



**34**<sup>th</sup> Annual **INCOSE**  
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# AI-Enhanced Autonomous Formation Flying Definition of a Mission-driven and Safety-critical Software Development Environment

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# The Presenters



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- System and Embedded Software
- MBSE Methodology
- AI/ML-enabled Autonomy
- Secretary of DO-330 Tool Qualification Subgroup (RTCA SC 205/DO-178C)
- Member of SAE G34/EUROCAE WG114 AI in Aviation (SAE ARP6983)



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- Automation, Optimization
- Hybrid Analytics
- MBSE
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- GfSE Chapter (21-24), AFIS (24-)

# Impact of AI/ML on Aviation

EASA Artificial Intelligence Roadmap 2.0: Human-centric approach to AI in aviation (May 2023)

“AI, and more specifically the ML field of AI, is bringing an enormous potential for developing applications that would not have been possible with the development techniques that have been used so far.”

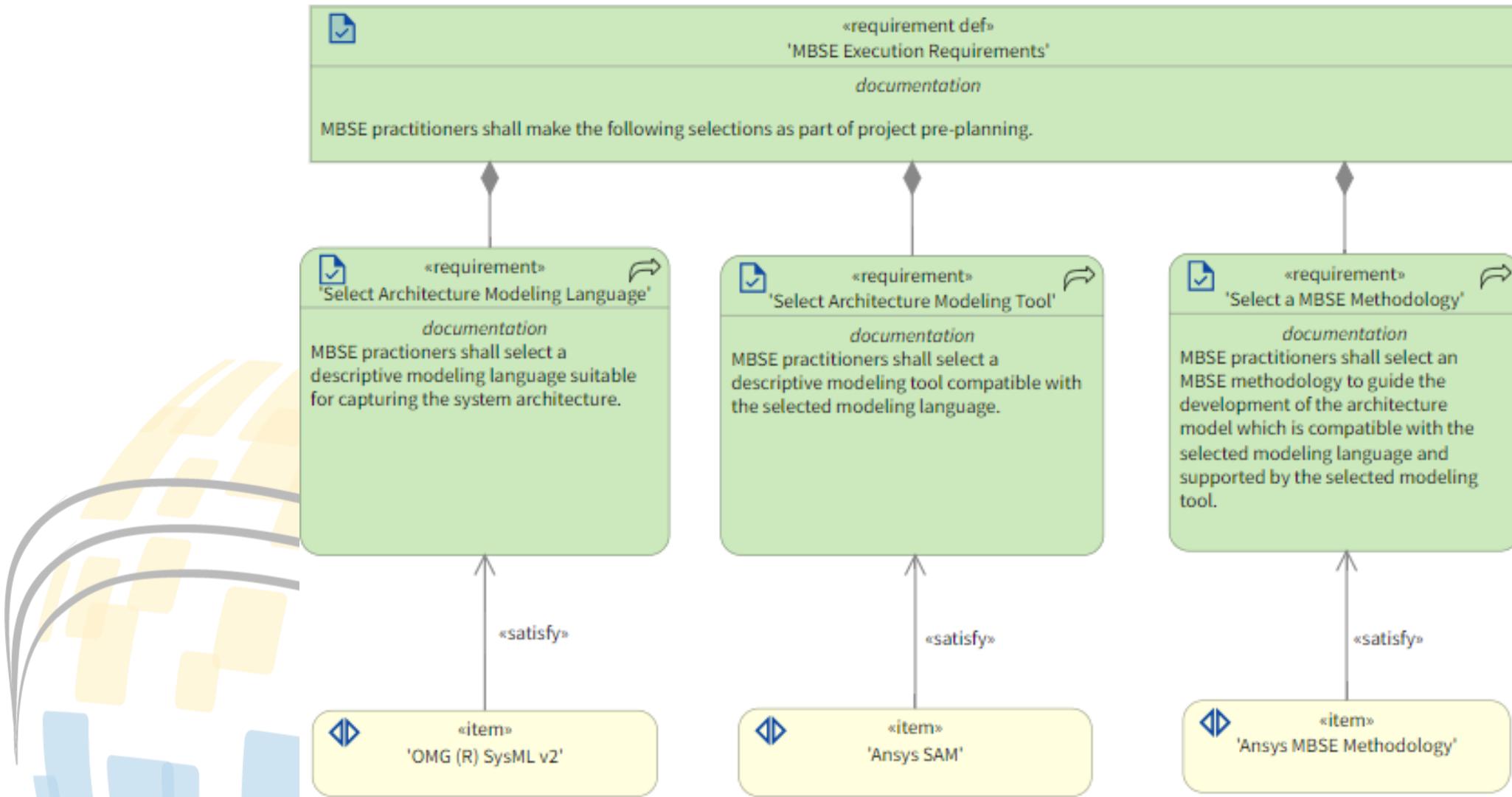
“AI could also be used in nearly any application that implies mathematical optimization problems, removing the need for analysis of all possible combinations of associated parameter values and logical conditions. Typical applications of ML could be flight control laws optimization, sensor calibration, fuel tank quantity evaluation, icing detection and many more to come.”



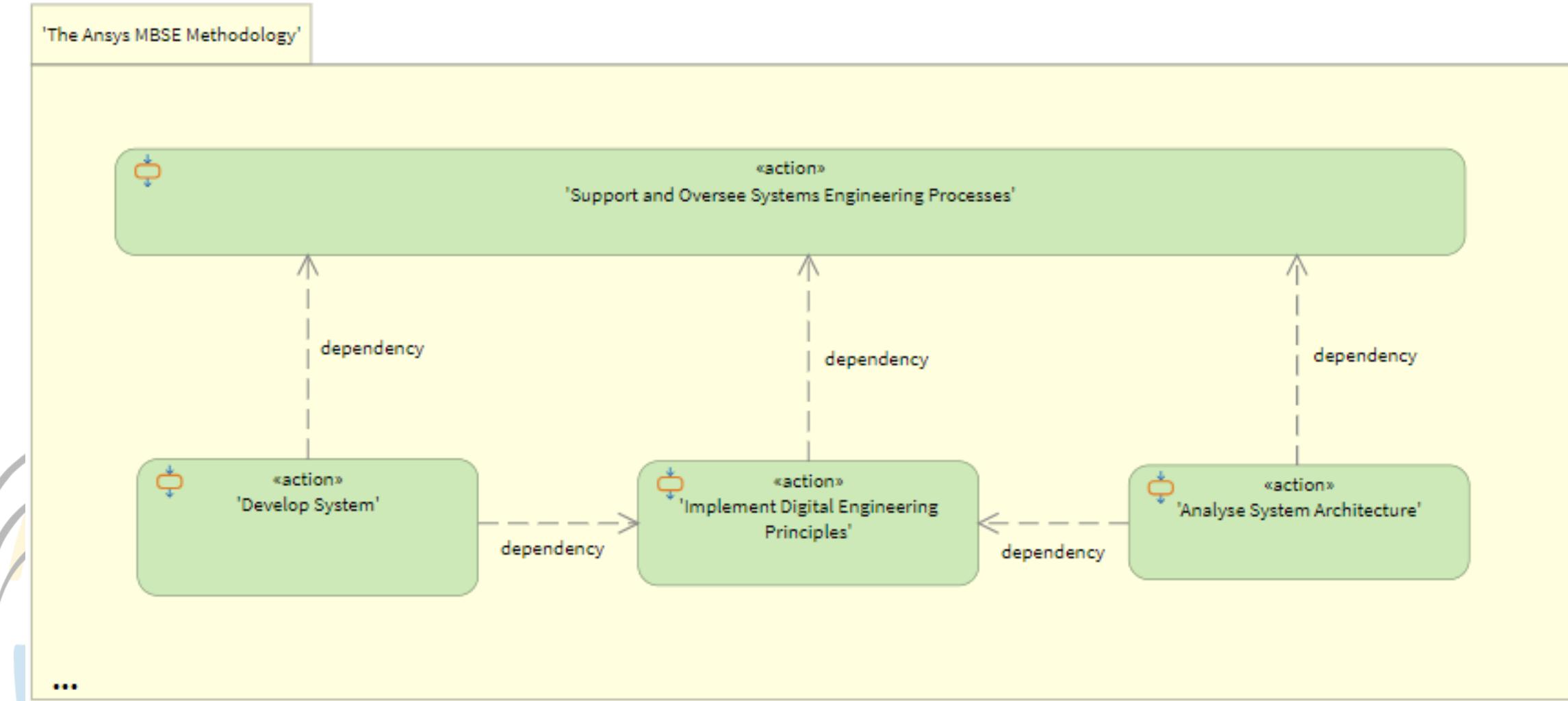
# The (SysML v2 ®) MBSE Methodology

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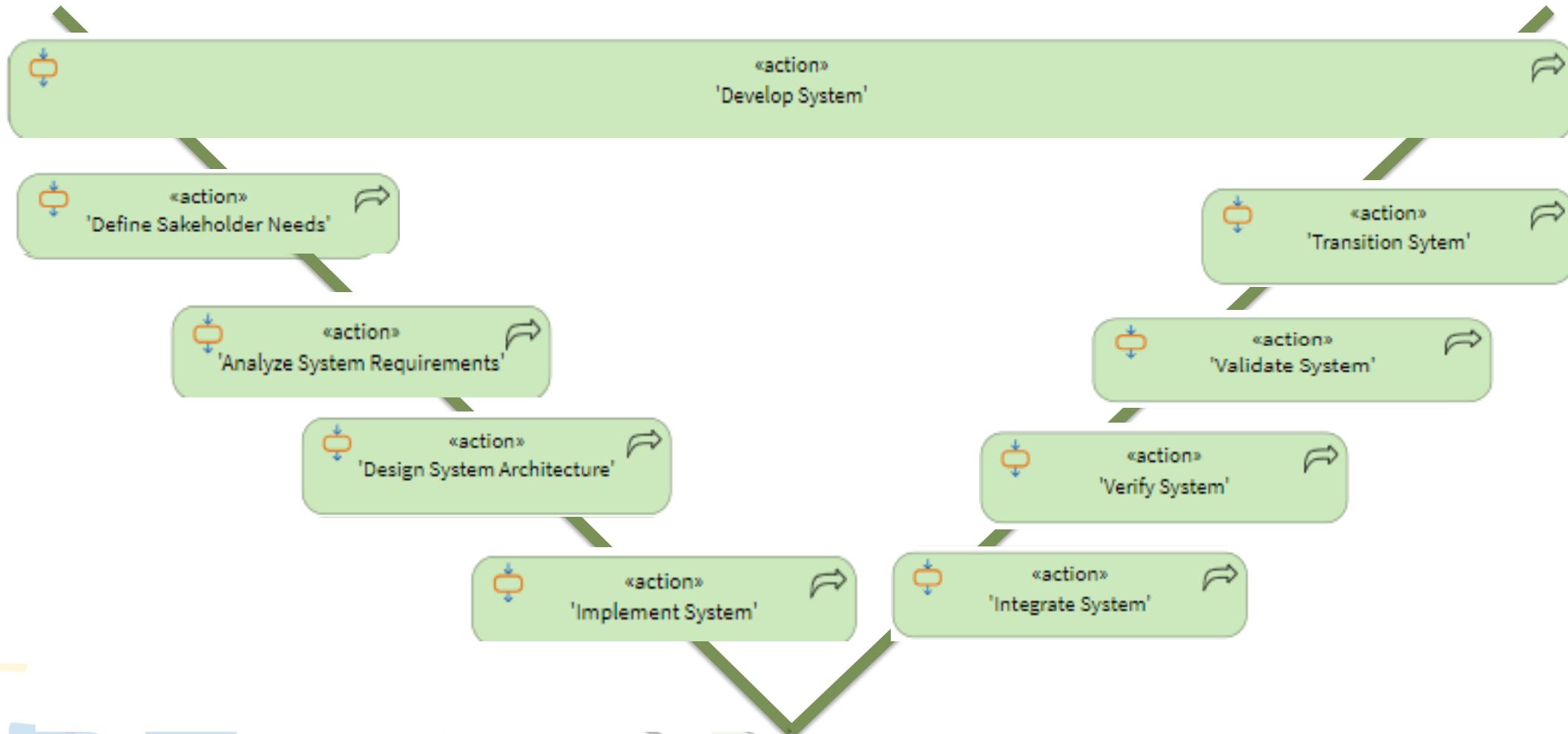
# The Three Requirements for Doing MBSE Effectively



