A SYSTEMS ENGINEERING METHODOLOGY FOR INTEGRATING AUTONOMY WITH SYSTEM OF SYSTEMS AND CONDUCTING DATA-DRIVEN TRADE STUDY ANALYSES

Mohammadreza Torkjazi
Ph.D. Candidate – Systems Engineering and Operations Research
mtorkjaz@gmu.edu

Dr. Ali K. Raz (Research Advisor)
Assistant Professor – Systems Engineering and Operations Research
Associate Director – Intelligent Systems and Integration – C5I Center
araz@gmu.edu

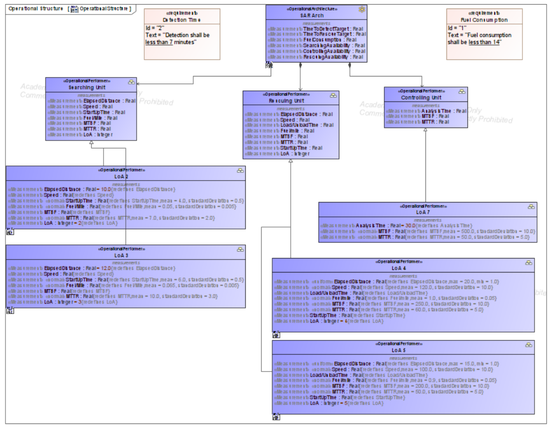
AI4SE & SE4AI

GEORGE MASON UNIVERSITY

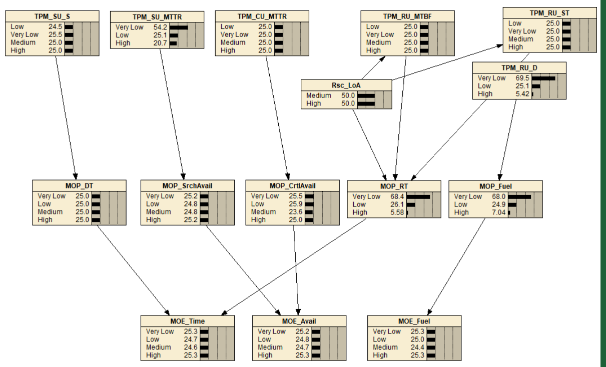
RESEARCH OVERVIEW

- **Motivation**
  - Advancements in AI/ML have enabled autonomy in engineered systems that reduce human workload and involvement in hazardous missions.
  - Autonomous engineered systems can be integrated into existing SoSs to improve mission capabilities, evolving it to a System of Autonomous Systems (SoAS).
  - Autonomy comes in different levels (LoAs), each associated with uncertainty that makes the SoAS integration and Test and Evaluation (T&E) very challenging.

- **Research Questions**
  - How to examine the impacts of integrating varying LoAs into an existing SoS during the development phase?
  - How to develop a generic architecting method to manage the complexity of SoAS integration while it is applicable to various domains?
  - How to evaluate an SoAS while accounting for uncertainties and emergent behaviors due to varying LoAs?



Executable MBSE architecture with LoA

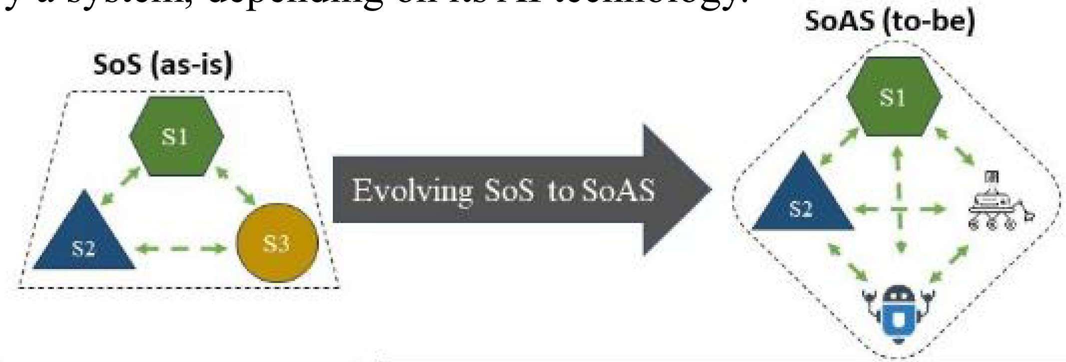


Bayesian Network built for SoAS T&E

LEVEL OF AUTONOMY (LOA)

- Traditional definition of *autonomy* in SoS:
  - Managerial and Operational autonomy: Constituent systems operate and are managed independently.
- Definition of *autonomy* in AI and autonomous systems:
  - The ability of a system to sense, perceive, analyze, communicate, plan, make decisions, and act/execute, to achieve its goals as assigned independent of human intervention.
- LoA refers to a set of these autonomous capabilities provided by a system, depending on its AI technology.

Levels	*Definition*
Hands-on	*Supported by driver assistance abilities such as lane-keep assist, auto cruise control, parking support*
Hands-off	*Supported by an autopilot requiring constant attention*
Eyes-off	*still Supported by a human under any emergency situations with communication by speech, gesture control, or via a touchscreen*
Mind-off	*No human intervention*
Fully Autonomous	*No human intervention, no steering wheel, no pedals, no breaks, even no windshield*



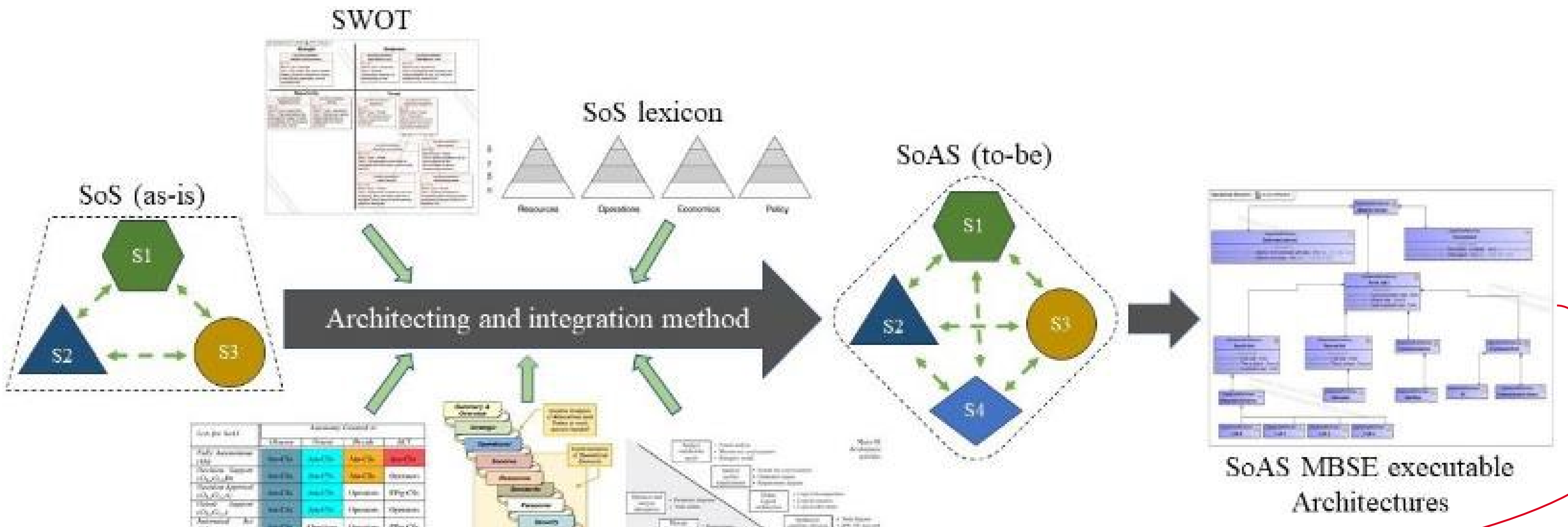
Constituent Systems:
- are engineered systems
- have well-defined requirements, behaviors, V&V, …

- Constituent Systems are a combination of Legacy and autonomous engineered Systems with varying LoAs
- Challenges due to LoA are:
  - impacts on organizational policies
  - impacts on human-systems integrations
  - incompatibilities in interfaces and data types between legacy and autonomous systems
  - cybersecurity needs due to data exchange and communication
  - Selecting the suitable SoAS architecture while accounting for uncertainty due to AI/ML and varying LoAs
  - Explaining root causes for SoAS-level undesirable emergent behaviors

The concept of LoA is missing in SoS, as defined in AI/ML literature, but it is crucial to be considered in SoAS

