Purdue University
School of Aeronautics and Astronautics

# Assessing the Impact of Development Disruptions in Interdependent Systems

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**Synopsis of ongoing work sponsored by the**
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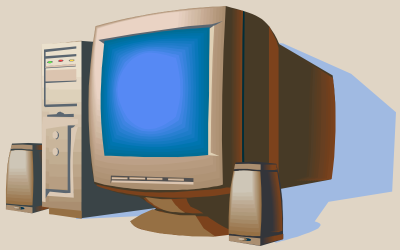
# Research Objectives

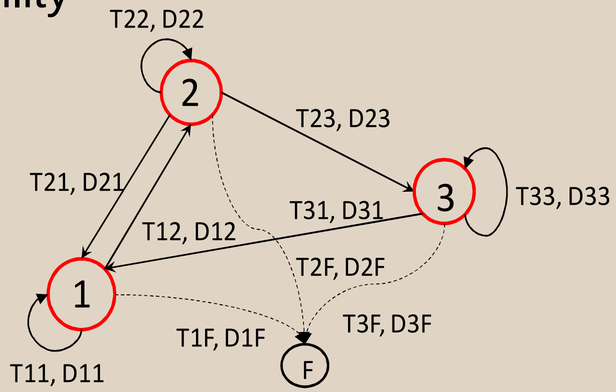
- *Develop M&S capability, supporting especially pre-acquisition program initiation, to answer …*
- How do system-specific characteristics AND interdependency features impact the development of systems of systems capability?
- In particular, focus on dynamic interactions?
  - How do disruptions propagate in complex networks of interdependent systems?
  - How can we quantify the cascading consequences of unexpected disruptions?
  - Can computable metrics be developed to AoA and solution analysis?
- Impact: Answers to these questions can increase the probability of success in systems (and sys-of-sys) capabilities development

# Methods of Approach

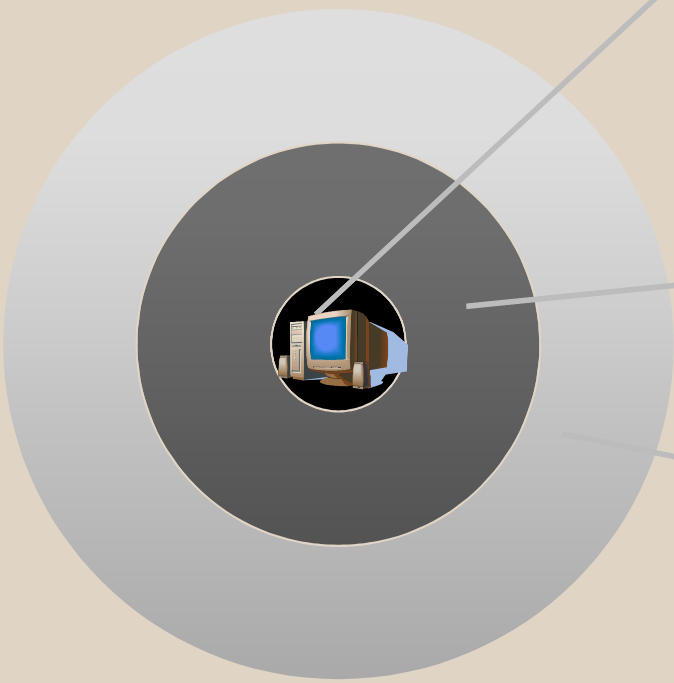
- Simulation Approach
  - Developing Computational Exploratory Model (CEM)
  - Discrete-event, stochastic simulation based on steps in DoD SoS SE Guide
  - Capture propagation of disruptions, not full scale simulation of program development
  - Output: Total time to complete development of capability



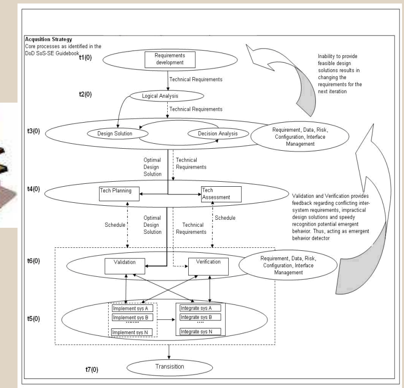
- Analytical Approach
  - Initially looking at probability and network theory
  - Starting to examine Petri Nets, circuit analogies
  - Desire- A more fundamental foundation for delay propagation for arbitrary SoS network configurations)



# CEM Development



Year 1



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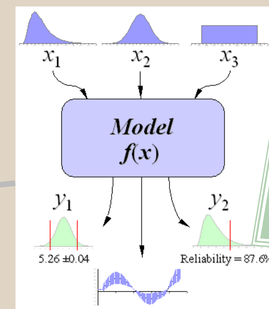
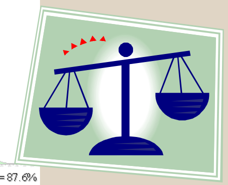
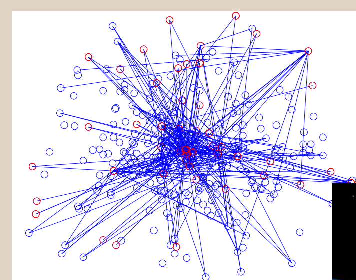
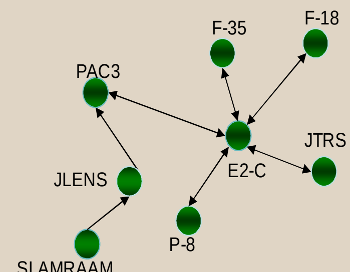


