

Toward Scaling Model-Based Engineering for Systems of Systems

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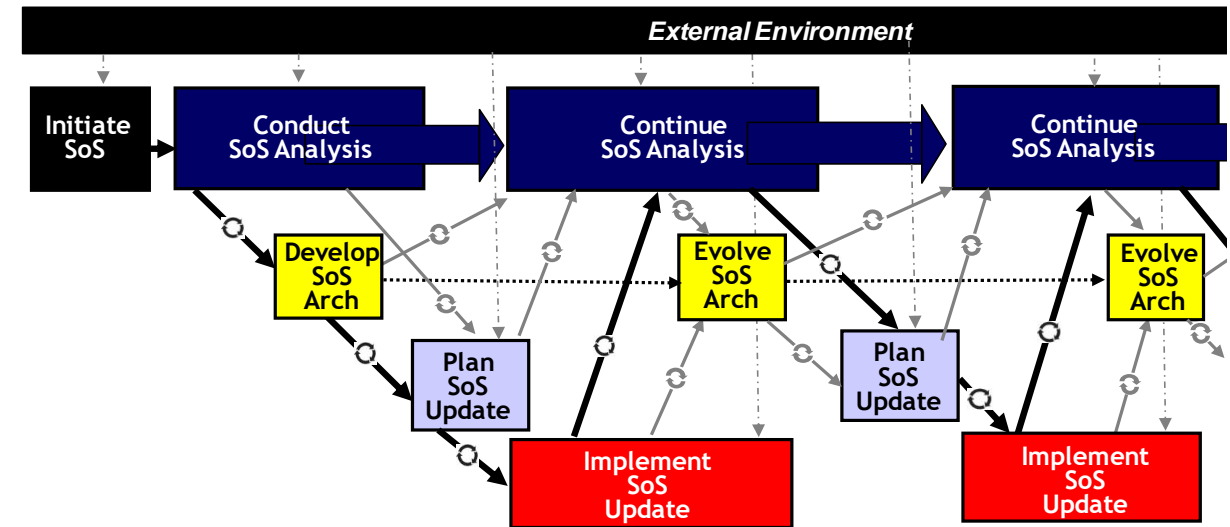
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Agenda

- **Model-Based Systems-of-Systems Engineering**
- **Scalable Modeling and Analysis**
- **Technical Approach and Results**
- **Conclusions and Opportunities**

The System of Systems (SoS) Context

- Nearly every system operates as part of an SoS
- An SoS is “a set or arrangement of systems that results when **independent and useful systems are integrated** into a larger system that delivers unique capabilities” [DoD SE Guide for SoS]
- SoS:
 - Are **not ‘designed’** top down, green field systems
 - **Evolve over time** based on changing capability needs and systems
 - Engineering follows an **evolutionary ‘wave’** process versus traditional system ‘V’