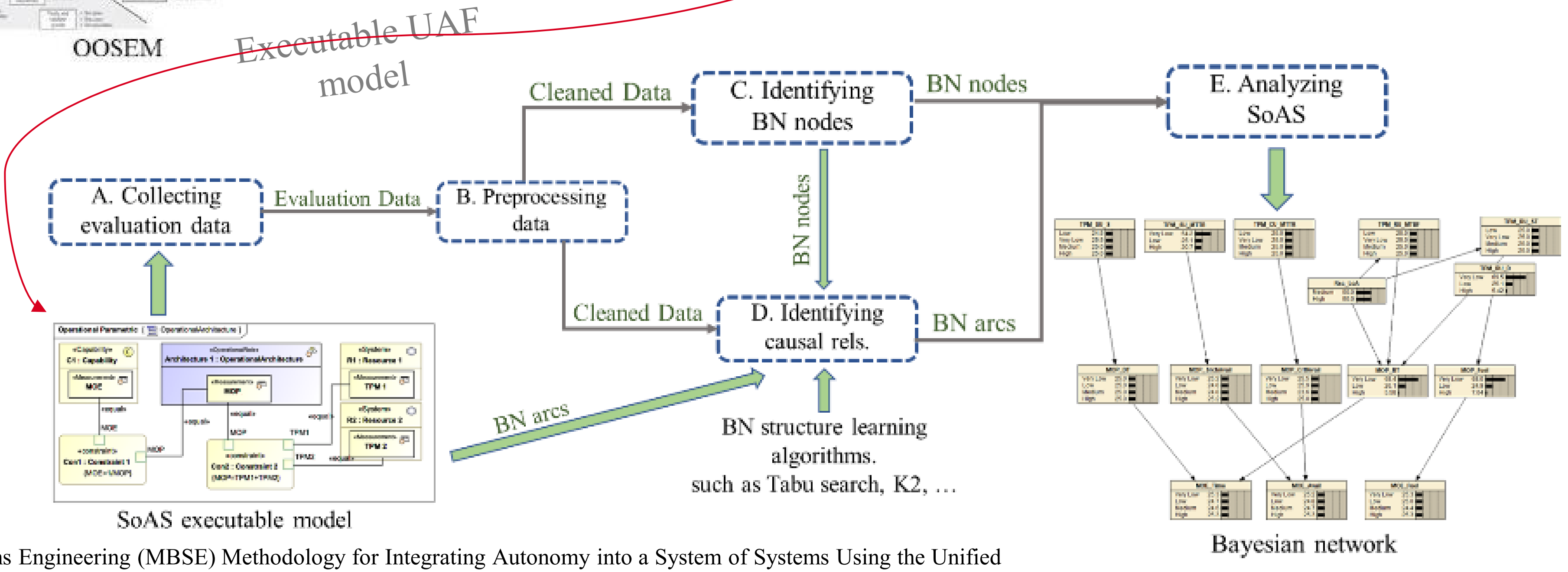
Torkjazi, M., & Raz, A. K. (2024a). A Review on Integrating Autonomy into System of Systems: Challenges and Research Directions. *IEEE Open Journal of Systems Engineering.* https://ieeexplore.ieee.org/document/10669760

THE PROPOSED SYSTEMS ENGINEERING METHODOLOGY



- The architecting method employs the UAF and OOSEM to build various executable LoA architectures and simulate their performance.

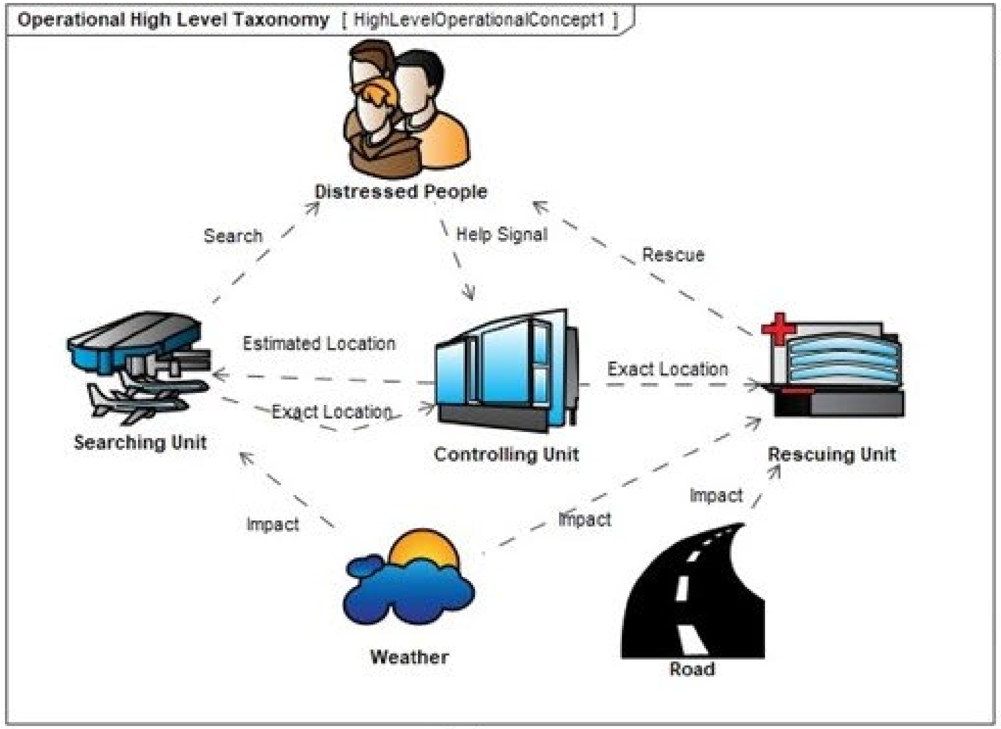
- The T&E method employs Bayesian Network (BN) and Machine Learning (ML) to provide a decision-making dashboard to explore the design space.

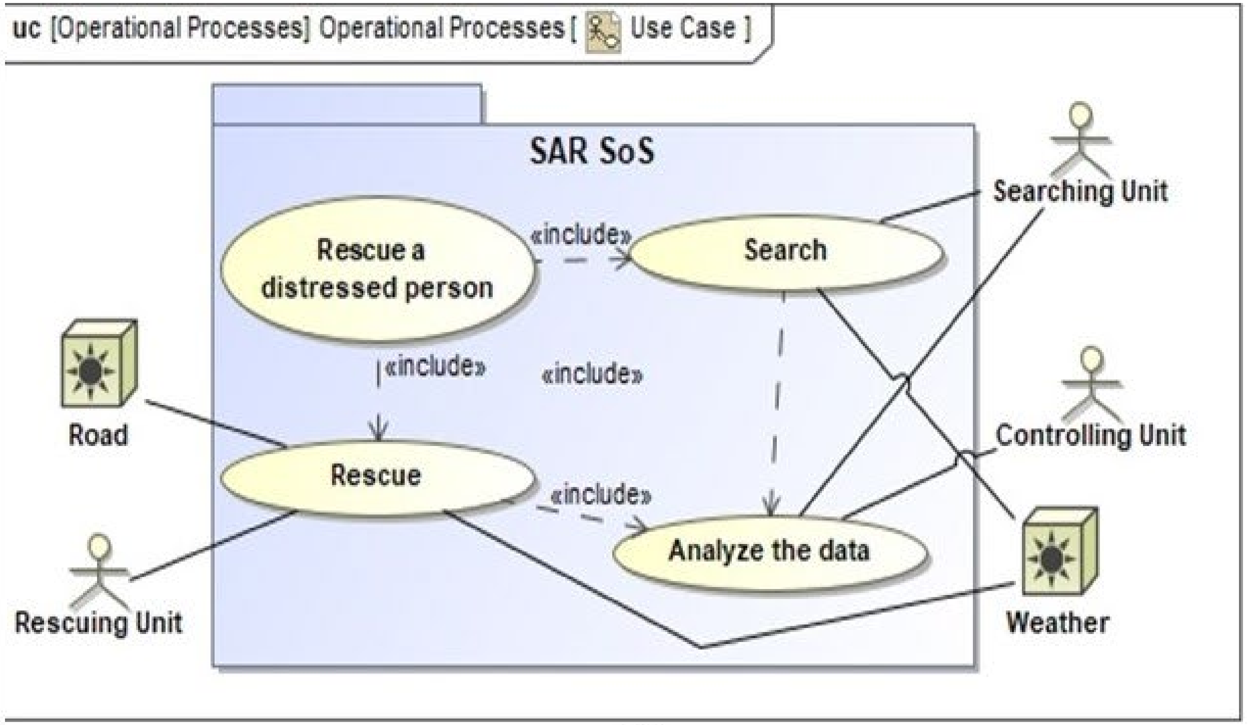


- Torkjazi, M., & Raz, A. K. (2024b). Model-Based Systems Engineering (MBSE) Methodology for Integrating Autonomy into a System of Systems Using the Unified Architecture Framework. *INCOSE International Symposium*, 34, 1051–1070. https://doi.org/10.1002/iis2.13195
- Torkjazi, M., & Raz, A. K. (2024c). Predictive and Prescriptive Analyses of Autonomy Integration into the System of Systems. In A. Salado, R. Valerdi, R. Steiner, & L. Head (Eds.), *The Proceedings of the 2024 Conference on Systems Engineering Research* (pp. 213–228). https://doi.org/10.1007/978-3-031-62554-1_14

CASE STUDY: SEARCH AND RESCUE (SAR) SOS

- Assume that the current SoS operations result in low-efficiency rates of fuel and the stakeholders desire to investigate improvement alternatives for the systems.
- One approach is using new autonomous systems available in the market that consume less fuel.

