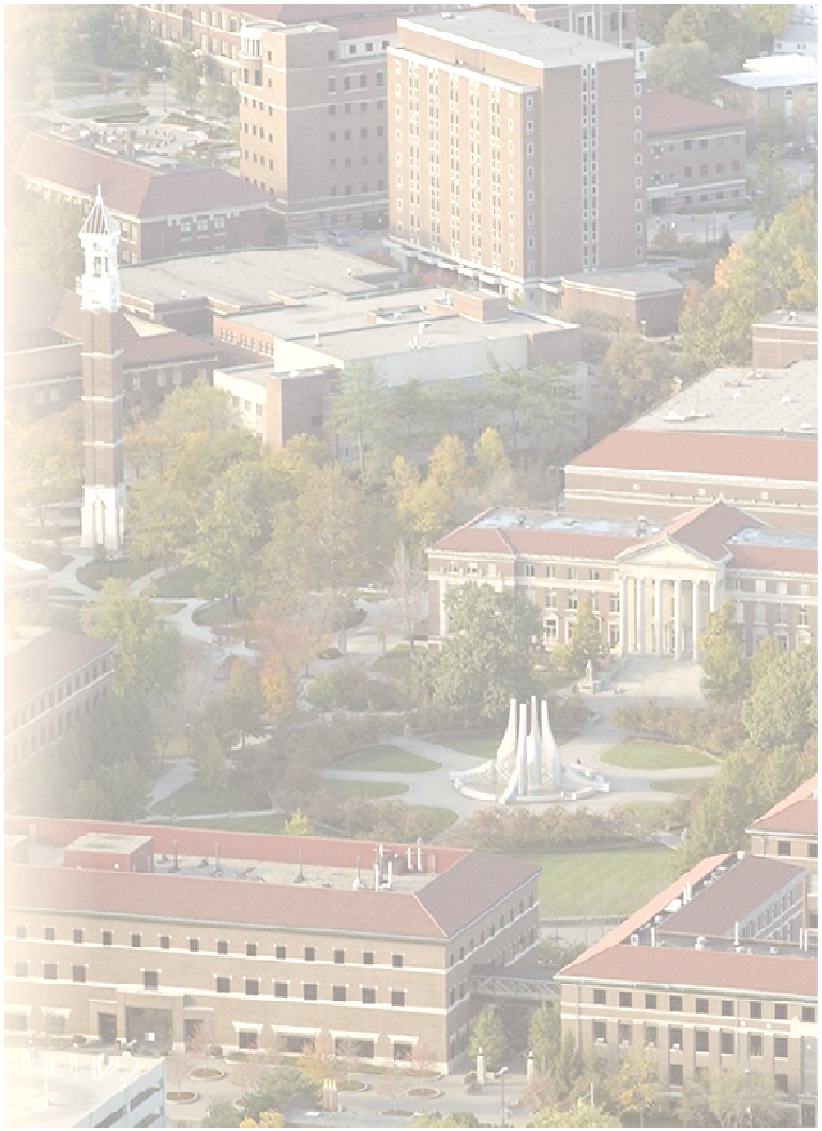
Dynamic Modeling of Programmatic and Systematic Interdependence for System of Systems

System of Systems Engineering Collaborators Information Exchange (SoSECIE)
April 13, 2010

Dan DeLaurentis, Assistant Professor
ddelaure@purdue.edu
School of Aeronautics & Astronautics
and System-of Systems Signature Area
Purdue University

Brian Sauser- Assistant Professor
Stevens Institute of Technology
Brian.sauser@stevens.edu

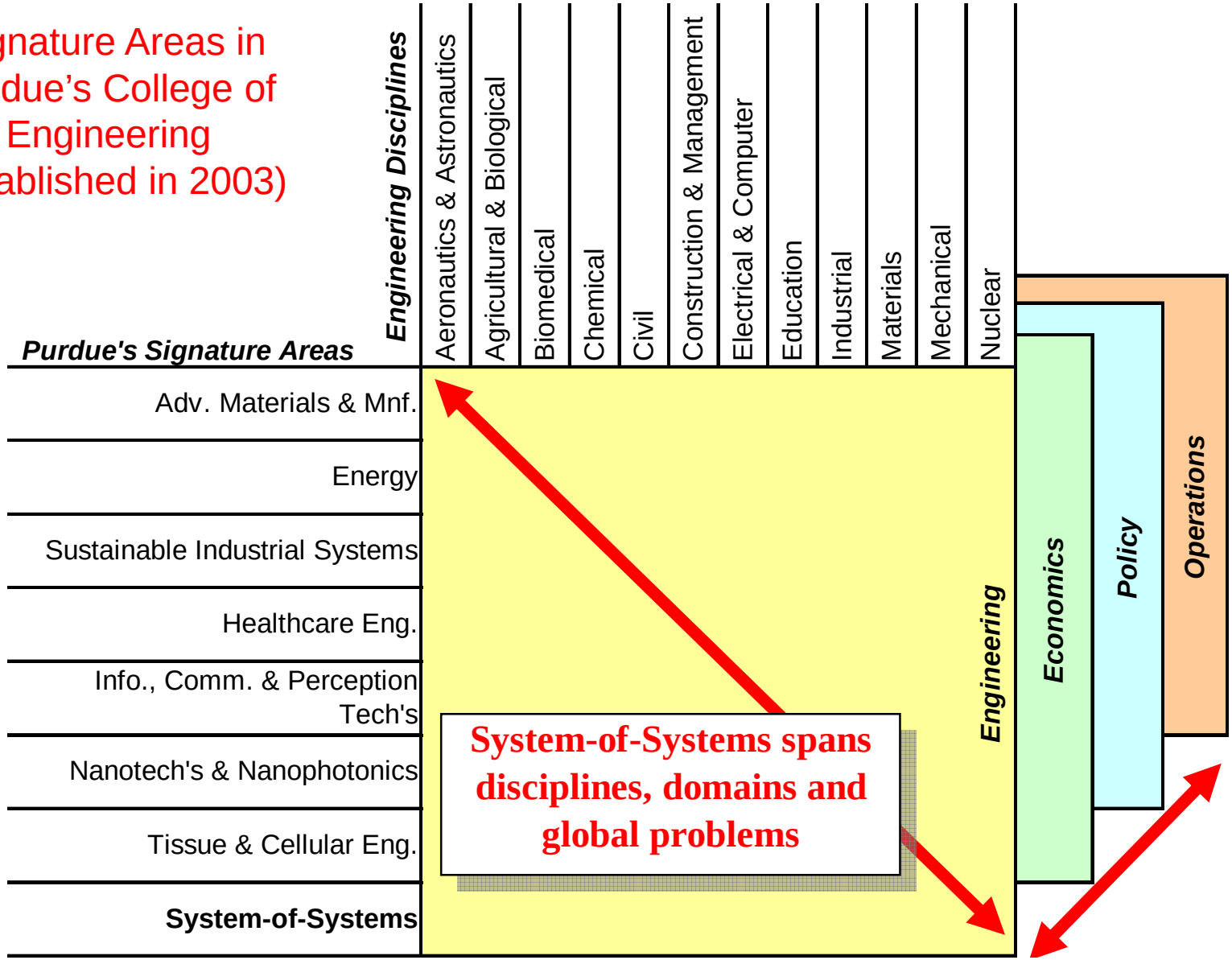


Overview of Agenda/Presentation

- Brief Introduction via Context Setting
- Investigating System Interdependencies
  - Conceptual model based on OSD's SoS SE Guide
  - Computer simulation: Computational Exploratory Model (CEM) for SoS Acquisition
- Snapshots from illustrative problems
  - Dynamic impacts of risk
  - Implementation of system-specific risk
  - Impact of system-specific risk and SoS network topology
- Summary

