SYSTEMS ENGINEERING RESEARCH CENTER

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A Systems Engineering Methodology for Integrating Autonomy with System of Systems and Conducting Data-Driven Trade Study Analysis

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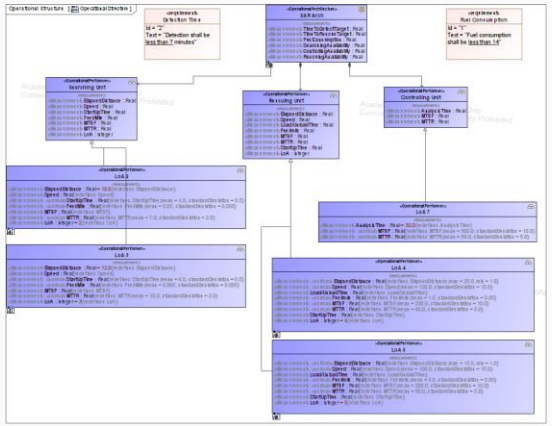
RESEARCH OVERVIEW

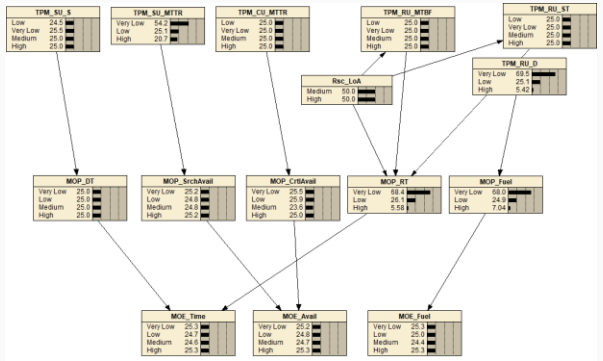
- **Motivation**
  - Advancements in AI/ML have enabled autonomy in engineered systems that reduce human workload and involvement in hazardous missions.
  - These systems can be integrated into existing SoSs to improve mission capabilities, evolving them to a System of Autonomous Systems (SoAS).
  -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

- **Research Questions**
  - How to analyze the impacts of integrating varying LoAs on the current SoS structure and operations?
  - How Systems Engineering practices can help with developing SoAS architectures with varying LoAs?
  - How to evaluate an SoAS while accounting for uncertainties due to LoA?

Results of the reviewed 198 papers in 3 fields



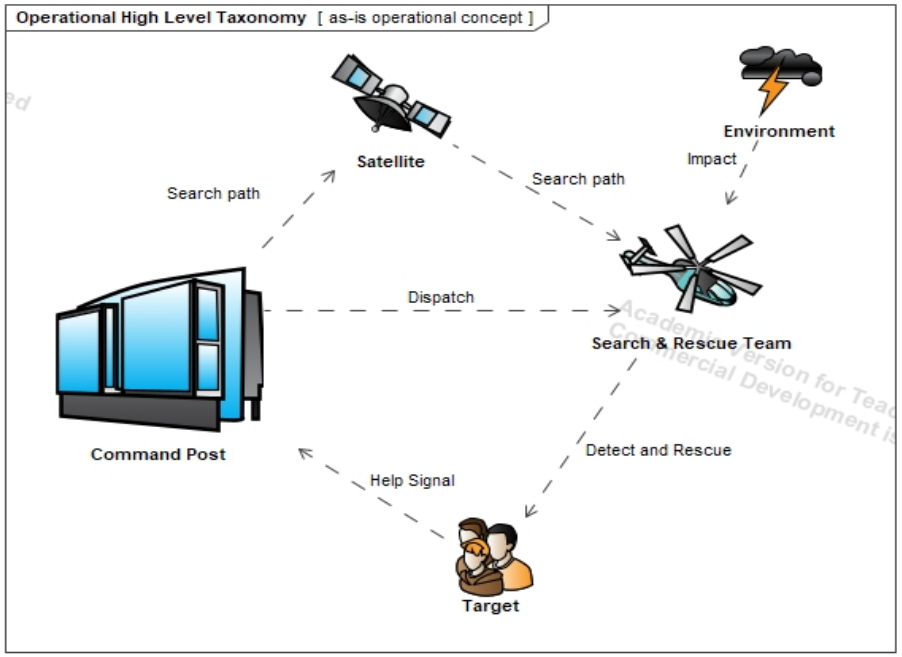
Executable MBSE architecture with LoA

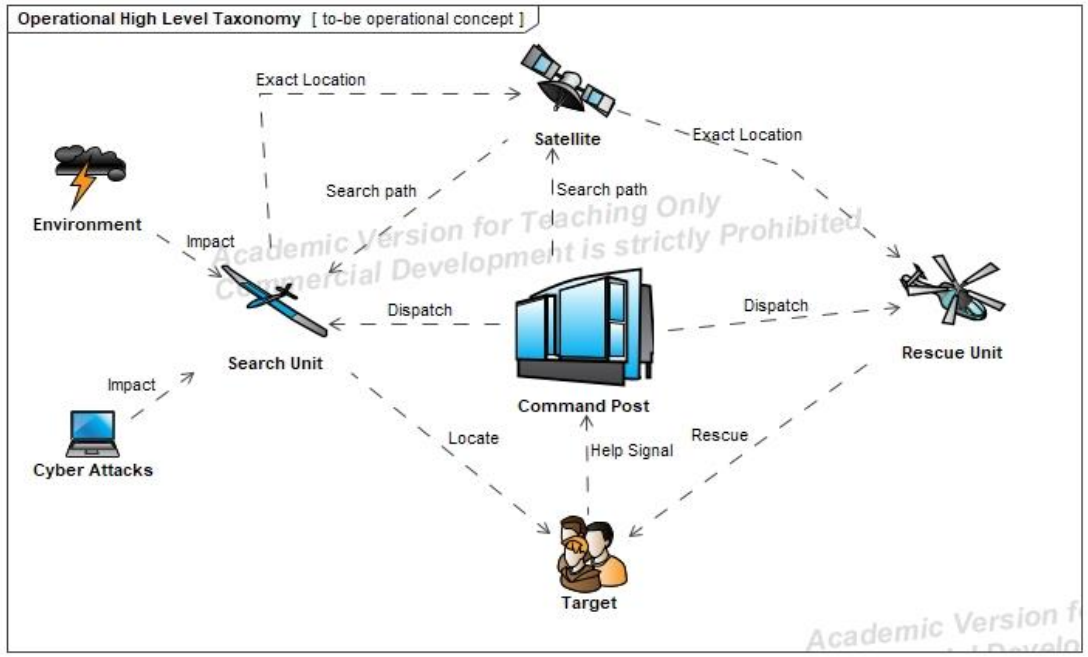


Bayesian Network built for SoAS T&E

CASE STUDY: SEARCH AND RESCUE (SAR) SoS

- Assume stakeholders argue that conducting both operations with one resource leads to extra operational costs in terms of fuel and time.
- They are interested in investigating whether integrating drones can improve the current performance.



