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Capability and Development Time Trade-off Analysis in Systems-of-Systems

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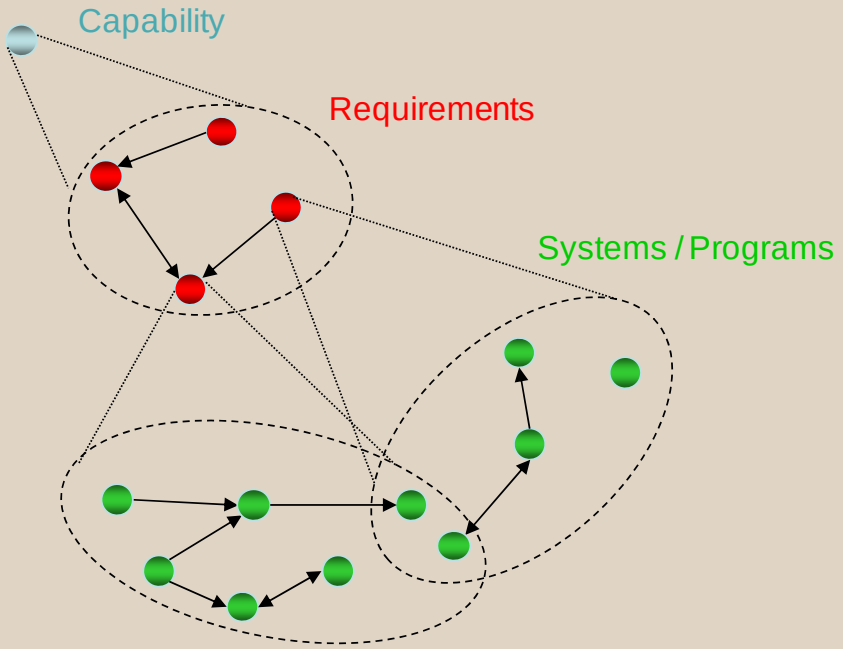
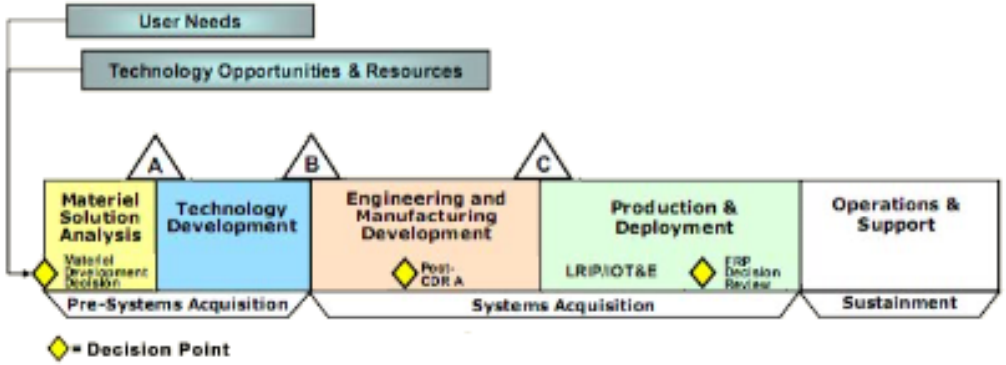
Sponsor: NPS Acquisition Research Program

Overview

- Development of SoS is complex
  - Numerous interdependencies
  - Changing over time
- SoS capability comprised of system capabilities
  - Interdependent system requirements
  - Legacy systems
- Goal: make the AoA smarter in pre-acquisition
  - Potential capability vs. expected development
- A high-level approach can aid in the early development stages and requirement definition and allocation



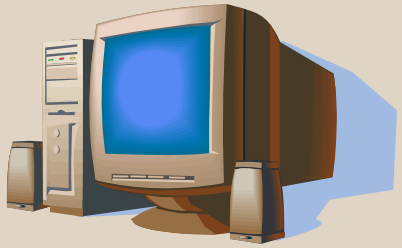


Research Questions

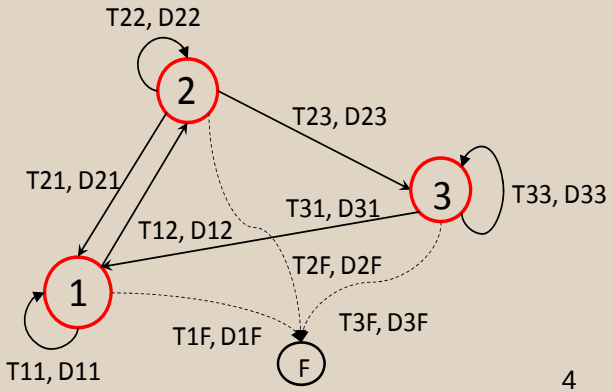
- Given a network of systems
  - How do system-specific (node) characteristics impact the successful development of SoS capability?
  - How do system interdependencies impact the development process?
    - How do disruptions propagate in complex networks of interdependent systems?
    - How can we quantify the cascading effects of development risk?
    - Focus of previous year research
- What is the tradeoff between SoS capability and expected development time?
  - Key tradeoff in analysis of alternatives (AoA)
  - Focus of this year's work

Methods of Approach

- Simulation Approach
  - Developing Computational Exploratory Model (CEM)
  - Discrete-event, stochastic simulation based on steps in DoD SoS SE Guide
  - First-order modeling of capability