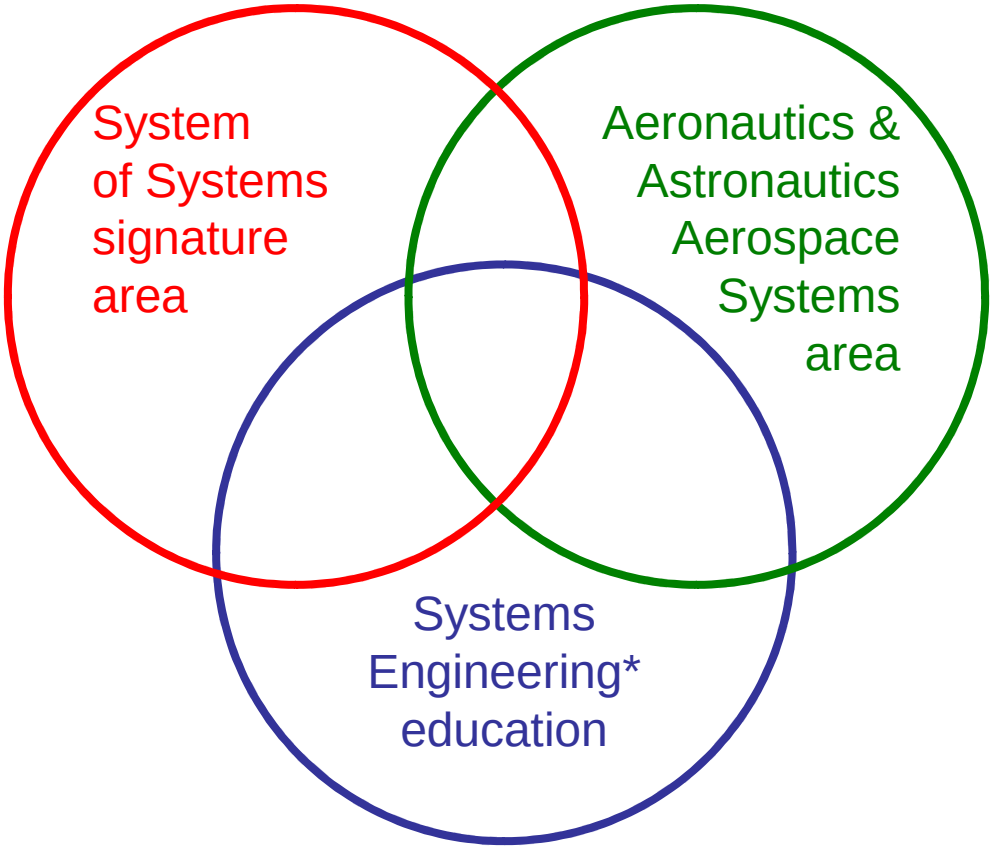
Context: SoS at Purdue (1)

Signature Areas in Purdue's College of Engineering (established in 2003)



SoS at Purdue (2): AeS, SoS, SE

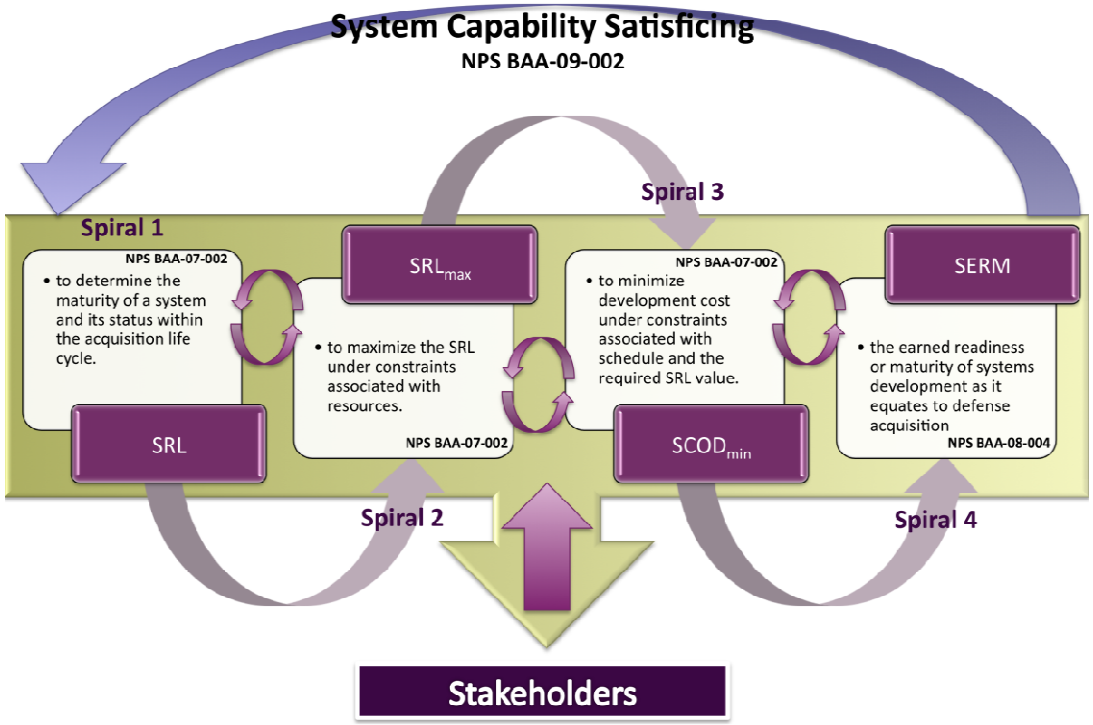
- System of Systems signature area
  - College-level, involves faculty in several schools
  - Transportation, Healthcare Delivery, Logistics, etc.
  - Recent CoE Strategic Plan calls for creation of Sys-of-Sys Institute
- Aeronautics & Astronautics Aerospace Systems area
  - Research and curriculum for:
    - Design Phase
    - ***Development, Planning Phase***
    - Operations, Control Phase
  - NASA, FAA, and DoD funded work in Aerospace-oriented SoS
- Systems Engineering education
  - Educational support to SoS research
  - Address external stakeholder needs for graduate education in SE
  - Currently IE / AAE led effort to establish graduate concentration



* Purdue is now member of the SERC

ddelaure@purdue.edu brian.sauser@stevens.edu

Context at Stevens: Brian Sauser's NPS-sponsored System Capability Work



"*What technologies and integrations are important or critical to each architectural view to achieve a functionality or capability?"… "How will the systems maturity vary depending on the architectural variants?*"

"*What functionalities or capabilities are sufficient, critical, or important to achieving a level of system maturity that can satisfy a warfighter's needs?*"

"*What impact does this have on system maturity and ultimately the acquisition of a deployable system?*"

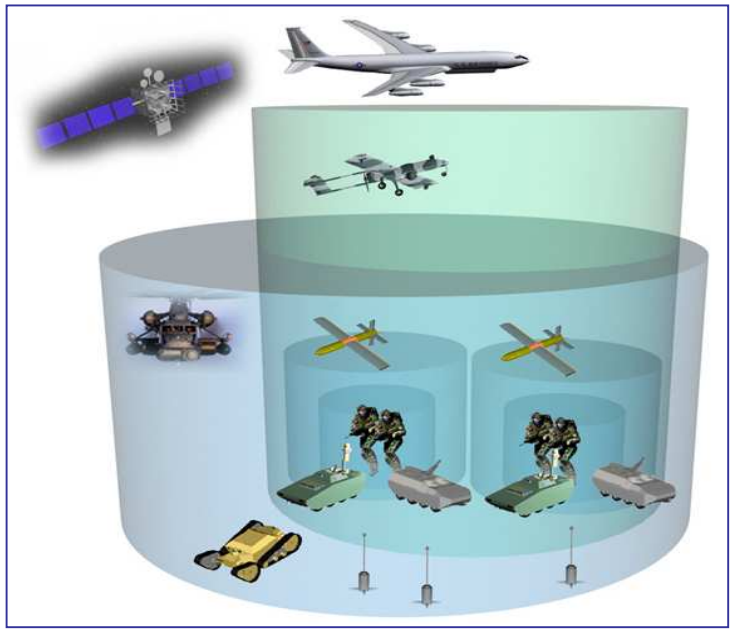
"*Can we use multi-attribute decision making/techniques in systems maturity assessment; parametric sensitivity analysis on how various TRL/IRL combinations drive SRL; and sensitivity analysis to determine what the most critical technologies are?*"