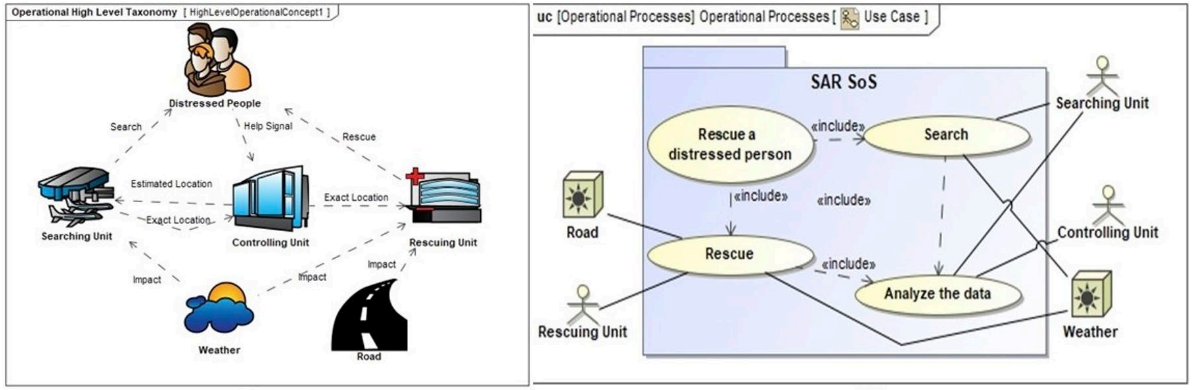




OBJECTIVES

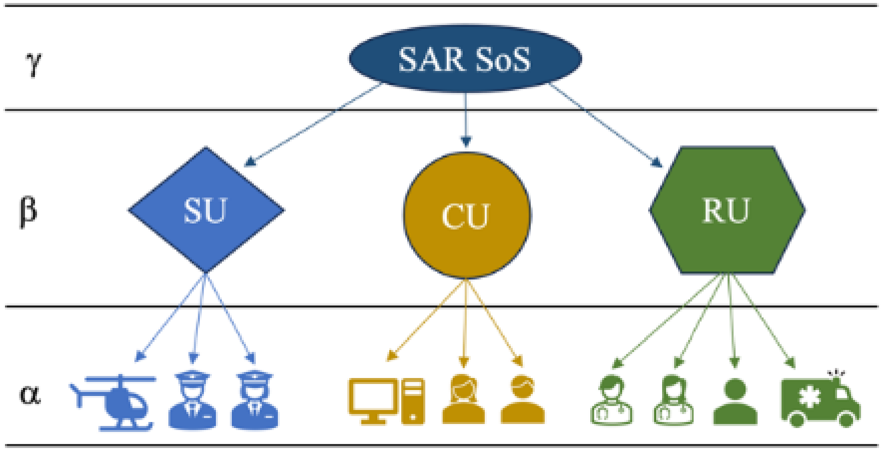
1) Identify the legacy systems to be replaced with autonomous systems
2) Determine the most suitable LoAs of autonomous systems that improve the SAR mission effectiveness metrics while considering uncertainty due to AI/ML

ANALYZE STAKEHOLDERS NEEDS



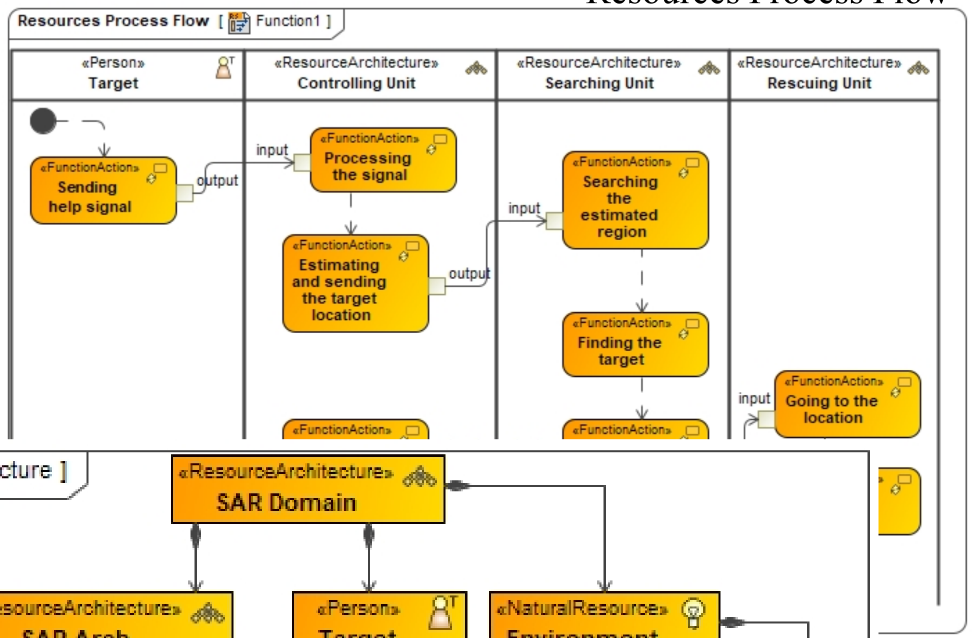
(a) (b)

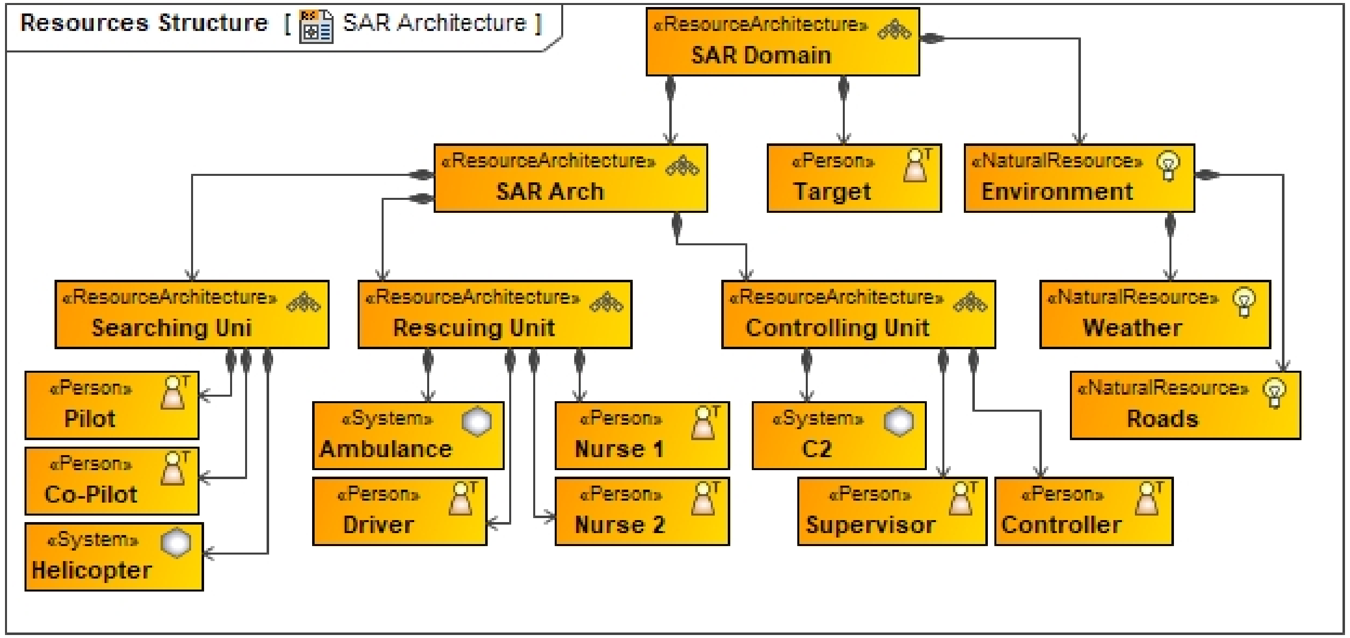
(a) Operational concept; (b) Use case diagram



