Applications of Model-Based Systems Engineering for JAXA's Engineering Test Satellite-9 Project

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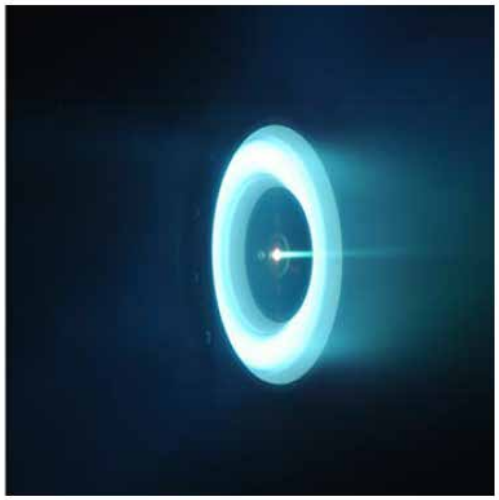
ETS-9

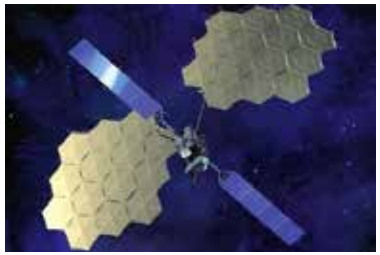
Hall Effect Thruster



Engineering Test Satellite-9: ETS-9

Main objective

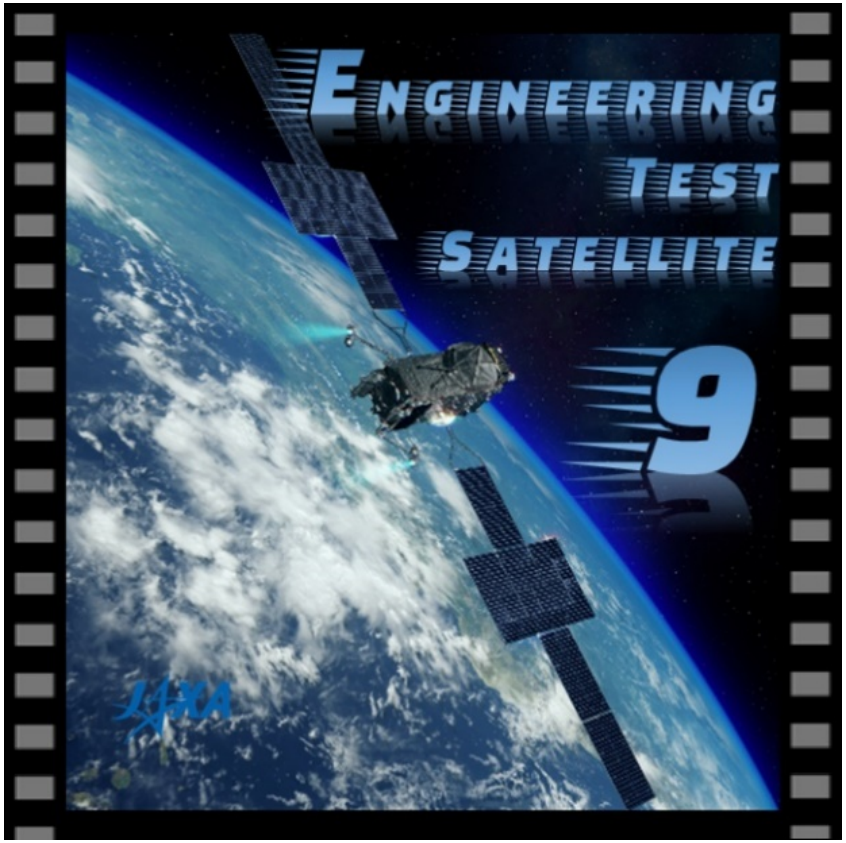
ü Demonstrate advanced and competitive technologies for “Next Generation Geostationary Communication Satellite” in 2020s.



ETS-VIII (8kW, 2006)

Commercial satellites (8-13kW)

Beyond current capability

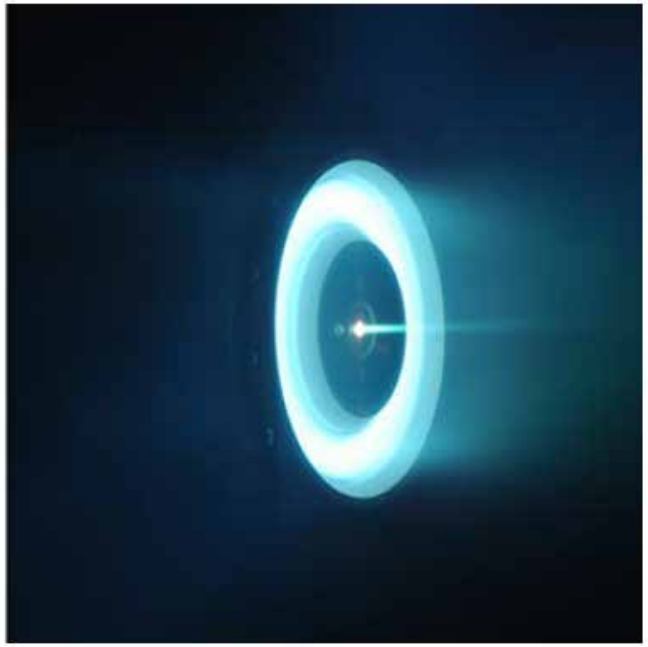


Key technologies

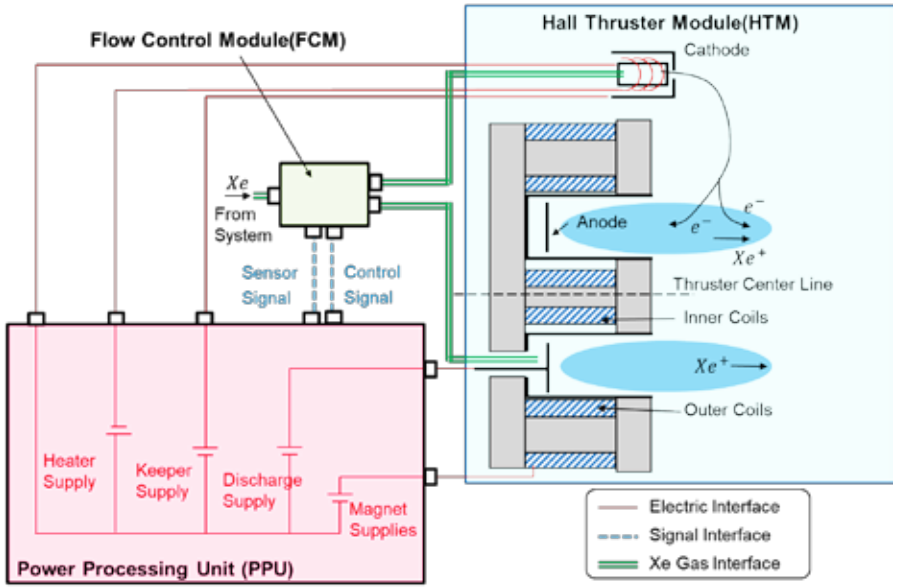
- ü All electric propulsion with hall effect thruster
- ü 25kW System power supply
- ü High Thermal control capacity with deployable radiator
- ü 6kW class hall effect thruster(HET)
- ü GPSR for GEO and GTO
- ü RF Spot beams with Digital Channelizer and Digital Beam Forming technology
- ü Optical Feeder link

