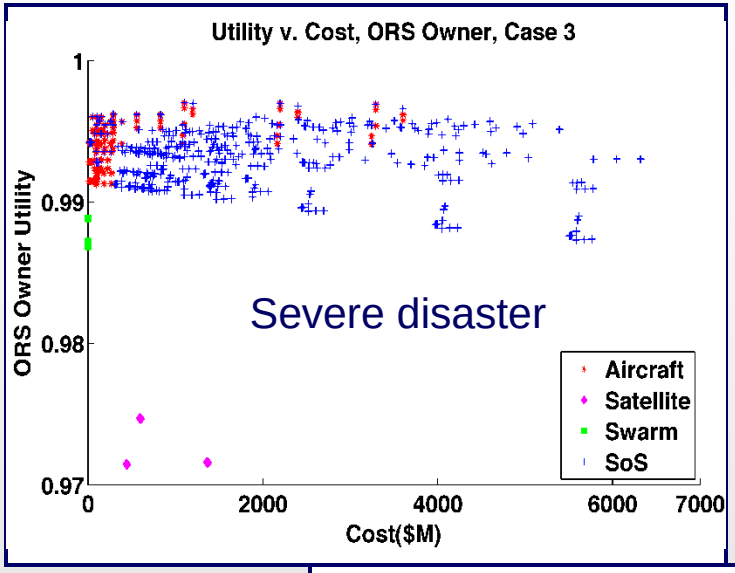
Epoch Changes in Stakeholder Preference

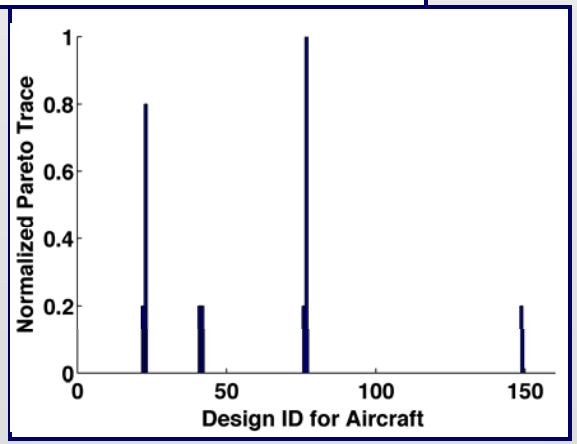
Original Attribute Relative Weights



Changed Attribute Relative Weights



Concept	Description	Normalized Pareto Trace (N=5)
Aircraft	ScanEagle	1.00
SoS	ScanEagle and Camera Swarm (150 units)	1.00
SoS	RQ-11 Raven UAV and Camera Swarm (150 units)	1.00



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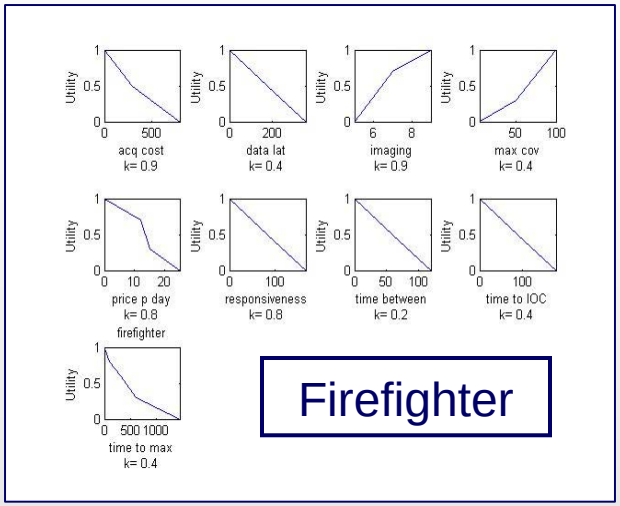
Second-Pass Model

Stakeholder Info



Area of Interest Info

AOI Num	Description	Latitude Range	Longitude Range	Time
1	Hurricane Katrina disaster area, LA	29°50´N - 30°05´N	89°50´W - 90°15´W	0-12 hours
2	Witch Creek Fire, CA	32°55´N - 33°22´N	116°41´N - 116°59´N	0-20 hours
3	Cyclone Nargis disaster, Yangon area, Burma	16°40´N – 18°0´N	95° 50´N - 97° 10´N	0-24 hours

- Aircraft and Satellite selected for detailed modelling
- Both legacy and new designs included
- AOI definition more refined compared to first-pass
- Stakeholder utility curves are non-linear
- SoS modelling is similar to first-pass, using combination of Aircraft and Satellite