Levels of the SoS based on the lexicon

Resources Process Flow

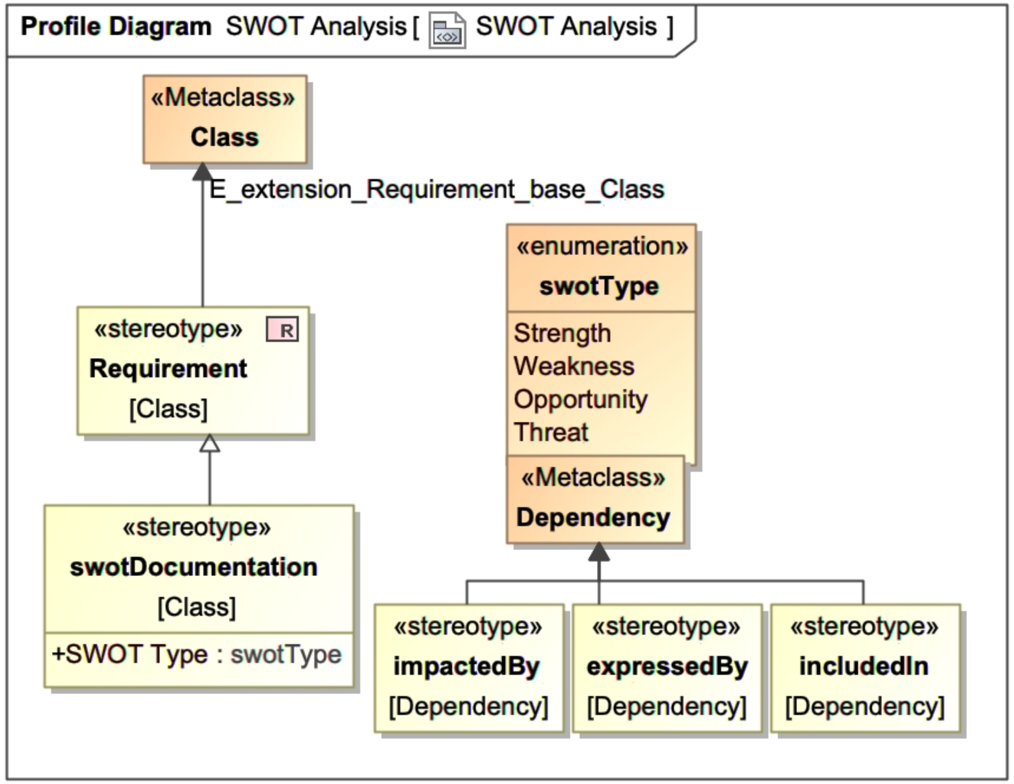




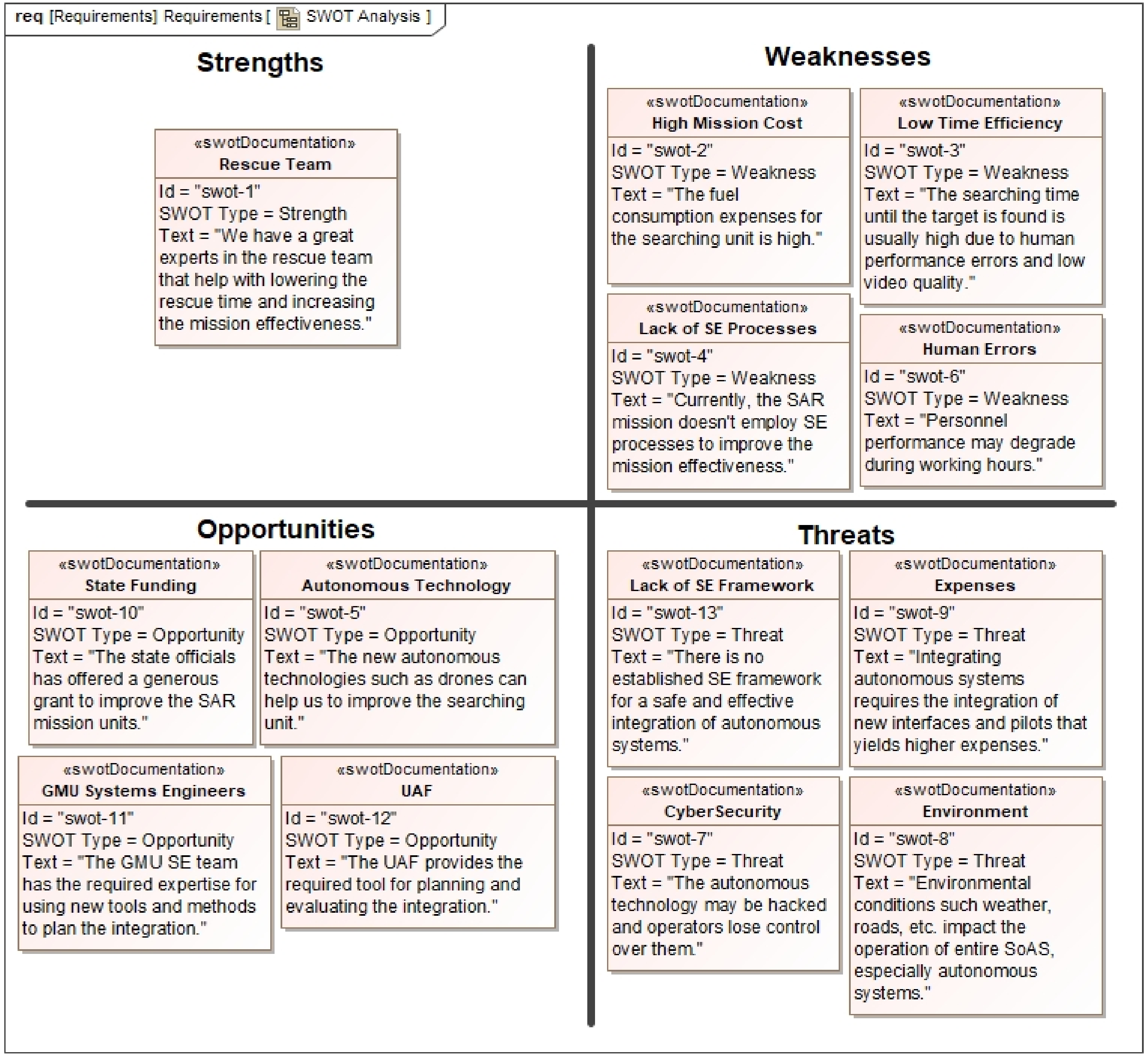
Resources Structure

Output:
SoS “as-is” architecture and activities

ANALYZE STAKEHOLDERS NEEDS



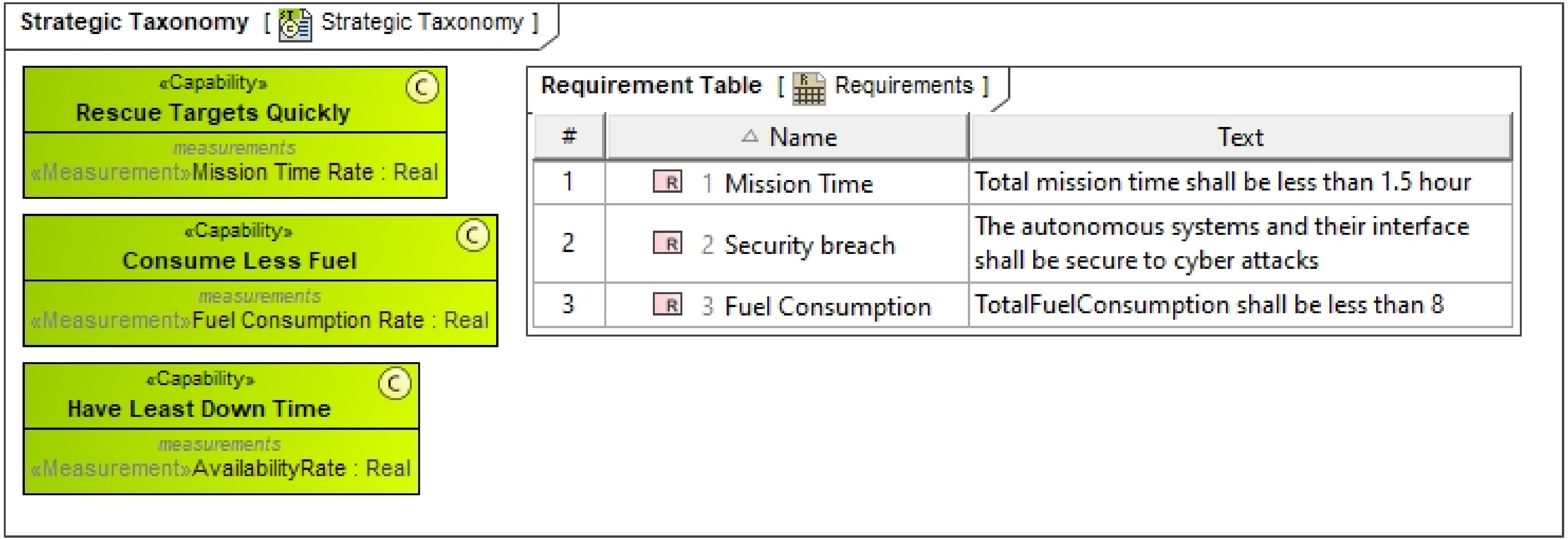
The UAF Profile Extension for including the MBSE SWOT analysis