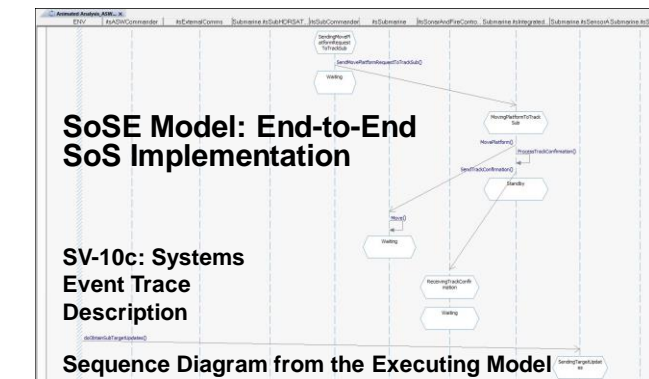
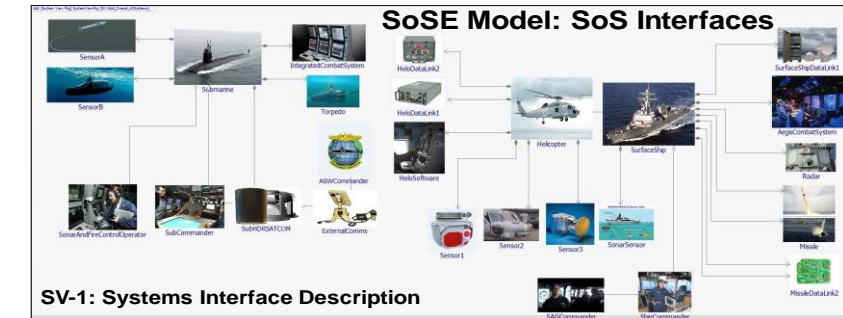
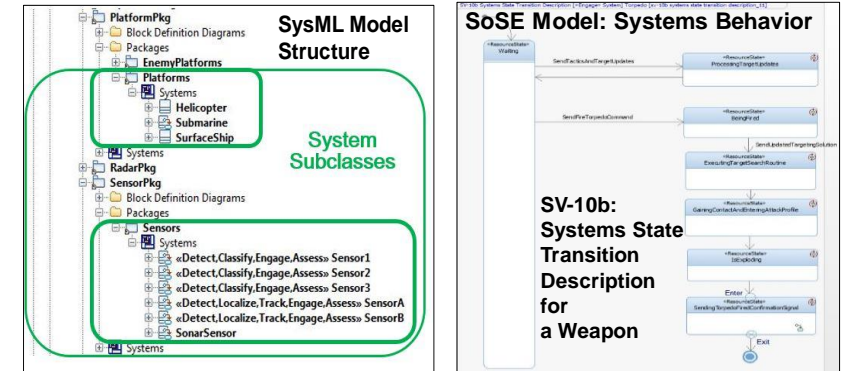


J. Dahmann, G. Rebovich, J. Lane, R. Lowry, and K. Baldwin, “An Implementers’ View of Systems Engineering for Systems of Systems,” in *2011 IEEE International Systems Conference*, 2011, pp. 212–217.

- SoS engineering (SoSE) requires an iterative approach of planning, analyzing, organizing, and integrating a mix of existing and new systems

