Dynamic Modeling of Programmatic and Systematic Interdependence for System of Systems Acquisition

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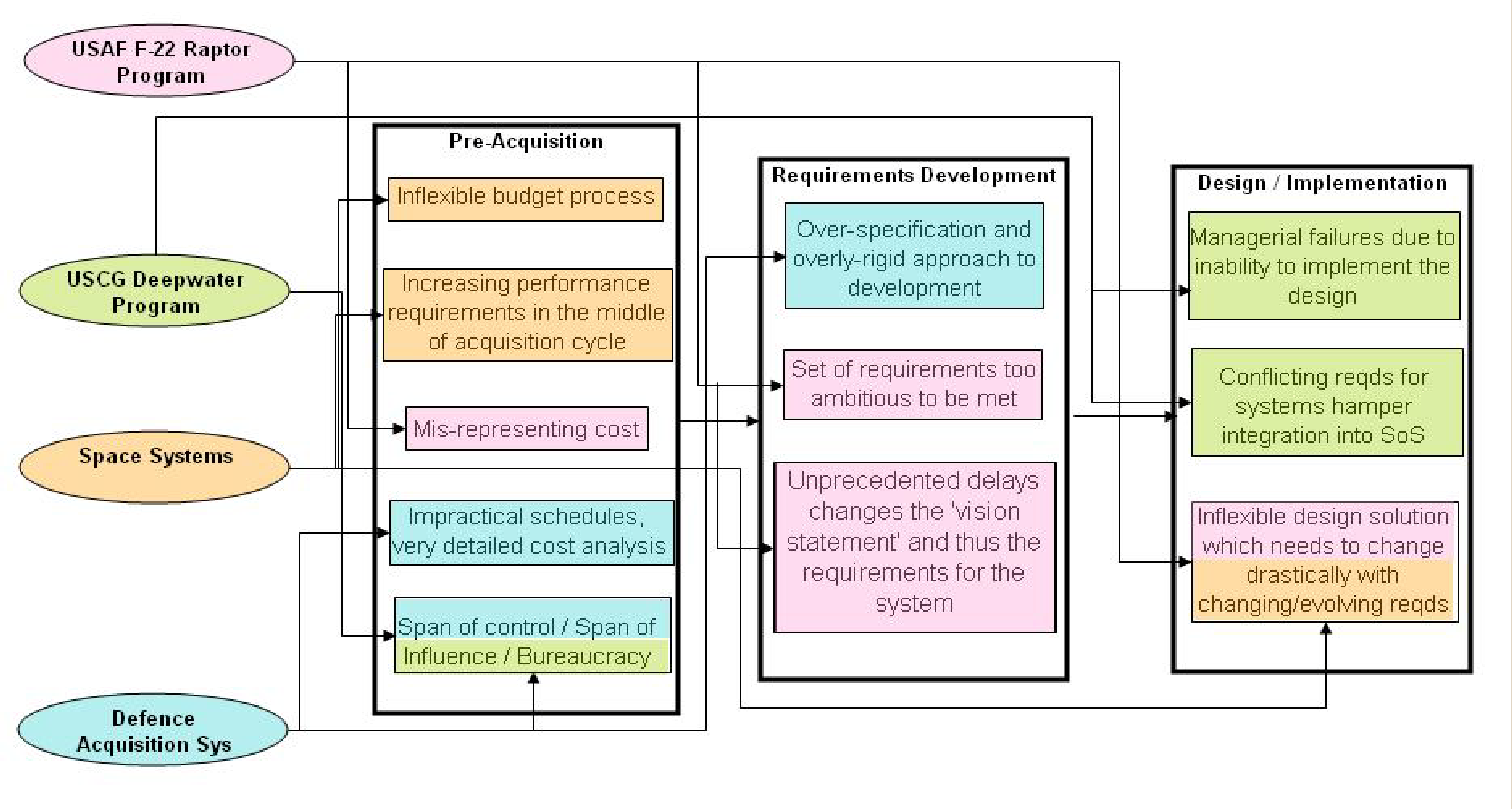
Overview of Agenda/Presentation

- Motivation and problem statement
- Recap from prior work
  - Conceptual model based on OSD's SoS SE Guide
  - Computer simulation: Exploratory SoS Acquisition Model
- Snapshots from illustrative problems
  - Dynamic impacts of risk
  - Implementation of system-specific risk
  - Impact of system-specific risk and SoS network topology
- Summary

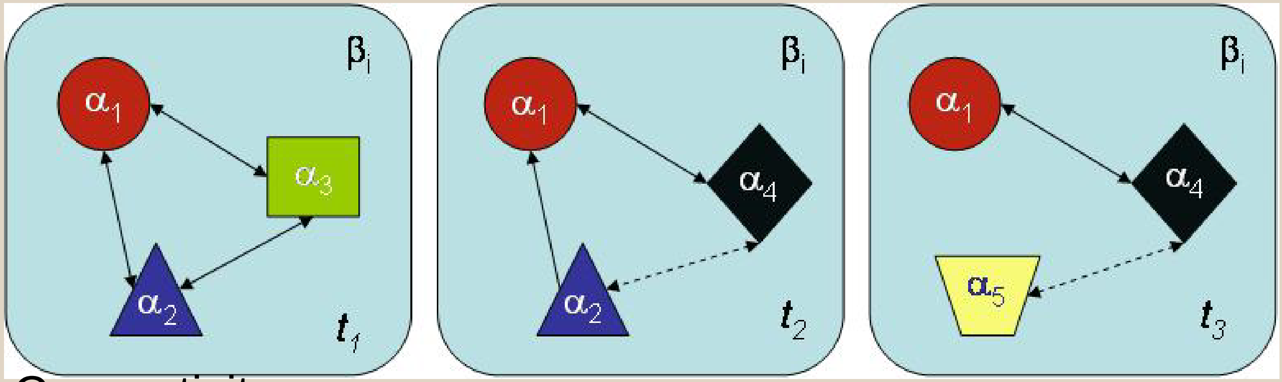
Motivation

Literature on recent history indicates a variety of challenges for SoS acquisition