Outputs:
the to-be SoAS capabilities, replaceable system, and risks

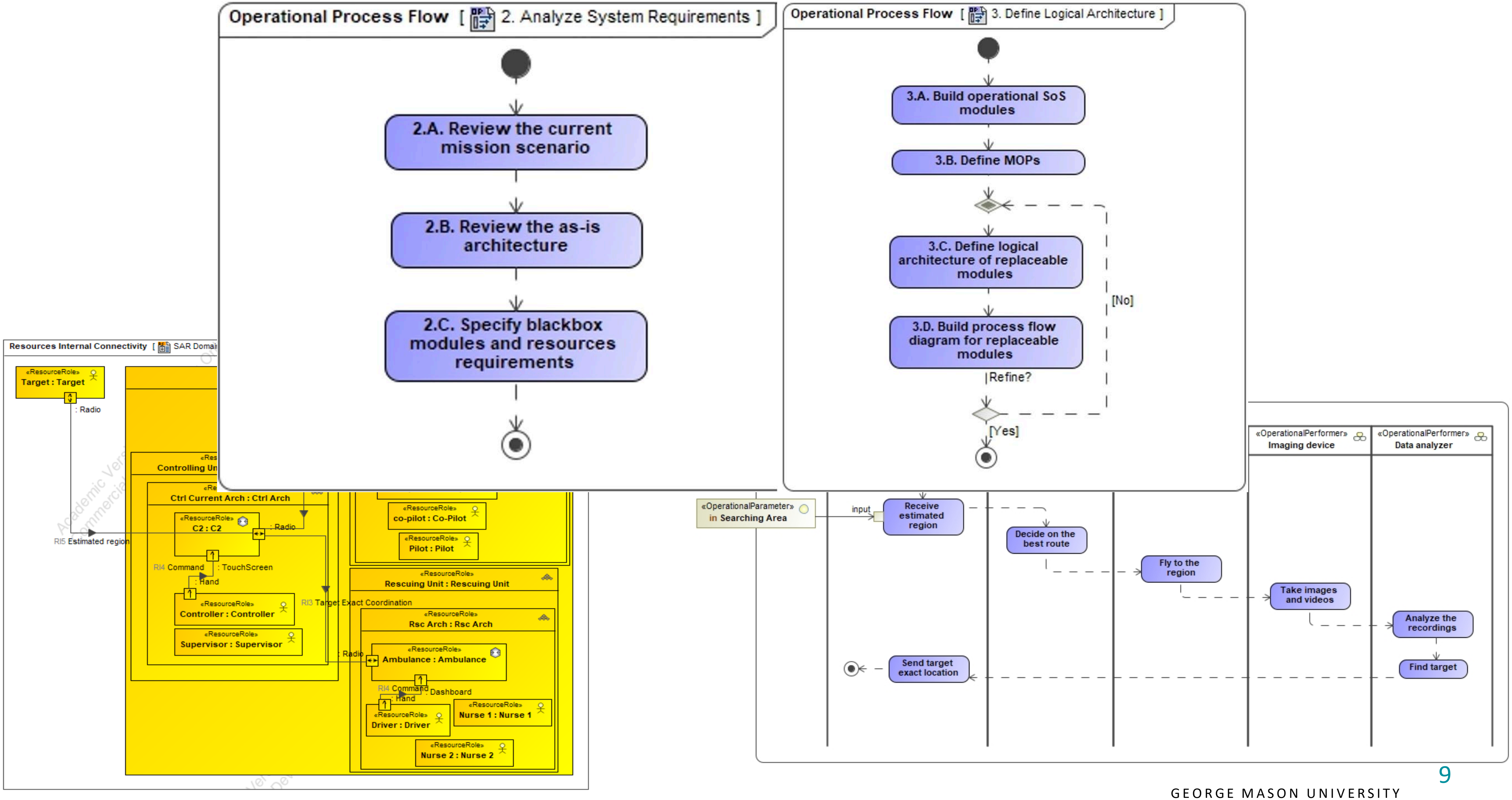
ANALYZE STAKEHOLDERS NEEDS

- Strategic Taxonomy view summarizes identified capabilities and their corresponding MOEs.
- Requirement table shows the identified mission and stakeholders' requirements.



#	Name	Text
1	1 Mission Time	Total mission time shall be less than 1.5 hour
2	2 Security breach	The autonomous systems and their interface shall be secure to cyber attacks
3	3 Fuel Consumption	TotalFuelConsumption shall be less than 8

Analyze System requirements & define logical architecture



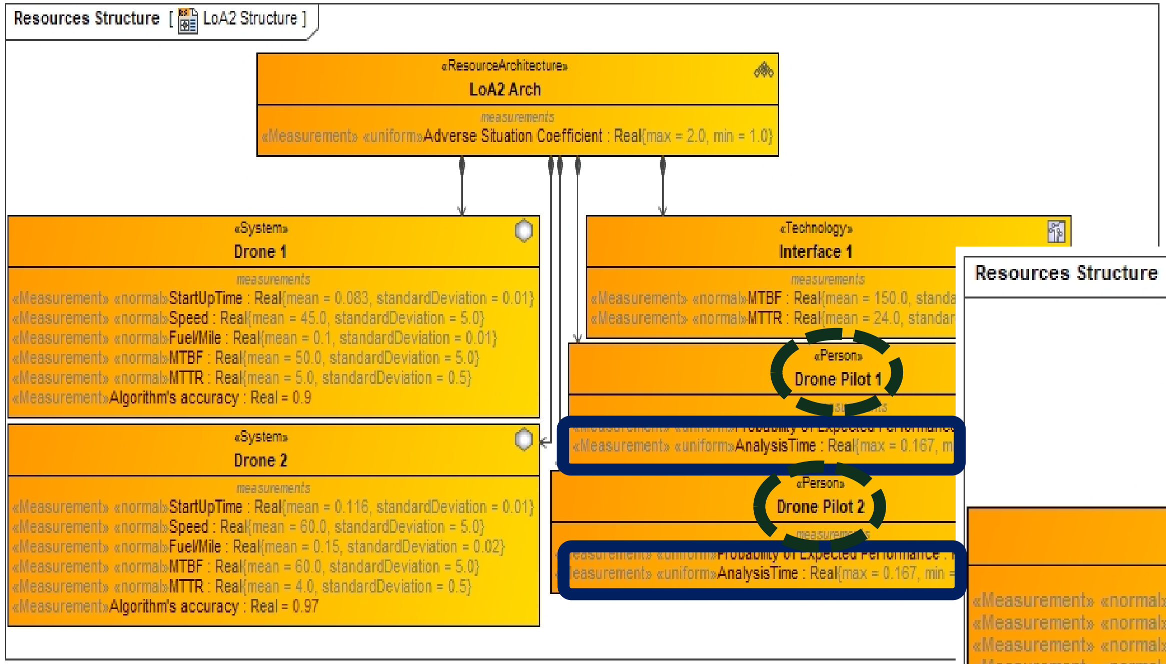
SYNTHESIZE CANDIDATE PHYSICAL ARCHITECTURE

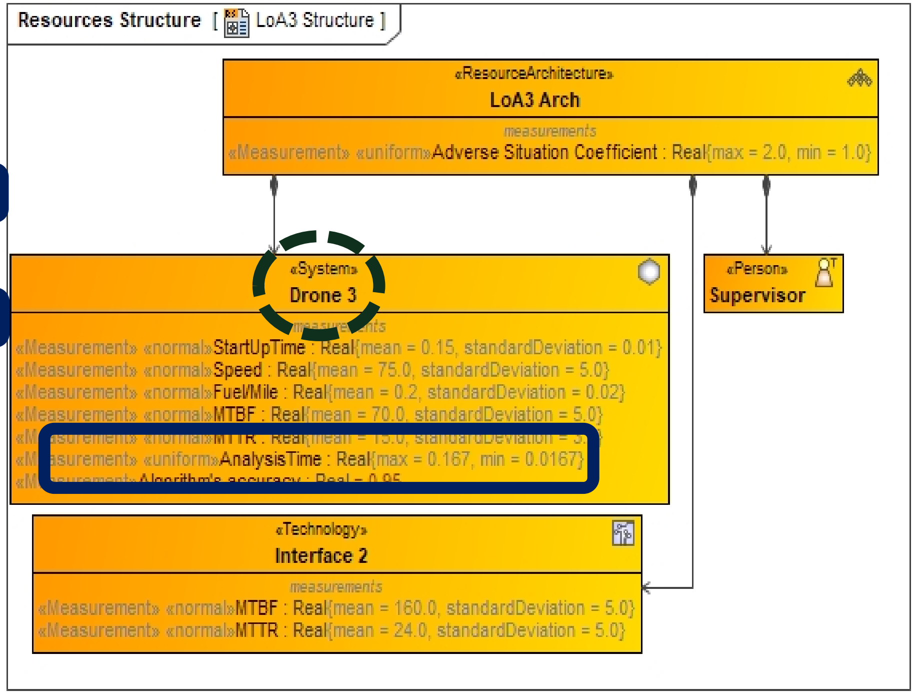
- The implementation matrix helps identify resources with varying LoAs that are able to implement logical entities and their corresponding functions.

