Combining Attributes for Systems of Systems in Multi-Attribute Tradespace Exploration

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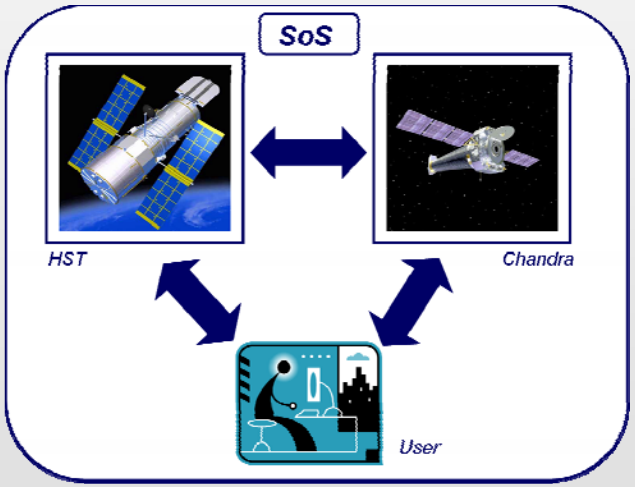
Systems of Systems (SoS)

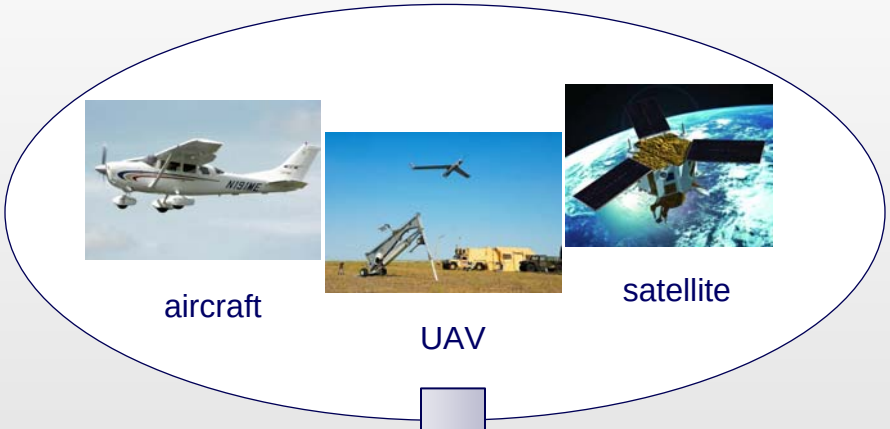
Systems of Systems (SoS) are dynamic higher order systems composed of other *independently managed systems* that together provide some emergent value.

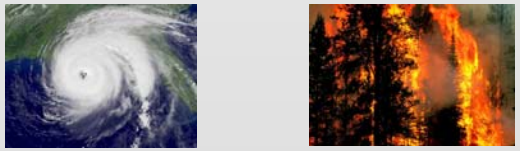
A system-of-systems is a set of *collaboratively integrated systems* that possess two additional properties: *operational independence* of the components and *managerial independence* of the components.
(Maier, 1998)



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

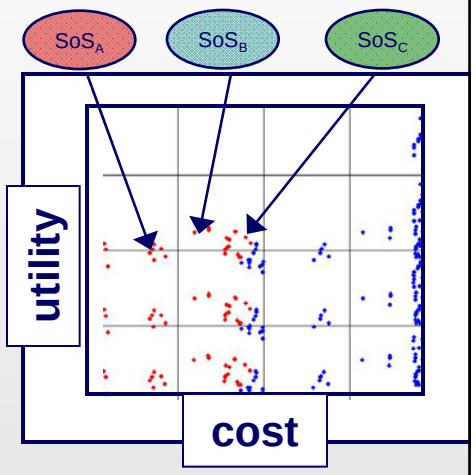
2. **What is a practical framework for SoS tradespace exploration?**
   - Step-by-step method utilizing Dynamic Multi-Attribute Tradespace Exploration

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

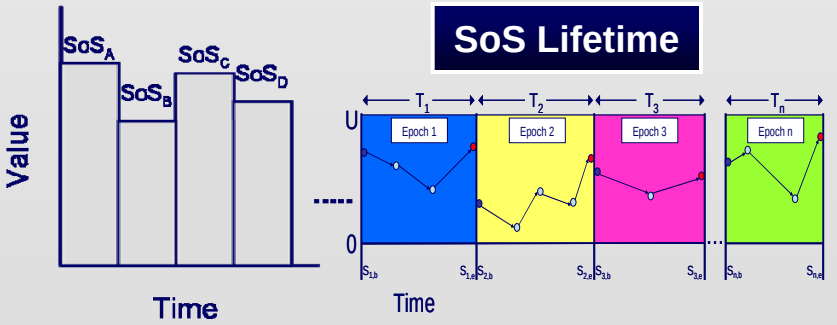
SoS Design Method

Step 1.....
Step 2.....
Step 3.....