SoS Sources of Complexity

Working Definition for Complexity:
the amount of information necessary to describe the regularities in a system effectively



- Dynamic and Uncertain Connectivity
  - **between** levels of abstraction
  - **across** scope dimensions
  - multiple time scales
  - emergence (unforeseen interdependencies)
- “Porous” boundary
  - Changes in constitution of SoS
  - Evolving nature of an ‘open system’
- Heterogeneity & Multiplicity
  - Multiplicity of perspectives: A root cause of interoperability issues
  - Heterogeneity of participants (within and between Human & Technical); Socio-Technical Systems

Root Causes of Failure
(within acquisition processes)

- *Misalignment* of objectives among the systems
- Limited *span of control* of the SoS engineer on the component systems of the SoS
- *Evolution* of the SoS
- *Inflexibility* of the component system designs
- *Emergent behavior* revealing hidden dependencies within systems
- *Perceived complexity* of systems
- Challenges in *system representation*

Used categories from Rouse, W. (2007, June). Complex Engineered, Organizational and Natural Systems. *Systems Engineering*, 10, 3., pp. 260-271

Recap: Research Goals

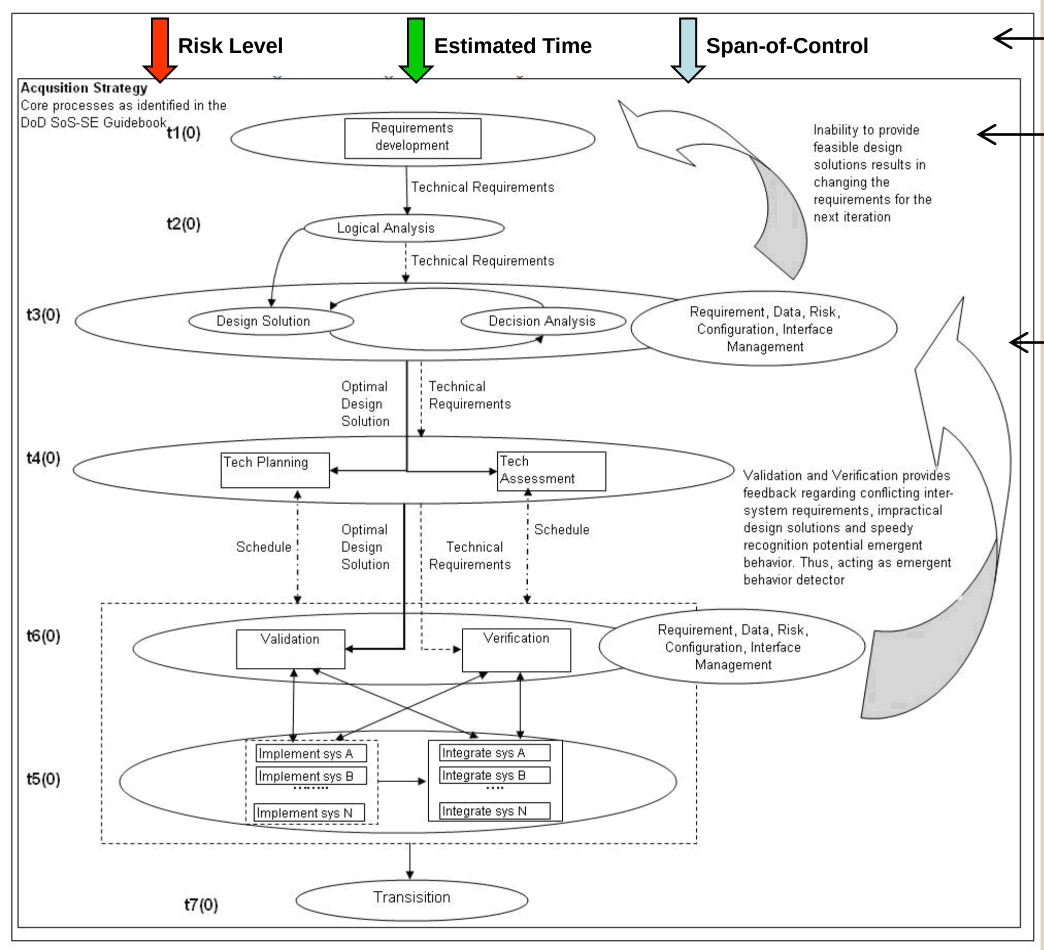
- Uncover underlying functions affected by complexities due to evolution in SoS acquisition and span-of-control
- Capture Dynamics: Exploratory SoS Acquisition Model
  - Depicts the processes (SoS SE Guide) in a hierarchical setting
  - Show the flow of control between the processes throughout the acquisition life-cycle
  - Interactive computational model: allow users to ‘explore’ complexities
- Experiment: Generate insights and approaches to improve the probability of program success
- Mapping of Operational Views (OV) to Systems Views (SV)
  - System capabilities and their interconnections

Recap: Development of a Dynamic, Exploratory Model for SoS Acquisition

1. *Pre-Acquisition Model (not included here)*
   - Understand the influence of external stakeholders on the acquisition process

2. *Acquisition Strategy Model*
   - Based on the 16 technical management and technical systems engineering processes outlined in the Defense Acquisition Guidebook (5000 series) applied to an SoS environment (SoS-SE Guide)
   - Conceptual model depicts the processes in a hierarchical setting to show the flow of control between the processes throughout the acquisition life-cycle

Recap: Acquisition / Development – The Paper Model
(based on SoS SE Guide)



