# Demonstration of System of Systems Multi-Attribute Tradespace Exploration on a Multi-Concept Surveillance Architecture

**Debarati Chattopadhyay**
**Adam M. Ross**
**Donna H. Rhodes**
Massachusetts Institute of Technology


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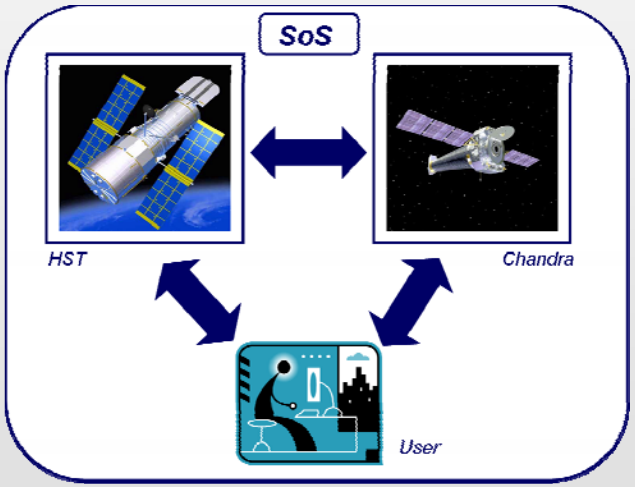
# Systems of Systems (SoS)

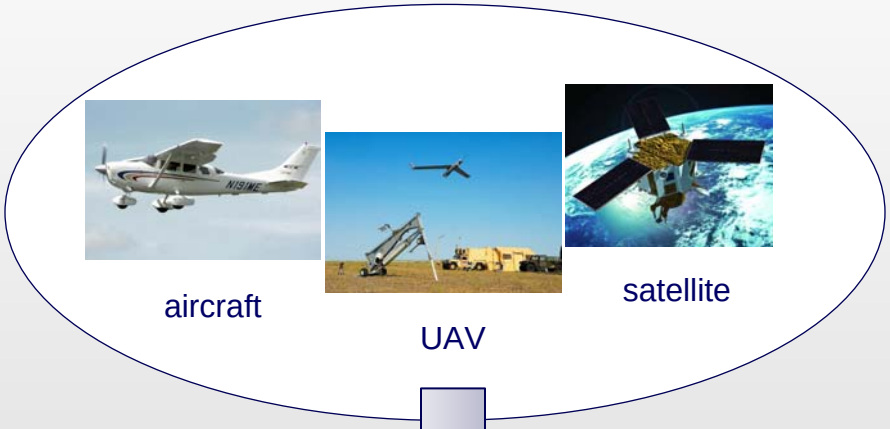
Systems of Systems (SoS) are dynamic higher order systems composed of other *independently managed systems* that together provide some emergent value.

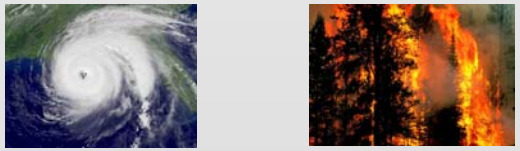
A system-of-systems is a set of *collaboratively integrated systems* that possess two additional properties: *operational independence* of the components and *managerial independence* of the components. (Maier, 1998)




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

- SoS are different from traditional systems in terms of design issues[1,2]
  - Operational independence
  - Managerial independence
  - Emergent behavior
  - Varying composition over time
- SoS engineering requires new methods
- Heuristics and qualitative guidelines in the literature[1]
  - 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

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

[2] J.Boardman B.Sauser, "System of systems – the meaning of OF", IEEE International Systems Conference, Los Angeles, CA, 2006.


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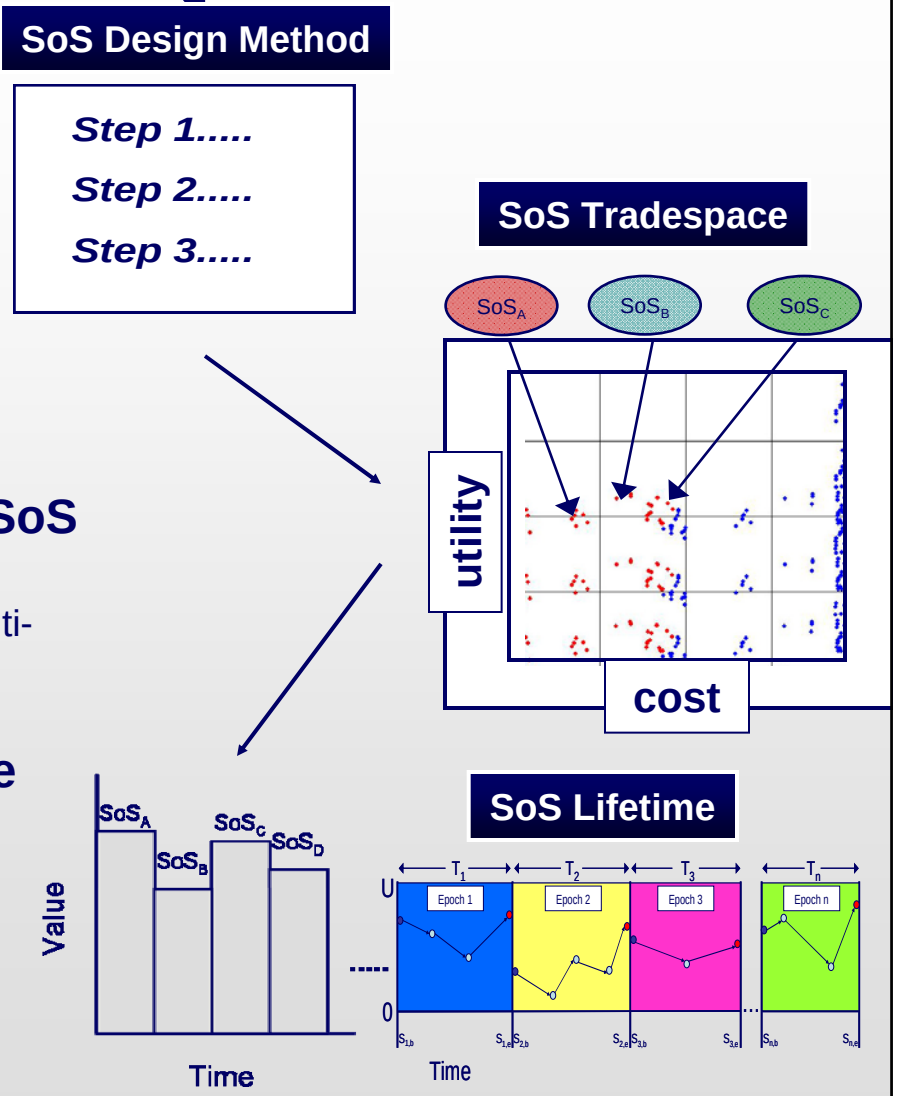
# Research Questions