SoS Tradespace



SoS Lifetime



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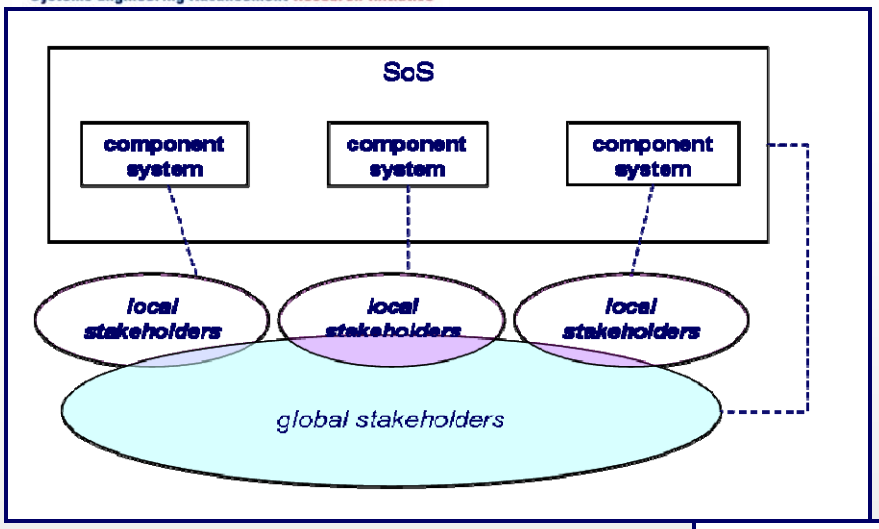
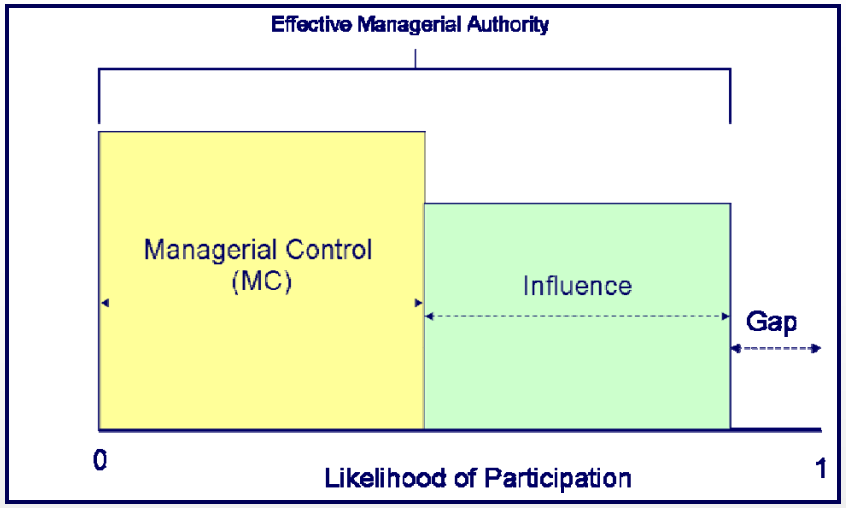
SoS - Specific Design Considerations