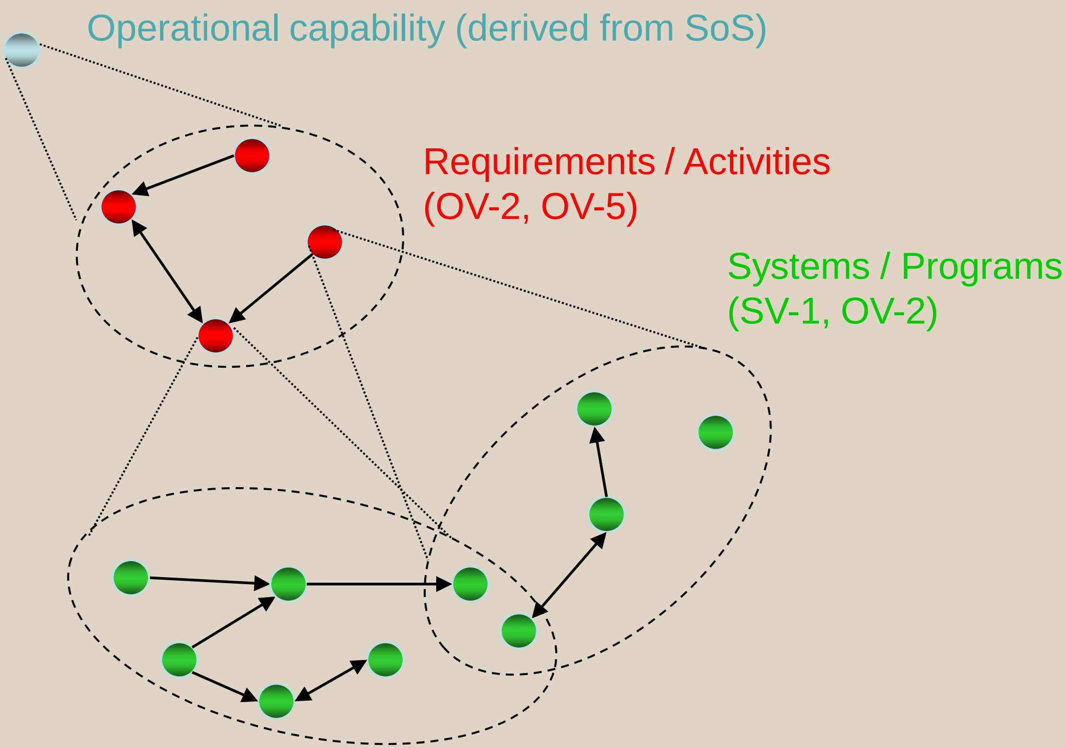
Project-level (SoS)
Risk profile: low, med, high
Span-of-control: low, high

Requirement-level
- Number of requirements
- Requirement dependency
- Probability of disruption

System-level
- System dependency
- Initial completeness level
- Int/Imp time
- Probability of disruption (comes from risk-profile)

Output
Completion time

Methodology Abstraction



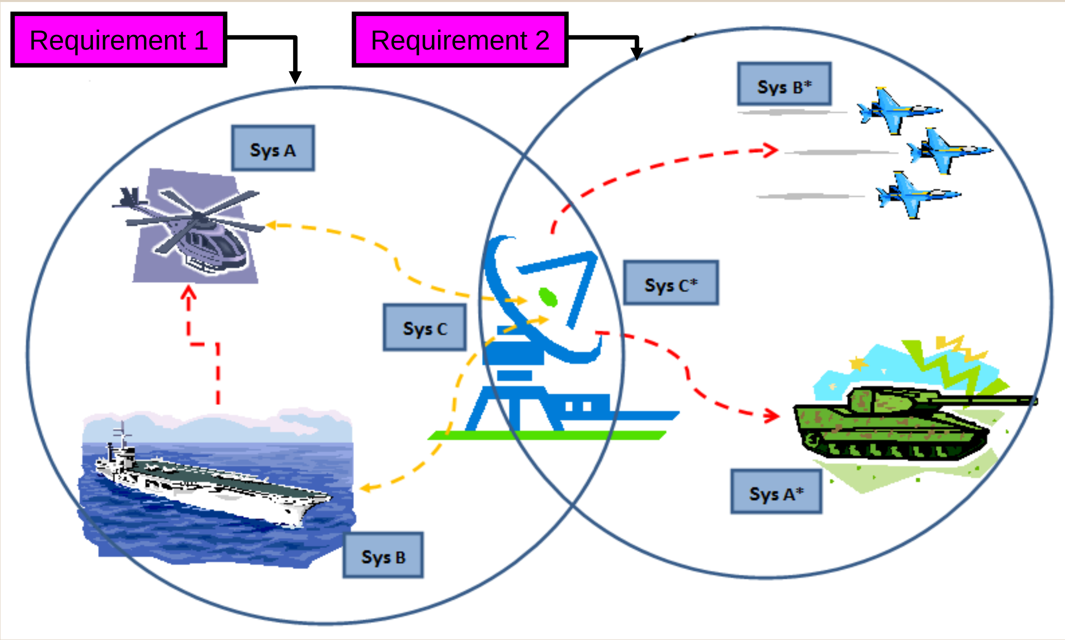
Operational (OV): systems work together to provide a capability