1. **What are the characteristics that distinguish SoS design from traditional system design?**
   - local and global stakeholders
   - dynamic composition of system
   - legacy and new components

2. **What is a practical framework for SoS tradespace exploration?**
   - Step-by-step method utilizing Dynamic Multi-Attribute Tradespace Exploration

3. **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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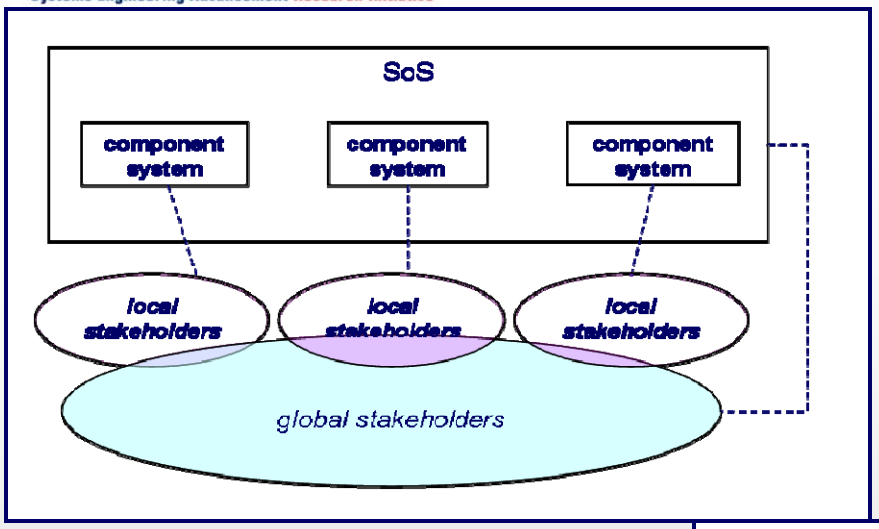
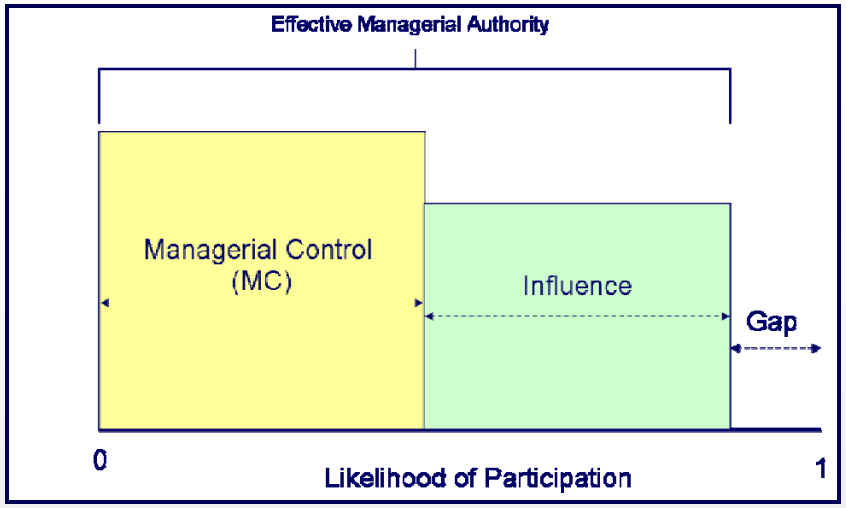
# SoS - Specific Design Considerations