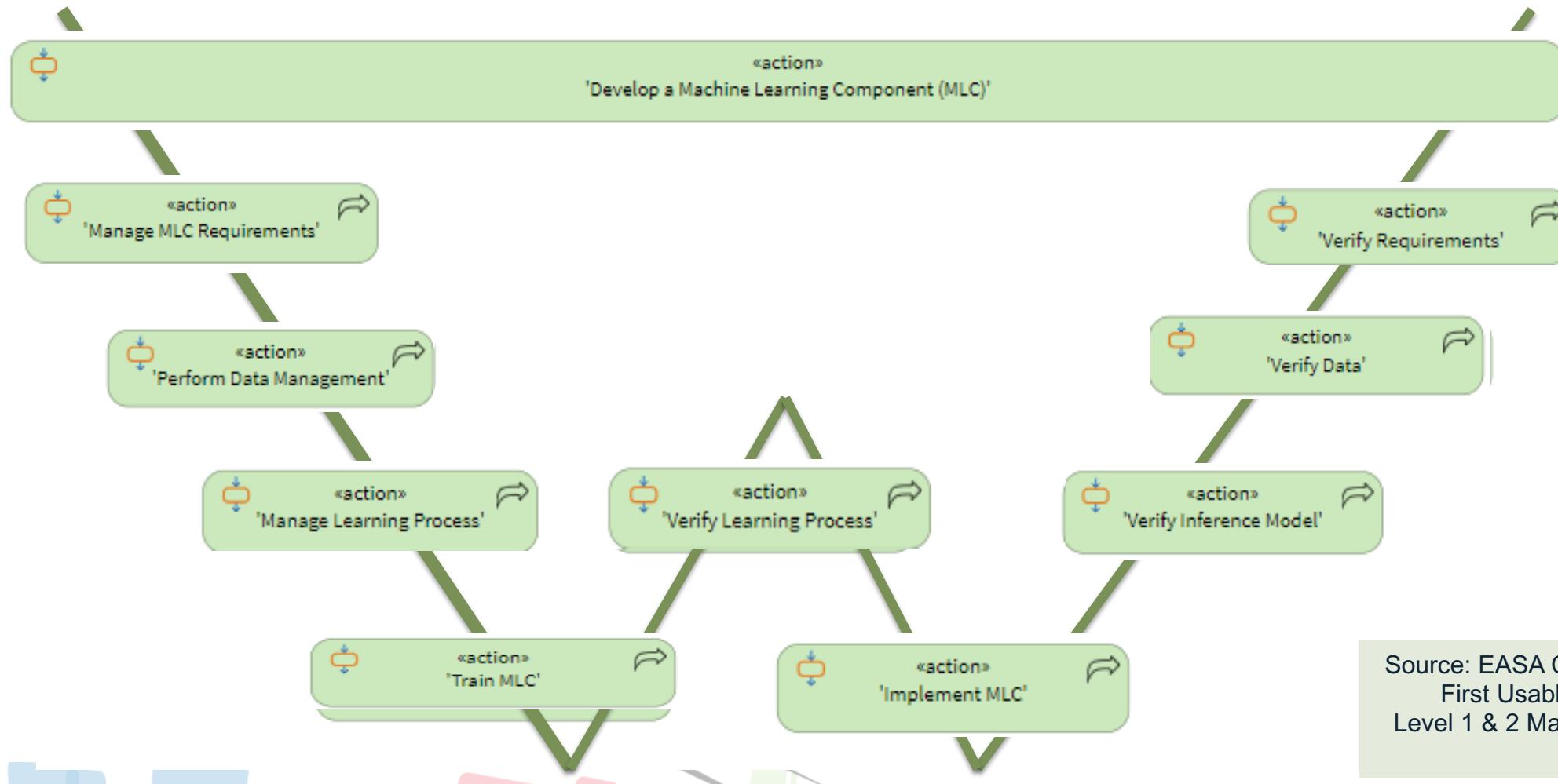
# Our MBSE Methodology is Built on Four Pillars



# MBSE is SE and Usually comes with a V-cycle

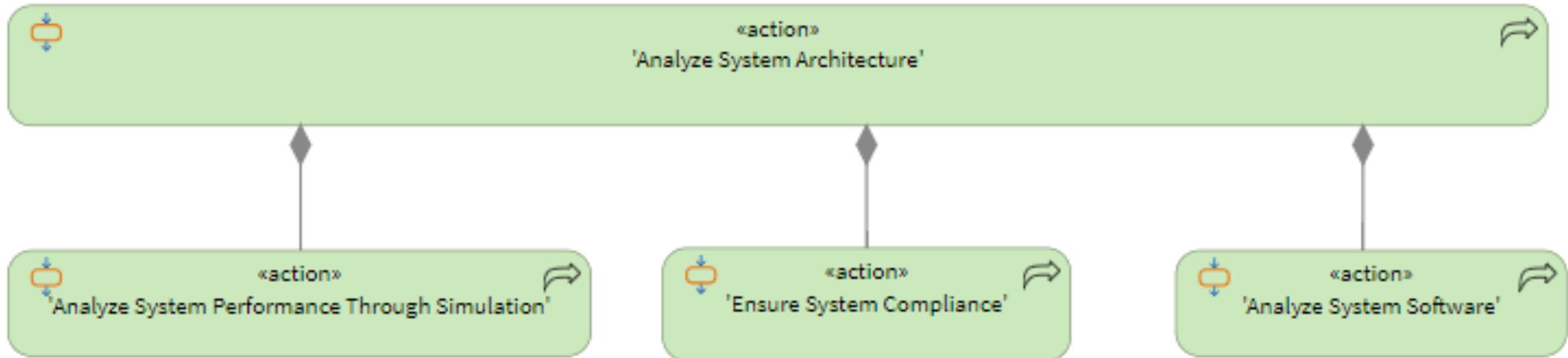


# ...which for Machine Learning Components has Evolved into a W-cycle

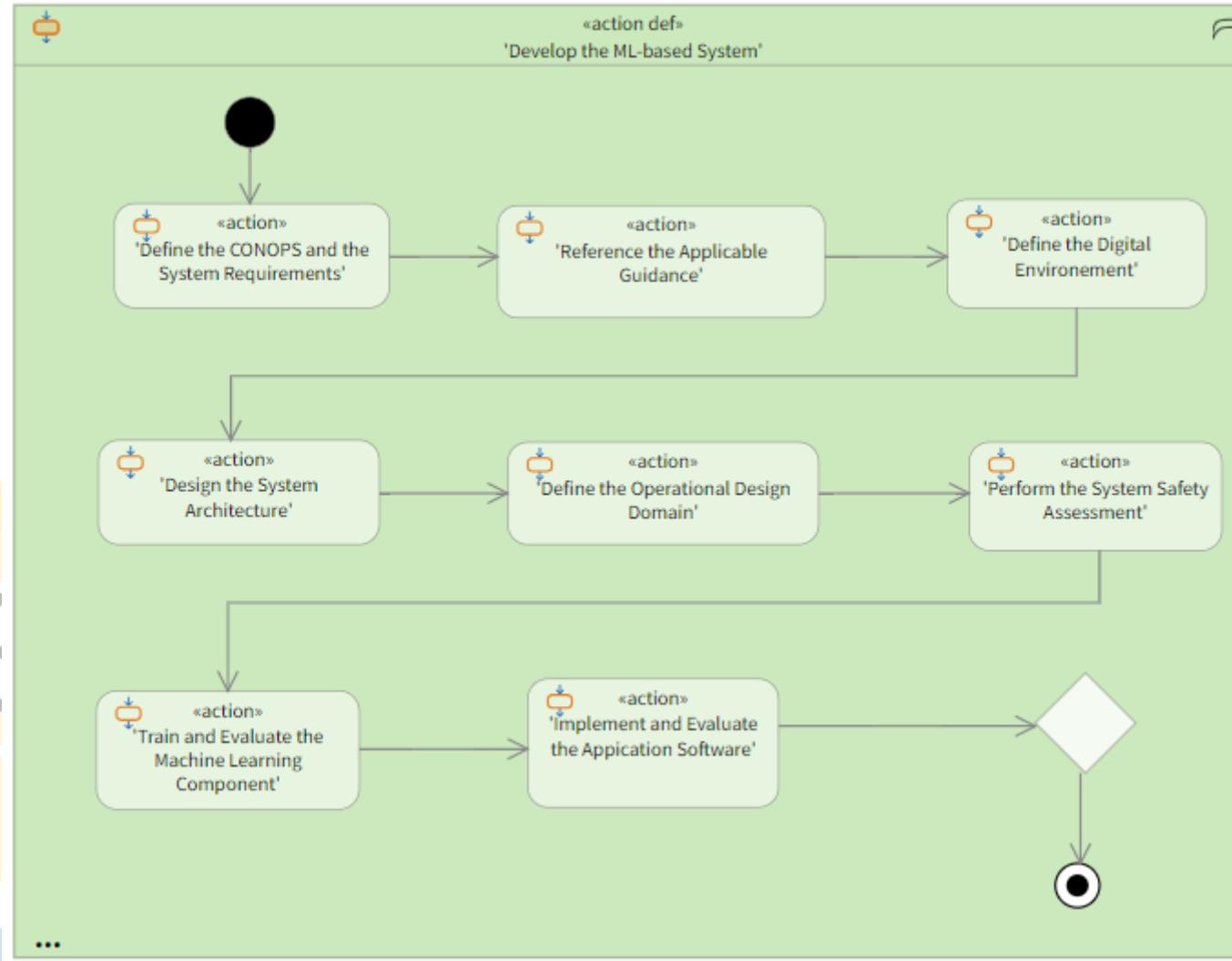


Source: EASA Concept Paper:  
First Usable Guidance for  
Level 1 & 2 Machine Learning  
Applications