Current research

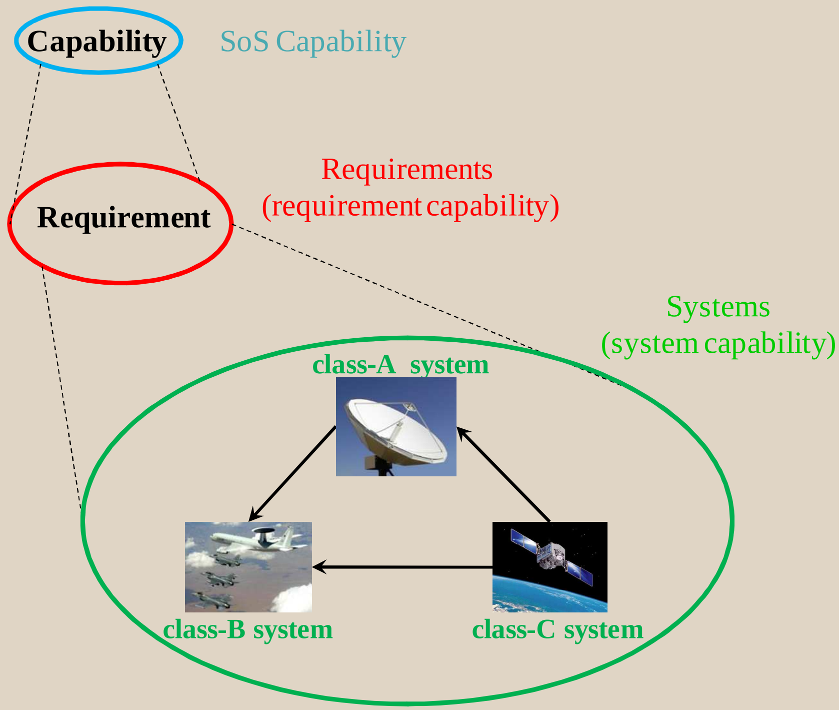





# Context- The CEM Simulation

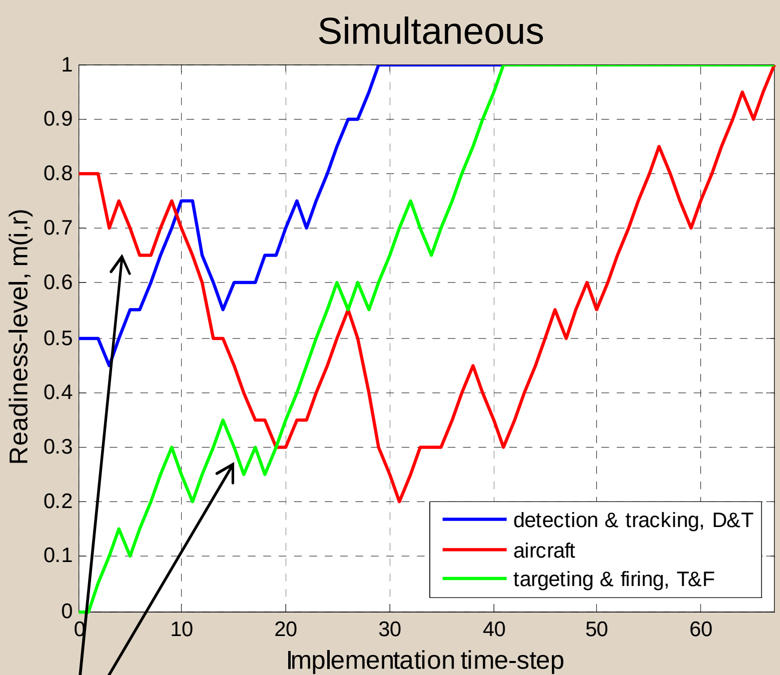
$$R_{sys}(i,r) = \alpha_i \left(1 - m(i,r)^{\beta_i}\right)$$

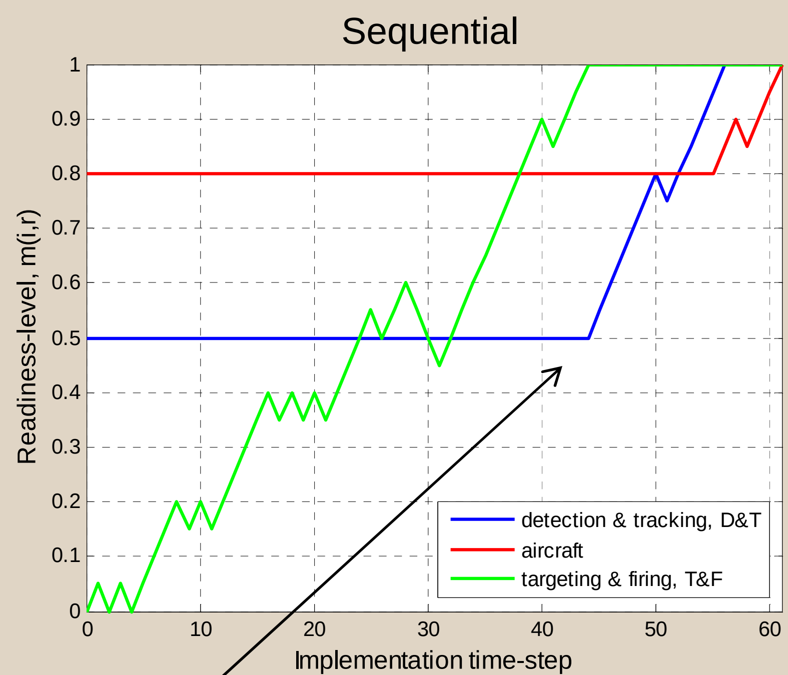
- Incremental increase in completion level (and readiness) of each system
  - Input parameters describe development time cycles
- Models disruptions at each phase
  - Input params describe risk profile
  - System risk ($R_{sys}$) as a function of system readiness-level ($m$)
    - Similar to TRL metric and SRL metric proposed by Sauser et al.
- Total time to complete as a function of system risk and interdependence topology
  - Disruptions propagate to dependent systems
  - Cascading effects of disruptions captured