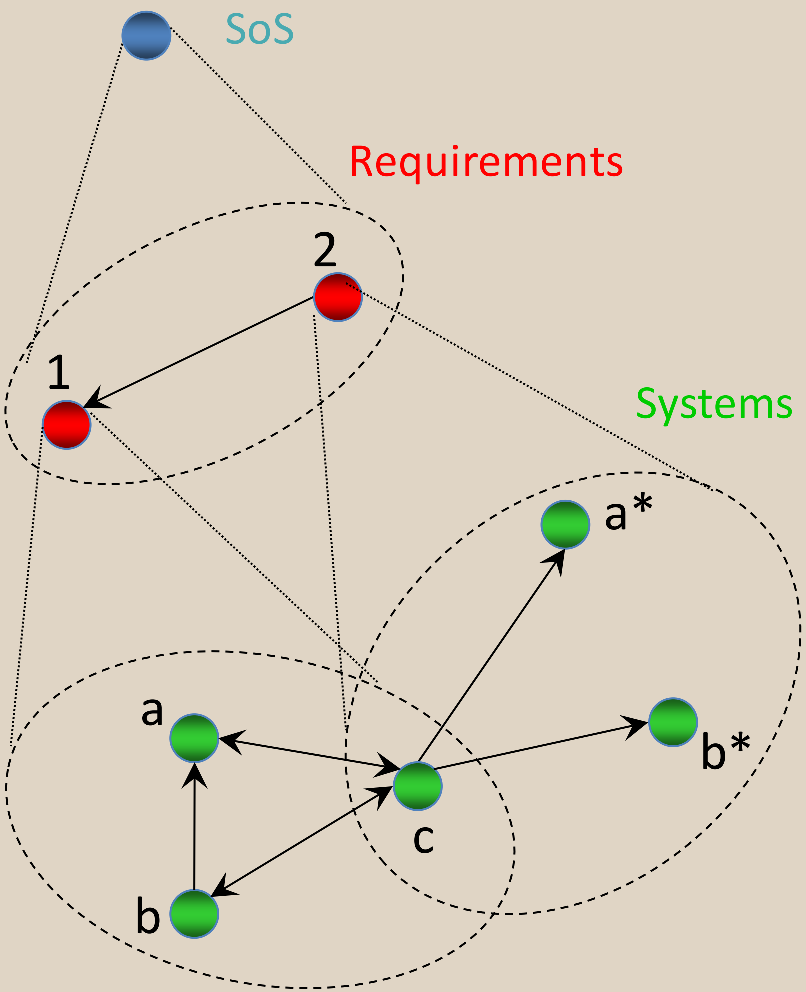
System (SV): define nature of interaction between systems

Programmatic: relationship between systems during development

- Discrete-event simulation with probabilistic behavior of systems
- Levels have predetermined probability of disruption
  - Requirement-level disruptions: affect design solutions (i.e. design solution of system X cannot meet requirement)
  - System-level disruptions: affects completeness level of system and completion time (i.e. set back in implementation phase of system X results in longer time)

Illustrative Example





System Dep (R1)

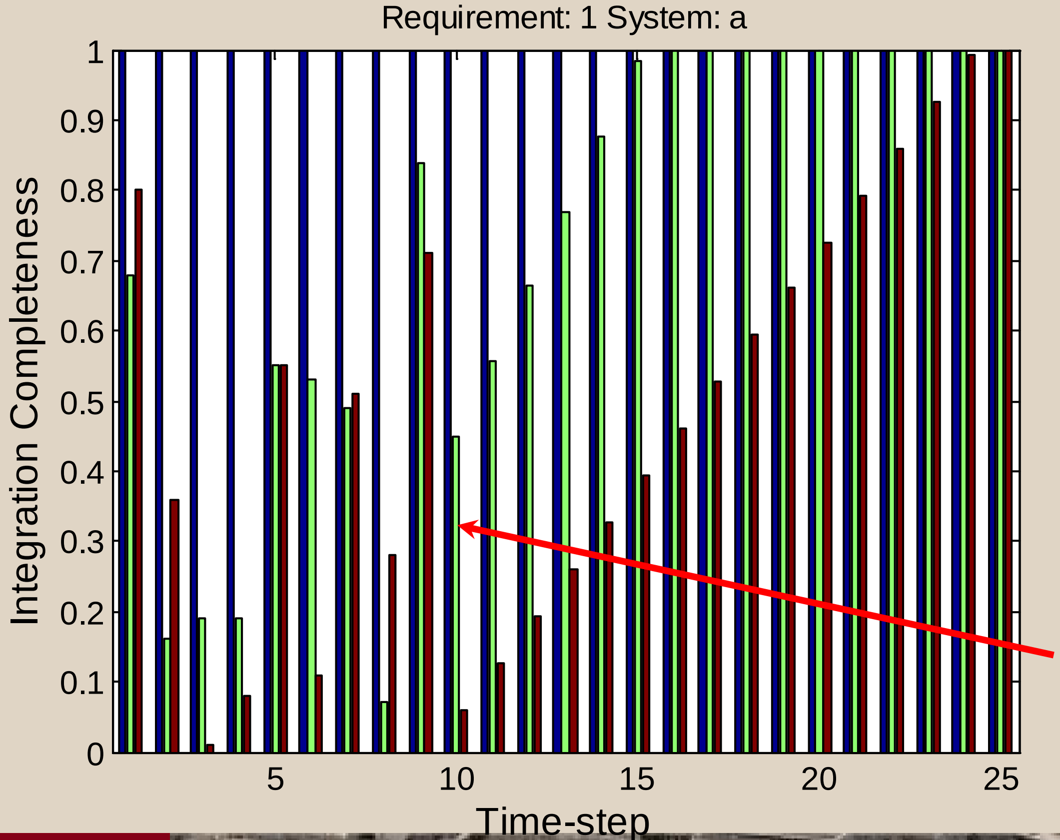
$$\begin{bmatrix} 0 & 1 & 1 \\ 0 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}$$

System Dep (R2)

$$\begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}$$

Effects of Disruptors (system-level)

- Inevitable disruptions on both system-level and requirement levels will occur
- *Technology Assessment* is able to immediately trace and resolve the problem
  - This prevents the development from stalling or regressing over multiple time-steps