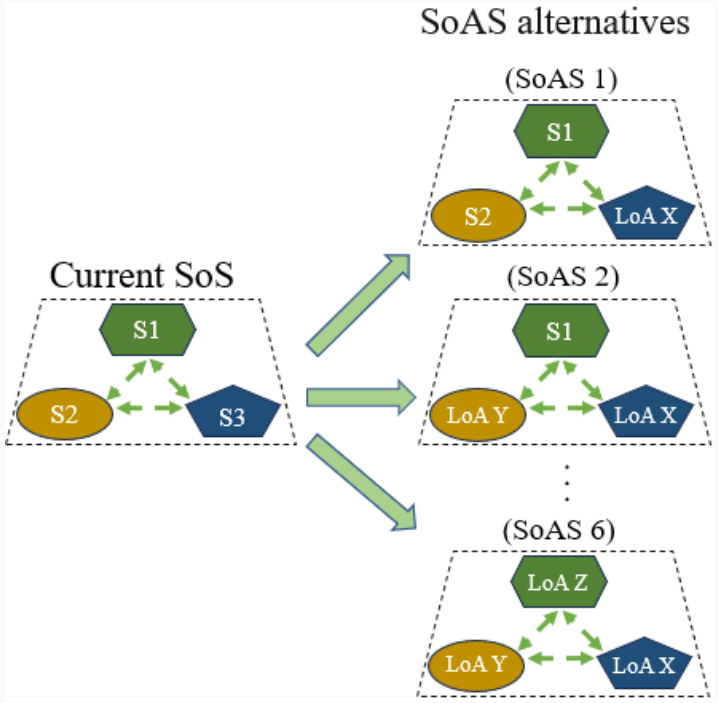


OBJECTIVES

1) Develop SoAS architectures with varying LoAs of drones
2) Determine the most suitable LoA architecture that improves mission effectiveness metrics in different mission settings while considering uncertainty

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.



Design	LoA	Observe	Orient	Decision	Act
SoAS-6	*LoA 7 - FA*	Fly, take images/videos (both autonomous)	Analyze images/videos, Confirm target (both autonomous)	Route planning, rescue planning (both autonomous)	Rescue target (autonomous)
SoAS-5	*LoA 6 – $O_{bs}O_{ri}D$*	Fly, take images/videos (both autonomous)	Analyze images/videos, Confirm target (both autonomous)	Route planning, rescue planning (both autonomous)	Rescue target (operator)
SoAS-4	LoA 5 – $O_{bs}O_{ri}A$	Fly, take images/videos (both autonomous)	Analyze images/videos, Confirm target (both autonomous)	Route planning (autonomous), rescue planning (operator)	Rescue target (operator)
SoAS-3	*LoA 4 - $O_{bs}O_{ri}$*	Fly, take images/videos (both autonomous)	Analyze images/videos (autonomous), Confirm target (operator)	Route planning, rescue planning (operator)	Rescue target (operator)
SoAS-2	*LoA 3 - AA*	Fly, take images/videos (both autonomous)	Analyze images/videos (operator), Confirm target (operator)	Route planning, rescue planning (operator)	Rescue target (operator)
SoAS-1	*LoA 2 - $O_{bs}S$*	Fly (operator), Take images/videos (autonomous)	Analyze images/videos (operator), Confirm target (operator)	Route planning, rescue planning (operator)	Rescue target (operator)
Current SoS	*LoA 1 - M*	Fly (operator), Take images/videos (operator)	Analyze images/videos (operator), Confirm target (operator)	Route planning, rescue planning (operator)	Rescue target (operator)

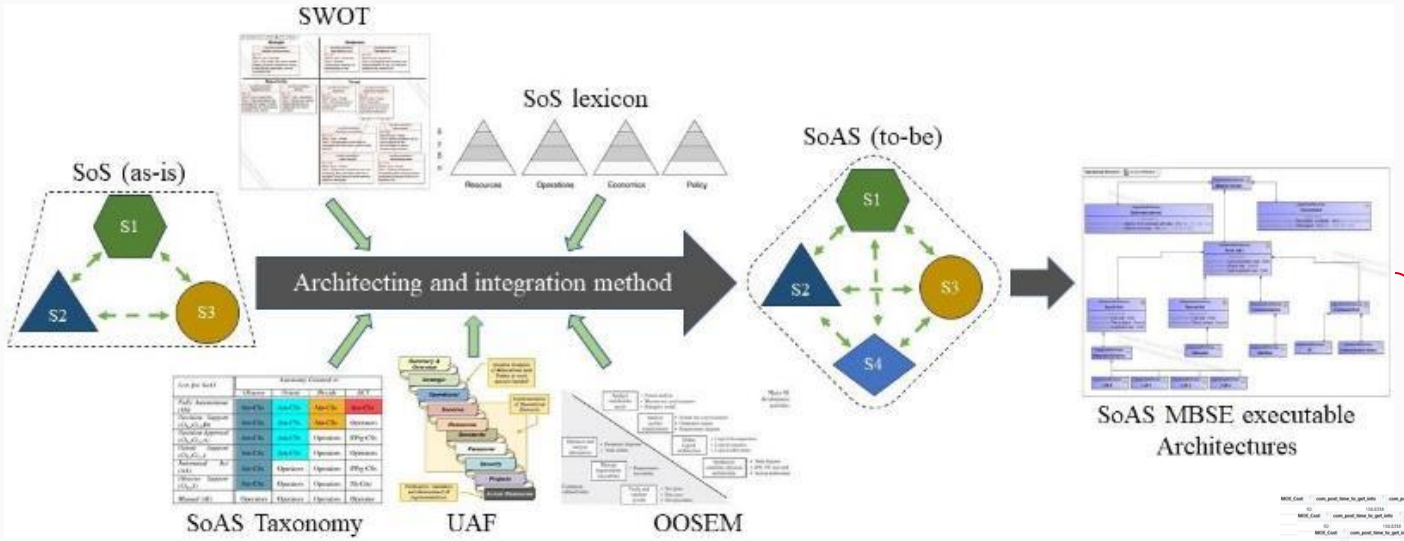
Example of LoAs of an SoAS used for search & rescue mission

