Ecology-Inspired Technique for Resilient Engineered System of Systems Design

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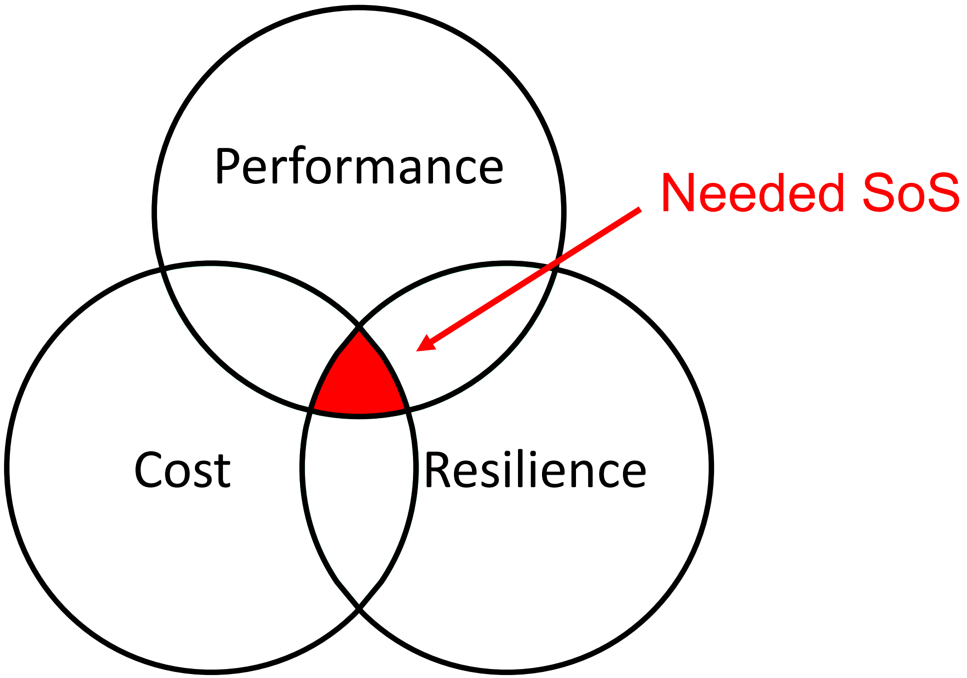
Research Task

Technique to *analyze/predict* trade-offs between **performance**, **cost**, & **resilience** of System of Systems

- Early in the design process
- Without need for detailed simulations/disruption models



Current State of the Art: Resilience

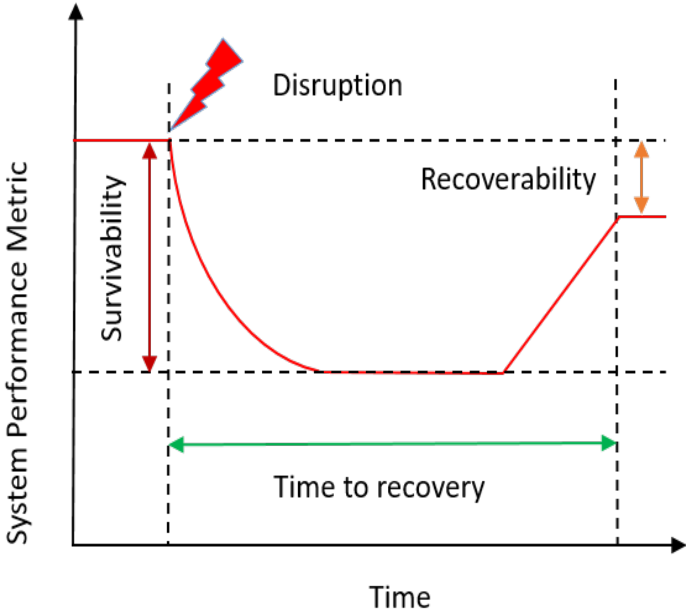
Design for Resilience is an iterative process[1]

Difficult to quantify early in project

Tend to rely on basic design rules

- physical redundancy, functional redundancy, localized capacity, etc.[2]

Desired: quantitative guidelines for engineering of resilient SoS

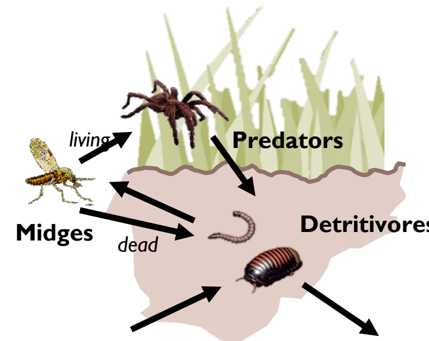


1. Uday, P. and K. Marais (2015). "Designing Resilient Systems-of-Systems: A Survey of Metrics, Methods, and Challenges." Systems Engineering **18**(5): 491-510.
2. Jackson, S. and T. L. J. Ferris (2013). "Resilience principles for engineered systems." **16**(2): 152-164.