# Based on Digital Engineering Practices, System Analyses are Performed to Support Development



# The Phases of a Method for Implementing the AI/ML W-cycle





# AI-Enhanced Autonomous F16 Formation Flying Use Case

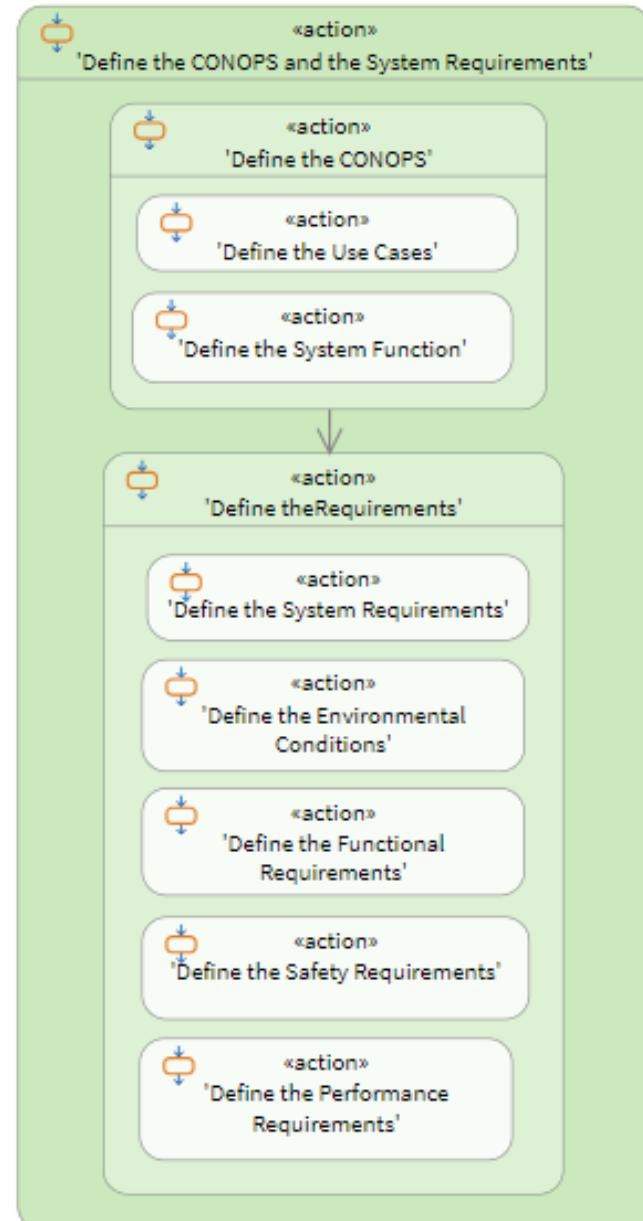
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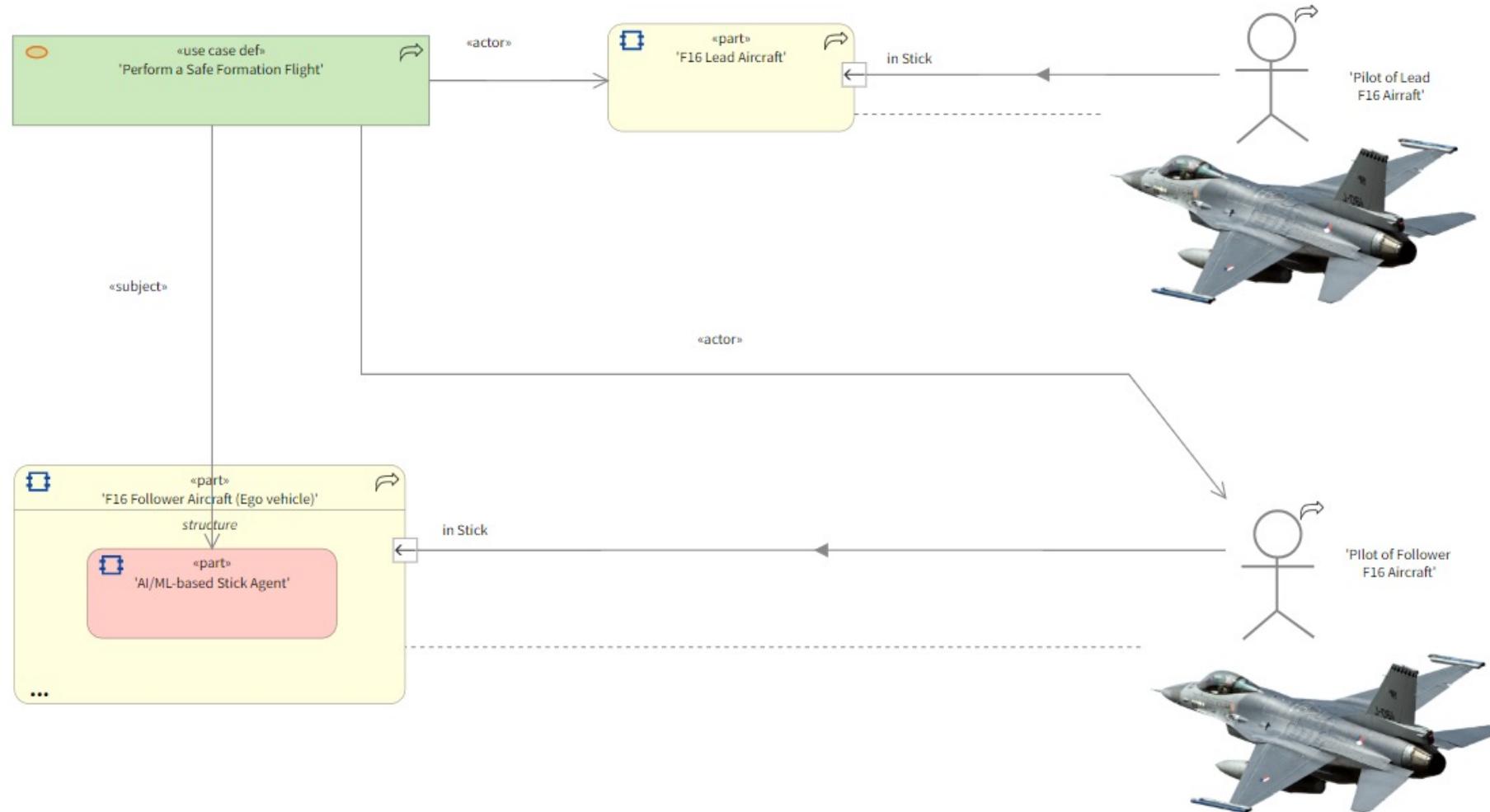


# Define the CONOPS and the Requirements

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# “CONOPS” Facilitates Common Understanding of the Future System



# If a Picture is Worth a Thousand Words...



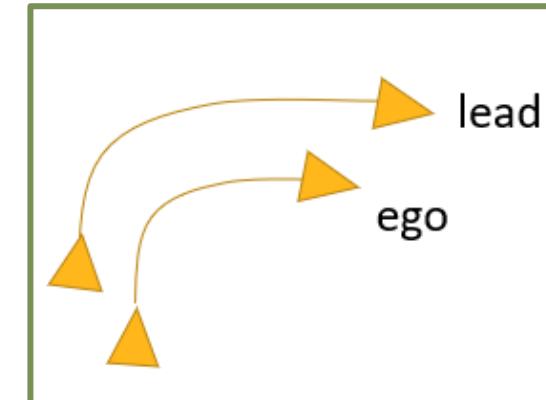
# Define the System Function and the Requirements

## Intended Function

- **F-16 formation flying** (two aircraft) executing series of 90 degree turns at speed of 685 mph (Mach 0.9) with turning radius of 5.550 ft (10 degrees/sec) at altitude of 25 K ft.
- **Functions already developed include:**
  - **AI-based perception software** based on camera sensors for ego F16 (using same methodology)
- **Function to be developed include**
  - Calculating **position and orientation** of lead F16
  - AI-based automated ego F16 **stick agent** to achieve formation flying objective (see KPI below)

## Requirements include

- System Requirements
- Environmental Conditions
- Functional Requirements
- Safety Requirements
- **Performance Requirements**



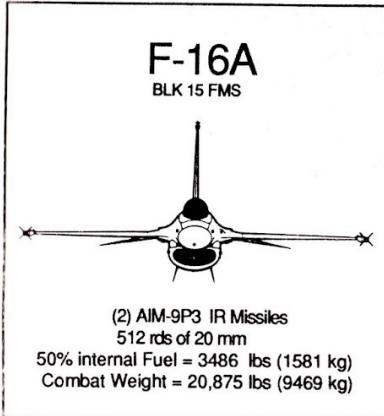
## Key Performance Indicator (KPI)

- $250\text{ft} < \text{Aircraft proximity} < 500\text{ft}$

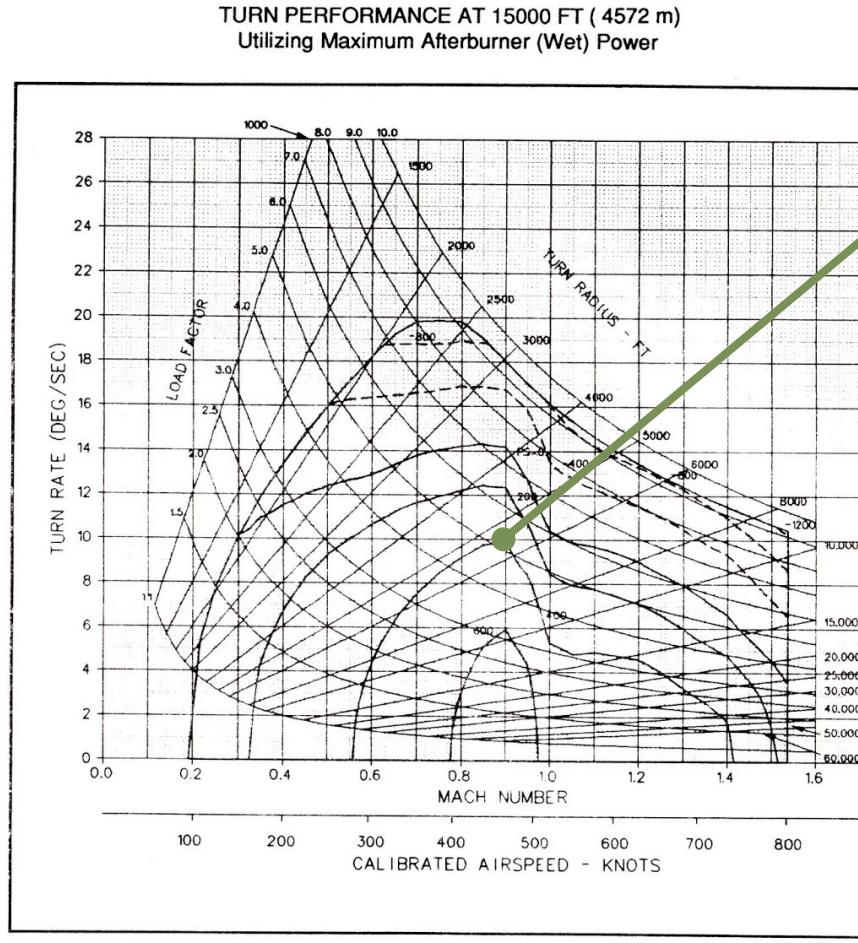
# F16 Flight Dynamics : Turning Radius

Length: 47 feet 8 inches (14.52 m)  
Height: 16 feet 5 inches (5.01 m)  
Wingspan: 31 feet (9.45 m)

Airspeed: 1,319 mph (2123 km/h) at 39,870 ft (12,000 m).  
Ceiling: 50,000 feet (15,420 m).