1. Introduction

New 6kW Hall Effect Thruster for faster electric orbit raising



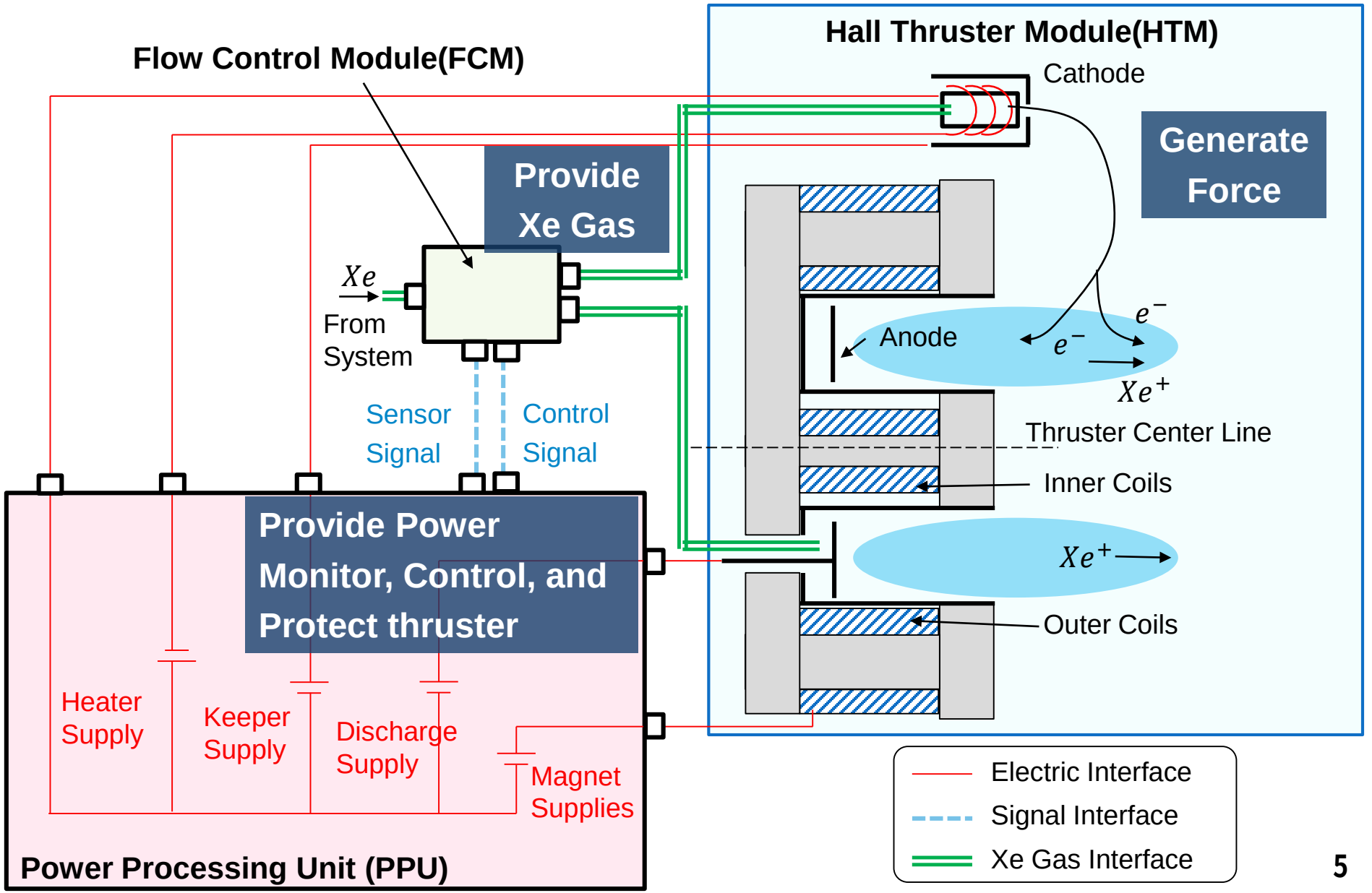
Hall Effect Thruster(HET)



Complex Behavior with Multiple Components Developed by Multiple Vendors

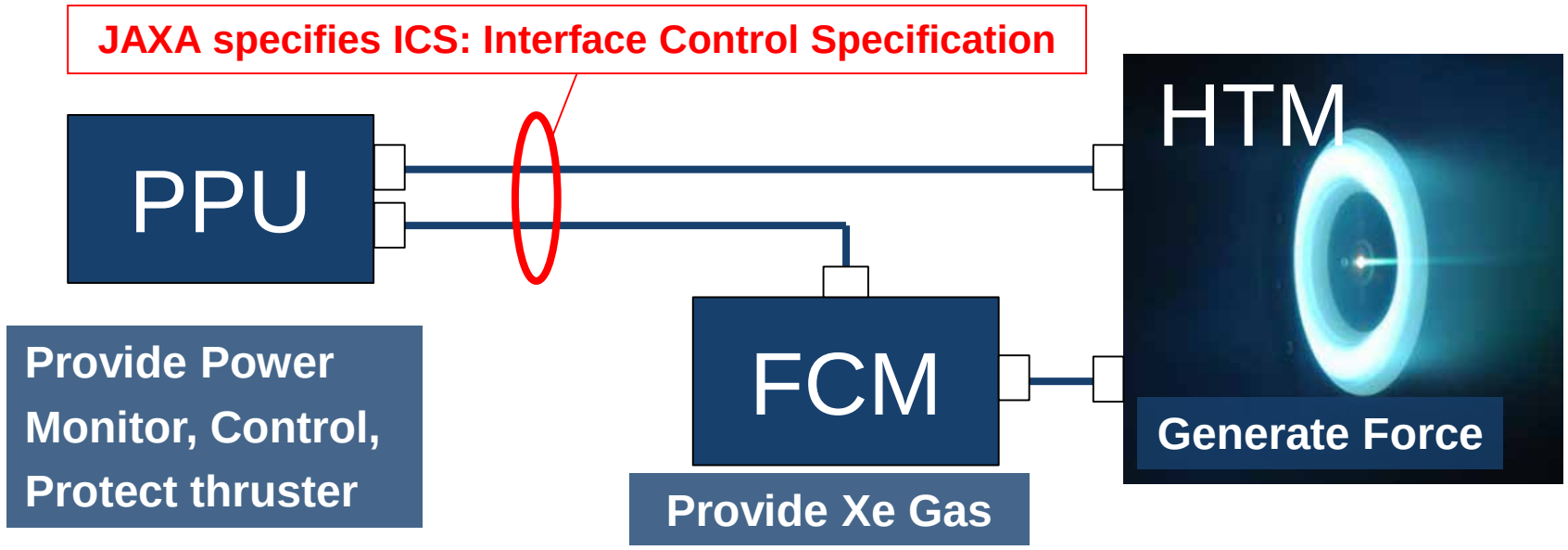
This presentation focuses on the application of MB4SE to the interface management of hall effect thruster development in Engineering Test Satellite-9(ETS-9) project.

2. Why MB4SE?
Complex Behavior and Interfaces of HET



2. Why MB4SE?
SE Challenge for HET Development

1. **Multiple manufacturers are involved in the development**
2. **Complex interactions between components**
   - Hall Thruster Module(HTM)： Vendor-A
   - Flow Control Module (FCM)：Sub-Vendor of Vendor-A
   - Power Processing Unit (PPU)：Prime Contractor



Interface Management of the Hall Effect Thruster is an important SE Challenge for the project, where interface specifications span multiple manufacturers with complex interactions

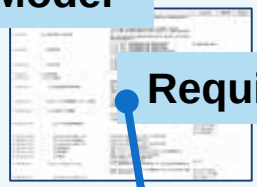
2. Why MB4SE?
How do we manage the complexity?