Inspiration: Resilient Ecosystems

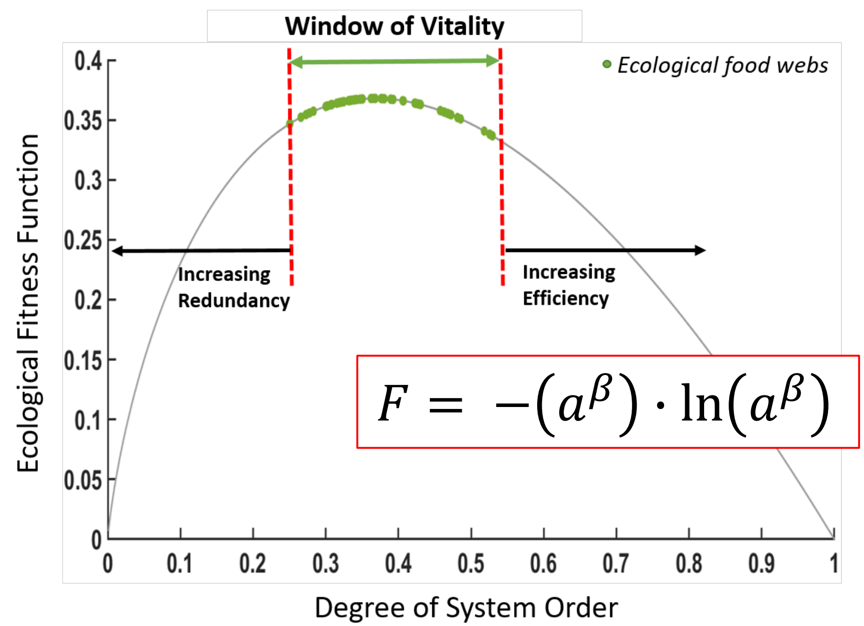
Ecosystems = *Biological SoS*

- **Resilient** to disturbances
- **Unique balance** of efficiency & redundancy



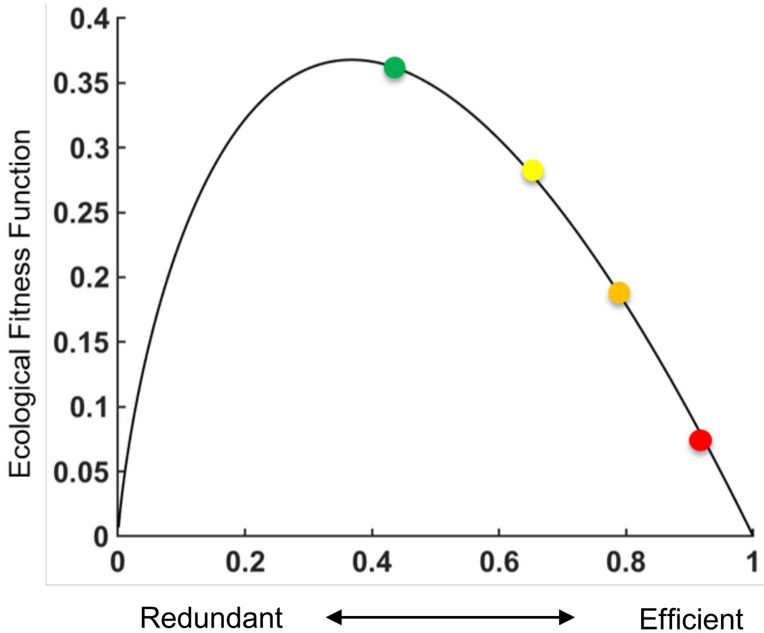
Observed *"Window of Vitality"*[3,4]

