Towards A Model-Based Implementation In Technology/Platform Life-Cycle Development Processes Applied To A Thrust Reverser Actuation System (TRAS) Concept

Jayesh B. Narsinghani

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Master's Committee:

Dr. Kamran Eftekhari Shahroudi (Advisor)

Dr. Daniel R. Herber (Co-advisor)

Dr. Bret C. Windom

Department of Systems Engineering

Colorado State University

Outline

1. Introduction
2. Integrated PLC Process and System Architecture Development Framework
3. TRAS System Architecture Modeling and Analysis
4. Interactive Requirements Development and Management
5. Conclusion and Future Work

1. Introduction

- 1.1 : Background
- 1.2 : Challenges in Current State
- 1.3 : Thesis Objective

Background

- ***Thrust Reverser (TR)*** remains a necessary commodity in most commercial aircrafts to reduce the ground stopping distances after touchdown in adverse conditions such as wet/icy, slippery runway by reversing the fan airflow.
- ***Thrust Reverser Actuation System (TRAS)*** power and control the deployment of TR to improve aircraft operational safety by minimizing runway stopping distances.
- Key components of an operational TRAS:
  - Self-locking and unlocking actuators
  - Primary and secondary locks
  - Tertiary/cowl locks
  - Motion synchronization system
  - Manual drives

Vid 1. TRAS Operation[Source]

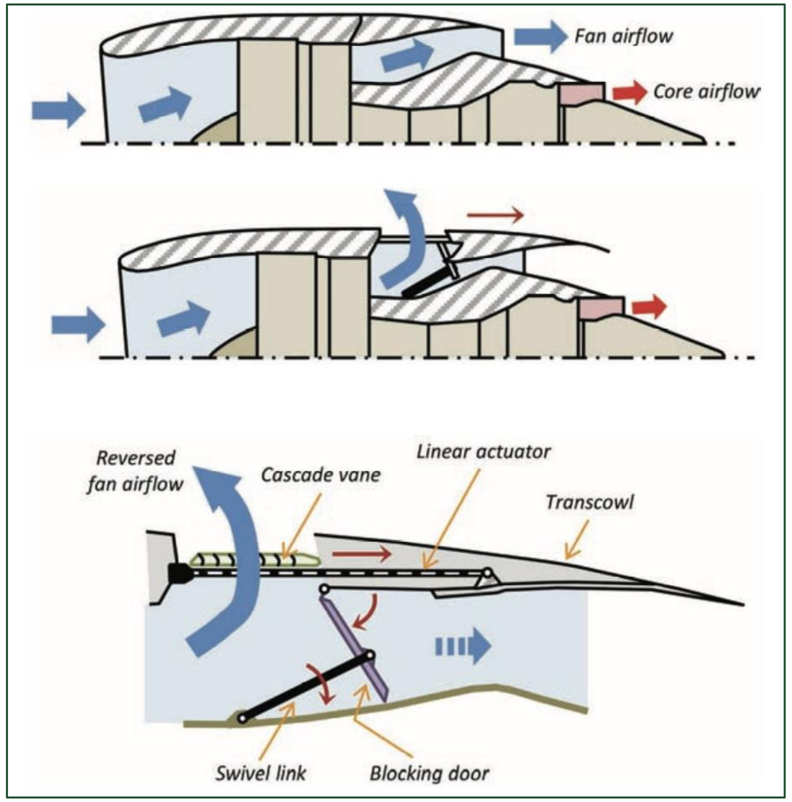


Figure 1. [Source]

- ***System*** is an assemblage or combination of functionally related elements or parts forming a unitary whole.
- ***Systems Thinking*** philosophy- the overall capability delivered by the assemblage of the system is more significant than the capability delivered by the individual pieces
- ***Systems Engineering (SE)*** is an interdisciplinary approach governing the total technical and managerial effort required to transform a set of stakeholder needs, expectations and constraints into a solution and to support that solution throughout its life. [ISO/IEC/IEEE 15288:2015, 4.1.49]
- SE focuses on ensuring the pieces work together to achieve the objectives of the whole.
- ***Document-centric*** approach reflects on the creation of work products using static document formats.
- ***Data/Model-centric*** approach follows capturing deliverables as views/artifacts that are generated from a formal architecture model.
- ***System Life Cycle*** stages include concept, development, production, utilization, support, and retirement.
- A System progresses through its life cycle as a result of actions, performed and managed by people in organizations using processes for execution of these actions.

- ***System Architecture*** model is the abstract representation of a complex system/entity specified in terms of:
    - Structure - piece parts that interact with each other, through well-defined interfaces
    - Behavior - functions that each structural entity performs
    - Rules - that shall be satisfied by the system of interest and how it evolves
- ***Architecture Modeling*** is an approach to deal with complexity of the modern world based on the following principles of object orientation:
    - Abstraction – a technique for identifying and capturing commonality among entities to create a classifier
    - Generalization – a technique for applying common characteristics from generalized entities to more specialized entities
- ***Model-Based Systems Engineering (MBSE)*** is the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases [INCOSE SE Vision 2020].
- Tool environment : Systems Modeling Language (SysML), Cameo Systems Modeler and Cameo Simulation Toolkit

Challenges

- (**I1**) Need for a cultural shift/transformation from documents to models within organizations.
- (**I2**) Need to break silos of knowledge to coordinate across engineering specialities and fill those gaps with an integrated modeling environment.
- (**I3**) Need to communicate holistic (big-picture) thinking that enables cross-collaboration among multiple disciplines in project team.
- (**I4**) Need to generate data and technology insight from a unified hub of true system information (technical truth) for early decision support capability.
- (**I5**) Understanding the value of applying MBSE tools, and its usage to perform system engineering activities.

Research Objectives

1. Investigation of a data modeling approach to integrate the early phase processes with MBSE framework
   - Focus of Chapter 2
2. Application of MBSE framework and methodology to a thrust reverser actuation system (TRAS) concept
   - Focus of Chapter 3
3. Investigation of some model-based improvements in requirements development and management efforts
   - Focus of Chapter 4

2. Integrated PLC Process and System Architecture Development Framework

- 2.1 : Model the Formal Phase Processes and Analyze Inter-Dependency
- 2.2 : Augment a System Architecture Framework and Architecting Methodology
- 2.3 : Coordinate the PLC Process with the System Architecture

Model the Formal Phase Processes and Analyze Inter-Dependency

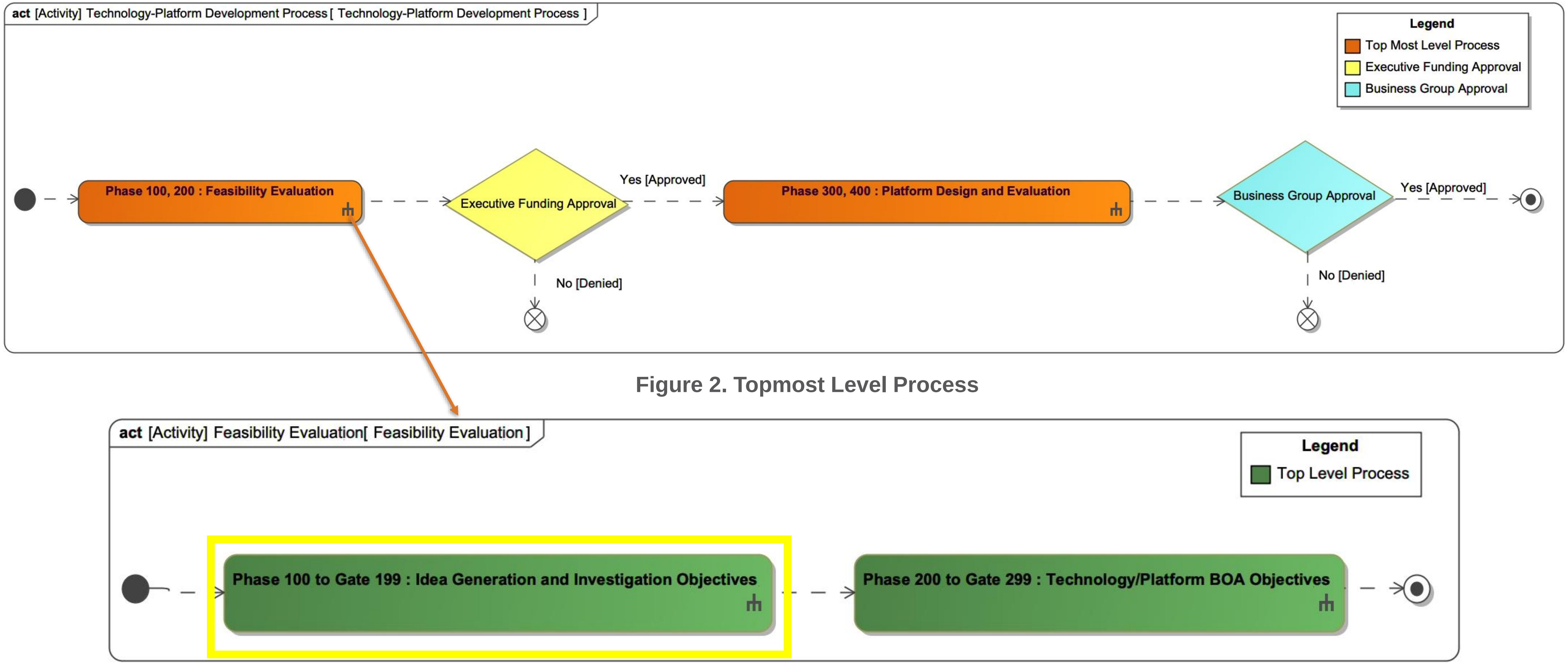


Figure 2. Topmost Level Process

Figure 3. Top Level Process

PLC Integration Model Framework : Model the PLC Process and Analyze Inter-Dependency

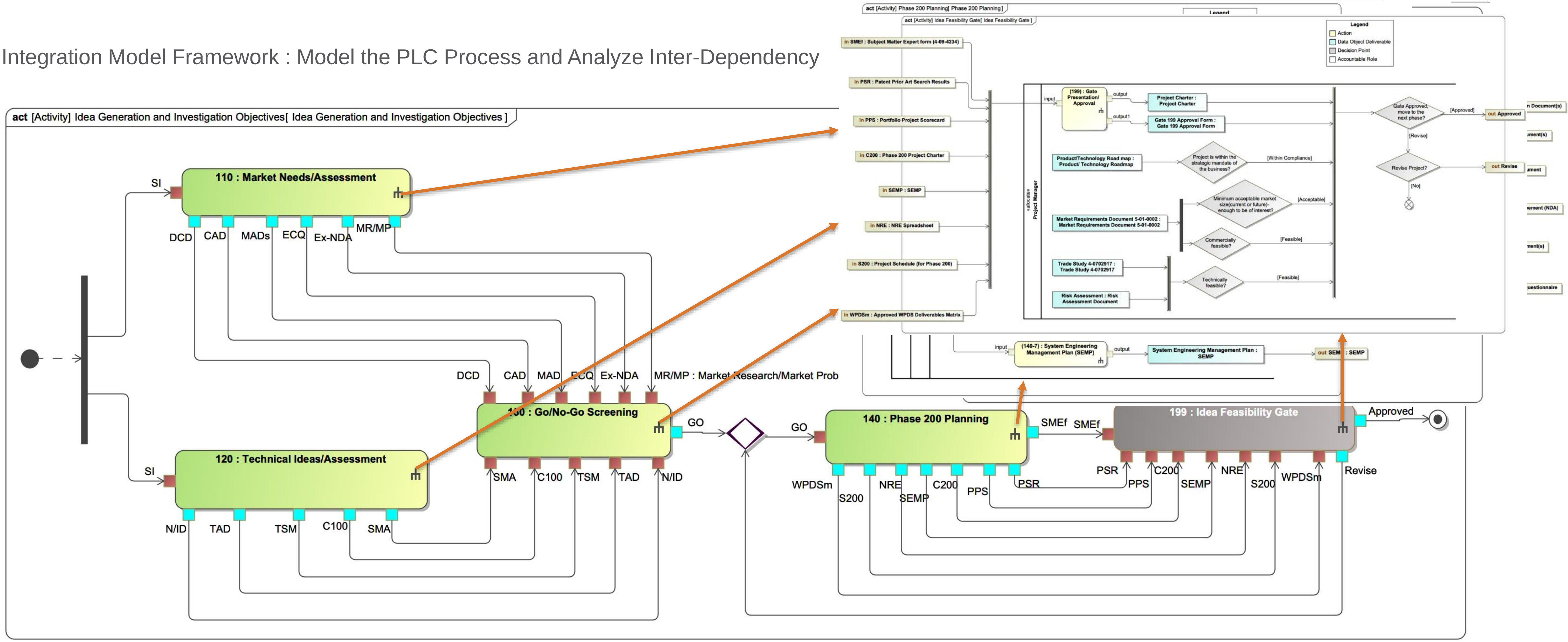


Figure 4. Second Level Process

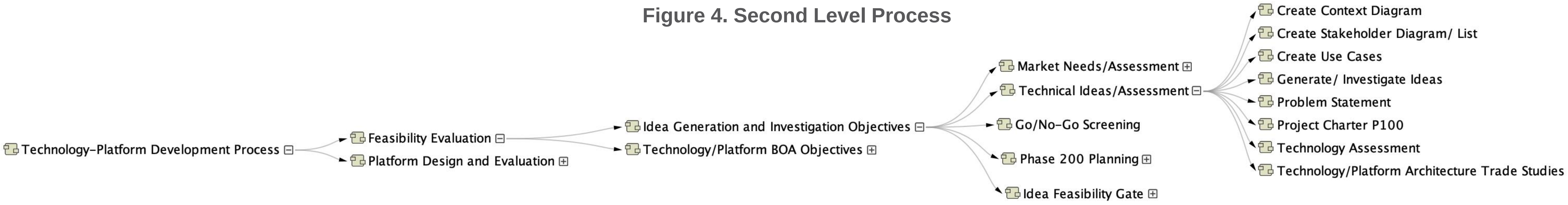


Figure 5. Overview of the Formal Phase Processes

PLC Integration Model Framework : Model the PLC Process and Analyze Inter-Dependency

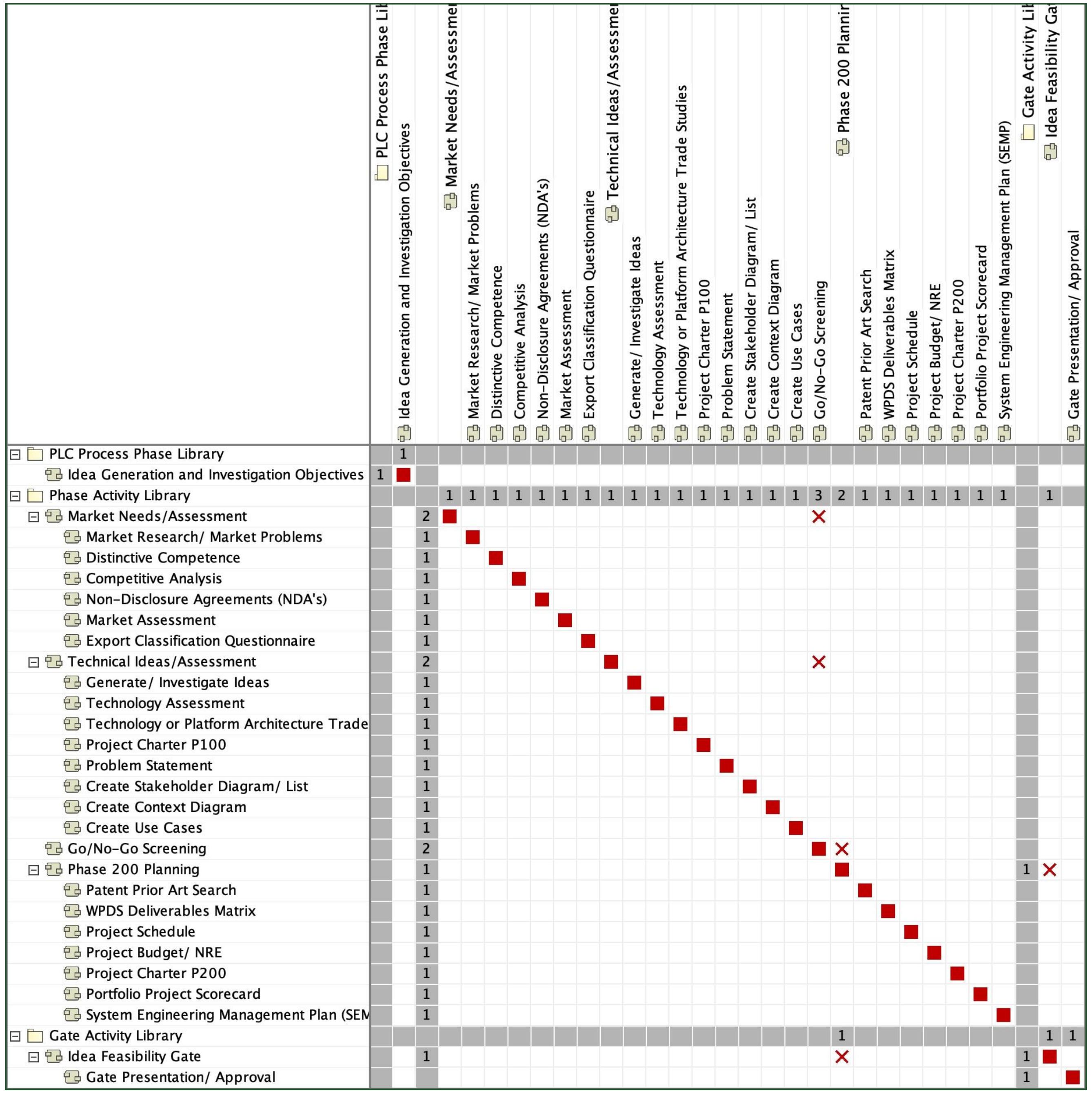
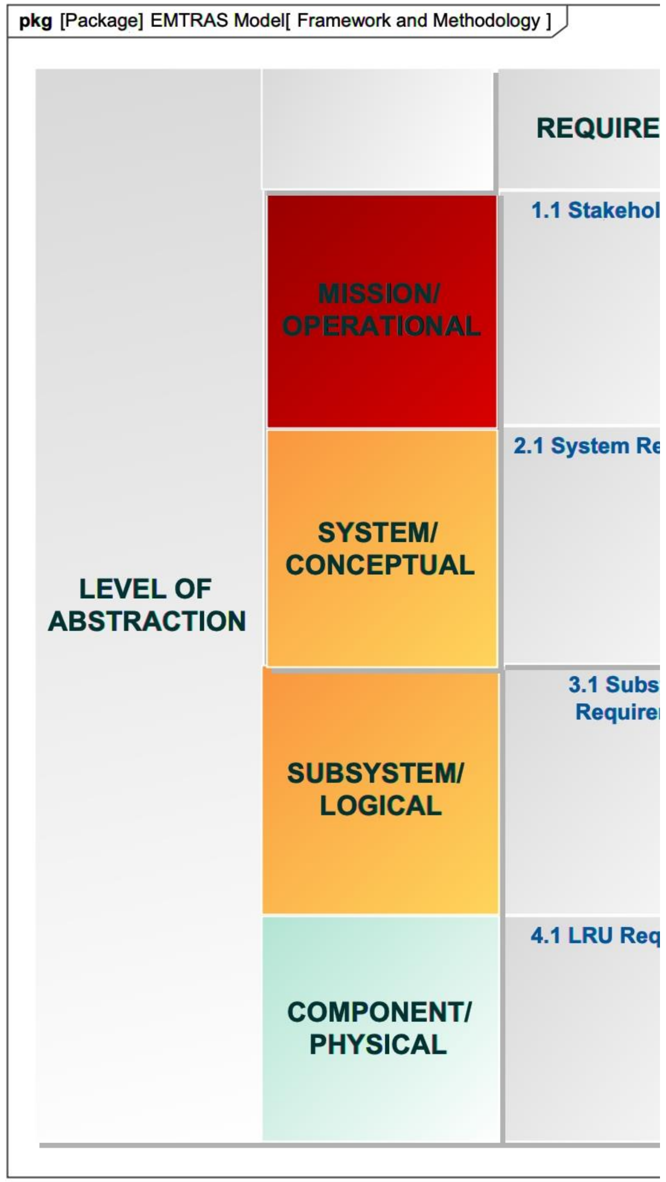


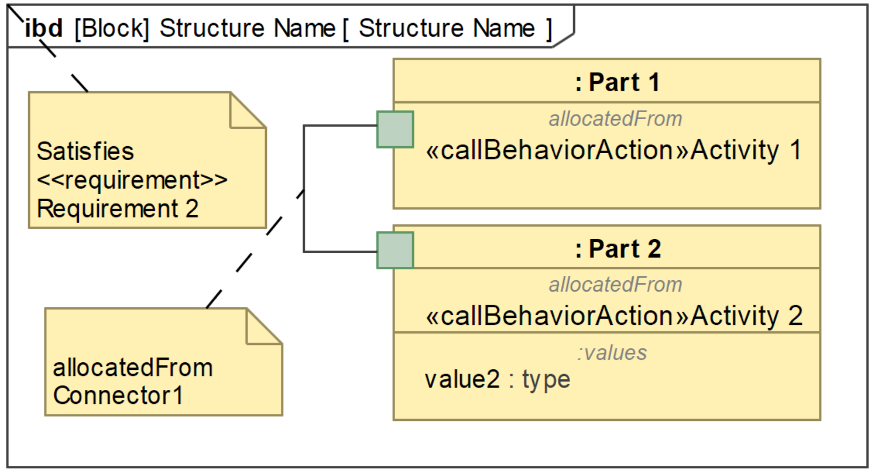
Figure 6. Analysis of Functional Interfaces using N^2 Diagram