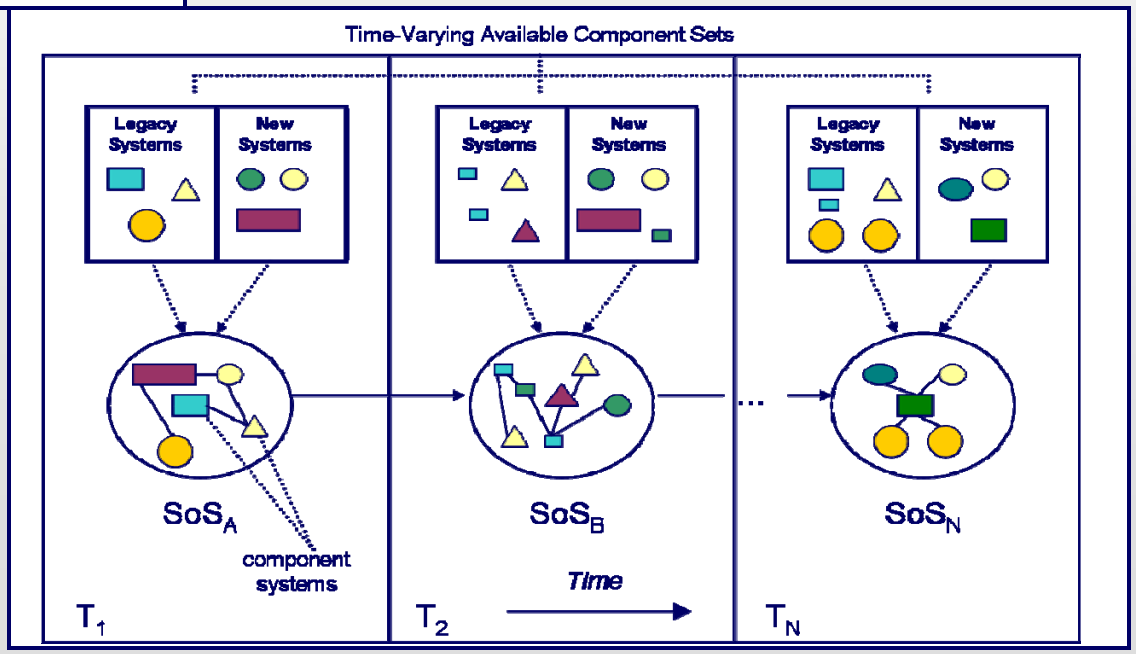




Local and Global Stakeholder Sets

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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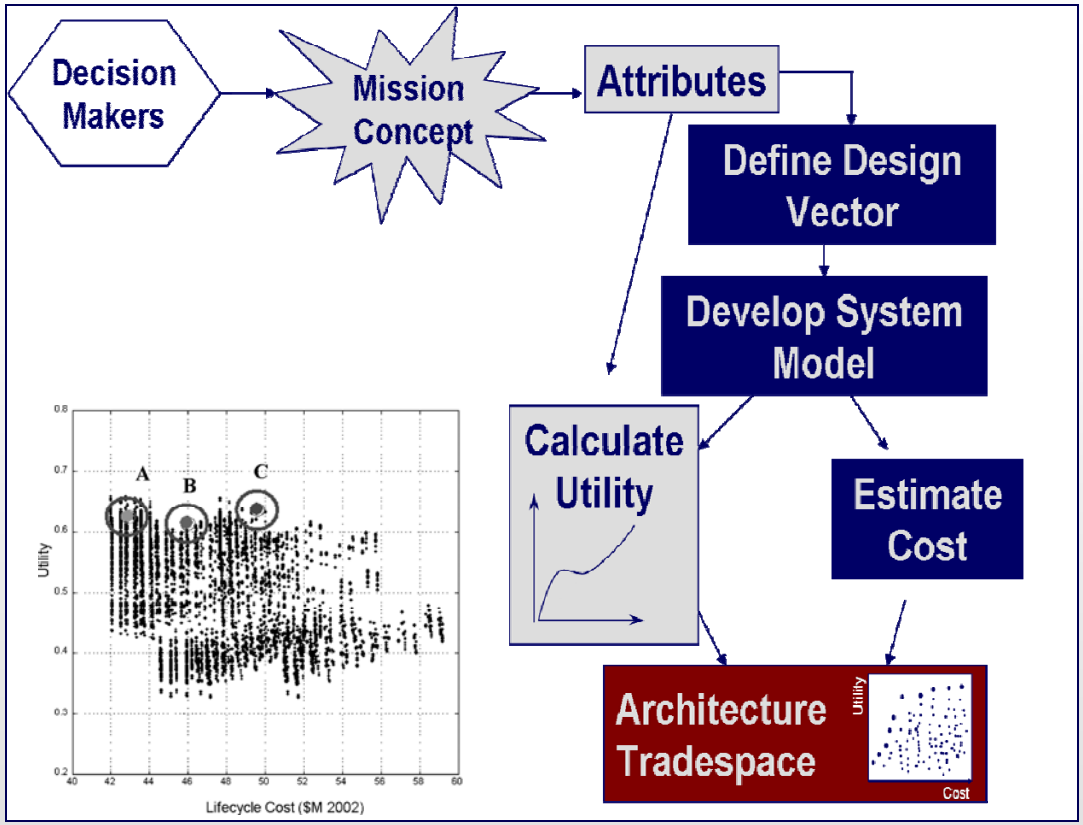
Multi-Attribute Tradespace Exploration

