SYSTEMS ENGINEERING RESEARCH CENTER

TEXAS A&M UNIVERSITY
J. Mike Walker '66 Department of Mechanical Engineering

ECOLOGY-INSPIRED TECHNIQUES FOR RESILIENT DESIGN OF SYSTEM OF SYSTEMS (SOS) [WRT-1027]

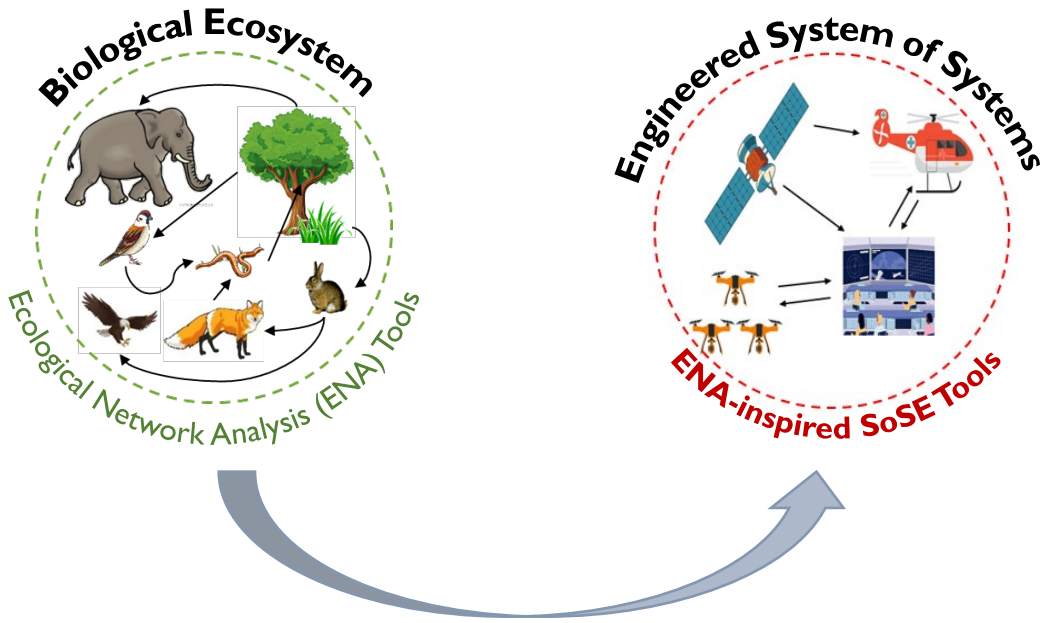
Dr. Richard Malak (rmalak@tamu.edu), Dr. Astrid Layton,
Mr. Abheek Chatterjee and Mr. Cade Helbig

Texas A&M University

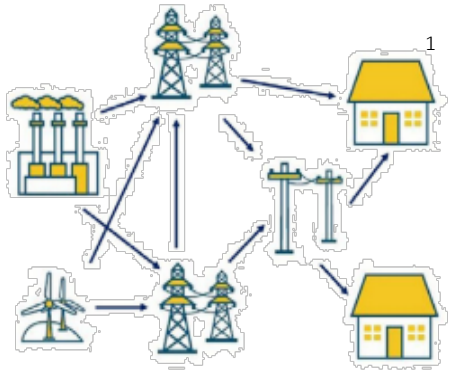
WASHINGTON DC | VIRTUAL
NOV. 2-4 2021
ANNUAL SPONSOR RESEARCH REVIEW

Project Objective

Create tools for resilient Systems of Systems (SoS) development based on ideas from Ecological Network Analysis (ENA)



Systems of Systems (SoS)



SoS is a ***networked integration*** of systems that

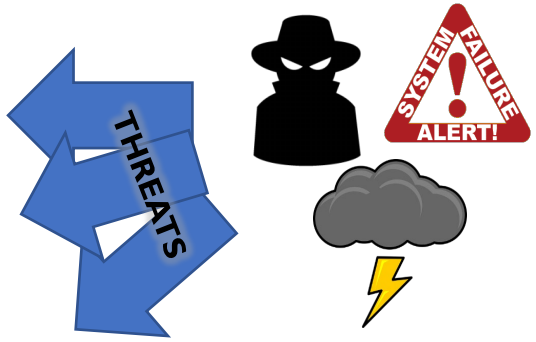
- Fulfill specific roles
- Are independently operable/managed
- (Often) are geographically dispersed

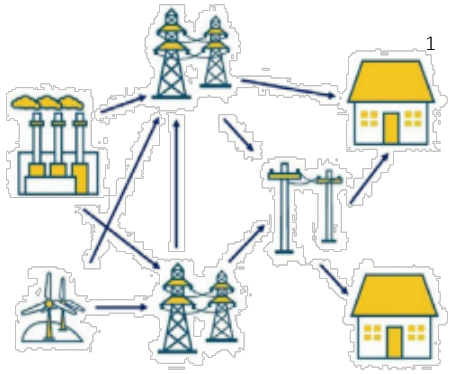
SoS results in ***new capabilities*** compared to collection of individual systems

SoS behavior is ***emergent***

[1] Panyam et al. (2019)

Threats and Disruptions to SoS Operation





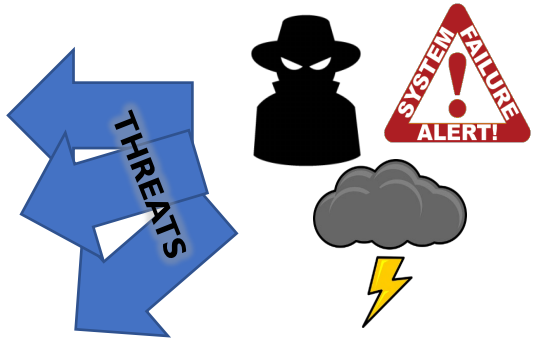
Many sources of ***threats*** that can lead to ***disruptions***

Threats are ***difficult to predict and difficult to model***

Significant ***loss of value*** to stakeholders when SoS disruptions occur

[1] Panyam et al. (2019)

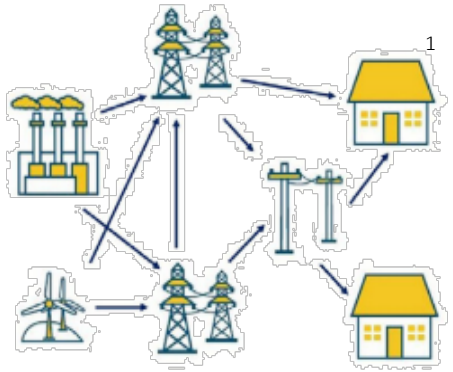
Resilient SoS

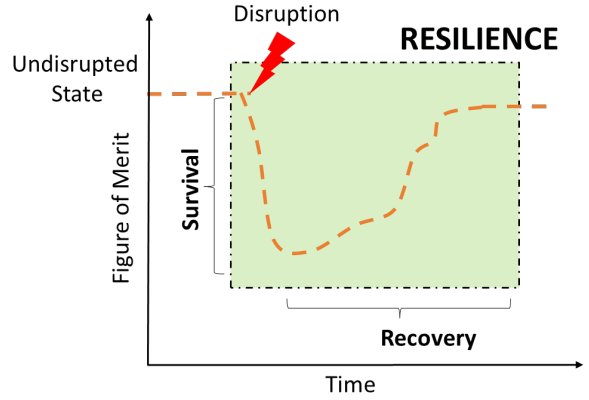


Many sources of ***threats*** that can lead to ***disruptions***

Threats are ***difficult to predict and difficult to model***

Significant ***loss of value*** to stakeholders when SoS disruptions occur

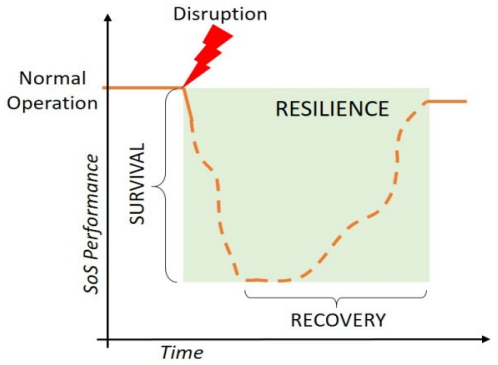




A resilient SoS ***survives*** disruptions ***and recovers*** from them quickly

[1] Panyam et al. (2019)

Designing Resilient System of Systems

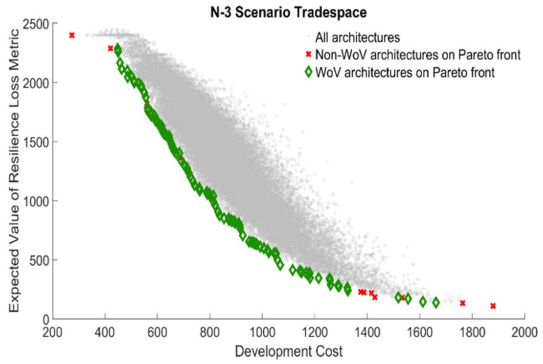


Potential Threats:

- Natural disasters
- Bad actors
- Errors
- …

Stakeholder Concerns:

- Performance
- Resilience
- Affordability
- …



Challenges

- Threats & disruptions difficult & time consuming to model
- Early-stage design principles (redundancy, localized capacity, inter-node communications, etc.) are useful but heuristic
- Difficulty accounting for trade-off with affordability
- Difficulty evaluating large numbers of candidate SoS architectures