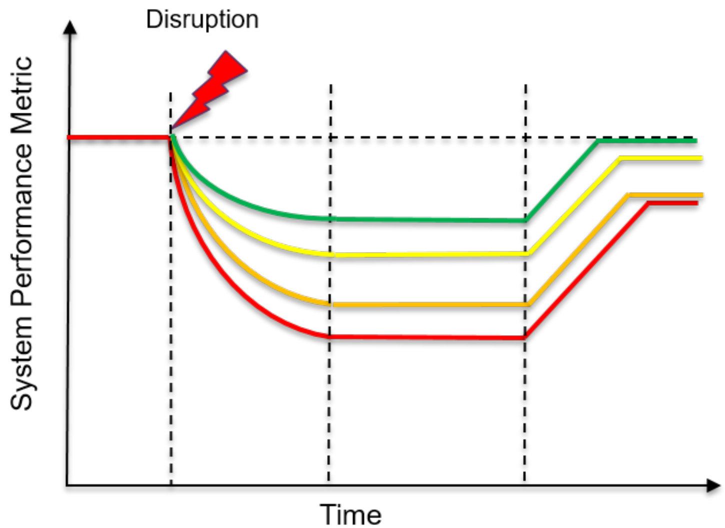
- Degree of System Order (a)[3]
- Quantifies balance of efficient & redundant network pathways



3. Ulanowicz, R. E., et al. (2009). "Quantifying sustainability: Resilience, efficiency and the return of information theory." Ecological Complexity **6**(1): 27-36
4. Fath, B. D. (2015). "Quantifying economic and ecological sustainability." Ocean & Coastal Management **108**: 13-19.

Research Questions





1. Do SoS architectures with bio-inspired balances of efficient & redundant interactions improve *performance, affordability, and response to disruptions*?

2. What factors influence a favorable "window of vitality" for an engineered SoS?

Ecological Network Analysis Framework

- Food Web Digraph: ENA ecosystem model
- Flow matrix **T**: flow magnitude information
- Organizational Development[5] (AMI):

$$AMI = \sum_{i=0}^{N+2}\sum_{j=0}^{N+2}\frac{T_{ij}}{TST_p}\log_2\left[\frac{T_{ij}\cdot TST_p}{T_{i\cdot}\cdot T_{\cdot j}}\right]$$

- Upper Limit of Organizational Development[5] (H):

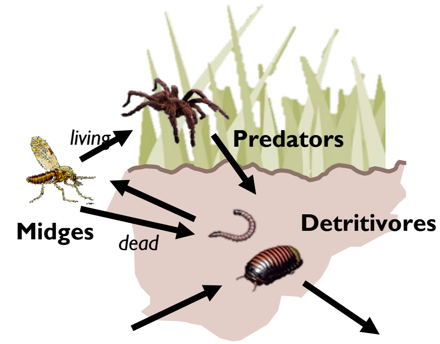
$$H = -\sum_{i=0}^{N+2}\sum_{j=0}^{N+2}\frac{T_{ij}}{TST_p}\log_2\left[\frac{T_{ij}}{TST_p}\right]$$

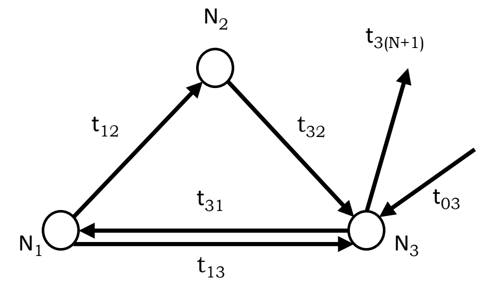
- Degree of System Order[3] (a):

$$a = AMI/H$$

- Ecological Fitness Function (F):

$$F = -(a^{\beta})\cdot\ln(a^{\beta})$$





		1	2	3	Output	Dissipation
Input	0	0	0	t_{03}	0	0
1	0	0	t_{12}	t_{13}	0	0
2	0	0	0	t_{23}	0	0
3	0	t_{31}	0	0	t_{34}	0
	0	0	0	0	0	0
	0	0	0	0	0	0

3. Ulanowicz, R. E., et al. (2009). "Quantifying sustainability: Resilience, efficiency and the return of information theory." Ecological Complexity **6**(1): 27-36
5. Ulanowicz, R. E. (1986). Growth and Development: Ecosystems Phenomenology, iUniverse.