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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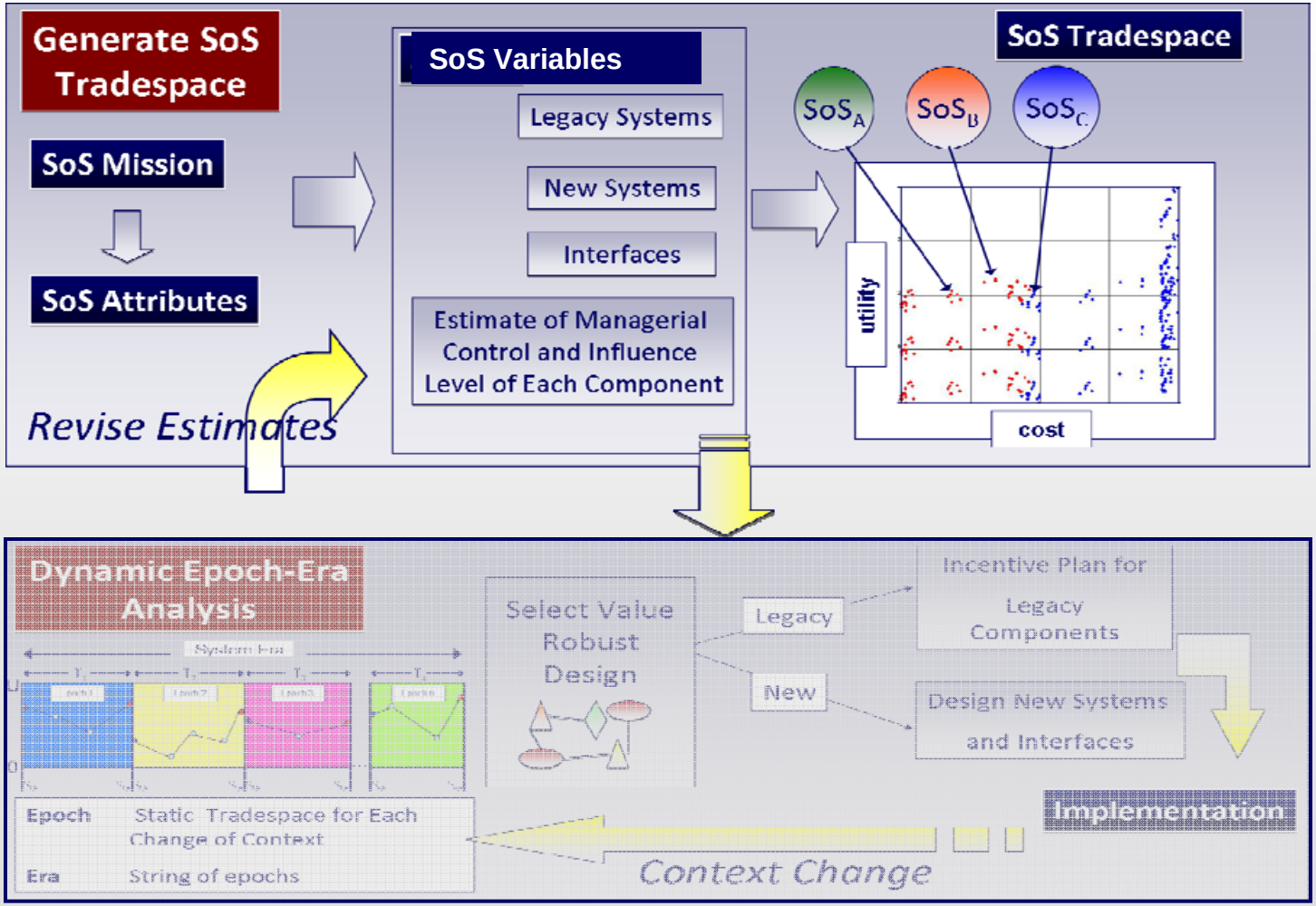
SoS Tradespace Exploration



Enhancing Dynamic MATE with SoS-specific considerations

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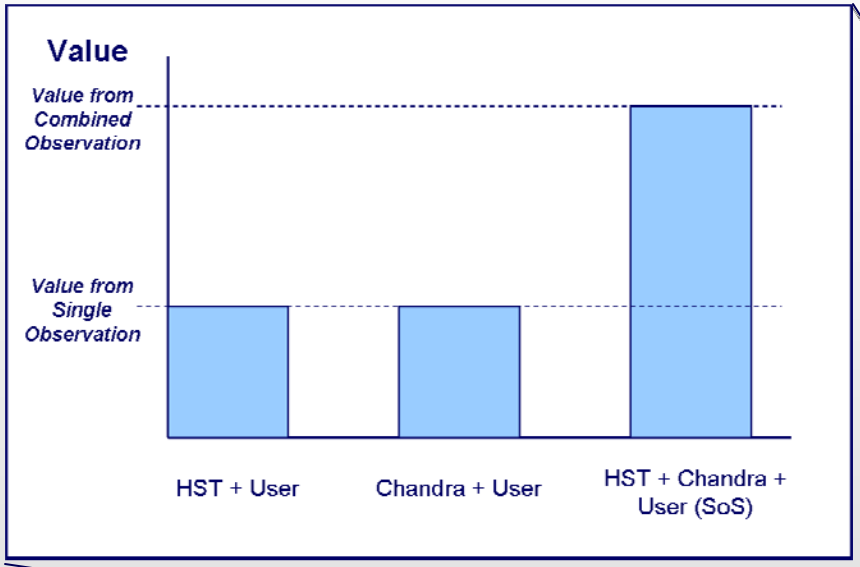
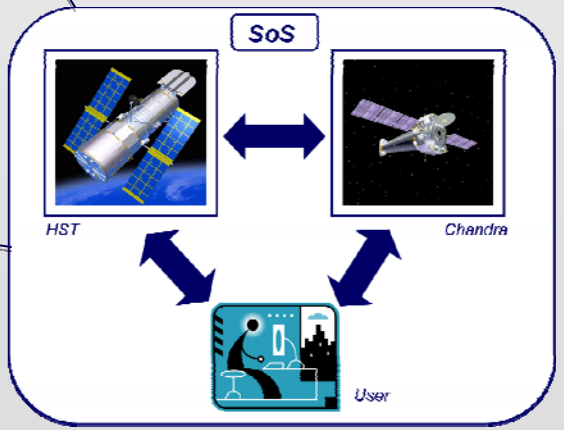
SoS Value Delivery