(1) Comprehensive system analysis supported by a system model and interactive digital artifacts that visualize system analysis
(2) Formalized description of system architecture by using SysML model to eliminate ambiguity as much as possible to manage complexity

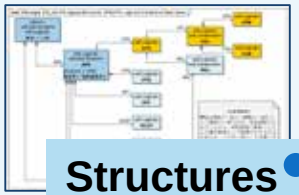
System of Interest

Describe

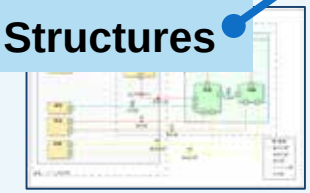
System Core Model



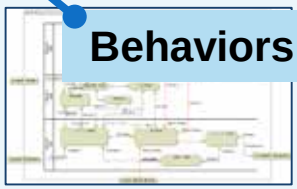
Requirements



Structures



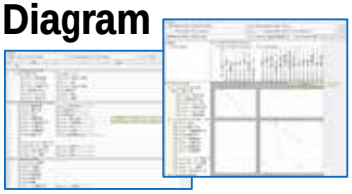
Behaviors



Generate

SE Artifacts

Table, Matrix, Diagram



Visualization (HTML, Python)

Guide

Project Manager
Systems Engineer

Perform

Failure Mode Analysis

Add to Model

Customized Model Query Rule

Analyses

Organize

"Meta-Model"

Architecture Description

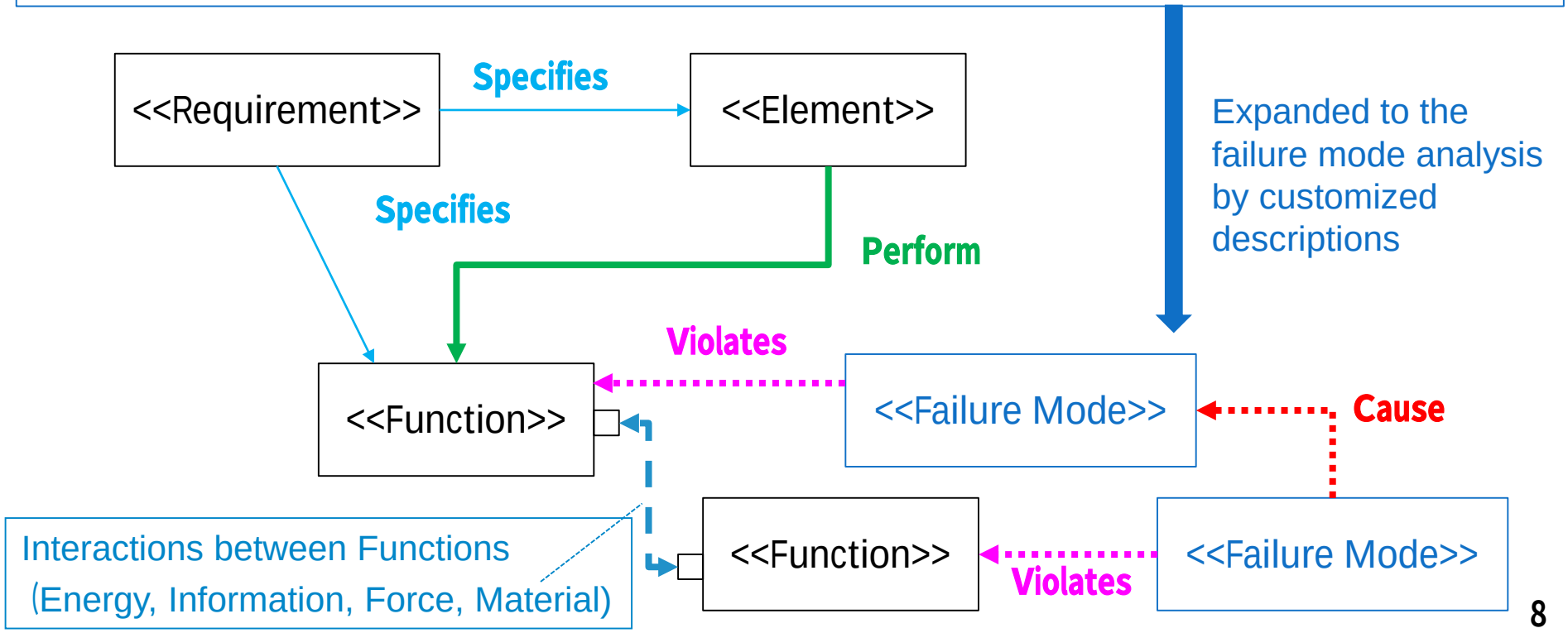
3. What to Model?

Formalized description of system architecture by using SysML

a. Focusing on System Behaviors/Functions, we describe the interactions between system elements to manage Interface Control Specifications(ICS)

b. Explicitly describe relationship between behaviors, structures and requirements

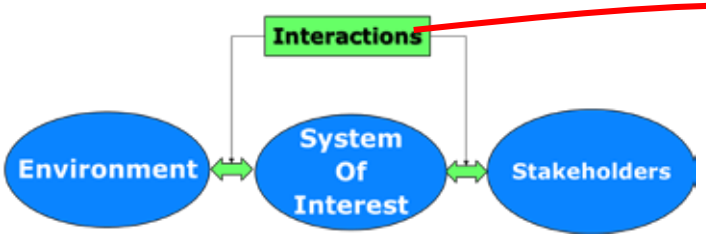
c. Restructure component-level information distributed across multiple vendors as system level structured information



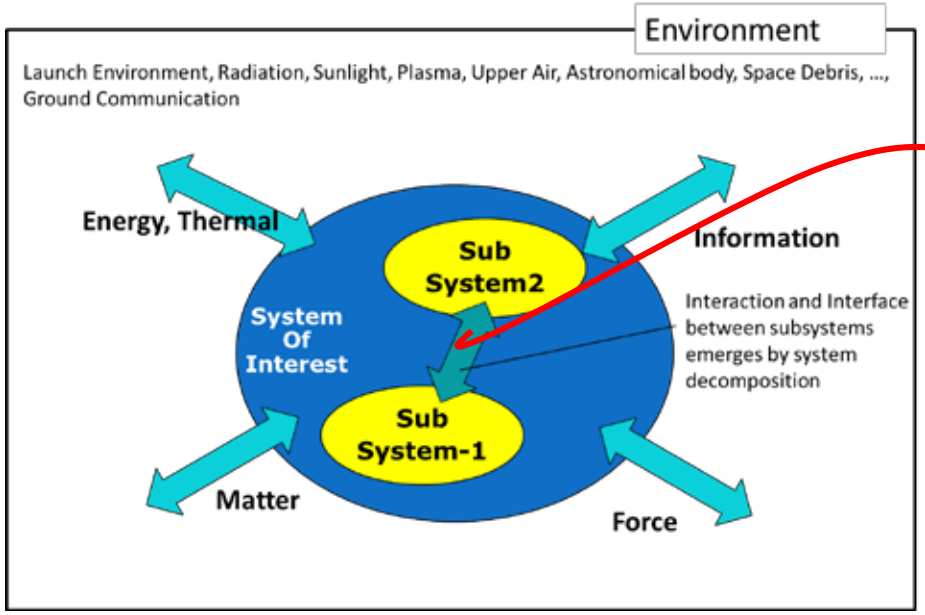
3. What to Model?

Core Methodology[*1] to manage complex behaviors of HET

1. A mission consists of value creation events.
2. A value creation event is generated from objects and the interactions among those objects.
3. Interactions are described by inputs and outputs among objects. A **conversion** from input to output is defined as a function (and performance) of an object.