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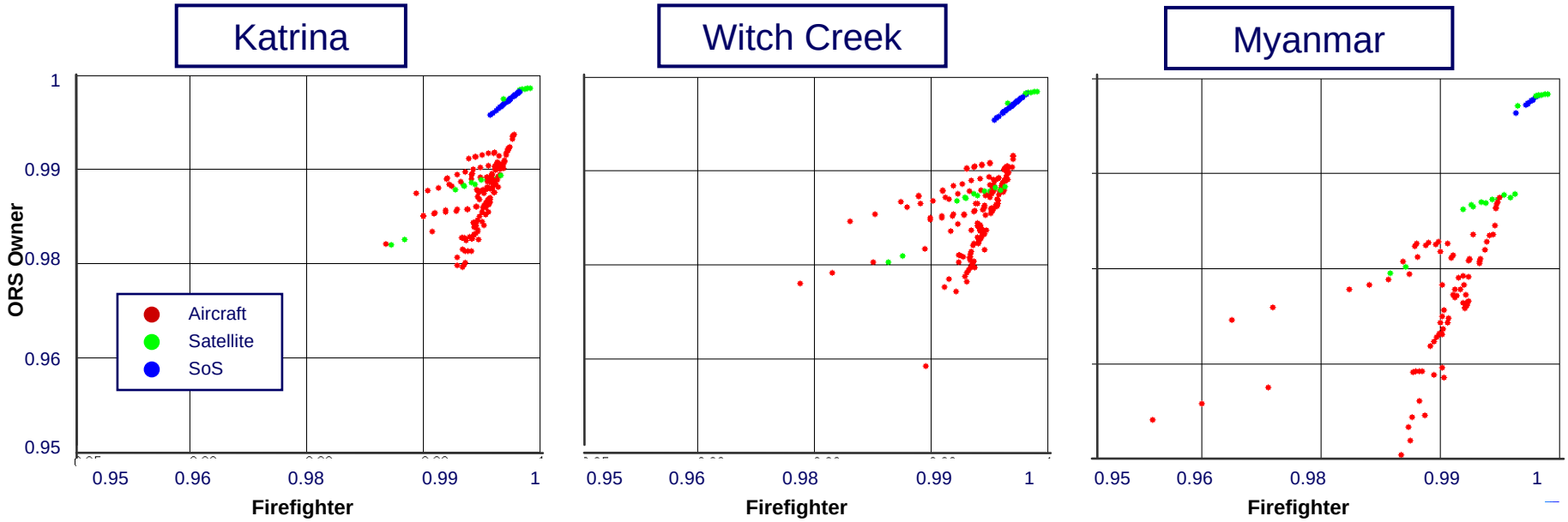
Epoch-Era Analysis for Change in AOI



Design Num	Concept	Description	Normalized Pareto Trace (N=3)
2116	Aircraft	ScanEagle	1.00
2764	Satellite	120 km sun-synch orbit, IR payload	1.00
925	SoS	Aircraft (UAV w/ piston, IR) + satellite (800 km, sun-synch, IR)	1.00
1061	SoS	Aircraft (Cessna, IR) + satellite (120 km, 23 deg, IR)	0.67

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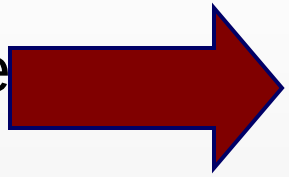
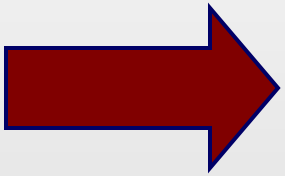
Case Studies

- Operationally Responsive Disaster Surveillance System



Illustrate key aspects of SoSTEM

- Satellite Radar System



System of Systems Tradespace Exploration Method (SoSTEM application)

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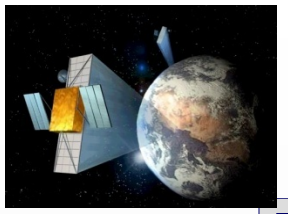
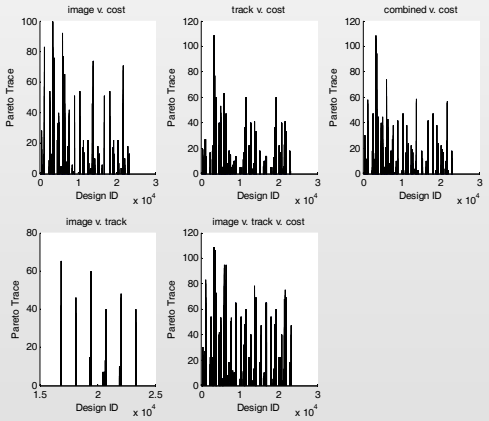
Satellite Radar