© 2010 Stevens Institute of Technology

<u>Today's Topic</u>: Exploring Impact of System Interdependencies in SoS Development

Research Sponsor: Naval Post Graduate School Acquisition Research Program

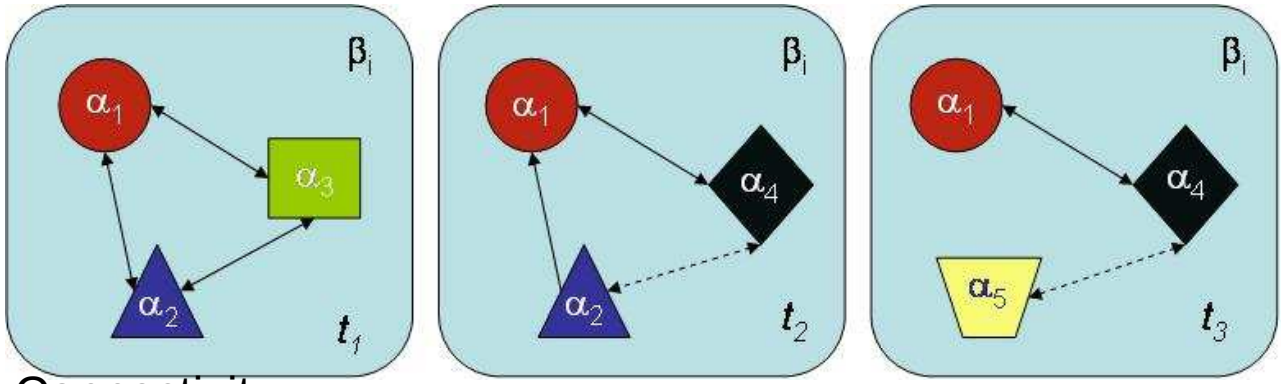
- What are the underlying complexities due to evolution in SoS acquisition …?
  - How does risk and *span-of-control* impact the time to develop capabilities?
  - Generate insights to improve the probability of program success in the midst of complexities.
- How do system interdependencies impact development time and risk for SoS?
  - Risk interdependencies and propagation in SoS network
- Are pursuing two tracks:
  - Exploratory Computer Model to simulate acquisition process Based on DoD SoS SE Guide
  - Analytical model based on conditional probability analysis (not discussed today)



ddelaure@purdue.edu brian.sauser@stevens.edu

Generic Motivation:
SoS Sources of Complexity

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



- Dynamic <u>and</u> Uncertain Connectivity
  - **between** levels of abstraction
  - **across** scope dimensions
- "Porous" boundary
  - Changes in constitution of SoS
- Heterogeneity & Multiplicity
  - Multiplicity of perspectives: A root cause of interoperability issues
  - Heterogeneity of participants (within and between Human & Technical); Socio-Technical Systems

- multiple time scales
- emergence (unforeseen interdependencies)

- Evolving nature of an 'open system'

ddelaure@purdue.edu brian.sauser@stevens.edu

Particular Motivation: Root Causes of Trouble
(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

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 success in developing systems for SoS capabilities

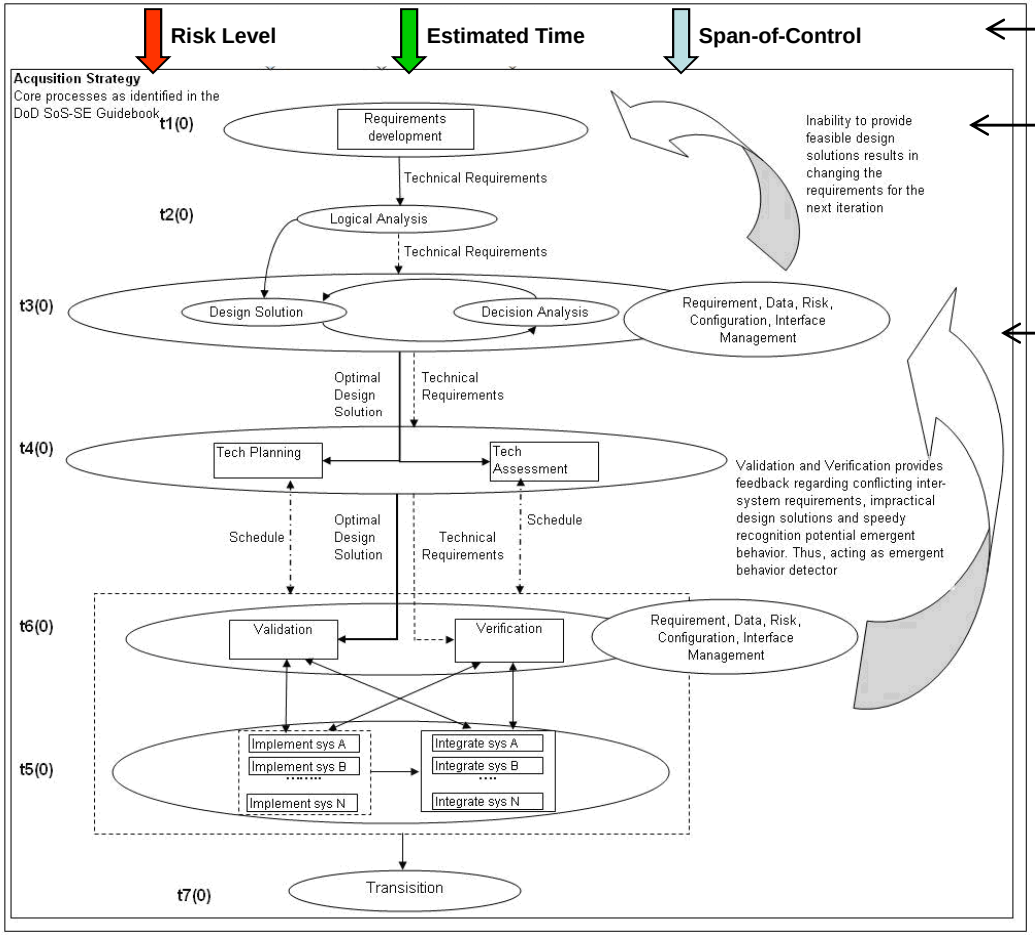
Development of a Computational Exploratory Model (CEM) SoS Acquisition