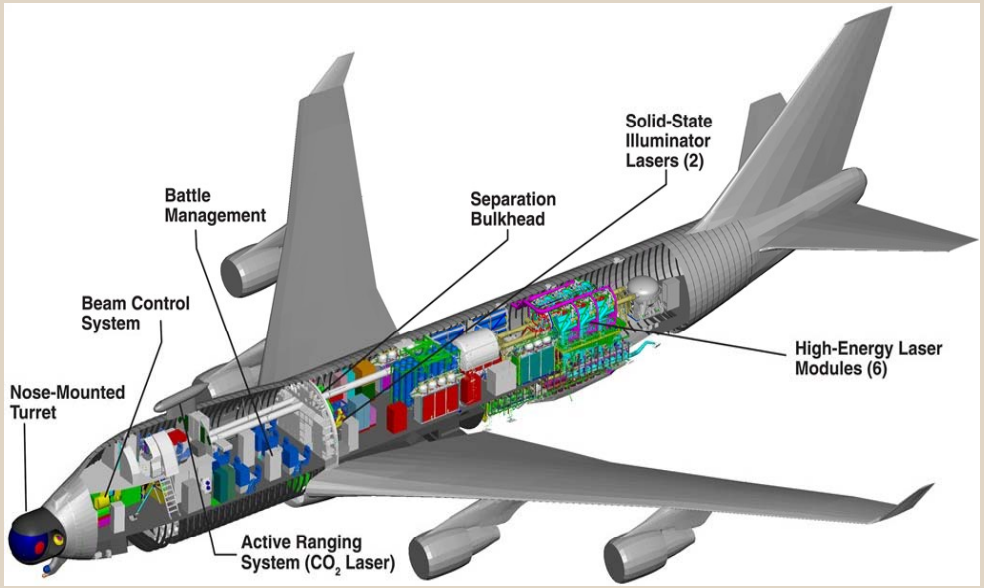


- Analytical Approach
  - Based on probability and network theory
  - Analysis of expected delay propagation for given SoS network configurations



Current Research Efforts

- Analysis of alternatives in the context of
  - Development time
  - Capability level
- First-order capability estimation model
- Capability / development time tradeoffs for alternative compositions of Airborne Laser system
  - Categories of components comprise the capability
  - Proof of concept application



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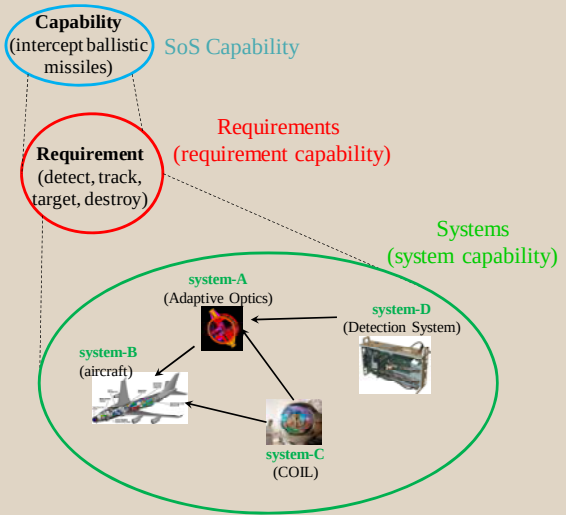
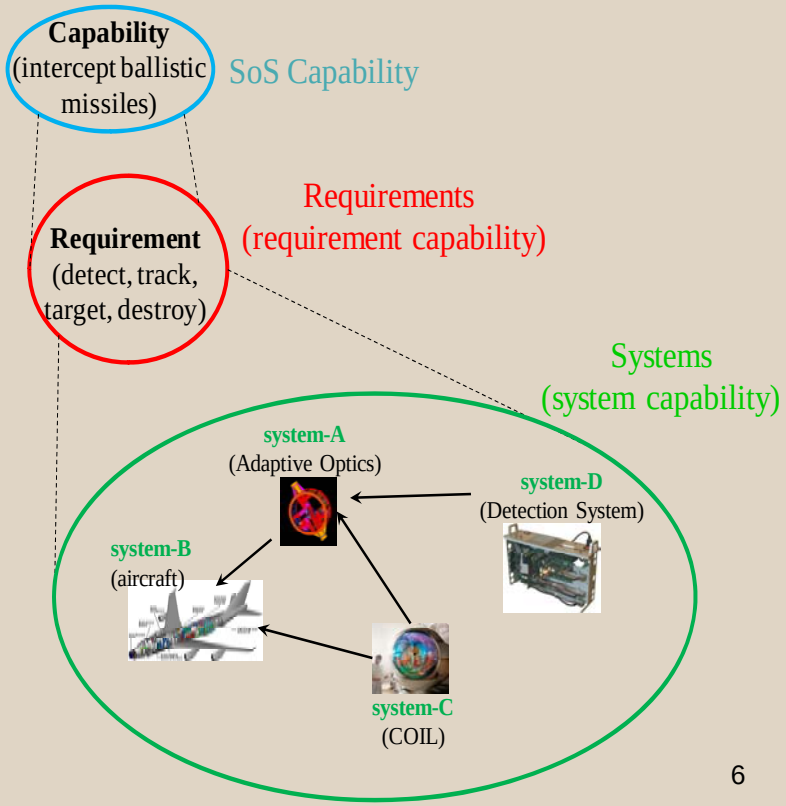


Development Model (CEM)

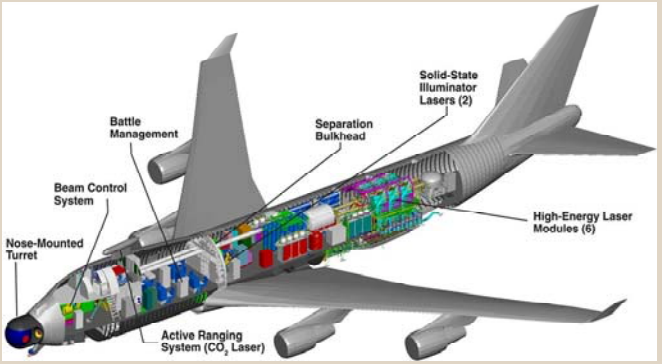
- Discrete-event, stochastic simulation
  - Disruption occurrence and propagation
- System risk (R_{sys}) as a function of system readiness-level (m)
  - Similar to TRL metric and SRL metric proposed by Sauser et al.
- Impact of disruptions a function of
  - Network topology and strength of system interdependencies

