Systems Engineering Advancement Research Initiative

A Framework for Tradespace Exploration of Systems of Systems

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System of Systems (SoS)

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

SoS is defined as a set or arrangement of systems that results when *independent and useful systems are integrated* into a larger system that delivers unique capabilities.

(DoD, "4.2.6. System of Systems Engineering," In *Defense Acquisition Guidebook*, Department of Defense, 2004)

System of systems are *meta-systems* that are themselves comprised of multiple autonomous embedded systems that can be diverse in technology, context, operation, geography and conceptual frame

(Keating, C., *et. al*, "System of Systems Engineering", *Engineering Management Journal*, 15, 3, pp 36-45, 2003)

1. *SoS are systems*
2. *SoS are composed of other systems that are value producing in their own right*
3. *SoS constituents have some level of independent management while participating in the SoS*
4. *An SoS design consists of not only the component systems, but also the interfaces between them*

(Shah, N.B., Rhodes, D.H. and Hastings, D.E., "System of Systems and Emergent System Context ", Conference on Systems Engineering Research, Hoboken, NJ, 2007)

Motivation

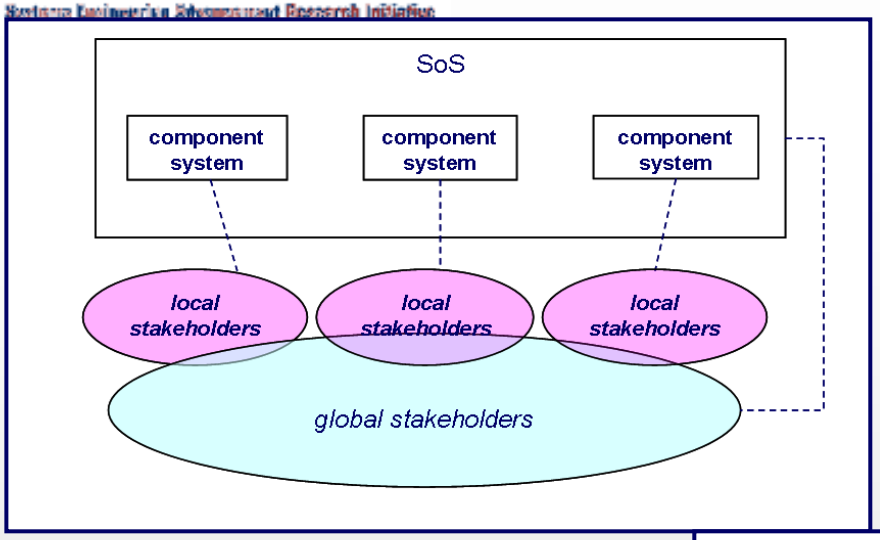
- The engineering of complex systems involves *sophisticated decision analysis under conditions of high uncertainty*, requiring taking into account many variables.
- DoD, NASA, and other agencies face *significant challenges in making decisions during concept phases* that will ensure positive outcomes throughout the system operational life as related to performance, cost, and supportability.
  - These challenges are much greater in context of SoS programs.
- The application of *formal tradespace exploration methodologies provides a means to more effectively understand the tradeoffs* between diverse stakeholder needs and possible design alternatives.
- *Assuming that an SoS can be designed* – i.e. the component systems and the interfaces can in some way be selected by an SoS designer – there is a need for a method to compare design alternatives in the concept exploration phase for SoS.

Need for development of new concept exploration methods for improving SoS selection decisions

Goals for SoS Tradespace Exploration Framework

- Develop a *prescriptive design methodology for SoS* that takes into consideration the specific issues that make SoS design difficult
- *Quantify SoS-specific characteristics* to begin to develop this methodology
- Use *tradespace exploration* for SoS conceptual design
- Begin to quantify SoS characteristics in this paper – first step in development of SoS framework