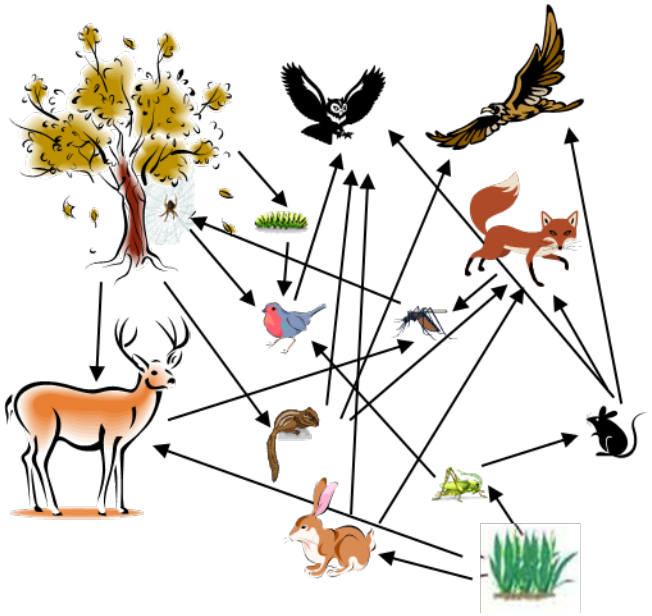
Desired Practice

- Means to rate SoS architectures without detailed threat/disruption models
- Resilience indicators for early-stage development
- Consideration of affordability-resilience tradeoffs
- Ability to compare many SoS architectures quickly

Inspiration: Resilient Ecosystems

Ecosystems: a biological SoS

- A species analogizes with a system
- Interactions through predator-prey relationships



Ecosystems exhibit **resilience** to disturbances

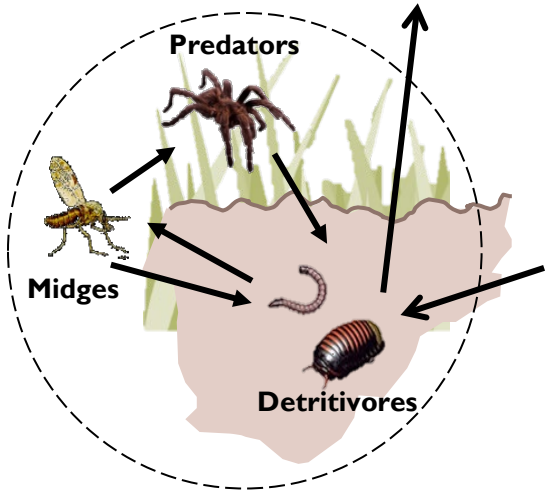
- Individual species are self-interested
- Species share complex interdependencies
- Random, small- & large-scale disturbances common
- Ecosystem as a whole survives and grows

Ecological Network Analysis (ENA)

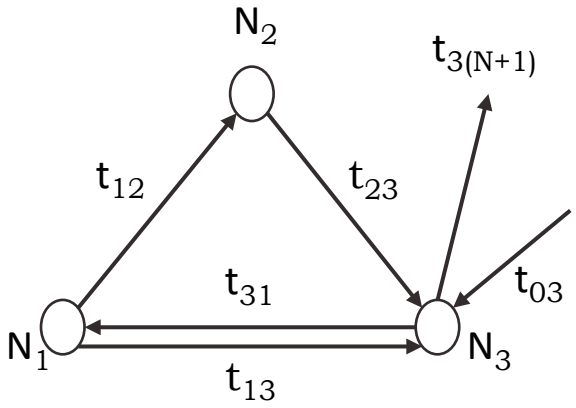
- Models ecosystems as directed flow networks
- Quantification of ecosystem architecture and functional characteristics
- Foundations in Graph Theory & Information Theory

Ecological Network Analysis (ENA) Modeling

Ecologists model ecosystems as flow networks to study their structural and functional characteristics



Ecosystem



Network Representation

		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

Flow Matrix Representation

Degree of System Order (DoSO) [4]

- Quantifies *relative flow pathway constraint* in a flow network
- Ranges 0 (high pathway redundancy) to 1 (highly constrained flow; high pathway efficiency)

$$DoSO = \frac{AMI}{H}$$

Average Mutual Information (AMI):
Measure of pathway constraints

$$AMI = \sum_i \sum_j \left(\frac{T_{ij}}{TST_p}\right) \log_2 \left(\frac{T_{ij} \cdot TST_p}{T_{i\cdot} \cdot T_{\cdot j}}\right)$$

Shannon Index:
Upper limit on pathway constraints

$$H = -\sum_i \sum_j \left(\frac{T_{ij}}{TST_p}\right) \log_2 \left(\frac{T_{ij}}{TST_p}\right)$$

Notation: T_{ij} is ij^{th} element from flow matrix (previous slide), $T_{i\cdot}$ is sum of flows in i^{th} row of matrix, $T_{\cdot j}$ is sums along j^{th} column and TST_p is total sum of flows in network.

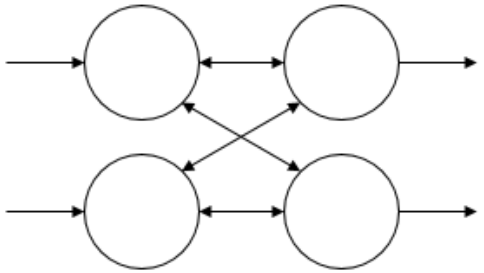
[4] Ulanowicz et al. (2009)

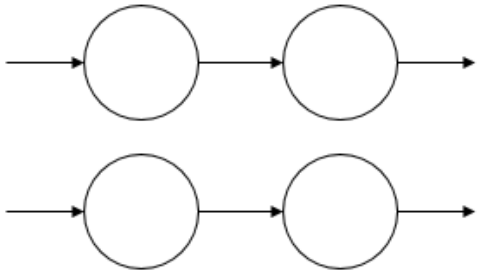
Degree of System Order (DoSO) [4]

- Quantifies *relative flow pathway constraint* in a flow network
- Ranges 0 (high pathway redundancy) to 1 (highly constrained flow; high pathway efficiency)

$$DoSO = \frac{AMI}{H}$$

$AMI \rightarrow 0$
$DoSO \rightarrow 0$





$AMI \rightarrow H$
$DoSO \rightarrow 1$

Highly **Pathway Redundant** Network Architectures

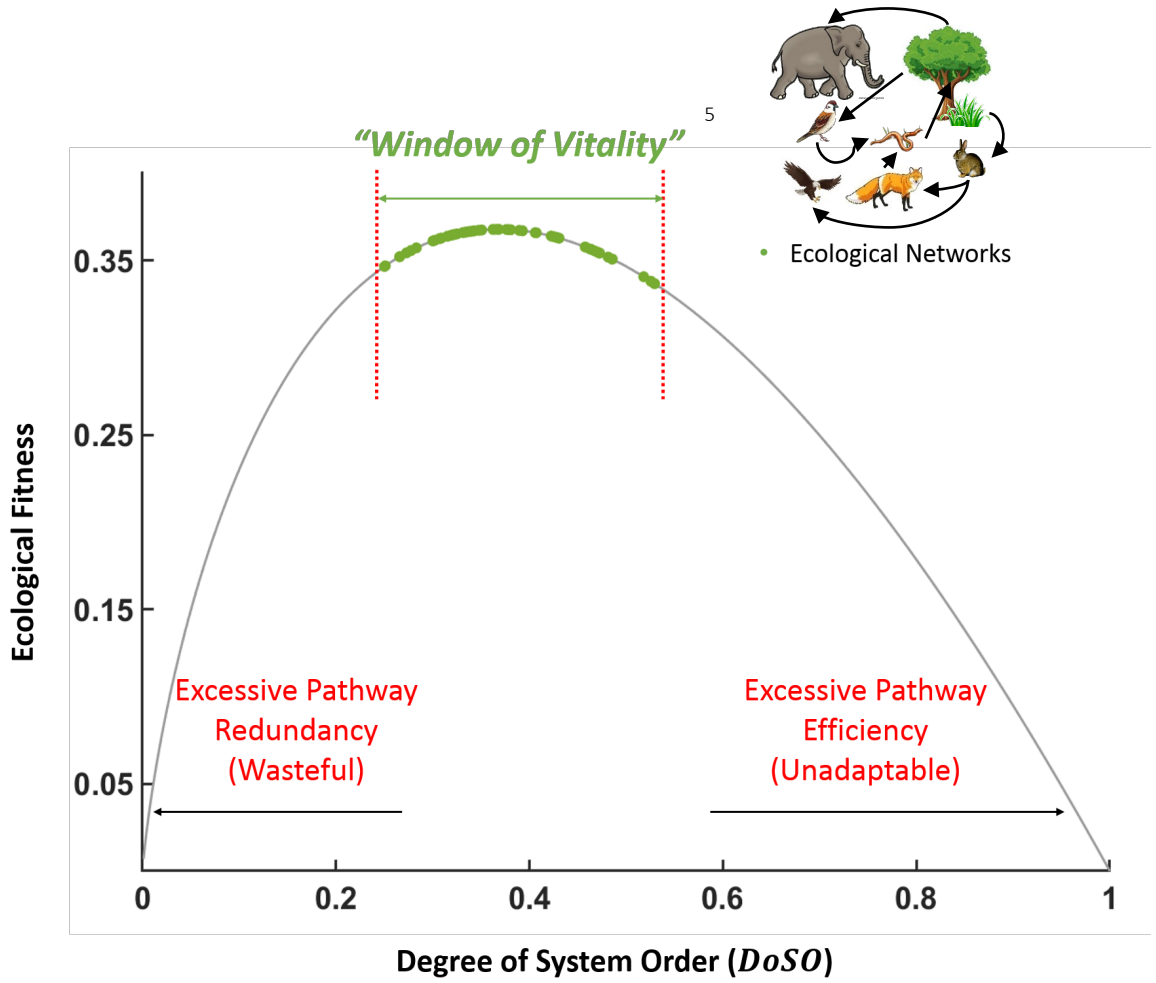
Highly **Pathway Efficient** Network Architectures

Important: Pathway redundancy is about flows through network—not same as redundancy in components or functionality

[4] Ulanowicz et al. (2009)

Window of Vitality in Ecological Networks

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



Empirical finding: **Biological ecosystems exist within a distinct range of DoSO values**

- Called the *Window of Vitality*
- Balance between pathway efficiency and pathway redundancy
- Represents effective resource utilization in undisturbed state & capability to survive and recover from disruptions

Interpretation: **Nature makes a particular trade between resiliency and affordability.**

[5] (Figure based on) Fath (2015)

Key Questions & Issues

Foundational Questions

Does the DoSO quantity provide information useful for developing engineered SoS?