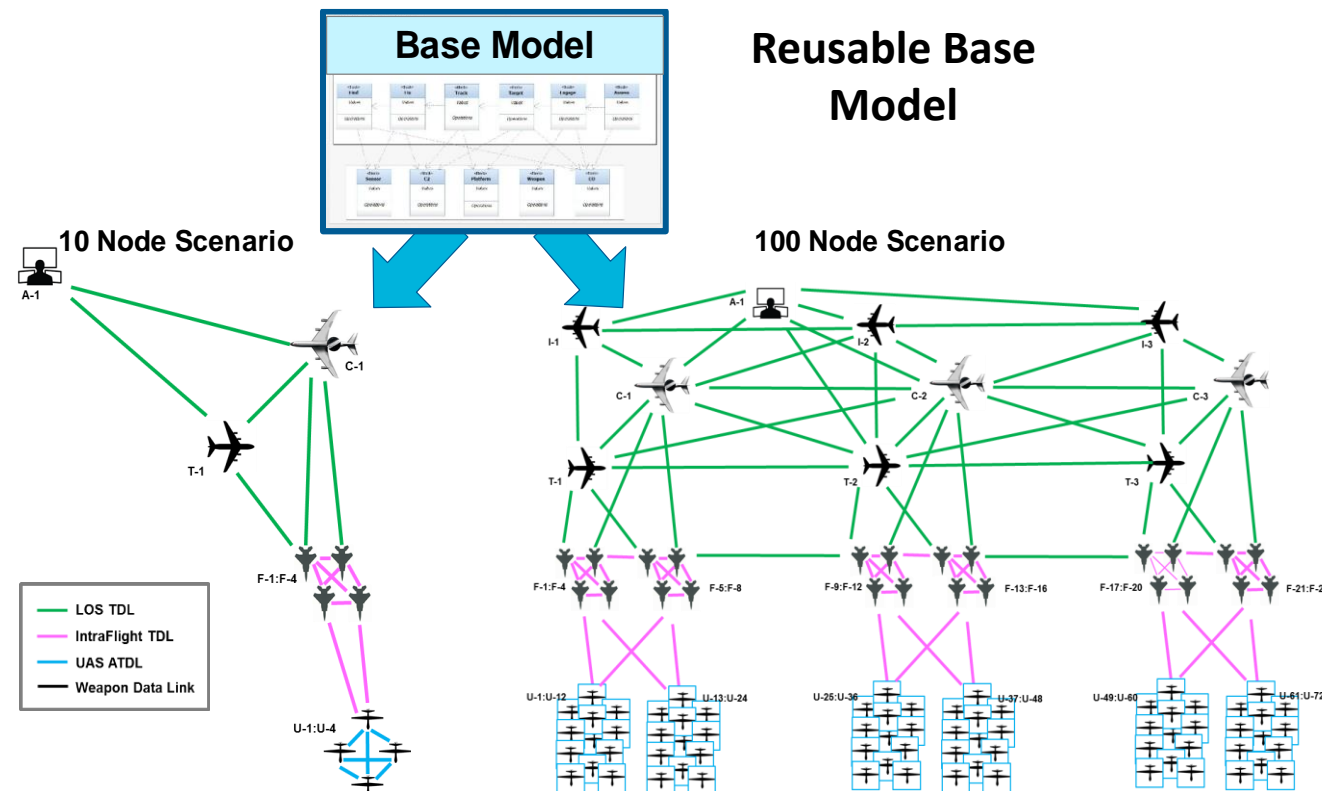
Model-Based SoSE

- For SoSE purposes, a SysML model is an unambiguous, structured, executable, digital representation of the SoS system architecture
- Ways MBE can provide value:
 - Fosters rigorous thinking about architecture decisions
 - Facilitates communication among stakeholders
 - Provides shared knowledge base for development team
 - Allows for automatic generation of documentation
 - Multiple consistent fit-for-purpose views
 - Changes anywhere in the model are propagated to all relevant views and documents



J. Dahmann, A. Markina-Khusid, A. Doren, T. Wheeler, M. Cotter, and M. Kelley, "SysML executable systems of system architecture definition: A working example," in *2017 Annual IEEE International Systems Conference (SysCon)*, 2017, pp. 1–6.

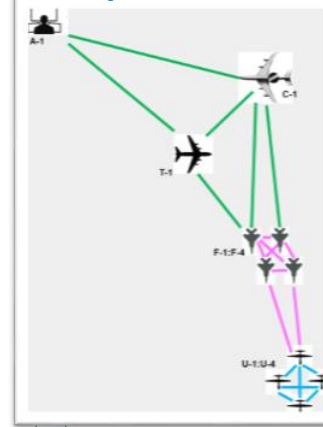
- **A key enabler of model-based SoSE is the ability to efficiently develop large complex SoS architecture models**
- **The effort required to build SoS architecture models can be reduced by starting the modeling process with a reusable base model template, independent of the architecture size**



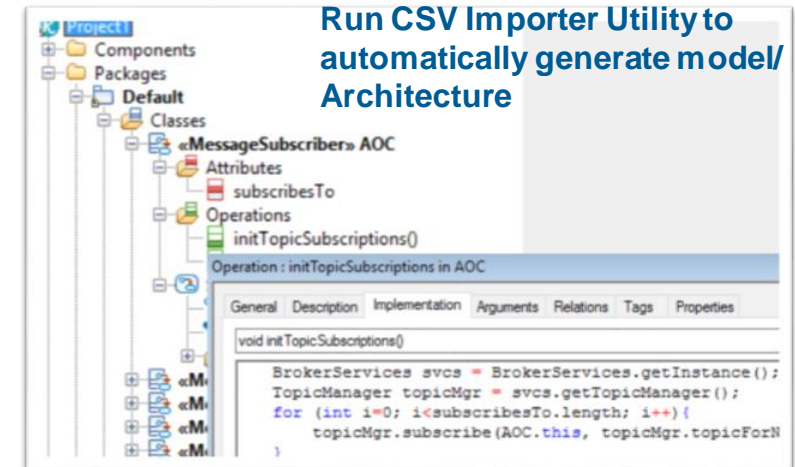
Scalable Model-Based SoSE: CSV Importer

- Tools can facilitate integration of SoS connectivity information into MBE tools, tightening the coupling between subject matter experts (SMEs), software engineers, and analysts — comma separated variable (CSV) importer tool