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

2. *Development/Acquisition 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

ddelaure@purdue.edu brian.sauser@stevens.edu

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



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

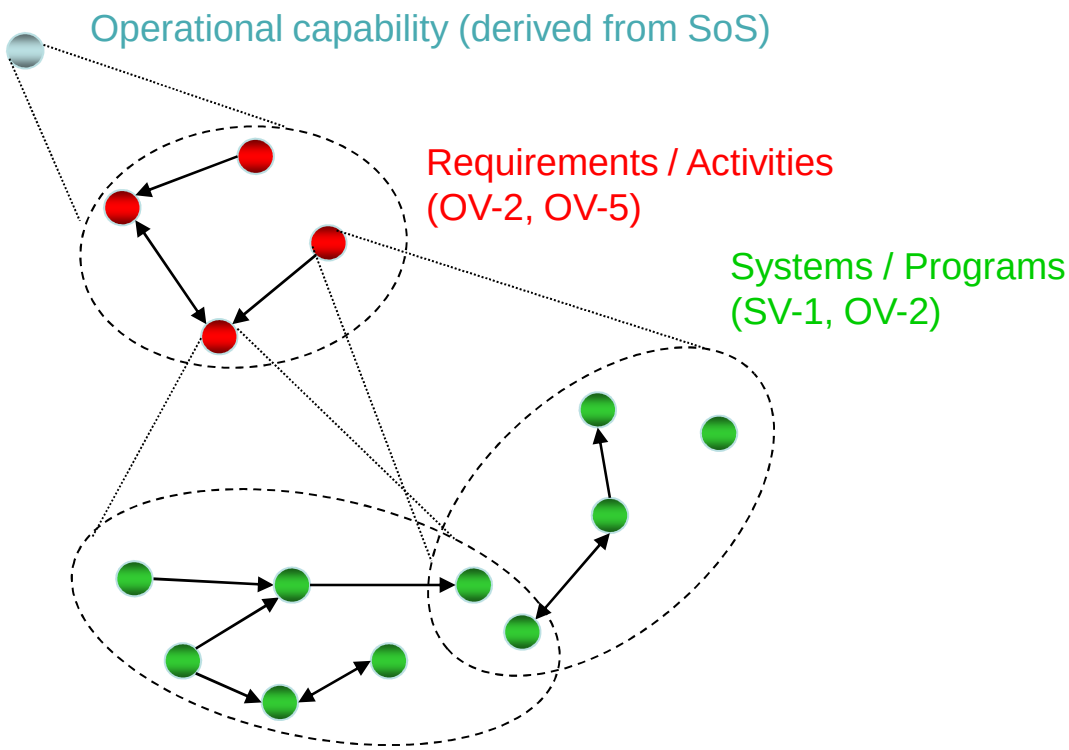
Requirement-level
- Number of requirements
- Requirement dependency
- Probability of disruption

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

Output
Completion time

ddelaure@purdue.edu brian.sauser@stevens.edu

Methodology Abstraction



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

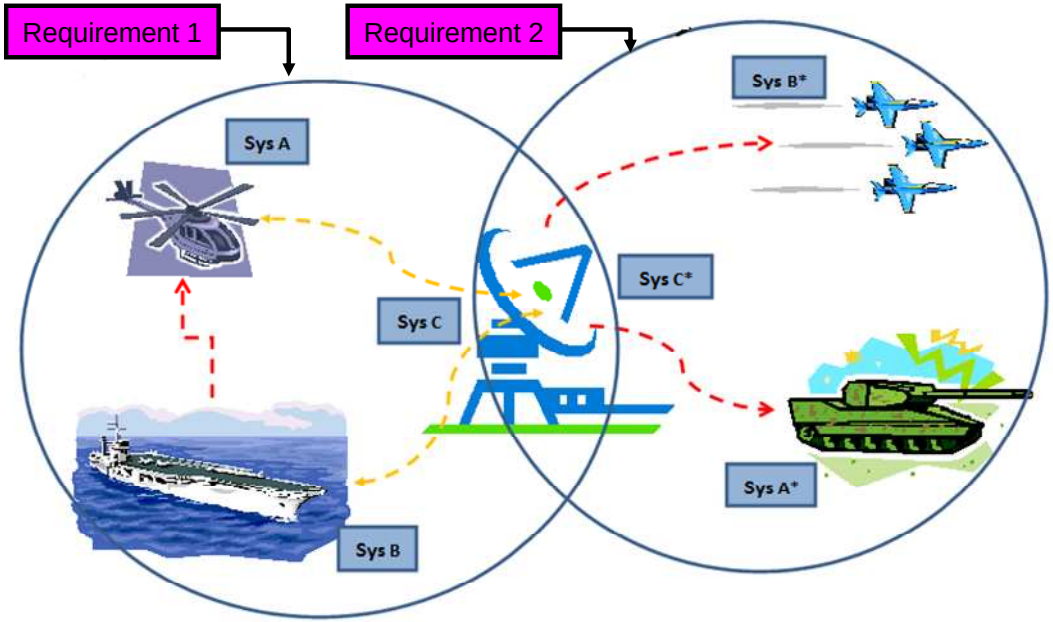
System (SV): define nature of interaction between systems

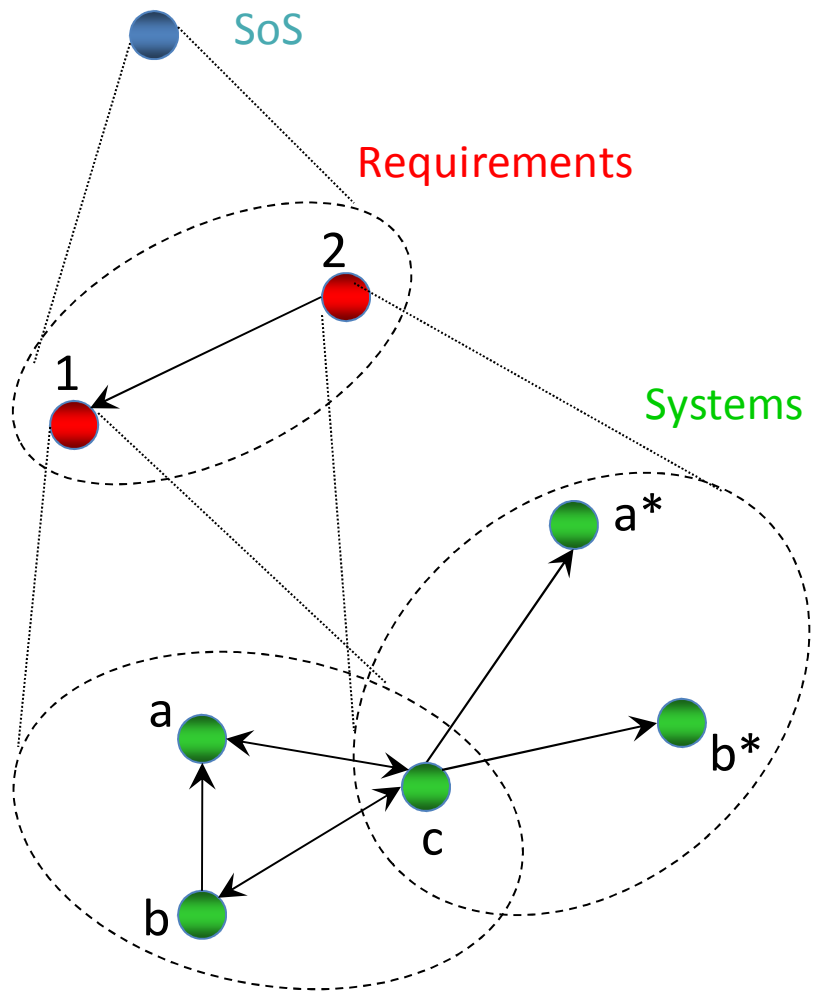
Programmatic: relationship between systems during development

- 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)

ddelaure@purdue.edu brian.sauser@stevens.edu

Illustrative Example





System Dep (R1)