Core Objects

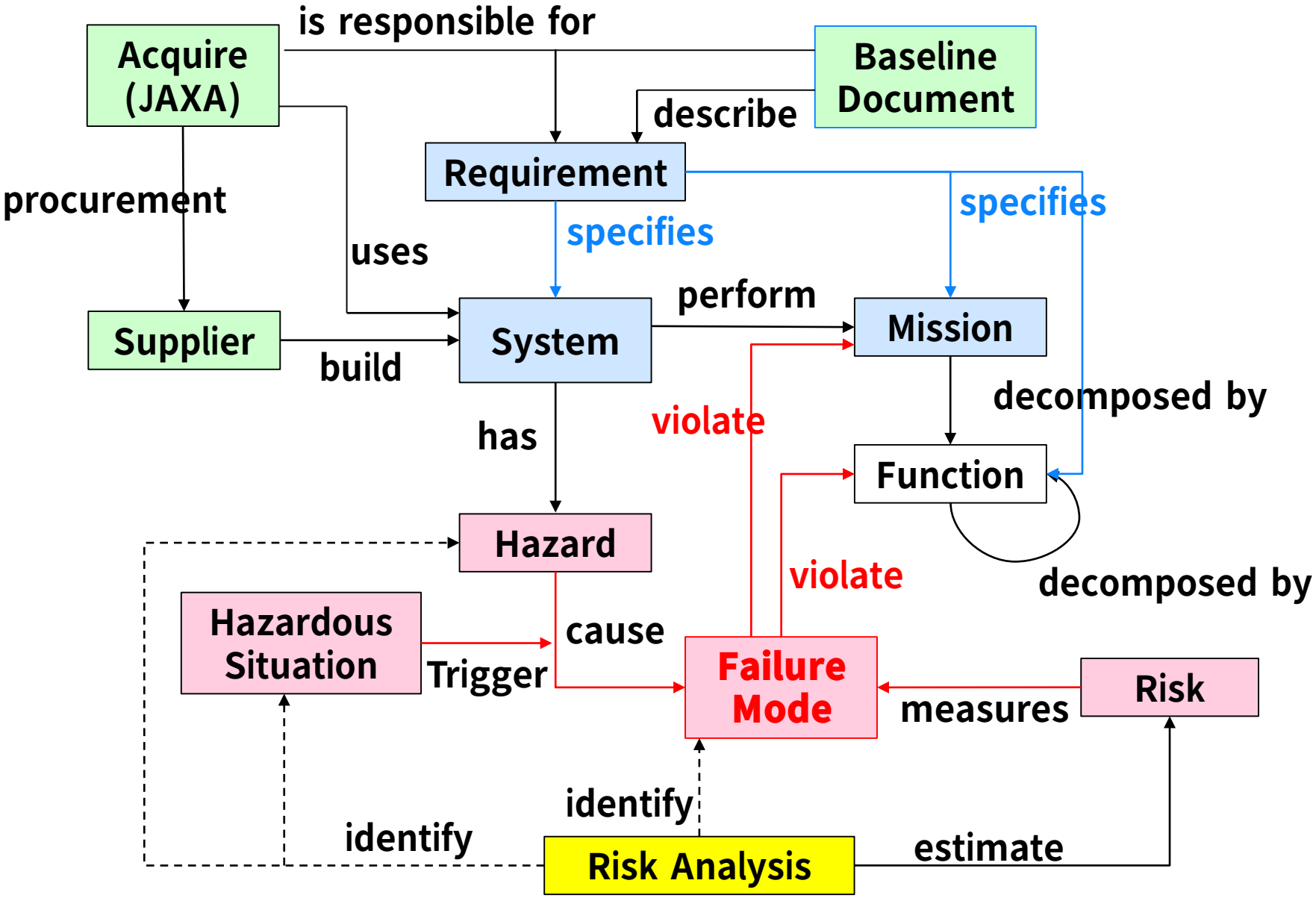


Conversion patterns

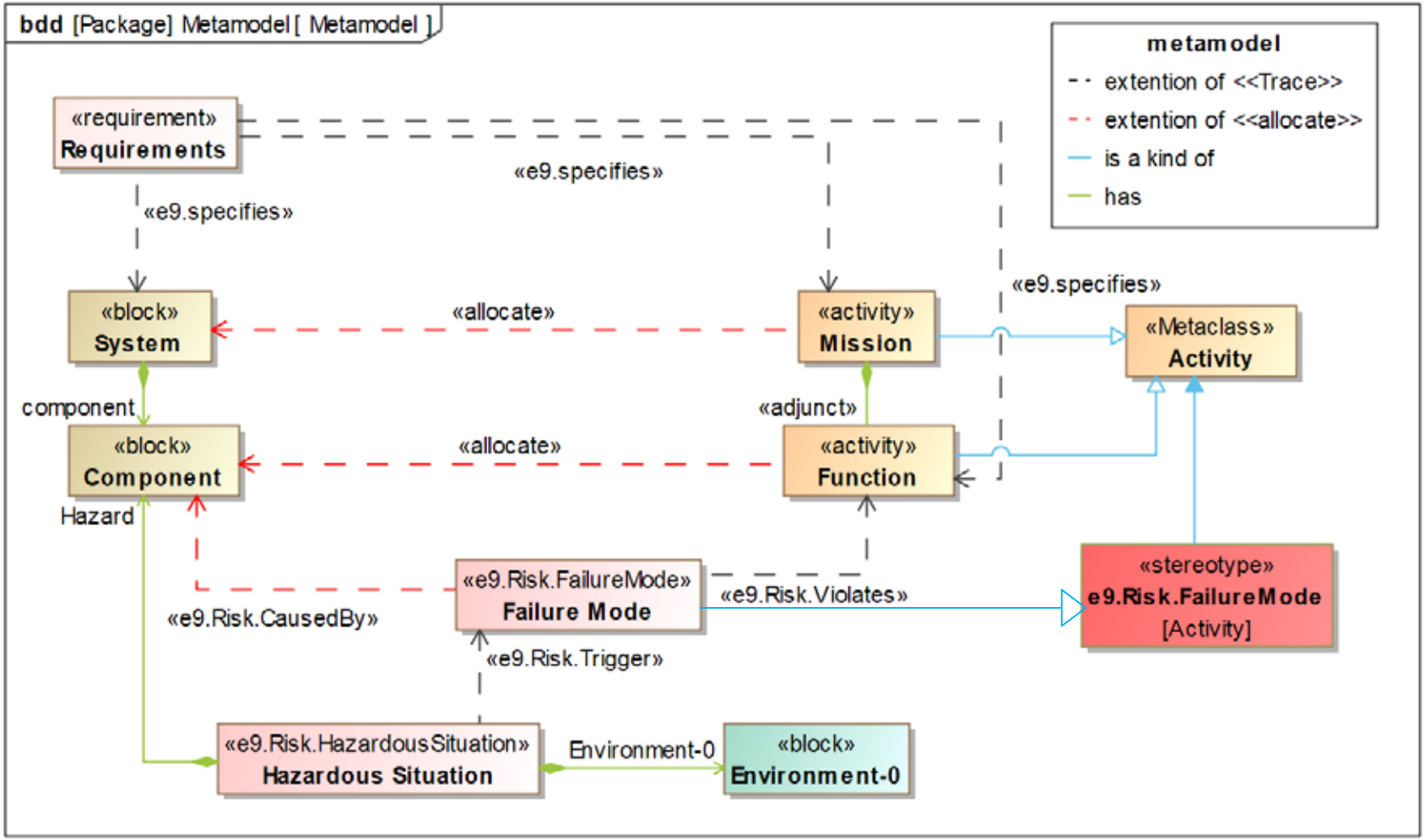
(In/Out)	Information	Energy, Thermal	Force	Matter
Information	Software (Algorithm)	Controller (Algorithm)	Controller (Algorithm)	—
Energy, Thermal	Sensor (Physics)	Energy Converter (Physics, Chemistry)	Motor (Physics, Chemistry)	— (nuclear reaction)
Force	Sensor (Physics)	—	Structural mechanism (Physics)	—
Matter	Sensor (Physics, Chemistry)	— (nuclear reaction)	Propulsion Device (Physics, Chemistry)	Plant (Chemistry)

*1: Kato, M., Nakajima, Y., Takei, Y., Noda, A., & Inaba, N. (2018). Interaction-Oriented Systems Engineering Methodology for Model-Based Systems Engineering. In 2018 AIAA SPACE and Astronautics Forum and Exposition (p. 5393).