LoA for SoAS	*Autonomy Granted to*			
	Observe	*Orient*	*Decide*	*ACT*
Fully Autonomous (FA)	Atn-CSs	Atn-CSs	Atn-CSs	Atn-CSs
Decision Support ($O_{bs}O_{ri}D$)	Atn-CSs	Atn-CSs	Atn-CSs	Operators
Decision Approval ($O_{bs}O_{ri}A$)	Atn-CSs	Atn-CSs	Operators	PPrg-CSs
Orient Support ($O_{bs}O_{ri}$)	Atn-CSs	Atn-CSs	Operators	Operators
Automated Act (AA)	Atn-CSs	Operators	Operators	PPrg-CSs
Observe Support ($O_{bs}S$)	Atn-CSs	Operators	Operators	Sh-Cntr
Manual (M)	Operators	Operators	Operators	Operator

SoAS Taxonomy

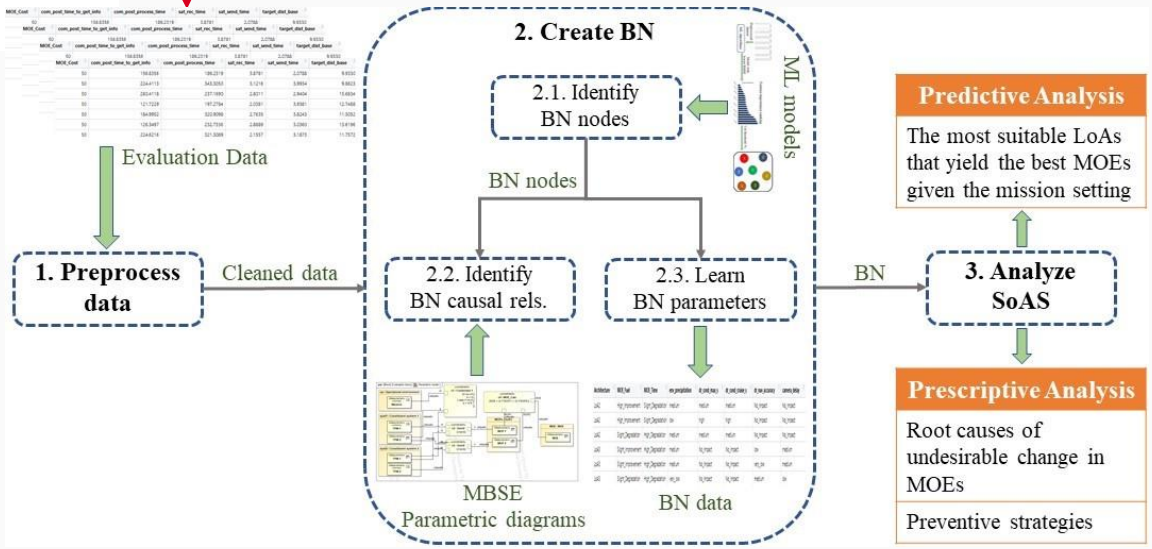
- Torkjazi, M., & Raz, A. K. (2022). A Taxonomy for System of Autonomous Systems. 2022 17th Annual System of Systems Engineering Conference (SOSE), 198–203. https://doi.org/10.1109/SOSE55472.2022.9812673
- Torkjazi, M., & Raz, A. K. (2024a). A Review on Integrating Autonomy into System of Systems: Challenges 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 Unified Architecture Framework (UAF) and Object-Oriented Systems Engineering Method (OOSEM) to build various executable LoA architectures and simulate their performance.

Evaluation data

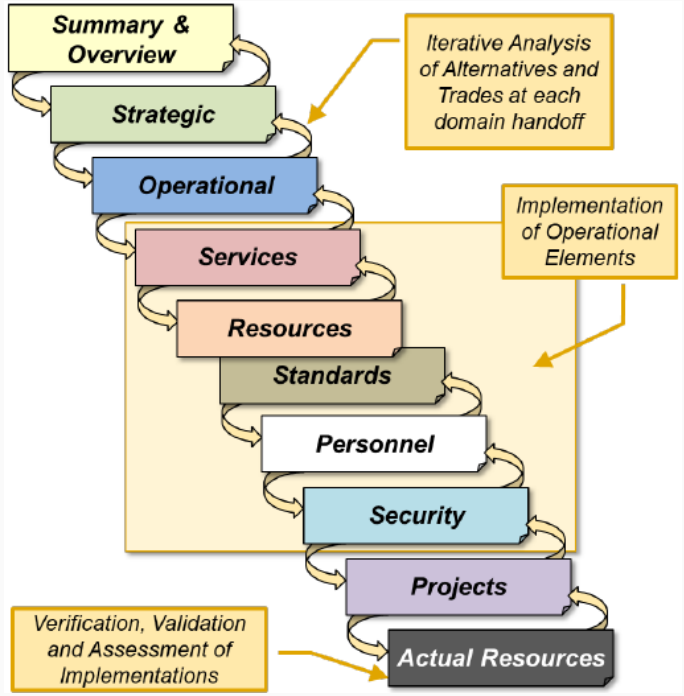


- The T&E method employs Bayesian Network (BN) and Machine Learning (ML) to provide a decision-making dashboard to explore the design space.

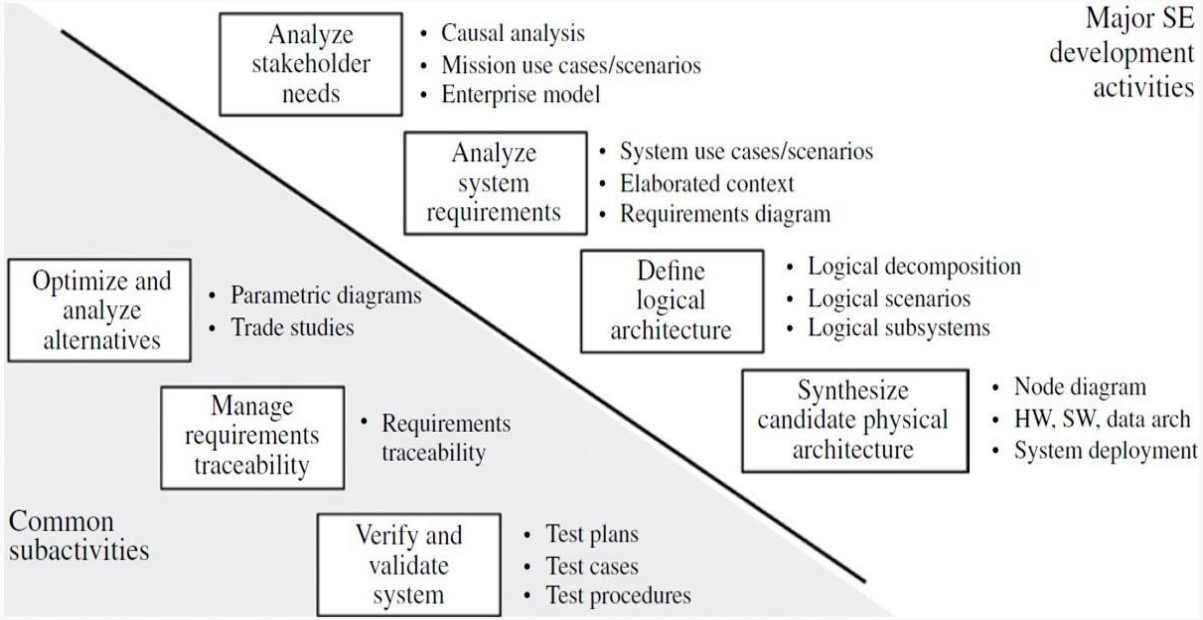
- Torkjazi, M., & Raz, A. K. (2024b). Model-Based Systems Engineering (MBSE) Methodology for Integrating Autonomy into a System of Systems Using the Unified Architecture Framework. *INCOSE International Symposium*, 34, 1051–1070. https://doi.org/10.1002/iis2.13195
- Torkjazi, M., & Raz, A. K. (2024c). 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