WING AREA	300 Sq Ft (28 Sq M)
EMPTY WEIGHT	16131 Lbs (7317 Kg)
INTERNAL FUEL	1073 US Gal (4060 Liter)
	6972 Lbs (3162 Kg)
TAKEOFF WEIGHT	
WITH (2) IR + GUN	24361 Lbs (11065 Kg)
MAX EXTERNAL FUEL	1465 US Gal (5545 Liter)
	9522 Lbs (4318 Kg)
COMBAT WEIGHT	20875 Lbs (9469 Kg)
MAX A/B THRUST	
AT SEA LEVEL	23744 Lbs (10770 Kg)
(F100-PW-220NSI)	106 KN
MAX MIL PWR THRUST	
AT SEA LEVEL	14601 Lbs (6623 Kg)
	65 KN
COMBAT T/W RATIO	1.14
COMBAT WING LOADING	70 Lb/Sq Ft (340 Kg/Sq M)
MAX TOGW	37500 Lbs (17010 Kg)
MAX SUBSONIC DSGN.	
LOAD FACTOR	9.3 g's





# Reference the Applicable Guidance



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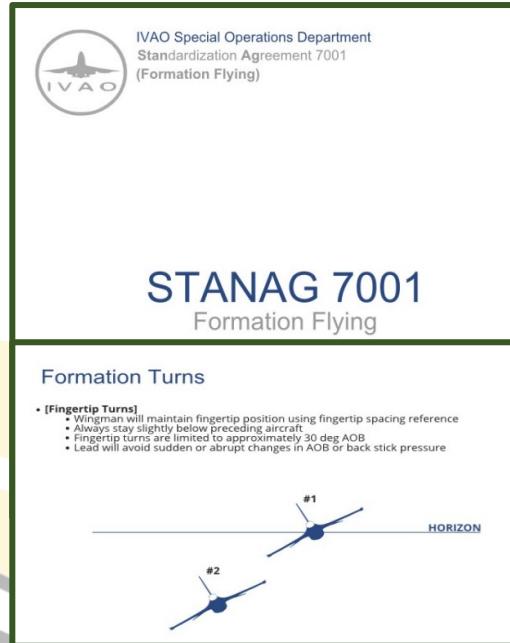
## Identify Guidance

- Formation Flying Operational Concept and Performance
- Safety

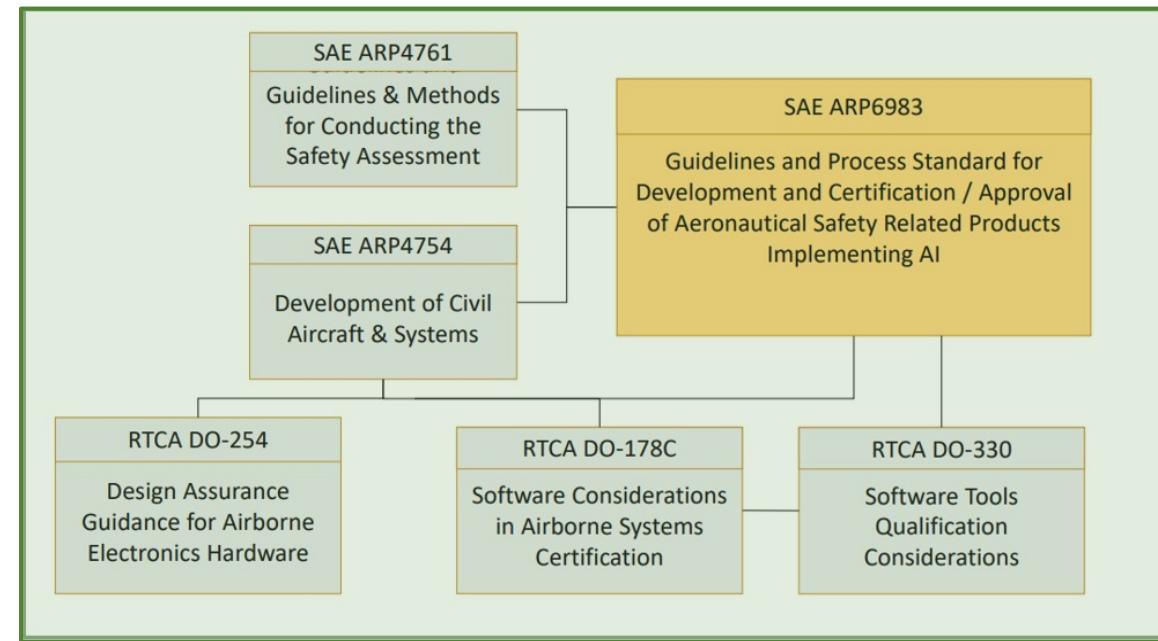
## Create a Glossary of Terms and a Bibliography

- (within the SysML v2 model)

## Operational Concept



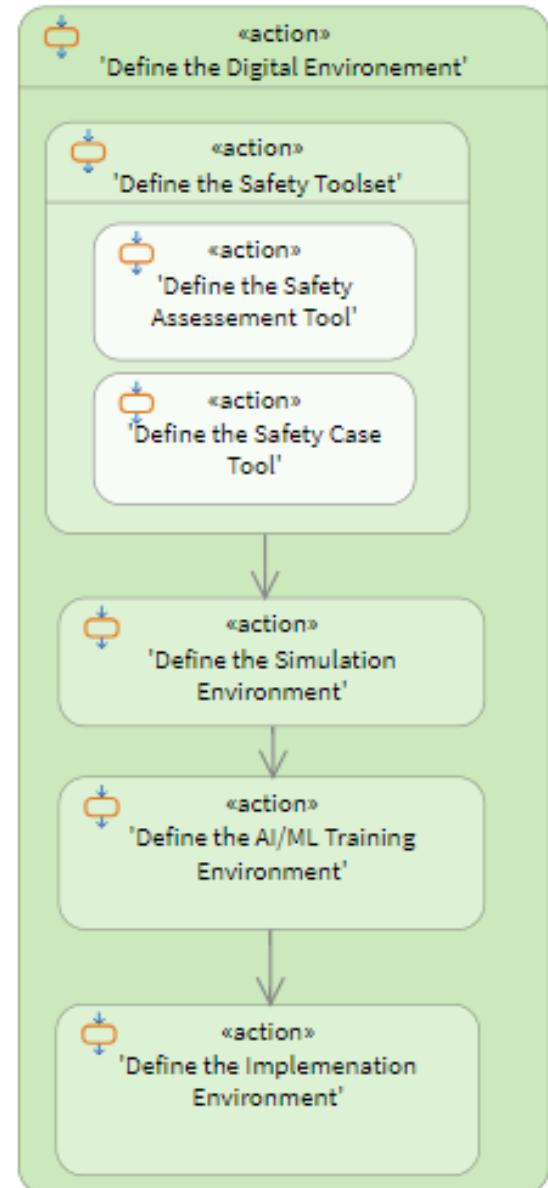
## Safety



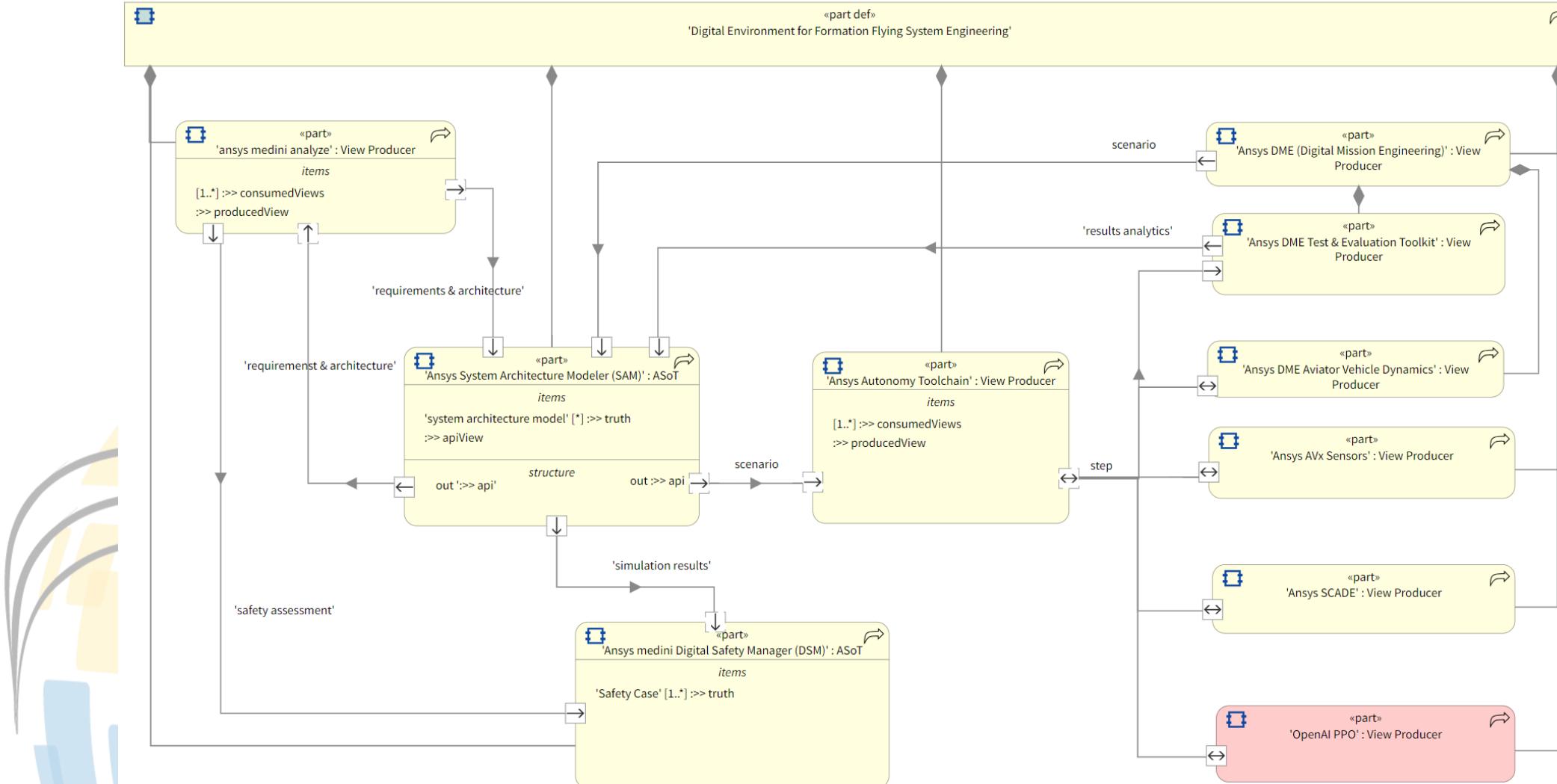


# Define the Digital Environment

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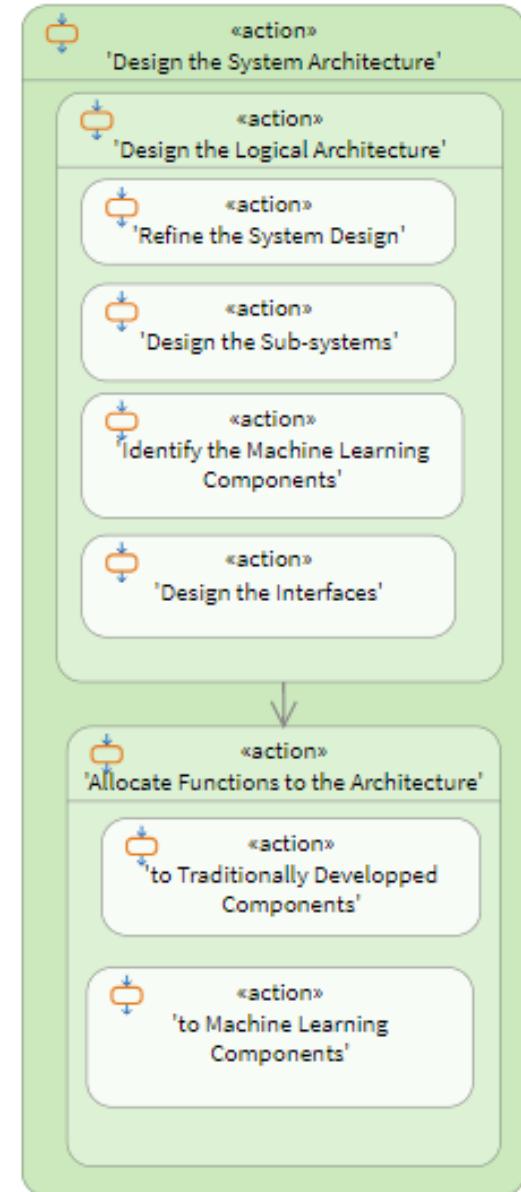
# Define the Digital Engineering Environment for Implementing the W-cycle of AI/ML