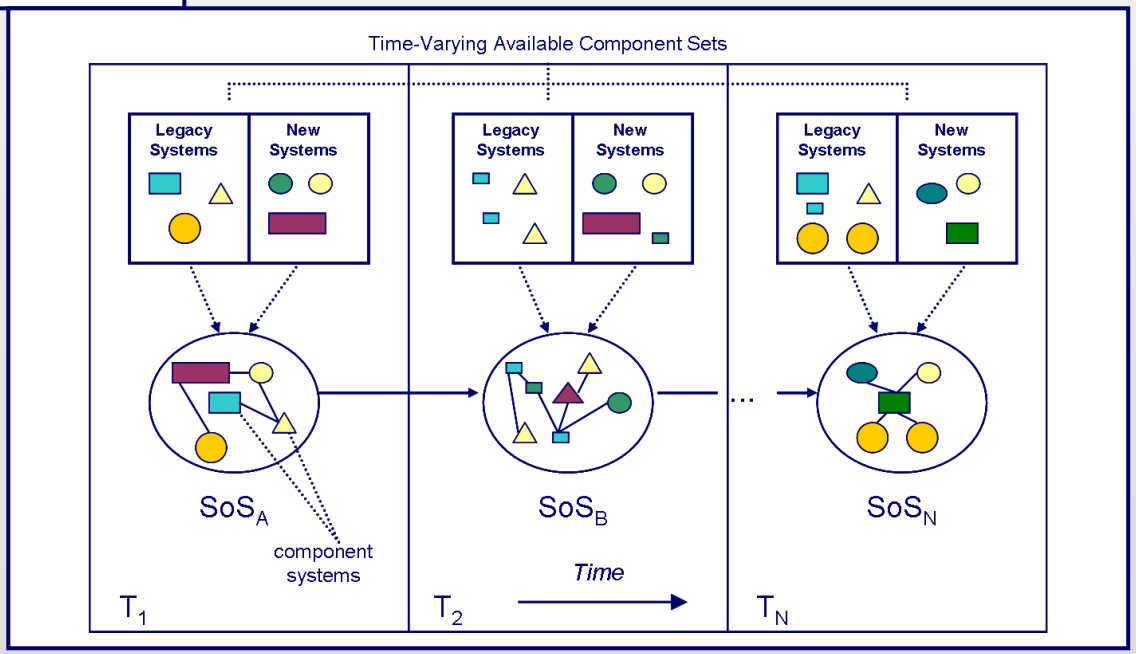
SoS - Specific Design Considerations



Local and Global Stakeholder Sets result in a multi-level multi-stakeholder value proposition when evaluating designs

Legacy and New Components may be included in the SoS design

Dynamic SoS Composition due to a time-varying set of available components and changing SoS context