INITIAL ANALYSIS OF TWENTY FEASIBLE ARCHITECTURES FOR A NOTIONAL HOSTILES SURVEILLANCE SoS

Case-study Description

- Surveillance area capacity, surveillance quality, exploitation capability, and operational cost characteristics selected based on literature[6]

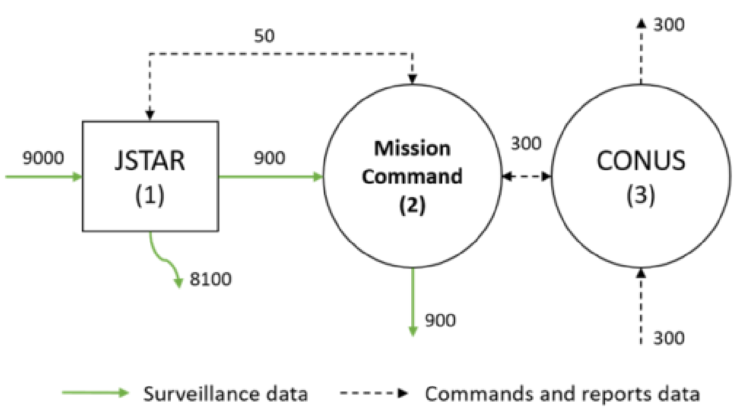
System	Surveillance quality	Max. surveillance area (sq. miles)	Exploitation capability	Operational Cost (10^3 $/hour-unit)
JSTAR	1	>9000	1 JSTAR	18
UAV	0.9	2250	-	2
Military Satellite	0.7	>9000	-	1
Theater	-	-	2 UAVs	10
CONUS	-	-	Unlimited	-

- **SoS Performance**: function surveillance and surveillance quality
- **SoS Operational Cost**: sum of operating costs of sub-systems
- **Validation**: *Standard N-X Contingency Analysis*
  - Investigate disruptions response
  - Loss of one, two, and three sub-systems (N-1, N-2, and N-3 contingencies)

6. Dagli, C. H., et al. (2013). "An advanced computational approach to system of systems analysis & architecting using agent-based behavioral model."

SoS Architectures as Flow Networks

- SoS architectures modeled as flow network digraphs
  - Participating systems = nodes
  - Operational data = flows
- Fitness Function (*F*) & Degree of System Order (*α*) calculated using the flow matrices (**T**)



Surveillance data flow matrix

	0	1	2	3	4	5
0	0	9000	0	0	0	0
1	0	0	900	0	0	8100
2	0	0	0	0	900	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0

Commands and reports data flow matrix

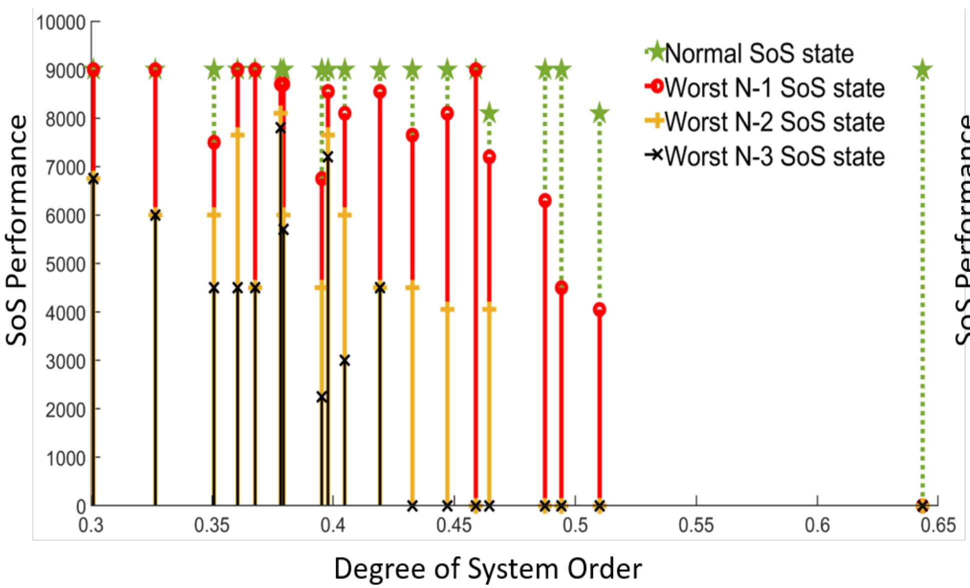
	0	1	2	3	4	5
0	0	0	0	300	0	0
1	0	0	50	0	0	0
2	0	50	0	300	0	0
3	0	0	300	0	300	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0