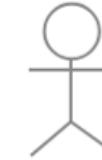


# Design the System Architecture

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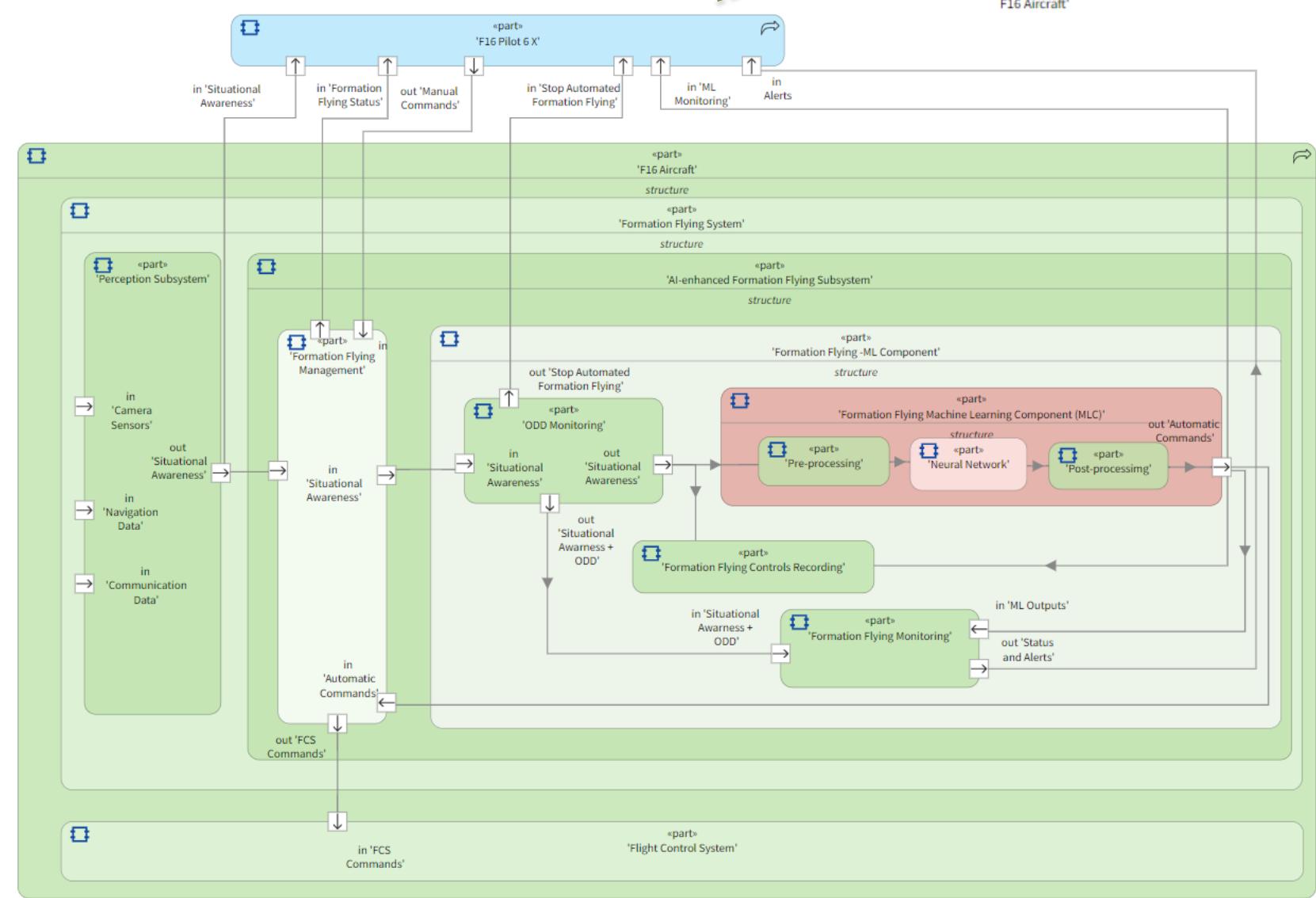
# Design the System Functional Architecture

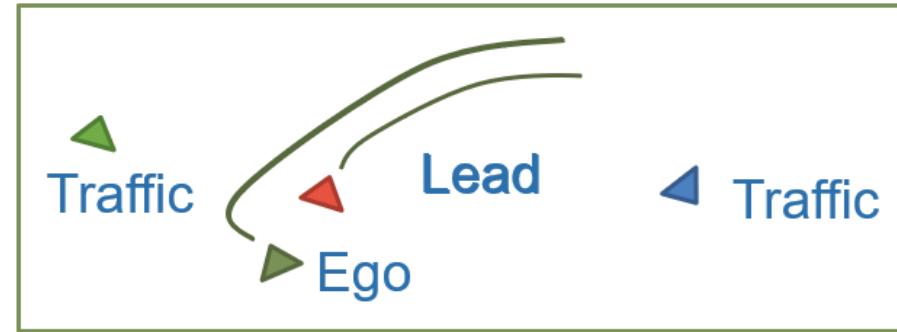


'Pilot of Follower F16 Aircraft'

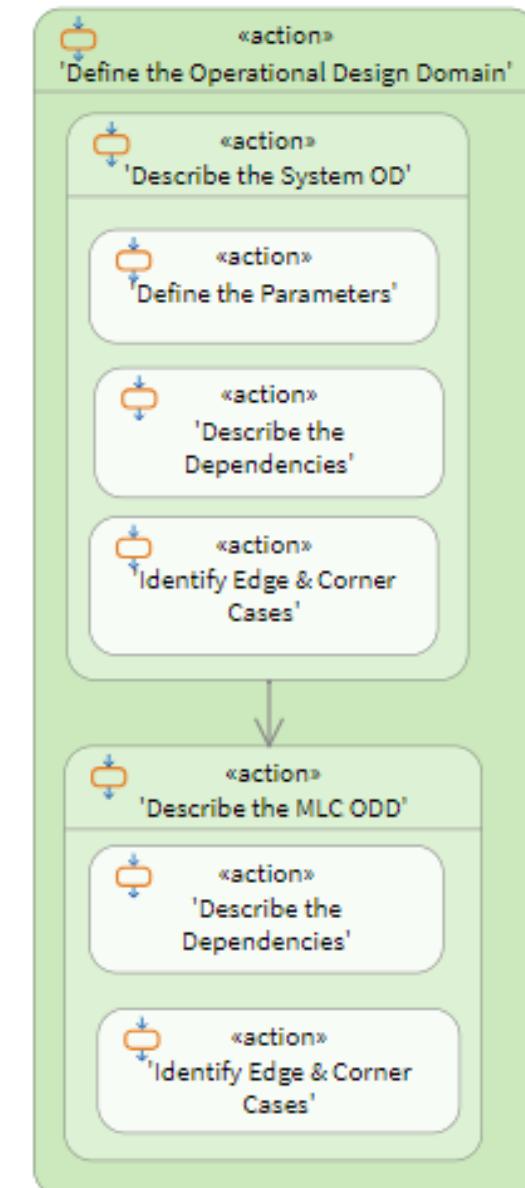
## Functional Architecture

- Perception Subsystem
- AI-enhanced Formation Flying Subsystem
- Formation Flying ML Component
- ODD and Output monitoring
- Pilot as Back-up





# Define the Operational Design Domain (ODD)



# Define the Operational Design Domain (ODD) and the Parameters

## ODD Analysis

- Parameters are defined
- Correlations are analyzed
- Edge cases and corner cases are identified

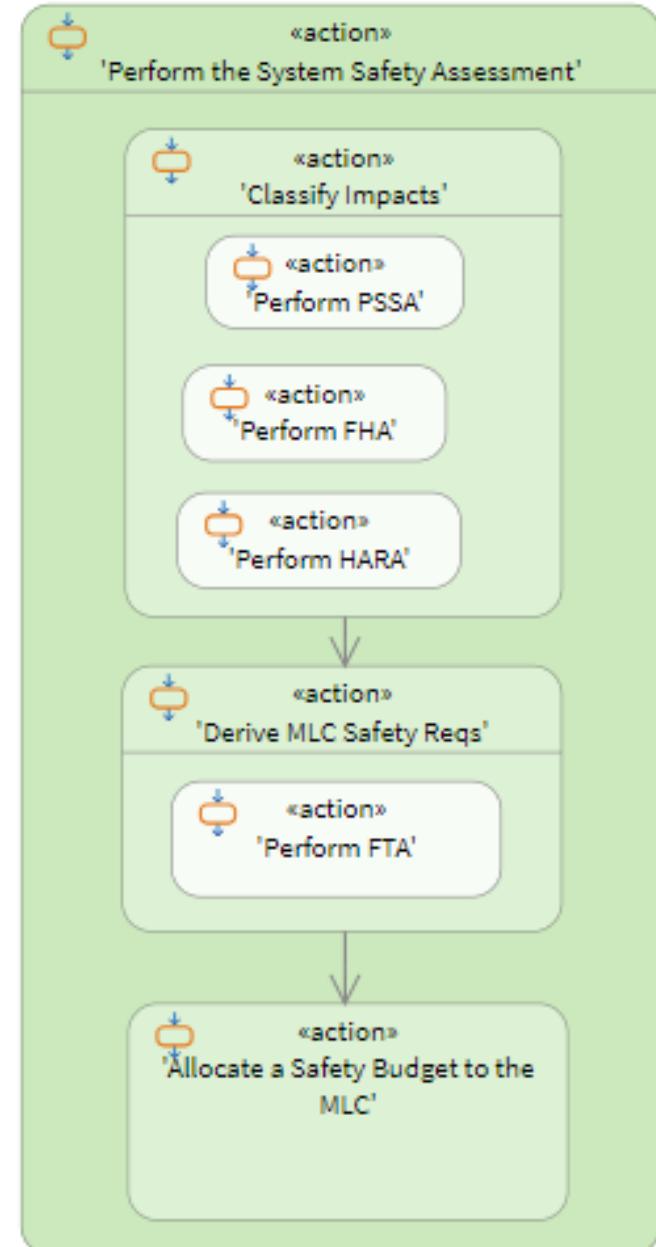


Operational Design Domain							
No birds							
Flat terrain							
Formation Merge and Flight maneuvers							
Parameters							
Aircraft positions and orientations							
Aircraft trajectories							
Time of day							
Visibility conditions							