Augment a System Ar

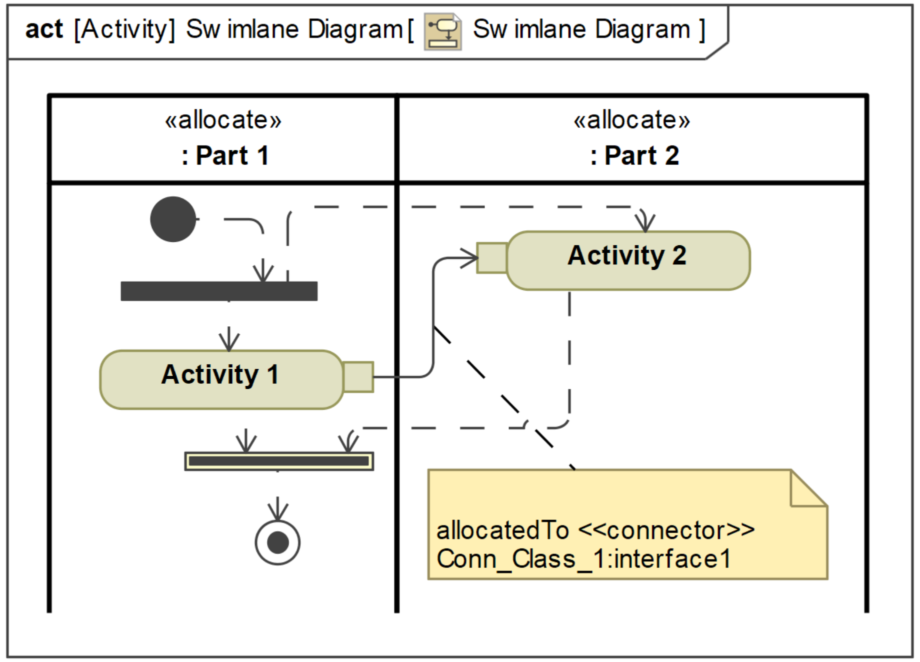


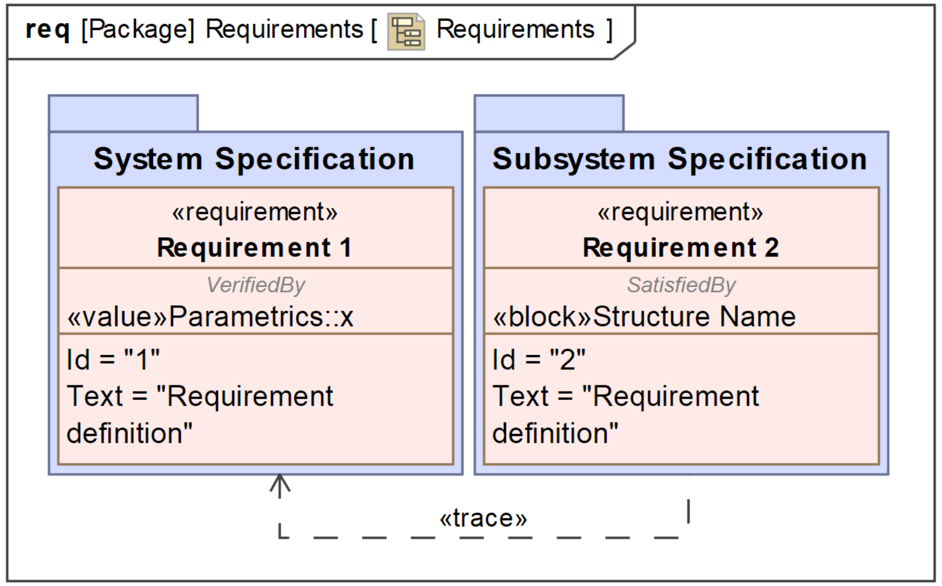
Figure

Structure

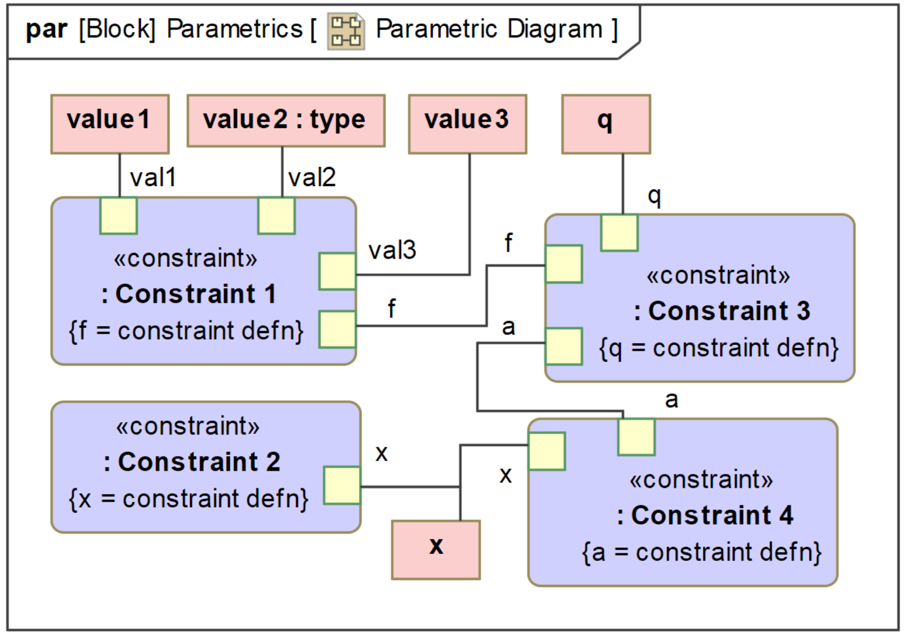


Behavior





Requirements



Artifacts/diagrams serve as views of the underlying model

Parametrics

Coordinate the PLC Process with the System Architecture

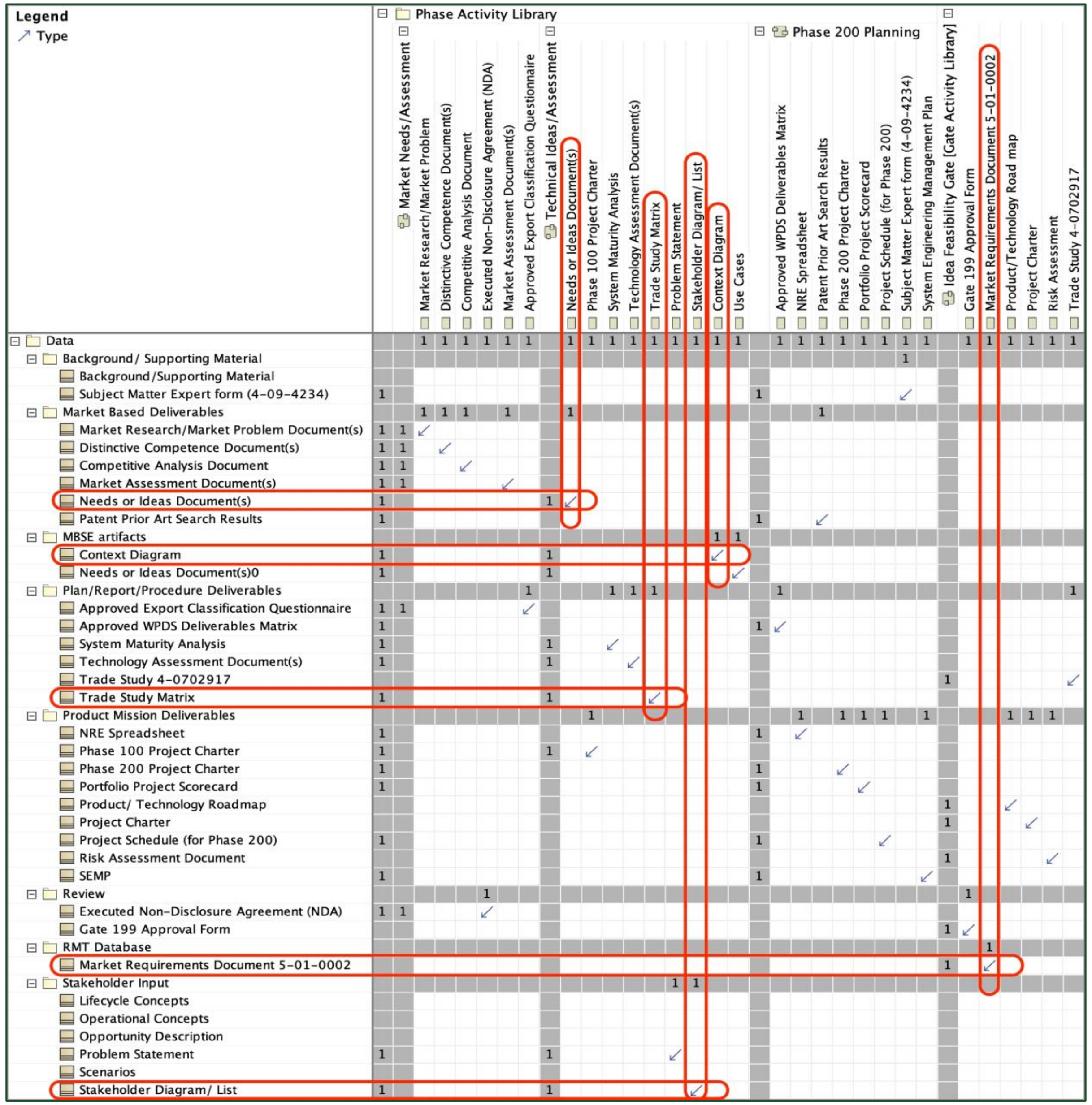


Figure 9. System Architecture Framework and Architecting Methodology

#	Name	Owned Comment	Concern	Allocated From
1	System Engineer	Primary Interest: will use it as the basis of unde...		
2	Product Line Manager	Primary Role: Business/Commercial Owner => Lead th...		Competitive Analysis Distinctive Competence Market Assessment Non-Disclosure Agreements (NDA's) Market Research/ Market Problems
3	Project Engineer	Primary Role: Project Owner => Owner of the projec...		Technology Assessment Technology/Platform Architecture Trade Studies Patent Prior Art Search Generate/ Investigate Ideas
4	V&V Engineering	Woodward team that confirms operation of the TRAS ...	Decelerate Aircraft Rapidly and Reliably	

Figure 11. Generating the stakeholder list as a deliverable/outcome from the model

Model-centric approach that documents the model to generate a deliverable

- Coordinating the SE technical processes per ISO/IEC/IEEE 15288 to model-derived artifacts

ISO/IEC/IEEE 15288			
Sr No	Clause	Technical Processes (Technical)	Mapping to EMTRAS Model Artifacts
1	6.4.1	Business or mission analysis process	1.1.1, 1.1.2, 1.1.3, 1.2.1
2	6.4.2	Stakeholder needs and requirements definition	1.1.4, 1.1.5, 1.1.6, 1.2.2
3	6.4.3	System requirements definition process	1.3.1, 1.3.2, 1.4.1, 2.1, 3.1
4	6.4.4	Architecture definition process	2.2.1, 2.2.2, 2.2.3, 2.3.1, 3.1, 3.2, 3.3
5	6.4.5	Design definition process	4.2.1, 4.1, 4.2
6	6.4.6	System analysis process	2.4.1, 3.4
7	6.4.7	Implementation process	TBD
8	6.4.8	Integration process	2.4.2
9	6.4.9	Verification process	2.1.4, 2.4.3
10	6.4.10	Transition process	TBD
11	6.4.11	Validation process	TBD
12	6.4.12	Operation process	TBD
13	6.4.13	Maintenance process	TBD
14	6.4.14	Disposal process	TBD

Sr No	Cell	Order	Description of Artifacts/Views	SysML Diagram Type
1	1.1		Stakeholder Needs	Package Diagram
2		1.1.1	Stakeholder Needs Analysis	Requirements Table/ Diagram
3		1.1.2	Stakeholder Views and Viewoints (Task specific views)	Views and Viewpoint Diagram
4		1.1.3	Mission Objectives Use Cases	Use Case Diagram
5		1.1.4	Mission Requirements Specification (MRS)	Requirements Table/ Diagram(s)
6		1.1.5	MRS allocation to Mission structure/behavior	Requirements Matrix
7		1.1.6	Refinement relation between Needs and MRS	Requirements Matrix
8	1.2		Mission Context	Package Diagram
9		1.2.1	Mission Context external structure	Block Definition Diagram
10		1.2.2	Mission Context internal structure	Internal Block Diagram
11	1.3		Operational Scenarios	Package Diagram
12		1.3.1	Mission Thread	Use Case Diagram
13		1.3.2	Mission Scenarios (Main, Alternative, Exceptional)	Activity Diagram(s)
14	1.4		Measures of Effectiveness	Package Diagram
15		1.4.1	System MOEs	Block Definition Diagram

Figure 10. System Architecture Framework and Architecting Methodology

(I1) Need for a cultural shift/transformation from documents to models within organizations.

(I5) Understanding the value of applying MBSE tools, and its usage to perform system engineering activities.

3. TRAS System Architecture Modeling and Analysis

- 3.1 : Develop the TRAS Architecture Model
- 3.2 : Analyze Architecture Alternatives to Setup a Trade Study
- 3.3 : Manage and Trace Requirements

Develop the TRAS Architecture Model

1. ***TRAS Operational***
   - Top-level structure of architecture model from the standpoint of the eventual user
   - Operational characteristics and views associated with the system and its interaction within the context
2. ***TRAS Logical***
   - Characteristics and views of system functionality
3. ***TRAS Physical***
   - Characteristics and views associated with implementation

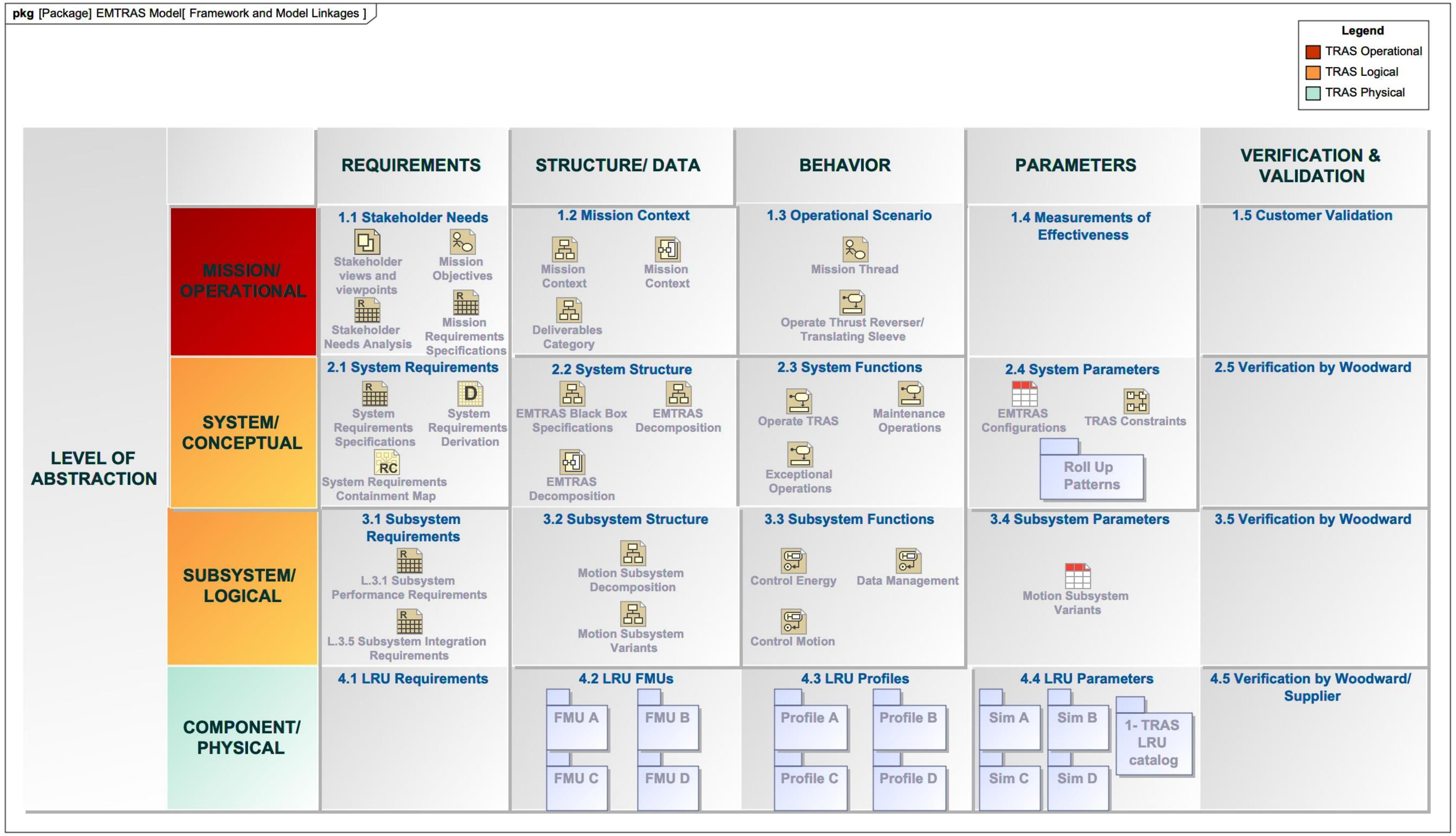


Figure 12. MBSE Framework and Methodology

Modeling effort proceeds from abstract to detail with creation of relevant artifacts that contribute to specific SE efforts

1.1 Stakeholder Needs

1.1 Stakeholder Needs:

- Introduces the key stakeholders and their interests

1.1.1 Stakeholder Needs Analysis:

- Captures the stakeholders, their needs, expectations/concerns, their level of interest and involvement
- Captures the broad categories of needs
  - Customer Needs
  - Corporate Needs
  - User Needs
  - Industry Needs
  - Project Team Needs
  - Supplier Needs
  - External Organization Needs, etc.
- Allocates the stakeholders to their perceived needs

#	Id	△ Name	Text
1	SN1	SN1 Customer needs	
19	SN2	SN2 Corporate needs	
36	SN3	SN3 User needs	
67	SN4	SN4 Industry needs	
72	SN5	SN5 Project Team needs	
73	SN5.1	SN5.1 Project Engineering	
74	SN5.1.1	SN5.1.1 Requirements	Clear understanding of technical requirements
75	SN5.1.2	SN5.1.2 Risk	Reduced development risk
76	SN5.1.3	SN5.1.3 Schedule	Adequate development time
77	SN5.2	SN5.2 R&D Engineering	
81	SN5.3	SN5.3 V&V Engineering	
84	SN5.4	SN5.4 Manufacturing/ Operations	
91	SN6	SN6 Supplier needs	
99	SN7	SN7 External Organization needs	

Figure 13. Stakeholder Needs Analysis

Legend
↗ Allocate
⇢ Allocate (Implied)

1– Stakeholders

		Air traffic controller	Aircraft OEM/ sponsor	Airline operator	Competitors	Engineering	Manufacturing/ Operations	Mission stakeholder	Partners	Passenger	Pedigree parts supplier	Product supplier	Project Engineering	R&D Engineering	Regulators	Sales marketing	Supply chain management	Support equipment supplie	V&V Engineering	Woodward Engineering	Woodward management	Woodward sales/marketing	Woodward TR manufacture
2– Needs		1		1	1	1	2		1	1	1	2	2	2	1	1	1	2	2	1	2	2	1
SN1 Customer needs						1										1	1						
SN2 Corporate needs																							
SN2.1 Supply Chain	11						⇠				⇠	⇠	⇠	⇠				⇠	⇠	⇠	⇠	⇠	↙
SN2.1.1 Supply base																							
SN2.1.2 COTS																							
SN2.2 Sales/ Marketing																						1	

Figure 14. Stakeholder Needs Allocation

1.1 Stakeholder Needs

1.1.2 Stakeholder Views and Viewpoints:

- A *view and viewpoint* diagram is created to reflect perspectives of different stakeholders
- Focus on aspects of the system model that are of particular interest to stakeholders

1.1.3 Mission Objectives Use Cases:

- High-level mission objectives that are relevant to the stakeholder concerns, modeled as Use Cases
- Specifies the stakeholders associated with mission objectives, level of interest, primary/secondary to expresses their direct/indirect involvement
- Outcomes of this activity lead to transforming the mission objective into stakeholder/mission requirements that are allocated to them