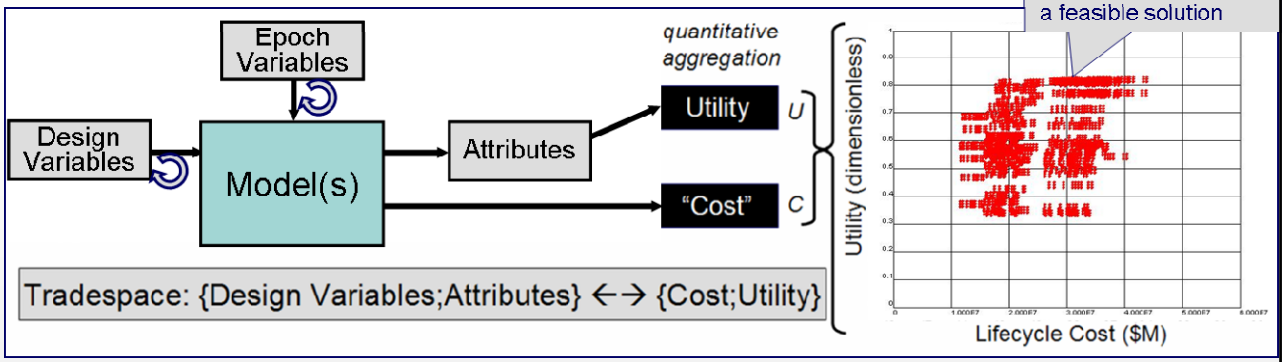
Concept Independent Attributes

	Attribute Name	units	range (U=0 to U=1)
Tracking	Minimum Target RCS	dB	12 --> 0
	Min. Discernable Velocity	m/s	40 --> 1
	Number of Target Boxes	#	0 --> 10
	Target Acquisition Time	min	120 --> 10
	Target Track Life	min	0 --> 30
	Tracking Latency	min	60 --> 1
Imaging	Resolution	m	100 --> .01
	Targets per Pass	#	0 --> 50
	Field of Regard	km^2	100 --> 1000000
	Daily Revisit Frequency	#	0 --> 8
	Imaging Latency	min	1440 --> 10
Program	Baseline Cost	$B	100 --> 5
	Deviation from Cost	%	200 --> 0
	Baseline Schedule	years	20 --> 3
	Deviation from Schedule	years	5 --> 0