- Do resilient engineered SoS tend to fall within a range of DoSO values like the Window of Vitality (WoV) for ecosystems?
- Does DoSO capture resilience-affordability trades?

Extensions and Application

Extensibility to multiflow cyber-physical systems of systems

Prototype ENA-inspired SoS development tool

Studies of SoSO and WoV

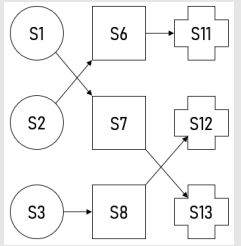
Foundational Questions

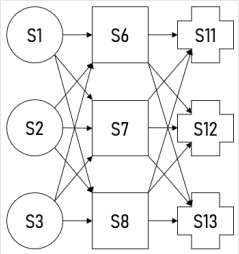
Does the DoSO quantity provide information useful for developing engineered SoS?

- Do resilient engineered SoS tend to fall within a range of DoSO values like the Window of Vitality (WoV) for ecosystems?
- Does DoSO capture resilience-affordability trades?

<u>Study Strategy</u>: broad exploration of SoS architectures

1. Automatically generate representative SoS architectures
2. Evaluate for development cost, performance under nominal operation and DoSO
3. Evaluate resilience under nodal and link failures
4. Examine resilience-affordability tradespace and Pareto frontier





Development cost accounts for system and interface costs

SoS performance based on analogy with industrial networks

DoSO as defined earlier

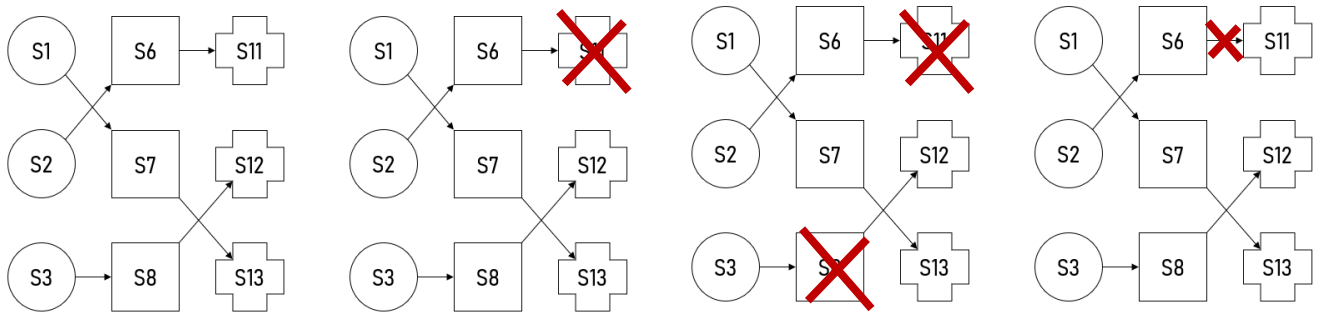
Resilience defined on next slide

Quantifying Resilience Loss

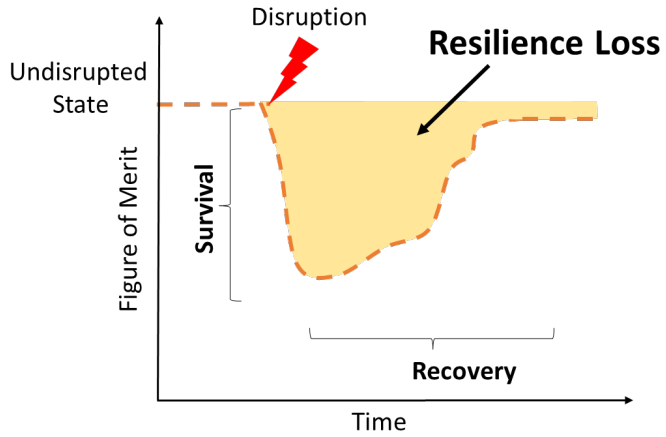
N-X analysis: impact of removing X **nodes**

L-X analysis: impact of removing X **links**

Nominal **N-1** **N-2** **L-1**



Exhaustive evaluation of all combinations at a given X-level
Average resilience loss value across all combinations



Resilience Loss [7] **:**

$$RL = \int_0^{25} 100 - MoP(t)\, dt$$

After disruption, SoS recovers over time as captured by $MoP(t)$

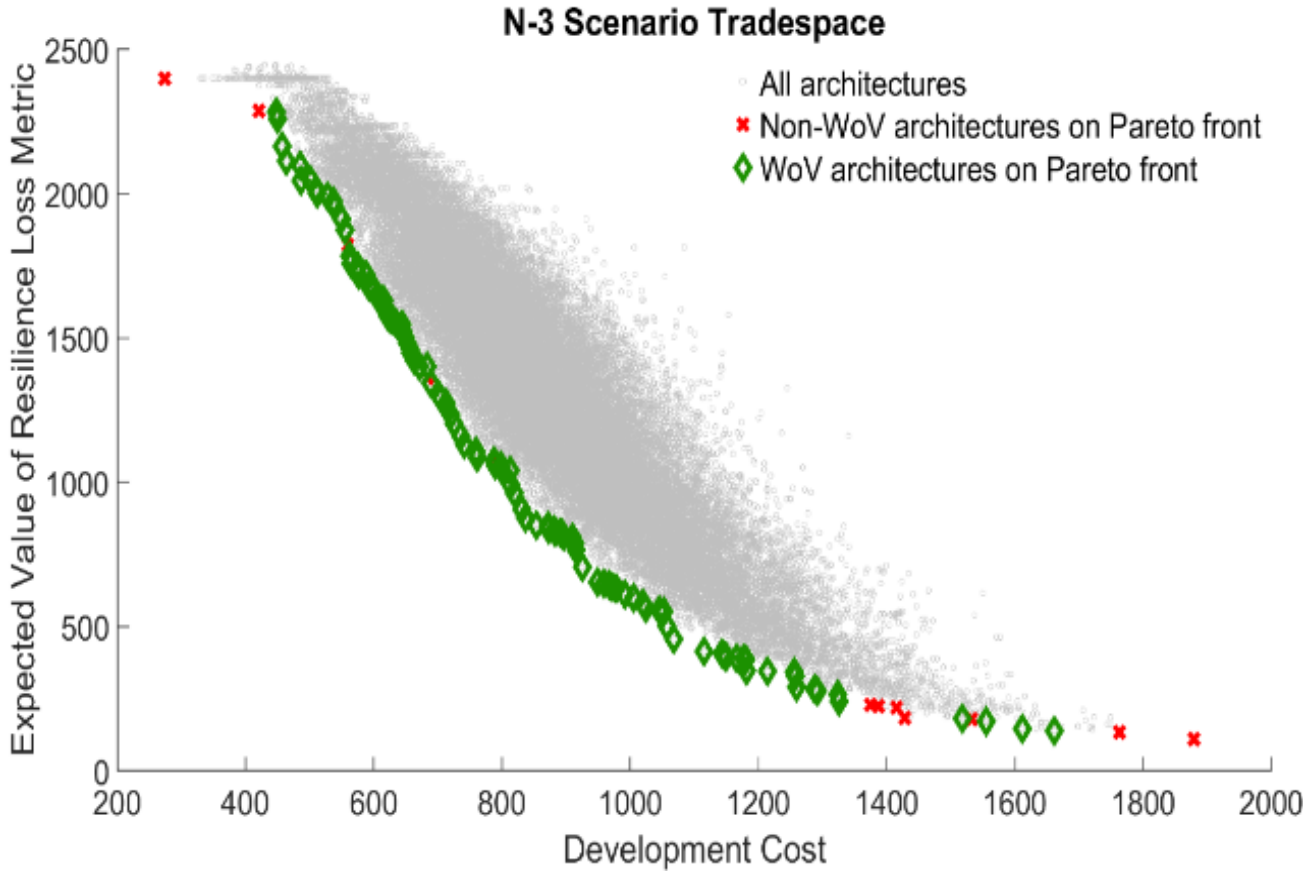
Resilience loss aggregates multiple aspects of resilience into single score (lower is better)

[7] Bruneau et al. (2003)

WoV and the Resilience-Cost Tradespace (for N-3)

N-3 Scenario:

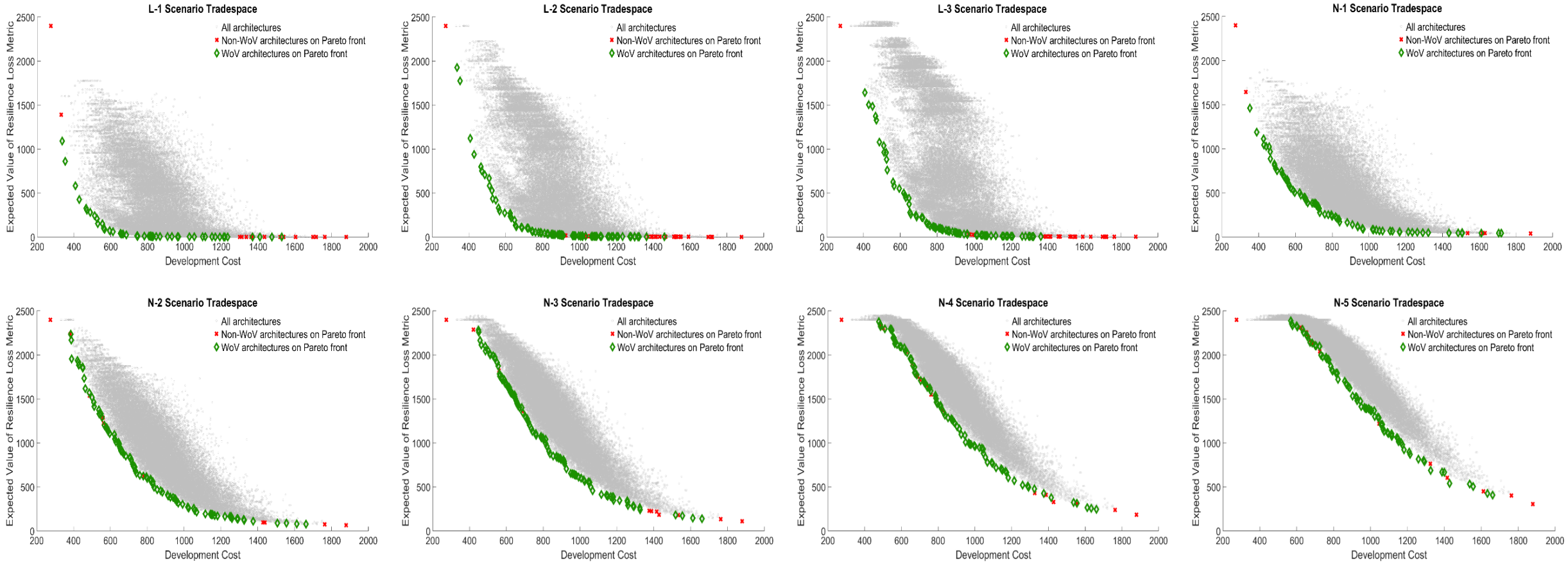
Any three constituent systems in the SoS are disrupted



Observations:

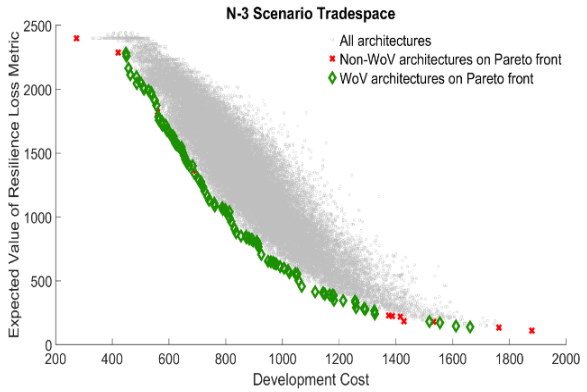
1. Majority of Pareto optimal SoS architectures lie within the ecological Window of Viatlity (WoV) on DoSO
2. Non-WoV architectures on the Pareto front tend to lie on the extreme ends

WoV and the Resilience-Cost Tradespace



Greater than **~75%** (in L-X scenarios) and **~85%** (in N-X scenarios) of Pareto optimal architectures fell within the ecological Window of Vitality range of DoSO

Further Analysis using Weighted Cost Function



Initial analysis → most Pareto architectures are in the WoV

What about the reverse: is an architecture in the WoV more likely to be on the Pareto frontier?

Weighted cost function: $WS = \lambda\left(\frac{\overline{RL}}{\overline{RL}_{max}}\right) + (1-\lambda)\left(\frac{DC}{DC_{max}}\right)$

- Architectures grouped as: in WoV or not in WoV
- All architectures evaluated with this cost function
- Compare averages across the two groups

$\overline{RL}$: Expected Resilience Loss
DC: Development Cost

λ: Weighting Factor scenarios

a) λ = 0.75, favoring minimizing resilience loss

b) λ = 0.5, neutral weighting

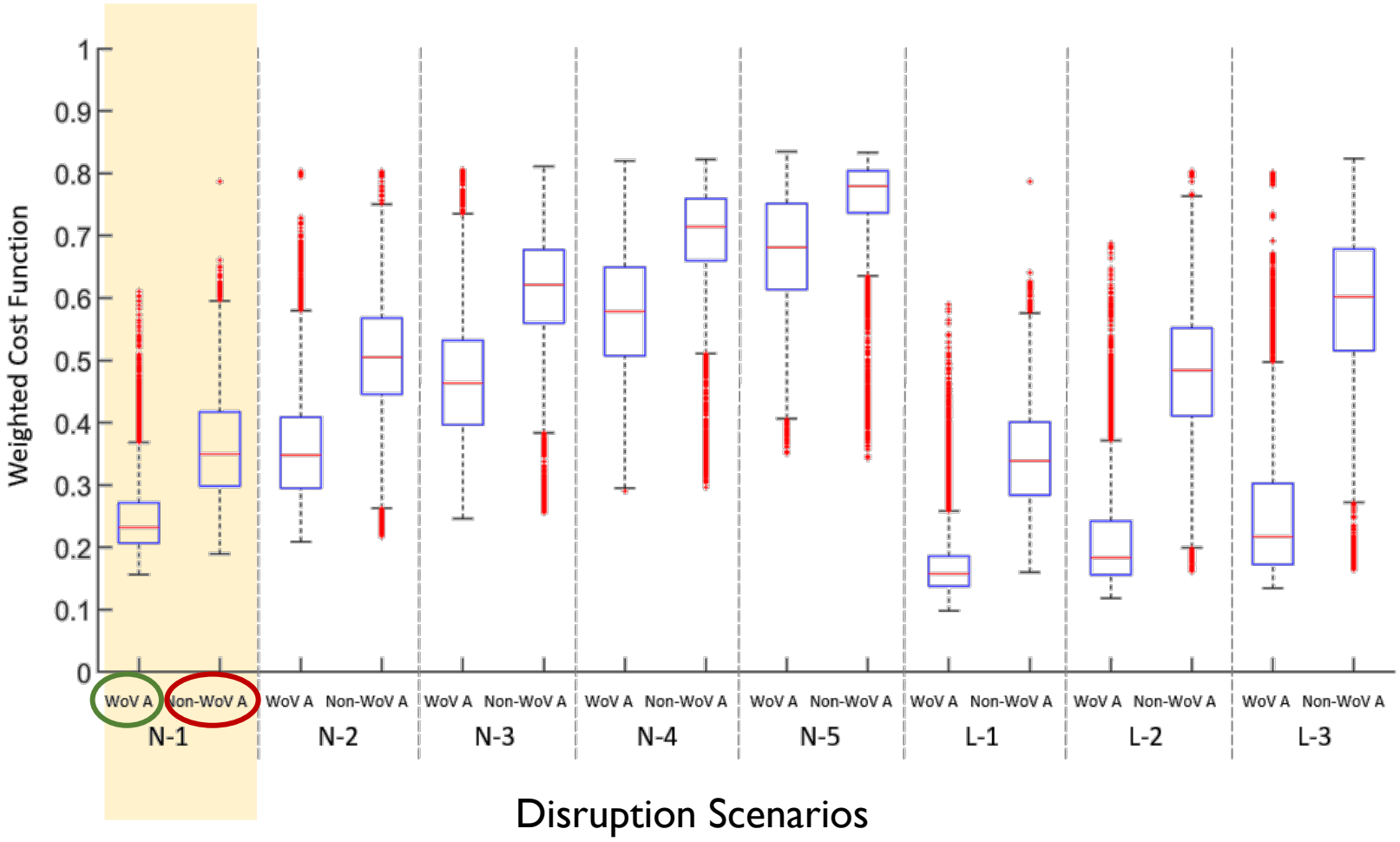
c) λ= 0.25:, favoring minimizing SoS development cost

Is the WoV Informative?