# Example Simulation

- Assume all constituent systems have same probability of disruptions and all interdependencies have same strength
- Consider sequential and simultaneous development



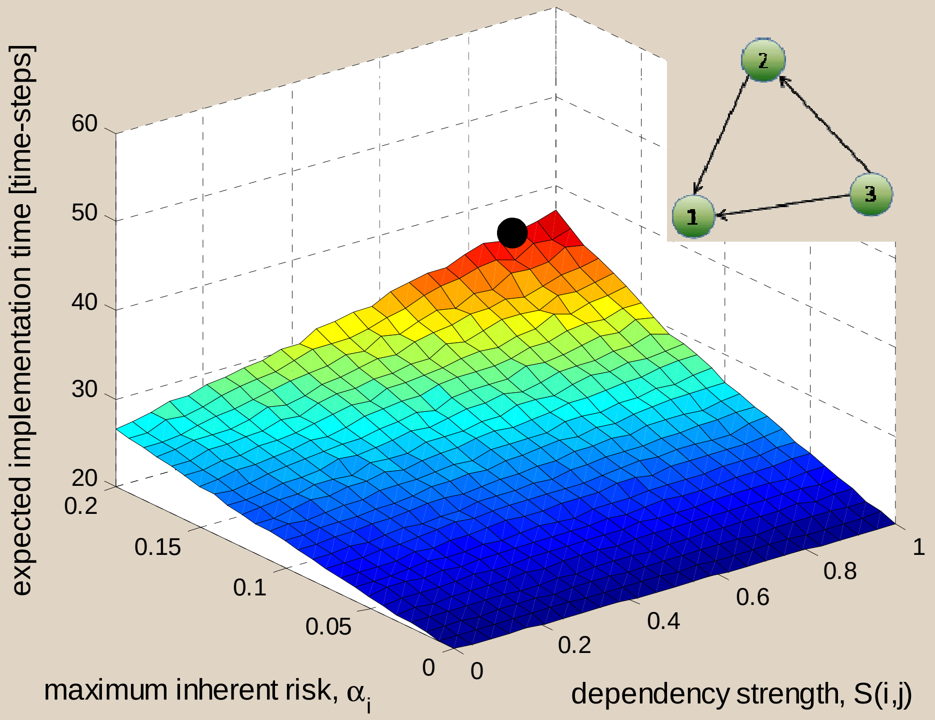



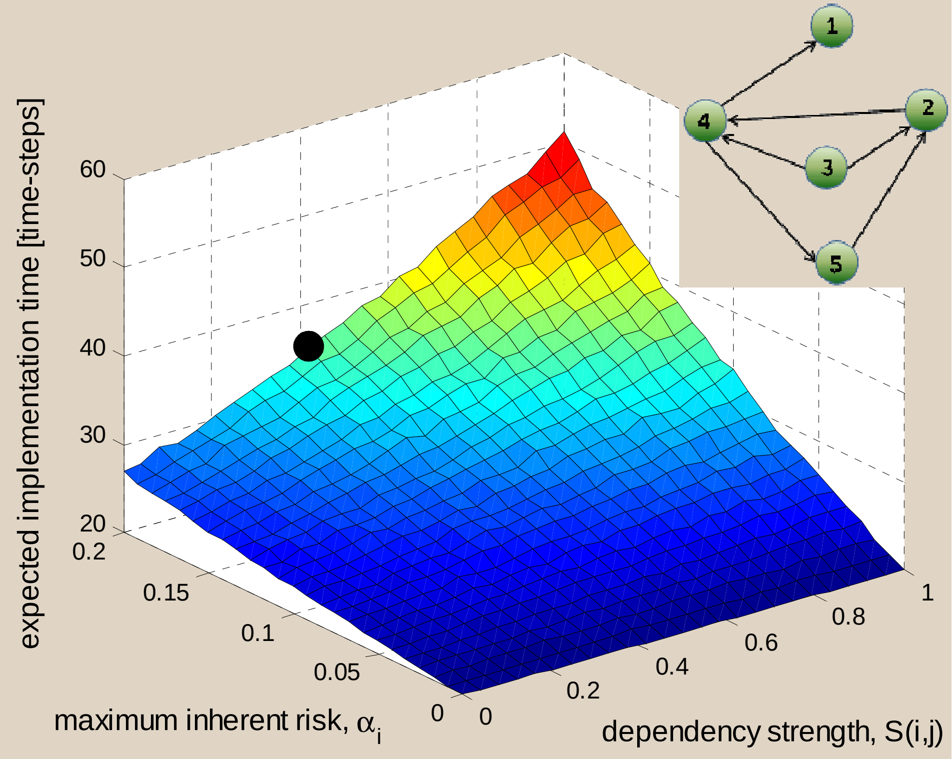

Disruptions due to inherent probability of disruptions AND disruptions from dependent systems