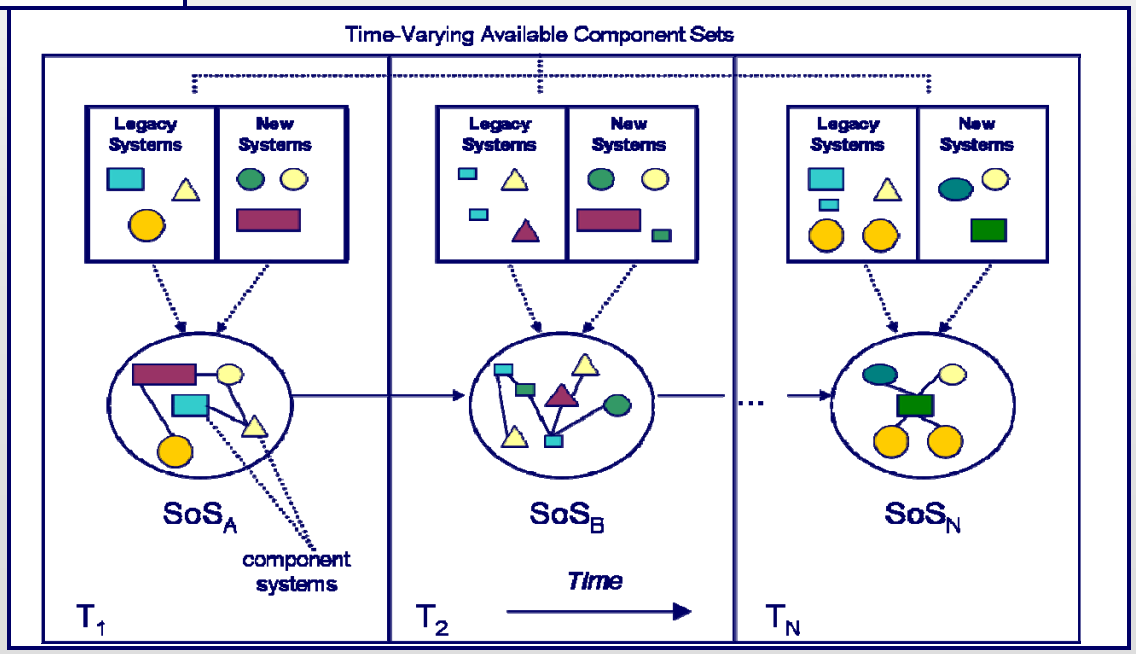



**Local and Global Stakeholder Sets**

**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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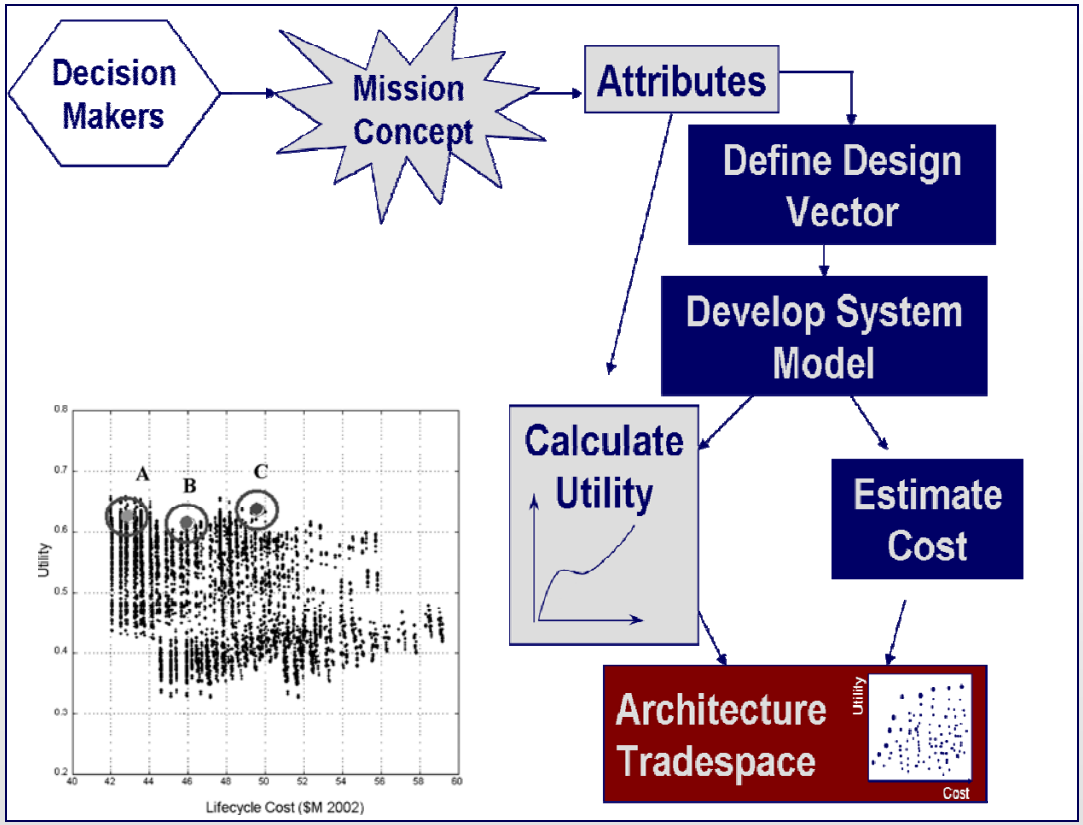
# Multi-Attribute Tradespace Exploration

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 modeling 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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# Epoch-Era Analysis for Generating Future Scenarios

## Compare Alternatives

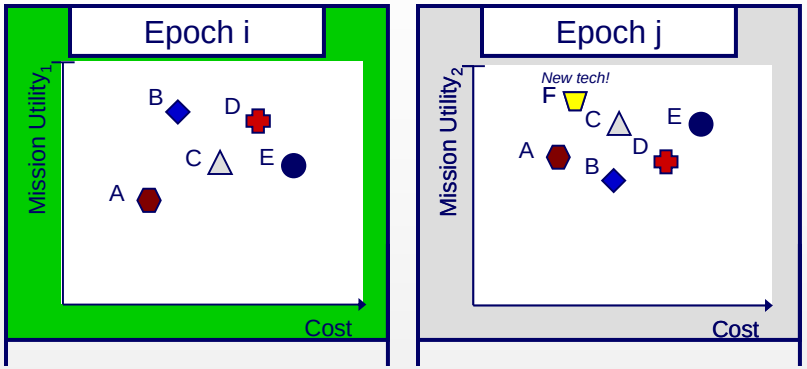
Static tradespaces compare alternatives for fixed context and needs (per Epoch)

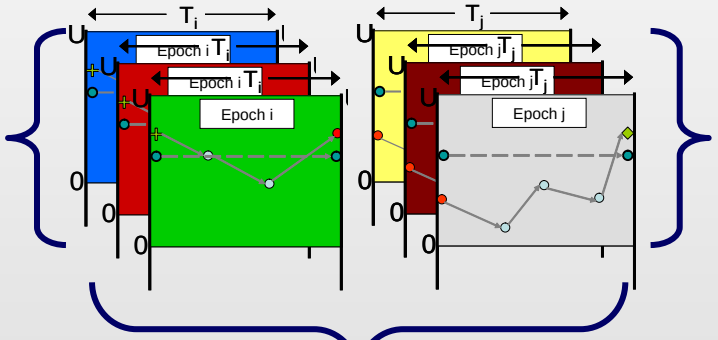
## Define Epochs

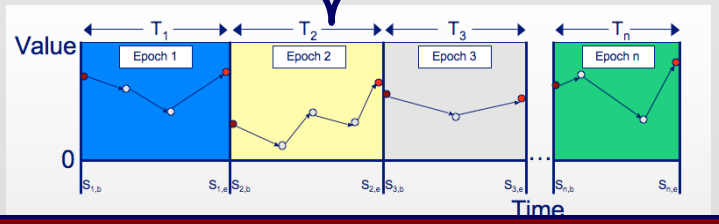
Epoch set represents potential fixed contexts and needs