UAF AND OOSEM

- **Unified Architecture Framework (UAF)**
  - Offers various viewpoints that cover most, if not all, of SoASs' levels of abstraction from its high-level managerial considerations to its detailed physical architecture.
  - Provides a standardized format for describing SoAS but does not offer an architecting method.



- **Object-Oriented Systems Engineering Method (OOSEM)**
  - Is a top-down method that uses Systems Modeling Language (SysML).
  - The first 2 steps need a comprehensive analysis of LoA impacts on the current SoS.
  - It must create different SoAS architectures, each corresponding to a particular LoA..



SoAS TAXONOMY AND MBSE SWOT ANALYSIS

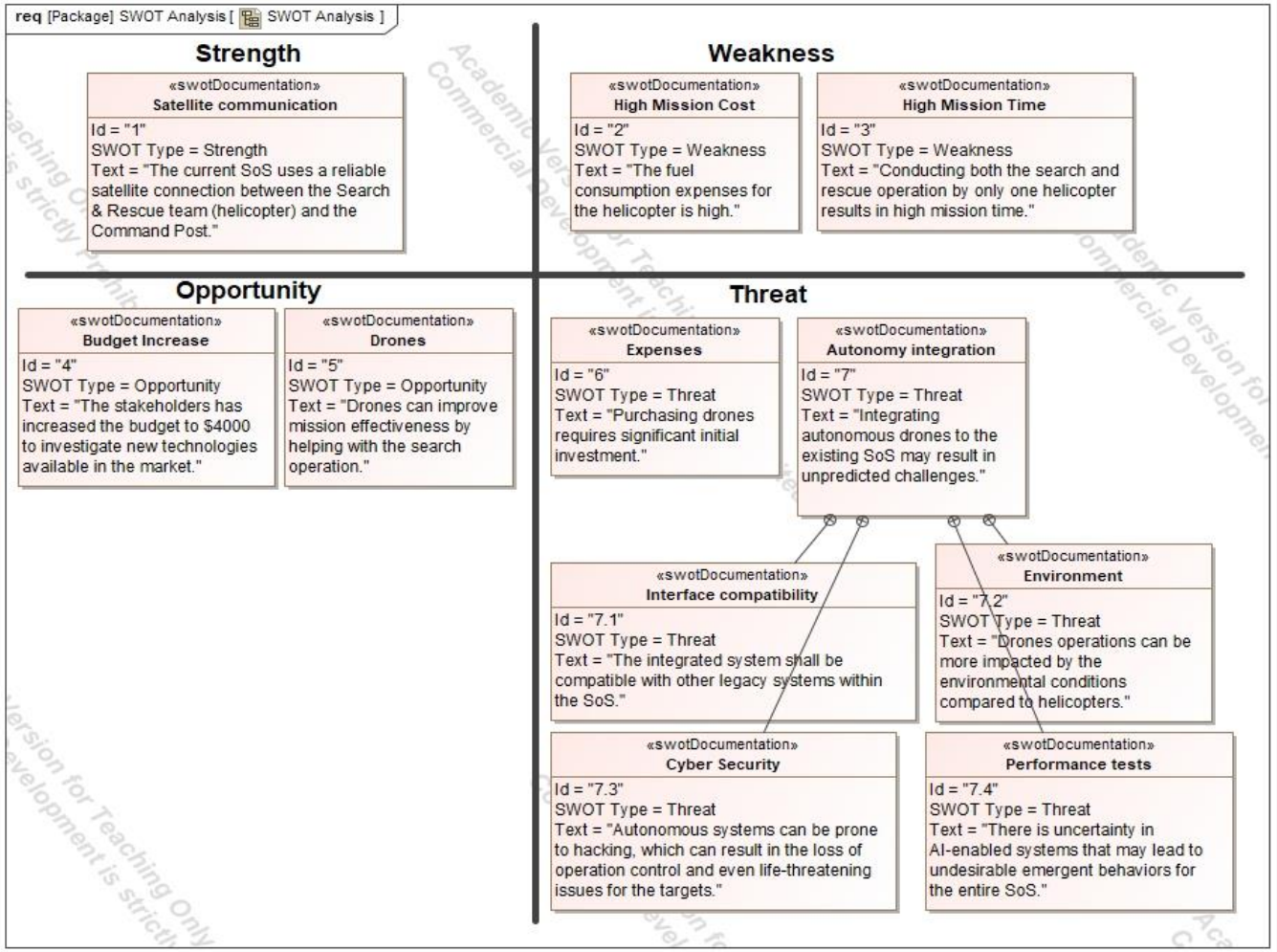
- SoAS taxonomy helps with understanding the maximum allowed LoA to be integrated into the SoS.