Legend
↗ Implements
⇗ Implements (Implied)

Resources Structure	Operational Struc	Aerial Navigation	Data Analyzer	Imaging Device	Route Planner
		5	7	5	5
Drone 1	2	↗		↗	
Drone 2	2	↗		↗	
Drone 3	3	↗	↗	↗	
Drone Interface 1	1		↗		
Drone Interface 2	1		↗		
Drone Pilot1	2		↗		↗
Drone Pilot2	2		↗		↗
LoA2 Arch	4	⇗	⇗	⇗	⇗
LoA3 Arch	4	⇗	⇗	⇗	⇗
Supervisor	1				↗

Implementation Matrix

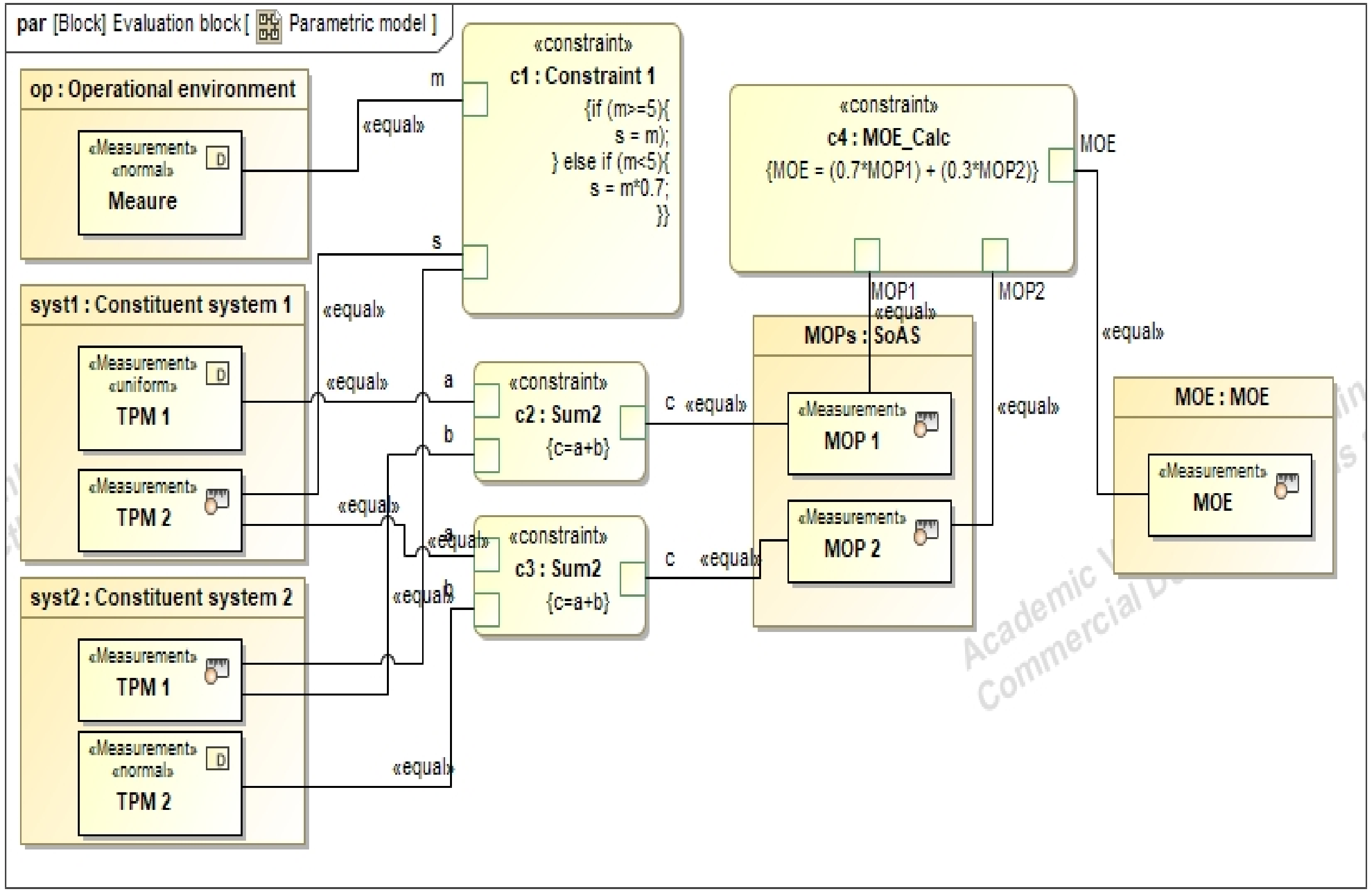




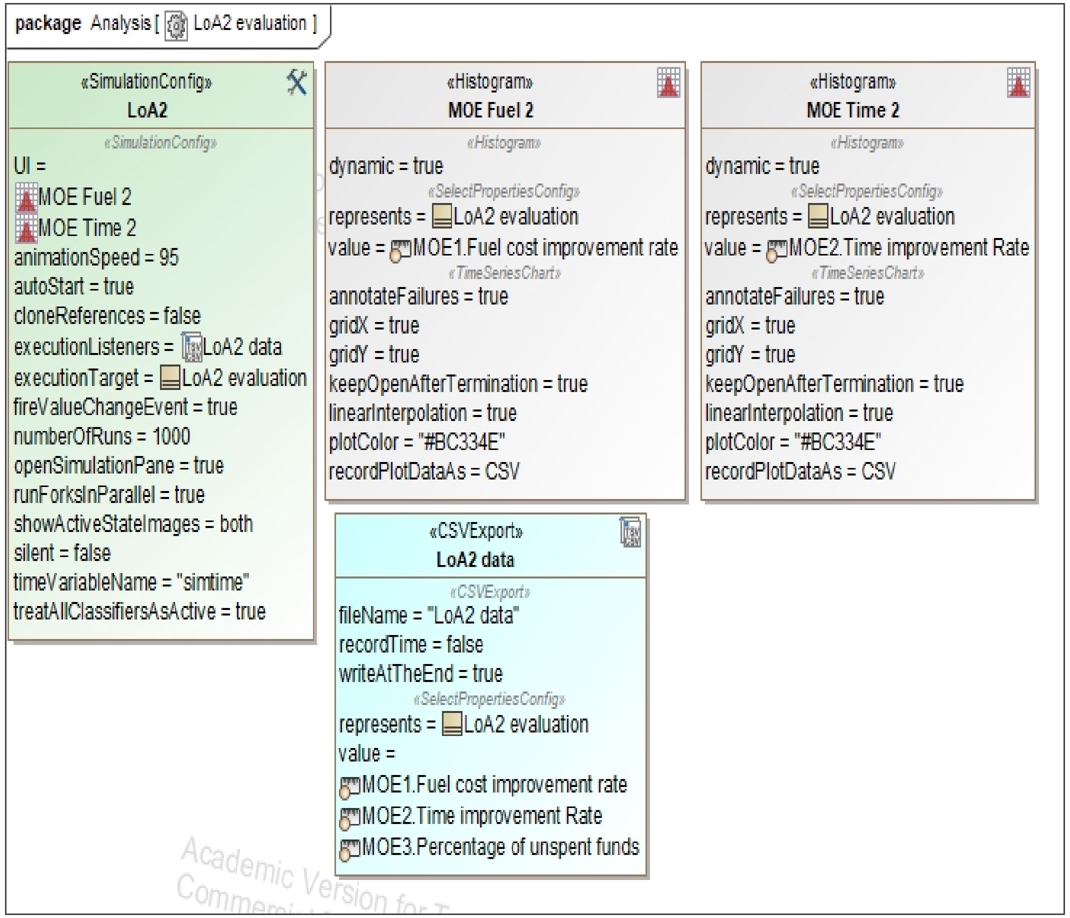
Two Possible alternative physical architectures

- LoA2 employs remotely operated drones and needs drone pilots.
- LoA3 is fully autonomous, and the drone provides autonomous navigation as well as image recognition.