Development of D&T begins when T&F complete

# Example CEM result- Comparison of Alternatives

- What effect does the number of systems and strength/topology of interdependencies have on development time?
  – Evaluate multiple alternatives for capability…



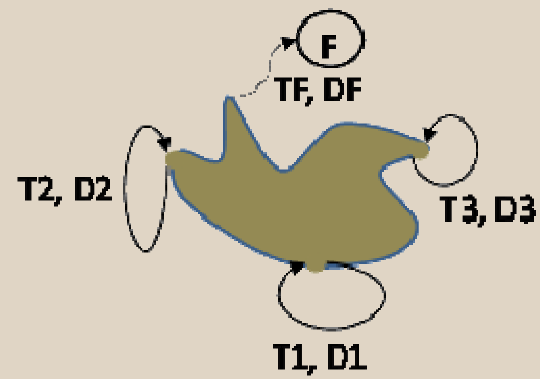



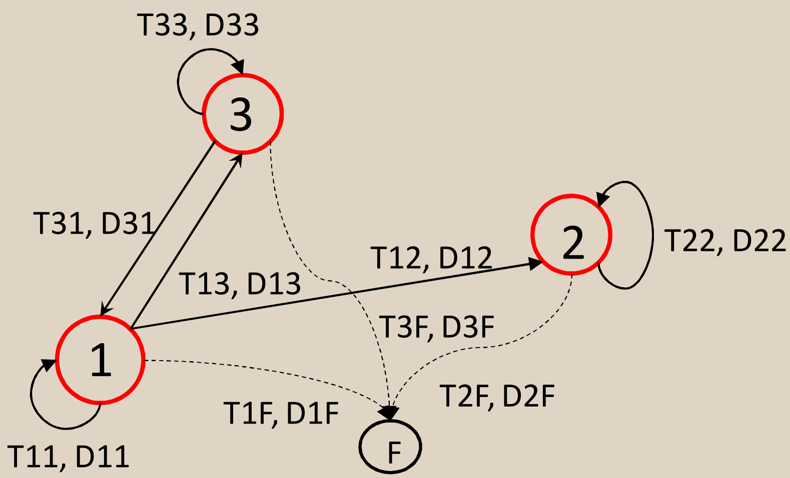
# Analytical Approach for Delay Propagation

- Capture and quantify the cascading effects of risk
  - Delay propagation as a metric for comparing the performance of SoS networks
- Enable the design of networks that reduce (minimize) impact of disruptions (e.g. development delay)
  - CEM is based on simulation
    - Cumbersome in the design (or analysis of alternatives) stage
  - Need analytical approach to
    - Identify network characteristics that increase probability of project success
    - Design networks that exploit these characteristics
    - Use network metrics to measure performance of candidate networks

# Approach

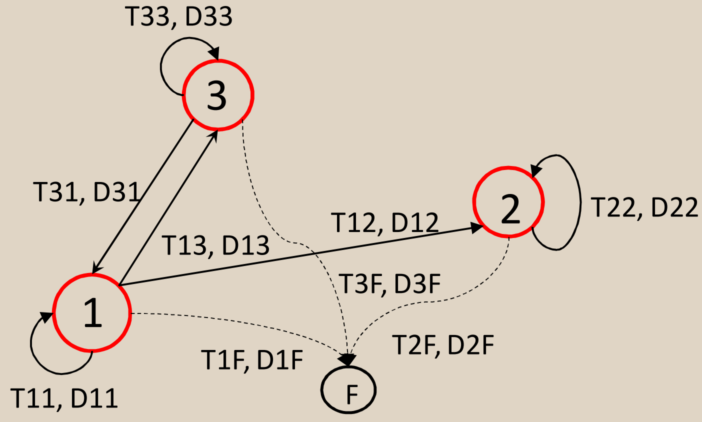
- Consider the "lost-miner" problem
  - A miner is lost in a mine and makes a series of choices to reach freedom
  - He chooses from a series of tunnels that can lead back to the mine or to freedom
  - Estimate the expected time that it takes the miner to reach freedom
- Analogy to delay propagation in a family of systems
  - A delay propagates among interdependent systems until it exits the system
  - Estimate the expected total delay



# Network Description

- Consider an example SoS with three constituent systems that must interact during development to achieve a target capability
- During development a disruption can hit any system $S(i)$ in the network with probability $P(S_i)$
- A delay
  - Is caused in the affected system $i$ with probability $P(T_{ii})$
  - Is propagated to dependent system $j$ with probability $P(T_{ij})$
    - This partly defines the strength of dependency between system $i$ and $j$
  - Causes additional delay of $D_{ij}$ time units to interdependent system
    - This partly defines the strength of dependency between system $i$ and $j$
  - Is arrested when it reaches node F (freedom)