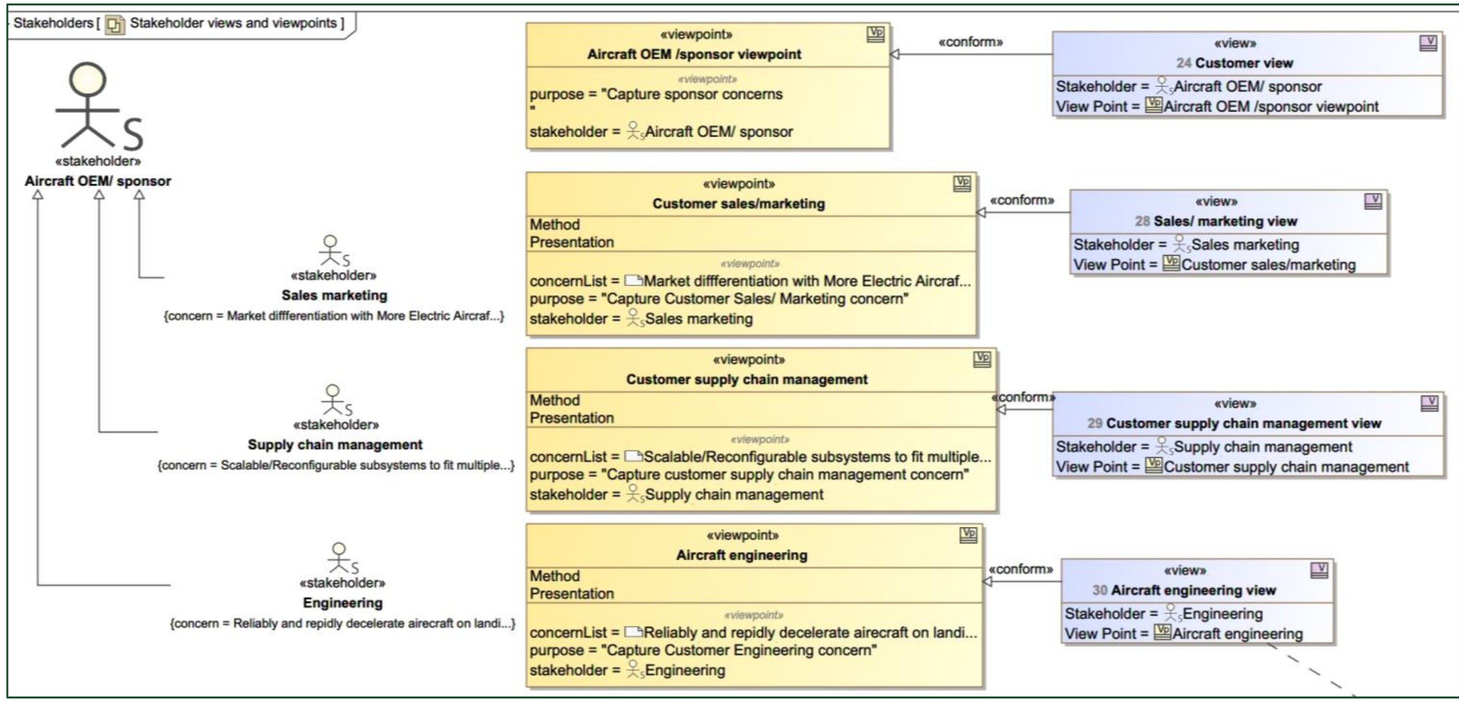


Figure 15. Stakeholder View and Viewpoints

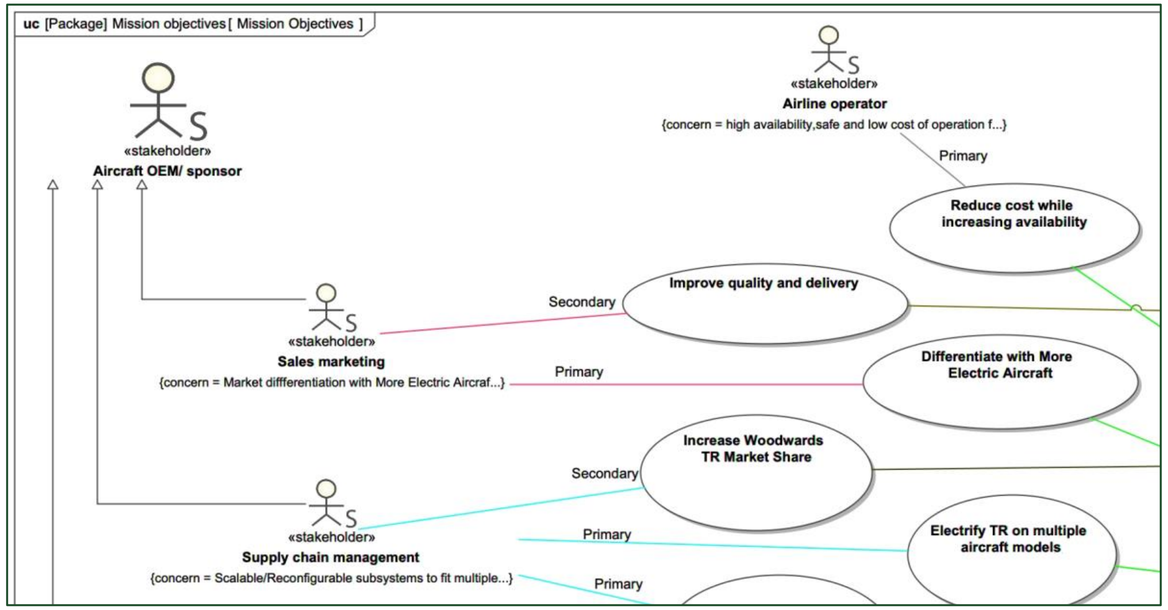


Figure 16. Mission Objectives

Artifacts/diagrams serve as views of the underlying model

1.1 Stakeholder Needs

1.1.4 Mission Requirements Specification (MRS)

- Derived from stakeholder needs
- Overall requirement in mission grouped under broad categories of stakeholder requirements
  - Business Requirements,
  - Design Requirements,
  - Functional Requirements,
  - Non-Functional Requirements, and
  - Project Requirements
- Each tier of hierarchy is elaborated to specify Mission Requirement Specifications (MRS), tagged with "L1"
- Improvised/refined by relevant mission objective Use Cases
- Captures a series of high-level mission requirement specifications that provide a baseline/source of information to derive further lower-level requirements in system (SRS).

#	△ Id	Name	Text
1	L1	L1 Overall TRAS Mission Requirements	Mission Requirements
2	L1.1	L1.1 Overall Business Requirements	Business Requirements
6	L1.2	L1.2 Overall Design Requirements	Design Requirements
17	L1.3	L1.3 Overall Functional Requirements	Functional Requirements
18	L1.3.1	L1.3.1 Normal Landing scenario	EMTRAS shall reliably and rapid on landing by diverting engine f
19	L1.3.2	L1.3.2 Refused Take Off (RTO) scenario	The system shall provide adequ stop aircraft following Refused T
20	L1.3.3	L1.3.3 Aborted Landing (ALD) scenario	The system shall provide adequ stop aircraft following Aborted L
21	L1.3.4	L1.3.4 Safety against IAD	EMTRAS shall provide 3 levels o
22	L1.3.5	L1.3.5 Detect failure condition before IAD	EMTRAS shall assure that there failures before IAD movement w failure condition detectable with
23	L1.3.6	L1.3.6 Safety against IAS	EMTRAS shall provide two levels inadvertent stow (IAS).
24	L1.3.7	L1.3.7 Ground maintenance scenario	EMTRAS shall have all the functi or automatic opening/closing fo
25	L1.4	L1.4 Overall Non-Functional Requirements	Non-Functional Requirements
32	L1.5	L1.5 Overall Project Requirements	Project Requirements

Figure 17. Mission Requirement Specifications

1.2 Mission Context

1.2 Mission Context:

- Obtain a clear definition of the system, its boundary and the context for the correct definition of requirements
- Establish system boundary with top-level partitioning (*what is internal and external? What separates the system from its context and external environment?*)

1.2.1 External Structure:

- Identify the system of interest, its users and external systems participating in the operational context
- Visualize the black-box environment (appears from the outside)

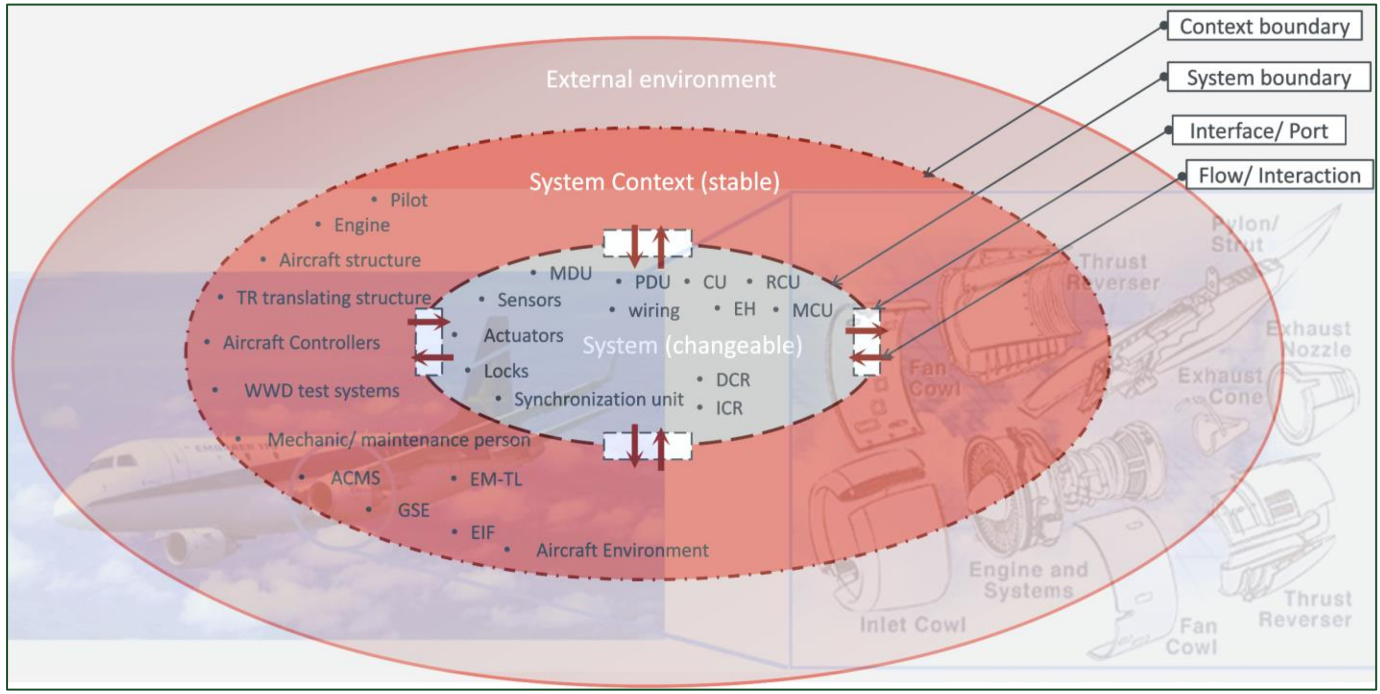


Figure 18. Sketch of the operational environment

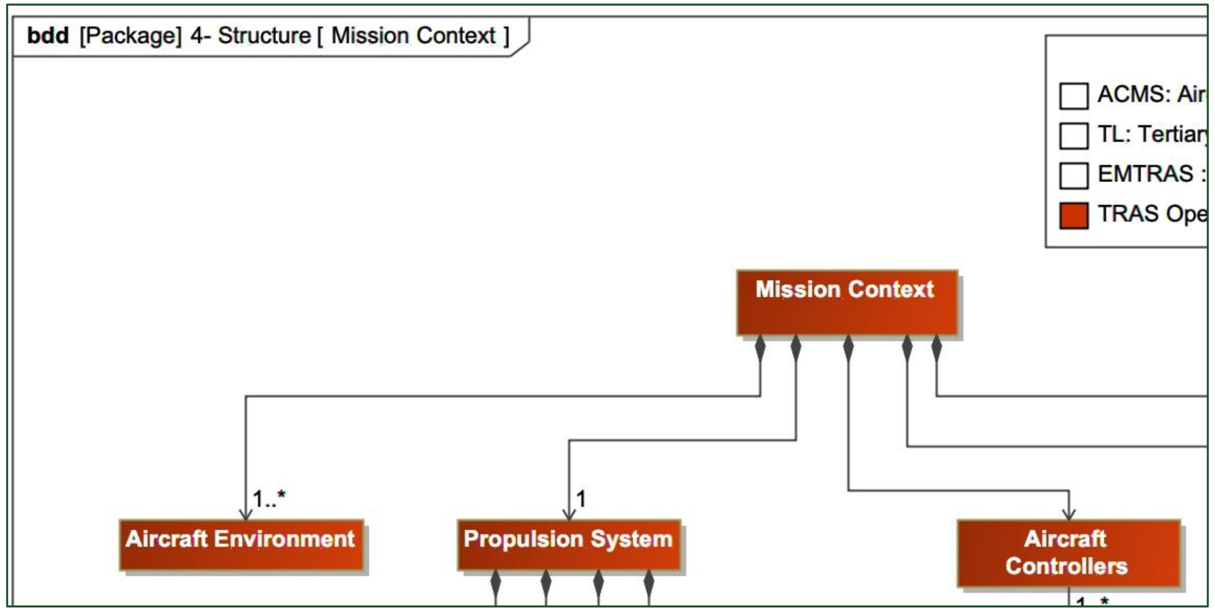


Figure 19. Mission context external structure

1.2 Mission Context

1.2.2 Internal Structure:

- Locates the system of interest in the operational context
- Usage of context entities to visualize the type of interconnections and nature of interactions between the system and its users, external systems
- Specifies the interfaces required to facilitate:
  - Analog signalling for transmission of measurable analog/discrete signals through SIO
  - Data signalling for communication protocol through DIO
  - Power signalling for hydraulic/electric/load transfer through harness, physical connections, etc
  - Torque, load, heat transfer and electrical bonding through power interface

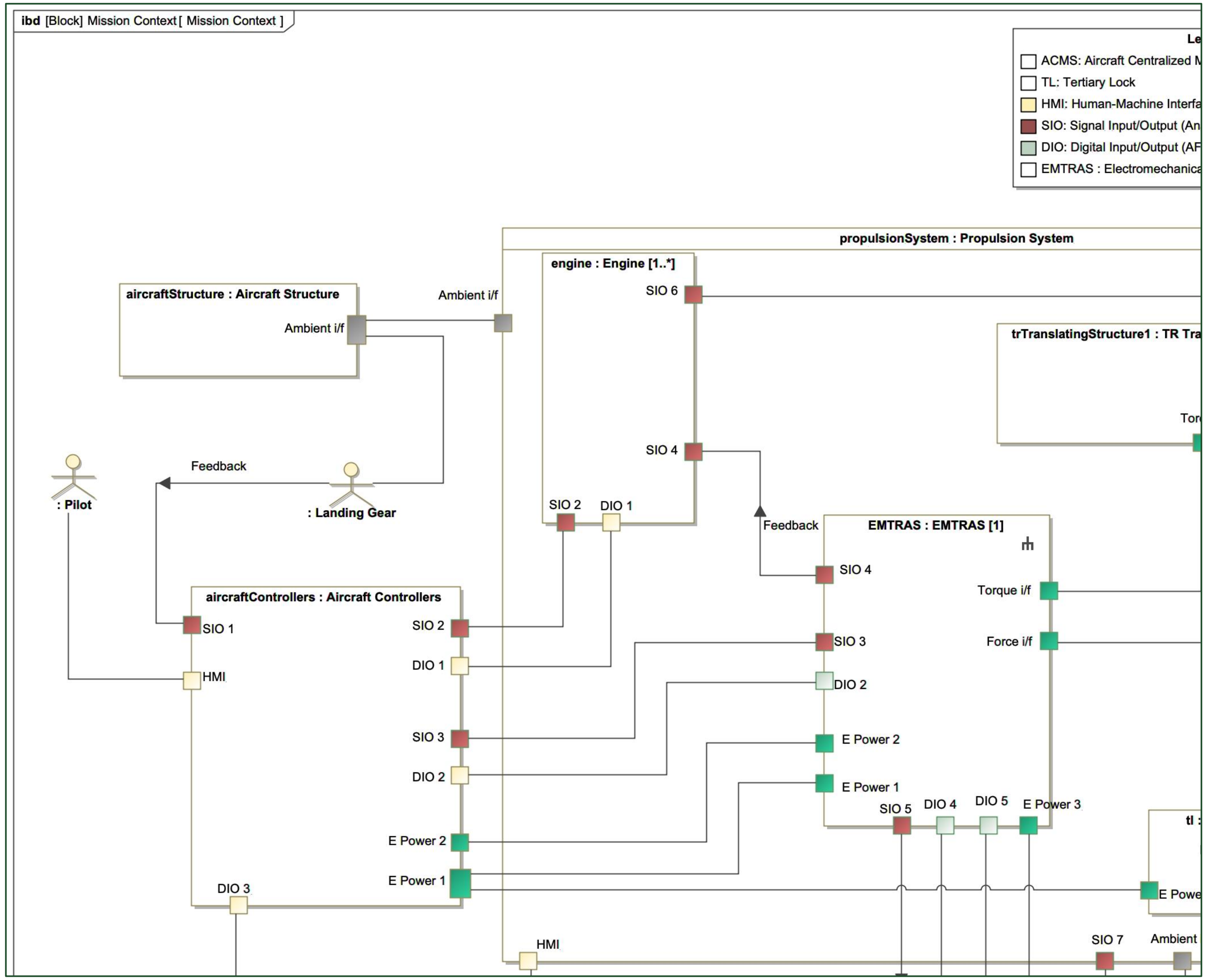


Figure 20. Mission context internal structure

Distinct views of the system are captured in separate SysML diagrams

1.2 Mission Context

1.2.3 PLC Data Deliverable Categorization

- Identify the broad categories of information content created in the PLC phase/gate deliverable
- Capture namespace of system data as data deliverable and associate with the PLC phase processes by including it within the workflow as “*data object”.*
- Data discovery continues through all phases of life cycle, and data is updated in the following stages as more information becomes available
- Proposed data modeling approach ensures that data remains current and available