DEVELOP EXECUTABLE MODEL



Parametric diagram



Simulation configuration diagram

Output:
Evaluation data for trade study analysis

OBTAINED DATASET

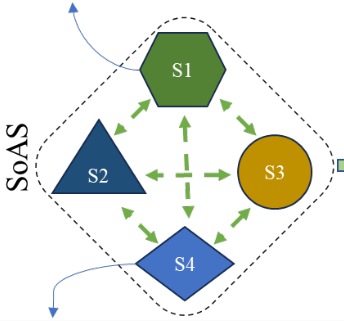
- The dataset contains:
  - SoAS-level MOEs and MOPs
  - System-level TPMs
  - Measures from the operational environment

MOE Fuel	MOE Availability	MOE time	MOP Control availability	MOP Fuel	MOP Rescue Availability	MOP Search Availability	MOP Time to Detect	MOP Time to Rescue	LoA	d1.MTBF	d1.MTTR
1.3009	0.7226	0.9075	0.9112	21.8552	0.7975	0.9944	6.7305	14.5183	4	83.5407	11.2597
1.8475	0.7421	0.9970	0.9128	20.6809	0.8236	0.9872	7.2388	17.0592	7	90.2946	12.0128
2.4472	0.7411	1.1651	0.9171	7.7239	0.8170	0.9891	5.9891	13.5002	5	85.7781	12.5671
1.7815	0.7046	1.1778	0.9073	11.3793	0.7831	0.9916	6.3652	14.8595	8	83.3677	9.9451
1.2781	0.7210	1.0395	0.9146	17.8002	0.7959	0.9905	5.6737	14.3785	1	93.5790	9.1624
1.2947	0.7040	1.2116	0.9062	17.1680	0.7837	0.9912	6.4611	14.3773	9	87.8606	16.2545
4.0373	0.7467	1.1492	0.9098	5.8721	0.8260	0.9936	6.2987	14.7848	5	103.1161	6.4781
2.3545	0.7362	1.0788	0.9077	6.2939	0.8180	0.9915	5.7129	13.4072	2	87.8215	13.9735
3.8299	0.7467	1.0749	0.9132	4.2661	0.8226	0.9940	7.2172	15.2926	9	94.8783	9.7105
1.8918	0.7217	0.8159	0.9033	9.1631	0.8038	0.9939	6.2711	15.1421	2	90.2549	6.1349
1.7098	0.7155	0.9040	0.9125	15.8540	0.7902	0.9922	6.5721	12.0259	3	101.1915	8.3018
1.7570	0.7180	0.9268	0.8988	19.8828	0.8073	0.9896	7.1763	15.1401	4	91.5865	8.1611

Evaluation challenge and solution approach

- **Challenge:** Varying LoAs with uncertain performance can lead to undesirable performance as noticeable changes in MOEs.

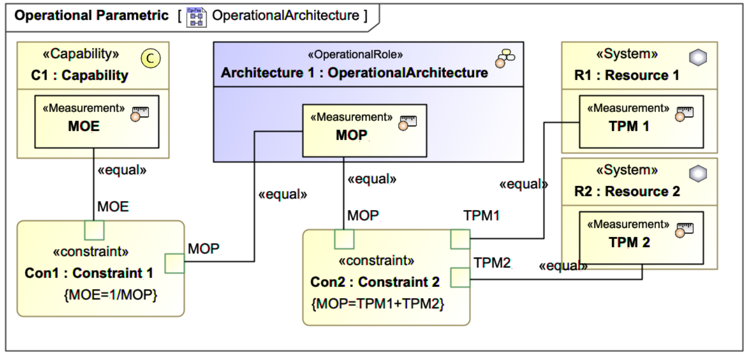
LoA	Example	TPM
1	Legacy System (e.g., Ambulance)	Fuel/Mile



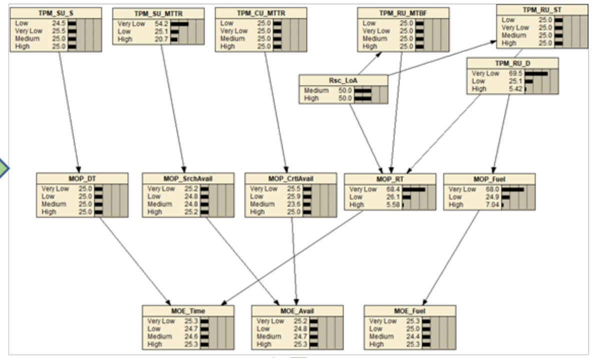
MOP	SoAS fuel consumption
MOE	SoAS fuel efficiency rate

LoA	Example	TPM	Autonomous Capabilities
1	Helicopter (Legacy System)	Fuel/Mile	N/A
2	Autonomous Drone Type 1	AI/ML Performance accuracy	Navigation
3	Autonomous Drone Type 2	AI/ML Performance accuracy	Navigation + Image/video recognition

SoAS executable model



Bayesian network



Predictive Analysis
Impact of TPMs on undesirable emergent behaviors in MOEs

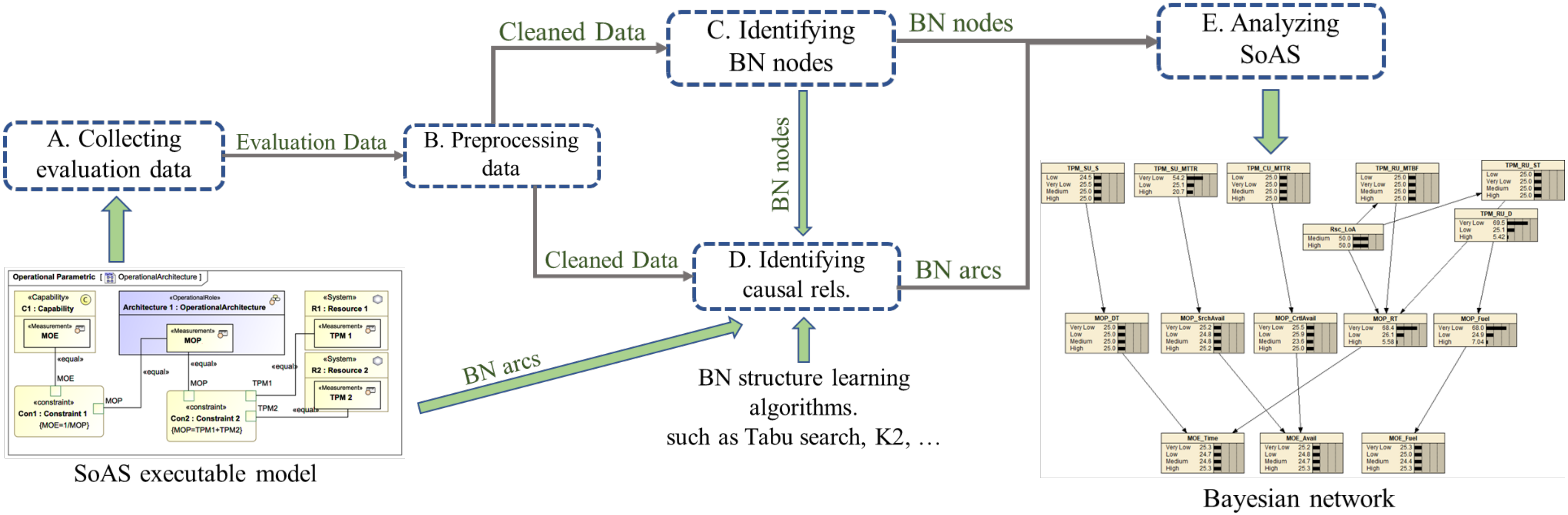
Prescriptive Analysis
Root causes (TPMs) of an undesirable emergent behavior in MOEs
Preventive strategies

- **Solution approach:** Employing BN to enable decision-making under uncertainty.

Uncertainty in TPMs leads to uncertain MOPs and MOEs

THE PROPOSED T&E METHOD

- **Objective:** Choosing the best SoAS configuration in terms of improved MOEs while considering uncertainty.
- The proposed method integrates MBSE architecture with Bayesian Networks and further improves the analysis by using Machine Learning and optimization algorithms.



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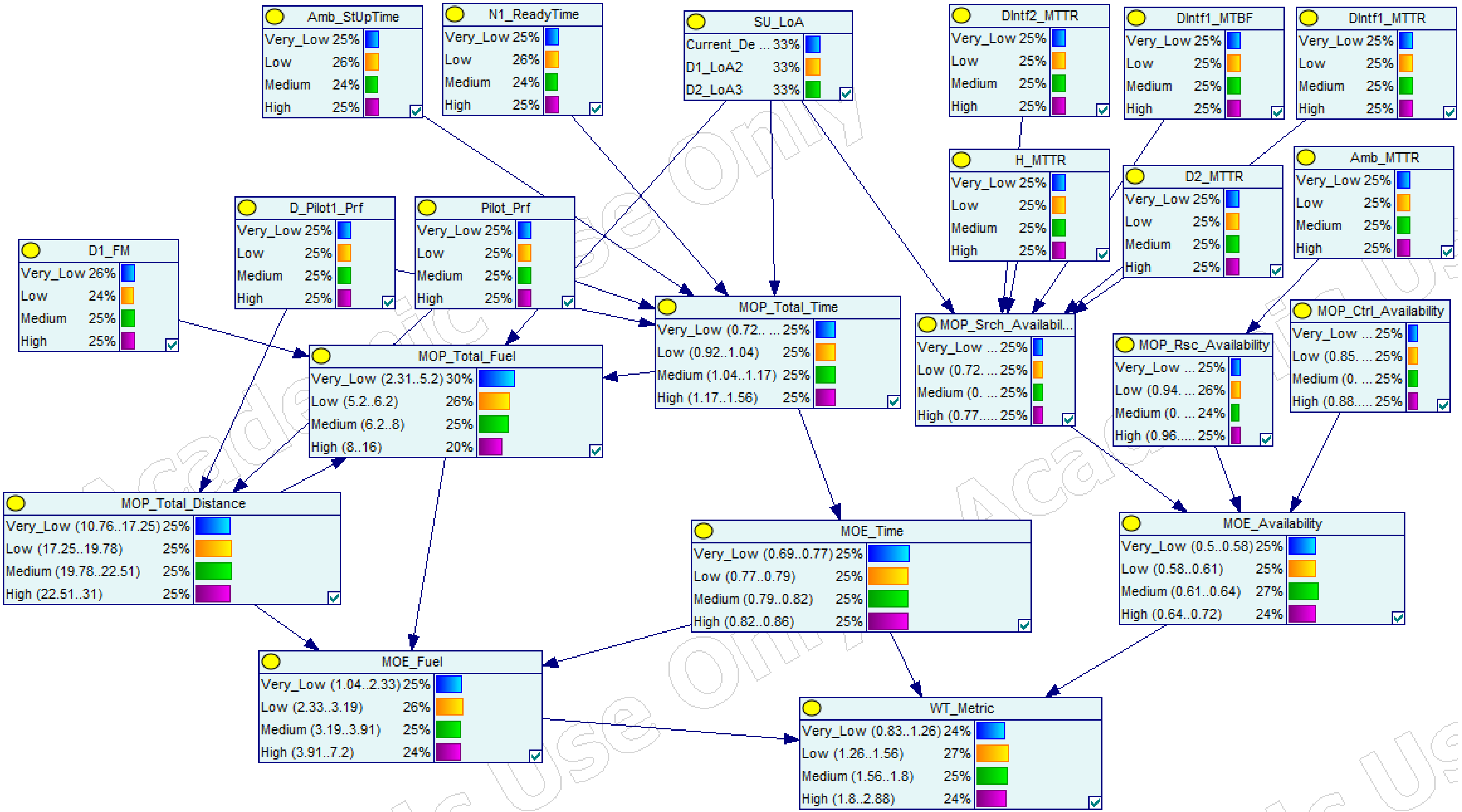
THE RESULTING BN