Conceptualize SoS Architecture



Run CSV Importer Utility to automatically generate model/Architecture



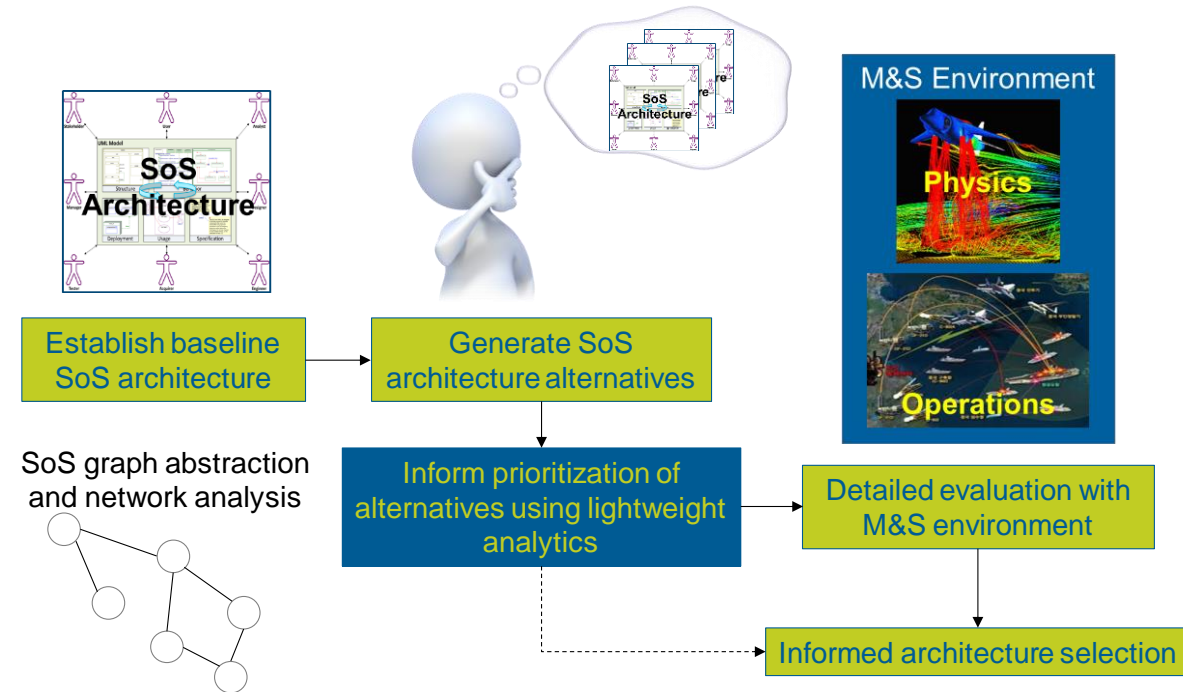
Add Connectivity Framework

SUBSCRIBERS	PUBLISHERS				
	AOC	C2	Tanker	Fighter	UAS
AOC		threats, missionOutcome			
C2	aocDecisions			fightersToC2	
Tanker		beginMission, missionOutcome		lowFuel	lowFuel
Fighter		beginMission		intraFlightTDL	UASsToFighters
UAS				fightersToUASs	uasATDL