# Expected Delay

- The expected total delay is analogous to the expected time to freedom in the "lost miner" problem
  - i.e. the expected time to reach "freedom"

$$E(F) = \sum_i E(F \mid S_i) P(S_i)$$

$$E(F \mid S_i) = E(F_i) = \sum_i E(F_j \mid T_{ij}) P(T_{ij})$$

Expected total delay if disruption hits system Si

Expected delay if disruption propagates to j from systems on which it depends

# Expected Delay

- Each time a disruption hits a given system a delay of Dij time units is experienced
  - These are aggregated to compute the total expected delay

$$E(F_i) = \sum_i E(F_j + D_{ij})P(T_{ij}) \qquad E(F_i) = \sum_i \left[E(F_j)P(T_{ij})\right] + D_{ij}P(T_{ij})$$

- Solution to this problem is a linear set of equations of the following form

$$\mu = A\mu + b \qquad A = \begin{bmatrix} Q & R \\ 0 & 1 \end{bmatrix}$$

- The transition probability matrix Q is Markovian and the system of equations has positive solution

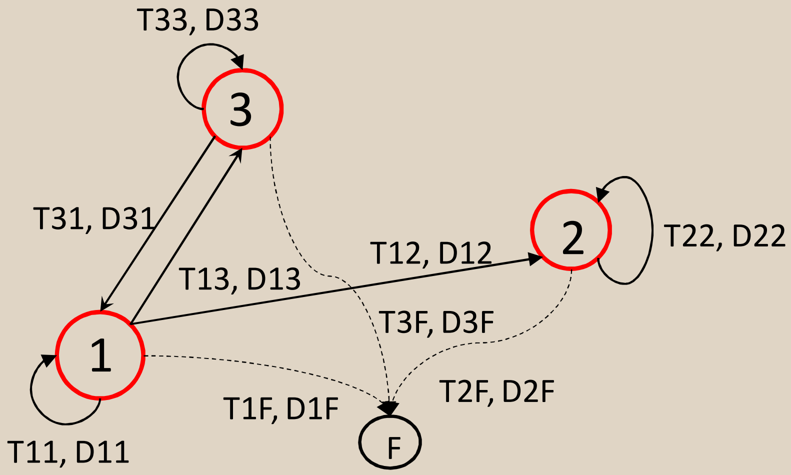
# Candidate Network Metric

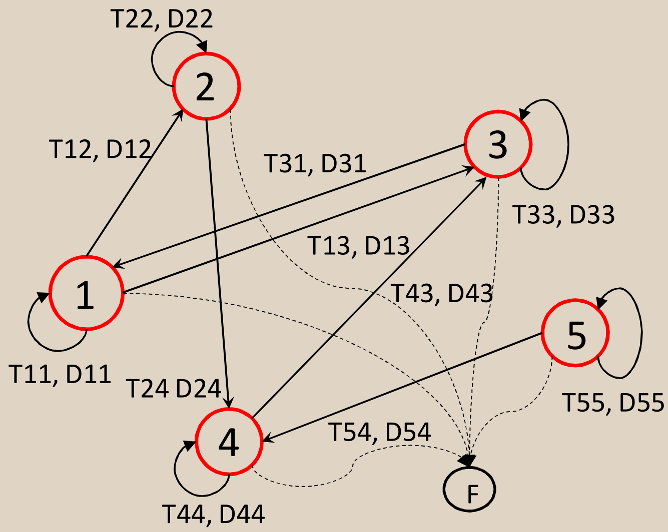
- Goal is to estimate the performance of the development of a network of systems
- Network-level metric that captures network characteristics
  - Number of nodes / links and importance of links
  - Bring these to the network level so that a network is described by a single value / metric
    - Enables comparison of networks

$$M = \sum_{i} \sum_{j} Q_{ij} b_i P(S_i)$$

# Network Comparison Example

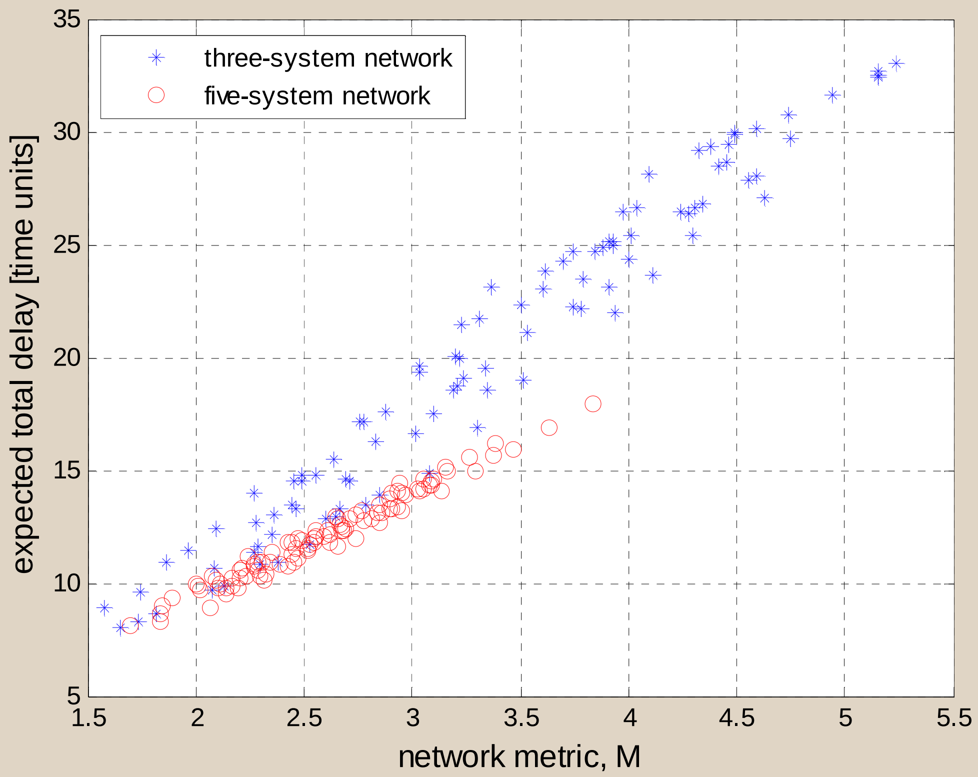
- Want to compare the performance of different networks
  - Current network analysis mostly focused on inter-network characteristics (e.g. critical node, critical links / paths, etc.)
- Ultimately, want to design networks that optimize their ability to arrest the propagation of delays