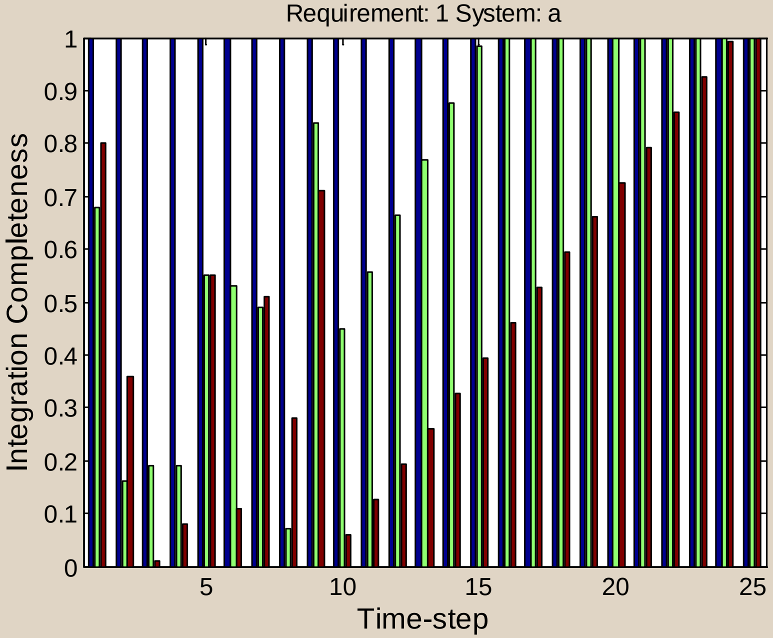


Each color represents an individual system (system 'a' is blue)

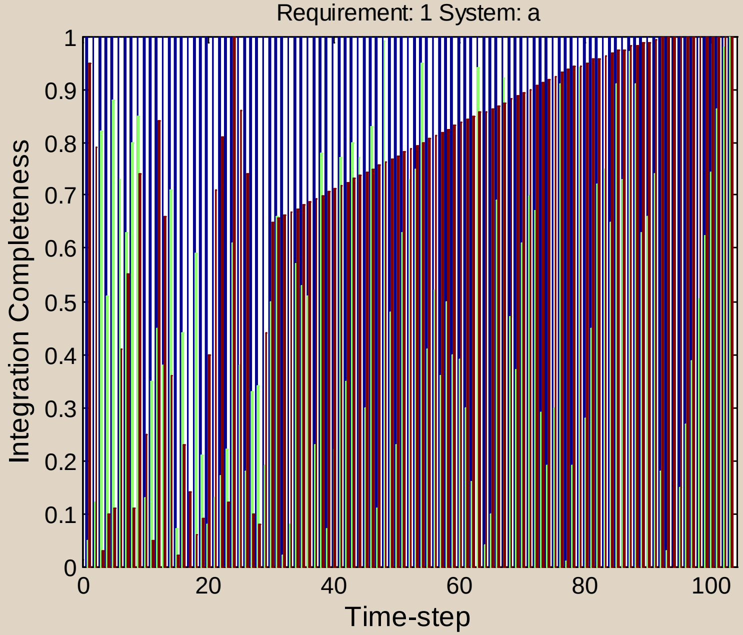
Negative disruptions correspond to system re-engineering and lower completeness level in Integration (and Implementation) phase

Effect of Project Risk

(determines probability of disruption in Integration and Implementation phase)



Low-risk instance

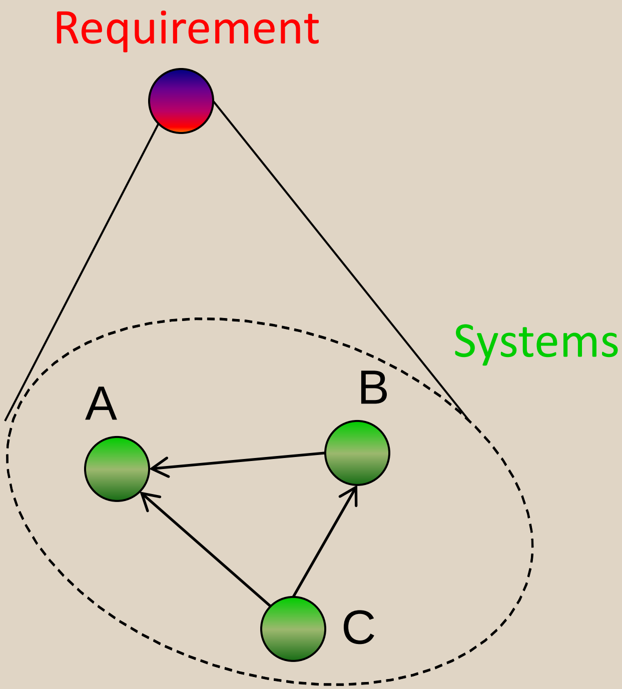


High-risk instance

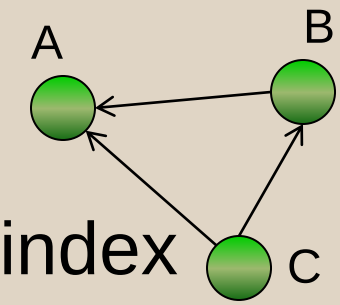
- Some projects have a much higher risk factor
  - They are more vulnerable to negative disruptions in their development
- Higher risk of disruptions implies more time to complete stages
  - In fact, completion may fail → return to Design Solution
- Not all systems in a SoS, however have the same risk-level

Impact of System-Specific Risk

- Quantify the impact that system-specific risk has on the completion time of the SoS
  - Measure risk in a SoS network
  - Observe changes in completion time due to different risk-levels
- Example problem
  - One requirement and three component systems
  - Each system can have a distinct risk-level
    - Risk-level indicates probability of disruption in implementation & integration phase
  - Risk for the SoS varies as the level and combinations of system-specific risk change
  - Wan to capture the effect of these changes and measure the risk for t he entire SoS