ILLUSTRATIVE EXAMPLE: 1/20 SoS Scenarios Investigated

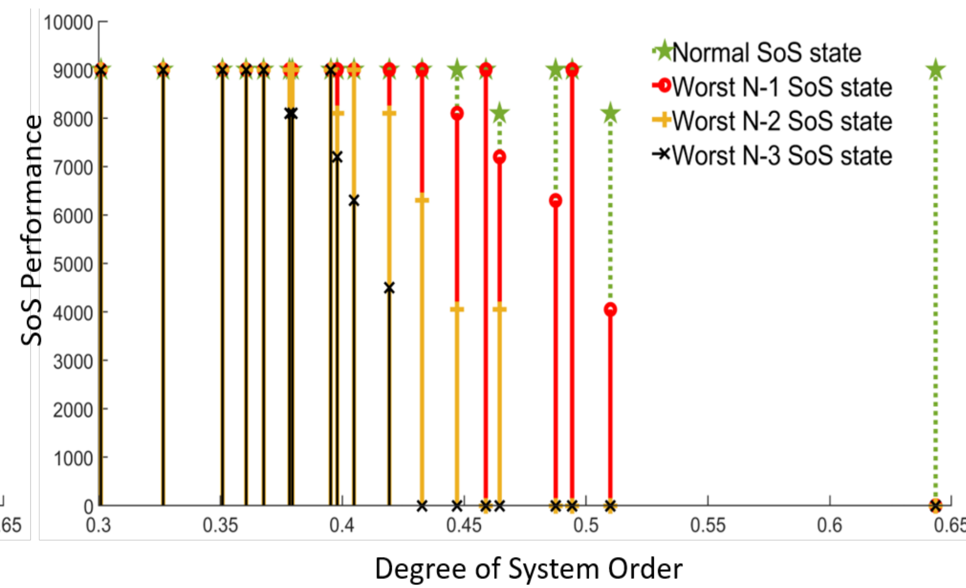
Results and Analysis

- Redundancy improves disruption response up to a point for each threat level
- *N*-1 Scenarios: closer to *a = 1* (efficient interactions)
- More Severe *N*-2 and *N*-3 scenarios: moves closer to *a = 0* (redundant interactions)