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



Capability Modeling

- Assume desired ABL capability to "disable threat from 600 km (slant range)"
  - Categories of systems and requirements create different capability levels
- Identify functions that comprise capability
- Identify systems that perform each function
- First-order quantification of capability
  - Aircraft system indirectly considered (host of other systems)



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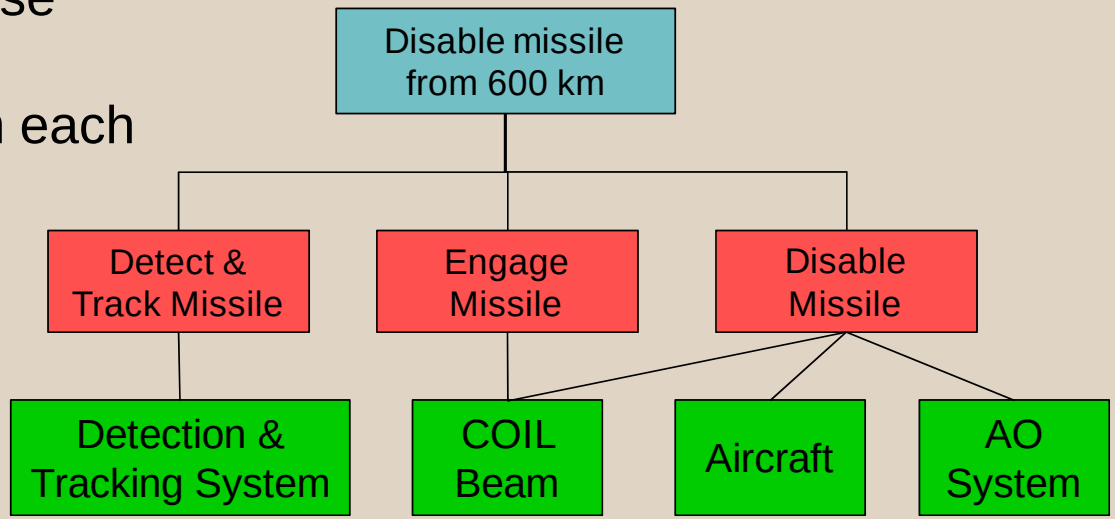
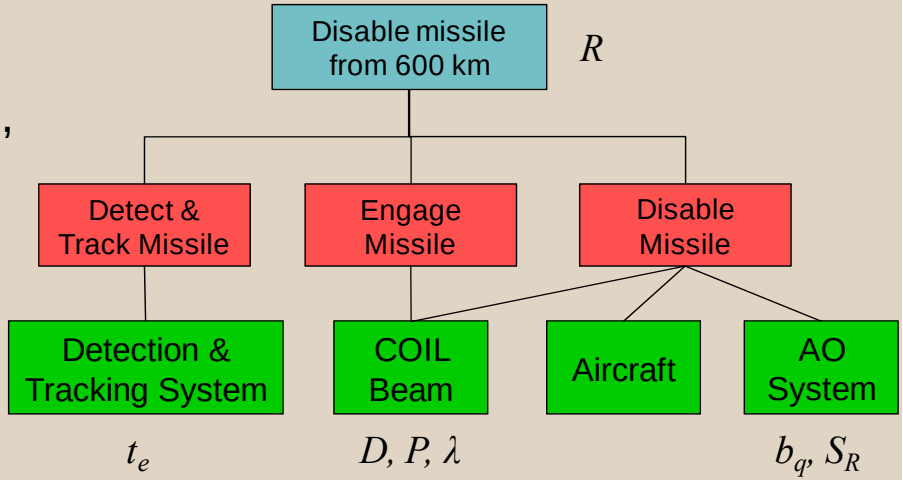


Capability Contributors

- Detection and tracking system
  - Detects threat and generates track to enable engagement
  - Capability contribution: detection time, T_d
    - Higher detection time reduces available dwell-time, t_e
- Adaptive Optics (AO) system
  - Accounts for atmospheric disturbances to deliver maximum laser power to target
  - Capability contribution: beam quality diffraction limited, b_q, that increases Strehl ratio, S_R
- COIL beam power
  - Laser power to disable a liquid fuel ICBM
  - 32 MJ/m^2 required (F_c)



- F_c: energy required to disable target
- D: laser beam diameter
- λ: laser beam wavelength
- R: slant range
- P: laser power
- t_e: dwell-time
- S_R: Strehl ratio