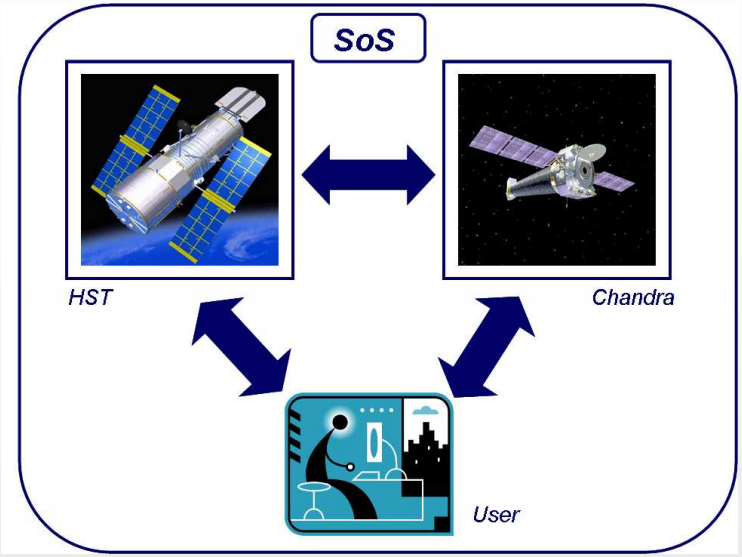


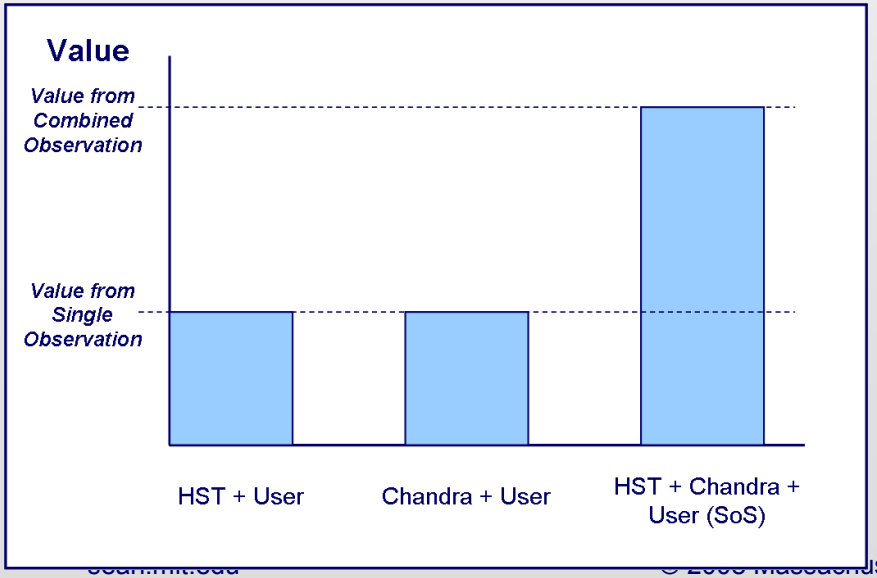
Collaborative SoS: Coordinating Astronomical Observatories

System Chandra and HST observing M31 simultaneously

Interfaces Chandra-HST, HST-user, Chandra-user

Control no central control, participation of observatories is voluntary





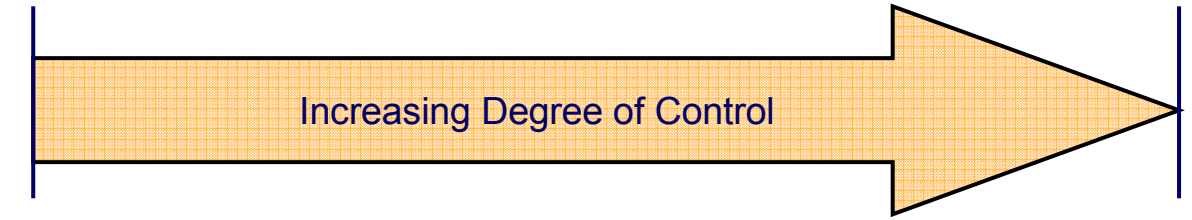
Multiple Stakeholder Groups Chandra, HST and the User all have separate stakeholder needs

Dynamics of Composition Components may leave, new components may join

Legacy and New Component Systems SoS consists of legacy components – new components may be designed for SoS