Performance at Disruption

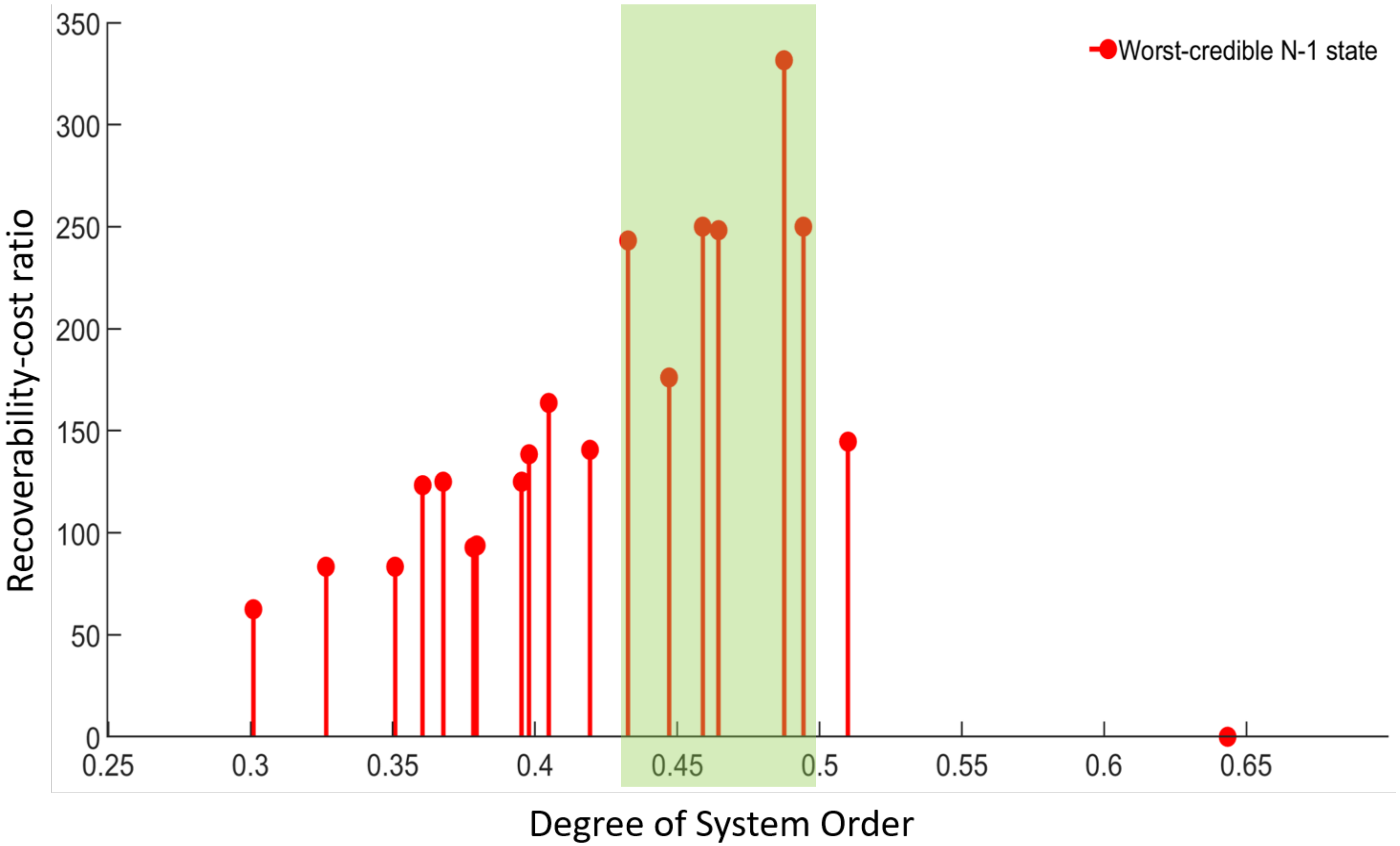


Performance after Re-Allocation



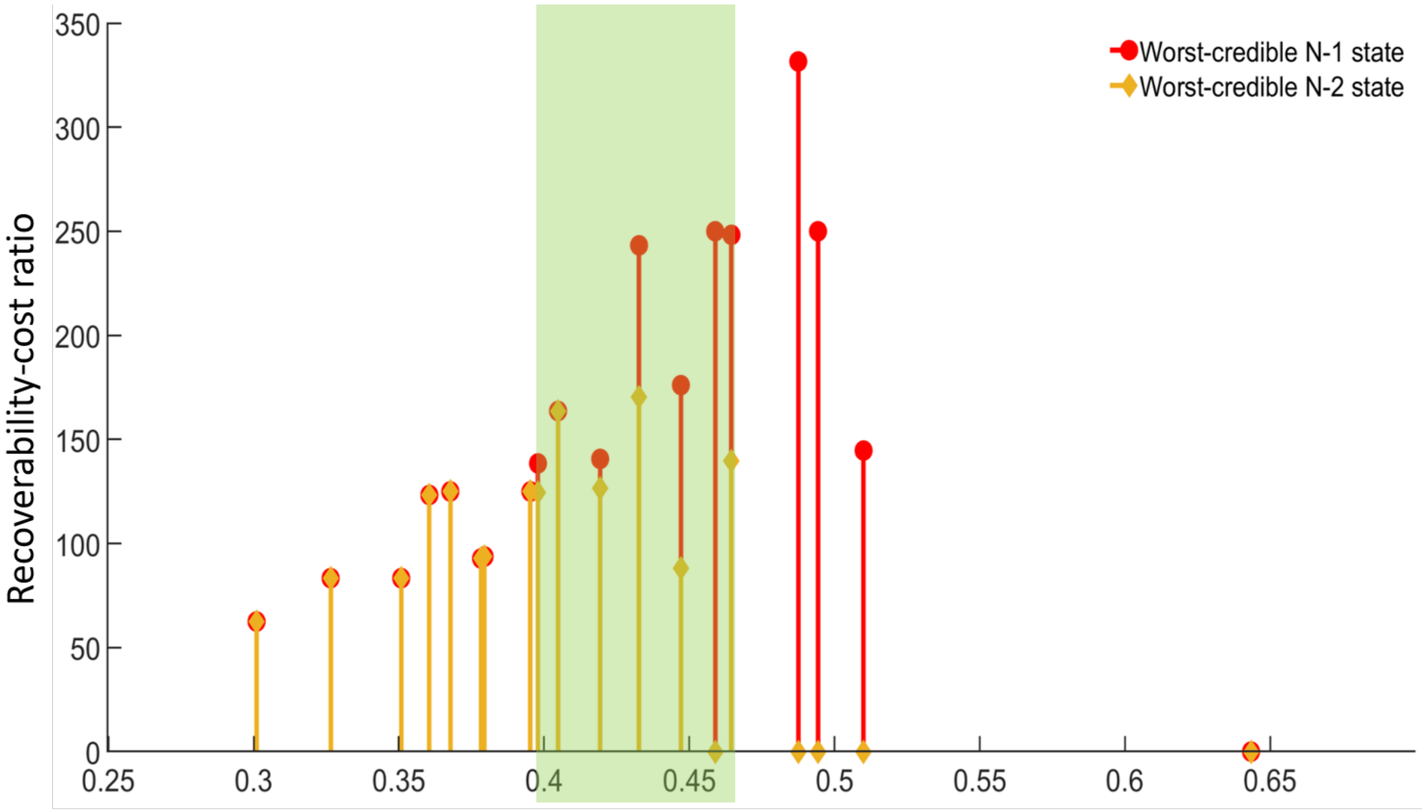
Results and Analysis: N-1

Recoverability-Cost Ratio: Level of performance that can be recovered by surviving systems *after* the ***worst credible