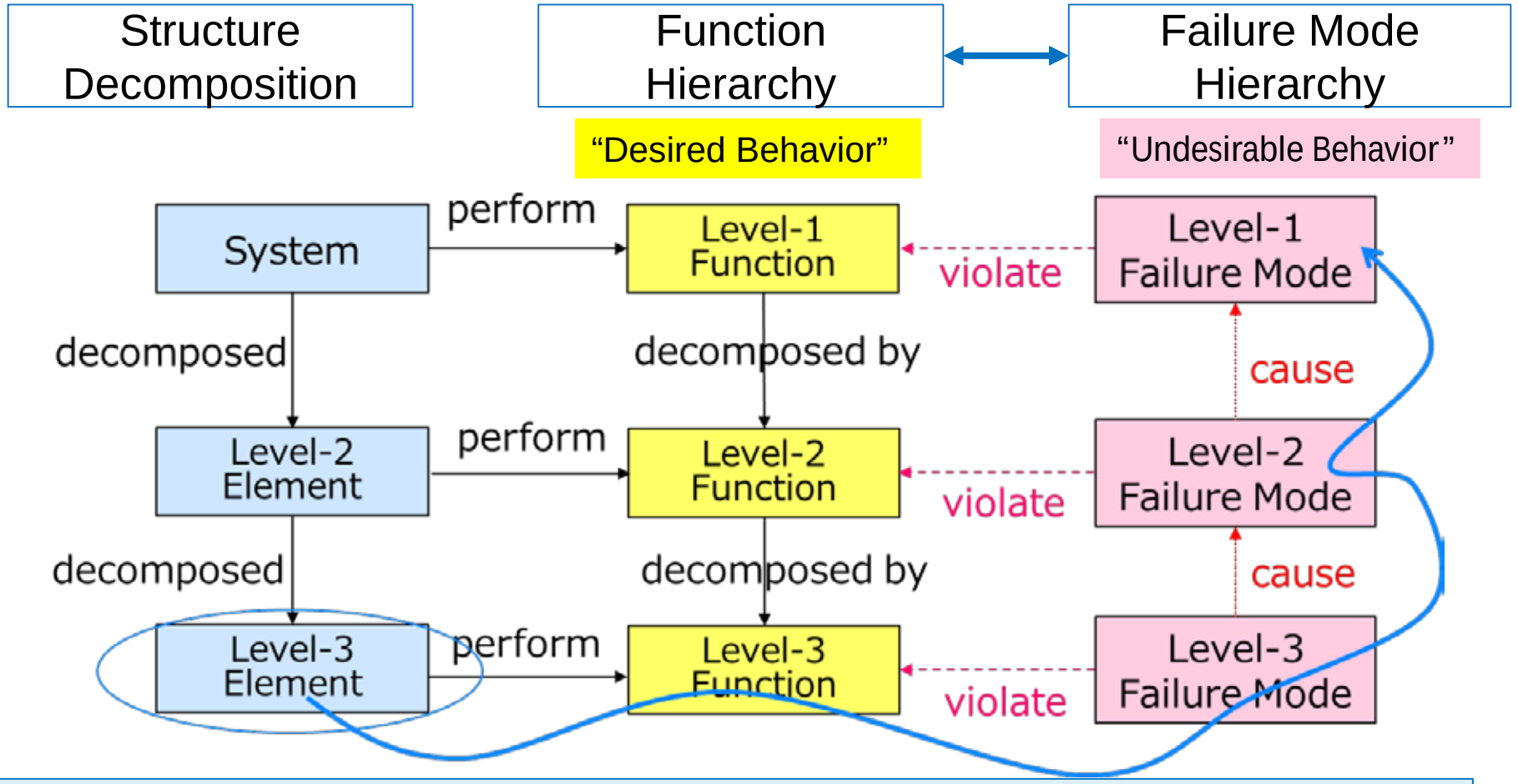
3. What to Model?



Selecting and Usage of Elements in SysML Descriptions



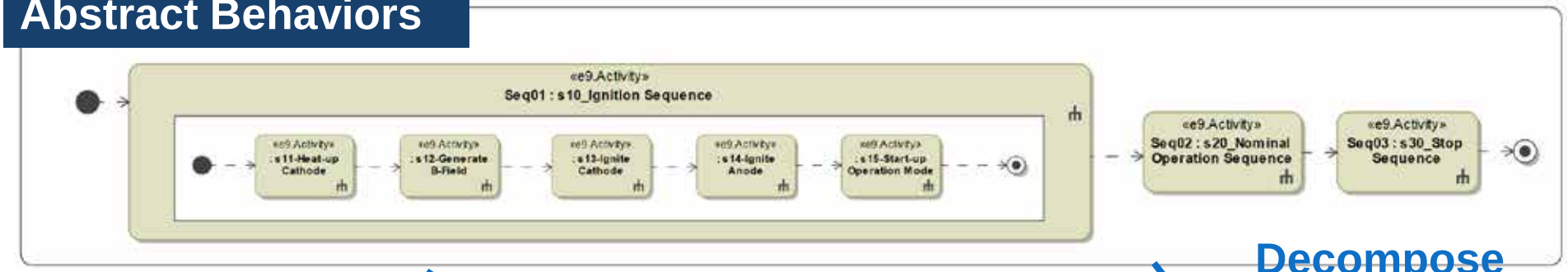
4. How to Model?
Model Query for Failure Mode Analysis



- Relate causal relationships between Structural and functional hierarchy to failure modes hierarchy
- It is possible to search for how the target failure spills over to the higher (lower) levels.