Managerial Control Structure

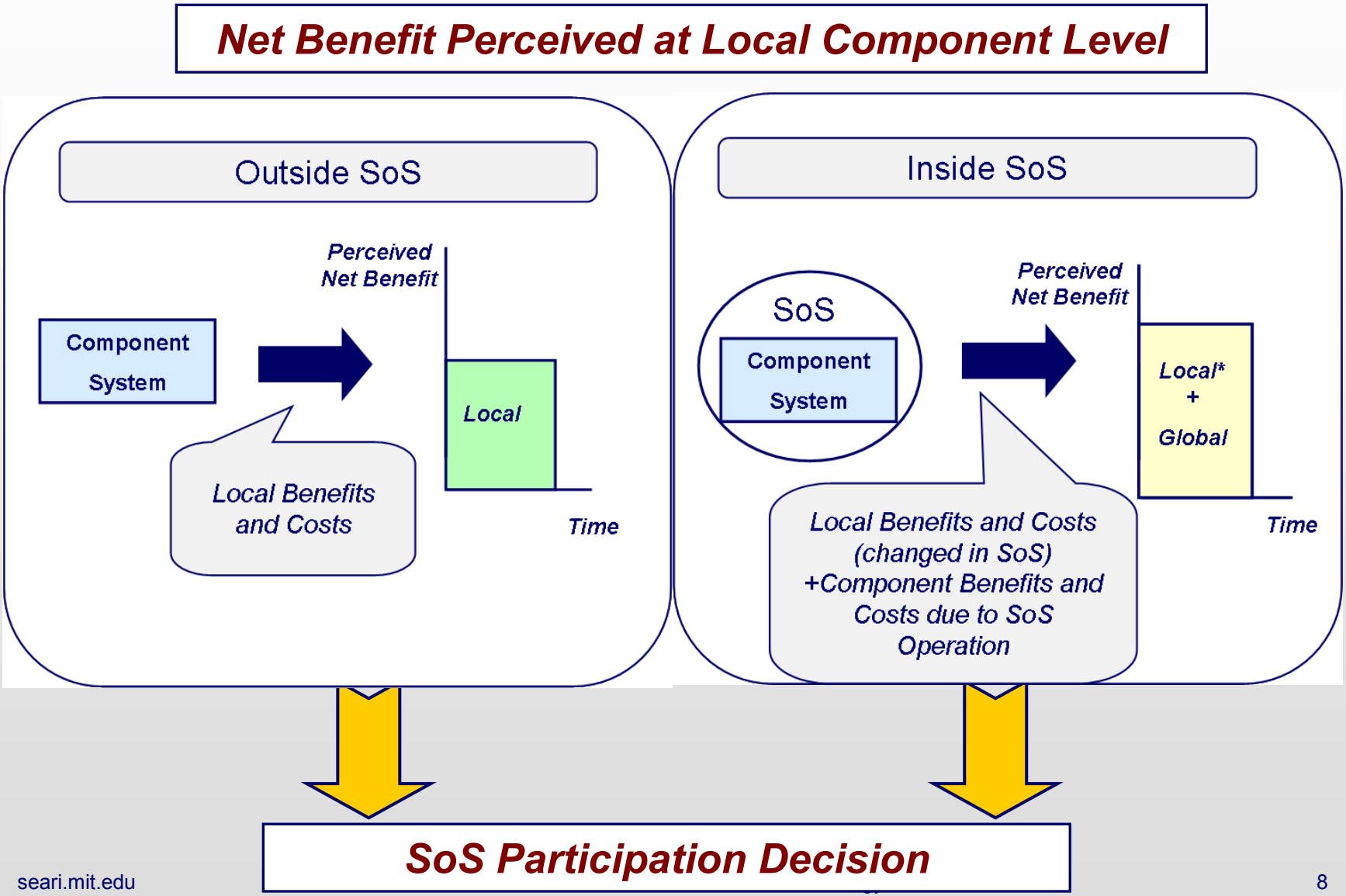
SoS Classification	*Managerial Control*
Directed	Centrally managed
Collaborative	Not centrally managed, component system participation voluntary
Virtual	Not centrally managed, no centrally agreed upon purpose