Disruption Scenarios:

L-X: Loss of x links

N-X: Loss of x nodes



Observation

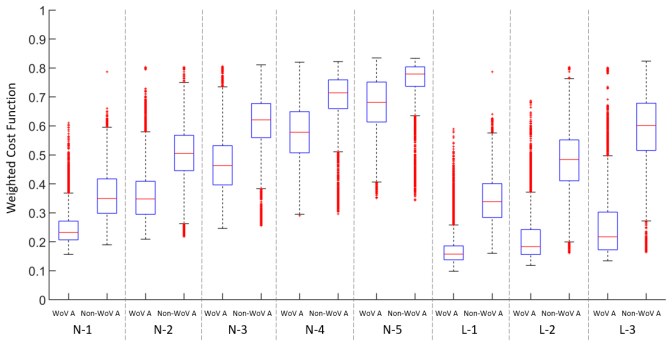
Architectures within WoV fare better on weighted cost model

Results Across Three Weighting Scenarios

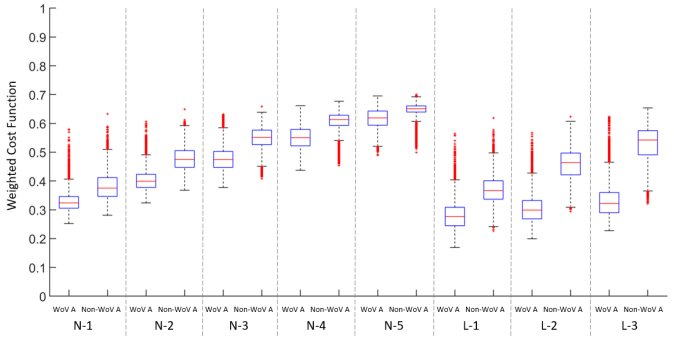
Architectures in the WoV rated better, on average, when:

1. Higher weighting for resilience loss ($\lambda = 0.75$)
2. Equal weighting ($\lambda = 0.5$) for minimizing resilience loss and development cost

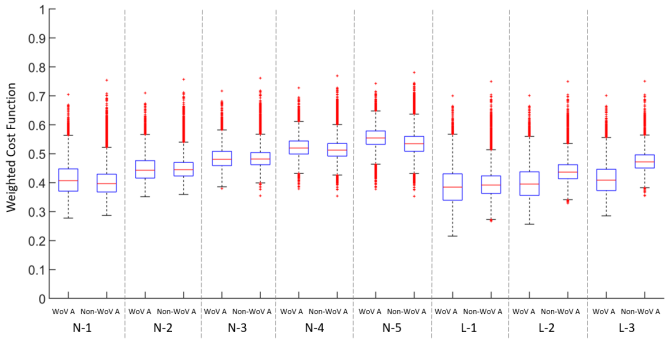
No significant difference observed when development costs given higher weighting ($\lambda = 0.25$)



$\lambda = 0.75$



$\lambda = 0.5$



$\lambda = 0.25$

Findings and Significance

FOUNDATIONAL QUESTIONS

Does the DoSO quantity provide information useful for developing engineered SoS?

- Do resilient engineered SoS tend to fall within a range of DoSO values like the Window of Vitality (WoV) for ecosystems?
- Does DoSO capture resilience-affordability trades?

We find that **DoSO is an informative quantity**:

- Most Pareto optimal SoS architectures are in the ecological WoV range of DoSO values
- When cost and resilience both are important, SoS architectures inside the WoV tend to outperform those outside the WoV

Significance: We can compute DoSO without specific assumptions about disruptions and without a detailed SoS simulation. ***This enables evaluation of larger number of architectures earlier in development process***.

Chatterjee, A, Malak, R, Layton, A. Ecology-inspired resilient and affordable system of systems using degree of system order. *Systems Engineering*. 2021 https://onlinelibrary.wiley.com/doi/full/10.1002/sys.21598

Key Questions & Issues

Foundational Questions

Does the DoSO quantity provide information useful for developing engineered SoS?

- Do resilient engineered SoS tend to fall within a range of DoSO values like the Window of Vitality (WoV) for ecosystems?
- Does DoSO capture resilience-affordability trades?

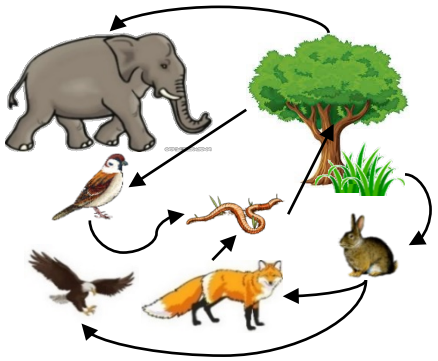
Extensions and Application

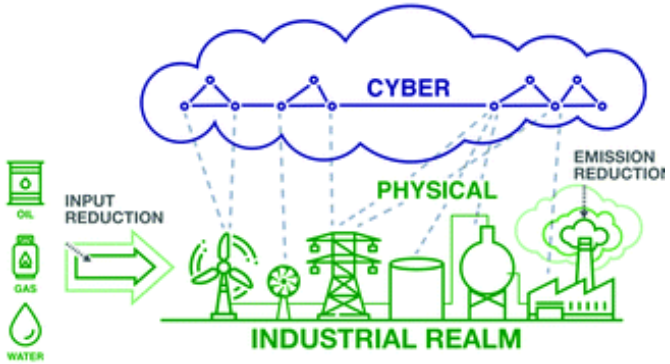
Extensibility to multiflow cyber-physical systems of systems

Prototype ENA-inspired SoS development tool

Limitations of Ecosystem Analogy

7





Ecologists primary concerned with energy (caloric) transfers between species

Inputs and outputs at nodes related using simple conservation laws

Only one flow type

Distinct but ***inter-dependent*** flows

Inputs and outputs at nodes can have more ***complex relationships*** and are ***not always conserved***

Cyber interactions unlike conserved physical flows of energy or materials

[7] Inderwildi et al. (2020)

Multiflow Cyber-Physical SoS using Directed Multigraphs

Directed Multigraph: A graph that is permitted to have multiple (directed) edges between nodes

Nodes model constituent systems

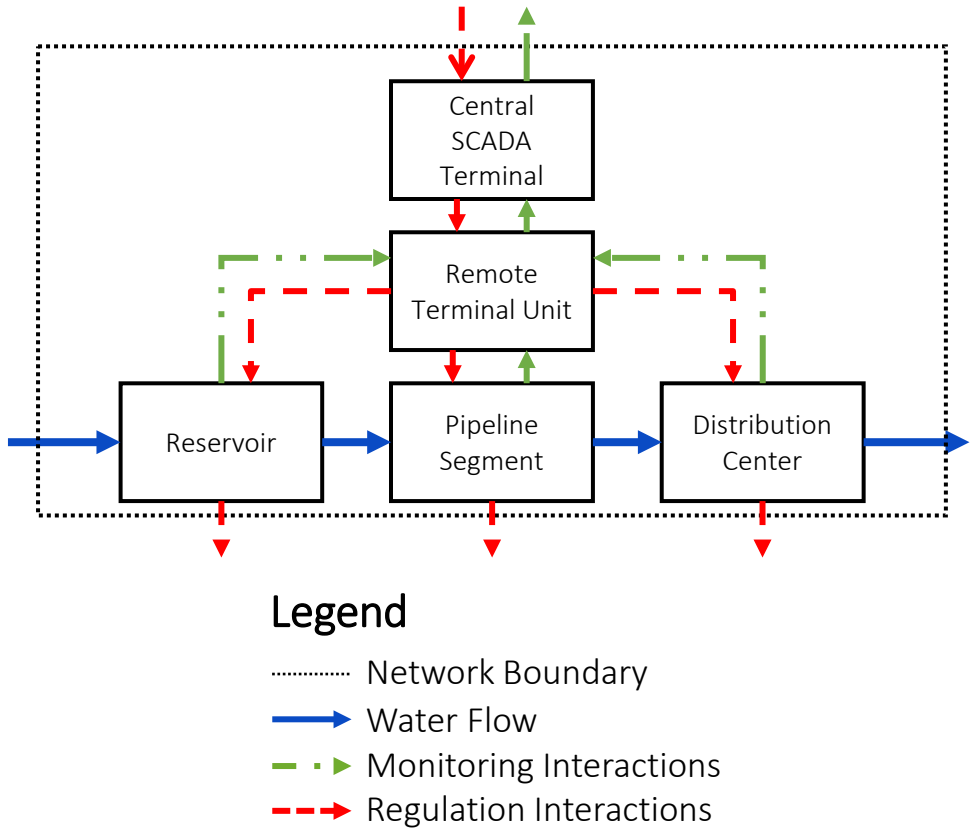
Edges model distinct types of interactions (physical flows, cyber interactions, etc.)

Interaction magnitudes assigned based on **task-loads**

Features:

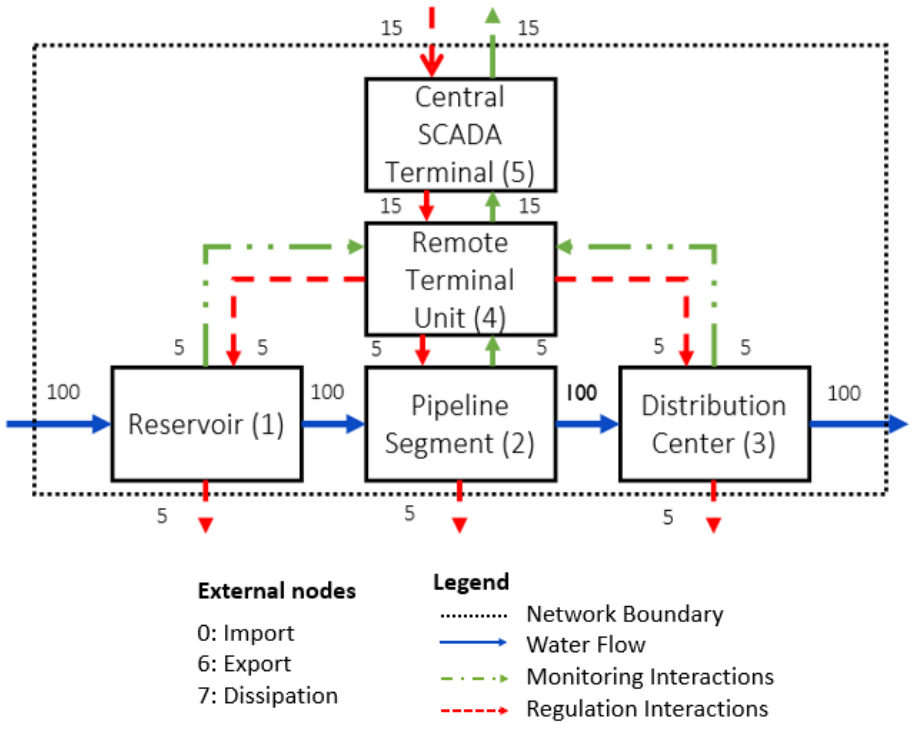
1. Does not necessitate *flow balance*
2. *Transformation of flows* is accounted
3. Evaluation is *scale-invariant*