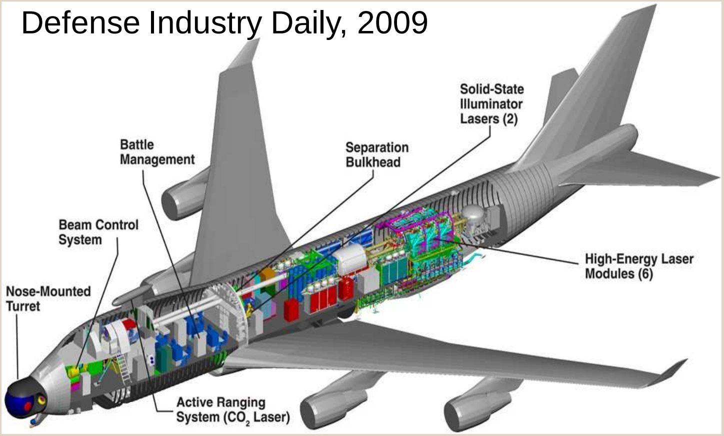
# Network Comparison Results

- Impact of disruptions is uniformly random between 1 and 10 time units (probability of disruptions is fixed)
  - Hence, the probability of disruption and disruption propagation is fixed




- Three-system network performs worse than five-system network
- In this example, the probability of arresting a disruption of the systems in the five-system network is higher than that of systems in the three-system network

# CEM Proof-of-Concept Application

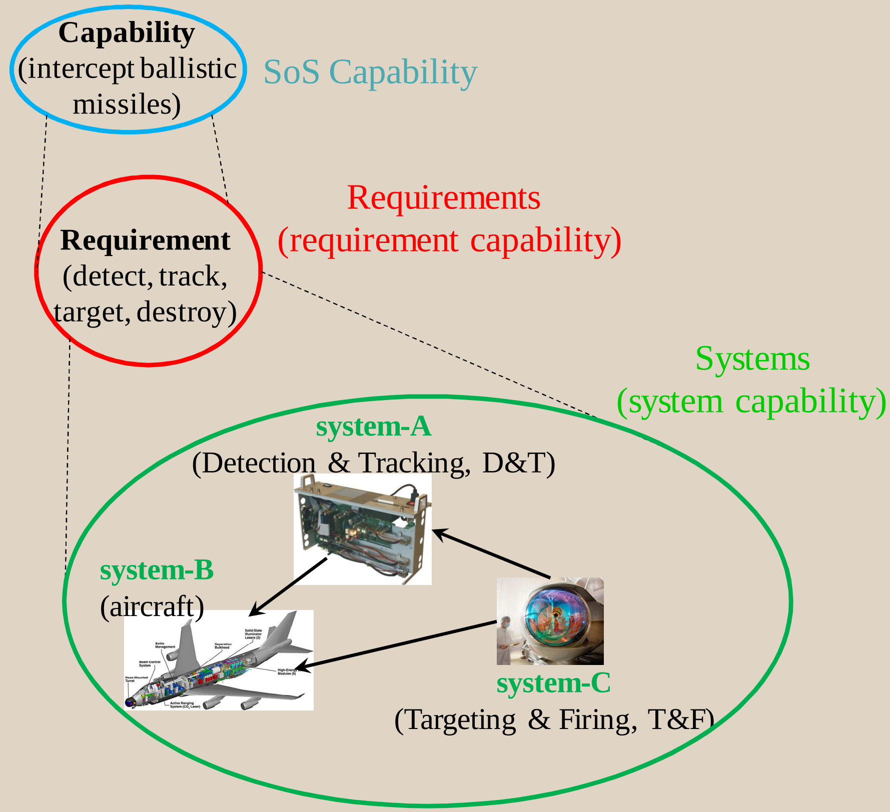


Defense Industry Daily, 2009

- Airborne Laser (ABL) Program
  - Theater defensive weapon concept
- Comprised of multiple constituent systems
  - Aerial platform – modified Boeing 747-400
  - Track Illuminator – Infrared Search and Track (IRST) sensors
  - Beacon Illuminator – solid state laser to adjust for atmospheric disruptions
  - Chemical Oxygen Iodine Laser (COIL) beam – to disable target