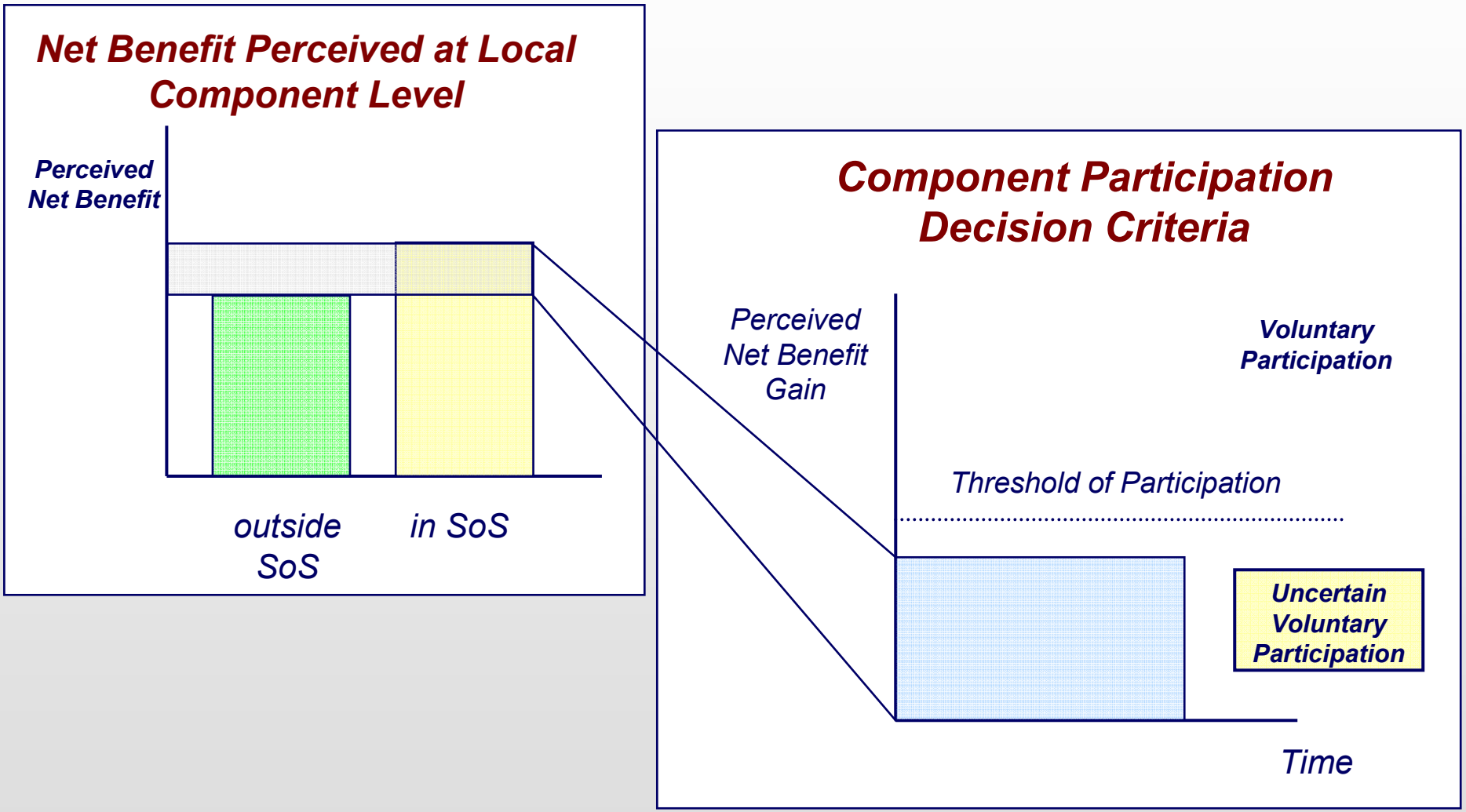
Virtual *Collaborative* *Directed*

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

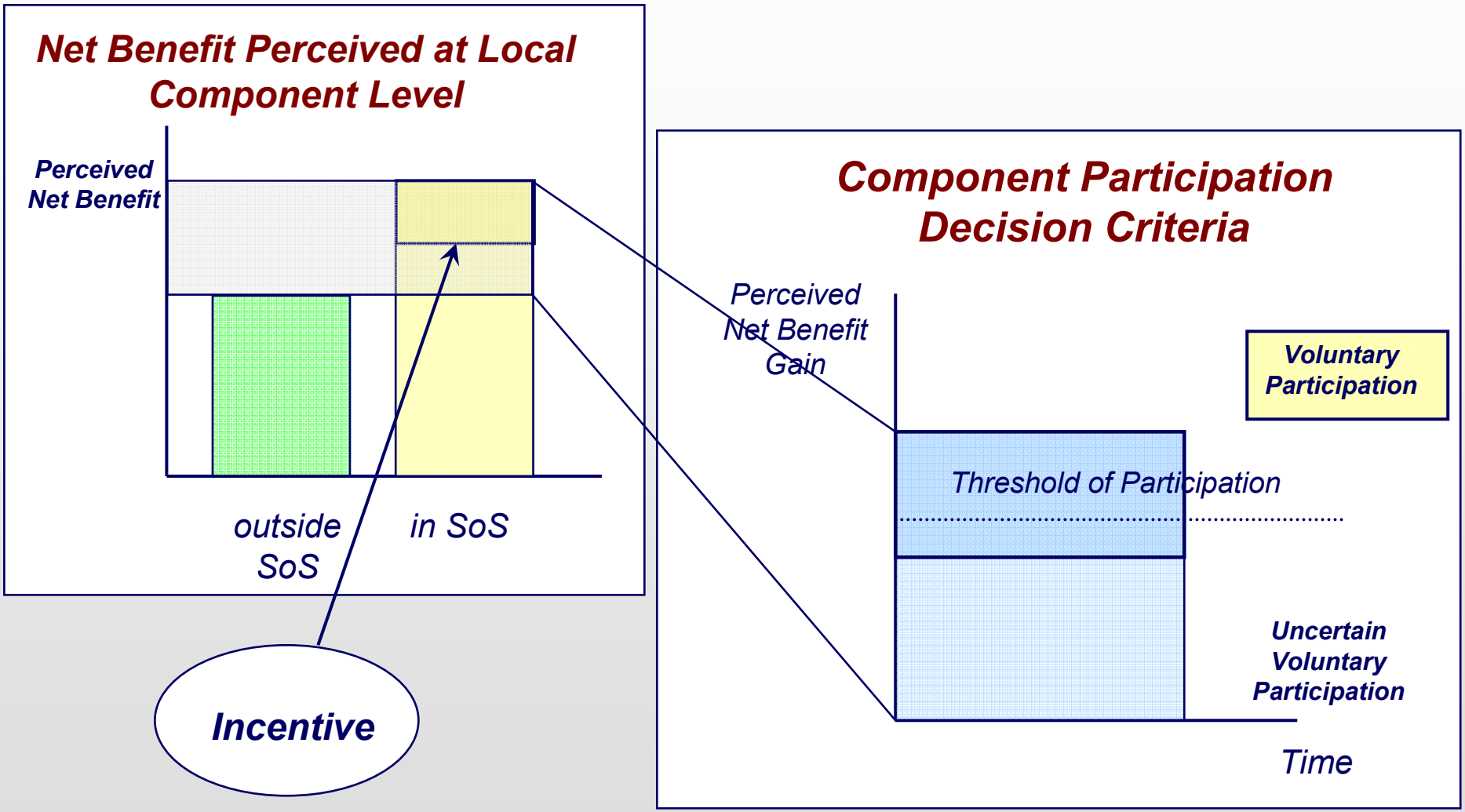
Perceived Net Benefit and the SoS Participation Decision: Component System Management View