5. Results

Abstract Behaviors



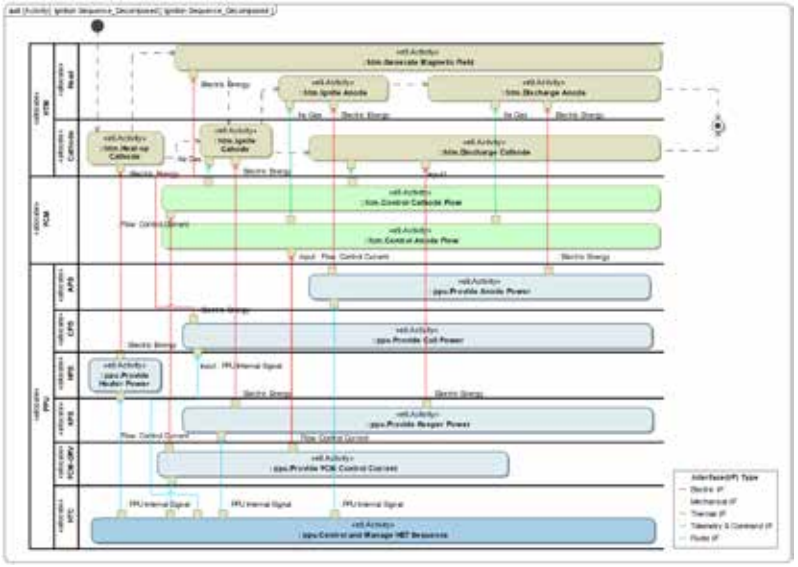
Decompose

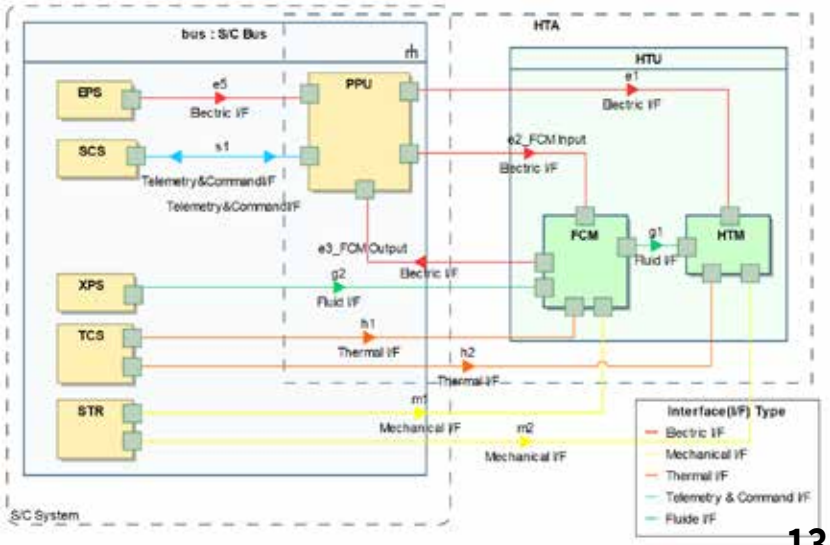
Perform

Decompose and Allocate

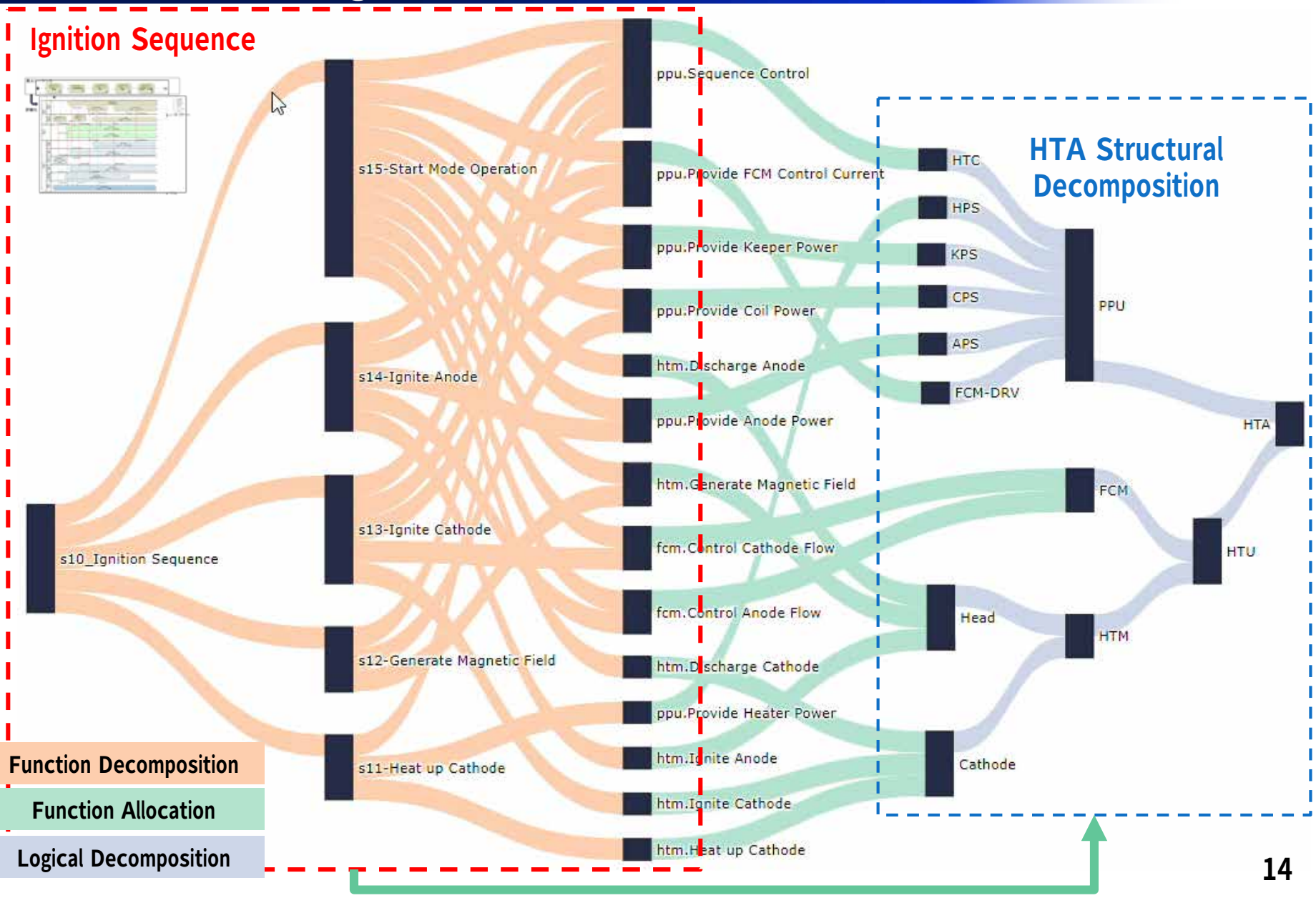
Function Allocation to Components in Activity Elements

Interface between Components in Block Elements(BDD, IBD)