Network-Risk Metric



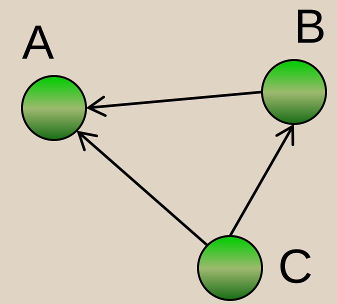
- Consider the following network-risk metric/index

$$R = \sum_{i=1}^{N} \sum_{j=1}^{N} r_j \cdot A_{i,j}$$

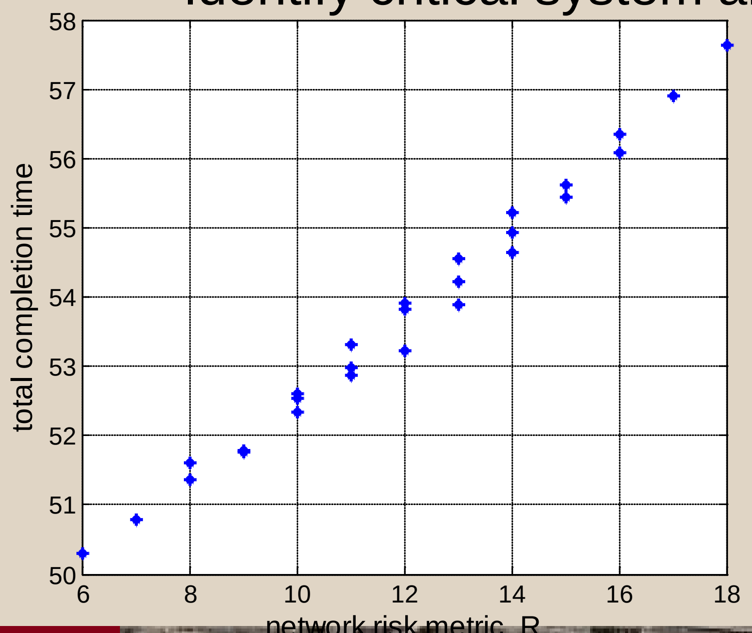
where r_j is the risk of system j and it has values of 1, 2, or 3 (for low, mid, and high risk) and A is the adjacency matrix (system interdependencies)

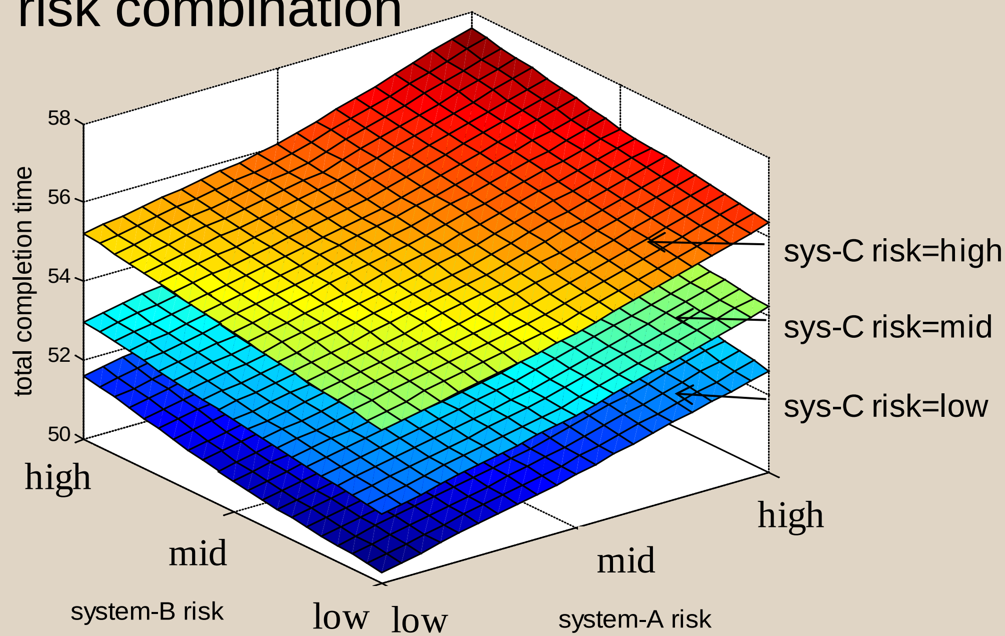
- The network-risk metric is a dimensionless number and considers the system-risk and the system dependencies simultaneously
- Current implementation does not yet consider the higher-order system interdependencies (cascading effects of risk)
  - i.e. system A is impacted by system B, but system B is also impacted by system C; risk of system A should be more than just the sum of the risk of system-A and system-B

Exploratory Model Experiments



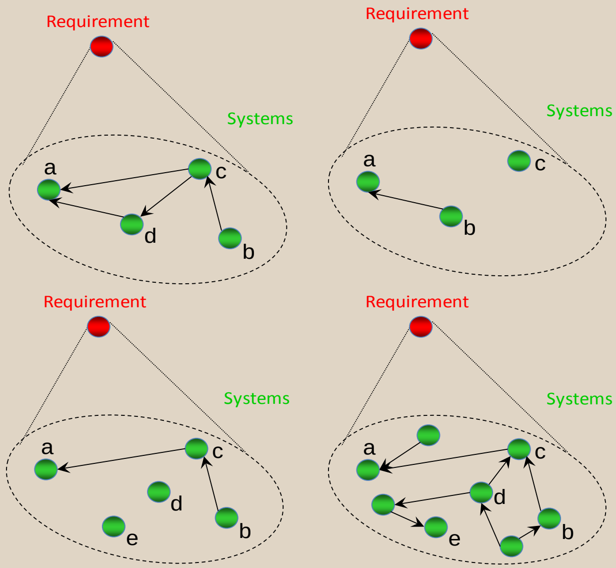
- Experiment set-up
  - Each system can have a low, mid, or high risk-level
    - A total of 27 combinations for the 3-system network
  - Run Monte Carlo simulation of Exploratory Model (500 samples)
- Experiment results
  - Capture impact of system-specific risk on SoS completion time
  - Identify critical system and risk combination