Perceived Net Benefit and the SoS Participation Decision : Component System Management View



Perceived Net Benefit and the SoS Participation Decision: SoS Designer View



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

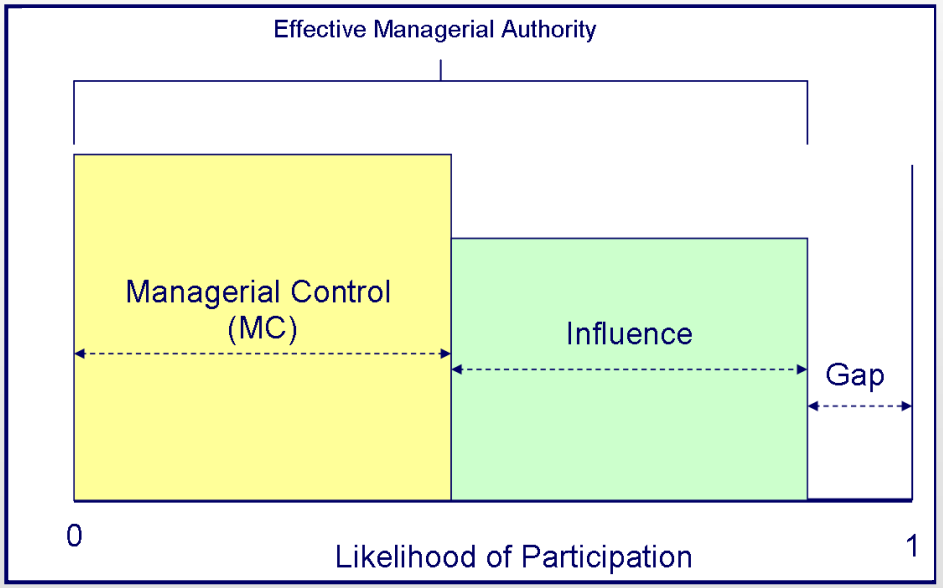
Effective Managerial Authority Combination of Control and Influence employed by SoS designer