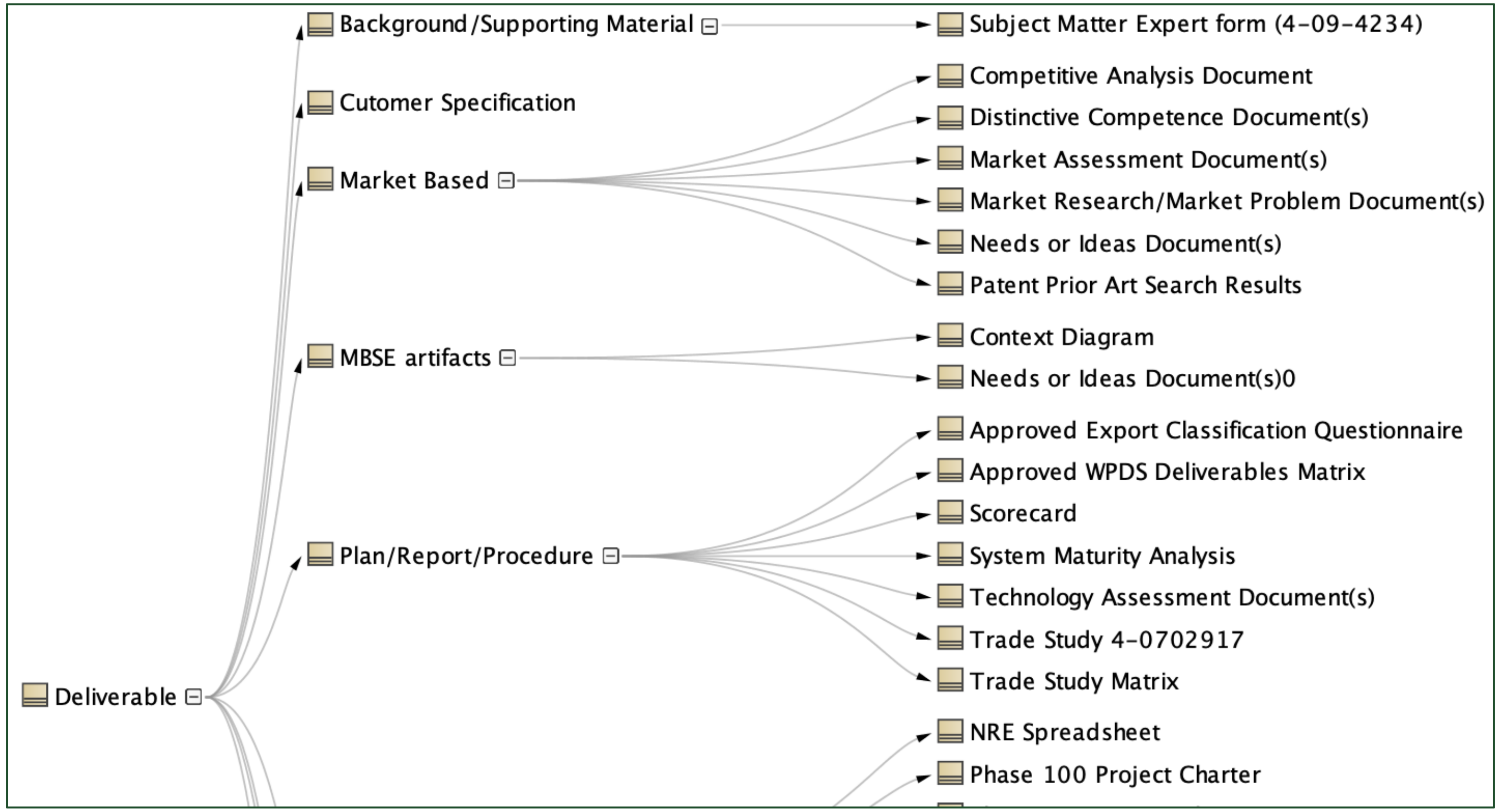


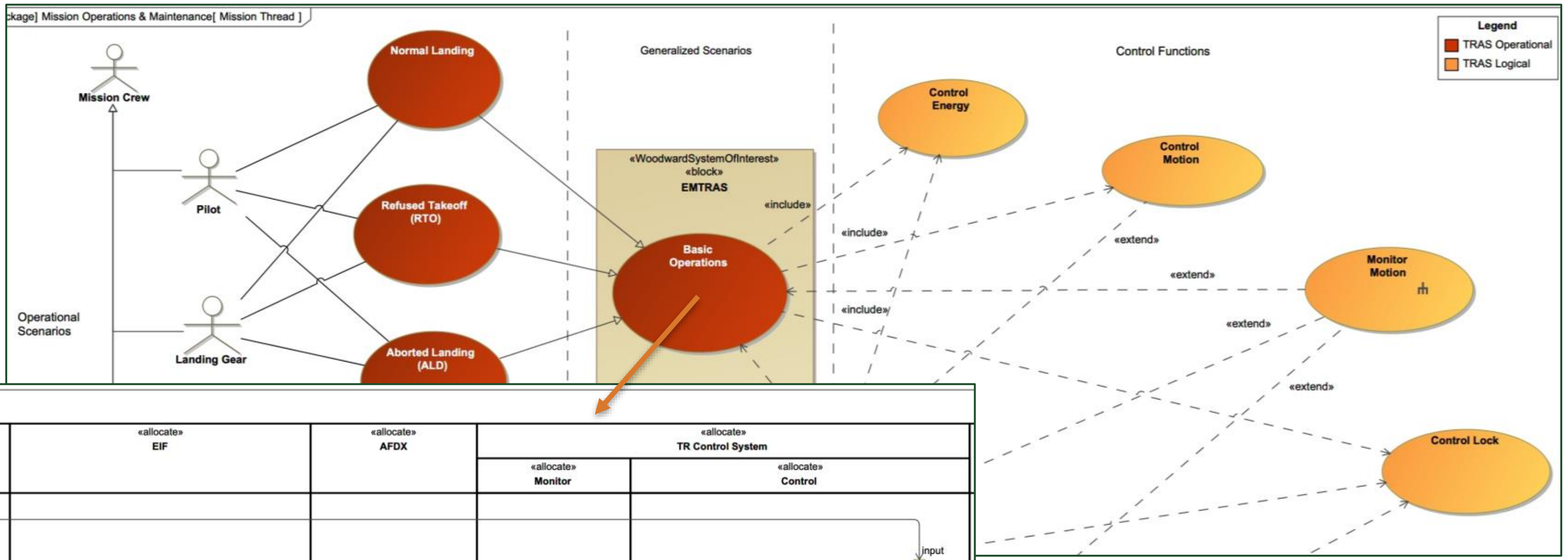
Figure 21. Categories of PLC deliverables modeled as data objects

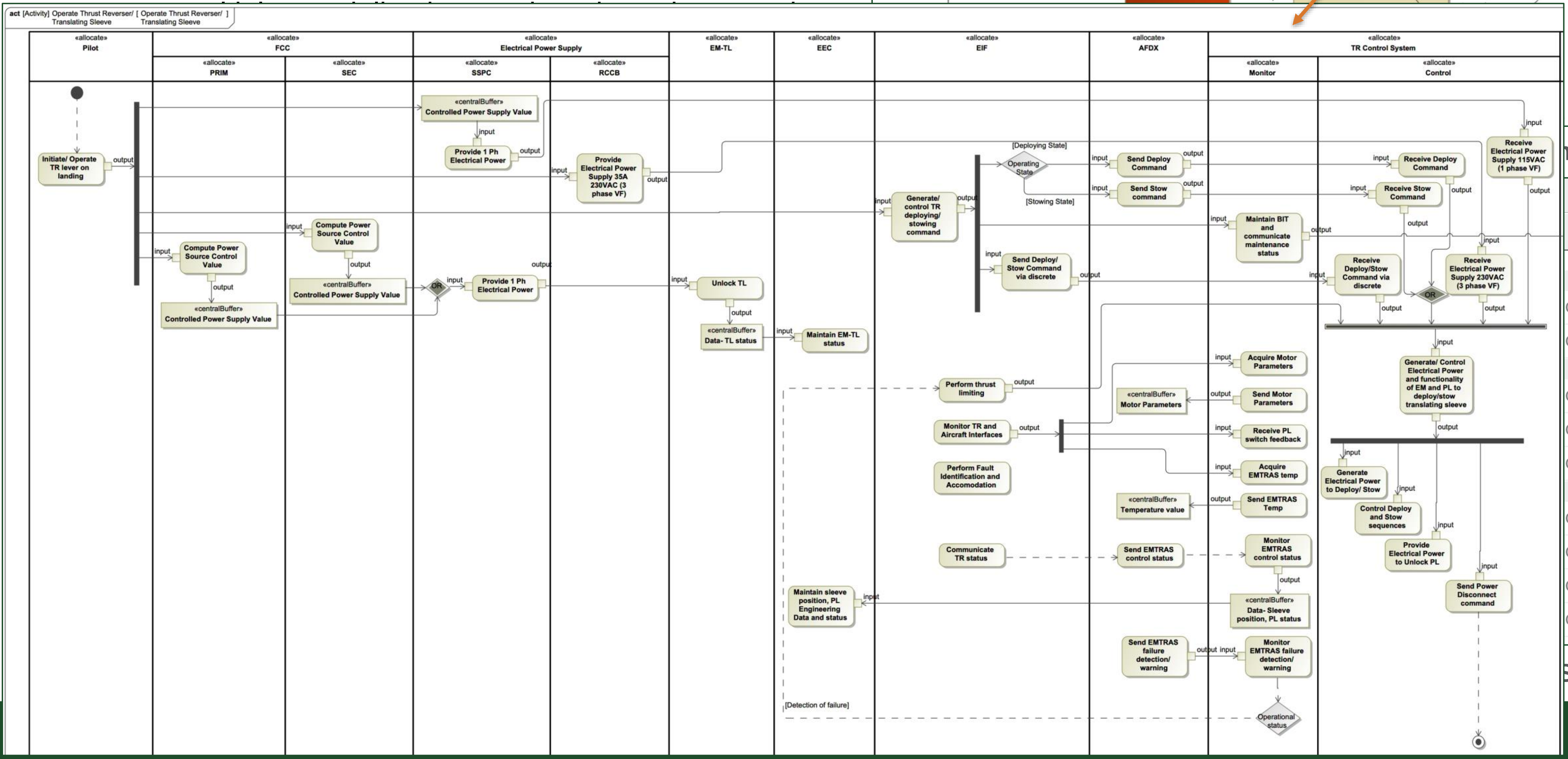
Data aspect channels the system data required within deliverable throughout the life cycle

1.3 TRAS Operational Scenarios

1.3.1 Mission Scenarios (Main, Alternative, Exceptional):

- Each operational scenario is characterized by





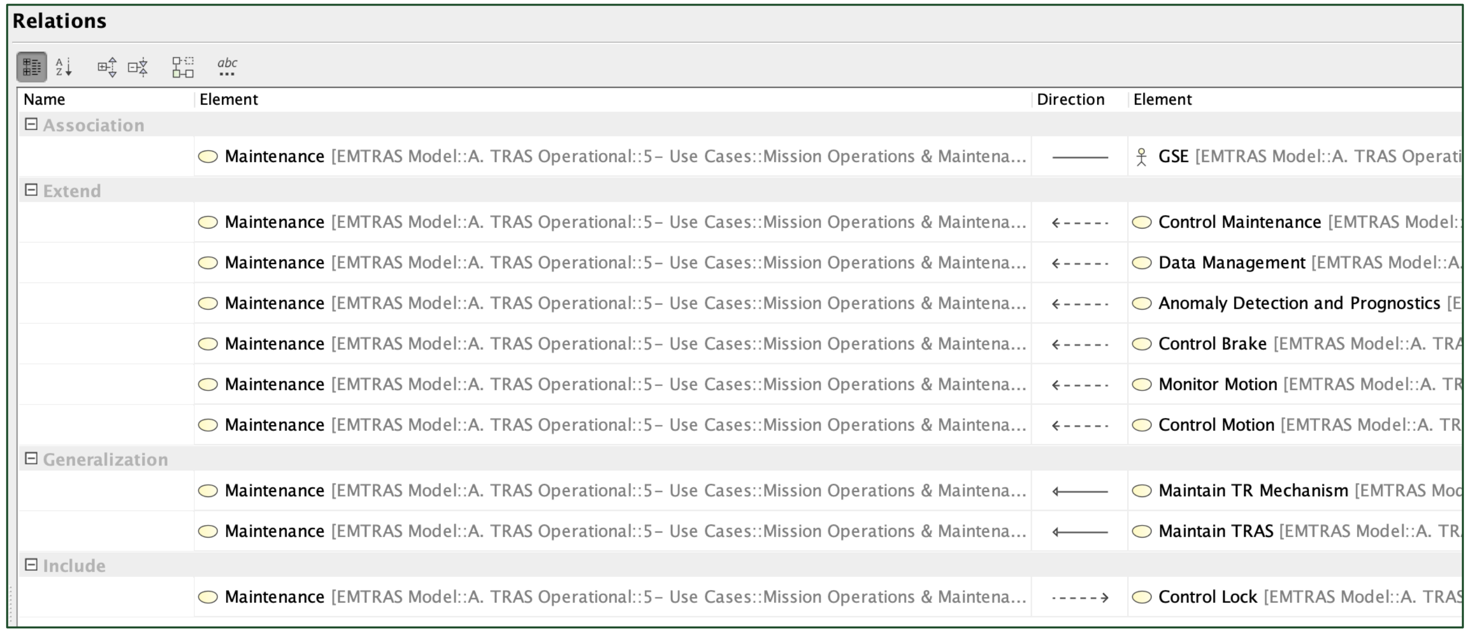
...nal Scenarios

...	Direction	Element
Operations & Maint...	<-----	Monitor Motion [EMTRAS M...
Operations & Maint...	<-----	Data Management [EMTRA...
Operations & Maint...	<——	Refused Takeoff (RTO) [E...
Operations & Maint...	<——	Normal Landing [EMTRAS...
Operations & Maint...	<——	Aborted Landing (ALD) [E...
Operations & Maint...	----->	Control Motion [EMTRAS M...
Operations & Maint...	----->	Control Energy [EMTRAS M...
Operations & Maint...	----->	Control Lock [EMTRAS Mo...
Operations & Maint...	----->	Operate EMTRAS [EMTRAS...

...Specifications

1.3 TRAS Operational Scenarios

- *Alternative Scenario*: an operating condition specified by a sequence of alternative functions performed to operate TRAS.
  - Maintain TRAS
  - Maintain TR Mechanism

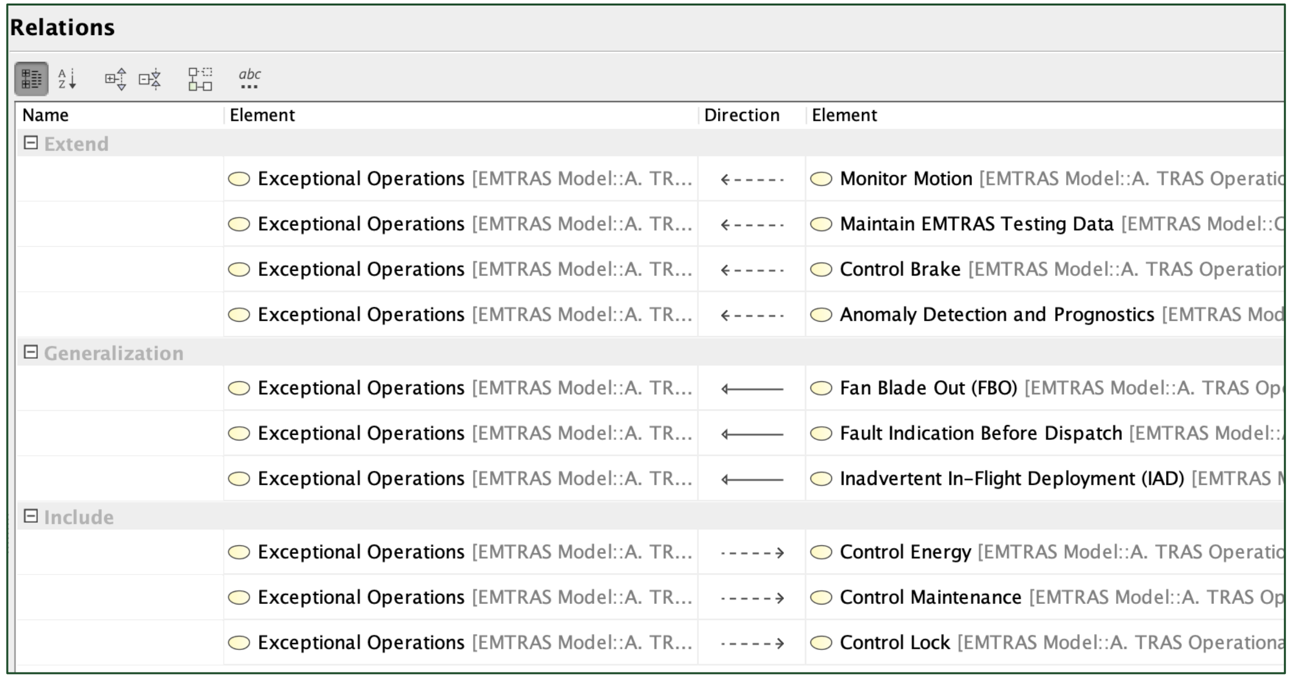


Relations

Name	Element	Direction	Element
Association			
	Maintenance [EMTRAS Model::A. TRAS Operational::5- Use Cases::Mission Operations & Maintena...	——	GSE [EMTRAS Model::A. TRAS Operati
Extend			
	Maintenance [EMTRAS Model::A. TRAS Operational::5- Use Cases::Mission Operations & Maintena...	<-----	Control Maintenance [EMTRAS Model:
	Maintenance [EMTRAS Model::A. TRAS Operational::5- Use Cases::Mission Operations & Maintena...	<-----	Data Management [EMTRAS Model::A
	Maintenance [EMTRAS Model::A. TRAS Operational::5- Use Cases::Mission Operations & Maintena...	<-----	Anomaly Detection and Prognostics [E
	Maintenance [EMTRAS Model::A. TRAS Operational::5- Use Cases::Mission Operations & Maintena...	<-----	Control Brake [EMTRAS Model::A. TRA
	Maintenance [EMTRAS Model::A. TRAS Operational::5- Use Cases::Mission Operations & Maintena...	<-----	Monitor Motion [EMTRAS Model::A. TR
	Maintenance [EMTRAS Model::A. TRAS Operational::5- Use Cases::Mission Operations & Maintena...	<-----	Control Motion [EMTRAS Model::A. TR
Generalization			
	Maintenance [EMTRAS Model::A. TRAS Operational::5- Use Cases::Mission Operations & Maintena...	<——	Maintain TR Mechanism [EMTRAS Mod
	Maintenance [EMTRAS Model::A. TRAS Operational::5- Use Cases::Mission Operations & Maintena...	<——	Maintain TRAS [EMTRAS Model::A. TR
Include			
	Maintenance [EMTRAS Model::A. TRAS Operational::5- Use Cases::Mission Operations & Maintena...	----->	Control Lock [EMTRAS Model::A. TRAS

Figure 25. Maintenance operation Use Case specification

- *Exceptional Scenario*: specified by a sequence of actions or interactions that is unintended/accidental, leading to one or more fault conditions.
  - Fault Indication Before Dispatch
  - Inadvertent In-Flight Deployment (IAD)
  - Fan Blade Out (FBO)



Relations

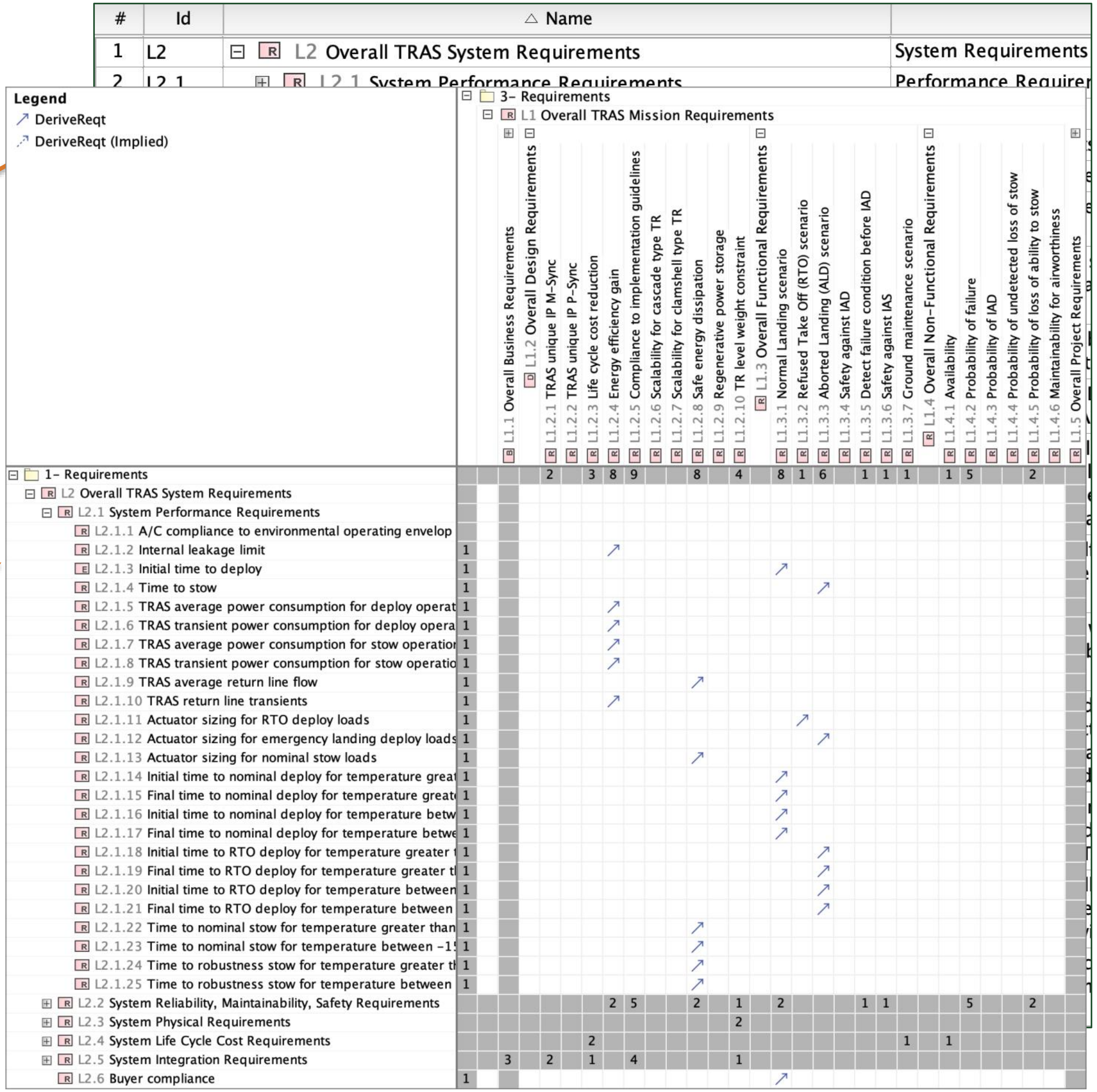
Name	Element	Direction	Element
Extend			
	Exceptional Operations [EMTRAS Model::A. TR...	<-----	Monitor Motion [EMTRAS Model::A. TRAS Operatio
	Exceptional Operations [EMTRAS Model::A. TR...	<-----	Maintain EMTRAS Testing Data [EMTRAS Model::C
	Exceptional Operations [EMTRAS Model::A. TR...	<-----	Control Brake [EMTRAS Model::A. TRAS Operation
	Exceptional Operations [EMTRAS Model::A. TR...	<-----	Anomaly Detection and Prognostics [EMTRAS Mod
Generalization			
	Exceptional Operations [EMTRAS Model::A. TR...	<——	Fan Blade Out (FBO) [EMTRAS Model::A. TRAS Op
	Exceptional Operations [EMTRAS Model::A. TR...	<——	Fault Indication Before Dispatch [EMTRAS Model::
	Exceptional Operations [EMTRAS Model::A. TR...	<——	Inadvertent In-Flight Deployment (IAD) [EMTRAS M
Include			
	Exceptional Operations [EMTRAS Model::A. TR...	----->	Control Energy [EMTRAS Model::A. TRAS Operatio
	Exceptional Operations [EMTRAS Model::A. TR...	----->	Control Maintenance [EMTRAS Model::A. TRAS Op
	Exceptional Operations [EMTRAS Model::A. TR...	----->	Control Lock [EMTRAS Model::A. TRAS Operationa