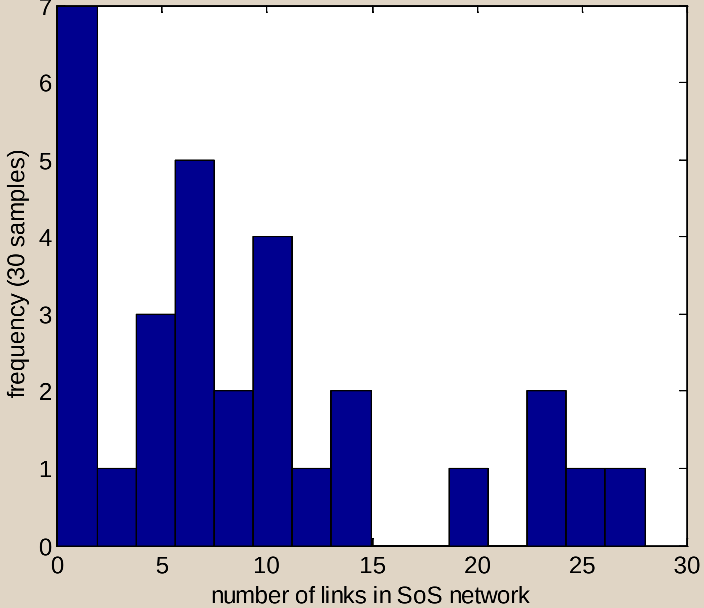




Impact of System-Risk and SoS Network Topology

- Previous experiment captured the impact of system risk for a fixed SoS network
- It is also possible to consider the impact of system-specific risk coupled with different network topologies
- Consider 30 randomly generated SoS configurations
  - Uniformly random selection of number of systems (up to10 systems)
  - Random selection of links between systems with correlation of 0.25

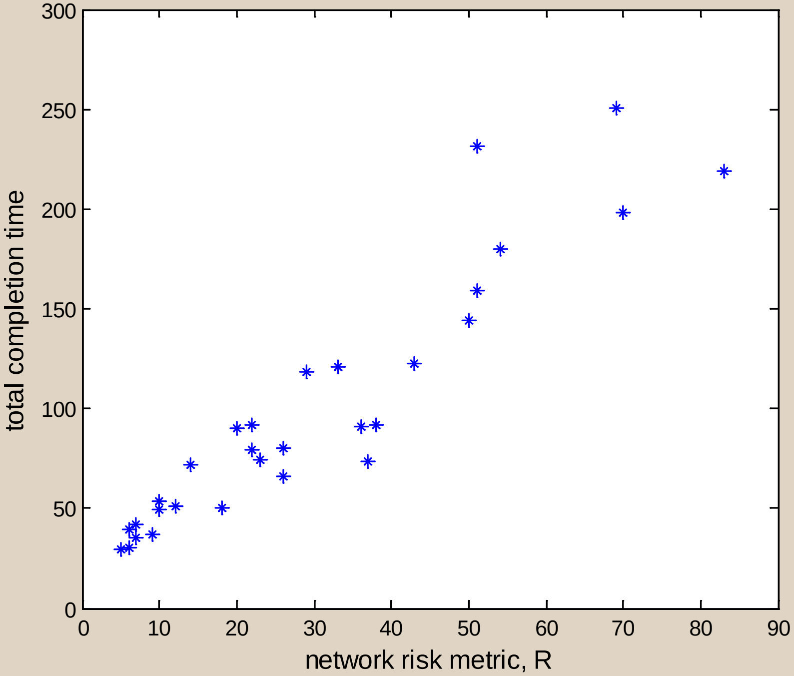




Exploratory Model Experiments

- Experiment set-up
  - For each system in each SoS network randomly generate a risk-level
  - Run Monte Carlo simulation of Exploratory Model (500 samples) for each SoS network

- Experiment results
  - Capture impact of system-specific risk AND network topology (i.e. interdependencies) on SoS completion time
- Observations
  - SoS with higher risk metric/index have higher completion time
  - Scatter potentially due to the higher-order impact of risk (i.e. cascading effects)



Observations

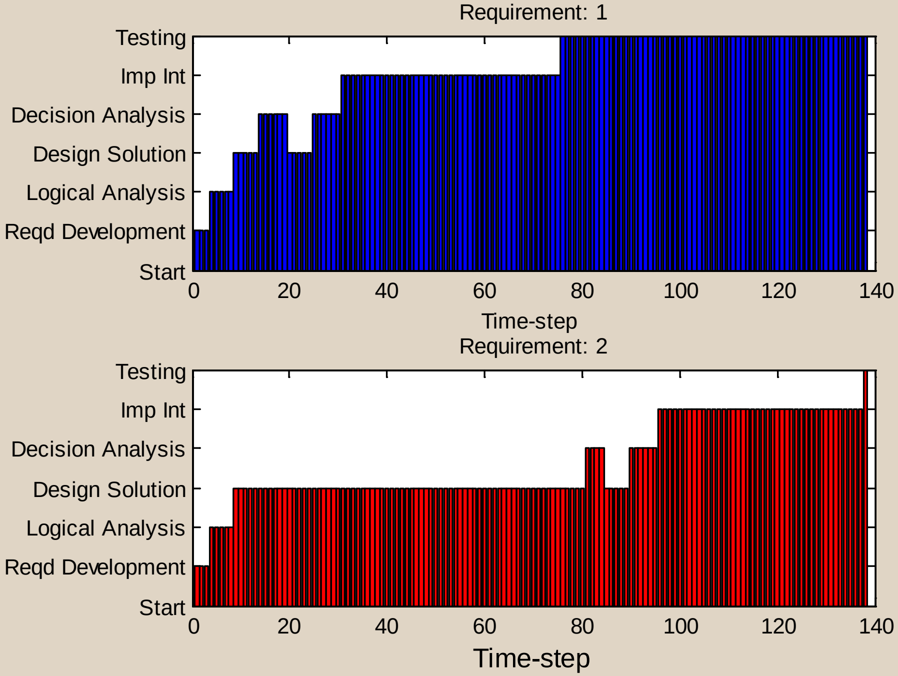
- Exploratory model is intended to enable acquisition professionals and program engineers to learn about complexities, dynamics, and disruptions, identifying markers of failure and success
  - Evolution of interdependencies
  - Network structure and span-of-control of SoS
- Current implementation if system-risk seems to capture the right things
- System-specific risk and SoS network topology experiments are a means to compare different SoS options that may satisfy the same requirement
- Shortcomings
  - R does not capture the higher order impact of dependencies
  - Current efforts focused on addressing this