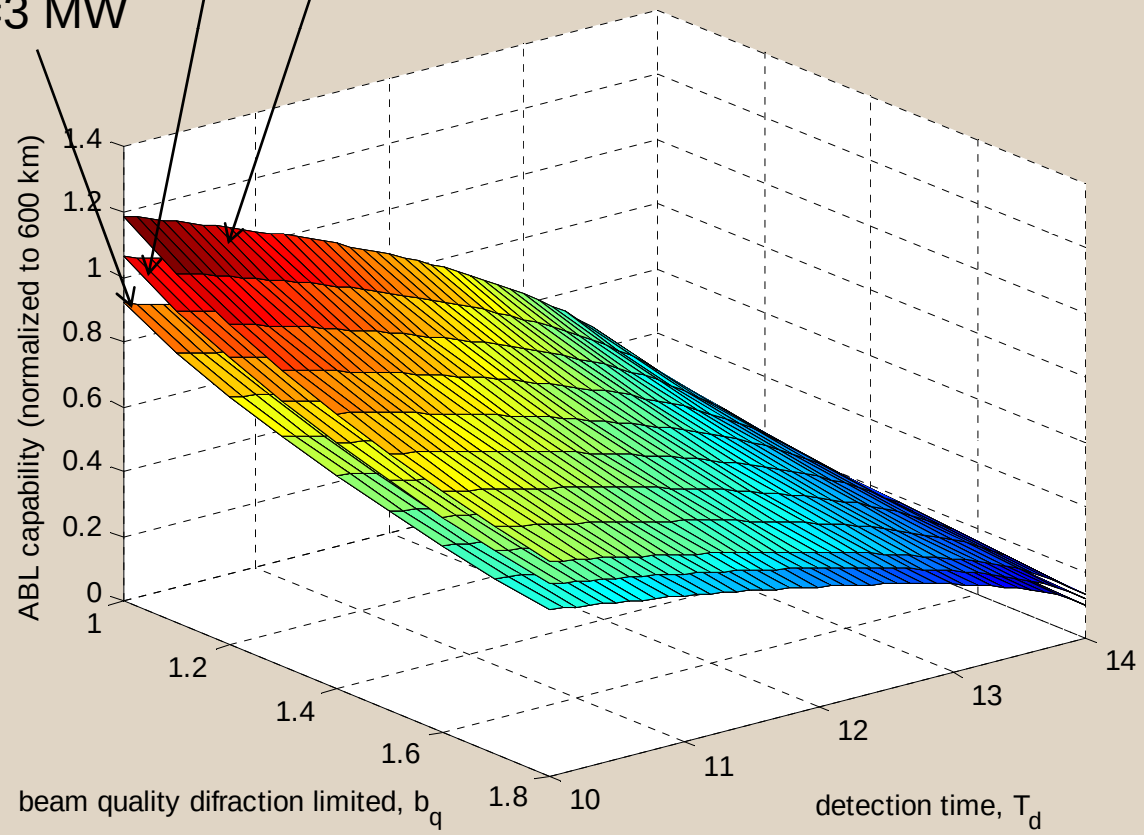
ABL Capability Space

P=5 MW

P=4 MW

P=3 MW

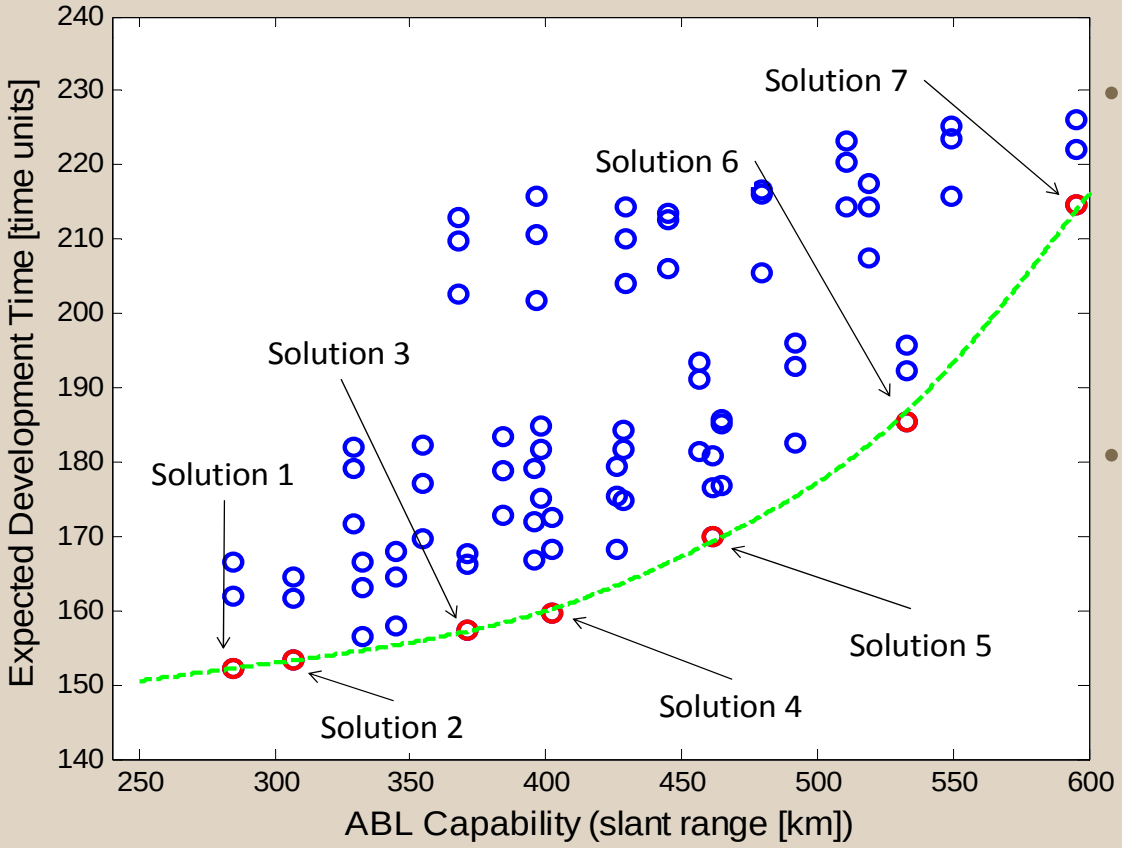
ABL capability = f(beam quality, laser power, available dwell-time)