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



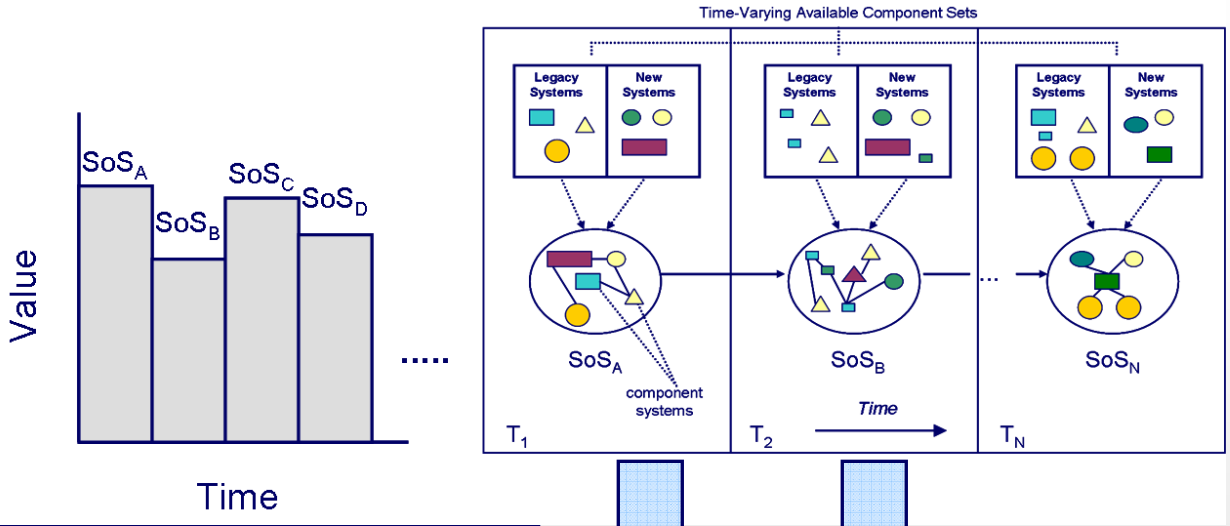
SoS Designer can use these values to make decisions – control and influence are knobs the designer can potentially turn to increase the likelihood of a component participating

Tradespace Exploration for SoS

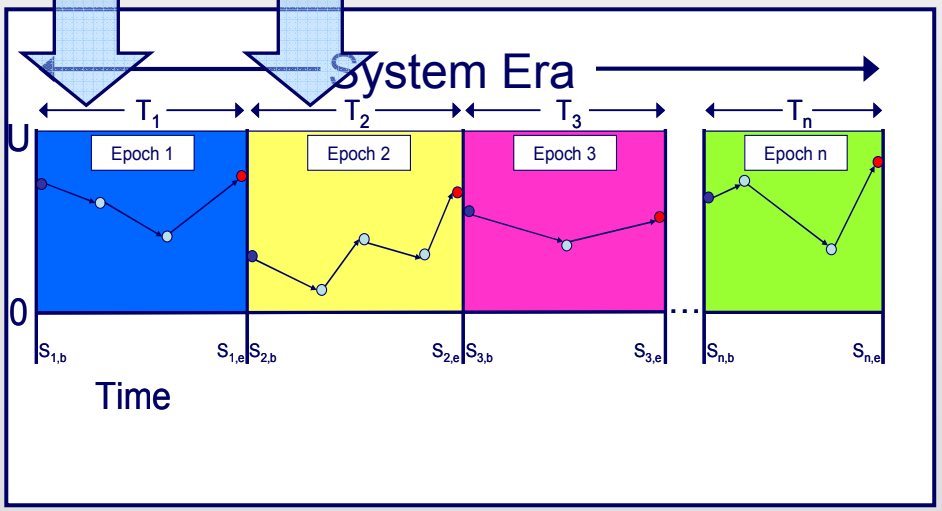
- *Tradespace Exploration* is a method for exploring the design space of possible system architectures rather than settling quickly on an optimum.
  - The power of the method comes primarily from the ability to *quantitatively assess many design* choices very early in the design process.
  - This ability allows designers and users/customers to trade design parameters and diverse stakeholder preferences.
- We will be using *Multi-Attribute Tradespace Exploration* method as a basis for extending to the SoS domain.
- Dynamic MATE is a framework for *analysis of dynamic issues* during the design process, such as unarticulated stakeholder preferences and changing system context over time and is thus particularly suitable for tradespace analysis for SoS throughout its lifetime
- The design knobs described – such as control and influence – can be traded using tradespace exploration to quantitatively understand the relationships between them and compare designs

Ref: Ross, A.M., *Multi-Attribute Tradespace Exploration with Concurrent Design as a Value-Centric Framework for Space System Architecture and Design*, S.M., Massachusetts Institute of Technology, 2003.