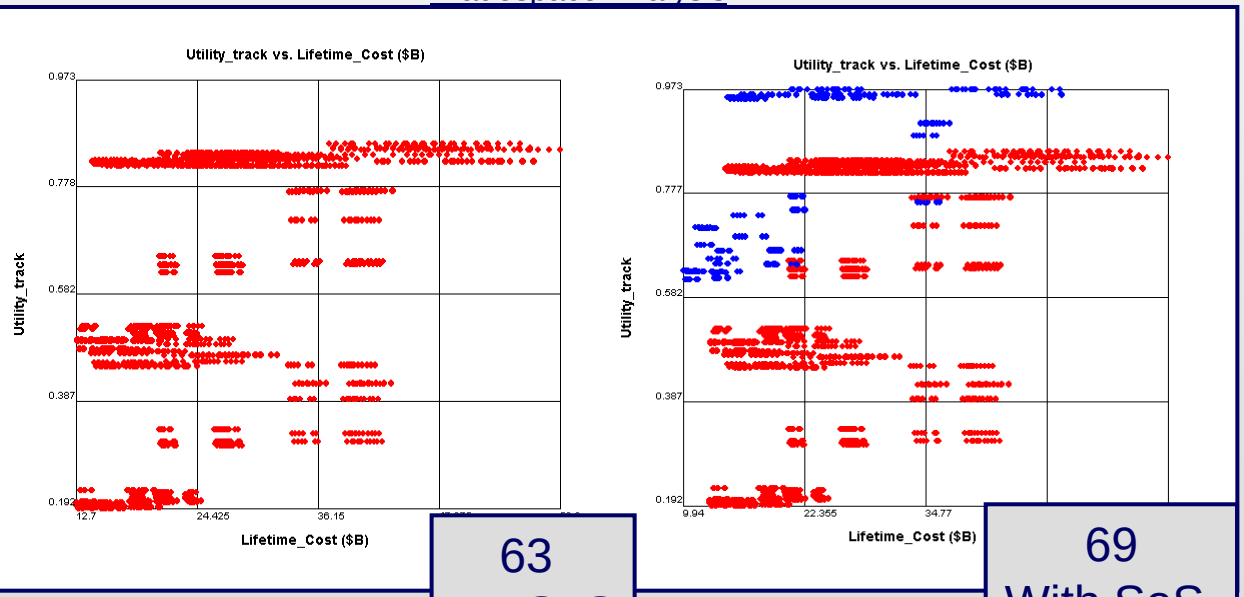


Generate list of possible value robust designs

Generate Tradespaces



Tradespace Analysis



63
No SoS

69
With SoS

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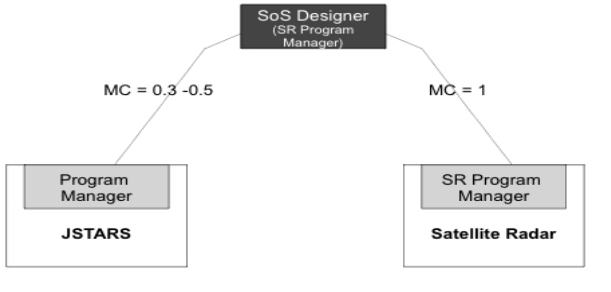
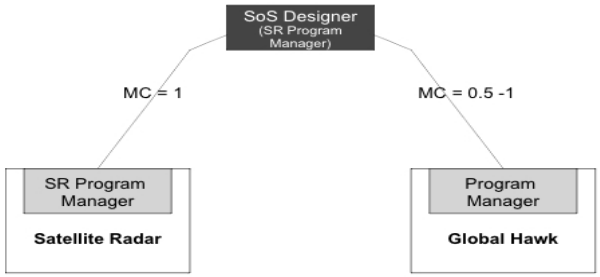
Satellite Radar SoS

SoS Architecture



(a) SoS Concept with JSTARS and SR



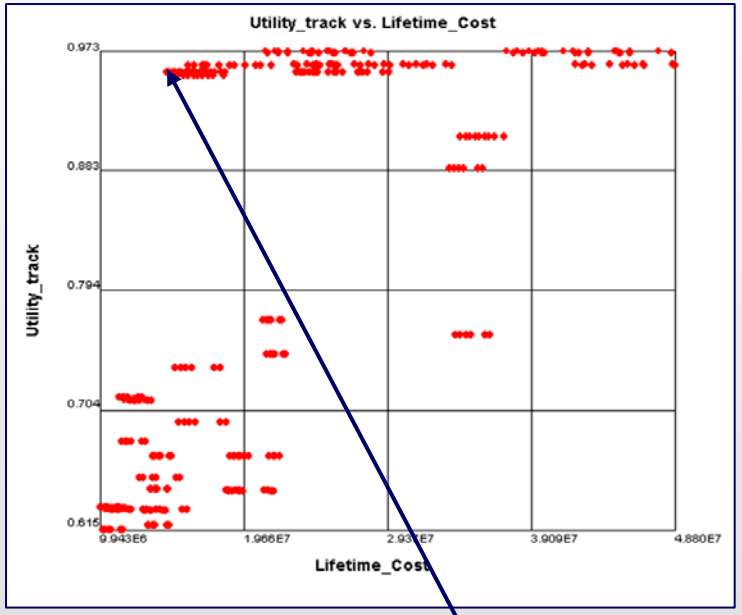
(b) SoS Concept with Global Hawk and SR

- Diverse SoS (with new and legacy component systems) on same tradespace
- Enables Pareto analysis over a large number of designs
- Consideration of Participation Risk during conceptual design

Can determine SoS design PR from component system PR

$PR = 1 - (MC+In)$

$SoS\ PR = 1 - (1- PR_A)\ (1-PR_B)$



Pareto Design 1718 (SR + Global Hawk)
SR: 40m antenna, 1500 km orbit, 10/10/1 Walker, 53 degree inc