System requirements;
Will drive development time

Analysis of Alternatives Results

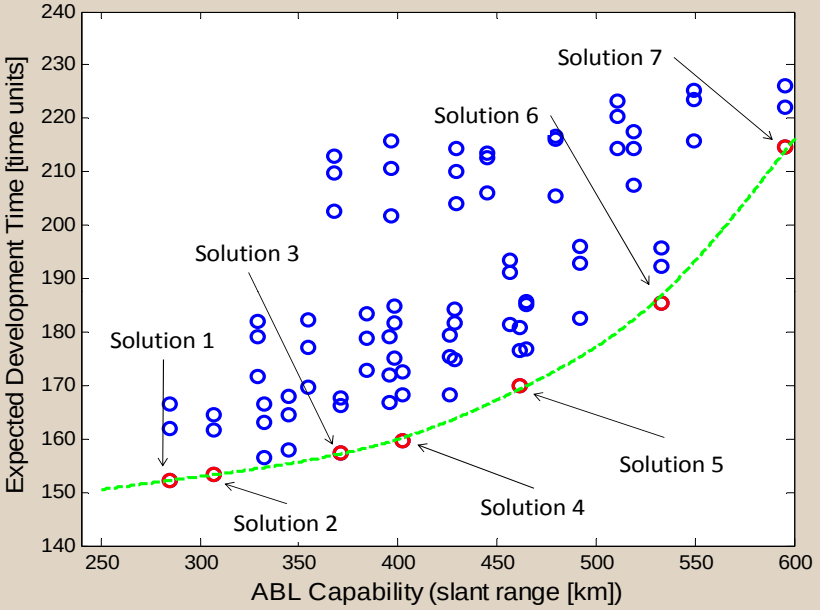
- 81 possible solutions
  - Three alternatives for each constituent system
- Non-dominated solutions result in a Pareto frontier



- Clear tradeoff between capability and expected development time
  - Higher capability requires higher development time (result of non-mature technology)
- Seven solutions identified here
  - Combination of new and existing systems (high and low capability)

Observations

- No single optimal solution
  - Tradeoff between capability and development time
- Non-dominated solutions are comprised of legacy and new systems
  - Development model captures higher order impact of interdependencies



Solution	D&T System	Aircraft System	COIL beam System	AO System	ABL Capability [slant range, km]	Expected Completion Time [time units]
1	STSS	new system	Alternative-1	Alternative-3	285	152
2	STSS	new system	Alternative-1	Alternative-2	307	153
3	UAV	new system	Alternative-1	Alternative-2	371	157
4	UAV	new system	Alternative-1	Alternative-1	402	160
5	new system	new system	Alternative-1	Alternative-1	461	170
6	new system	new system	Alternative-2	Alternative-1	533	185
7	new system	new system	Alternative-3	Alternative-1	596	215

Conclusions

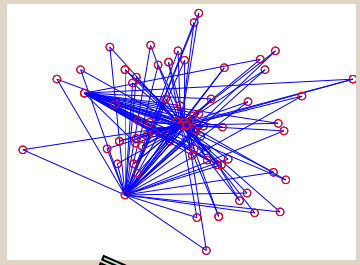
- CEM and capability modeling enables analysis of alternatives early in development process
  - CEM captures cascading effect of developmental disruptions
    - Enabling enhanced selection of constituent systems and requirements
- Analytical tools early in acquisition and development phase enhance decision-making
  - Build intuition and guide acquisition efforts

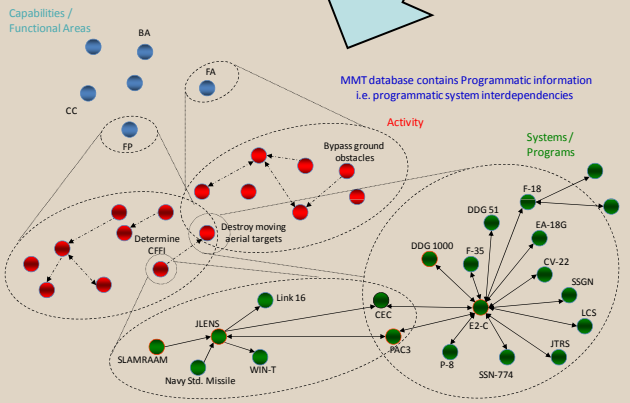
Future Work

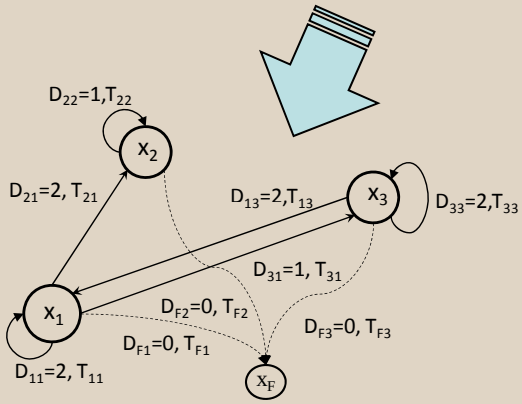
- Analytical model for measuring system development performance
  - Indicators of good network structure
  - Identification of features that can lead to problems or success
- Requirement evolution is at root of most development issues
  - Want more / better capability
  - Get schedule and cost overruns
- Continue development of a capability module for CEM
  - Analysis of impact of requirement dependencies on both development and capability
  - Can we “design” a controller for requirement evolution?
    - Ability to measure impact of requirement evolution on system (and SoS) development

Markov Perspective on Network Interdependencies

- Aggregation of system-specific disruptions to generate network-level performance metric
  - Focus on cascading effect of disruptions
  - Identify network characteristics that increase probability of project success
- Proposed approach gives ability to
  - Rank constituent systems based on criticality/vulnerability during development
  - A network-level metric enables comparison of networks (that can vary with time)