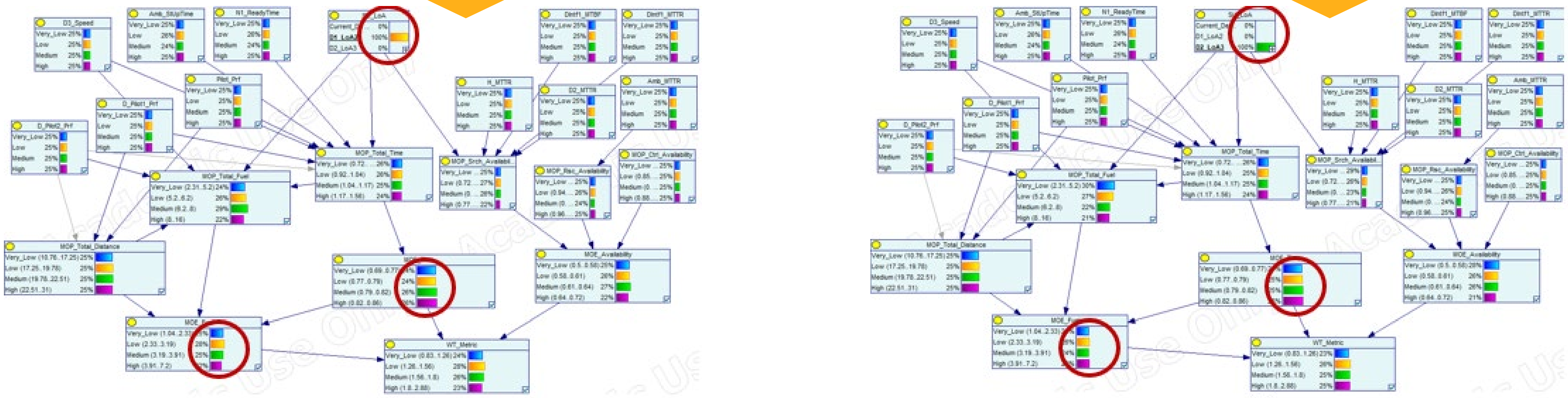


PREDICTIVE ANALYSIS WITH VARYING LOAS

- The LoA 2 and LoA 3 architectures were compared in terms of improvements in mission time and fuel consumption.
- In the current design, the MOEs fall within the *Very_Low* category (i.e., *MOE_Time* = [0.69 0.77] and *MOE_Fuel* = [1.04 2.33]).

Increased the probability of MOE_Time = [0.82 0.86] and MOE_Fuel = [2.33 3.19]

Did not make a significant change on MOE_Time but Increased the probability of MOE_Fuel = [3.91 7.2]



(a) Predictive analysis: (a) LoA 2 design; (b) LoA 3 design (b)

Output: Predicting potential undesirable SoAS performance and understanding suitable LoAs

PRESCRIPTIVE ANALYSIS WITH VARYING LOAS

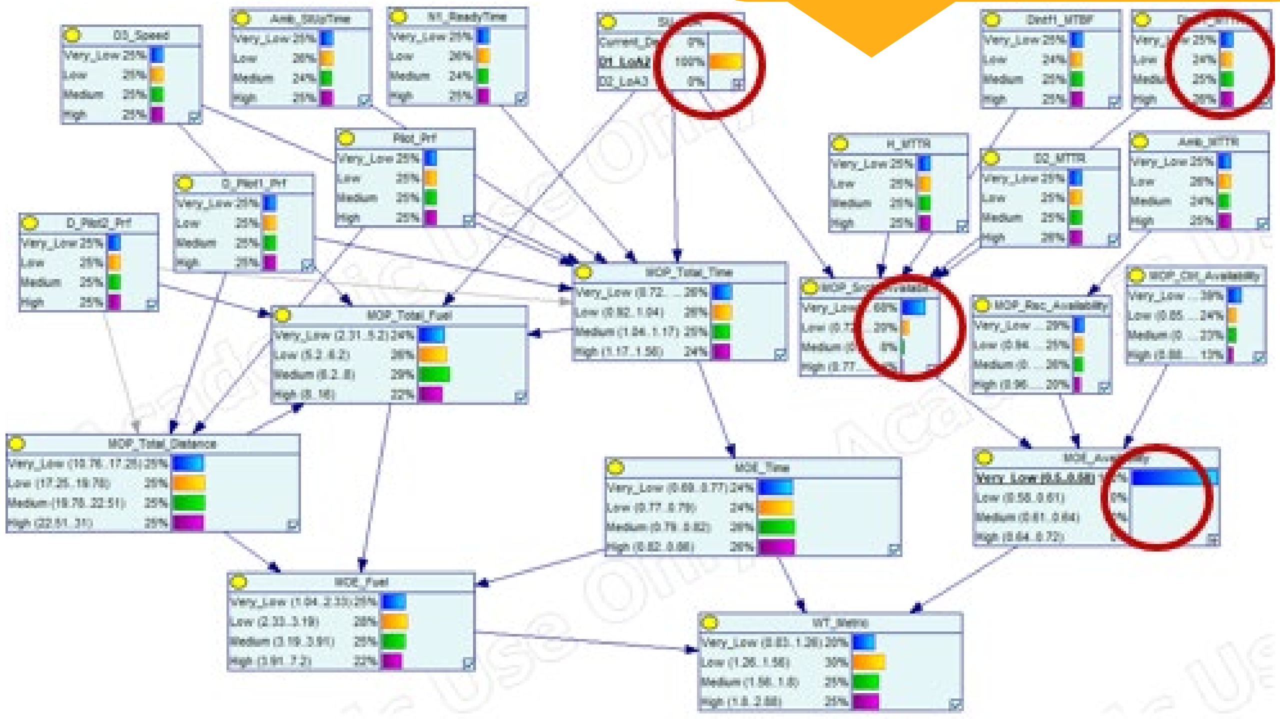
- Assume a scenario for the LoA 2 architecture in which an undesirable emergent behavior was noticed in *MOE_Availability* resulting in a value within the *Very_Low* category, i.e., [0.5 0.58].

Possible root causes

- Availability of Searching unit: probability of 68%
- Drone 1 interface MTTR: probability of 26%

(longer repair time leads to lower availability rates)

Output:
Possible root causes of undesirable emergent behaviors that help determine preventive strategies



BN with emergence in the *MOE_Availability*

CONCLUSIONS

- LoAs in systems exacerbate both architecting and evaluation challenges for SoAS.

- To address the architecting challenges, we proposed a UAF-based MBSE method that
  - establishes step-by-step guidance on how to begin the initial analysis, how to model the SoAS architecture, what UAF views to build, and what outputs to deliver in each step
  - produces multiple executable SoAS architectures within a single MBSE environment composed of varying LoAs
  - generates evaluation data for trade study analysis.

- To address the T&E challenges, we proposed a data-driven BN-based method reinforced by ML and optimization algorithms to provide
  - predictive analysis to examine various scenarios and predict undesirable changes in MOEs, and
  - prescriptive analysis to identify root causes of a possible undesirable performance and suggest preventive strategies.
  - These two analyses together help with a more informed identification of the suitable LoAs to be integrated into the existing SoS.

THANK YOU!