Multi-Attribute Tradespace Analysis for SoS



- Use defined decision criteria to determine potential SoS composition over time
- Calculate *actual performance data for different SoS designs*, and use tradespace to trade diverse stakeholder needs and possible design alternatives
- *Quantify changes in value delivery with time* for real designs – use models and simulations
- Identify value robust designs, low switching cost evolution paths - *test SoS design heuristics quantitatively*, using Epoch-Era Analysis



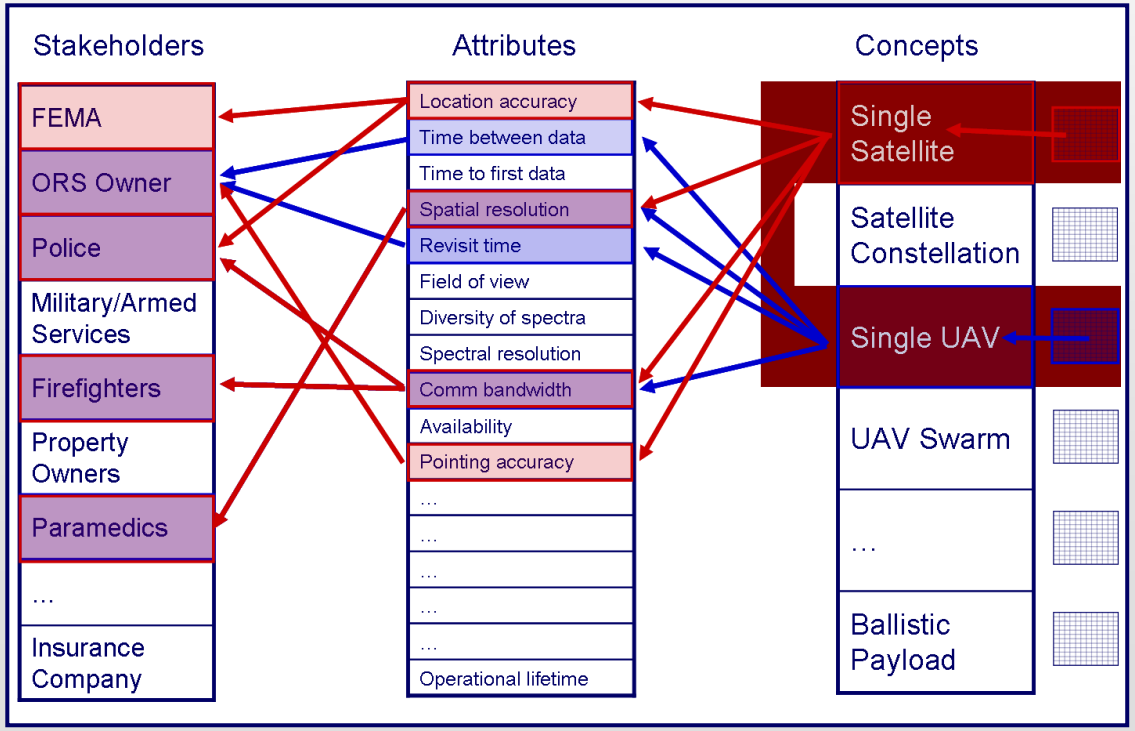
Epoch-Era Analysis in Dynamic MATE

Future Work

- Compare multiple design concepts in the same tradespace – initial step towards comparison of multi-concept SoS in single tradespace
- Apply Epoch-Era Analysis to study long-term evolution of SoS prescribe long-term strategies for sustaining SoS value

Apply framework to case study with industry partner: *Operationally Responsive Disaster Recovery Observation system*

- Multi-stakeholder analysis
- Multi-concept tradespace
- Combined concept tradespace



Conclusion

- **Goal of Thesis Research**
  - Develop a prescriptive design methodology for SoS that will take into consideration the specific issues that make SoS design difficult
- **Method**
  - Identify and quantify SoS-specific characteristics
  - Incorporate these characteristics into Dynamic MATE framework
- **Anticipated Contribution**
  - Development of SoS component participation decision metrics
  - Inform design considerations for the SoS designer, e.g. 'influence' requirements as part of SoS design
  - Provide a framework for testing SoS design heuristics suggested in literature