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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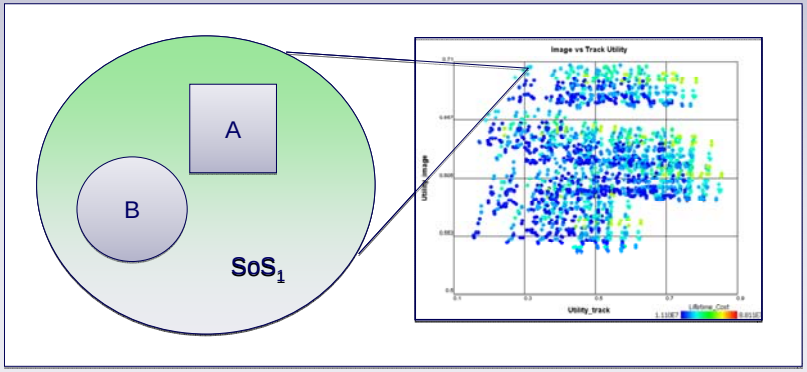
SoS Value Delivery

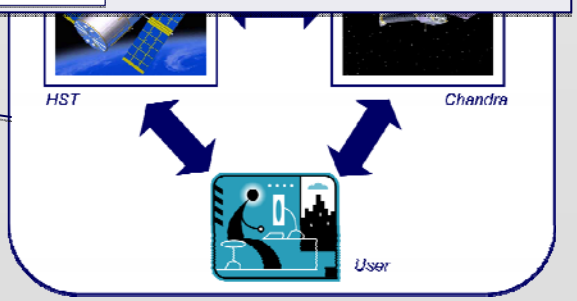
SoS 'Value' ~= sum of component value

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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Combining Component System Attributes to Generate SoS Value

Component Systems

A — *attribute* →

B — *attribute* →

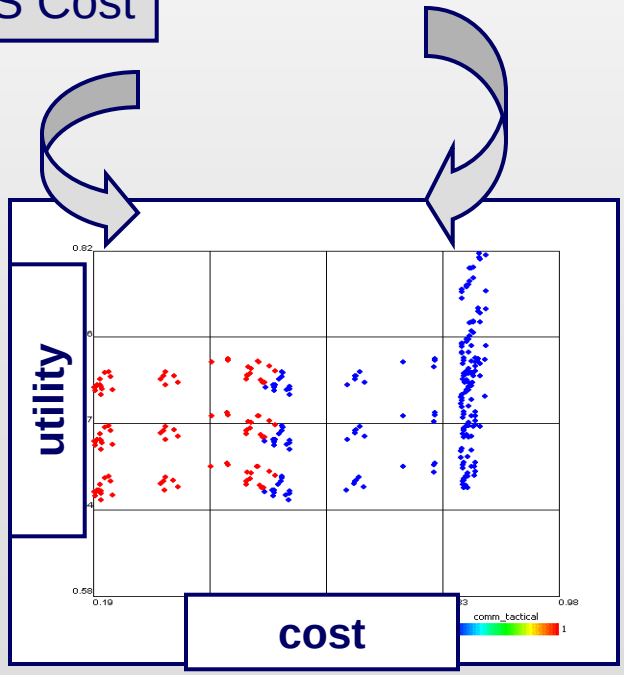
C — *attribute* →

Combine Attributes

Based on Attribute Classes, Level of Combination

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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Attribute Classification

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
4	Inaccessible Value	Cannot be added through changing design variable set (system too rigid)	Large -> Infinite

Component system attributes can be classified based on whether they are articulated by the decision maker, and displayed by the system