N-X disruptions***, normalized by operational cost



Results and Analysis: N-2

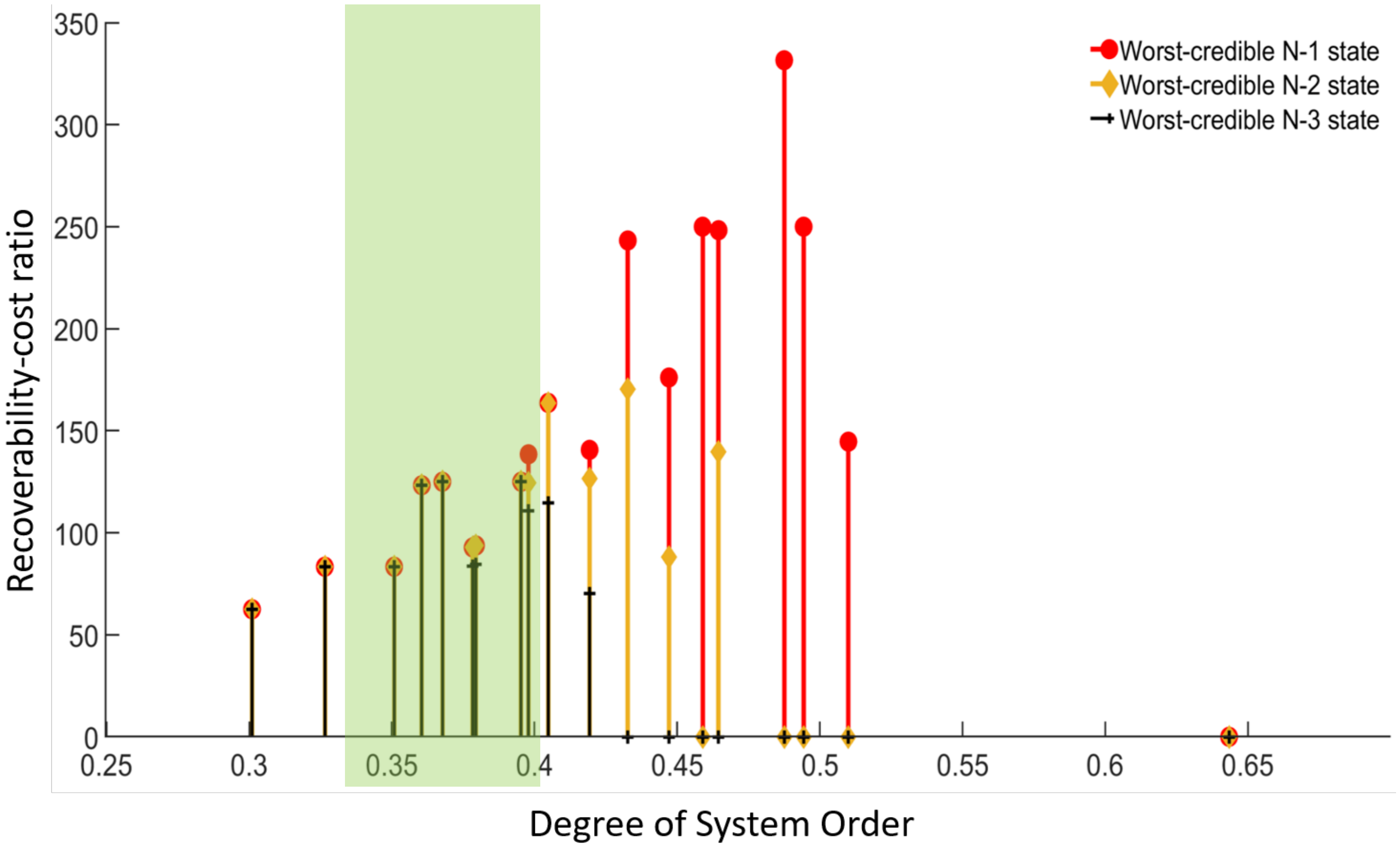
Recoverability-Cost Ratio: Level of performance that can be recovered by surviving systems *after* the ***worst credible N-X disruptions***, normalized by operational cost