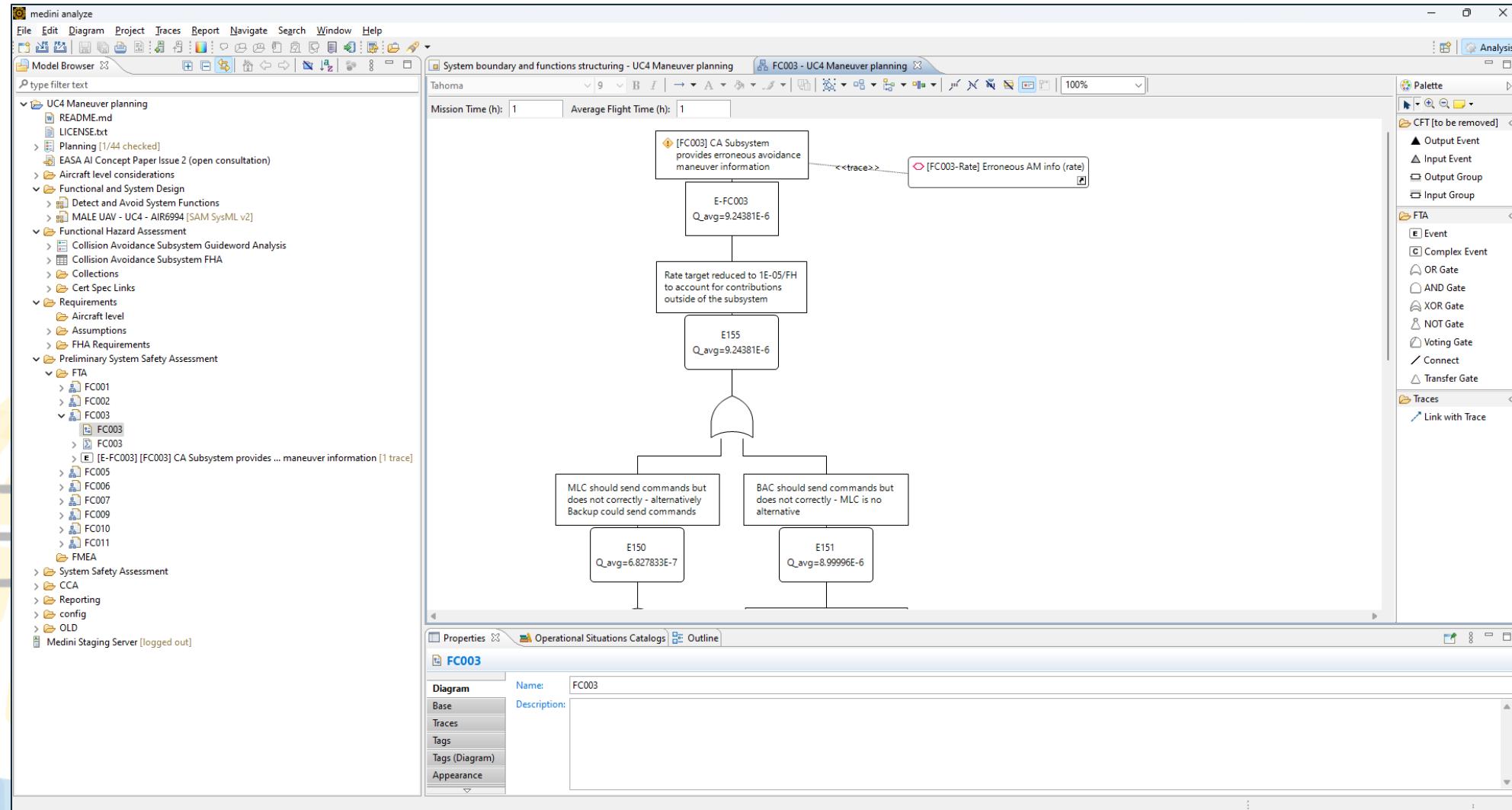
Parameter Ranges and Distributions										
Name	Parameter type	Reference value	Constant	PDF	Type	Mean	Std. Dev.	CoV	Distribution parameter	
1 EgoRotationX	Stochastic	0	<input type="checkbox"/>		NORMAL	0	0.5	10...	0; 0.5	
2 EgoRotationY	Stochastic	0	<input type="checkbox"/>		UNIFORM	0	1.81288	10...	-3.14; 3.14	
3 EgoRotationZ	Stochastic	0	<input type="checkbox"/>		NORMAL	0	0.5	10...	0; 0.5	
4 EgoPositionX	Stochastic	1	<input type="checkbox"/>		NORMAL	0	50	10...	0; 50	
5 EgoPositionY	Stochastic	50	<input type="checkbox"/>		BETA	50	10	20...	32.1115; 94.7214; 2; 5	
6 EgoPositionZ	Stochastic	1	<input type="checkbox"/>		NORMAL	0	50	10...	0; 50	
7 LeadDirection	Stochastic	0	<input type="checkbox"/>		NORMAL	0	1	10...	0; 1	
8 LeadDistance	Stochastic	0	<input type="checkbox"/>		BETA	34...	13.5138	39...	10.1115; 94.7214; 2; 5	
9 LeadAltitudeDiff	Stochastic	0	<input type="checkbox"/>		NORMAL	0	10	10...	0; 10	
10 Time	Stochastic	0	<input type="checkbox"/>		UNIFORM	0.5	0.288675	57...	0; 1	
11 FogVisibilityDistance	Stochastic	0	<input type="checkbox"/>		BETA	714...	1595.59	22...	10; 10000; 5; 2	
12 AirTurbidity	Stochastic	0	<input type="checkbox"/>		BETA	3.4...	1.91663	55...	0; 12; 2; 5	



# Perform the System Safety Assessment



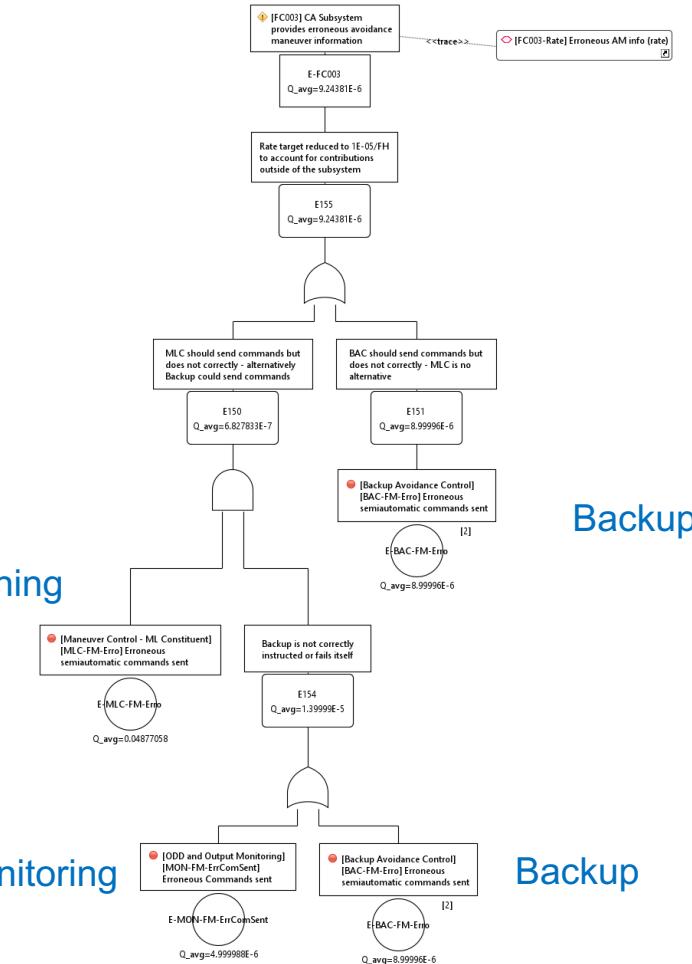
# Safety Assessment – Use a MBSE Approach



# Perform the Preliminary Safety Assessment – FHA and FTA

## Allocation of target failure rates per Hour of Flight (FpH)

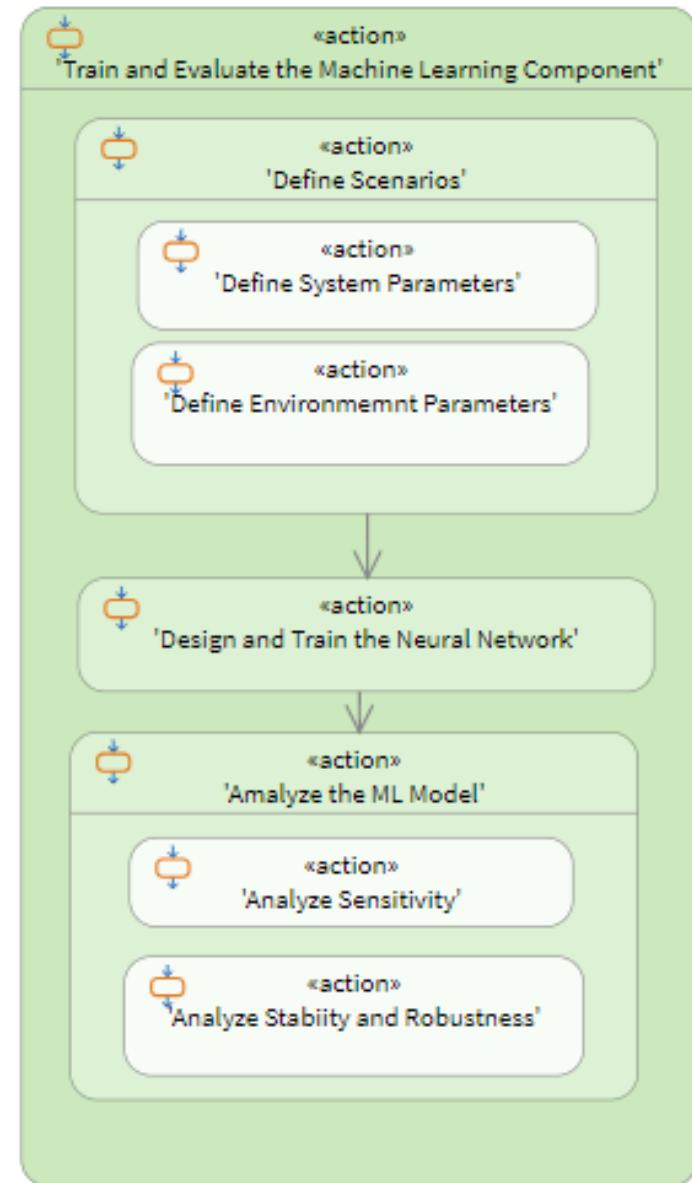
- Applies to electronics
- Applies to Machine Learning Component