[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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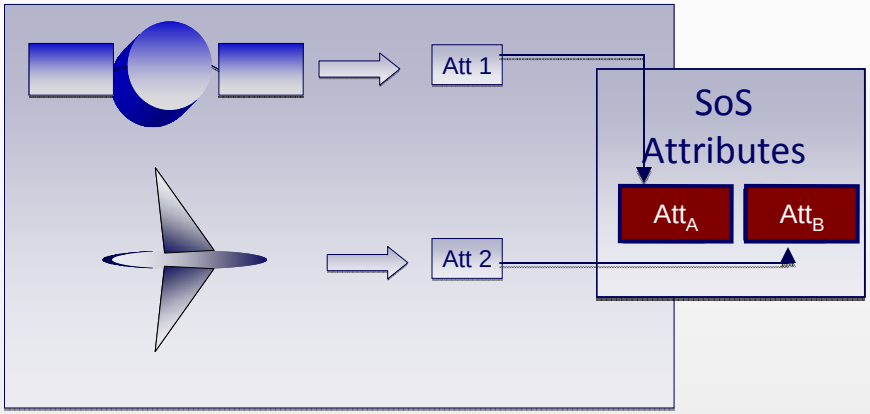
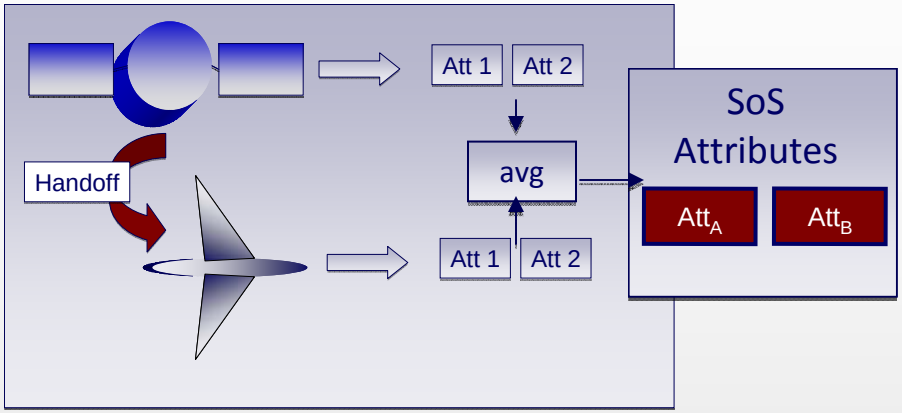
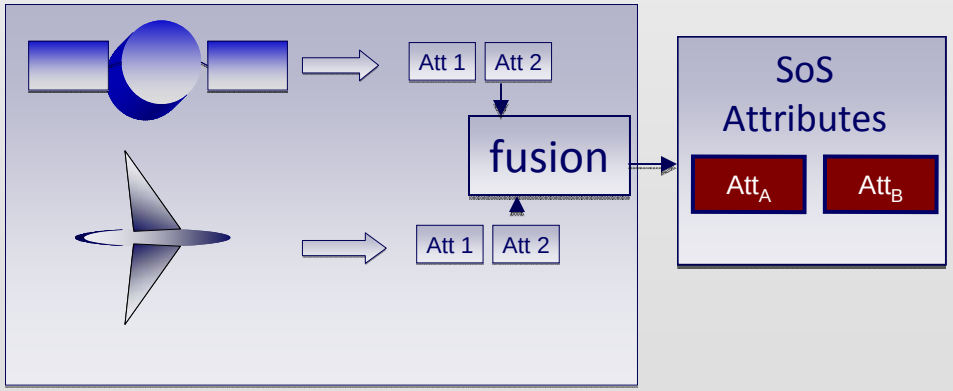
Level of Attribute Combination Complexity



'Low' Level Combination



'Medium' Level Combination



'High' Level Combination

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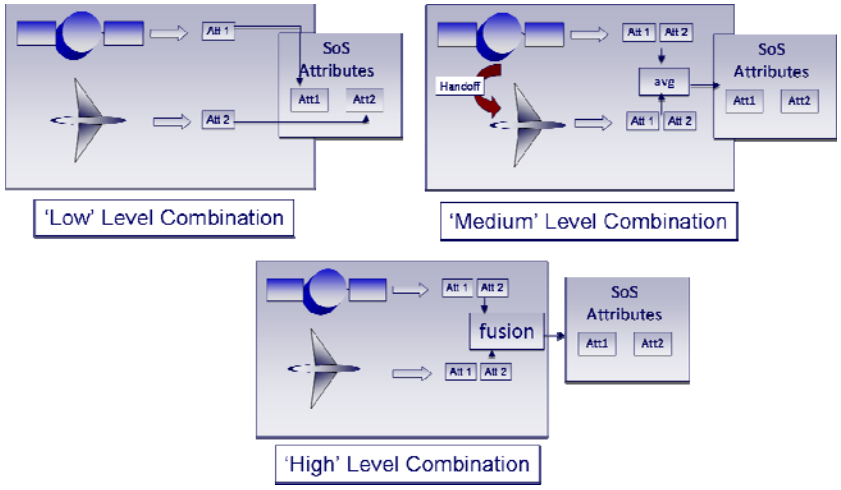
Combining Attributes to Quantify SoS Value Delivery