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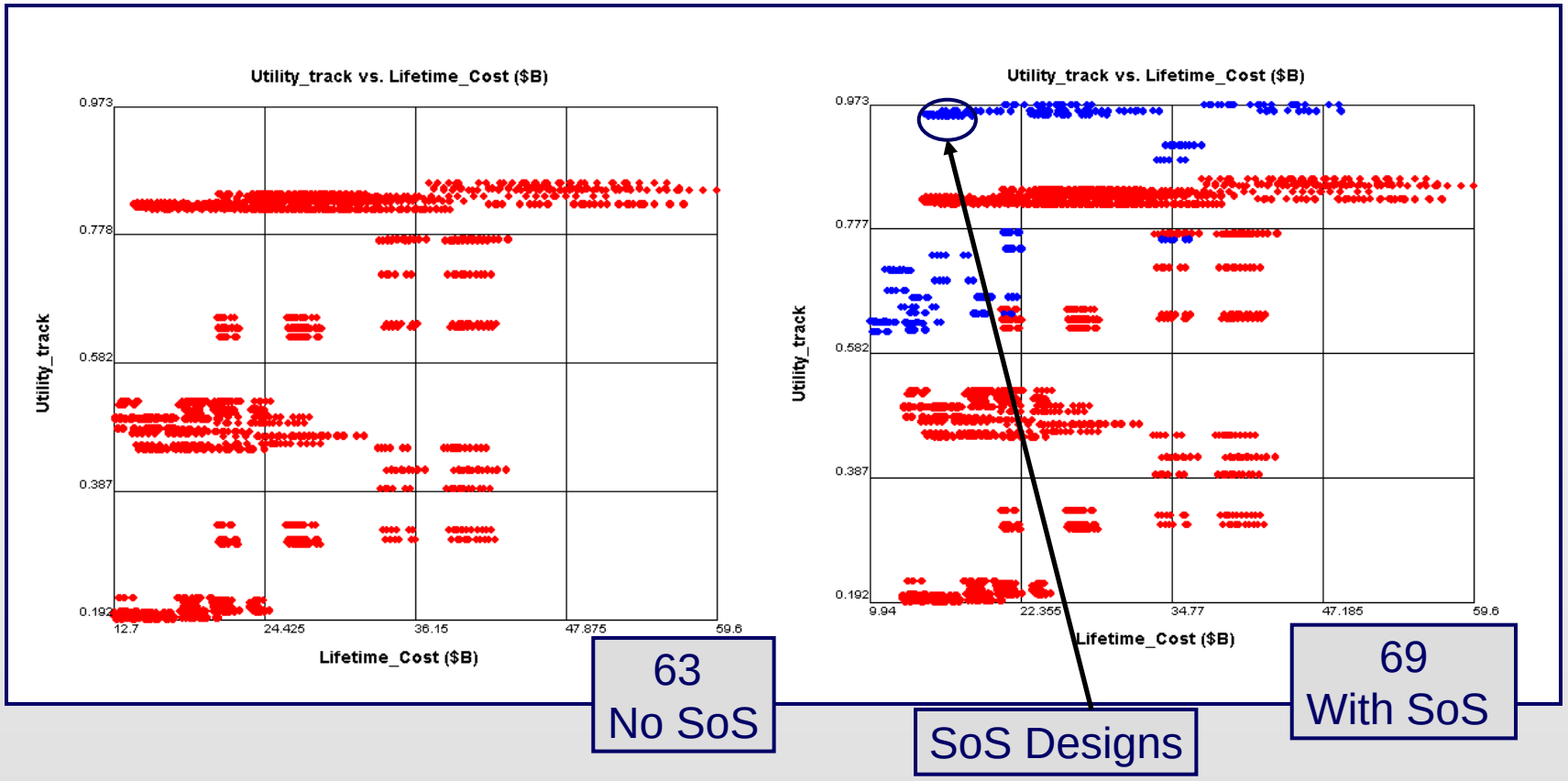
Epoch 63 v Epoch 69
Availability of Aircraft Assets



More designs at higher utility become available to the decision maker in SoS compared to single Satellite Radar system

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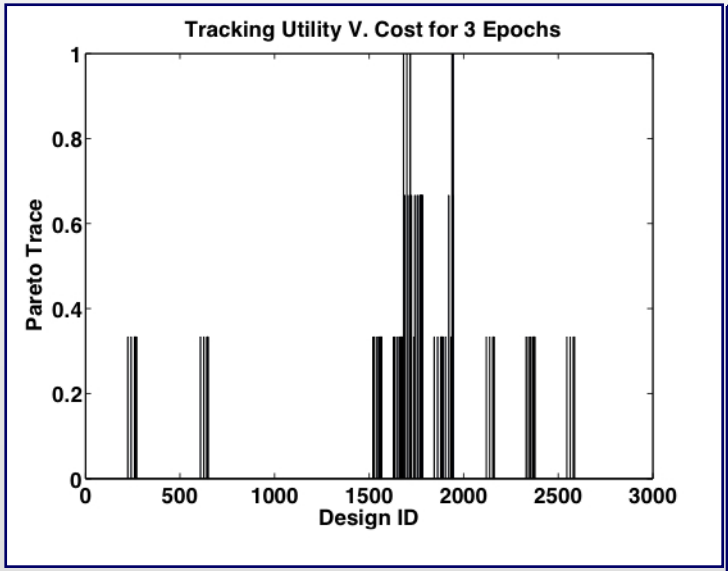
Pareto Trace for Satellite Radar