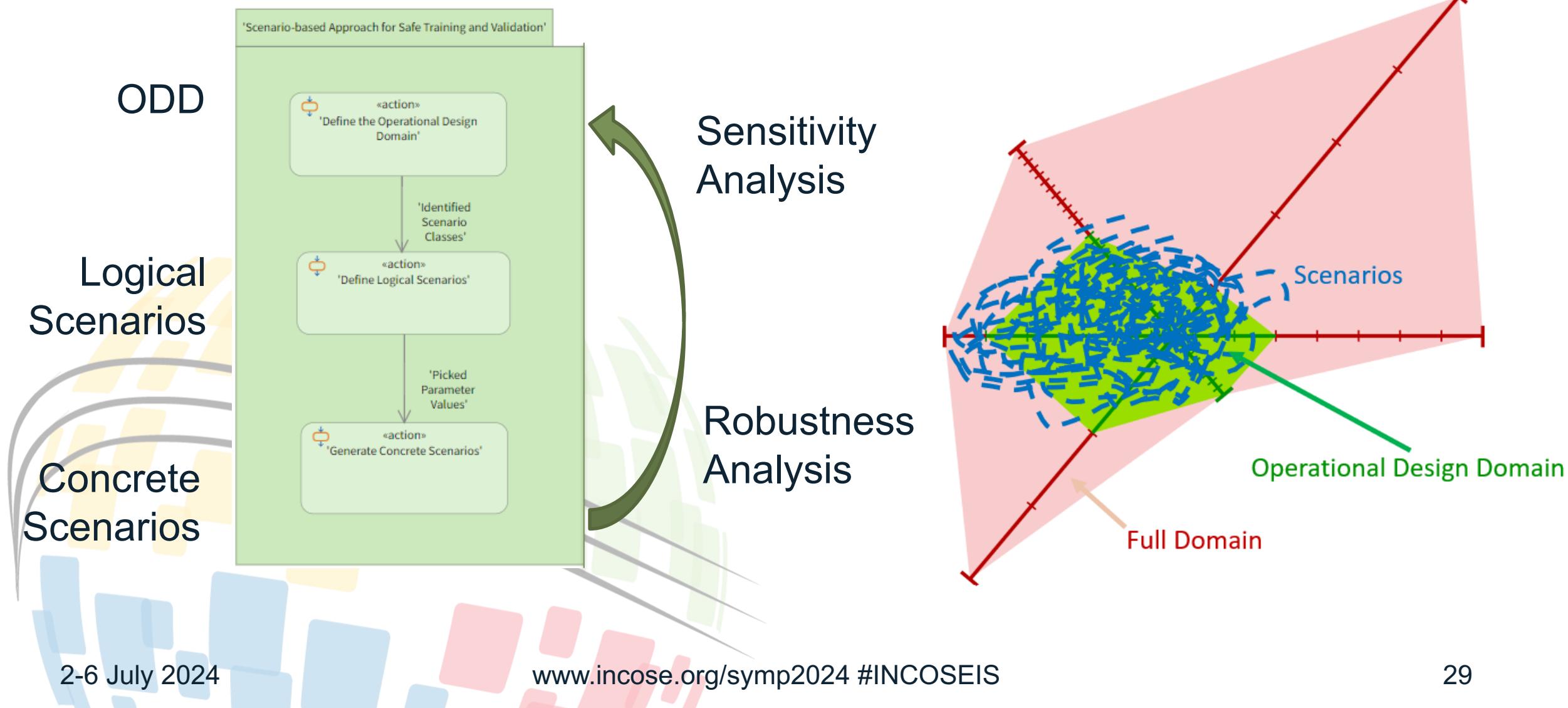


# Train and Validate the Machine Learning Component

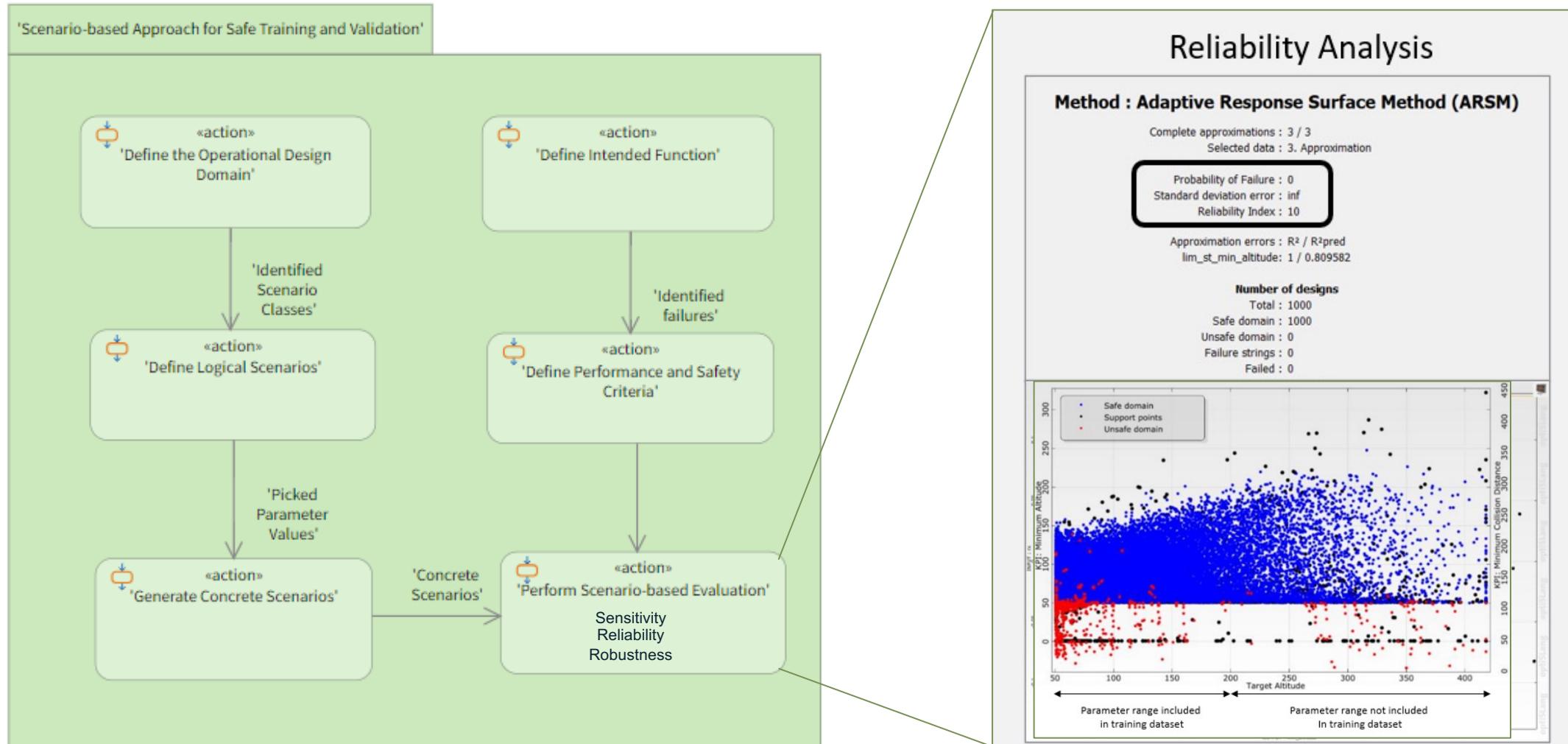
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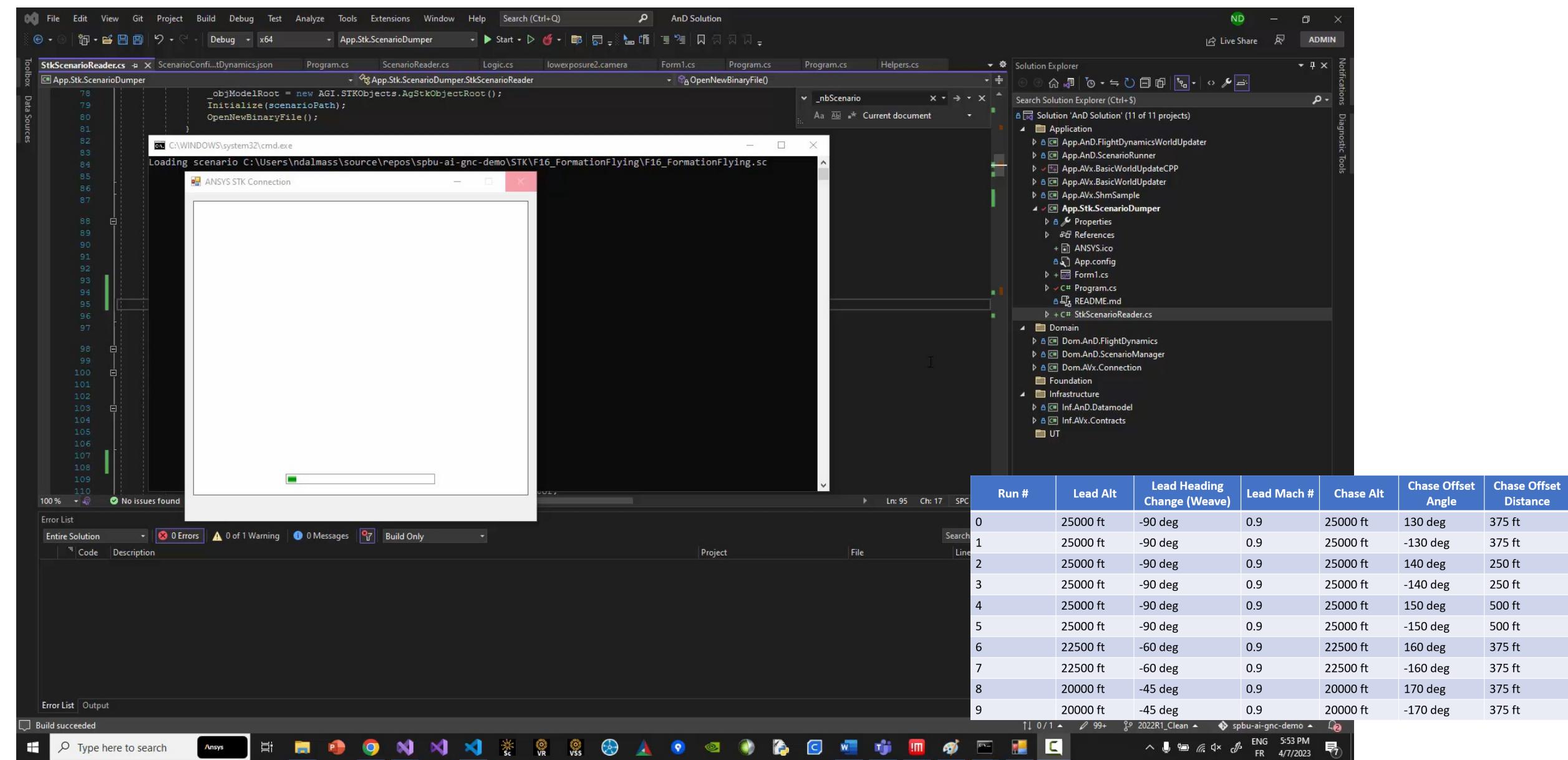
# The Scenario-based Evaluation Approach



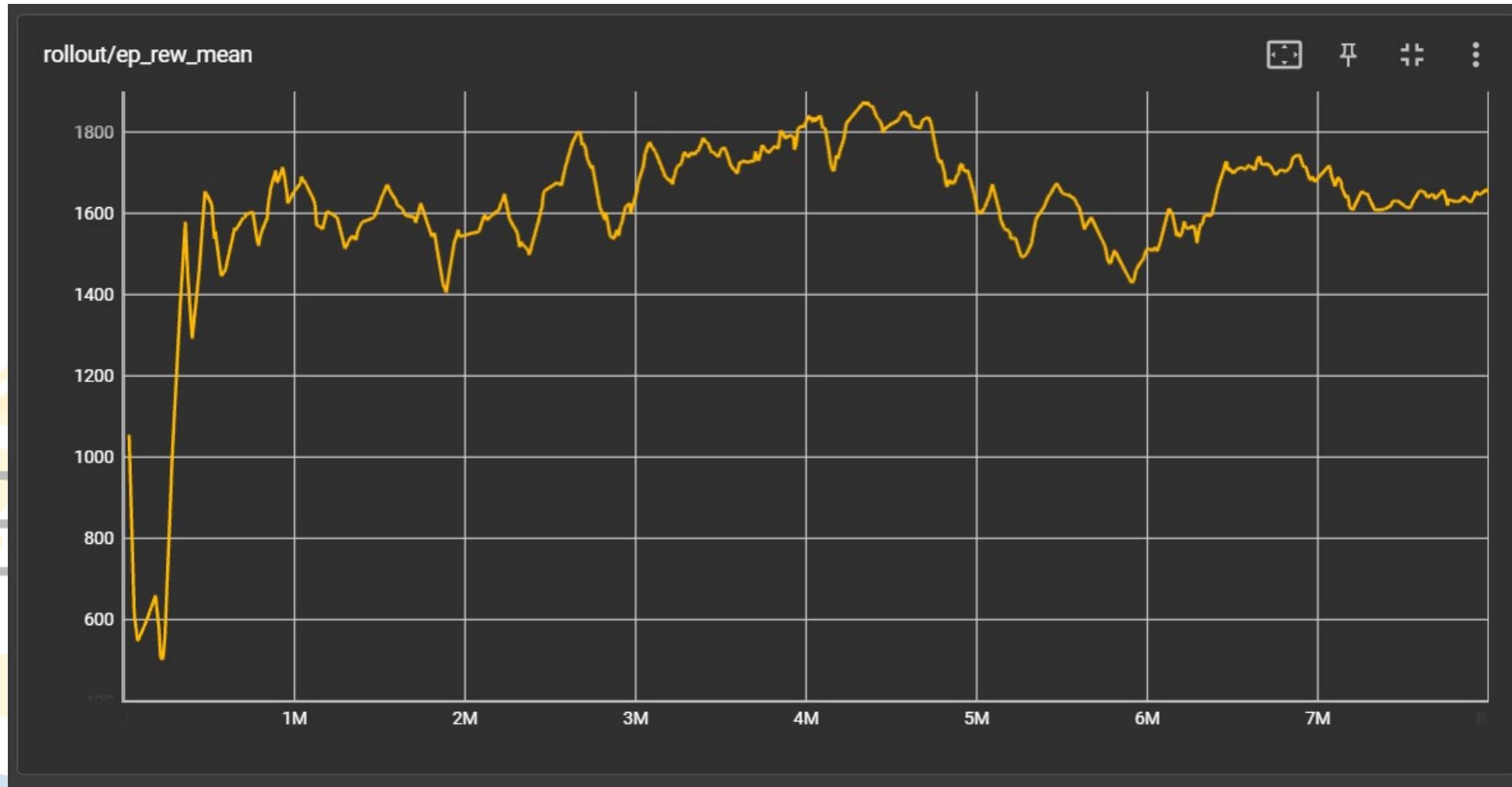
# Scenario-based Evaluation – Reliability Analysis