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 Value

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

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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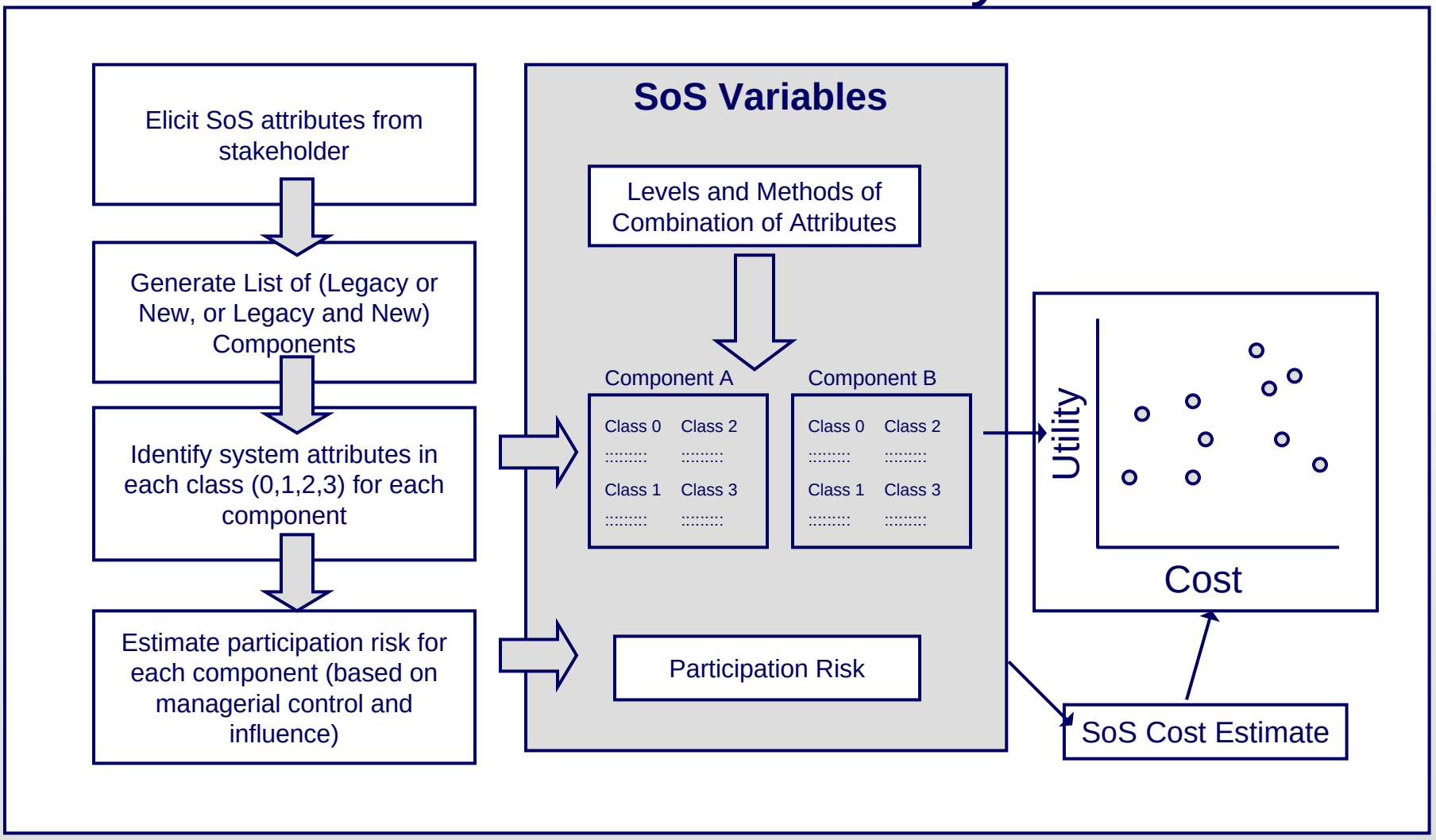
Steps for Modeling SoS Value Delivery



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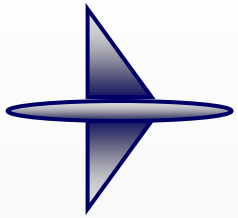
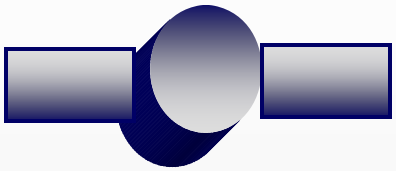
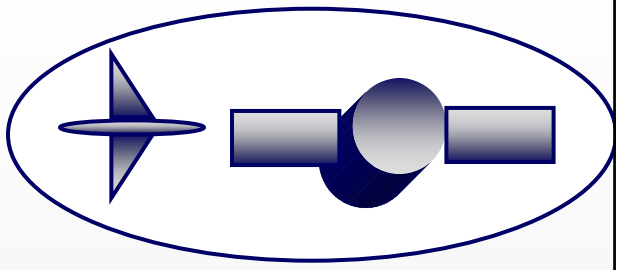
Qualitative Example of Application







Aircraft
Class 0
Acquisition Cost
Resolution
Target Track Life
Class 1
Field of Regard
…
Class 2
Imaging Capability (NIIRS)

Satellite
Class 0
Acquisition Cost
Imaging Capability (NIIRS)
Percentage of Area of Interest Covered
Class 1
Field of Regard
…
…
…

SoS
Acquisition Cost
Imaging Capability (NIIRS)
Field of Regard
Target Track Life
...
…
…
…

For each SoS attribute, a combination of the component system attributes along with a selected combining method is used to generate the SoS attribute level
Low attribute classes and low level combination have a low impact on cost

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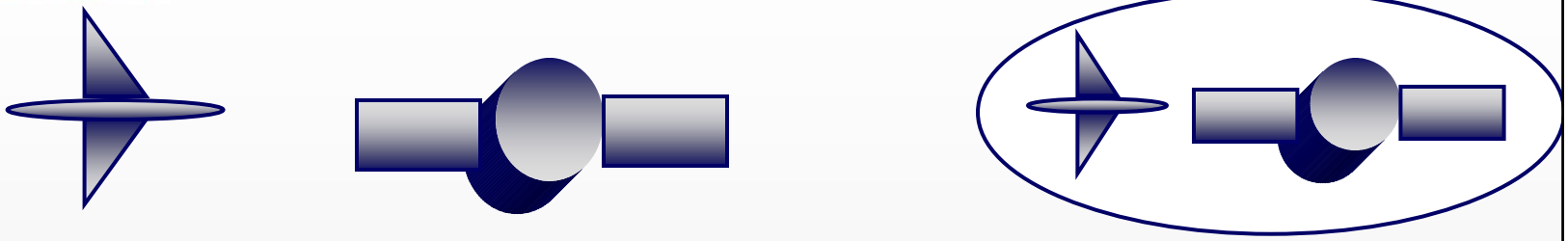
Qualitative Example of Application