## Construct Eras

Eras represent ordered epoch series for analyzing system evolution strategies




Parametrizing future contexts allows for the generation of a large number of future scenarios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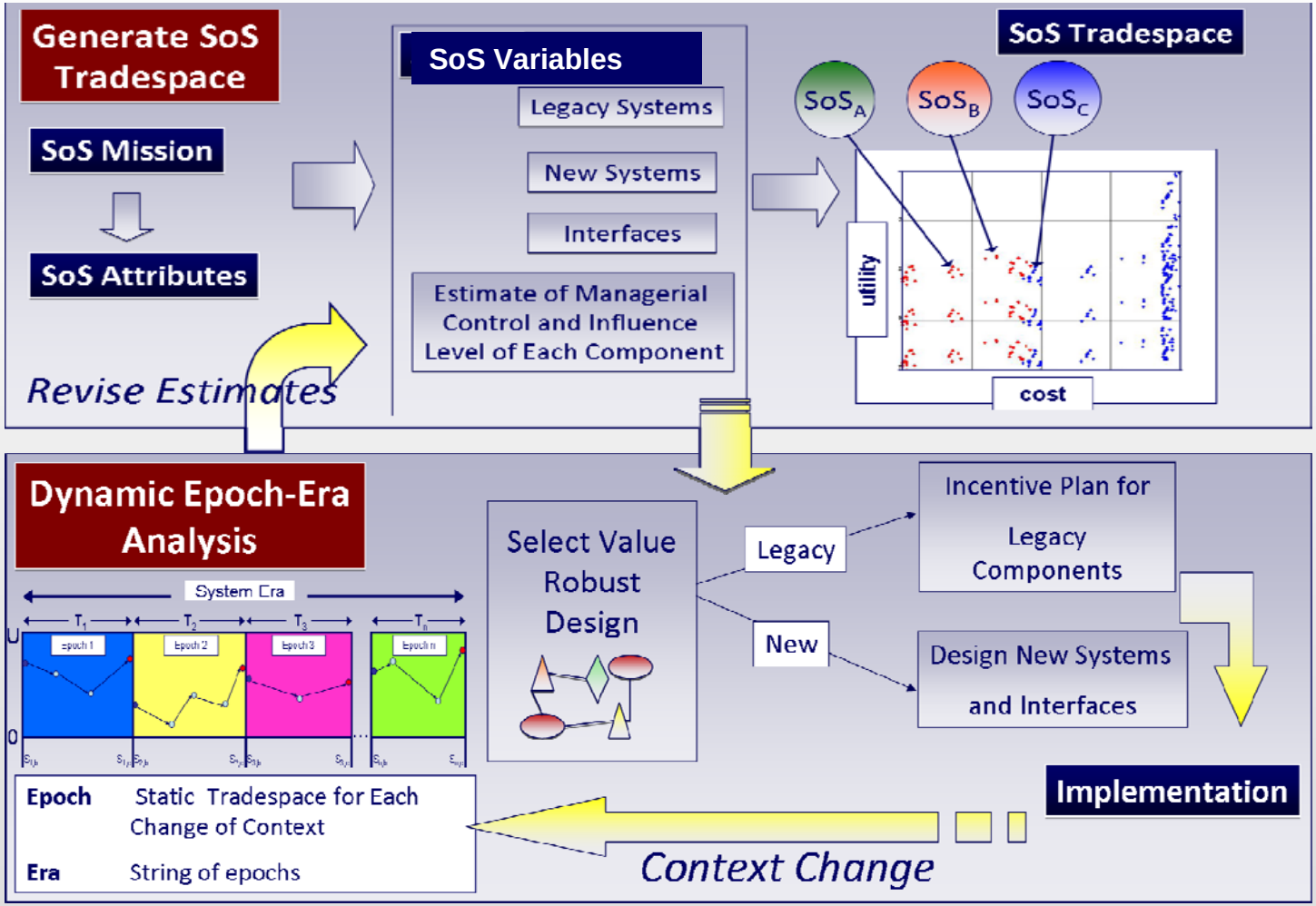
# SoS Tradespace Exploration




**Enhancing Dynamic MATE with SoS-specific considerations**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# Proposed Enhancements to MATE for Systems of Systems

- 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


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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

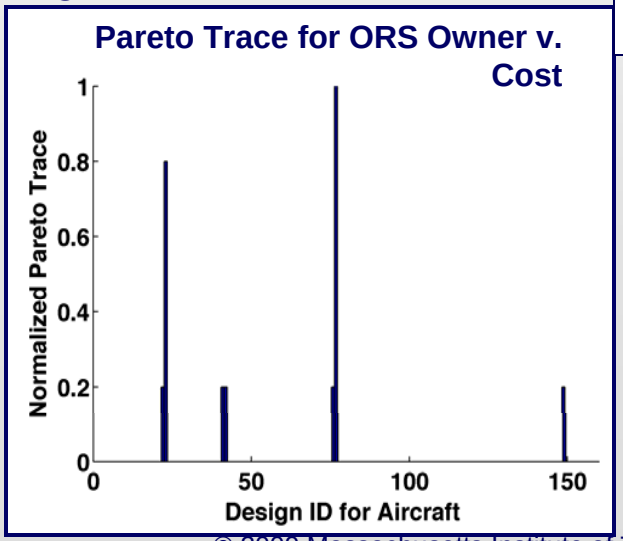
- Aircraft
- Satellite
- Sensor Swarm
- **SoS designs** consisting of any two of above