Thank You

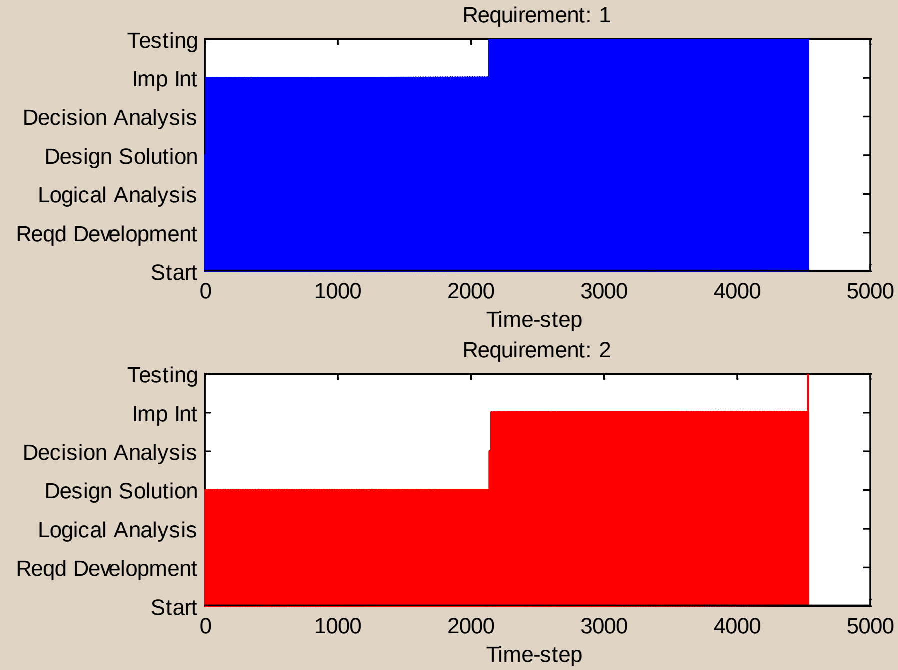
References

- Defense Acquisition Guidebook. Retrieved April 4, 2008, from Defense Acquisition Guidebook Web site: https://akss.dau.mil/dag/TOC_GuideBook.asp?sNode=R2-3-2&Exp=Y
- (2006). SoS Systems Engineering. Retrieved March 2, 2008, from Systems and Software Engineering Web site: http://www.acq.osd.mil/sse/ssa/initi atsos-se.html
- Saunders, T.et al. (2005, July). Report on System-of-Systems Engineering for Air Force Capability Development. *USAF Scientific Advisory Board.* SAB-TR-05-04.
- Rouse, W. (2007, June). Complex Engineered, Organizational and Natural Systems. Systems Engineering, 10, 3., pp. 260-271
- Sage, A. and Biemer, S. (2007) Processes for System Family Architecting, Design, and Integration. IEEE Systems Journal. 1,1. pp. 5-16.
- Maier, M. (1998).Architecting Principles for System-of-Systems. Systems Engineering. 1, 267-284.
- Anderson, M, Burton, D, Palmquist, M.S., & Watson, J.M (1999, May). The Deepwater Project - A Sea of Change for the U.S. Coast Guard. *Naval Engineers Journal*, RetrievedApril 01,2008,from http://www.prosoft.tv/aseaofchange.pdf.
- *United States Coast Guard Acquisition Directorate*. (1998). Coast Guard Recapitalization Fact Sheet. Retrieved January 3, 2008, from http://www.uscg.mil/acquisition/programs/pdf/CG-9recap.pdf
- Allen, T. (2007, April). Statement on the Converted 123-foot Patrol Boats and Changes to the Deepwater Acquisition Program.*USCG Press Release*.Retrieved June 1, 2007 from www.piersystem.com/go/doc/786/154307
- Caldwell, S. L. (2006, June).Coast Guard: Observations on Agency Performance, Operations and Future Challenges. *Government Accountability Office (GAO)* Retrieved January 3, 2008, from http://www.gao.gov/new.items/d06448t.pdf
- Fowler, C. A. (1994, August). The Defense Acquisition System Too Late for the Scalpel; Bring Out the Meataxe! *IEEE Aerospace and Electronic Systems Magazine*, *9*, 8., pp. 3-6.
- Spring, B. (2005,October). Congressional Restraint Is Key to Successful Defense Acquisition Reform. *The Heritage Foundation.* Retrieved March 26, 2008, from http://www.heritage.org/Research/NationalSecurity/bg1885.cfm
- Riccioni, E. (2005,March). Description of Our Failing Defense Acquisition System as Exemplified by the History,
- Nature and Analysis of the USAF F-22 Raptor Program. *Project On Government Oversight.* Retrieved March 4, 2008 from http://www.pogo.org/m/dp/dp-fa22-Riccioni-03082005.pdf
- 14 Capaccio.,T.(2006, December). Boeing Systems Delayed, 11 Others Killed in Proposed Army Budget.*Bloomberg*. Retrieved June 1, 2007 from http://www.bloomberg.com/apps/news?pid=newsarchive&sid=amNoYrTtynxQ

Effect of Span-of-Control



High Span-of-control



Low Span-of-control

- Span-of-control has large impact on project time
  - High span-of-control → SoS level authority, can implement in parallel
  - Low span-of-control → less coordination, implement in series, results in longer completion time