LoA for SoAS	*Autonomy Granted to*			
	Observe	*Orient*	*Decide*	*ACT*
Fully Autonomous (FA)	Atn-CSs	Atn-CSs	Atn-CSs	Atn-CSs
Decision Support ($O_{bs}O_{ri}D$)	Atn-CSs	Atn-CSs	Atn-CSs	Operators
Decision Approval ($O_{bs}O_{ri}A$)	Atn-CSs	Atn-CSs	Operators	PPrg-CSs
Orient Support ($O_{bs}O_{ri}$)	Atn-CSs	Atn-CSs	Operators	Operators
Automated Act (AA)	Atn-CSs	Operators	Operators	PPrg-CSs
Observe Support ($O_{bs}S$)	Atn-CSs	Operators	Operators	Sh-Cntr
Manual (M)	Operators	Operators	Operators	Operator

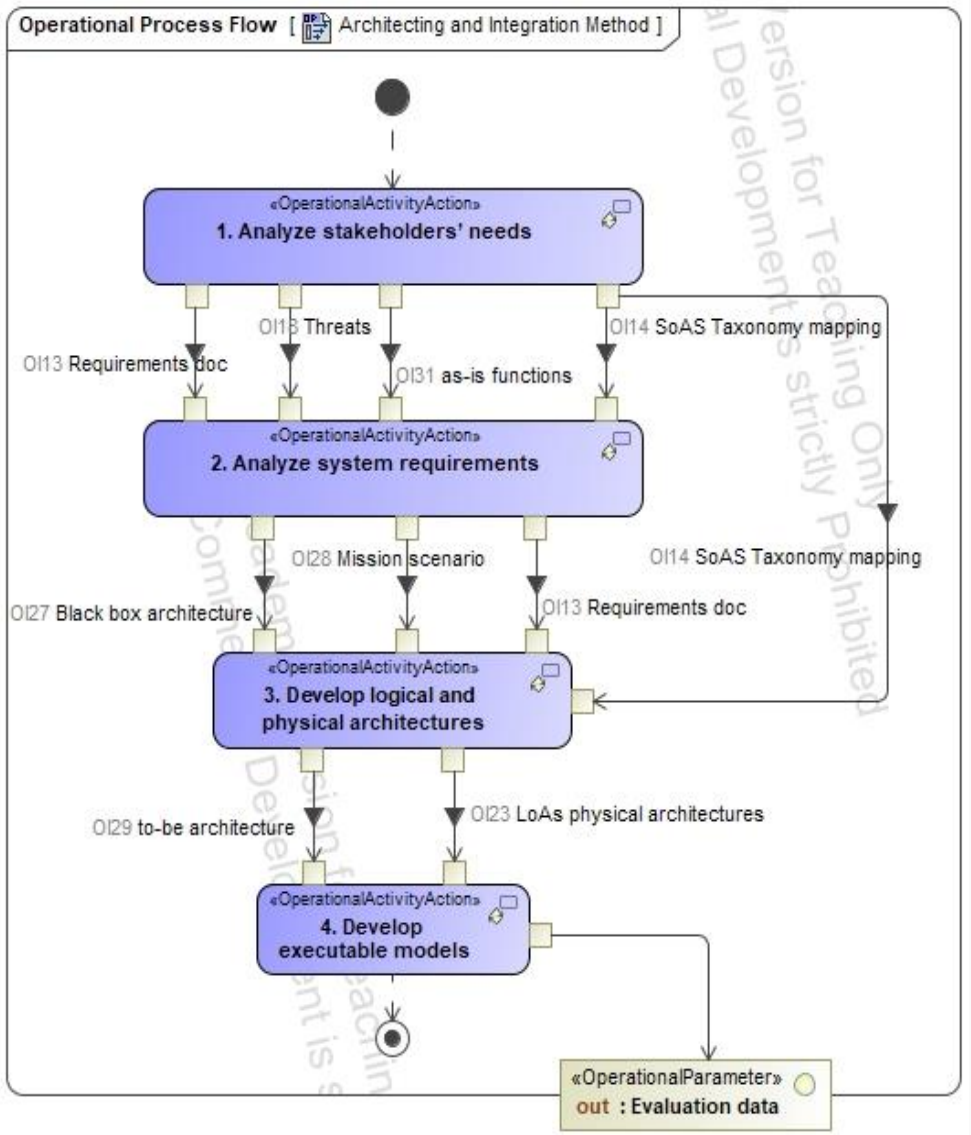
Outputs:

1. Capabilities & MOEs,
2. Allowed # of LoA architectures
3. Requirements including: stakeholders, functional, interfaces, safety, security, …,

- MBSE SWOT analysis helps with understanding the current status of the SoS and challenges of integrating autonomy (organizational and technical).