Example cyber-physical multiflow SoS:



Evaluating DoSO for Multiflow SoS

- Multiple interrelated flow matrices
- Modified ENA metrics to account for entire SoS



Water Flows (T_{ij1})

	0	1	2	3	4	5	6	7
0	0	100	0	0	0	0	0	0
1	0	0	100	0	0	0	0	0
2	0	0	0	100	0	0	0	0
3	0	0	0	0	0	0	100	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0

Monitoring Interactions (T_{ij2})

	0	1	2	3	4	5	6	7
0	0	0	0	0	0	0	0	0
1	0	0	0	0	5	0	0	0
2	0	0	0	0	5	0	0	0
3	0	0	0	0	5	0	0	0
4	0	0	0	0	0	15	0	0
5	0	0	0	0	0	0	15	0
6	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0

Regulation Interactions (T_{ij3})

	0	1	2	3	4	5	6	7
0	0	0	0	0	0	15	0	0
1	0	0	0	0	0	0	5	0
2	0	0	0	0	0	0	5	0
3	0	0	0	0	0	0	5	0
4	0	5	5	5	0	0	0	0
5	0	0	0	0	15	0	0	0
6	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0

Modified ENA Metrics

$$AMI = \sum_{i=0}^{N+2}\sum_{j=0}^{N+2}\left\{\left(\prod_{l=1}^{M}\frac{T_{ij_l}}{TST_{p_l}}\right)\log_2\left[\frac{\prod_{l=1}^{M}T_{ij_l}\cdot TST_{p_l}}{\prod_{l=1}^{M}T_{i.l}\cdot T_{.j_l}}\right]\right\}$$

$$H = -\sum_{i=0}^{N+2}\sum_{j=0}^{N+2}\left\{\left(\prod_{l=1}^{M}\frac{T_{ij_l}}{TST_{p_l}}\right)\log_2\left[\prod_{l=1}^{M}\frac{T_{ij_l}}{TST_{p_l}}\right]\right\}$$

$$\boldsymbol{DoSO = {}^{AMI}/_{H}}$$

where,

$$TST_{pl} = \sum_{i=0}^{N+2}\sum_{j=0}^{N+2}T_{ijl}$$

$$T_{i.l} = \sum_{j=0}^{N+2}T_{ijl};\quad T_{.jl} = \sum_{i=0}^{N+2}T_{ijl}$$

Resilient SoS Development Workflow

Step	Toolset/Approach
1. Generate many candidate SoS architectures	SoS design guidelines; automation
2. Evaluate candidates and identify most promising few candidates	**ENA-inspired tool** (multi-architecture comparison mode)
3. Further analyze/refine remaining candidates	**ENA-inspired tool** (side-by-side comparison & single architecture modes)
4. Detailed SoS refinement/development	Detailed simulations with specific disruption models

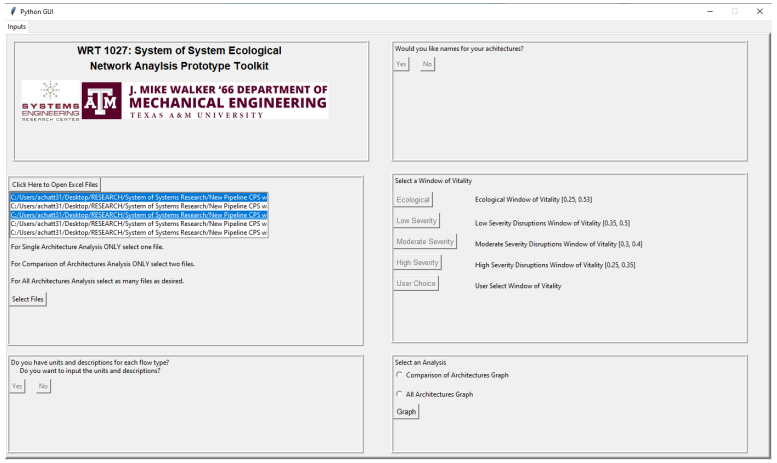
- Current practice limited to steps 1 and 4 and, consequently, narrower exploration of SoS architectures
- ENA-inspired tool enables new insights and broader architectural exploration (steps 2 & 3)
- Complementary to current tools/practice

SoS Development Tool and Demonstration

Python-based decision support tool for development of resilient SoS

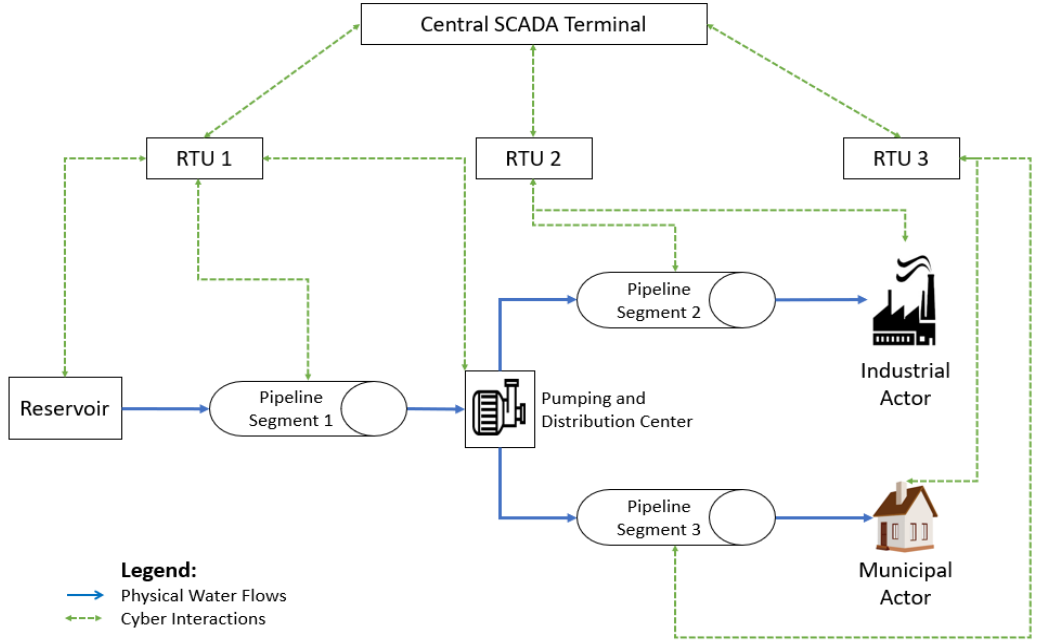
Analysis modalities:

1. Multi-architecture comparison
2. Detailed side-by-side comparison of two SoS architectures
3. Detailed single SoS architecture analysis