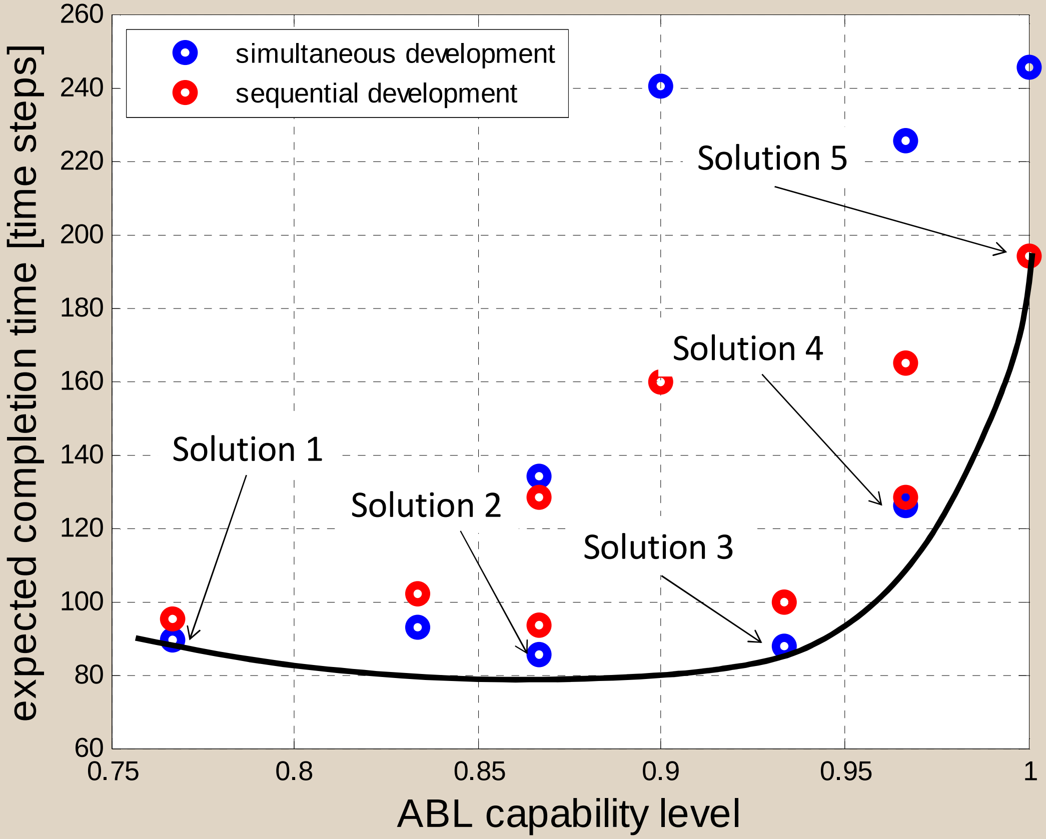
# Levels of Abstraction

- Group requirements into one
  - Detect, track, target, and destroy
- Group sub-systems into three constituent systems
  - Aircraft system
  - Detection and tracking (D&T) system
  - Targeting and firing (T&F) system
- Result is a hierarchical network of constituent functions



# Pareto Front: Capability vs. Development Time

- Quantify tradeoff between capability & development time (or delays)
  - Pareto Frontier
- Each solution represents a combination of constituent systems
  - A total of nine (9) combinations are possible here
- Higher capability requires more development
  - Potential capabilities of constituent systems arbitrarily chosen here
- CEM enables quantification of the impact of disruptions and their propagation in development network
  - Capture indirect(and cascading) impact of disruptions



# What could be done next …

- "Field Test" these approaches
  - Where does the approach break down?
  - Where is fidelity inappropriate (low or high)?
- Integrate more feature dimensions in network representation
  - cost and/or level of effort
  - Multi-dimensional Pareto surfaces (perf., cost, time)
  - Study the evolution of risk
    - Probability of disruption propagation changes as a function of time (or development stage / phase)
- Consider "branching-out" of disruptions that result in multiple disruptions that propagate in network