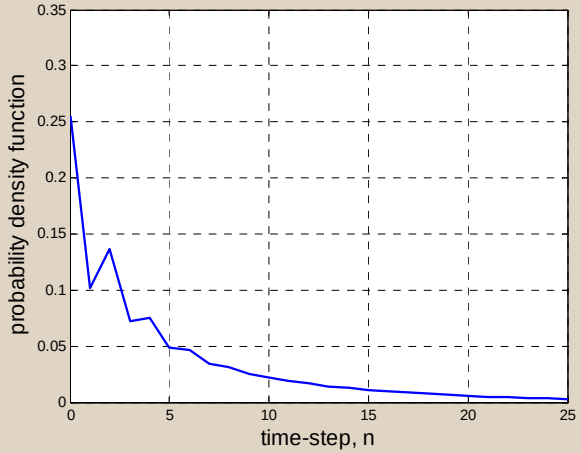


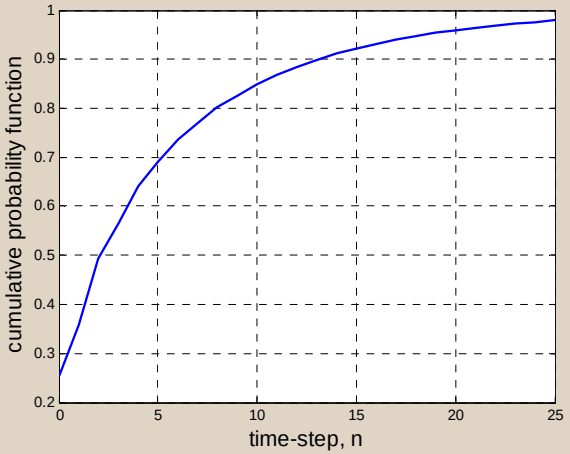
Network-Level Metric

- Compute expected accumulated delay
  - Measure of network performance
    - Measure of system criticality / vulnerability when contributions from each system are ranked
- Compute variation about the expectation
  - Measure of the risk associated with the estimated network performance

$$\zeta(n+1) = A\zeta(n) \quad subject\ to\ \ \zeta(0) = b$$
$$F(n \mid x_j(0)) = c\zeta(n)$$

$$E\left[F(n \mid x_j(0))\right] = \sum_{n=1}^{\infty} ncA^n b$$





Thank You

Back-Up Slides

Contributors to Capability: Detection & Tracking

- Capability assumptions
  - 170 seconds of boost-time (engagement window)
  - Desired raid size of 12 missiles: determines required dwell-time
    - Ideal detection time is 10 seconds; allows interception of 12 missiles
- Development assumptions
  - Normalized TRL indicates initial readiness-level
    - Determines probability of disruptions during development

Detection Alternative	Detection time [sec]	TRL Level	Initial Readiness-Level $[m^o(i,r)]$
New System	10	6	0.67
UAV	11	8	0.89
STSS	12	9	1.00

Contributors to Capability: Adaptive Optics

- Capability assumptions
  - Only a function of the beam quality diffraction limit, b_q
  - Ideal beam quality diffraction limited is 1.2
- Development assumptions
  - Normalized TRL indicates initial readiness-level
    - Determines probability of disruptions during development

Detection Alternative	Beam Quality Diffraction Limited	TRL Level	Initial Readiness-Level $[m^o(i,r)]$
Alternative 1	1.2	2	0.22
Alternative 2	1.3	3	0.33
Alternative 3	1.4	5	0.56