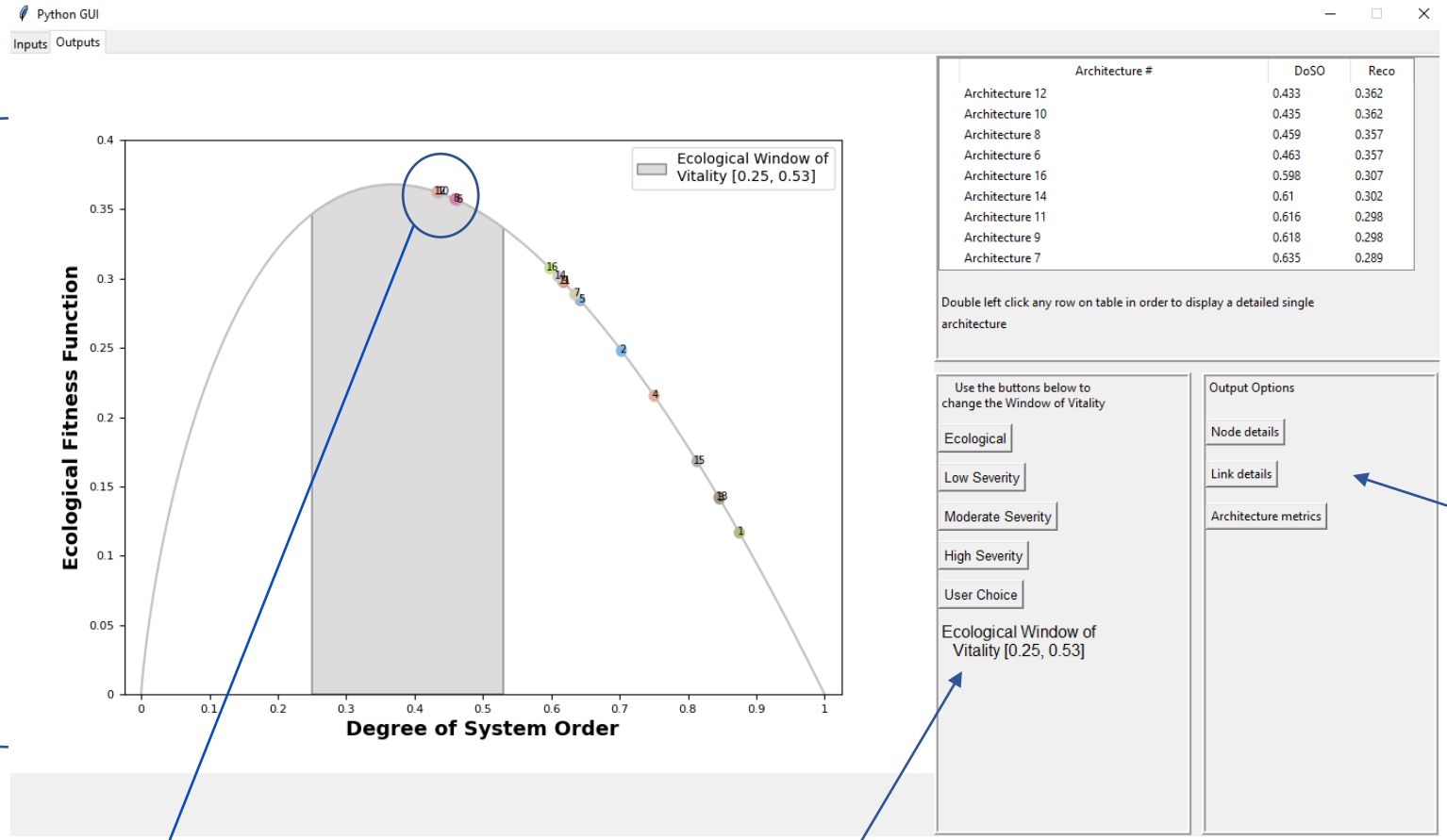


Distribution pipeline cyber-physical SoS demo

- Cyber systems (RTUs, SCADA terminal)
- Physical systems (reservoir, pipeline segments, pumping & distribution, consumers)



Multi-Architecture Analysis



Compare all candidate SoS architectures

Compare and sort SoS architectures based on ENA-inspired metrics

Can select individual architecture to see details

Network Analysis evaluations for the architecture as well as nodes and links can be output for further use.

Select Architecture 10 within WoV for further analysis

Defaults to ecological Window of Vitality

Can specify own preferred DoSO range

Side-by-Side SoS Comparison

Comparing Architecture 10 to the base architecture (1) to understand special features in architecture 10

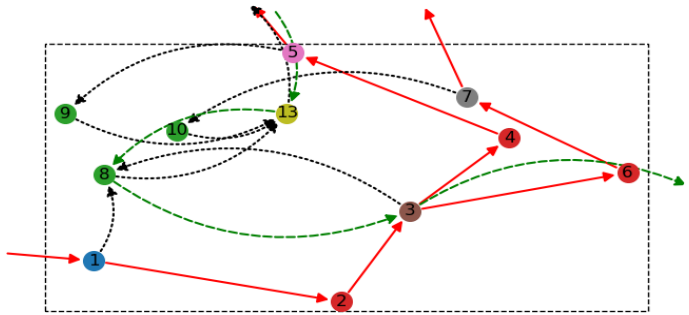
ENA metrics comparison →

ENA based comparison of selected SoS architectures

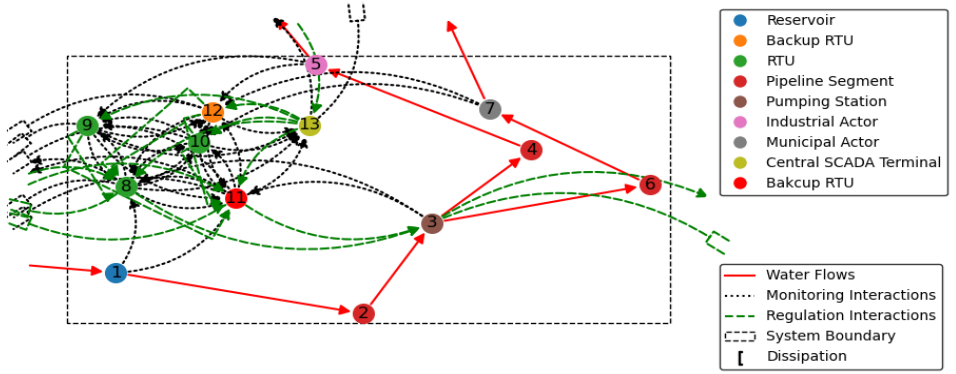
Table 1: Metrics for each Architecture

Metrics	Architecture 1 (Base)	Architecture 10 (WoV Architecture)
Average Mutual Information (AMI)	6.823	4.133
Shannon Index (H)	7.796	9.491
Conditional Entropy (H_c)	0.973	5.359
Degree of System Order (DoSO)	0.875	0.435
Ecological Fitness Function (R_{eco})	0.117	0.362

Architecture 1 (Base)



Architecture 10 (WoV Architecture)



Side-by-Side SoS Comparison

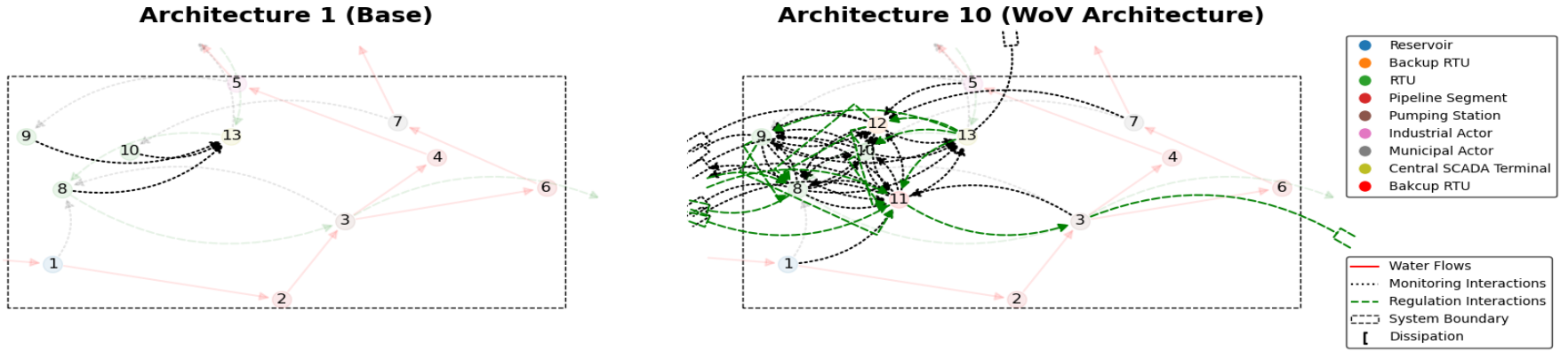
Comparing Architecture 10 to the base architecture (1) to understand special features in architecture 10

ENA based comparison of selected SoS architectures

Table 1: Metrics for each Architecture

Metrics	Architecture 1 (Base)	Architecture 10 (WoV Architecture)
Average Mutual Information (AMI)	6.823	4.133
Shannon Index (H)	7.796	9.491
Conditional Entropy (H_c)	0.973	5.359
Degree of System Order (DoSO)	0.875	0.435
Ecological Fitness Function (R_{eco})	0.117	0.362

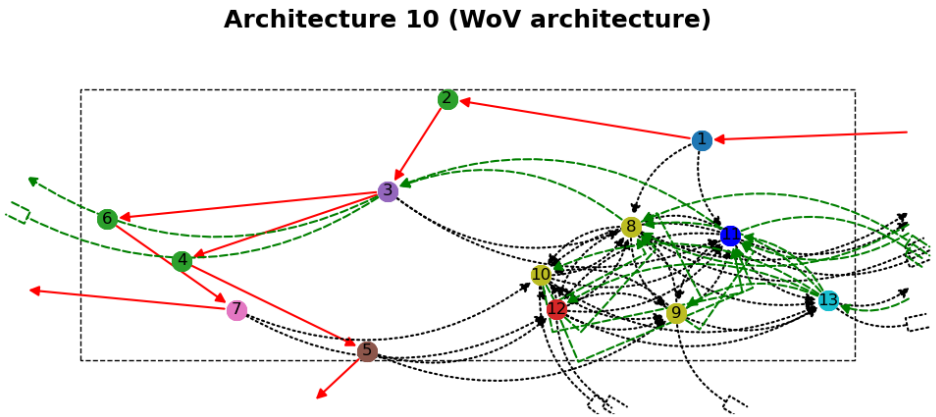
Can highlight architectural differences



The nodes and edges highlighted in the network diagrams are those that are only present in one of the architectures or have a difference in magnitude.