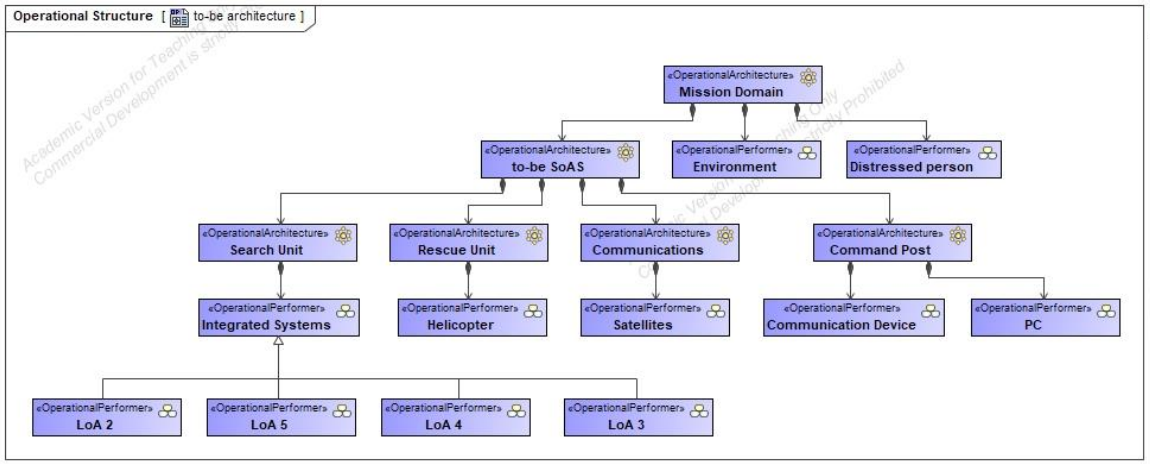
THE PROPOSED ARCHITECTING AND INTEGRATION METHOD



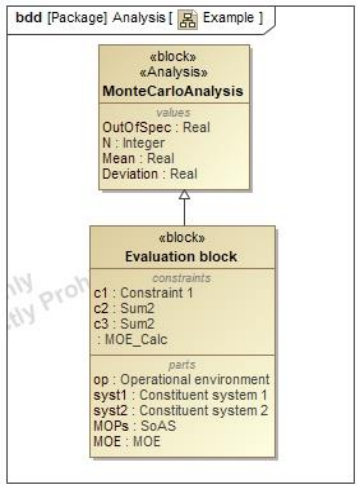
Step	Rationale	Sub-Steps	Diagrams	Outputs
1. Analyze Stakeholders' Needs	Understanding stakeholders' desired capabilities and Understanding the maximum allowed autonomy integration	1.a	Operational High Level Taxonomy, SoS lexicon, Resources Structure, Resources Process Flow	as-is architecture, as-is scenario, as-is performance benchmarks
		1.b	Profile Diagram, Generic Table, Requirement Diagram	SWOT artifacts
		1.c	Strategic Motivation, Strategic Taxonomy	SoAS capabilities & MOEs
		1.d	Requirement Diagram, Requirement Table	Stakeholders' requirements
		1.e	Resources Processes	# of LoA architectures
2. Analyze System Requirements	Understanding system requirements for different LoA architectures	2.a	Operational High Level Taxonomy, Operational Structure, Operational Process Flow, Functions to Operational Activities Mapping Matrix, Operational Internal Connectivity	Black box to-be architecture, Black box to-be mission scenario, Functional requirements, Interfaces requirements
		2.b	Risks, Security Structure	Safety and security requirements
		2.c	Requirement Diagram, Requirement Table	All system requirements
3. Develop Logical and Physical Architectures	Defining the logical and physical architectures for each LoA	-	Operational Structure, Operational Process Flow, Operational Internal Connectivity, Implementation matrix, Resources Structure, Resources Internal Connectivity, Dependency Matrix	SoAS architecture, LoAs' logical and physical architectures, LoAs' system scenarios, LoAs' interfaces
4. Develop executable models	Generating evaluation data for future trade study analysis	-	Standards Taxonomy, Operational Constraints Definition, Resources Constraints Definition, SysML Block Definition Diagram, SysML Parametric Diagram, SysML Simulation Configuration Diagram	LoAs parametric diagrams, Evaluation data

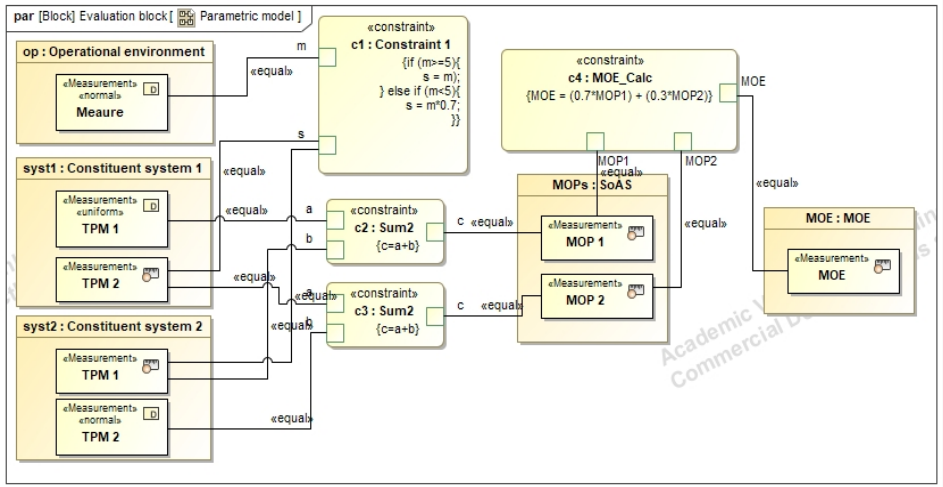
Version for Teaching Only
Academic Development is strictly Prohibited