Degree of System Order

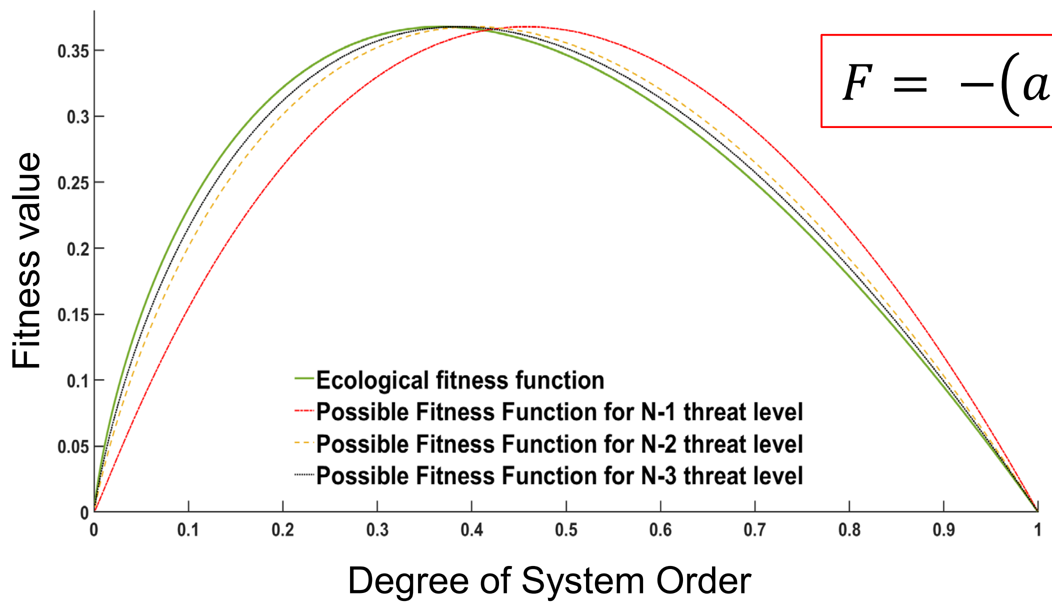
Results and Analysis: N-3

Recoverability-Cost Ratio: Level of performance that can be recovered by surviving systems *after* the ***worst credible N-X disruptions***, normalized by operational cost



Results and Analysis

- Recoverability-Cost Ratio *improves* with redundancy, peaks, and then worsens (*excessive redundancy*)
  - Similar behavior to ecosystems
- SoS fitness (*F*) *estimated* based on best recoverability-cost ratios design for each contingency analysis
  - Increasing threat levels cause fitness trend to **move towards the *ecological fitness function***



$$F = -\left(a^{\beta}\right) \cdot \ln\left(a^{\beta}\right)$$

Future Work

- Additional SoS case studies
  - —More complex scenarios
  - —More complex disruption models
- Investigate effects of excessive redundancy on SoS, such as organization interoperability
- Investigate mathematical framework for SoS trends and trades
  - —SoS fitness function: peak location trends
  - —Explanatory understanding of redundancy-efficiency trades on SoS fitness
- Guidelines for quantitative modeling SoS and evaluation in early stages of mission engineering