Figure 26. Exceptional operations Use Case specification

2.1 System Requirements

2.1.1 System Requirements Specification (SRS)

- Overall requirement in mission grouped under broad categories of stakeholder requirements
  - Performance Requirements,
  - Reliability Requirements,
  - Physical Requirements,
  - Life Cycle Cost Requirements, and
  - System Integration Requirements
- Derived from requirement in mission, MRS
- Each tier of hierarchy is elaborated to specify System Requirement Specifications (SRS), tagged with “L2”



2.2 System Structure

2.2.1 System Decomposition External Structure

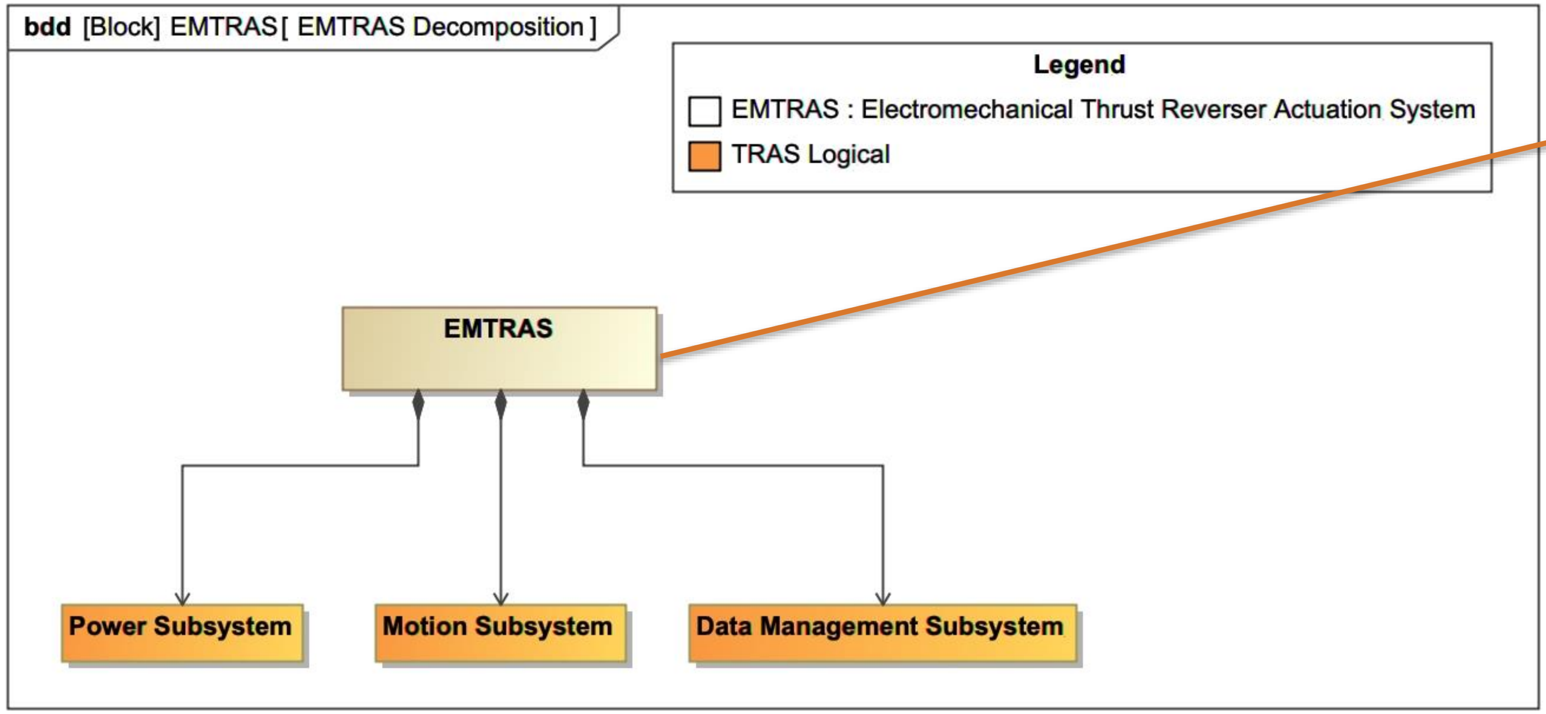
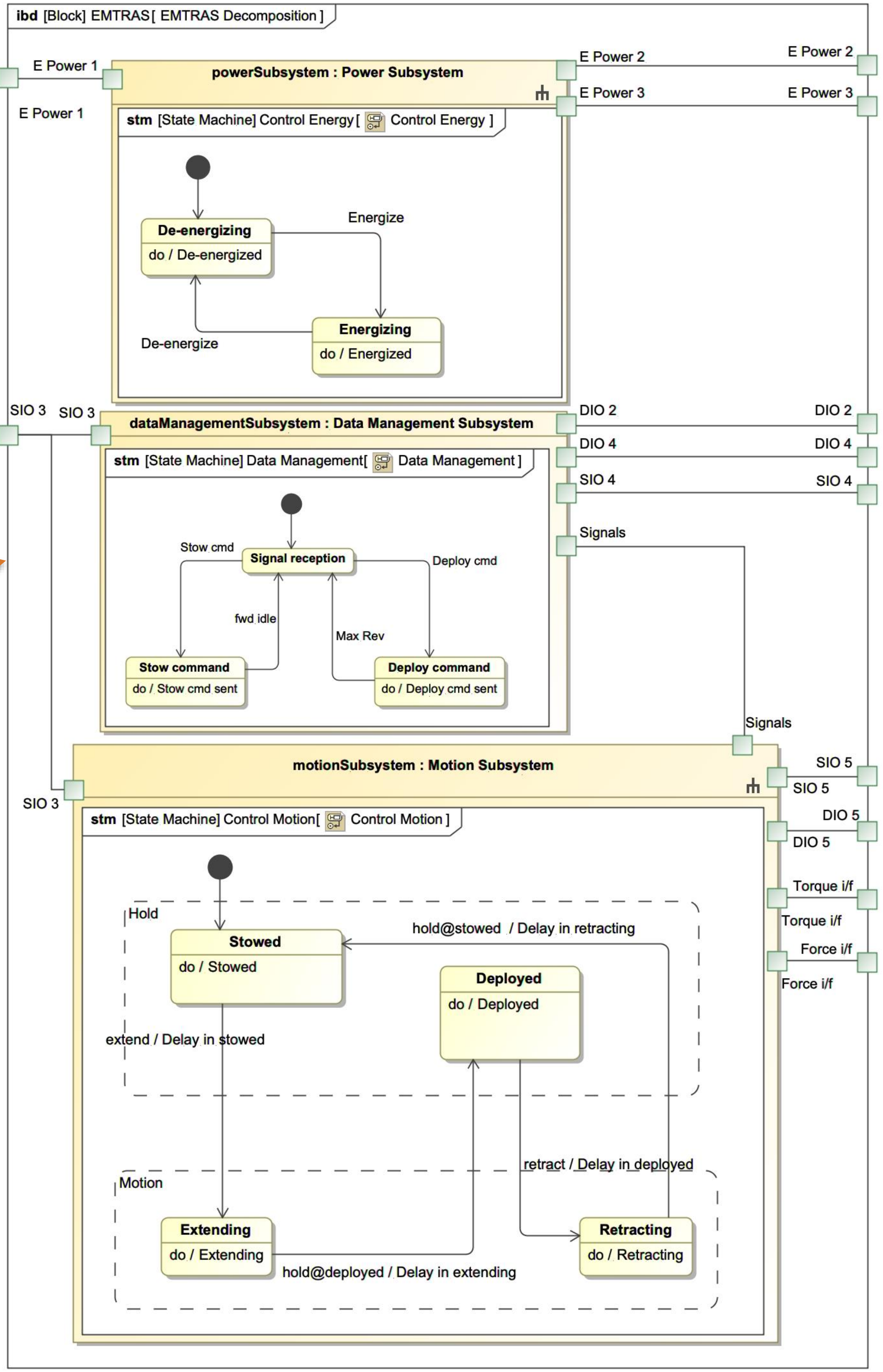


Figure . System Decomposition to Logical Subsystems

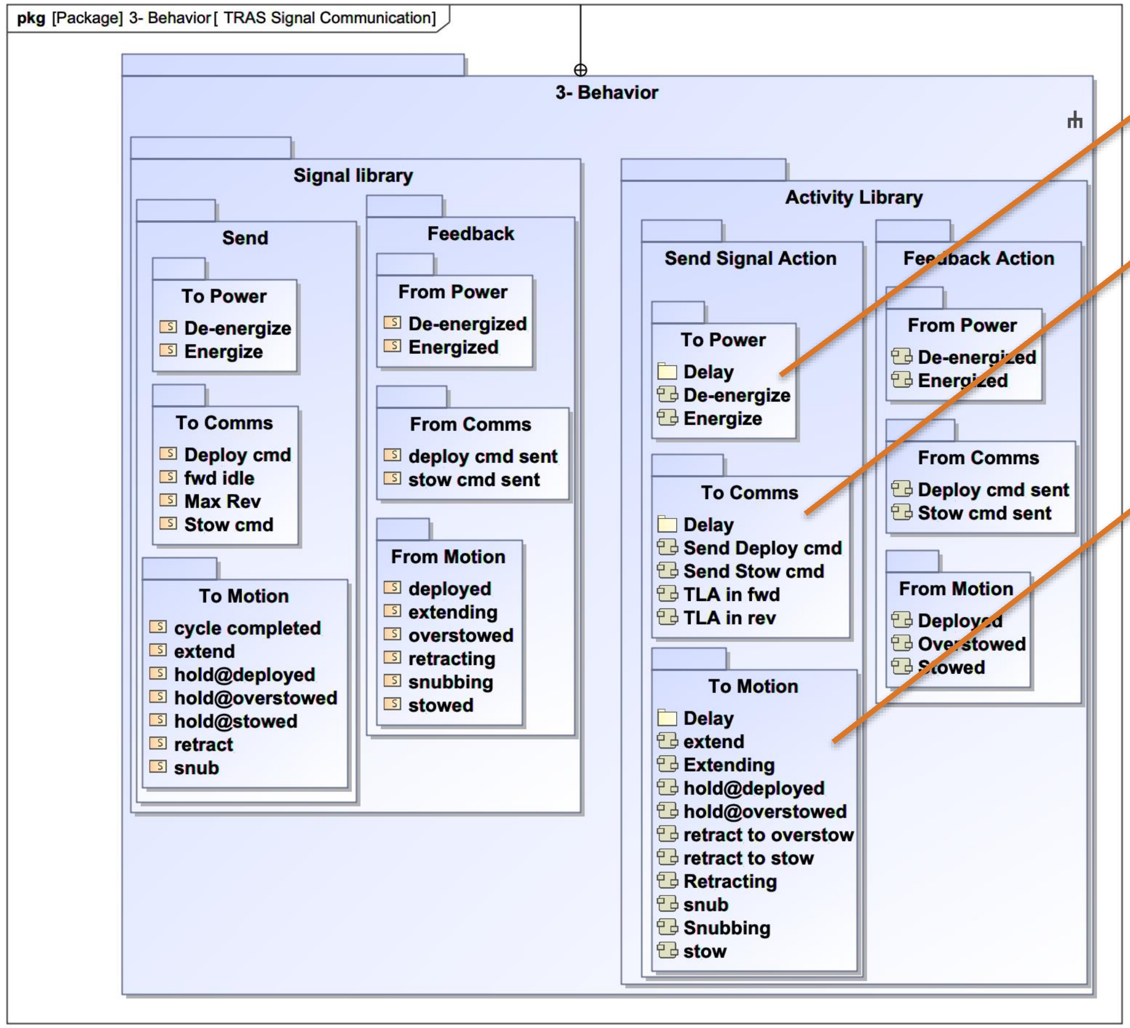


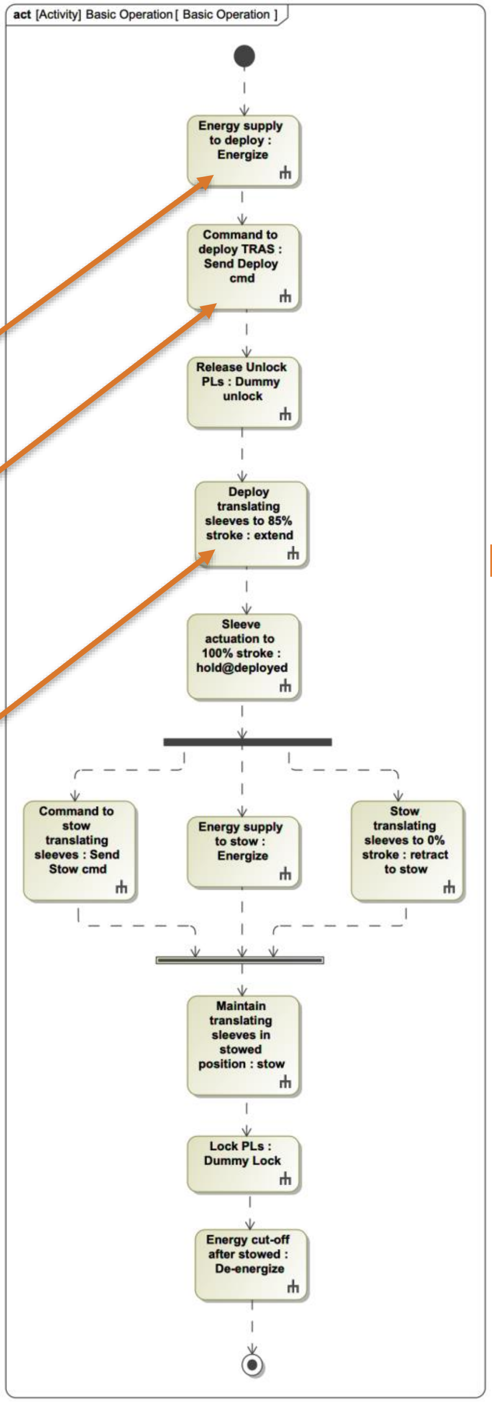
2.2.2 System Decomposition Internal Structure