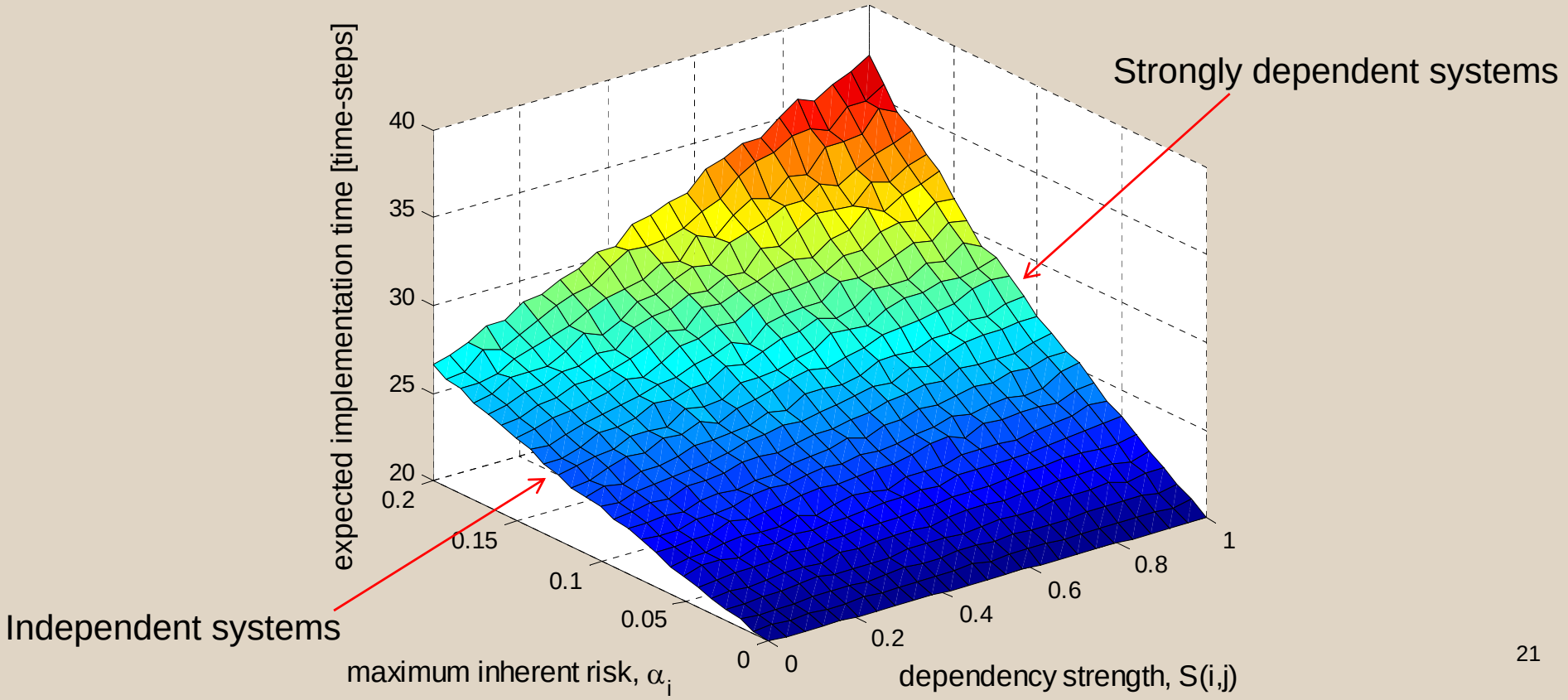
Contributors to Capability: COIL beam

- Capability assumptions
  - Published “achievable” COIL beam power of 3 MW
- Development assumptions
  - Normalized TRL indicates initial readiness-level
    - Determines probability of disruptions during development
  - Published TRL level of 4 for a power of 3 MW

COIL beam Alternative	Power [MW]	TRL level	Initial Readiness-Level $[m^o(i,r)]$
Alternative 1	3	4	0.44
Alternative 2	4	3	0.33
Alternative 3	5	1	0.11

System Risk and Interdependencies

- Candidate families of systems can have different combinations of system-risk and interdependency strengths
  - These characteristics have different impact on development success



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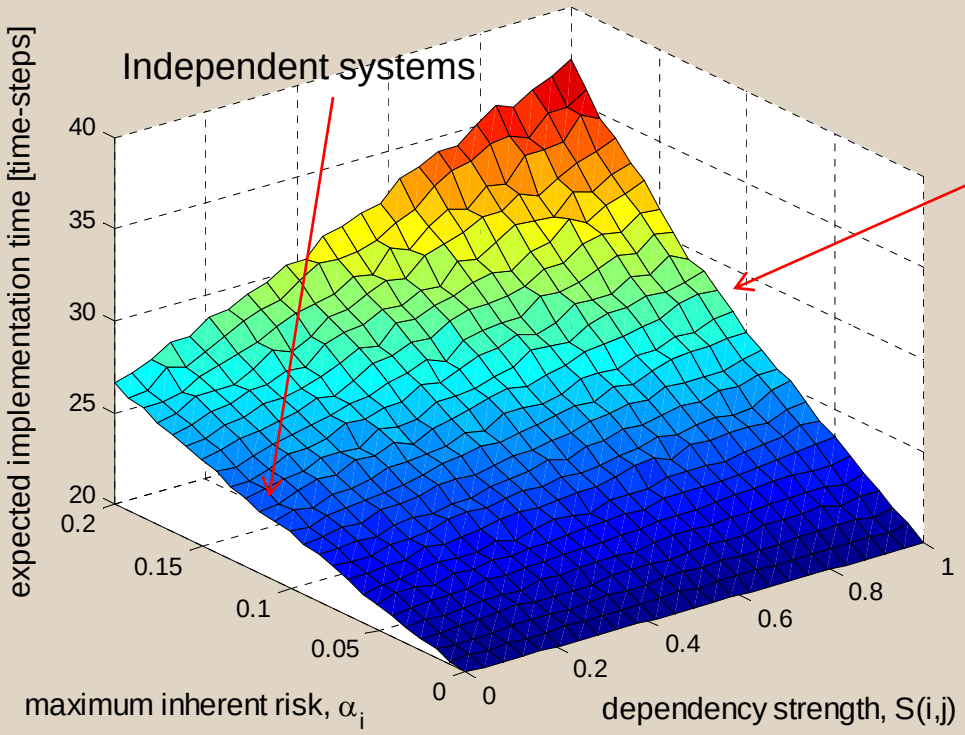

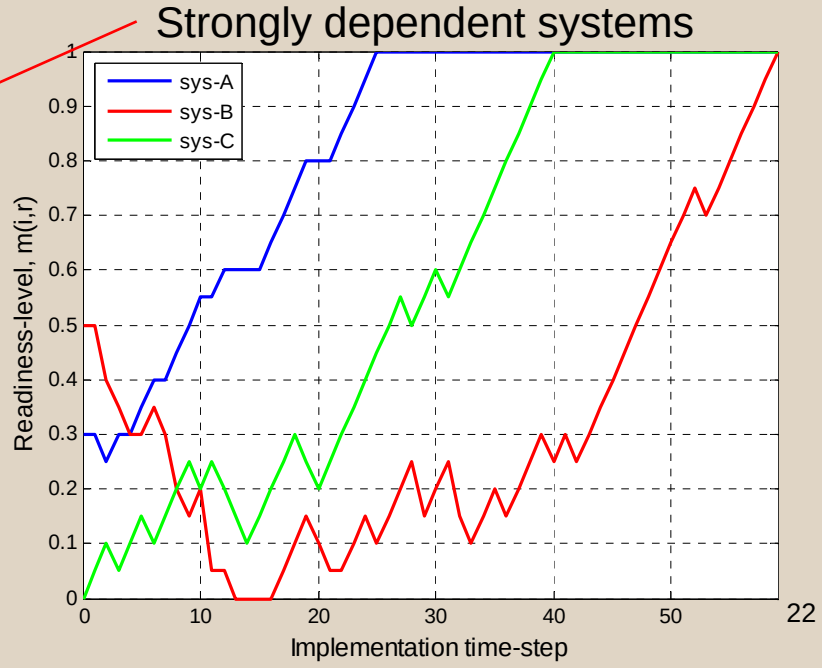

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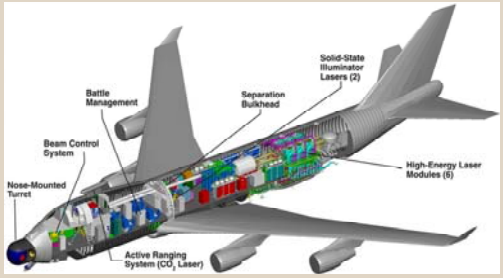