# Using the DME Tool Kit to Create Scenarios



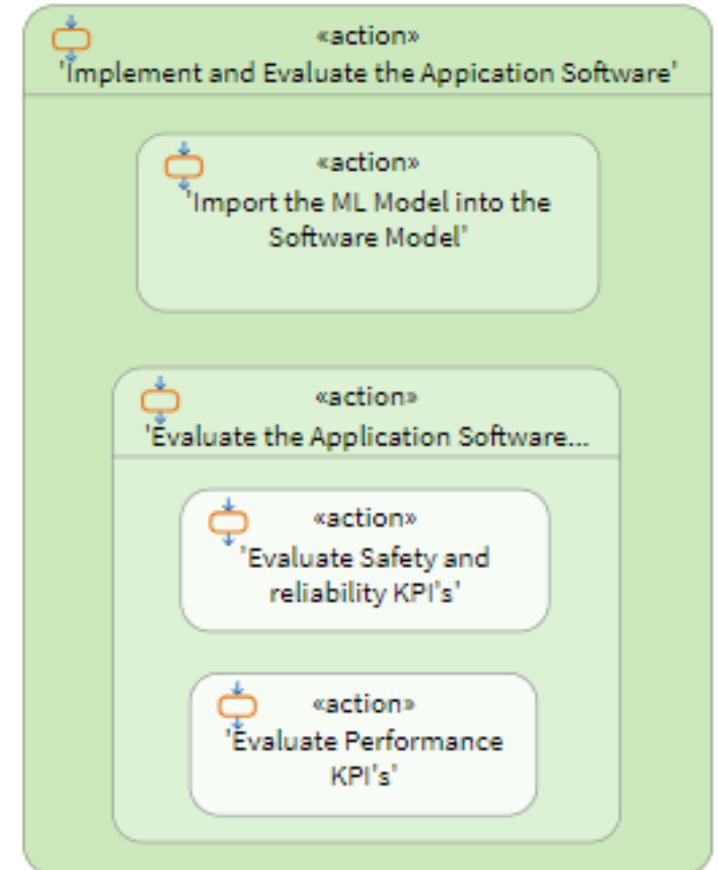
# F16 Formation Flight Training Convergence



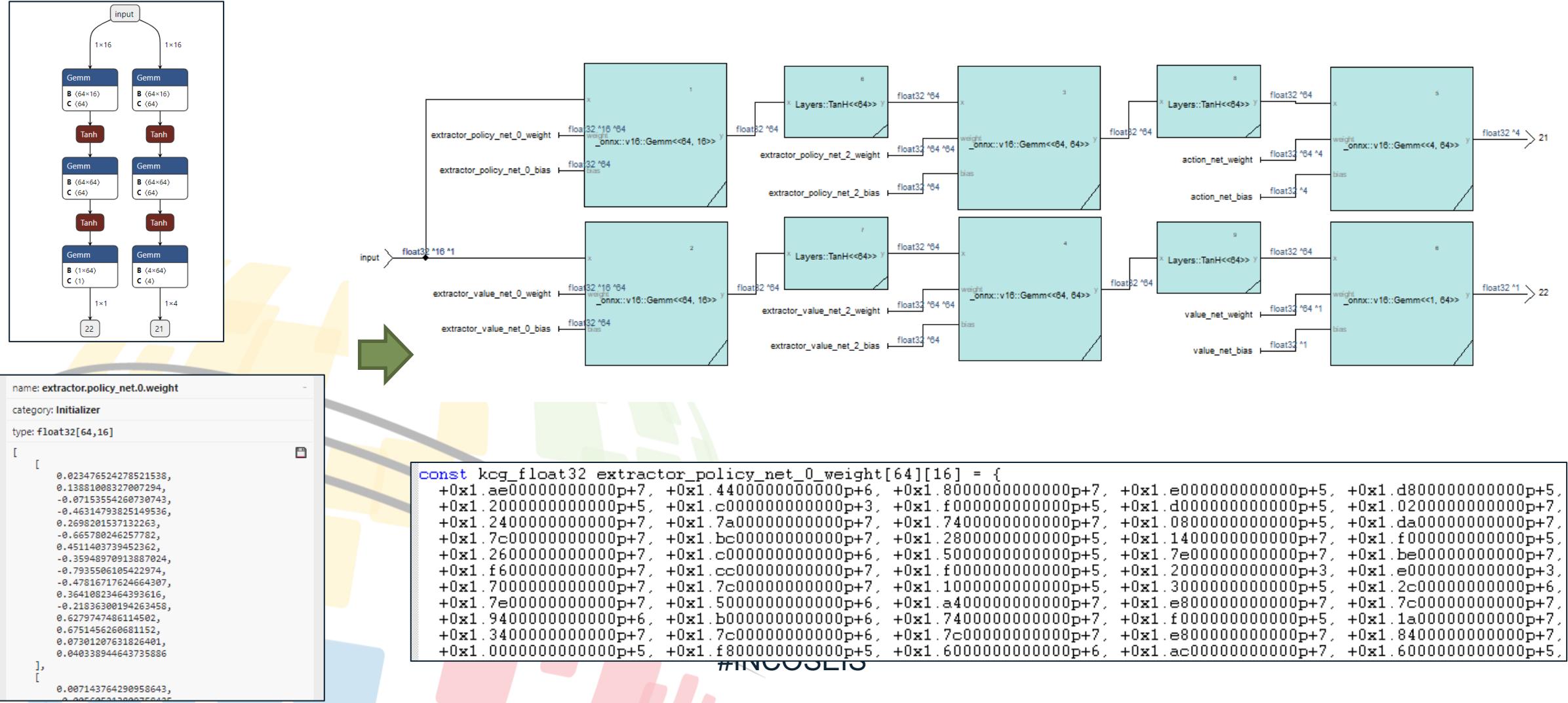


# Implement and Evaluate the Application Software

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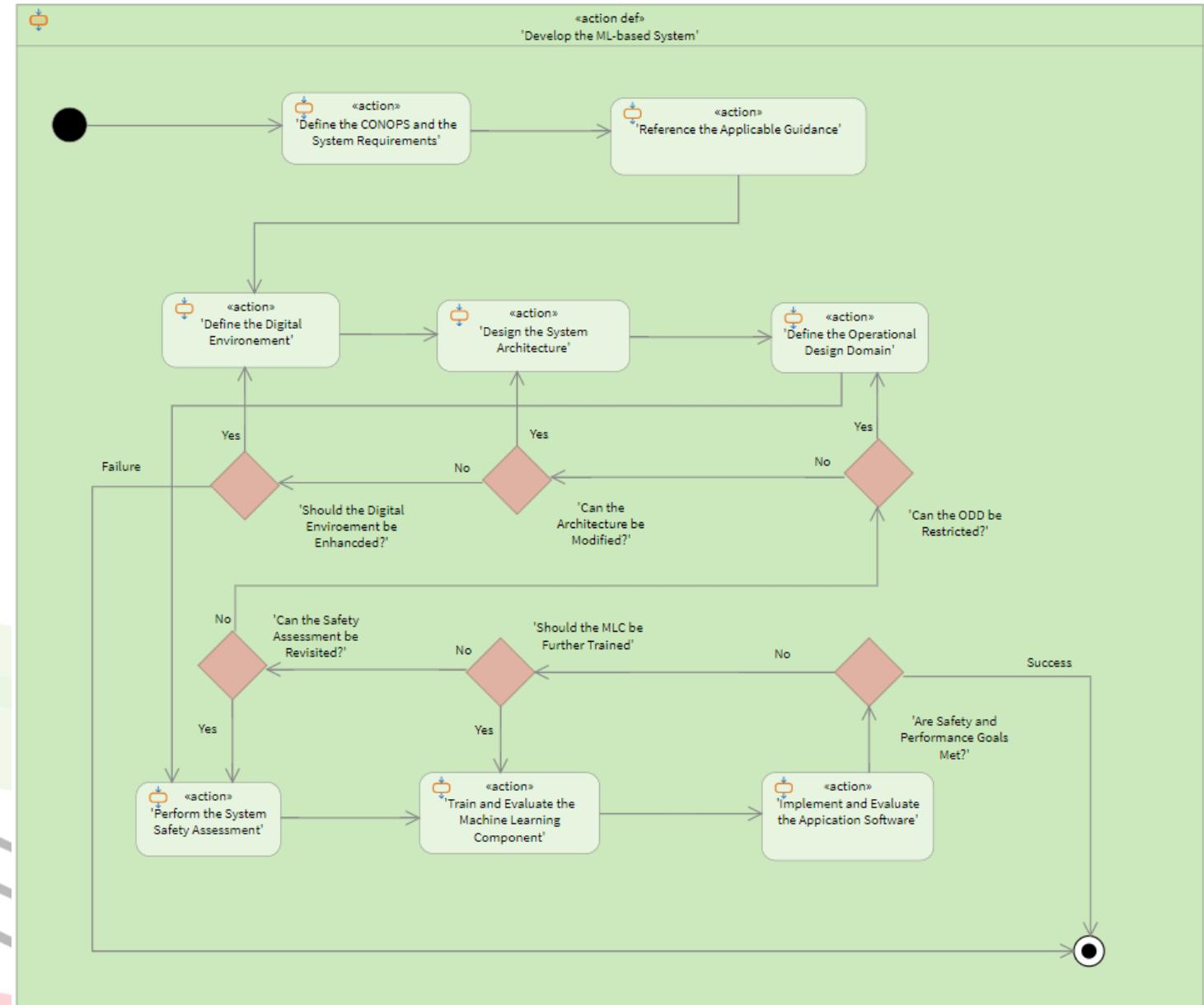


# ONNX is Used to Import the Trained Neural Network into the Embedded Software Model





# Iterating the AI/ML Workflow





# Conclusions and Future Work

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# Conclusions and Future Work

- AI/ML is seen as a **key-enabler** of Autonomous functions.
- **MBSE Methodology** and **Digital Engineering** bring together all Disciplines and Stakeholders in a well-defined digital environment that is needed for developing safe AI/ML-based software.
- We will pursue our development of the Ansys MBSE Methodology, enabling **Domain Specific Methodologies** (e.g., Autonomy in Aeronautics, Autonomy in Automotive).
- Together with **authorities, manufacturers, suppliers, and tool vendors**, we participate to the creation AI/ML-based Certification standards (e.g., SAE ARP6983 in Aeronautics, ISO/PAS 8800 in Automotive) to ensure the required level of safety of these applications.



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