Single Architecture Analysis

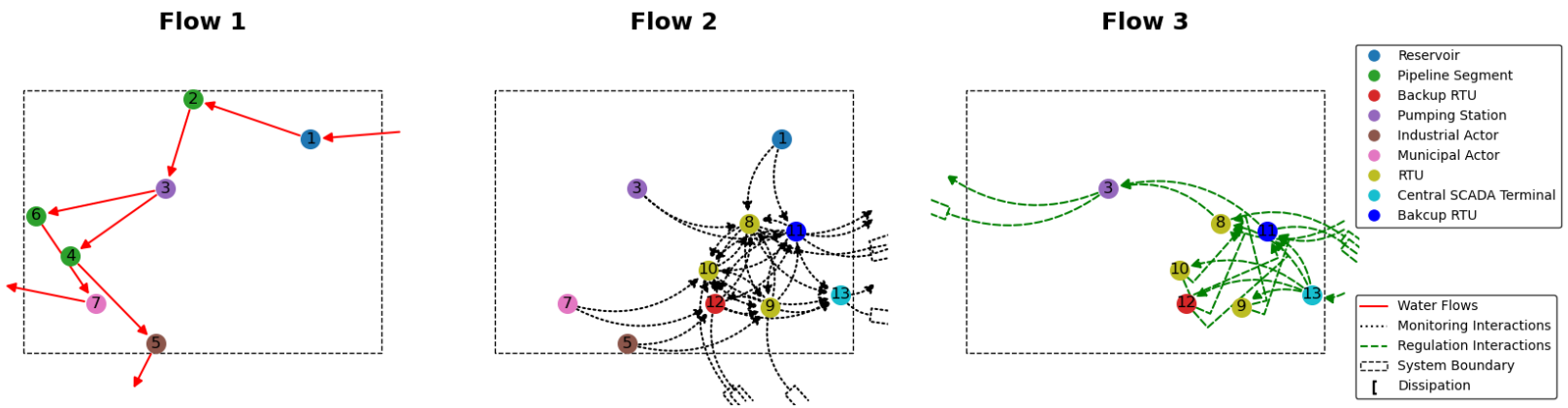
Can view full architecture and isolate individual flow networks



	AMI	H	DoSO	R_{eco}
Overall	4.133	9.491	0.435	0.362
Flow 1	2.738	3.044	0.899	0.095
Flow 2	0.635	4.977	0.128	0.263
Flow 3	1.418	4.085	0.347	0.367

Highlighted rows indicate that those architectures are within the selected DoSO range

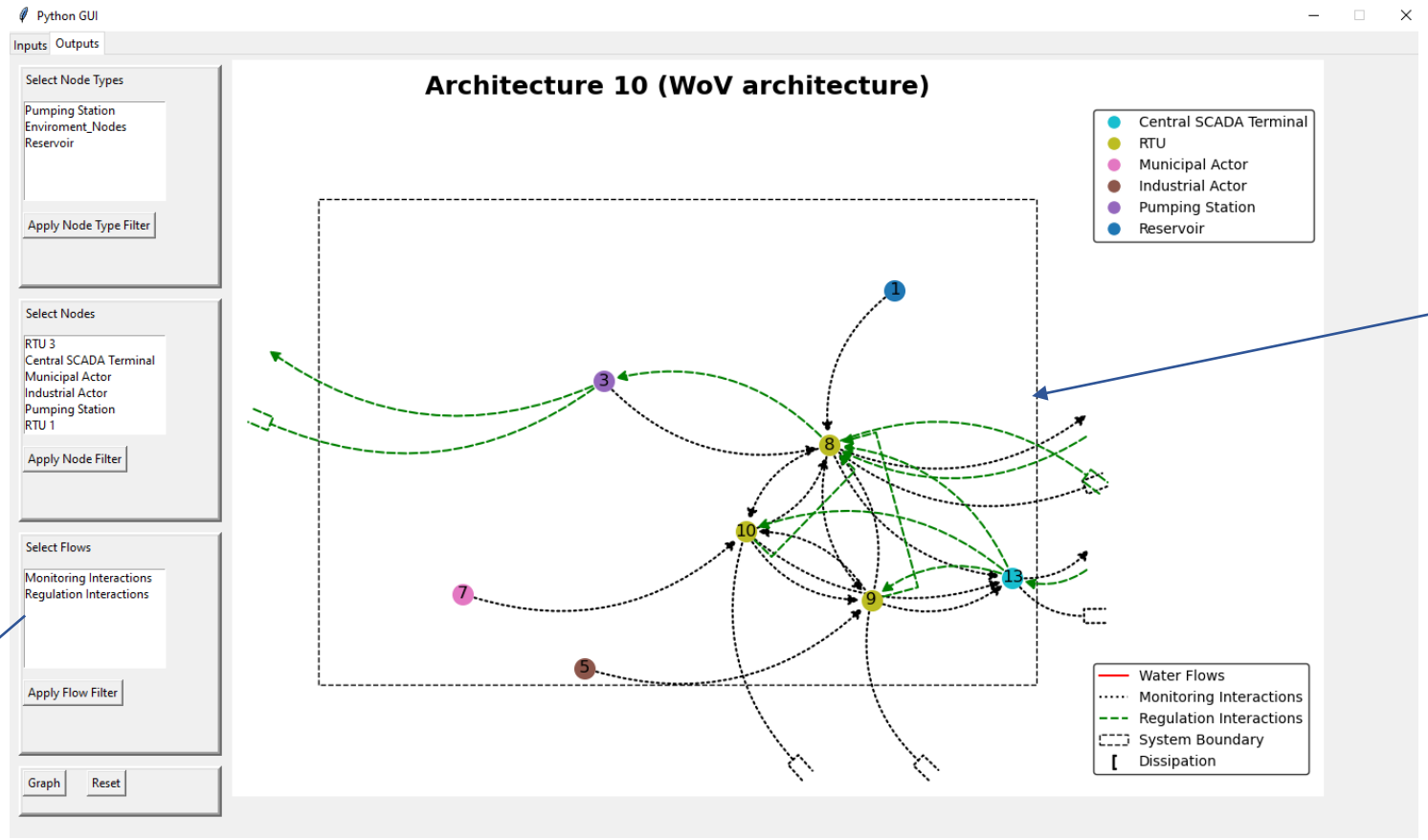
ENA-inspired metrics
- Full SoS
- Each interaction type



Single Architecture Analysis

Functionality to focus on:

1. Constituent system types
2. Constituent Systems
3. Interactions types



In this case focusing on the two cyber interactions and primary RTUs

Network architecture visualization focusing on features of interest selected by the design team

Main Results

Foundational insights into SoS engineering based on insights from ecological network analysis (ENA)

- Network flow redundancy as distinct from other redundancies in SoS
- Degree of System Order (DoSO) as indicator of SoS performance
- Window of Vitality (WoV) as desirable range for DoSO quantity
- ***New capability to identify SoS that inherently balance cost and resilience without detailed disruption models or SoS simulations***

Modeling framework for cyber-physical SoS

- Directed multigraphs for handling multiple flow types
- Guidelines for modeling non-conserved flows (e.g., cyber interactions)
- Extended DoSO to directed multigraphs

Prototype decision support tool for resilient SoSE

- Important expansion of SoSE capabilities—middle ground between entirely qualitative and highly detailed and costly
- Supports screening of many SoS architectures via ENA-inspired metrics
- Detailed comparisons and analyses of candidate SoS architectures
- Distribution pipeline cyber-physical SoS demonstration

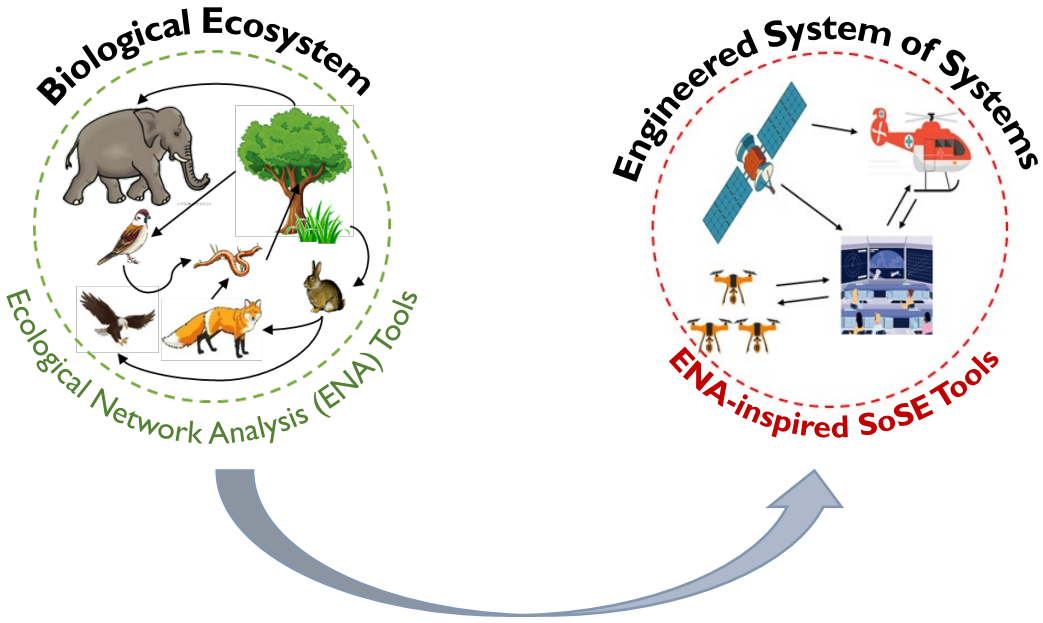
Potential Extensions and Future Work

- Application of prototype tool to new problems—interested in collaborations & potential customers
  - New SoS development
  - Existing SoS analysis and/or modification
  - Potential role in systems development and/or acquisitions (e.g., defining systems that contribute to making existing or planned SoS more resilient)

- Introduction of SoS refinement and optimization capabilities
  - Automatically identify modifications to a SoS to move it closer to WoV
  - Optimize SoS for other criteria under constraint to be within WoW

- Tool extensions and updates
  - Improved user interface
  - Expanded visualization capabilities
  - Extended data input capabilities
  - Algorithmic improvements (for scalability)

Thank you!


Biological Ecosystem
Ecological Network Analysis (ENA) Tools
Engineered System of Systems
ENA-inspired SoSE Tools