RESULTS OF IMPLEMENTING THE PROPOSED INTEGRATION METHOD

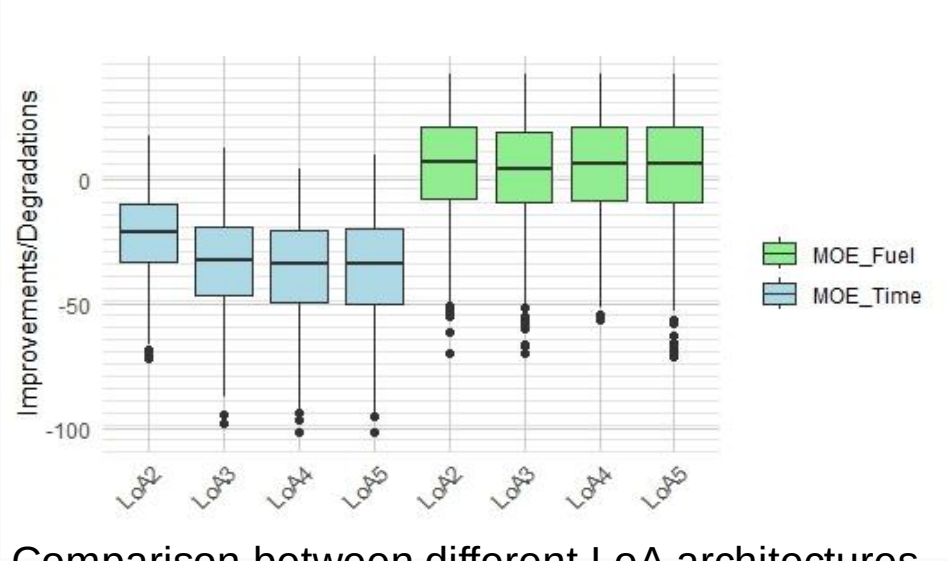


MBSE architecture with different LoAs





MBSE executable models for different LoA architectures

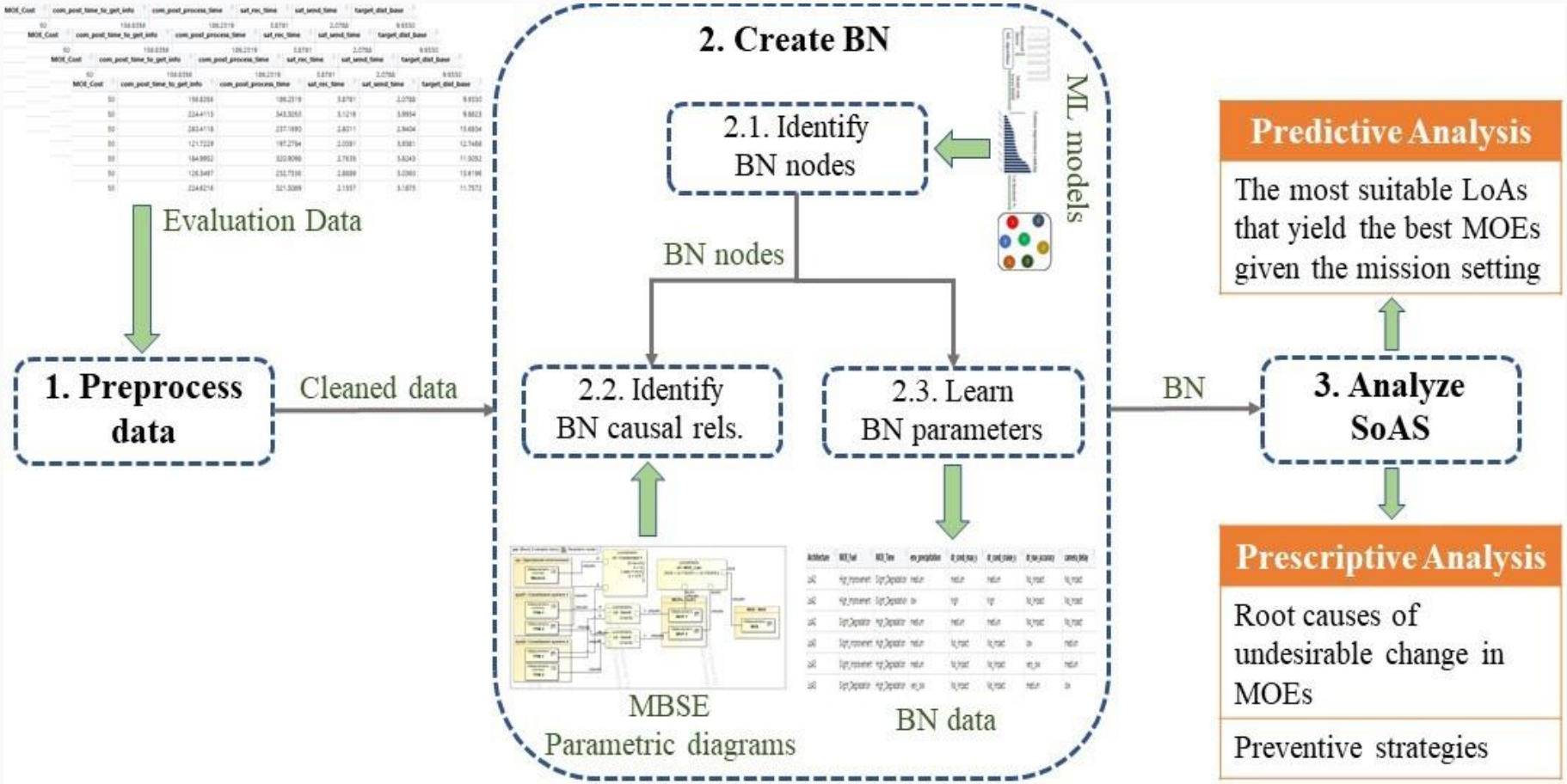


Comparison between different LoA architectures

How to select?

The regular data analysis techniques cannot help with exploring the design space and choosing the most suitable LoA architecture based on the mission context

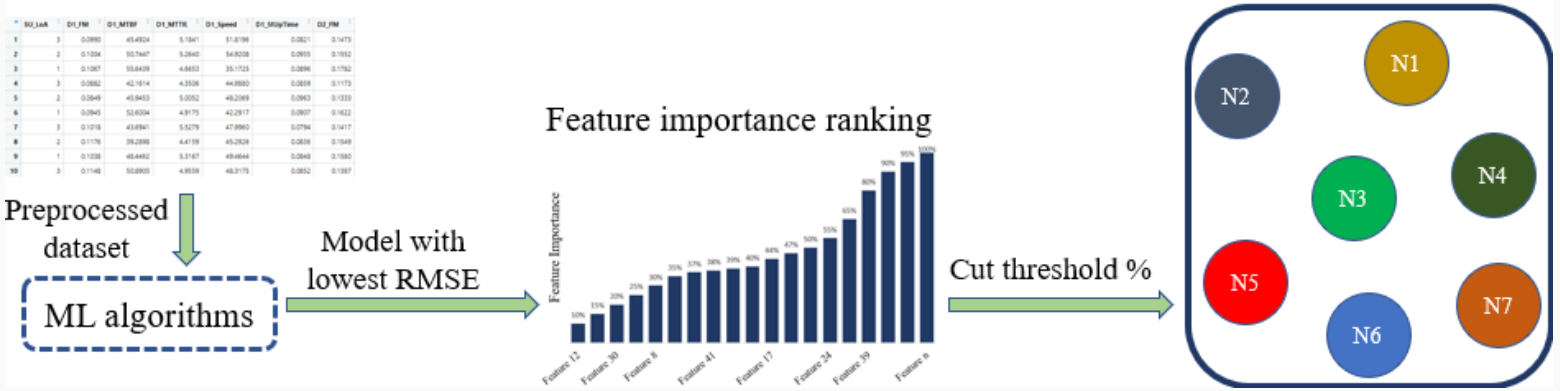
THE PROPOSED T&E METHOD



OBJECTIVES

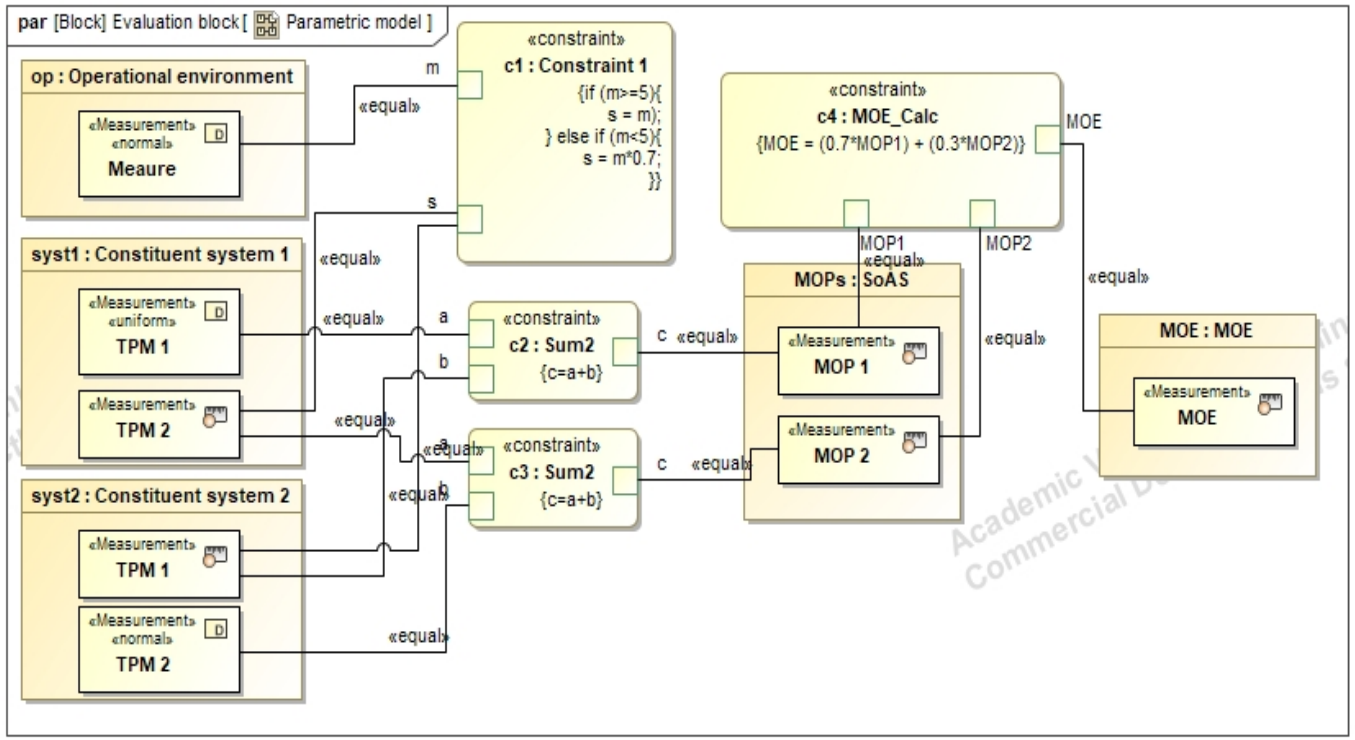
1) Exploring the design space and select the most suitable LoA architecture given the mission and operational environment.
2) Understanding the root causes of an undesirable change in SoAS-level metrics to prevent it in future operations.