# Summary

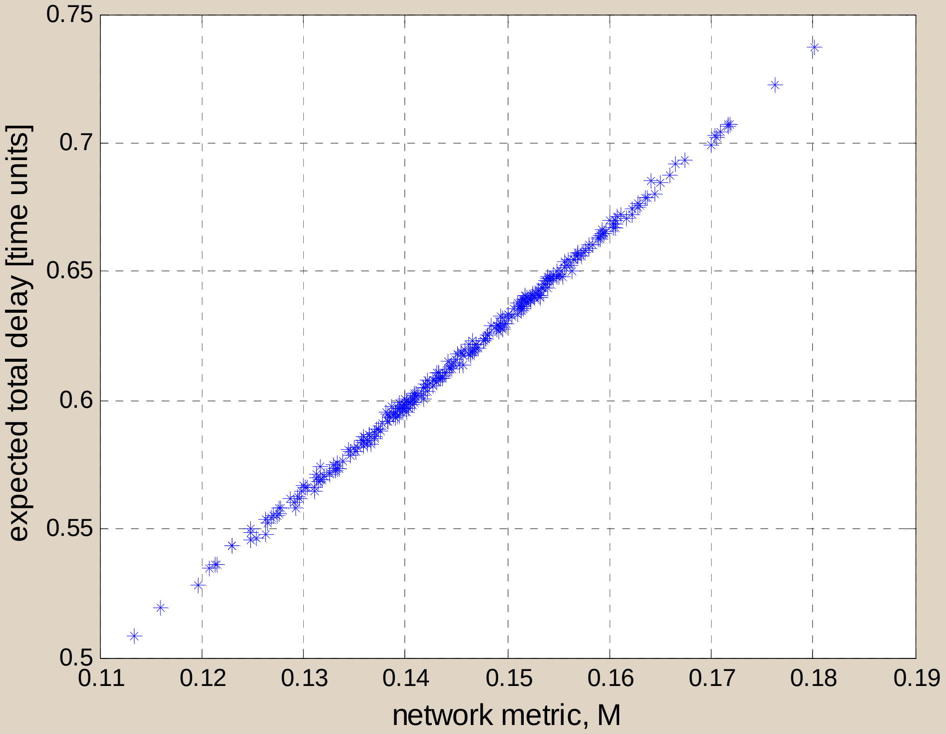
- Study development process of complex SoS via experimental and analytical approach
  - Exploratory model is intended to enable acquisition professionals and program engineers to learn about complexities, dynamics, and disruptions, identifying markers of failure and success
- Analytical approach for estimating expected development delays presented here
  - Goal is to provide meaningful metrics for analyzing development network
    - Enable comparison of development networks, not only performance / criticality of constituent systems
  - Understand cascading effects of risk (budget, schedule, technology, etc.)
  - Utilize insights and methodology to design development networks that reduce schedule and cost overruns

# Thank You

# Extra Slides

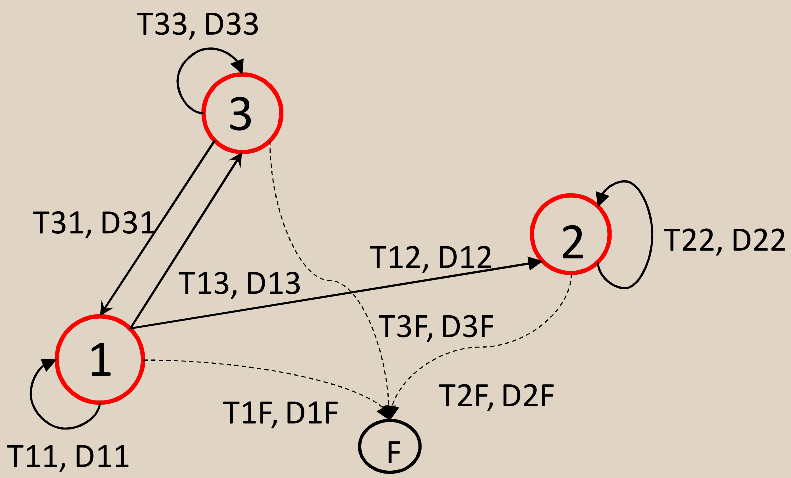
# Network Performance

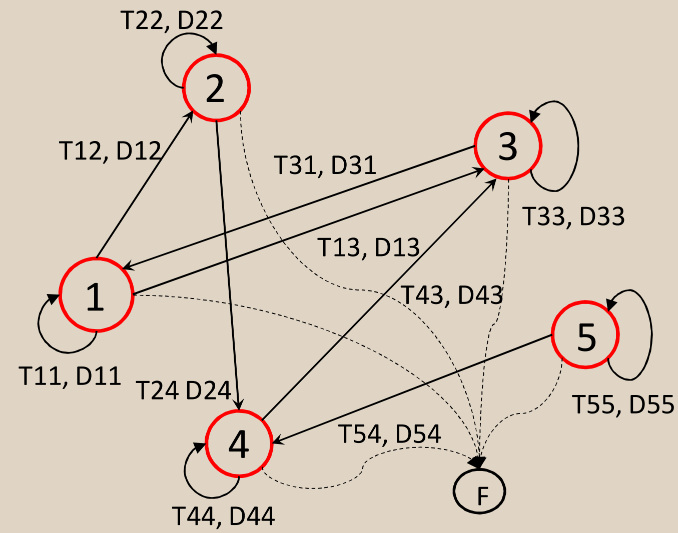
- Vary the number of nodes, links, and interdependency strengths of nodes
  - Uniformly random number of nodes and links
  - Uniformly random impact of disruptions




- Large number of systems, many interdependencies, and strong interdependencies result in worst delay propagation performance
  - As seen in previous chart, different combinations of these factors can still result in different performance
- Trends are expected and they confirm intuition

# Network Comparison Example




Probability of propagation, Q

Probability of arrest, R

[illegible] $=$ [illegible] $=$

$$\begin{bmatrix} 1/4 & 1/4 & 1/4 & 1/4 \\ 0 & 4/5 & 0 & 1/5 \\ 2/4 & 0 & 1/4 & 1/4 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

[illegible] $=$

$$\begin{bmatrix} 1/4 & 1/4 & 1/4 & 0 & 0 & 1/4 \\ 0 & 1/3 & 0 & 1/3 & 0 & 1/3 \\ 1/3 & 0 & 1/3 & 0 & 0 & 1/3 \\ 0 & 0 & 1/3 & 1/3 & 0 & 1/3 \\ 0 & 0 & 0 & 1/3 & 1/3 & 1/3 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$