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

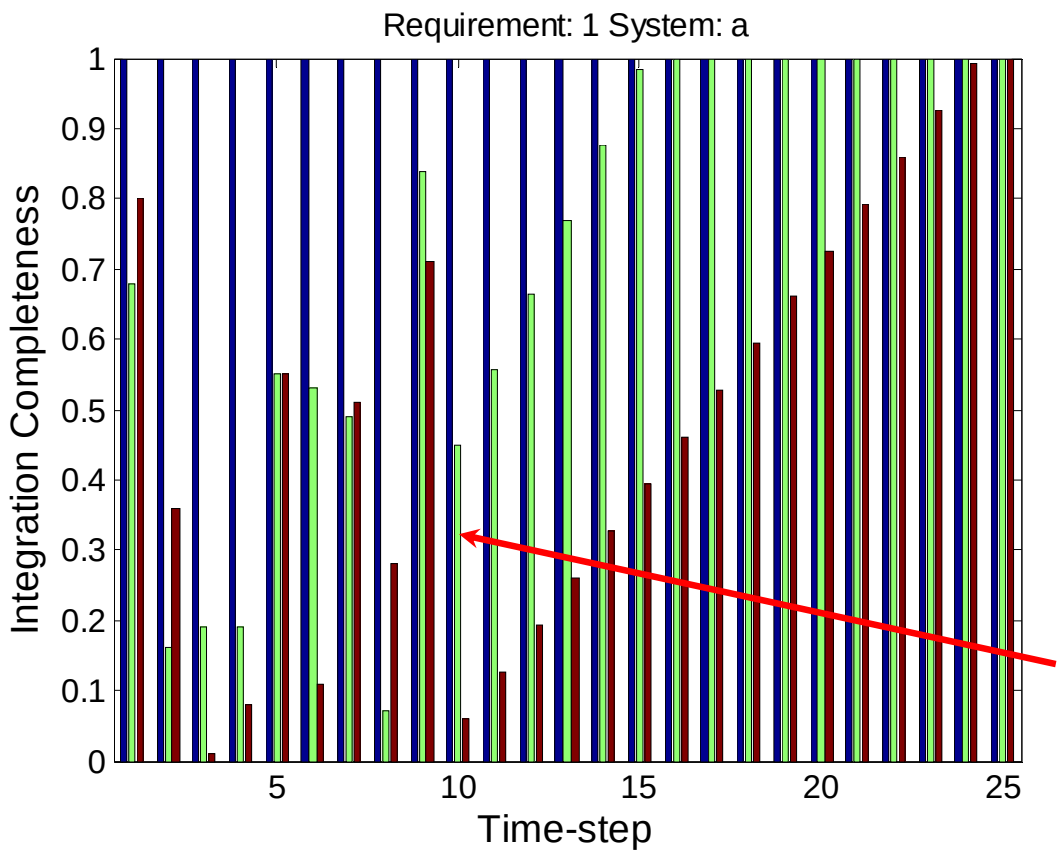
System Dep (R2)

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

ddelaure@purdue.edu brian.sauser@stevens.edu

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



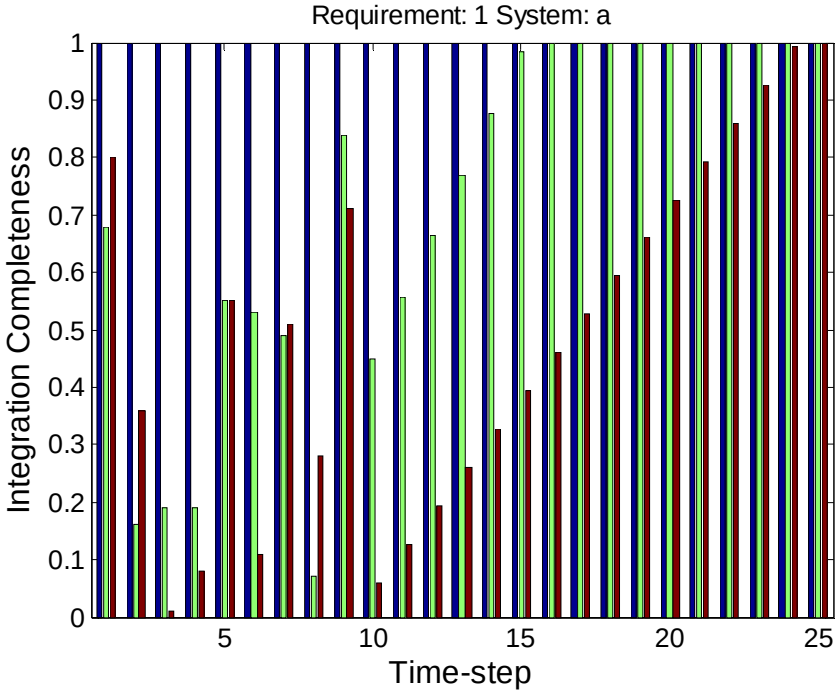
Each color represents an individual system (system 'a' is blue)

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

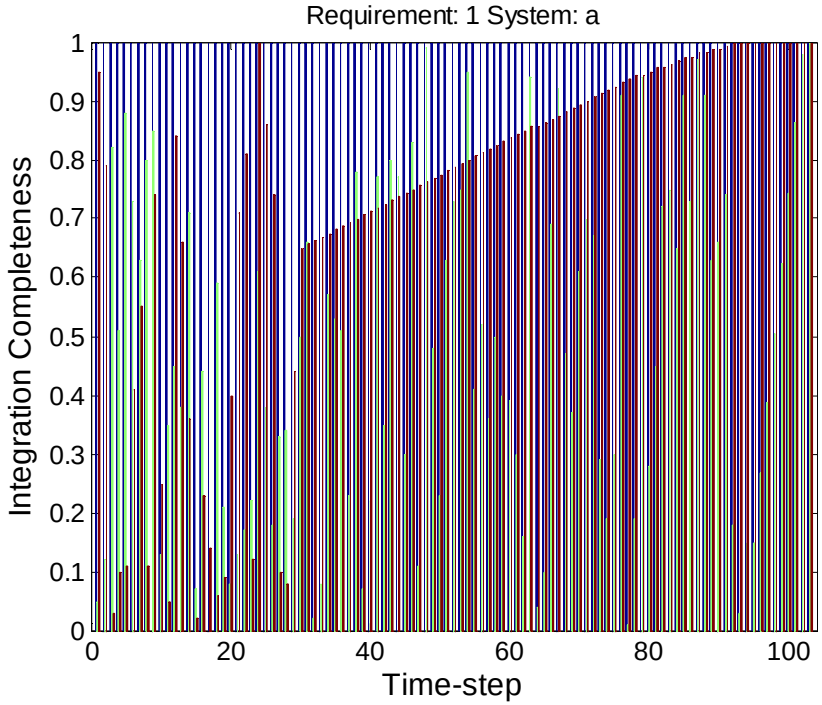
ddelaure@purdue.edu brian.sauser@stevens.edu

Effect of Project Risk

(determines probability of disruption in Integration and Implementation phase)



Low-risk instance



High-risk instance

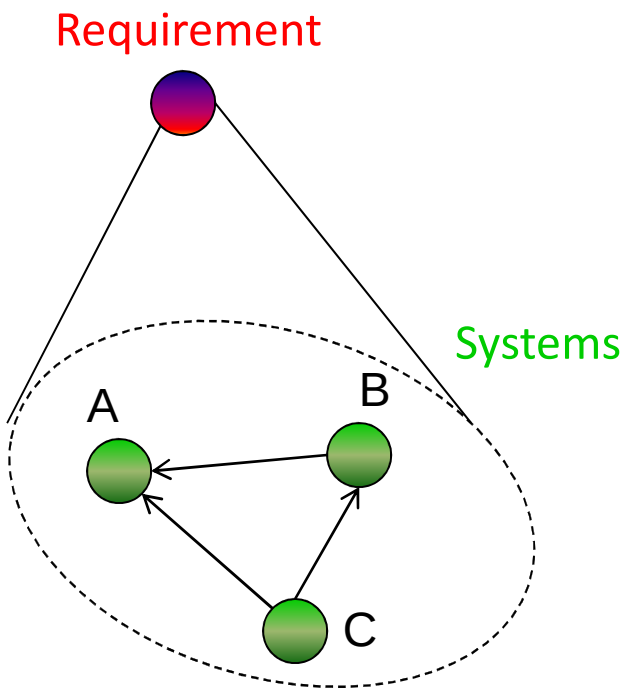
- Some projects have a much higher risk factor
  - They are more vulnerable to negative disruptions in their development
- Higher risk of disruptions implies more time to complete stages
  - In fact, completion may fail → return to Design Solution
- Not all systems in a SoS, however have the same risk-level

ddelaure@purdue.edu brian.sauser@stevens.edu

Next Example: Impact of System-Specific Risk

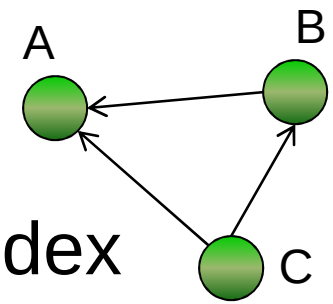
- Quantify the impact that system-specific risk has on the completion time of the SoS
  - Measure risk in a SoS network
  - Observe changes in completion time due to different risk-levels