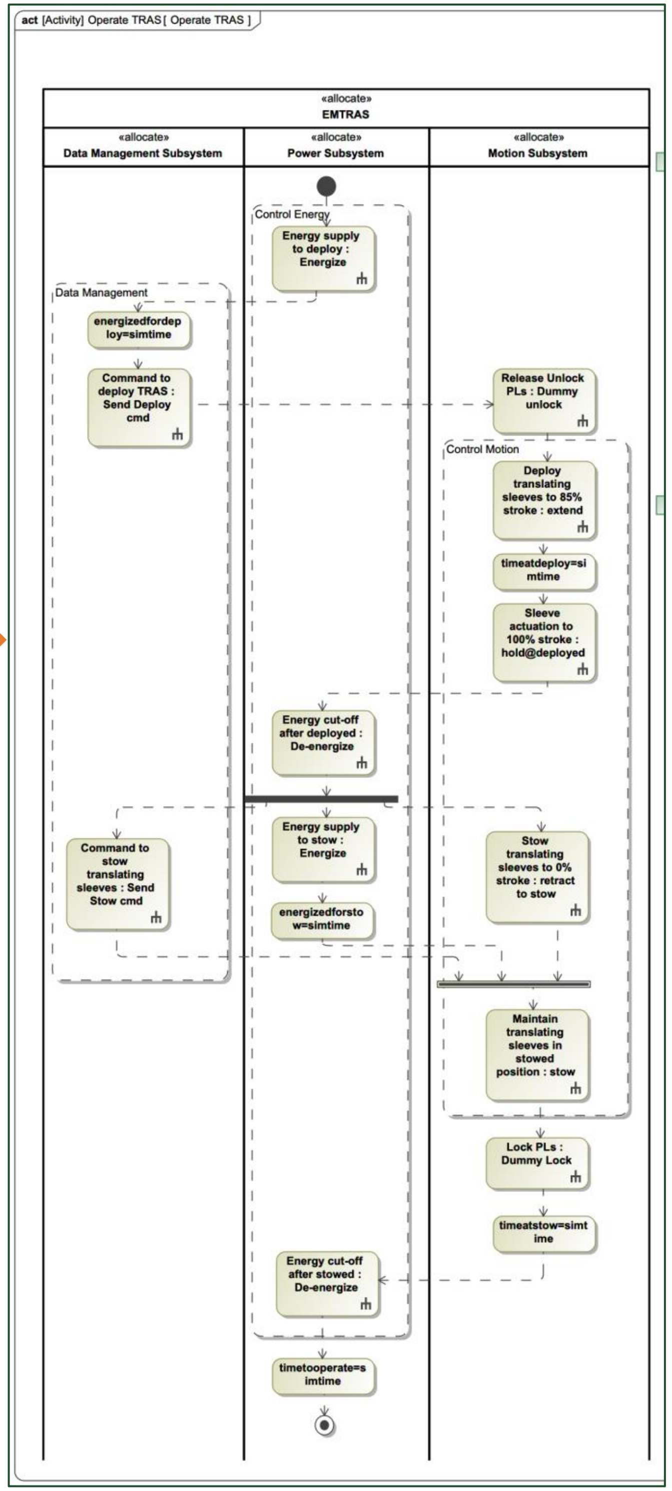
2.3 System Functions

2.3.1 System Behavior

2.3.2 System Functional Analysis and Allocation







2.4 System Parameters

2.4 System Parameters

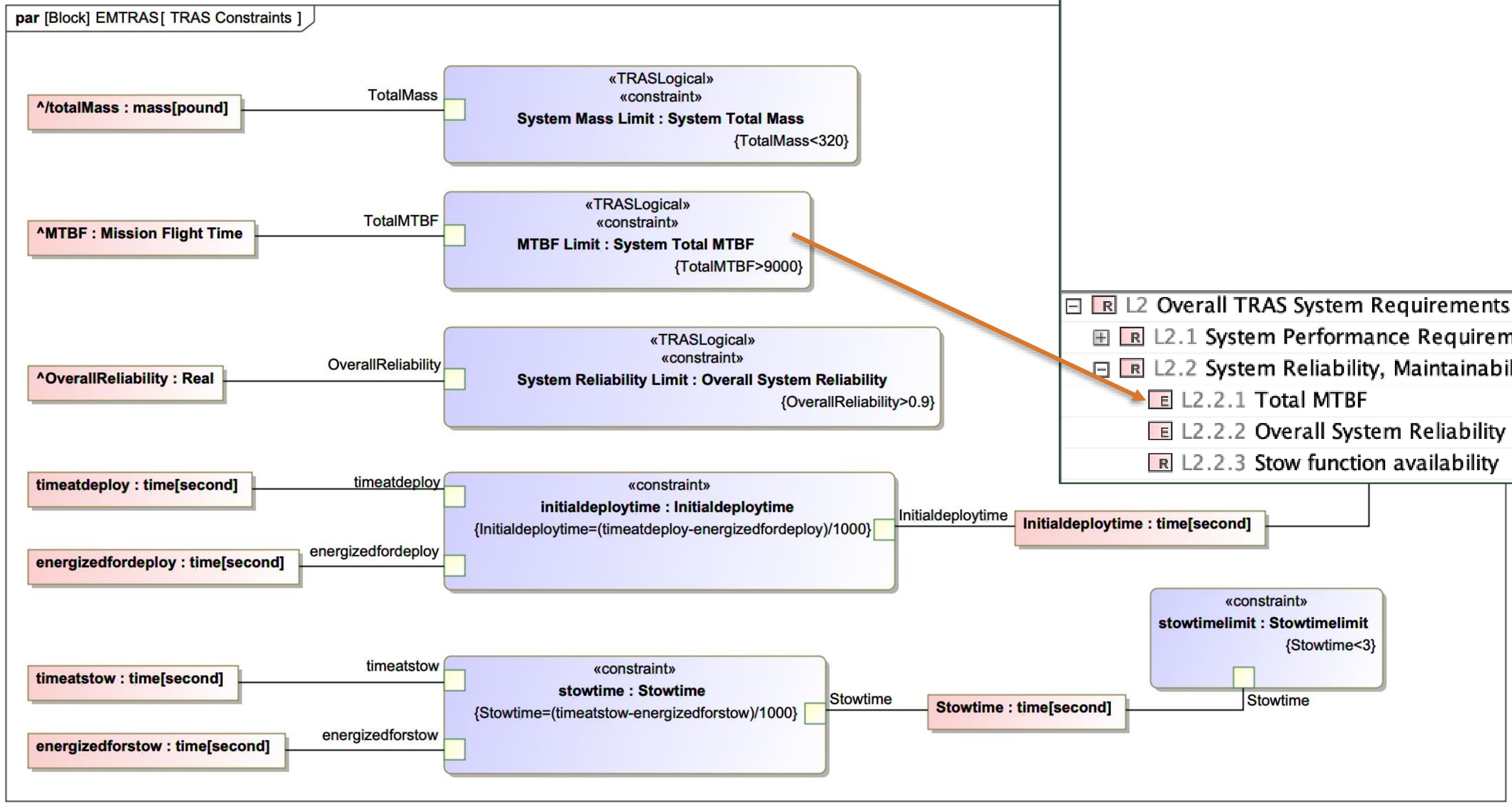


Figure 29. Applying Constraints to System Performance Parameters

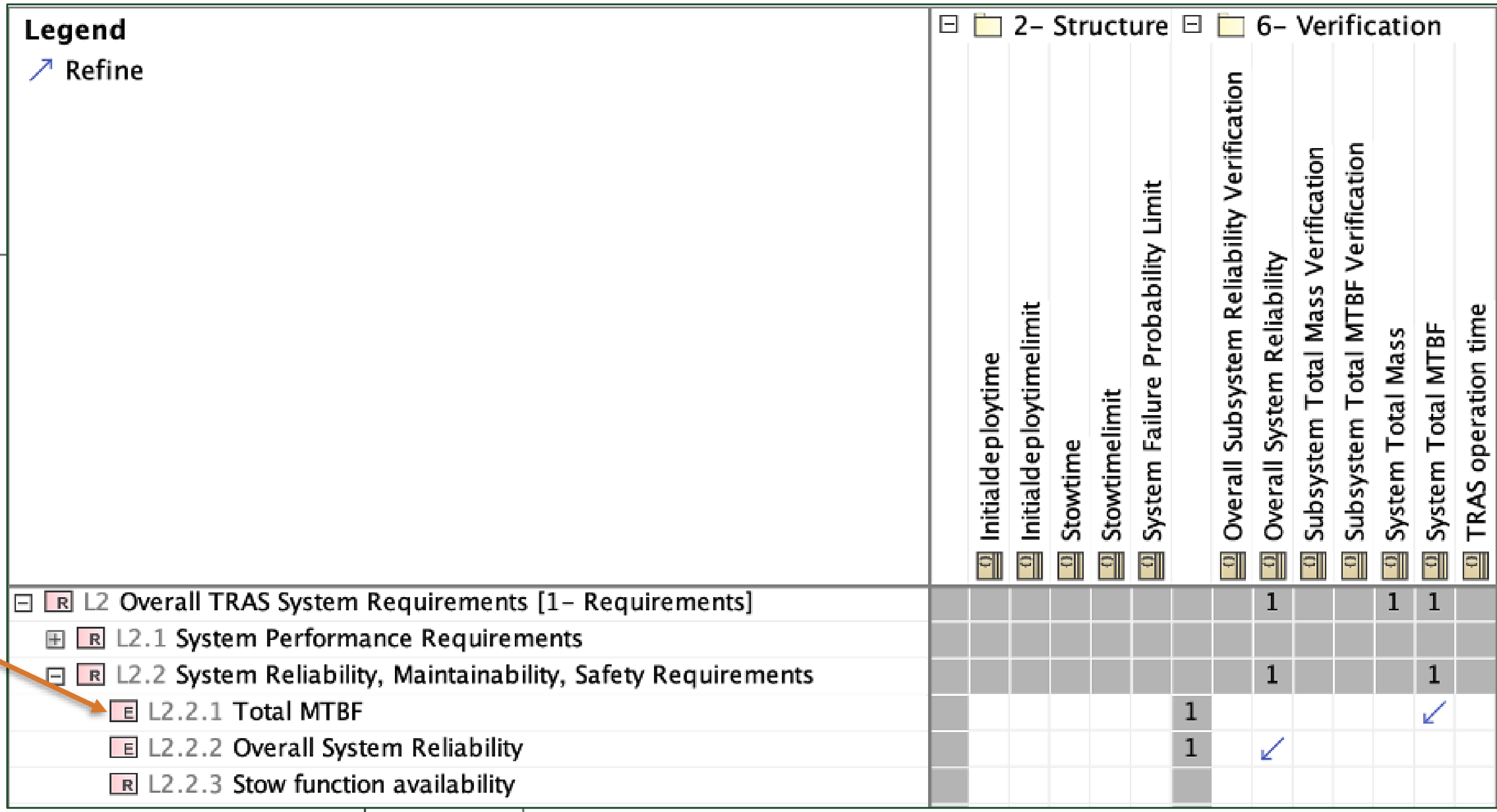


Figure 30. System Constraints Refine SRS

3.2 Subsystem Structure

3.2.1 Subsystem Alternative Configurations

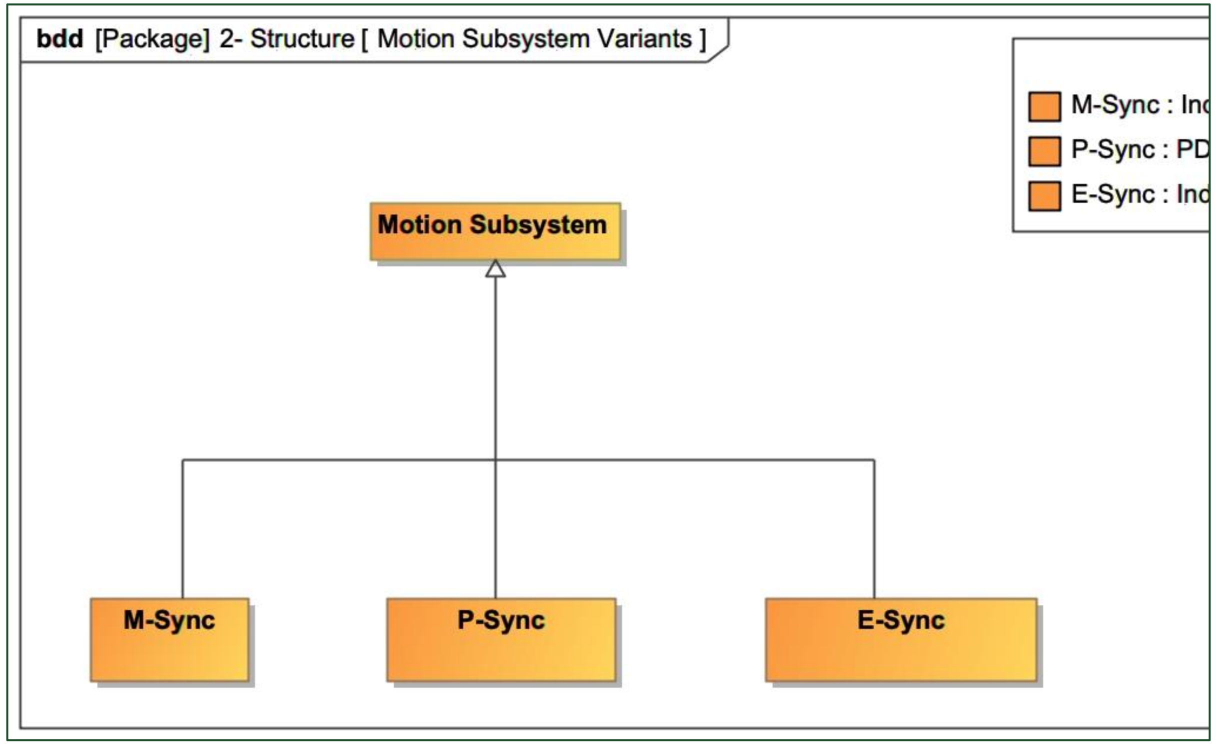


Figure 31. Alternative configurations of the synchronized motion subsystem

3.2.2 Subsystem Decomposition external structure

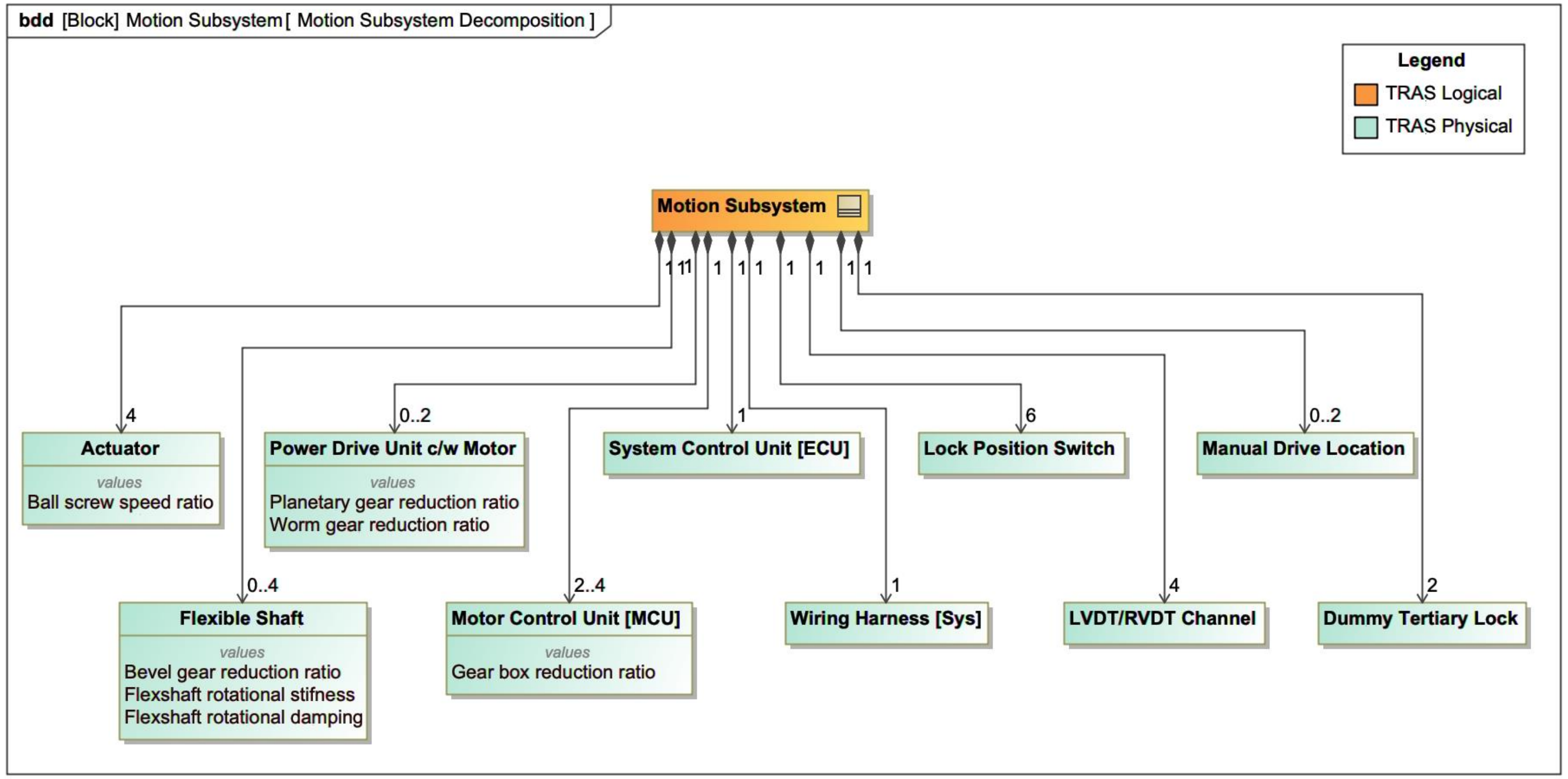


Figure 32. Motion subsystem decomposition to physical LRU

3.3 Subsystem Functions

3.2.1 Subsystem Stateful Behavior

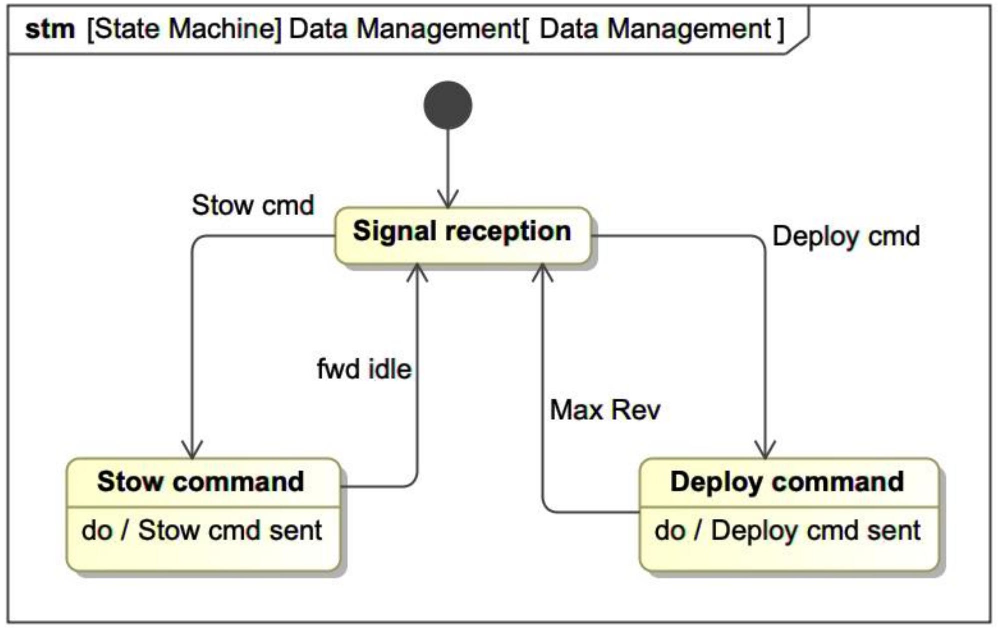


Figure 33. Data Management Subsystem States

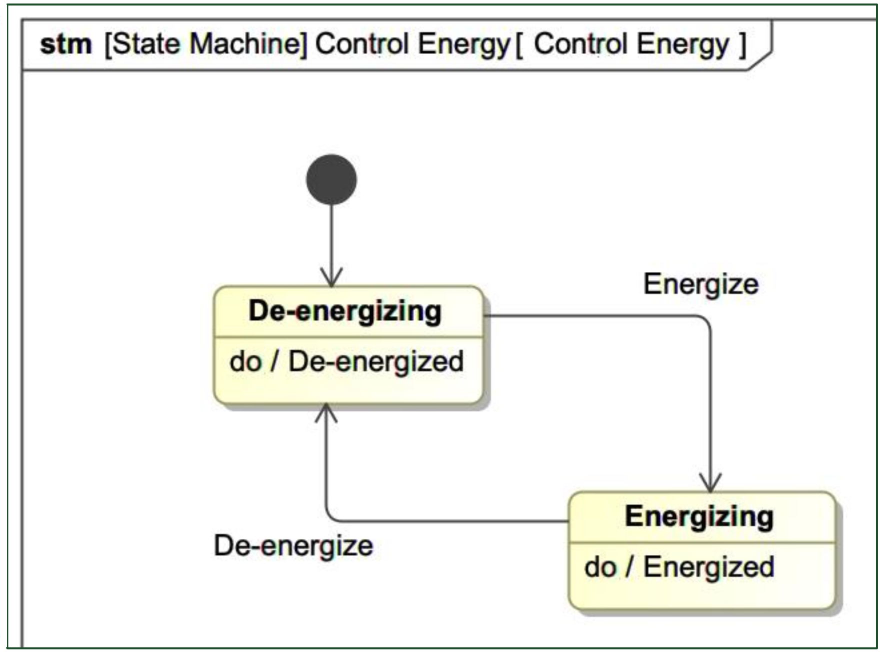


Figure 34. Power Subsystem States

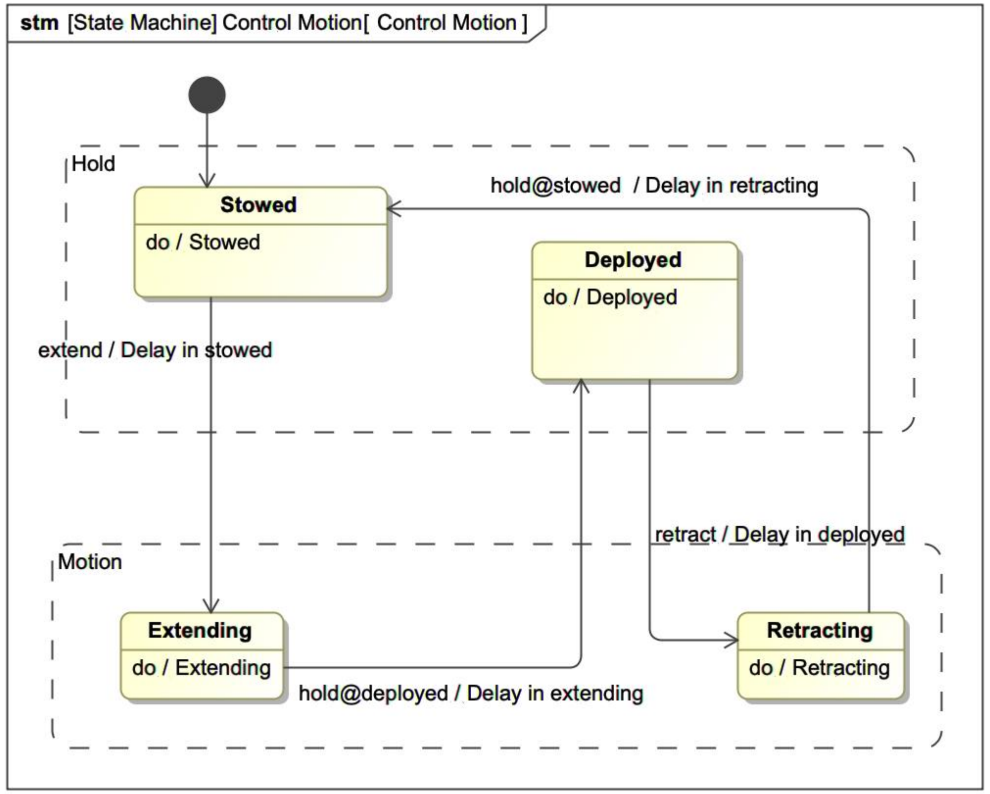


Figure 35. Motion Subsystem States

4.2 LRU Structure

- The TRAS physical level of abstraction captures the physical characteristics associated with implementation.
- This is where the component catalog and point design is established.