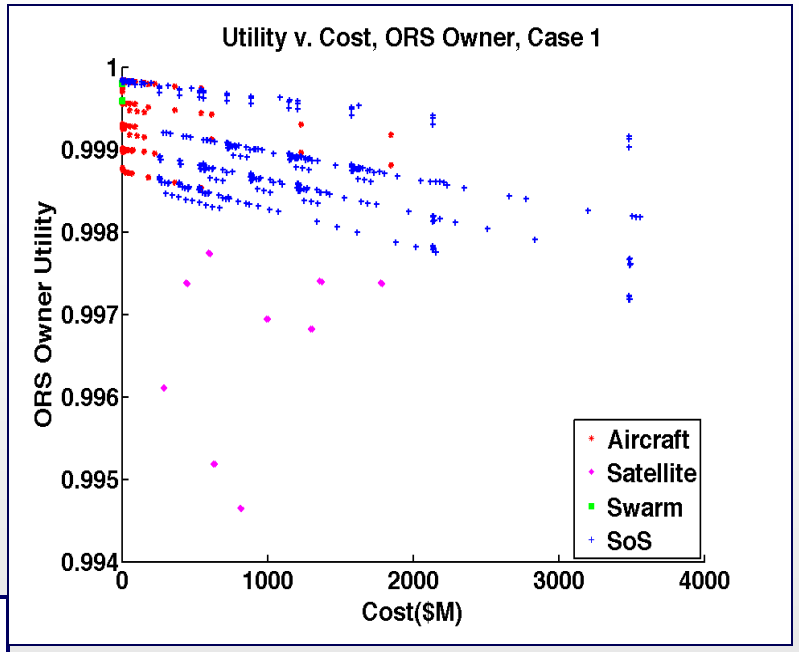
## Stakeholders

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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# Phase I: Mission Description and Attributes

## Selection of Candidate Disasters

### List of Disasters

| | |
|---|---|
| Fires | Riots |
| Hurricanes | Epidemic |
| Thunderstorms/Tornados | Drought |
| Floods | Traffic Accident |
| Earthquakes | Oil Spills |
| Tsunami | Blizzard |
| Global Warming Effects | Meteor Hit |

### Selection

| | |
|---|---|
| *Fires* | *Hurricanes* |

*Primarily concerned with reducing the loss of value to stakeholders using the responsive system*

**Mission: Obtain images of Areas of Interest in a 'timely' manner.**

Primarily concerned with reducing the loss of value to stakeholders using the responsive system

Selected the two disasters for the case study in order to focus on surveillance needs for the aftermath of short-duration disasters


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# Stakeholder Analysis

| | |
|---|---|
| FEMA | ORS Owner |
| Police | Military/Armed Services |
| Firefighters | Property Owners |
| Paramedics | Insurance Company |

## Stakeholder Selection

| | |
|---|---|
| Firefighter | Firefighters serve the general role of helping rescue people who are in danger. Firefighter here implies fire chief, in charge of allocation of personnel and resources. |
| ORS Owner | The ORS Owner's main need is to provide a useful service that customers will pay for. Maintain a profitable service by providing useful data at an affordable cost. |

### *STAKEHOLDERS*

### *OBJECTIVES*

Reduce and Prevent Damage to
People
Property

### *GOALS*

Locate Victims
Predict Path of Disaster
Communicate
Locate Disaster
Locate Assets

### *ATTRIBUTES*

Data Latency, Imaging Quality, Coverage, Responsiveness....

Generated attributes for all the listed stakeholders; selected two representative stakeholders for further analysis


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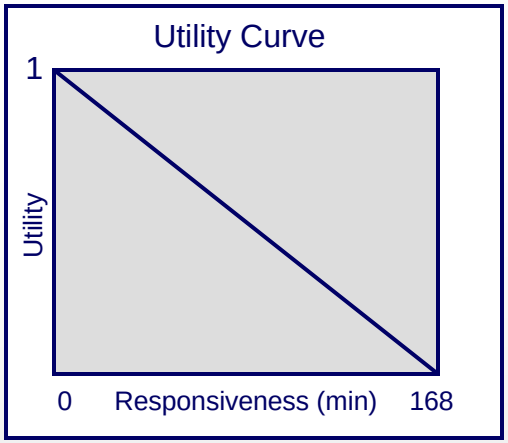
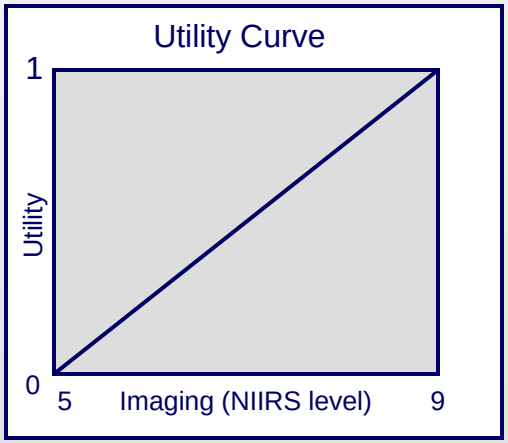
# Attributes for Selected Stakeholders