- 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
  - Want to capture the effect of these changes and measure the risk for t he entire SoS



ddelaure@purdue.edu brian.sauser@stevens.edu

Network-Risk Metric



- Consider the following network-risk metric/index

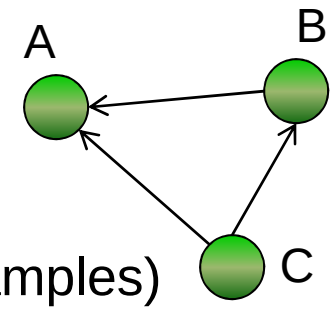
$$R = \sum_{i=1}^{N} \sum_{j=1}^{N} r_j \cdot A_{i,j}$$

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)

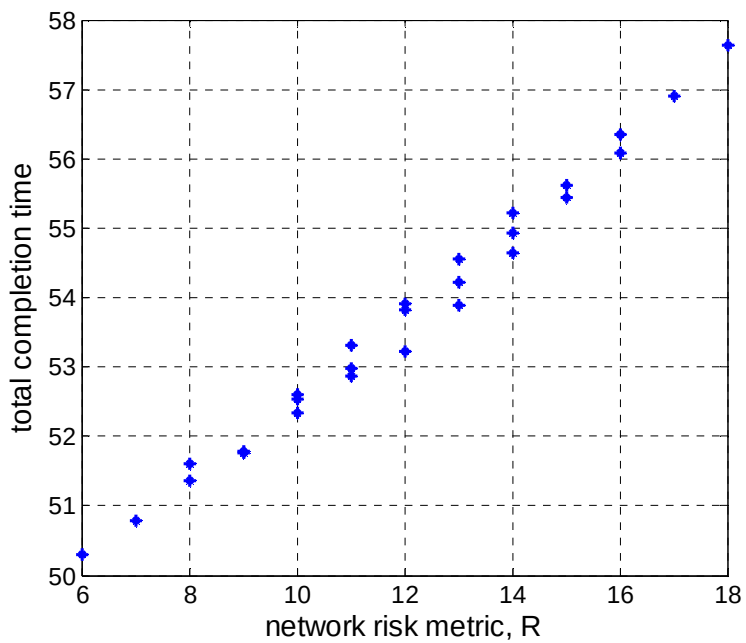
- The network-risk metric is a dimensionless number and considers the system-risk and the system dependencies simultaneously
- Current implementation does not yet quantify and report the higher-order system interdependency effects (cascading effects of risk)
  - i.e., system A is impacted by system B,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

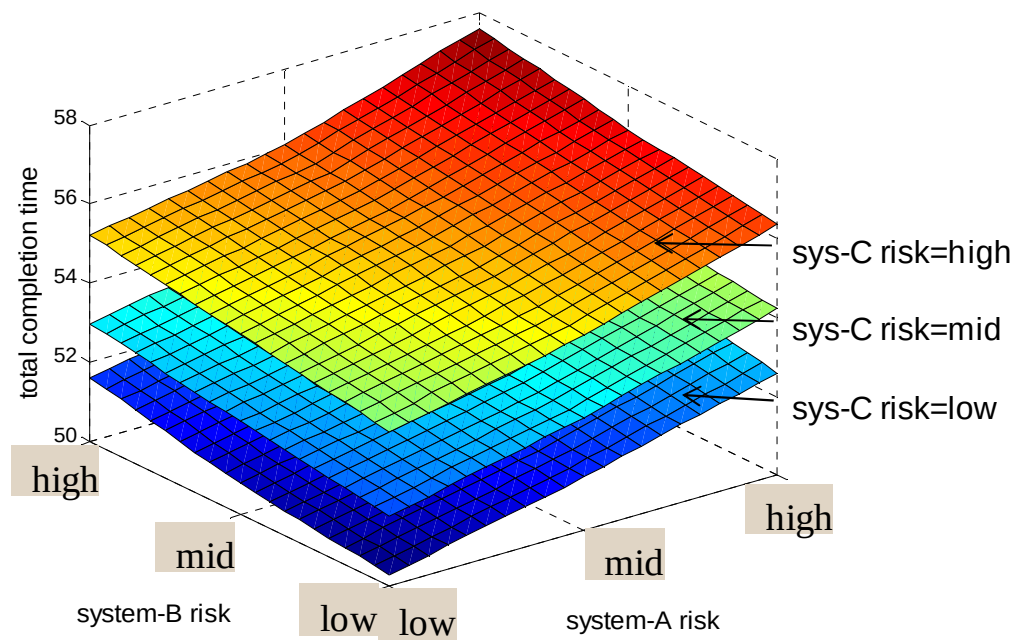
ddelaure@purdue.edu brian.sauser@stevens.edu

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 and observations
  - Time to complete correlates with SoS risk Metric
  - Can identify critical system and risk combination