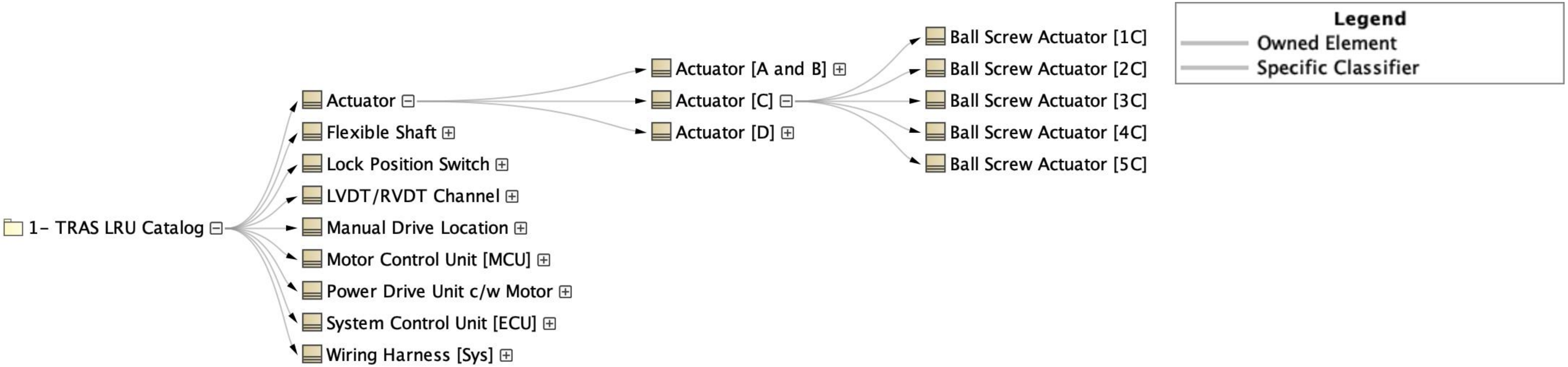


Figure 36. Modeling a catalog of line replaceable units (LRU)

- LRU requirements, functions and parameters are excluded from the presentation

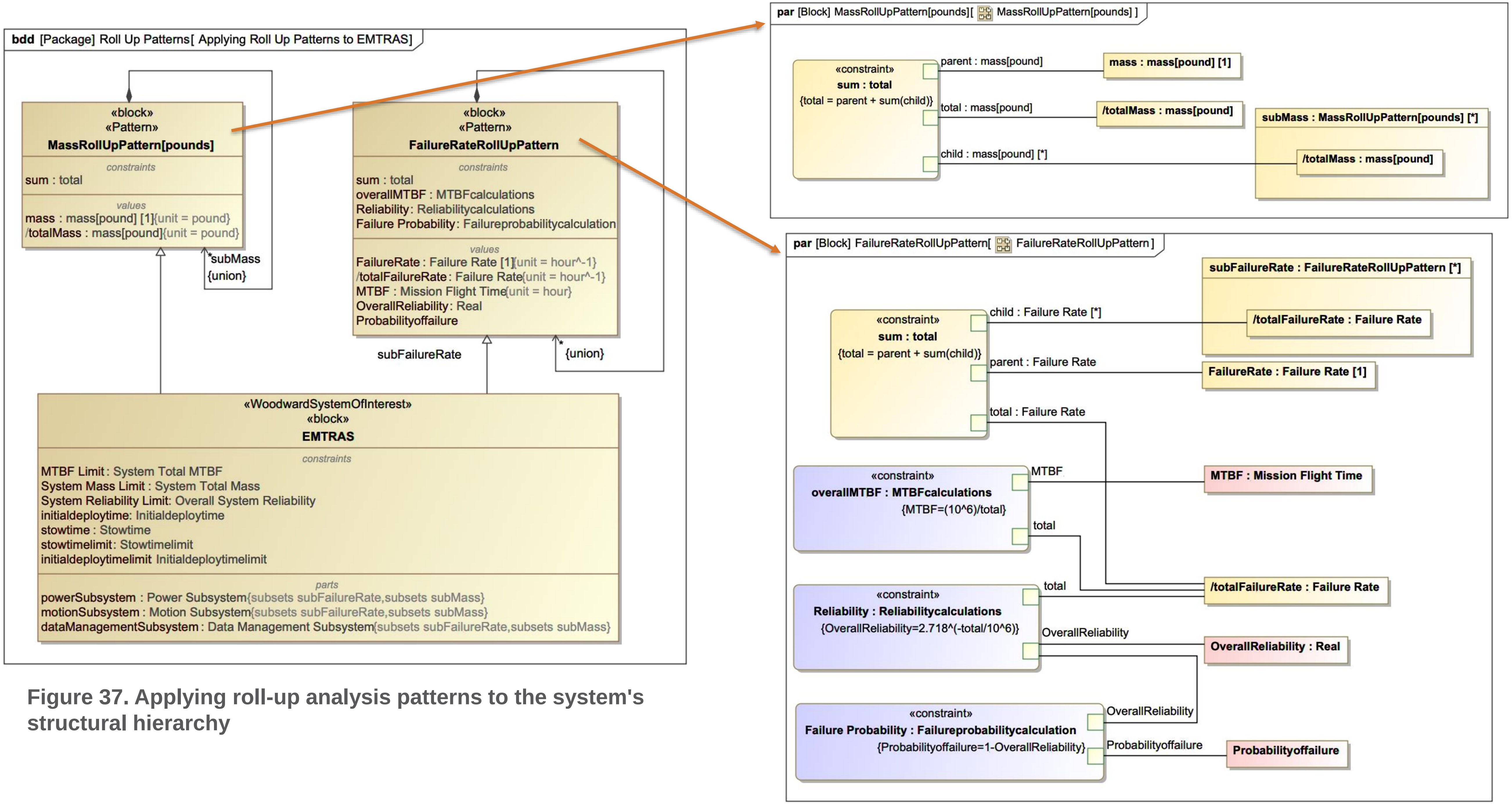


Figure 37. Applying roll-up analysis patterns to the system's structural hierarchy

TRAS Architecture Modeling and Analysis : Analyze Architecture Alternatives to Setup a Trade Study

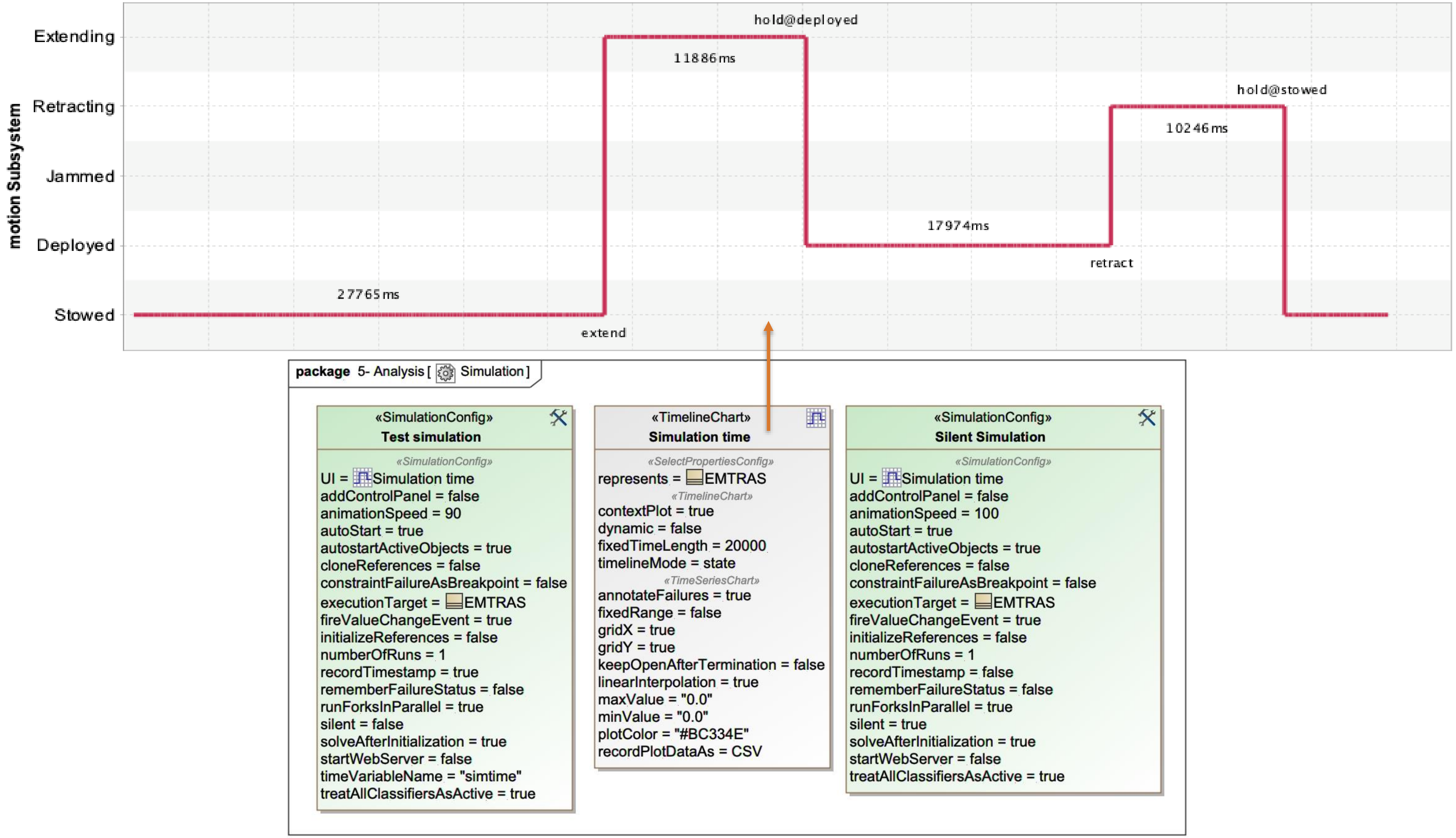


Figure 38. Simulation configuration and timeline chart for timing simulation

Motion Subsystem Variants: M-Sync : Independent Drive with Mechanical Synchronization [A and B] P-Sync : PDU Drive and Synchronization [C] E-Sync : Independent Drive with Electric Synchronization [D]

Specifications: 1: Master Specifications 2: Inferior Specifications

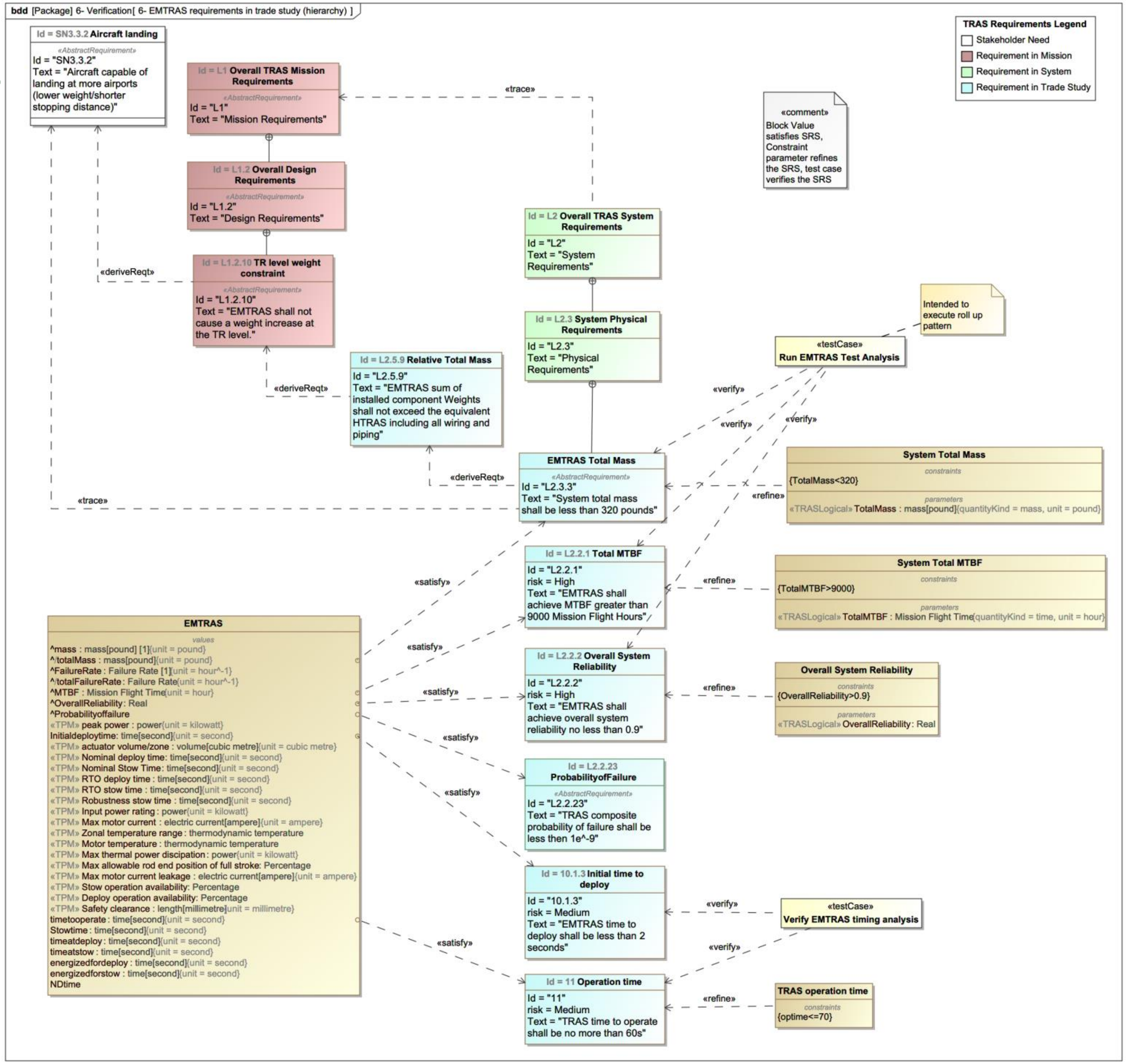
#	Name	actuator : Actuator	flexible Shaft : Flexible Shaft	power Drive Unit c/w Motor : Power Drive Unit c/w Motor	motor Control Unit [MCU] : Motor Control Unit [MCU]	: System Control Unit [ECU]								
1	E-Sync [1D]	ball Screw Ac ball Screw Ac ball Screw Ac ball Screw Ac			mcu [d] : MC mcu [d]1 : M mcu [d]2 : M mcu [d]3 : M	ecu [d] : ECU								
2	E-Sync [2D]	ball Screw Ac ball Screw Ac ball Screw Ac ball Screw Ac			mcu [d]4 : M mcu [d]5 : M mcu [d]6 : M mcu [d]7 : M	ecu [d]1 : EC								
3	P-Sync [1C]	ball Screw Ac ball Screw Ac ball Screw Ac ball Screw Ac	flex Shaft [1C flex Shaft [1C flex Shaft [1C flex Shaft [1C	pdu [1c] : PD pdu [1c]1 : P	mcu [c] : MC mcu [c]1 : M	ecu [c] : ECU								
4	P-Sync [2C]	ball Screw Ac ball Screw Ac ball Screw Ac ball Screw Ac	flex Shaft [2C flex Shaft [2C flex Shaft [2C flex Shaft [2C	pdu [2c] : PD pdu [2c]1 : P	mcu [c]2 : M mcu [c]3 : M	ecu [c]1 : EC			lock Position lock Position lock Position lock Position	lvdt/ rvdt cha lvdt/ rvdt cha		164.1 lb	8491.199 h	1.177E-4
5	M-Sync [1A ar	ball Screw Ac ball Screw Ac ball Screw Ac ball Screw Ac	sync shafts [sync shafts [		mcu [a and b mcu [a and b mcu [a and b mcu [a and b	ecu [a and b]	wiring Harne	dummy Terti dummy Terti	lock Position lock Position lock Position lock Position lock Position lock Position	lvdt/ rvdt cha lvdt/ rvdt cha lvdt/ rvdt cha lvdt/ rvdt cha	manual Drive manual Drive	125.14 lb	9775.84 h	1.023E-4
6	M-Sync [2A ar	ball Screw Ac ball Screw Ac ball Screw Ac ball Screw Ac	sync shafts [sync shafts [		mcu [a and b mcu [a and b mcu [a and b mcu [a and b	ecu [a and b]	wiring Harne	dummy Terti dummy Terti	lock Position lock Position lock Position lock Position lock Position lock Position	lvdt/ rvdt cha lvdt/ rvdt cha lvdt/ rvdt cha lvdt/ rvdt cha	manual Drive manual Drive	139.9 lb	8963.063 h	1.116E-4

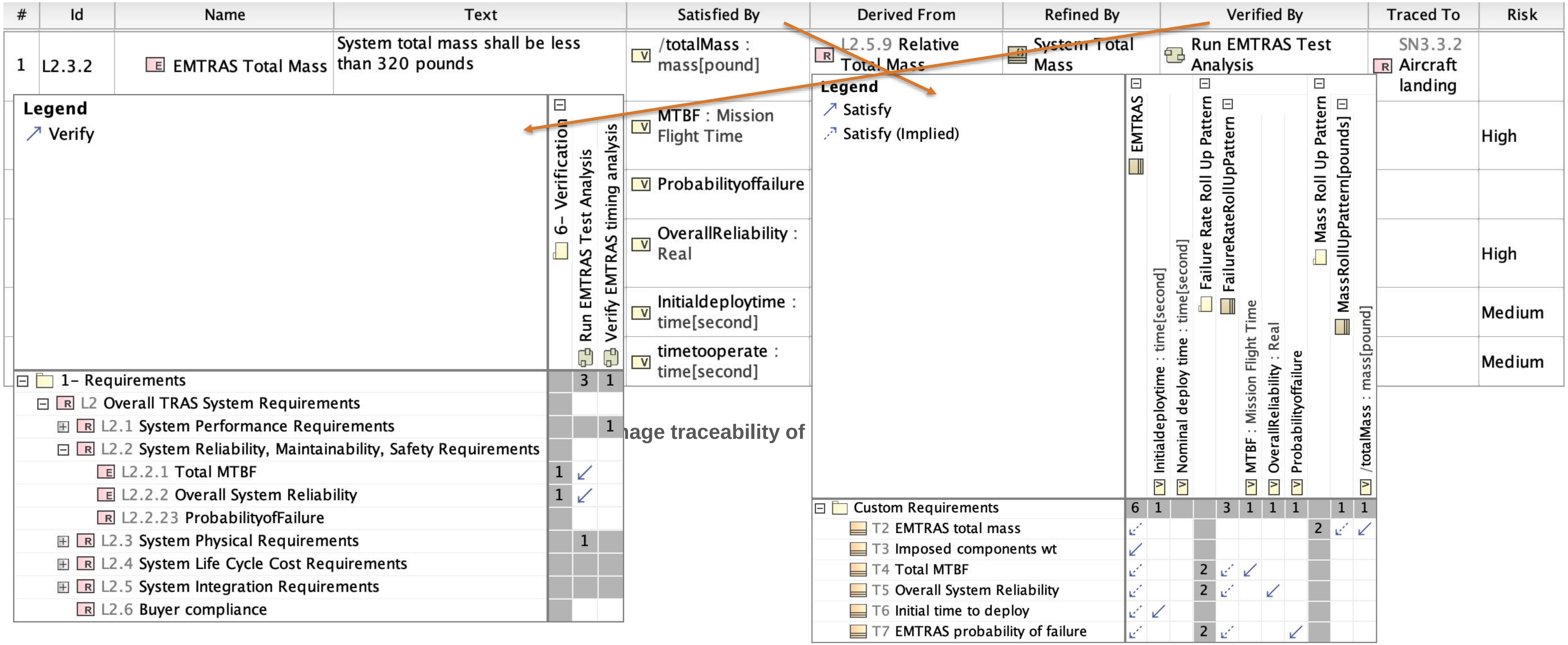
#	Name	motion Subsystem : Motion Subsystem	power Subsystem : Power Subsystem	data Management Subsystem : Data Management Subsystem	totalMass : mass[pound] (lb)	MTBF : Mission Flight Time (h)	Probabilityc
1	EMTRAS [D]	E-Sync [1D] : E-Sync	Power [1D] : Power Subsystem	Data [1D] : Data Management Subsystem	302.9 lb	9209.121 h	1.086E-4
2	EMTRAS [C]	P-Sync [1C] : P-Sync	Power [1C] : Power Subsystem	Data [1C] : Data Management Subsystem	347.14 lb	9385.001 h	1.065E-4
3	EMTRAS [A and B]	M-Sync [1A and 1B] : M-Sync	Power [1A and 1B] : Power Subsystem	Data [1A and 1B] : Data Management Subsystem	325.14 lb	9775.84 h	1.023E-4

Figure 39. Instances of Motion Subsystem Configurations

Manage and Trace Requirements

- Top 5 requirement in trade study are analyzed
- Requirement decomposition hierarchy is established to trace the requirement in trade study
- Visualize upstream and downstream relationships
- Traceability relationships between requirement and model elements





(I2) Need to break silos of knowledge to coordinate across engineering specialities and fill those gaps with an integrated modeling environment.

(I3) Need to communicate holistic (big-picture) thinking that enables cross-collaboration among multiple disciplines in project team.

4. Interactive Requirements Development and Management

- 4.1 : Identify Customized Attributes
- 4.2 : Develop Well-Structured Requirements
- 4.3 : Analyze Interactively Requirement Changes

Problem with Requirements

- It is observed that stakeholder requirements captured initially are often crude, lacks completeness and consistency.
- Involves a lot of manual rework to refine by identifying the missing gaps in requirement statements.
- ***Requirements Engineering (RE)*** deals with effectively generating high quality requirements that are complete, correct, consistent, traceable and verifiable.
- An attribute-centric approach is investigated, wherein requirement properties are customised to establish completeness for definition, traceability, and management aspects.
- A requirement statement can be assembled by specifying the necessary attributes typed with model elements pertinent to a requirement.
- An approach for eliciting a typical requirement statement/specification could look like:

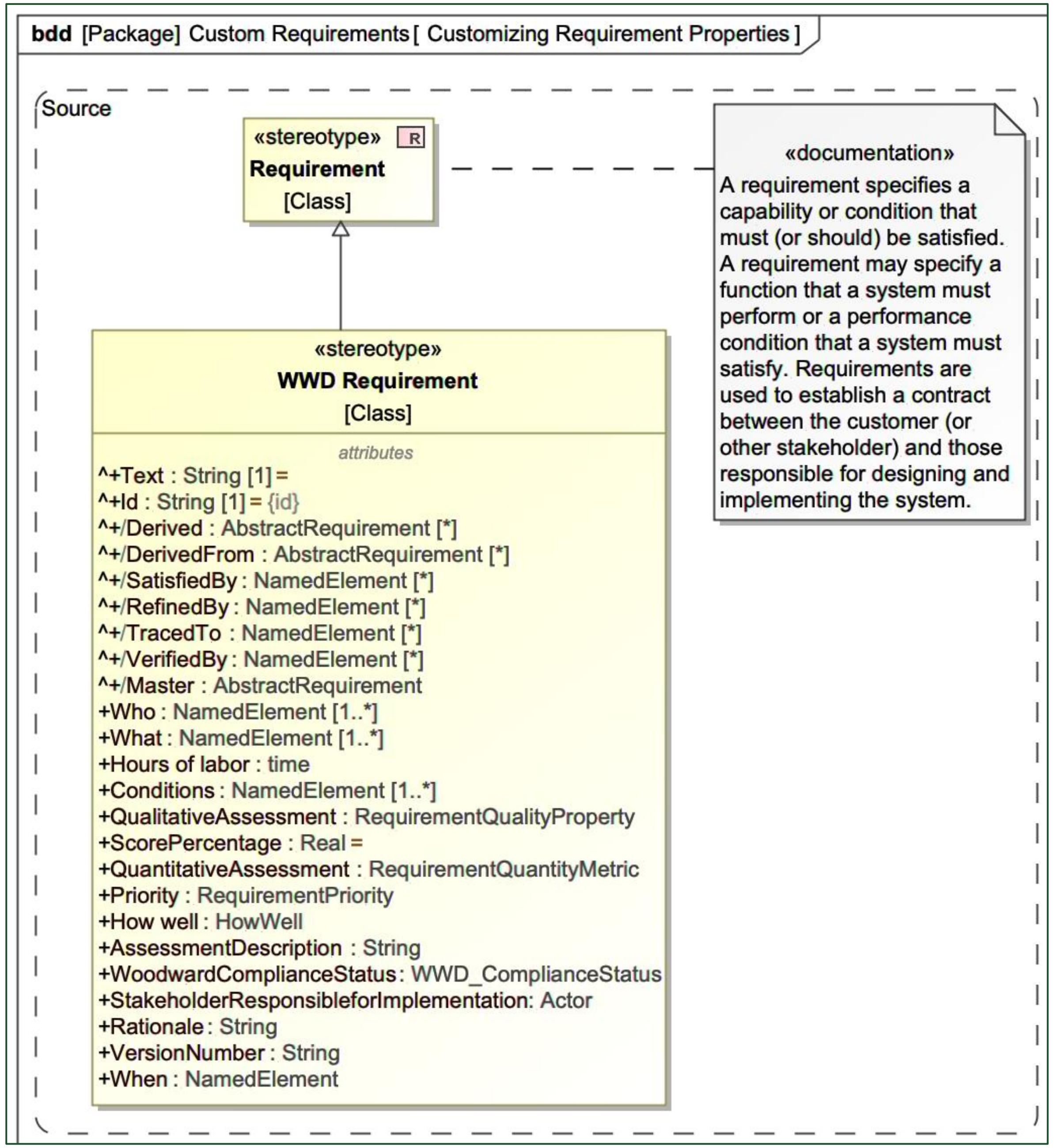
The [*Who*] shall do [*What*] constrained by [*How Well*] subject to [*Condition*]

- This effort aims to develop well-defined requirements using structured attributes in the form of model elements/set of measurable quality properties while creating a requirement.