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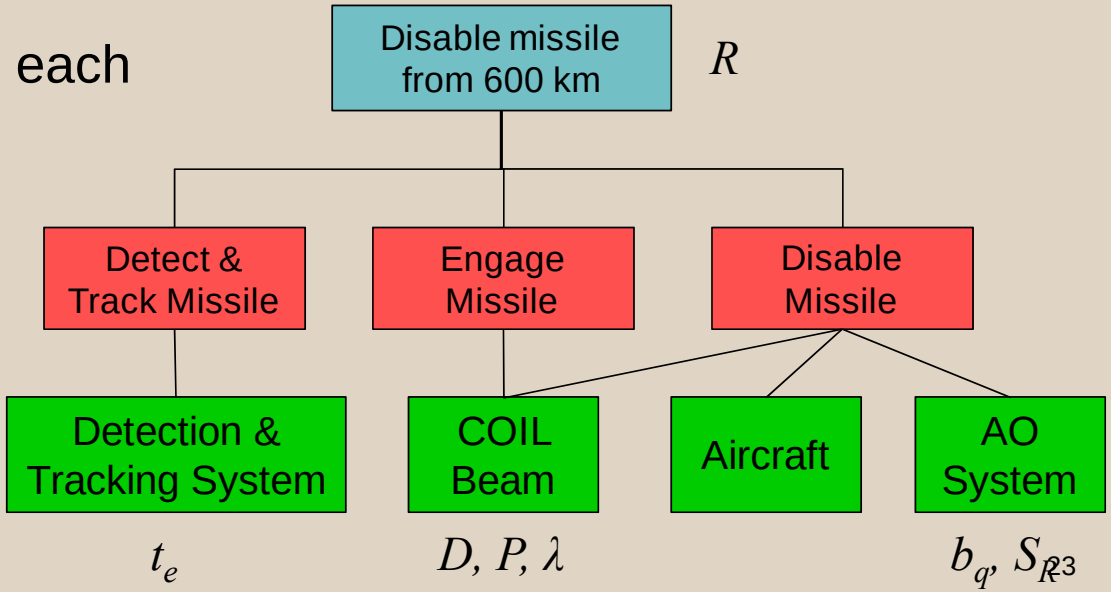

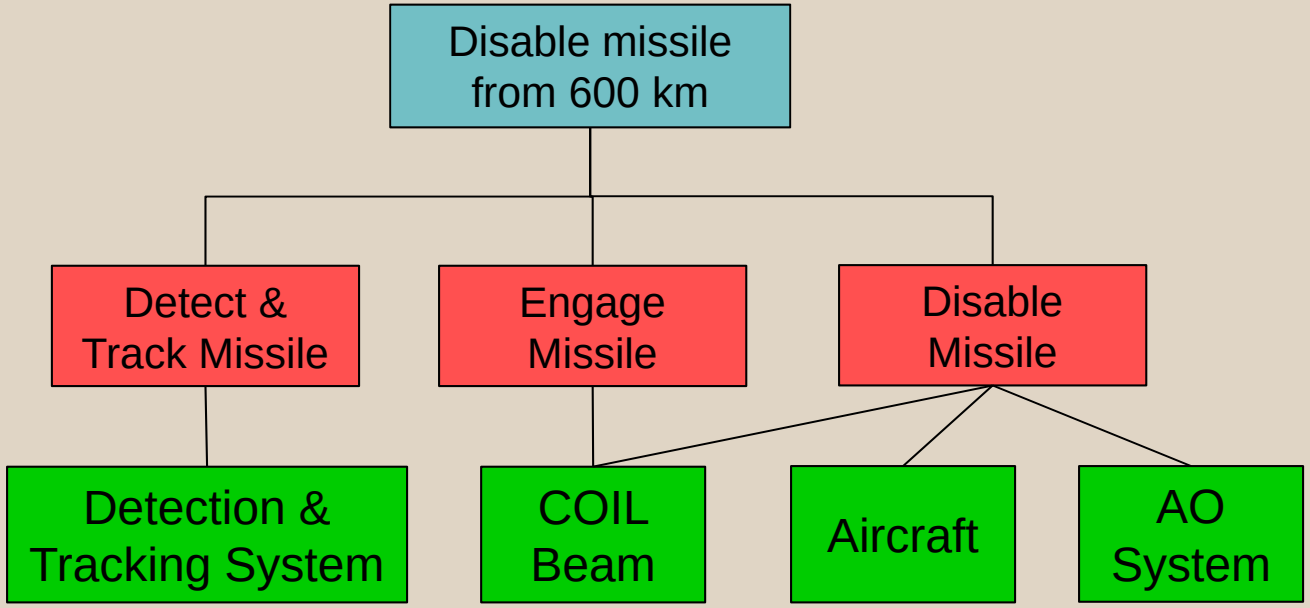
Disable missile from 600 km
Detect & Track Missile
Engage Missile
Disable Missile
Detection & Tracking System
COIL Beam
Aircraft
AO System