| 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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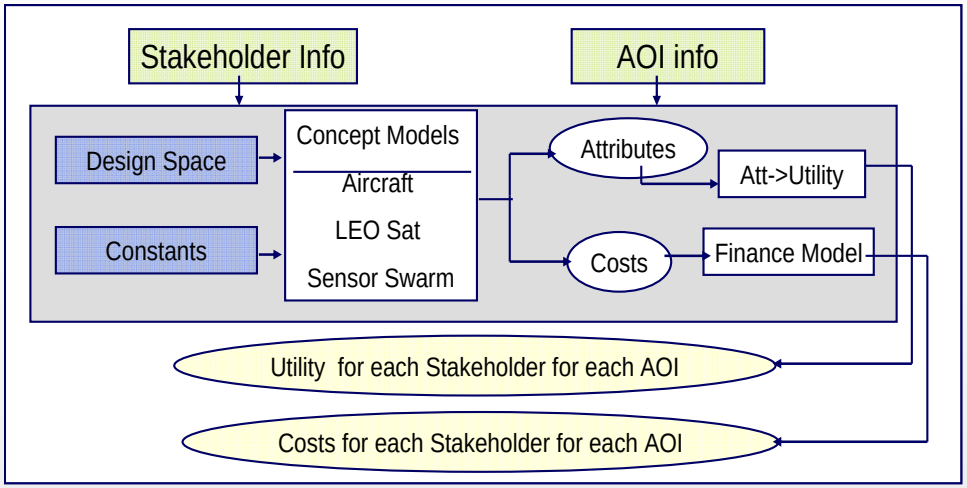
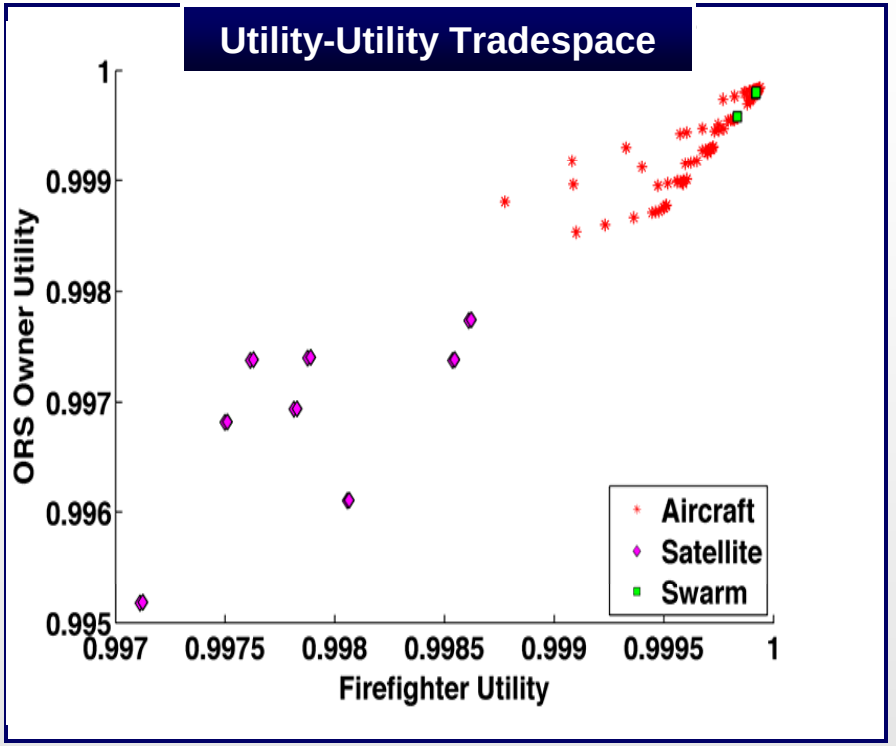
# Phase II: First-Pass Model
# Single System Concepts




## First-Pass Model Flow

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

## Utility-Utility Tradespace




**Comparison of diverse concepts on tradespace**
**Pareto Set includes multiple concepts**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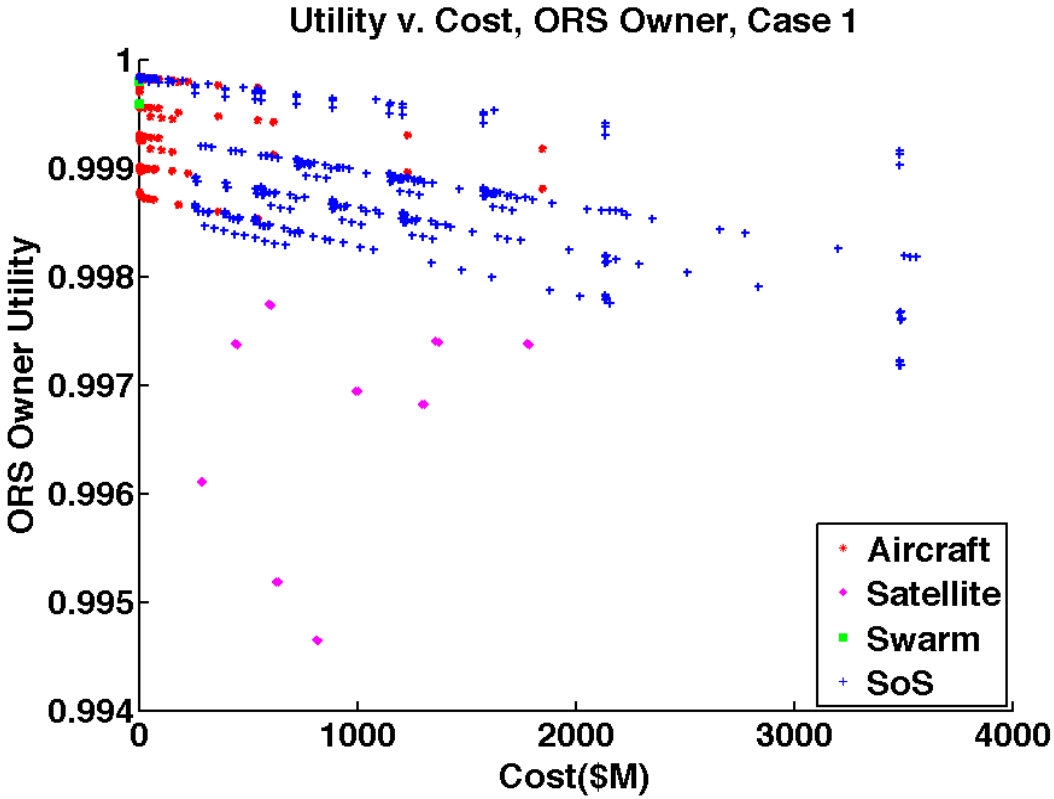
# SoS Modeling for First-Pass Model

Combine pairs of concepts from aircraft, satellite and swarm to generate multi-concept SoS designs