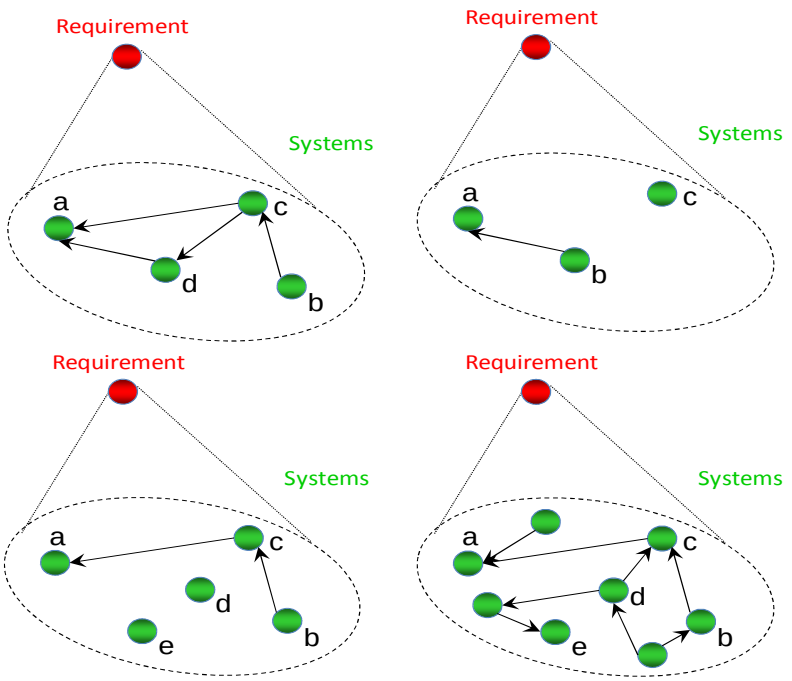


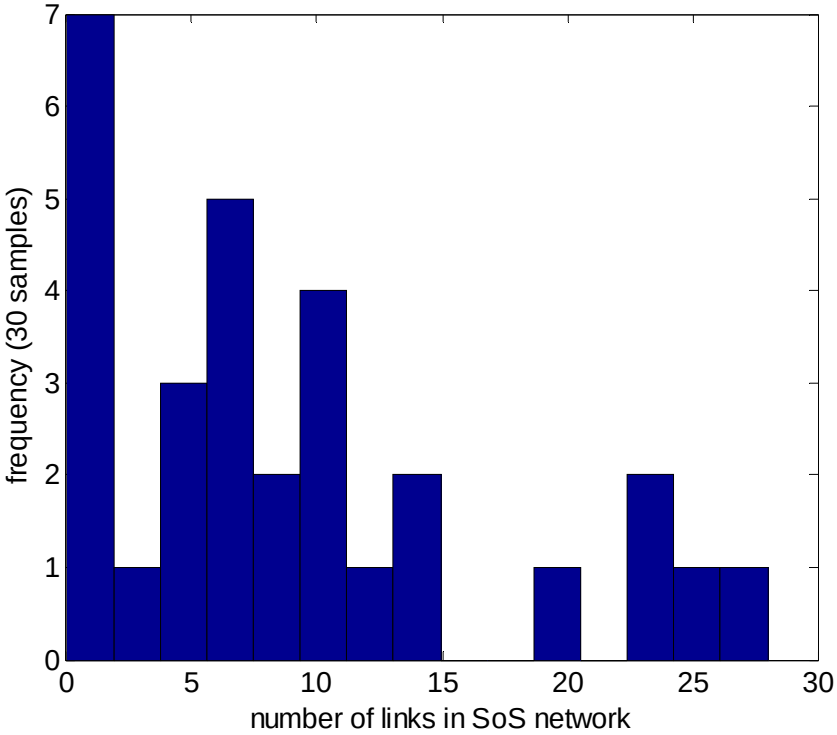
ddelaure@purdue.edu

brian.sauser@stevens.edu

Next Example: 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





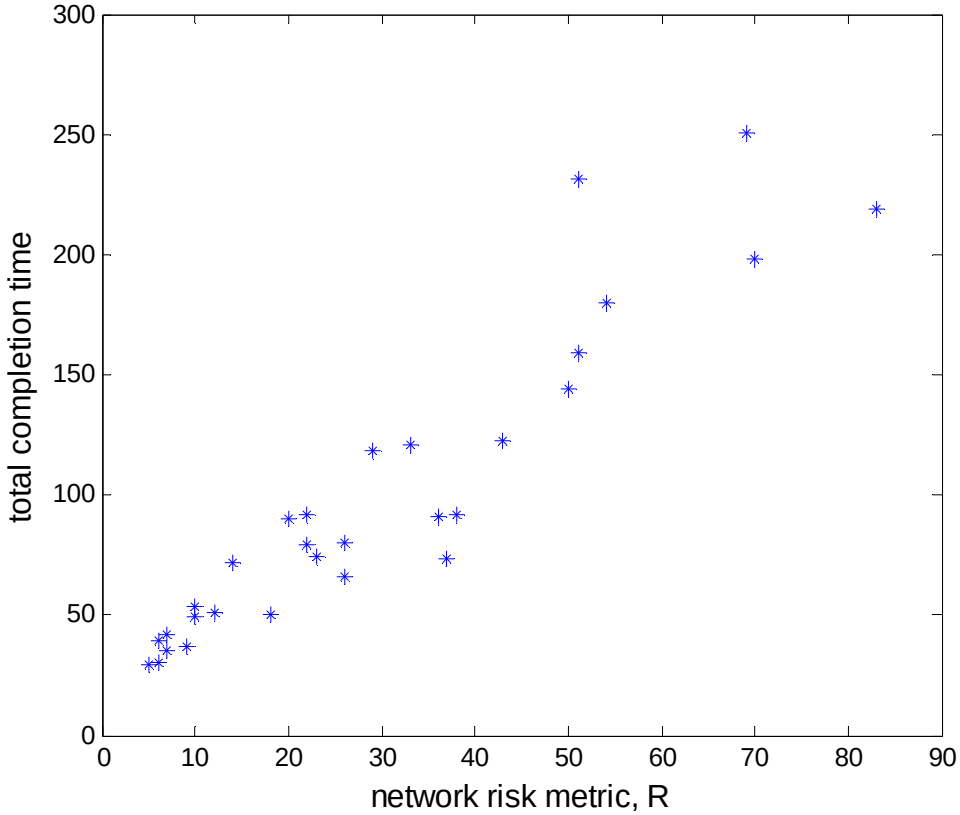
ddelaure@purdue.edu

brian.sauser@stevens.edu

Exploratory Model Experiments

- Set-up
  - Randomly generate a risk-level for each system in each SoS network
  - Run Monte Carlo simulation of Exploratory Model (500 samples) for each SoS network

- 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. network cascading effects)



ddelaure@purdue.edu brian.sauser@stevens.edu

Current Work- Adding a Capability Model (based on readiness-level)

- Purdue's notion of "System Readiness Level" for acquisition
  - Describes the developmental completion-level of a system (which is part of a program or SoS) in its ability to provide a certain capability
  - Presented in values between 0 and 1
    - Value of 0 means that system must be designed from scratch
    - Value of 1 means that system is fully developed (i.e., a well-matched legacy sys)
- Metric utilization
  - Add as additional nodal parameter in CEM
  - During simulation, use to:
    - indicate the initial readiness level of a system
    - track development history of capability for a system until completion

Sauser's System Readiness Level

- TRL – Technology Readiness Level
  - Metric that quantifies the level of maturity of a technology
  - Used by DoD to asses the maturity of a program's technology before system development begins
- IRL – Integration Readiness Level
  - Metric that quantifies the level of maturity of integration of technologies with each other
- SRL = fcn (TRL, IRL) = System Readiness Level
  - Indicates maturity level of the components of a system and integration of the entire system
  - Combines TRL and IRL into a single metric to describe the maturity of a technology as well as its integration with other technologies

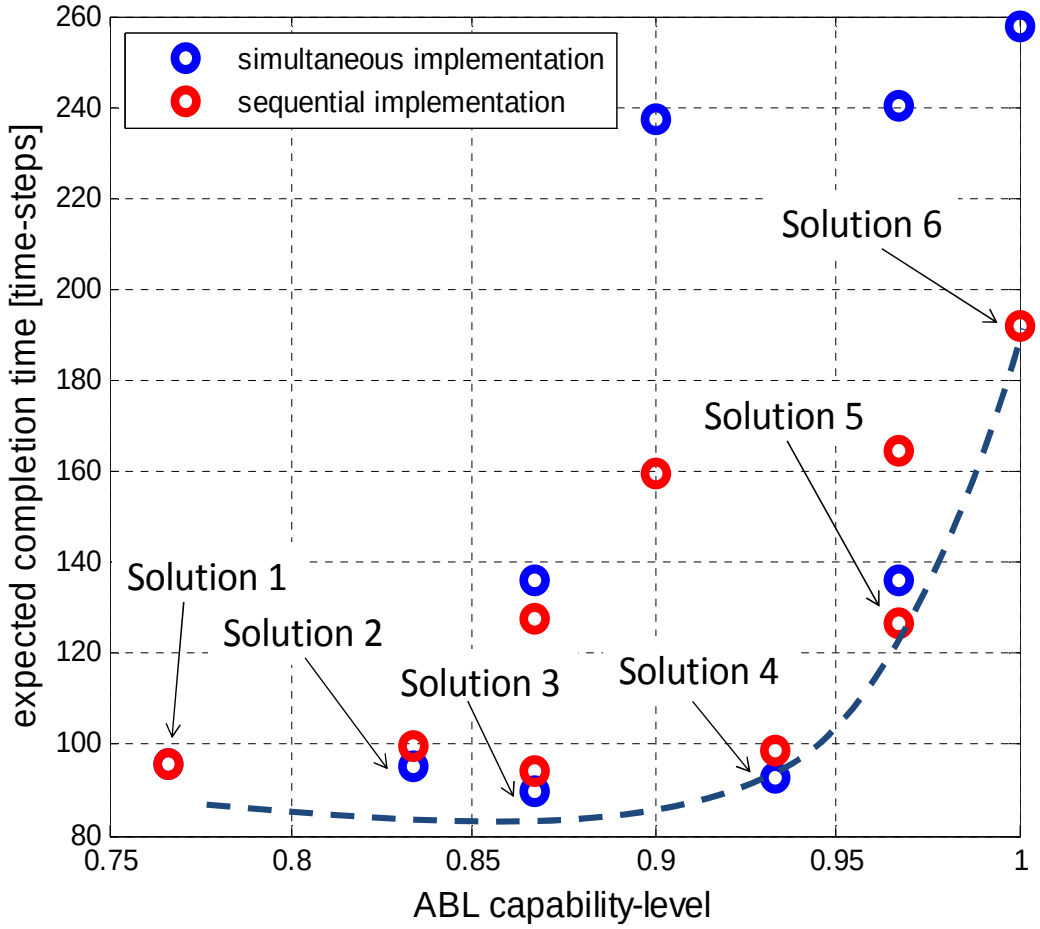
Close to convergence …..?