Epoch Number	Target Location and Size
69	(35 ◦ 41', 51 ◦ 25') (medium RCS) and (31 ◦ 12', 121 ◦ 26') (large RCS)
33	(35 ◦ 41', 51 ◦ 25') (small RCS) and (55 ◦ 46', 37 ◦ 40') (large RCS)
45	(35 ◦ 41', 51 ◦ 25') (small RCS) and (39 ◦ 02', 125 ◦ 41') (small RCS)



Design Num	Concept	Description	Lifetime Cost ($B)	Normalized Pareto Trace (N=3)
1718	SR and Global Hawk	SR: 40m antenna, 1500km alt, 10/10/1 Walker,53 degree inc	14.4	1.00
1944	SR and JSTARS	SR:100m antenna,1500km alt, 20/5/1 Walker, 53 degree inc	45	1.00

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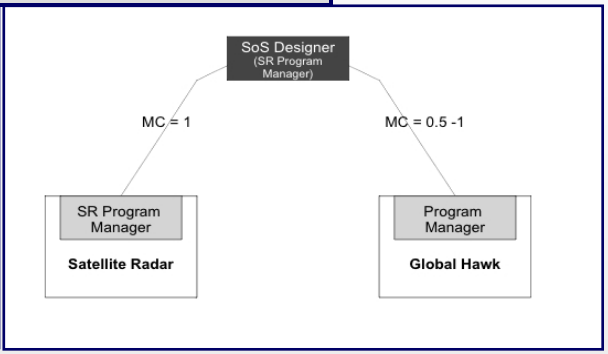
Participation Risk for Satellite Radar

Can determine SoS design PR from component system PR

PR = 1 – (MC+In)

SoS PR = $1 - (1- PR_A) (1-PR_B)$

	Satellite Radar	JSTARS	Global Hawk
Managerial Control	1	0.3-0.5	0.5-1.0
Influence	None	0-0.3	0-0.3
Participation Risk	0	0.2-0.7	0-0.5



Example Case Number	Satellite Radar			Global Hawk			SR+ Global Hawk SoS
	MC	In	PR	MC	In	PR	PR
1	1	0	0	0.5	0	0.5	0.5
2	1	0	0	0.5	0.3	0.2	0.2
3	1	0	0	1	0	0	0

Can study the SoS Participation Risk for different designs
Include PR in selection of designs

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Conclusions of Case Studies

- **Case study demonstrates the ability to quantitatively compare diverse single systems as well as heterogeneous SoS on same tradespace**
  - Enables trades across concepts (aircraft vs SoS) and within concepts (Cessna vs UAV)
  - Comparison of legacy and new single systems, as well as SoS composed of both legacy and new systems
- **Tradespaces can be easily generated for a number of possible system contexts and needs (epochs)**
  - Epochs for stakeholder preference changes, disaster location changes
  - Different types of tradespace can be used to provide insights for decision analysis (e.g., utility-utility plots to identify compromise designs)
- **Value robust designs can be identified by tracking high-utility designs over a variety of changing value propositions**
  - Use of metrics such as Pareto Trace
- **Participation Risk can be included in conceptual design to investigate managerial complexity of coordinating multiple component system organizations**

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Research Outcomes

System of Systems Tradespace Exploration Method (SoSTEM)

Combining Attributes Control, Influence,

Participation Risk

Comparison of multiple single concepts and SoS on same tradespace

Future Work

1. Further study of distribution of costs and benefits between SoS and component systems and effect of distribution on Participation Risk
2. Improve SoS cost modelling fidelity
3. Detailed methods for combining attributes
4. Strategies for maintaining SoS value over time

Chattopadhyay, D., *A Method for Tradespace Exploration of Systems of Systems*, Master of Science Thesis, Aeronautics and Astronautics, MIT, June 2009

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Thank you.

Questions?

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