- Assumption that all concepts in SoS operating simultaneously
- Best performance between options chosen for each attribute
- Additional coordination and interface cost estimated by multiplying component system cost by a factor

Tradespace of ORS Owner utility v. cost for both single system concepts and SoS





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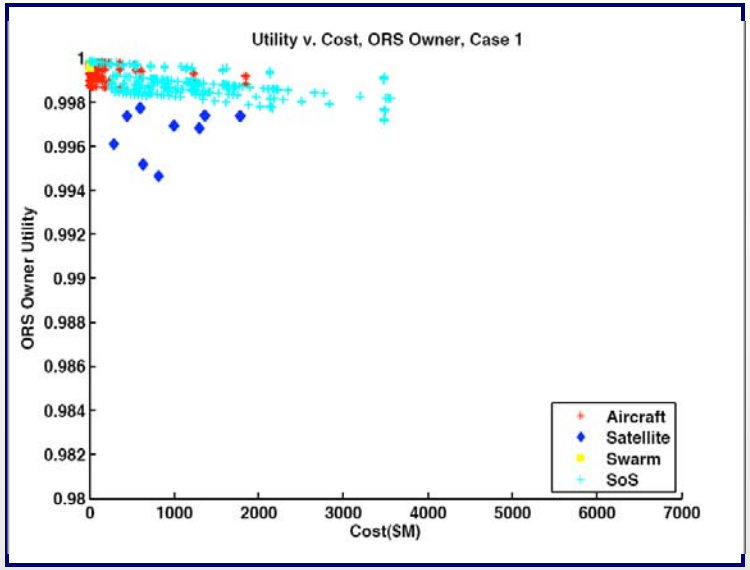
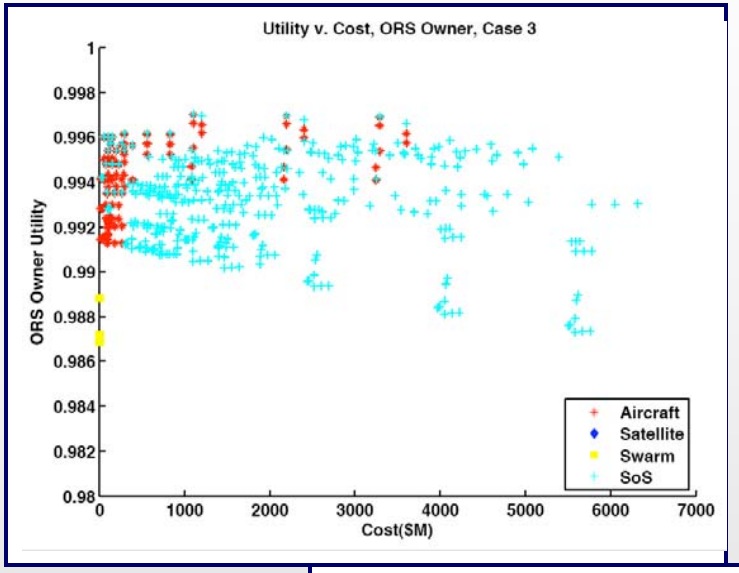
# Epoch Changes in Stakeholder Preference

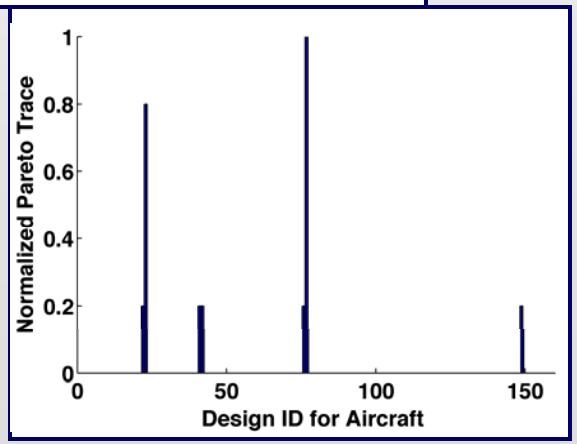
**Original Attribute Relative Weights**




**Changed Attribute Relative Weights**




| Concept | Description | Normalized Pareto Trace (N=3) |
|---|---|---|
| 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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# Epoch Changes in Stakeholder Preference