- Dr. Sauser's SRL describes maturity level <u>before</u> development of a program begins.
- Purdue's Computational Exploratory Model (CEM) needs readiness described for system development <u>during</u> program execution.
- The two metrics are similar and aim to convey the same type of information to decision-makers
  - Purdue's readiness notion is abstract, but with specific purpose
  - Sauser's SRL provides greater detail in readiness estimate
- <u>Our thinking</u>: SRL-Sauser could be used to determine readiness in Purdue model and increase the "fidelity" level of the CEM

ddelaure@purdue.edu brian.sauser@stevens.edu

Present Work…Notional Example of Balancing Capability Potential and Risk Among Alternatives

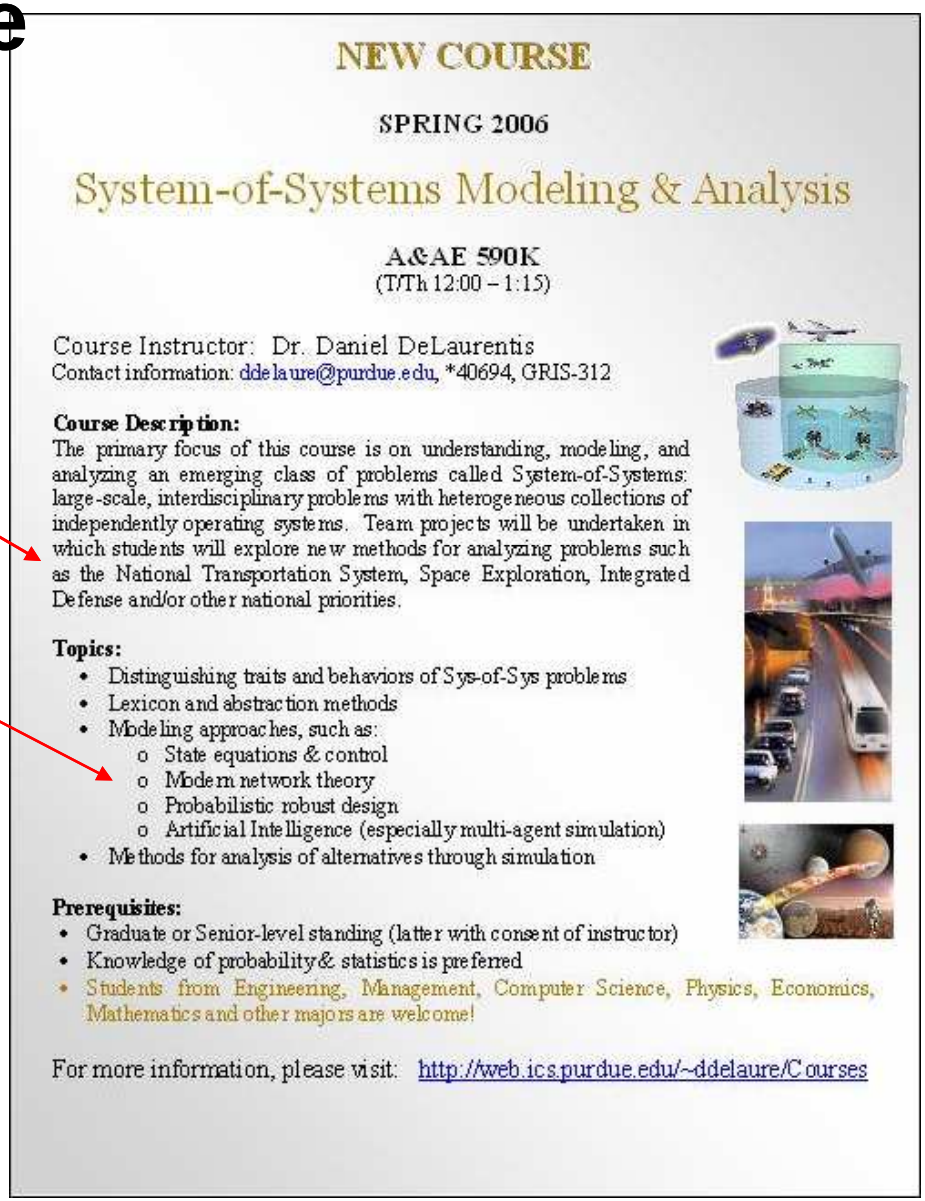
- We have added rudimentary capability estimation to the CEM.
- This makes the model more "effective" as a SoS analysis tool.
- The example shown here examines a Pareto frontier for alternate configurations of a Airborne Laser Platform used in missile defense applications.



Shameless Advertisement: The Purdue SoS Course

- Graduate (MS) level offering
- Application project emphasis across domains
- Methodological emphasis is on understanding dynamic system interactions and problem definition, and then mathematical modeling

Sp06 Semester = 27 Students
Sp07 Semester = 27 Students
Sp08 = 32 Students (10 Distance)
Sp09 = 30 Students (11 Distance)
Sp10 = 47 Students (17 Distance)



NEW COURSE

SPRING 2006

System-of-Systems Modeling & Analysis

A&AE 590K
(T/Th 12:00 – 1:15)

Course Instructor: Dr. Daniel DeLaurentis
Contact information: ddelaure@purdue.edu, *40694, GRIS-312

Course Description:
The primary focus of this course is on understanding, modeling, and analyzing an emerging class of problems called System-of-Systems: large-scale, interdisciplinary problems with heterogeneous collections of independently operating systems. Team projects will be undertaken in which students will explore new methods for analyzing problems such as the National Transportation System, Space Exploration, Integrated Defense and/or other national priorities.

Topics:
- Distinguishing traits and behaviors of Sys-of-Sys problems
- Lexicon and abstraction methods
- Modeling approaches, such as:
  - State equations & control
  - Modern network theory
  - Probabilistic robust design
  - Artificial Intelligence (especially multi-agent simulation)
- Methods for analysis of alternatives through simulation

Prerequisites:
- Graduate or Senior-level standing (latter with consent of instructor)
- Knowledge of probability & statistics is preferred
- Students from Engineering, Management, Computer Science, Physics, Economics, Mathematics and other majors are welcome!

For more information, please visit: http://web.ics.purdue.edu/~ddelaure/Courses

Thank You

ddelaure@purdue.edu brian.sauser@stevens.edu

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

ddelaure@purdue.edu brian.sauser@stevens.edu