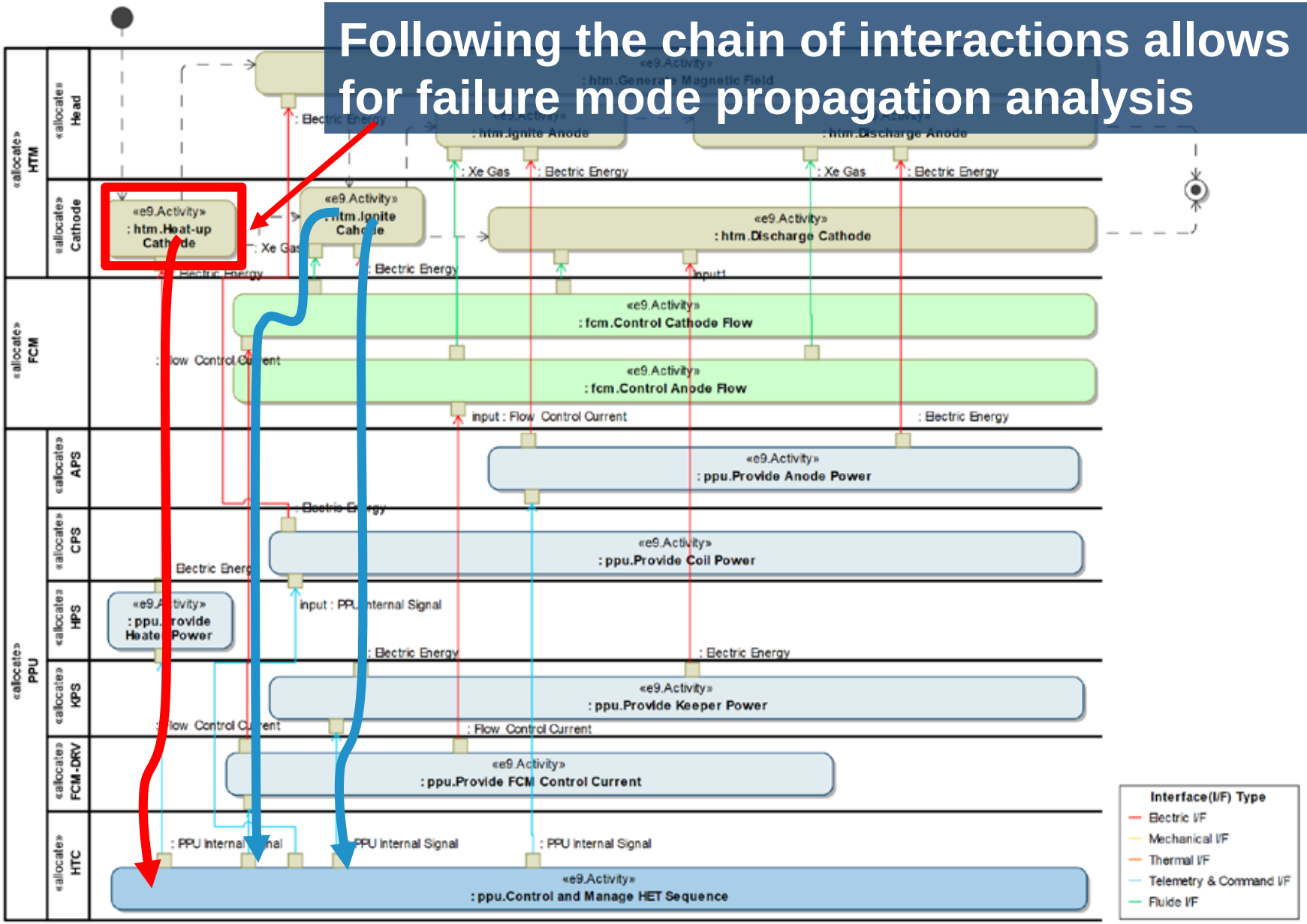


5. Results
Interactive Digital SE Artifact

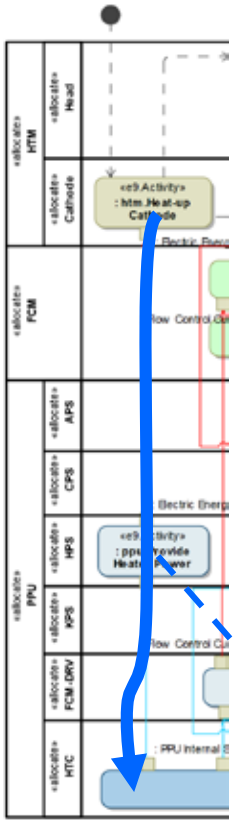


5. Results
Model Guided Analysis

Following the chain of interactions allows for failure mode propagation analysis

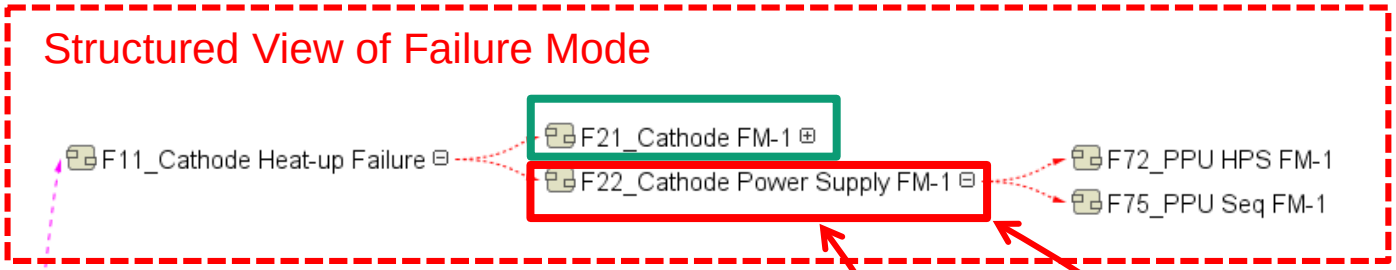


5. Results
Model Guided Analysis



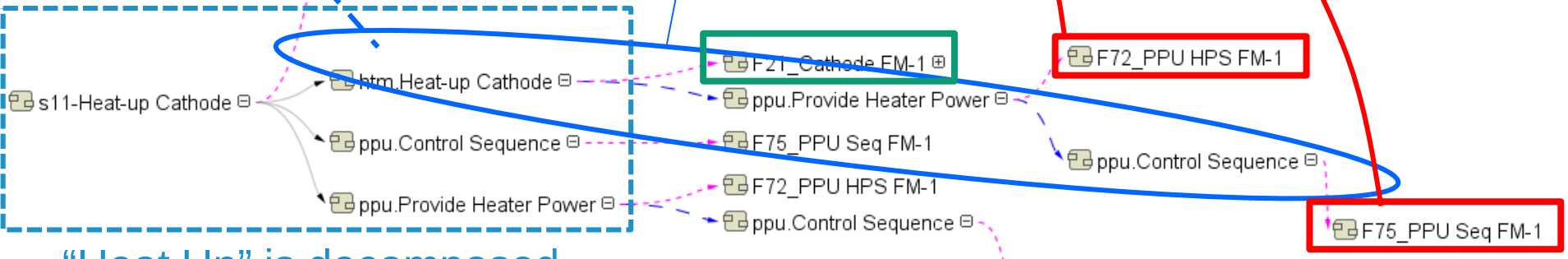
Model Query and Network Views

- Guide for extracting Failure Modes from the chain of interactions
  - A Failure Mode violates a Function