CSV Importer

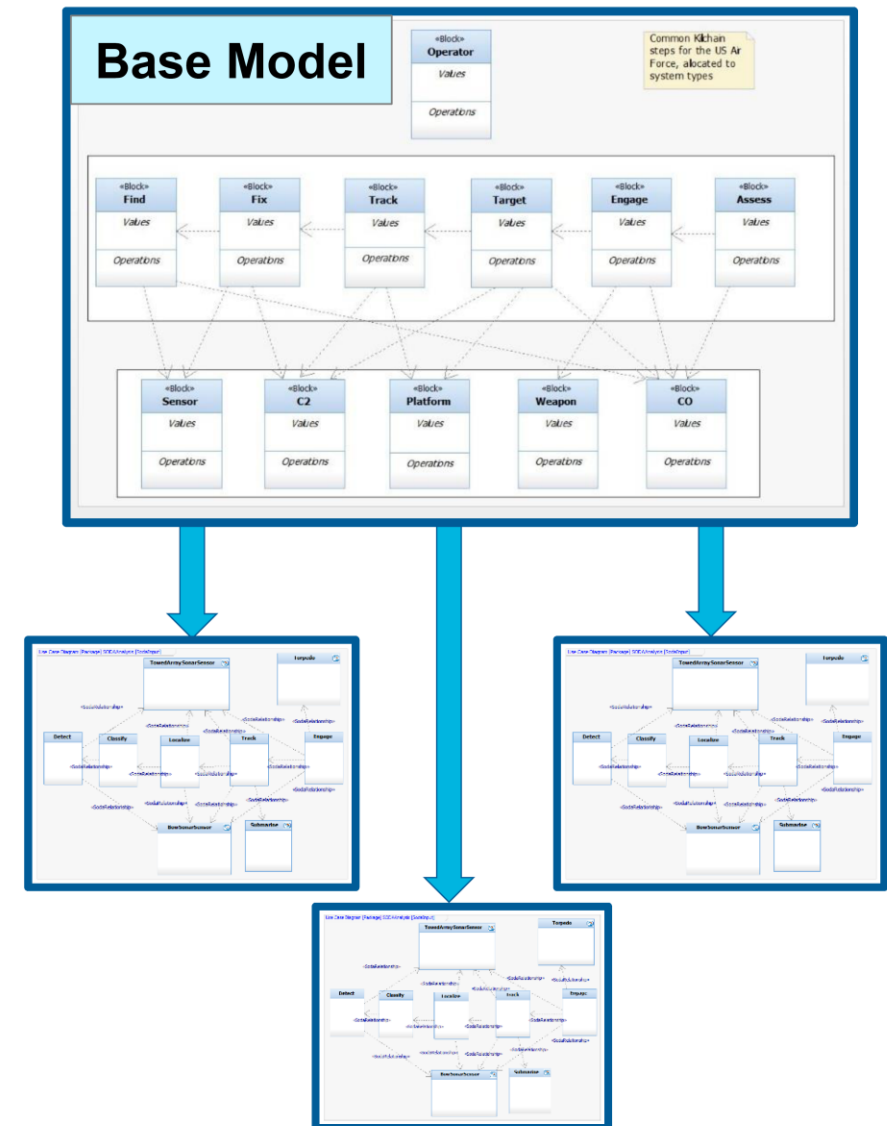
Scalable Model-Based SoSE: Analysis

- **Representing SoS architecture in a model opens the options for analysis**
 - Interfacing a SoS model with other tools to assess performance, cost, other aspects of the SoS, provides a shared representation of the architectures for analysis from different perspectives
 - Developing approaches to assess alternative architectures is a challenge from the perspective of scalability
 - How do you identify viable options for more detailed analysis when there is such a large tradespace?



Technical Approach: Base Model

- **Base/Derivative model framework**
 - Base model captures generic SoS functional architecture, structure, and behavior
 - Derivative model represents domain-specific structure and behavior
- **Preliminary findings from user experiments**
 - Base model may require too many modifications to add value to SoS modeling in some project contexts
 - **39% average time savings** to model an Air Force kill chain scenario



Technical Approach: CSV Importer

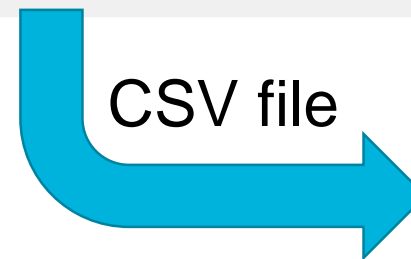
■ CSV importer utility

- Enables SMEs, who may not be adept at MBE modeling, to transfer their knowledge to the model
- MATLAB GUI automates process of creating links between constituent systems

■ Preliminary findings from user experiments

- 63% average time savings
- 91% average reduction in number of mistakes

	itsAOC_1	itsC2_1	itsTanker_1	itsFighter_1	itsFighter_2
itsAOC_1	0	0	0	0	0
itsC2_1	0	0	0	1	1
itsTanker_1	0	0	0	0	0
itsFighter_1	0	1	0	0	0
itsFighter_2	0	1	0	0	0