HOW TO CREATE THE BN?

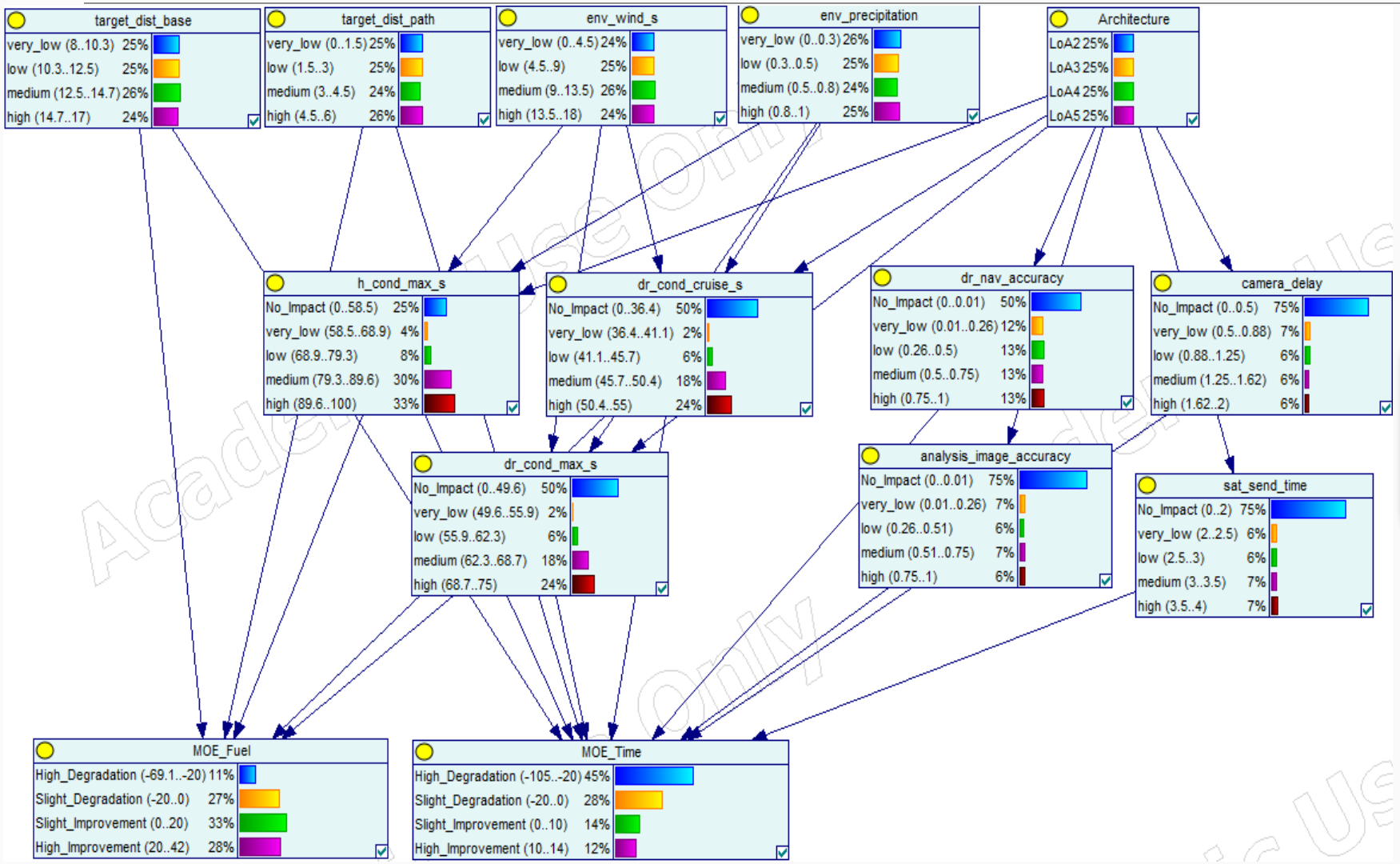


- ML models help with identifying the TPMs that have the most contributions to the MOEs.

- MBSE parametric diagrams help with understanding the causal relationships between the identified TPMs and MOEs.



RESULTS OF IMPLEMENTING THE T&E METHOD



The Bayesian Network helps with exploring the design space and conducting predictive and prescriptive analyses

CONTRIBUTIONS

- Modified the OOSEM by using SoAS taxonomy and MBSE SWOT analysis to facilitate identifying LoA impacts on organizational and technical aspects of the current SoS.
- Proposed a method to use the UAF for modeling SoAS with varying LoAs and creating executable models within a single MBSE environment.
- Developed a data-driven BN-based decision-making dashboard for SoAS with different LoA architectures that
  - provides predictive analysis to explore design space and select the most suitable LoA architecture,
  - provides prescriptive analysis that helps to explain root causes of a possible undesirable SoAS performance and suggest preventive strategies, and
  - evaluates multiple LoA architectures simultaneously.

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Thank you!

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