Re-Structure Failure Modes

the chain of interactions



"Heat Up" is decomposed into three functions

5. Results
Failure Mode Analysis Result

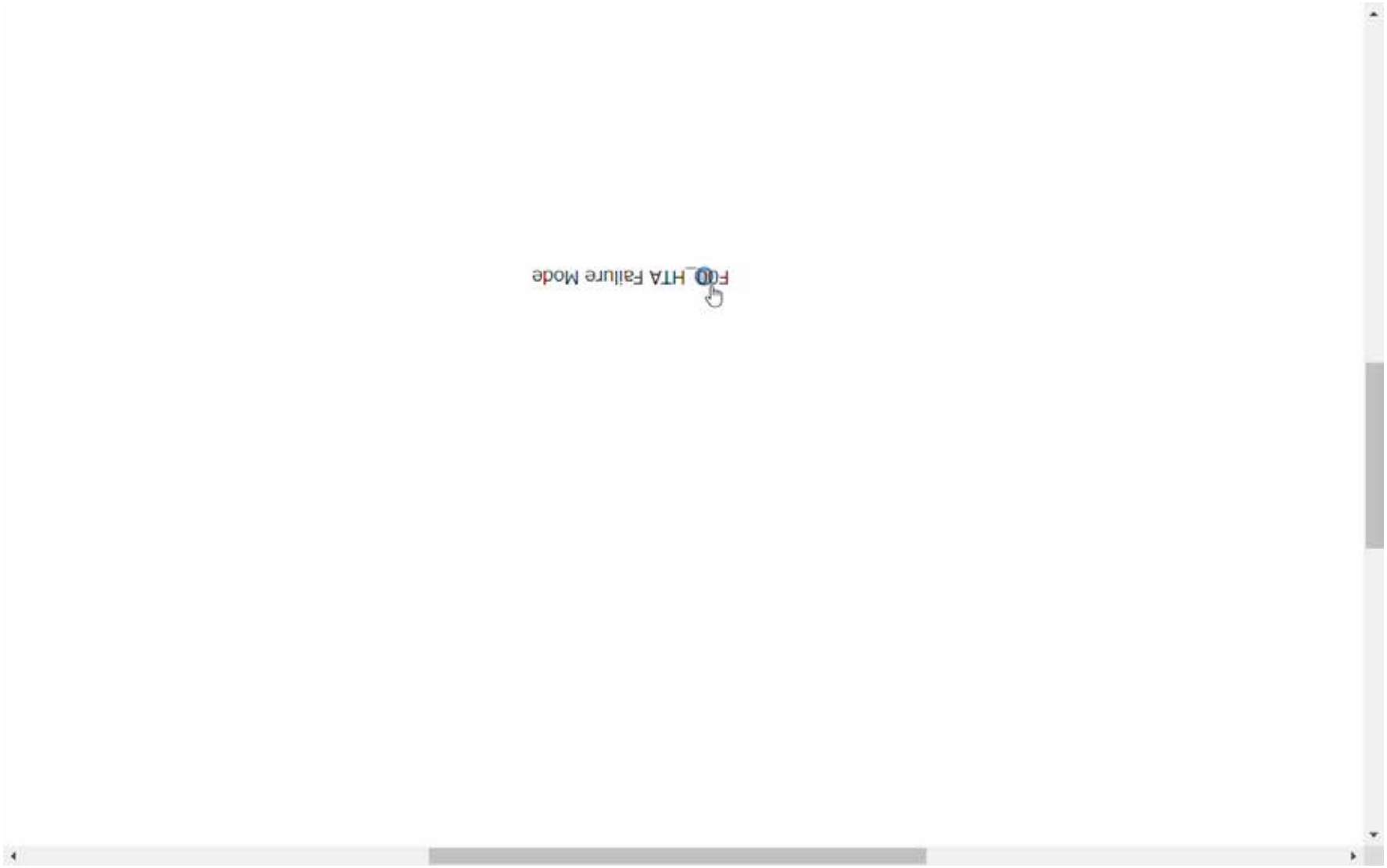
<<Failure Mode>> FM-A — Is Caused by → <<Failure Mode>> FM-B

Failure Modes extracted from System-Level functions

Failure Modes extracted from Component functions

Expanded to lower-level

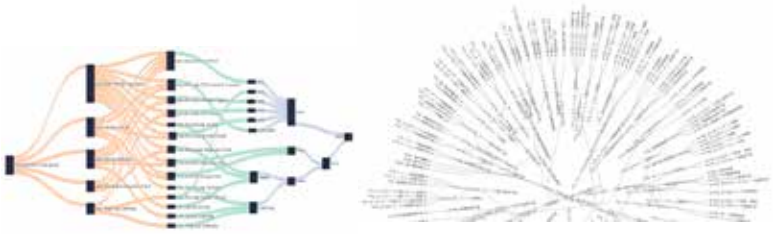
5. Results
Failure Modes as Interactive Digital Artifacts



5. Results
Key Findings

1. “System Model” guides Systems Engineer to perform system level failure mode analysis by using “Model Query” and “Visualization”
   - Before MB4SE: Depends on “Experience” and “Intuition”
   - Lessons Learned: Model should be organized to consider how we consume model generated SE artifacts

2. “System Model” and “Extracted SE artifacts” augment Systems Engineer’s capability to capture and understand system complexity
   - Before MB4SE: Depends on “Individual skills”
   - Lessons Learned: Automation is attractive but needs extensive modeling. Human and Machine hybrid approach works well.



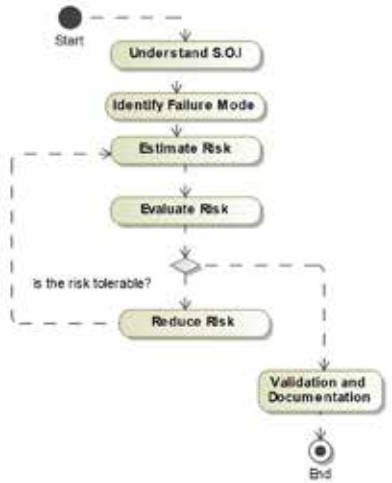
“Interactive Digital Artifacts” as SE artifacts in Digital Age

5. Results
MB4SE for Project Systems Engineers

Decision-Making Issue (Why Model?)

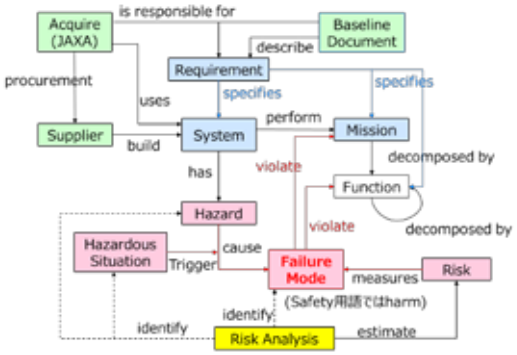
Project Manager
Systems Engineer

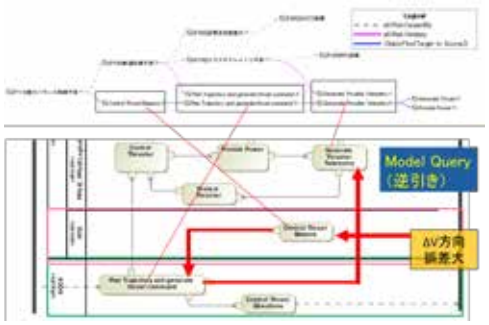
SE Process Analysis



e.g. ISO/IEC GUIDE 51:2014(E) Safety aspects Guidelines for their Inclusion in standards

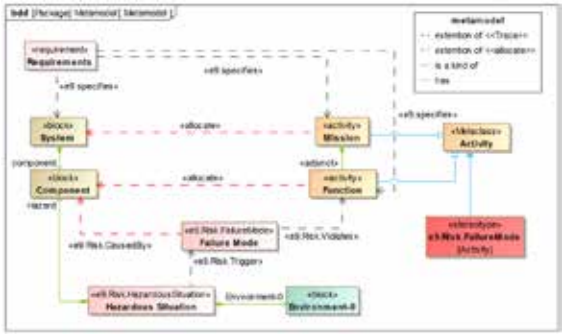
Meta-Model





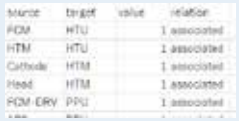
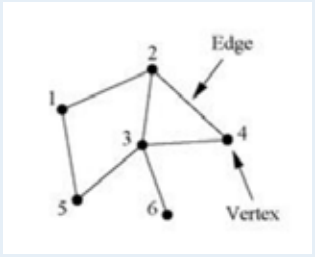
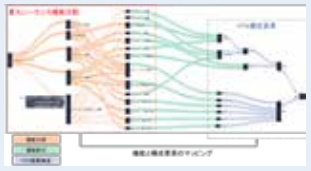
Analysis + Guide +Visualize

System Modeling



SysML Rule

5. Results
Extracting SE Artifacts

Methodology	Systems Engineering Methodology	*Intermediate processing*	Graph Theory	Data Visualization
Structured Information	 System Architecture			  
Language	SysML	CSV	python pandas NetworkX	HTML plotly bokeh D3
Tools	Cameo Systems Modeler Modeling Environment	export → Excel → import → ANACONDA → export → chrome		

6. Conclusion

1. We present the practice of Model-Based Systems Engineering approach to the actual flight project focusing on the interface management of the Hall Effect Thruster system.

2. The proposed system model and the interactive digital artifacts guide the system level analysis of the Hall Effect Thruster System supported by model queries and visualization of the hierarchical structure of system architecture.

3. We find the effective use of MBSE application to the failure mode analysis in the implementation phase of the ETS-9 flight project.

Thank you for your attention