Aircraft	Satellite	SoS
Class 0	**Class 0**	
Acquisition Cost	Acquisition Cost	Acquisition Cost
Resolution	Imaging Capability (NIIRS)	Imaging Capability (NIIRS)
Target Track Life	Percentage of Area of Interest Covered	Field of Regard
Class 1	**Class 1**	Target Track Life
Field of Regard	Field of Regard	...
…	…	…
Class 2	…	…
Imaging Capability (NIIRS)	…	…

Low level combination

For each SoS attribute, a combination of the component system attributes along with a selected combining method is used to generate the SoS attribute level
Low attribute classes and low level combination have a low impact on cost

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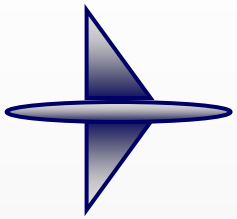
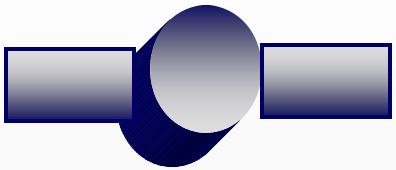
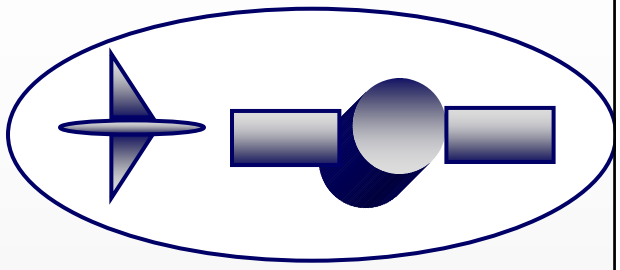
Qualitative Example of Application







Aircraft
Class 0
Acquisition Cost
Resolution
Target Track Life
Class 1
Field of Regard
…
Class 2
Imaging Capability (NIIRS)
…

Satellite
Class 0
Acquisition Cost
Imaging Capability (NIIRS)
Percentage of Area of Interest Covered
Class 1
Field of Regard
…
…
…

SoS
Acquisition Cost
Imaging Capability (NIIRS)
Field of Regard
Target Track Life
…
…
…
…
…

Higher level of component attribute used in higher level combination has higher impact on cost

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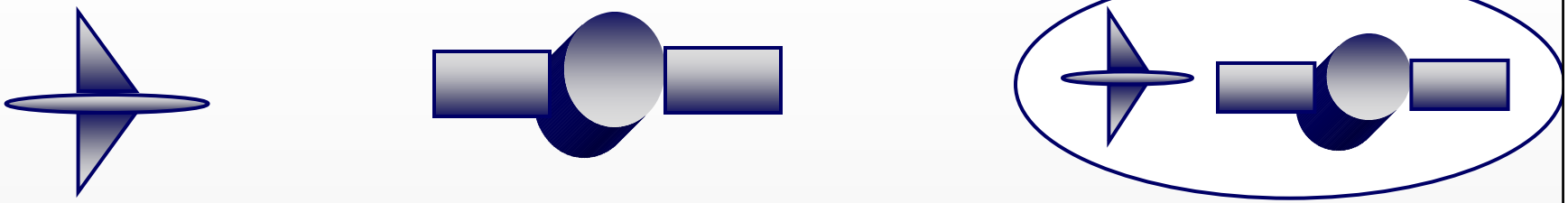
Qualitative Example of Application



Aircraft
Class 0
Acquisition Cost
Resolution
Target Track Life
Class 1
Field of Regard
…
Class 2
Imaging Capability (NIIRS)
…

Satellite
Class 0
Acquisition Cost
Imaging Capability (NIIRS)
Percentage of Area of Interest Covered
Class 1
Field of Regard
…
…
…

High level combination

SoS
Acquisition Cost
Imaging Capability (NIIRS)
Field of Regard
Target Track Life
…
…
…
…
…

Higher level of component attribute used in higher level combination has higher impact on cost

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Conclusion

- **Component system attribute combination provides a means to quantitatively estimate SoS value delivery**
  - As comprehensive lists of attributes for each component system is generated, comparison of these lists may lead to identification of potential undesirable (or desirable) SoS emergent properties
- **Modeling SoS value is a key aspect of the quantitative SoS tradespace exploration method that enables the comparison of a large number of designs on the same tradespace**

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Future Work

- Incorporation of combining attributes and participation risk concepts into the full SoS Tradespace Exploration Method
- Application of full SoS Tradespace Exploration Method to a quantitative case study
- Detailed study of the types of attribute combination methods available within each level of combination complexity

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Systems Engineering Advancement Research Initiative

Questions?

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