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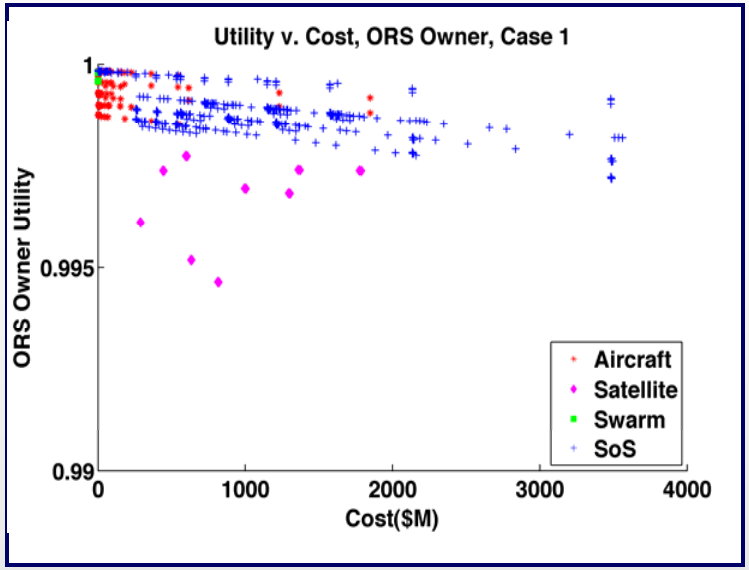
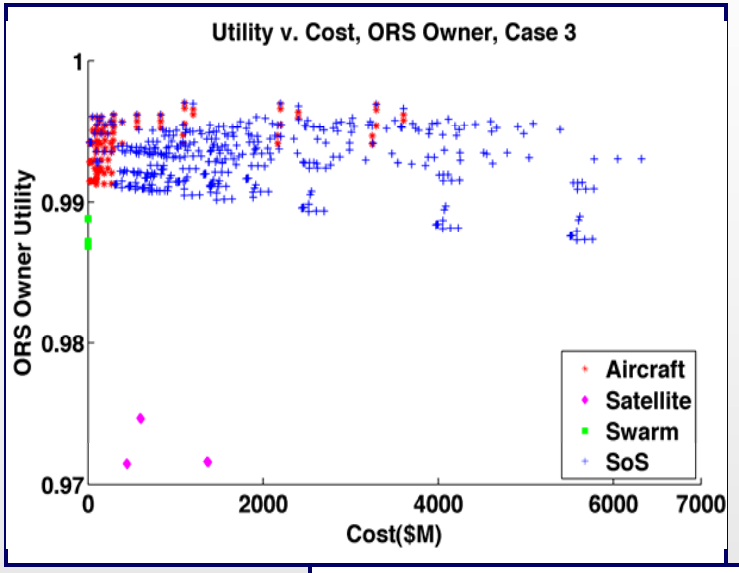
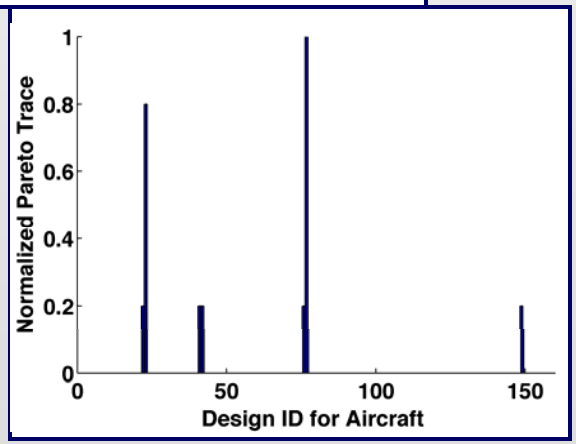



**Changed Attribute Relative Weights**




| 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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# Phase III: Second-Pass Model

- Change in attribute curves to non-linear base
- Change in AOI definition
- Consideration of both new and legacy designs


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# Phase III: 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 modeling
- Both legacy and new designs included
- AOI definition more refined compared to first-pass
- Stakeholder utility curves are non-linear
- SoS modeling is similar to first-pass, using combination of Aircraft and satellite


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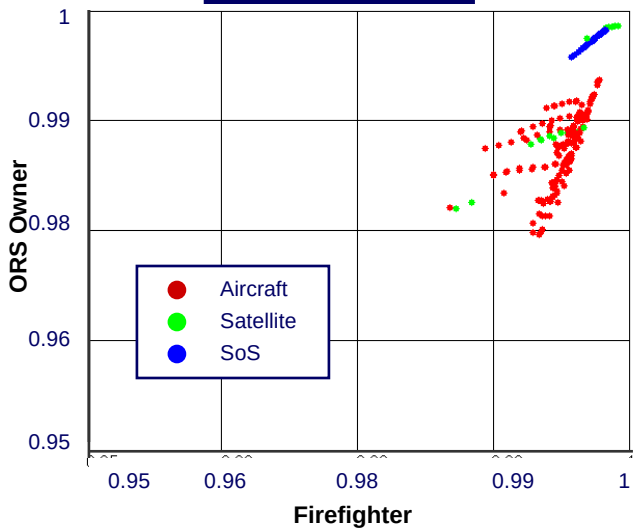
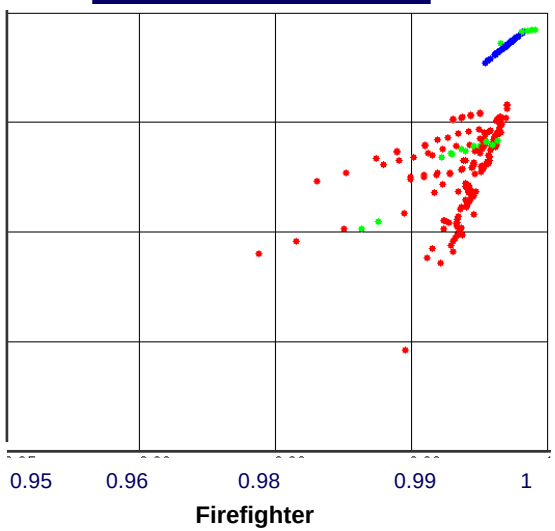
# Epoch-Era Analysis for Change in AOI

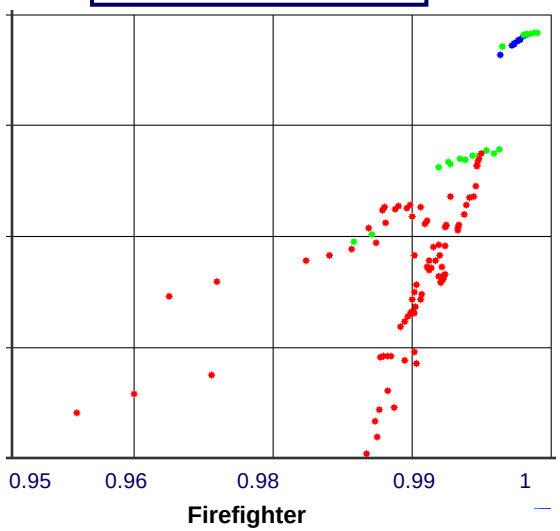
Katrina




Witch Creek




Myanmar




| 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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# Conclusions

- **Case study demonstrates the ability to quantitatively compare diverse single systems as well as heterogeneous SoS on same tradespace**
  - Enables trades across concepts (aircraft v. SoS) as well as within concepts (Cessna v. 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, i.e. possible 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, using metrics such as Pareto Trace**


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# Future Work

- Demonstration of full SoS Tradespace Exploration Method on a case study
  - including approaches to combining attributes and multi-stakeholder alignment issues arising from component system independent management
- Fuzzy Pareto analysis to identify additional compromise designs that are valuable for multiple stakeholders


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