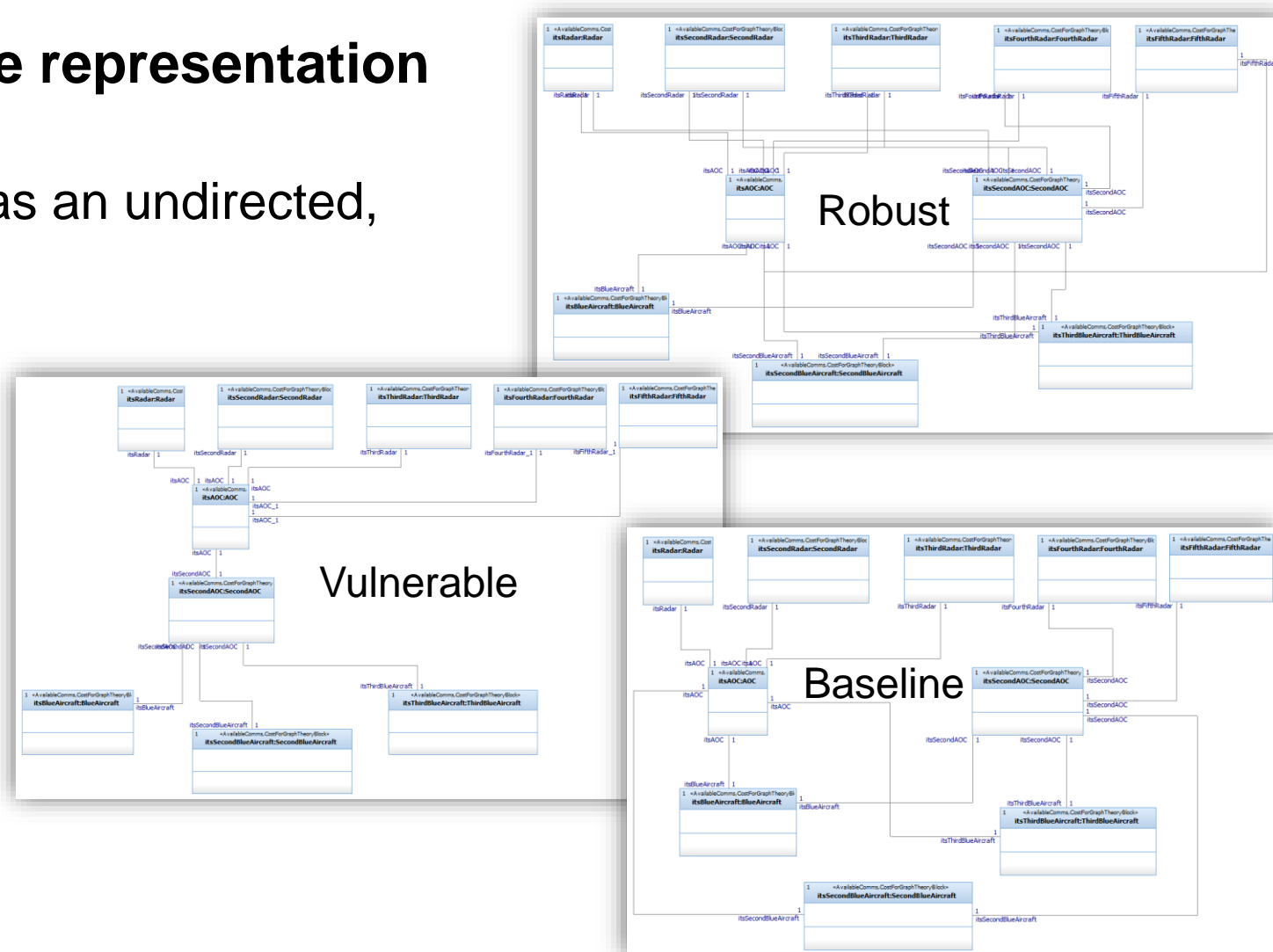


SysML Architecture Model

Technical Approach: Robustness Analysis

■ Leverage SysML architecture representation for robustness analysis

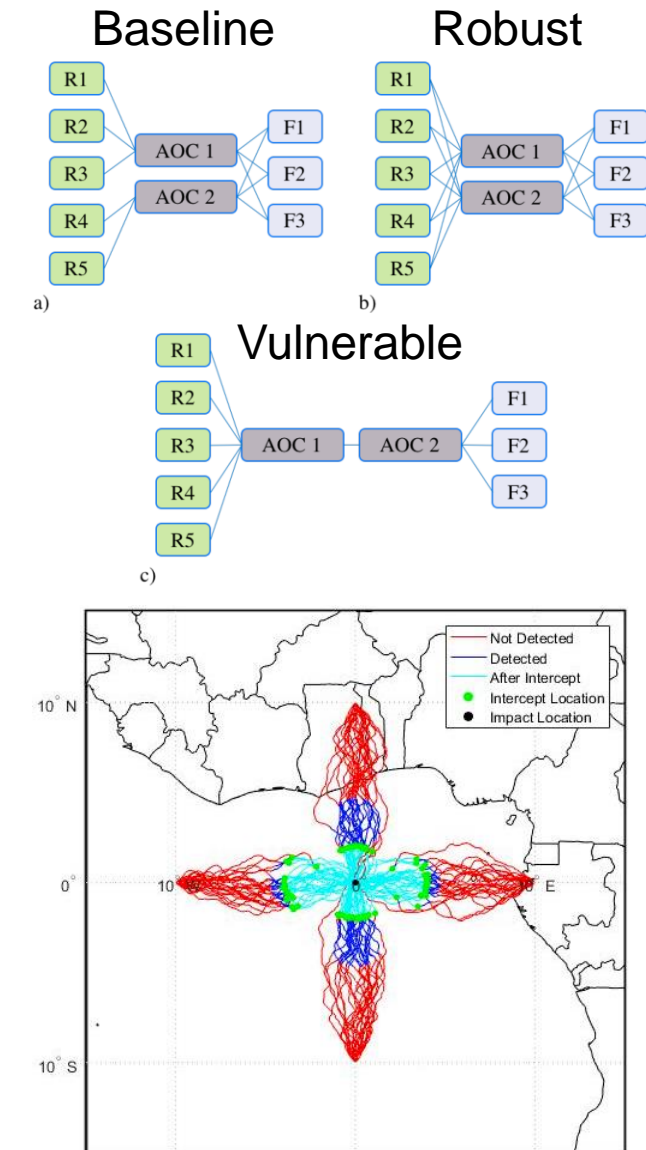
- SoS structure can be viewed as an undirected, unweighted graph
- Graph robustness metric investigated: **algebraic connectivity** — the minimum number of nodes and links whose removal disconnects the graph
- Low computational cost of graph metrics enables scalable tradespace analysis



Technical Approach: Robustness Analysis

- Preliminary findings from comparison with simulation
 - Algebraic connectivity follows a similar trend to the simulation probability of engagement success
 - Algebraic connectivity is more sensitive to architecture changes made for the robust column

Case	System Disabled	Baseline P_{ES}	Robust P_{ES}	Vulnerable P_{ES}
0	-	0.608	0.608	0.608
1	R1	0.448	0.448	0.448
2	R2	0.608	0.608	0.608
3	R3	0.454	0.454	0.454
4	R4	0.467	0.467	0.467
5	R5	0.454	0.454	0.454
6	AOC 1	0.314	0.608	0.0
7	AOC 2	0.294	0.608	0.0
8	F1	0.582	0.582	0.582
9	F2	0.461	0.461	0.461
10	F3	0.589	0.589	0.589
Mean P_{ES}		0.467	0.528	0.406
Algebraic Connectivity		0.506	2.000	0.309



Conclusions and Opportunities

- **We propose:**
 - An **SoS base model** to save model-building time
 - A **CSV importer** to ease the modeling process for SMEs, modelers, and analysts
 - **Graph-theoretic architecture analysis** that leverages MBE model data
- **Preliminary findings indicate substantial time savings and error reduction with the base model and CSV importer**
- **Correlation of algebraic connectivity and simulation results is encouraging**
- **Research opportunities:**
 - Continue experimenting with base model and CSV importer
 - Multilayer graph representations for analysis
 - Further investigation of the correlation between graph-theoretic metrics and simulations

Questions?