Identify Customized Attributes

1. Definition Attributes

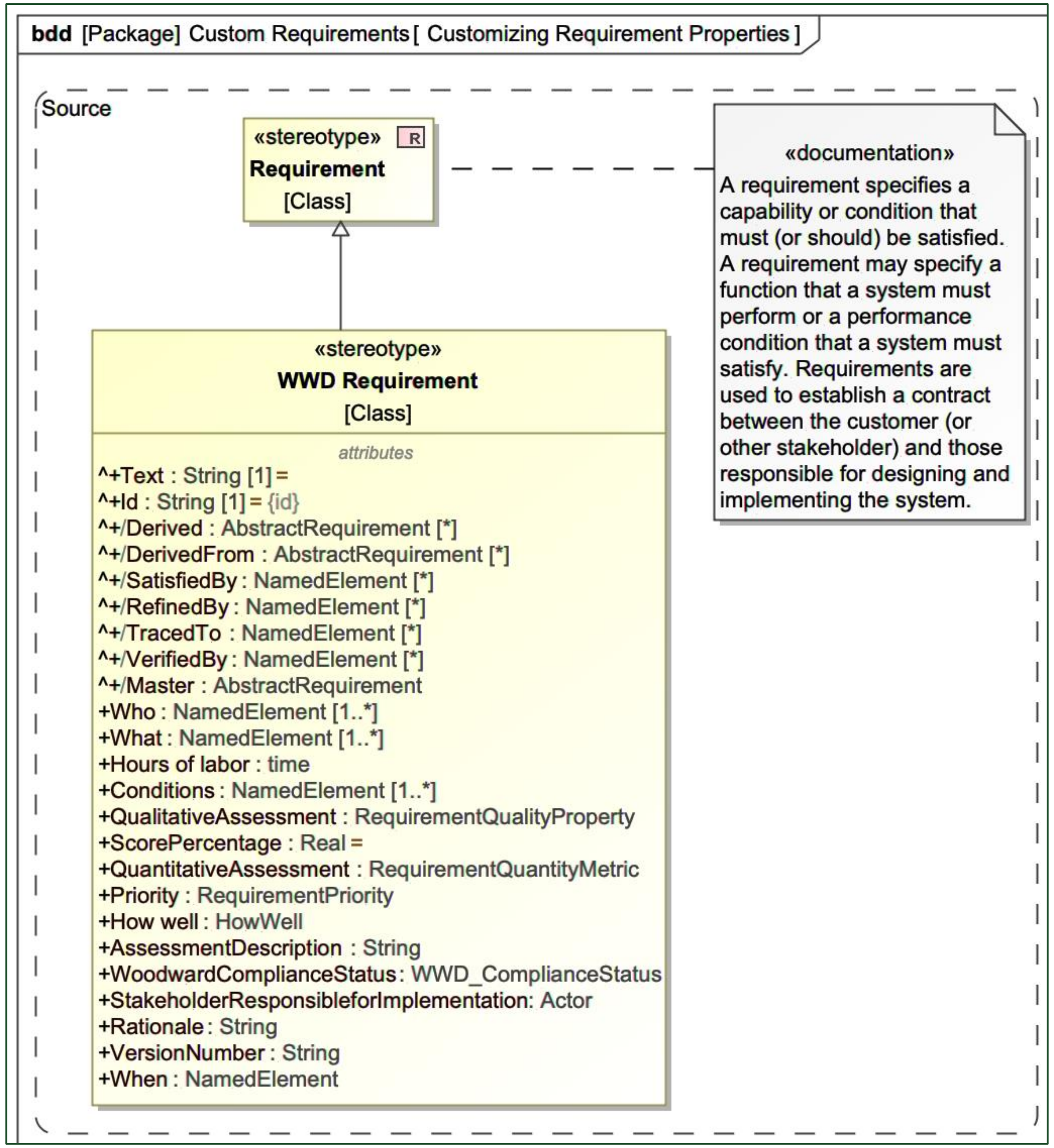
- *Who* (subject): specifies the subject model element that performs the action or acts upon the capability.
  - Actor/User Role/any subject model element
- *What (*capability): describes the expected capability/function in terms of an observable action or outcome.
  - Activity/demonstration/design characteristics
- How Well (constraint): describes how well the system performs its functions.
  - Performance criteria/qualifying threshold
- Condition (scenario): describes the intended operational scenario/condition of use under which the system operates.
  - Operational scenario/state of operation/subject to duration



Customizing Requirement Properties for definition, traceability and management attributes

2. Traceability and Management Attributes

- *Owner/Author* : describes the stakeholder who creates a requirement and is responsible for managing the requirement.
- *Version Number* : describes the serial/version of a requirement
- *Qualitative Assessment* : assessment criteria to measure the quality of a requirement
  - Missing/Incomplete/Complete/to be reviewed (TBR)
- *Quantitative Assessment* : measure of coverage in terms of overall quantity or percentage of passed/failed requirements.
- *Score Percentage* : overall score of how well the requirement is elicited, performed manually.
- *Compliance Status* : describes the status of a requirement's compliance to rules/regulations to track the compliance and maintain traceability with verification methods



Customizing Requirement Properties for definition, traceability and management attributes

Develop Well-Structured Requirements

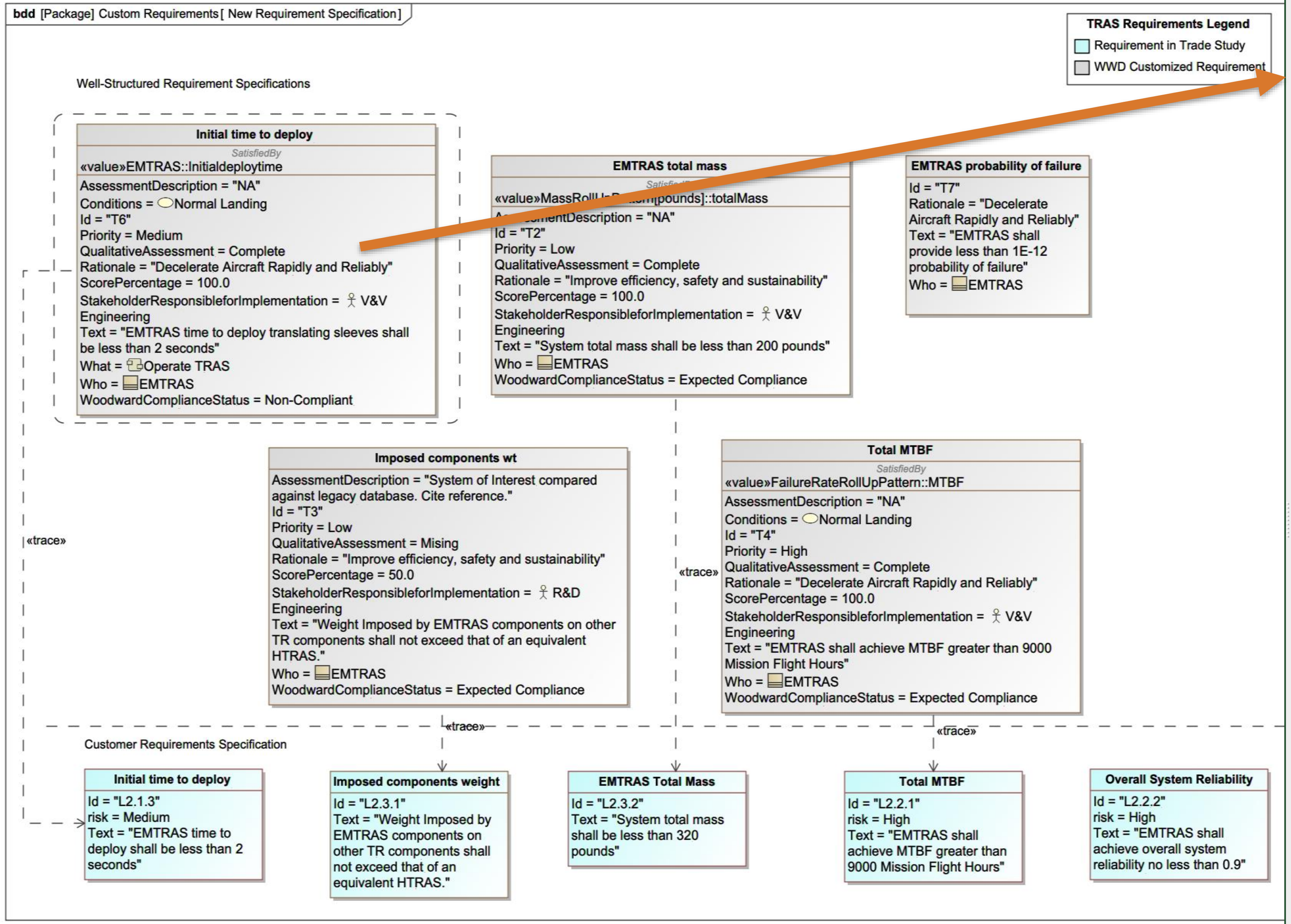


Figure .

Initial time to deploy

WWD Requirement	
Name	Initial time to deploy
Id	T6
Text	EMTRAS time to deploy translating sleeves shall be less than 2 seconds
Applied Stereotype	«» WWD Requirement [Class] [EMTRAS Model::Requirement Properties]
Source	
Qualified Name	EMTRAS Model::Custom Requirements::Initial time to deploy
Verify Method	
Risk	
Assessment Description	NA
Conditions	Normal Landing [EMTRAS Model::A. TRAS Operational::5- Use Cases:
Hours of labor	
How well	
Priority	Medium
Qualitative Assessment	Complete
Quantitative Assessment	
Rationale	Decelerate Aircraft Rapidly and Reliably
Score Percentage	100
Stakeholder Responsiblefor Implementation	V&V Engineering [EMTRAS Model::A. TRAS Operational::1- Stakeholde
Version Number	
What	Operate TRAS [EMTRAS Model::B. TRAS Logical::2- Structure::EMTRA
When	
Who	EMTRAS [EMTRAS Model::B. TRAS Logical::2- Structure]
Woodward Compliance Status	Non-Compliant
Traceability	
Owner	Custom Requirements [EMTRAS Model]
Refined By	
Traced To	L2.1.3 Initial time to deploy [EMTRAS Model::B. TRAS Logical::1- Req
Satisfied By	Initialdeploytime : ISO80000-3 Space and Time::Quantities::time::tim
Master	
Derived	L.3.1.10 Initial time to deploy ND [Cosim-Trade Study Model::B. TRA L.3.1.11 Initial time to deploy RTO [Cosim-Trade Study Model::B. TR L.3.1.12 Initial time to deploy ELD [Cosim-Trade Study Model::B. TRA
Derived From	L1.3.1 Normal Landing scenario [EMTRAS Model::A. TRAS Operationa
Verified By	Verify EMTRAS timing analysis [EMTRAS Model::B. TRAS Logical::6- V

- Specifying attributes tailored to the requirement development and management effort enable requirements to relate with model elements and other requirements within a model.
- Attributes restricts the developer to make specific selection from a predefined list of model elements.
- Ensures that the requirement specifications are complete and unambiguous, consistent, and not duplicated.
- Attribute-centric requirements are more interactive in contrast to the static, text-based requirements,

#	Id	Name	Text	Rationale	Who	What	Conditions	Satisfied By	Refined By	Traced To	Woodward Compliance Status	Assessment Description	Score Percentage
1	T2	T2 EMTRAS total mass	System total mass shall be less than 200 pounds	Improve efficiency, safety and sustainability	EMTRAS			/totalMass : mass[pound]	EMTRAS total mass	L2.3.2 EMTRAS Total Mass	Expected Compliance	NA	100
2	T3	T3 Imposed components wt	Weight Imposed by EMTRAS components on other TR components shall not exceed that of an equivalent HTRAS.	Improve efficiency, safety and sustainability	EMTRAS			EMTRAS		L2.3.1 Imposed components weight	Expected Compliance	System of Interest compared against legacy database. Cite reference.	50
3	T4	T4 Total MTBF	EMTRAS shall achieve MTBF greater than 9000 Mission Flight Hours	Decelerate Aircraft Rapidly and Reliably	EMTRAS		Normal Landing	MTBF : Mission Flight Time	Total MTBF	L2.2.1 Total MTBF	Expected Compliance	NA	100
4	T5	T5 Overall System Reliability	EMTRAS shall achieve overall system reliability no less than 0.9	Decelerate Aircraft Rapidly and Reliably	EMTRAS		Normal Landing	OverallReliability : Real	Overall System Reliability	L2.2.2 Overall System Reliability	Non-Compliant	NA	100
5	T6	T6 Initial time to deploy	EMTRAS time to deploy translating sleeves shall be less than 2 seconds	Decelerate Aircraft Rapidly and Reliably	EMTRAS	Operate TRAS	Normal Landing	Initialdeploytime : time[second]		L2.1.3 Initial time to deploy	Non-Compliant	NA	100
6	T7	T7 EMTRAS probability of failure	EMTRAS shall provide less than 1E-12 probability of failure	Decelerate Aircraft Rapidly and Reliably	EMTRAS			Probabilityoffailure	EMTRAS probability of failure				

Analyze Interactively Requirement Changes

- Providing visibility into assessing change adds value in understanding the impact and efficiently managing those changes.
- Interactive model-based requirements enables to trace the change in model elements through upstream and downstream relationships, including higher-order relationships.
- Enables a collective understanding of system aspects that have been affected, thus improving communication and reducing the time and effort taken to report the status of change impact.
- Savings in hours of labor to perform a requirement change impact assessment.

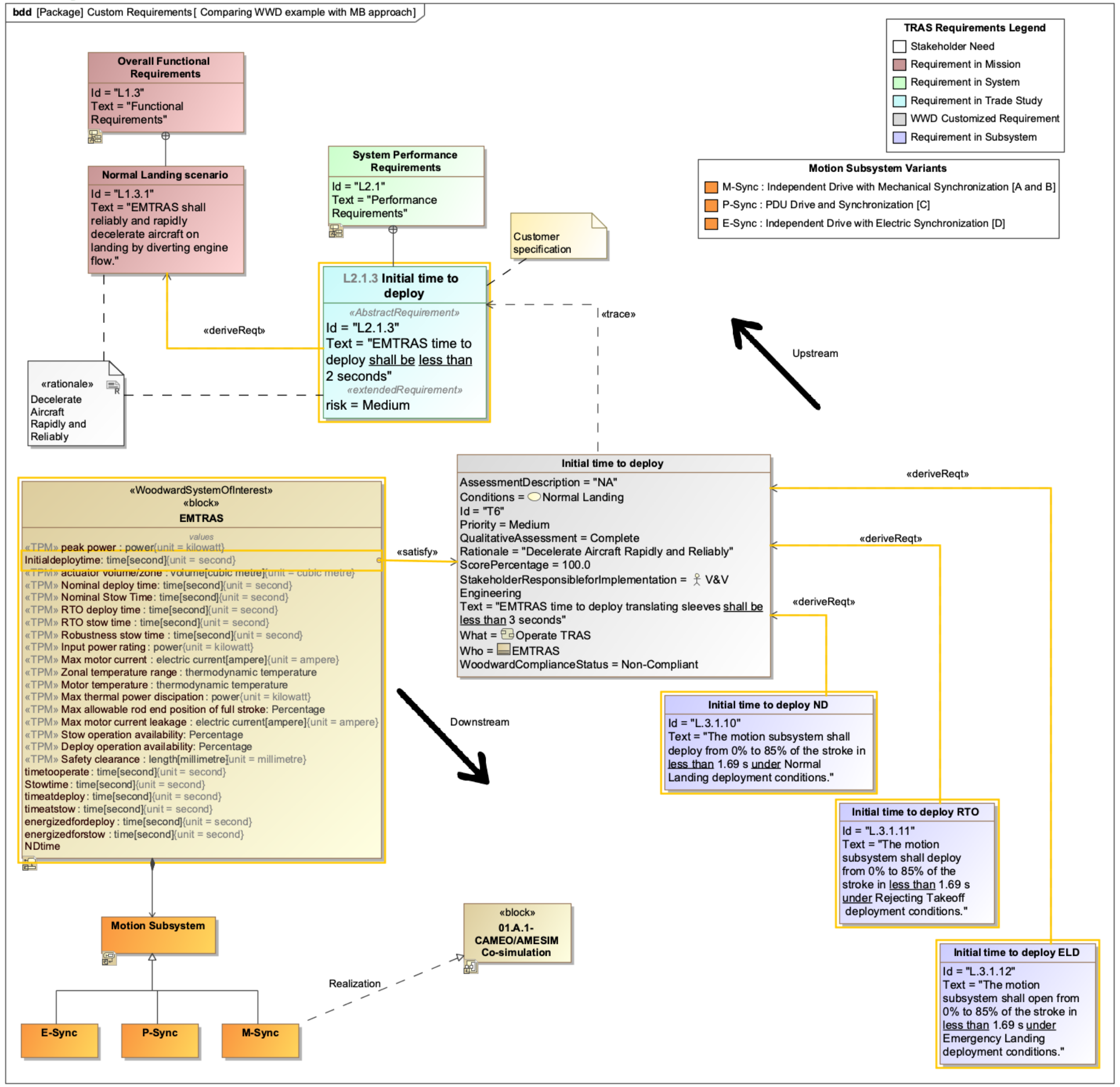


Figure 1

- Any missing gap/redundancy is identified to improve the requirement specification further.
- Helps identify and validate whether a requirement is necessary or redundant.
- In conclusion, the existing text-based approach to develop and manage requirements is improved by attribute-based techniques that allows to perform quality more interactively and ensures that the gaps are filled for the completeness of requirements.

(I1) Need for a cultural shift/transformation from documents to models within organizations.

(I4) Need to generate data and technology insight from a unified hub of true system information (technical truth) for early decision support capability.

(I5) Understanding the value of applying MBSE tools, and its usage to perform system engineering activities.

5. Conclusion & Future Work

- 5.1 : Key Takeaways
- 5.2 : The Path Forward

Conclusion

- This thesis demonstrates an approach to implement MBSE for supporting the system development effort in technology/platform projects.
- The MBSE framework and methodology was successfully applied to a thrust reverser actuation system concept by specifying the system aspects from abstract to detailed within the operational, logical, and physical levels of abstraction.
- The proposed framework also filled the gap for channeling data between a PLC process and a unified system model through data modeling resulting in the coordination of the PLC phase process deliverables/outcomes with model-derived artifacts.
- The tailored framework also exposed the aspects of system verification and validation integrated within the model.
- The TRAS model was synthesized to analyze architecture alternatives.
- Requirements and their dependencies with model elements were analyzed to assess traceability.
- Deficiencies in current methods of requirement development were identified and an attribute-based approach was augmented to transform poorly written text-based requirement to well-structured requirements that could be assessed more interactively.
- Overall, this thesis demonstrates how model-based implementation can be targeted to identify capabilities and develop them to address a span of challenges and issues faced in today's complex system development.

Future Work

1. Further coordinating PLC Phases 200, 300, 400 with model-derived artifacts and automating the process model for gate reviews.
2. More comprehensive and automated model-based requirements to help guide requirements development as well as investigate problems with requirements
   - Creation of custom rules (profile of validation rules) to assess/test the quality of requirement statements.
   - Automatic generation of natural language requirement statements from the model attributes.
3. Full integration of simulation models with architecture model for engineering analysis and requirements verification.
   - Detailed interface modeling, safety and reliability analysis using RAAML extension to SysML,
   - integration of external testbed models to establish traceability with system requirements

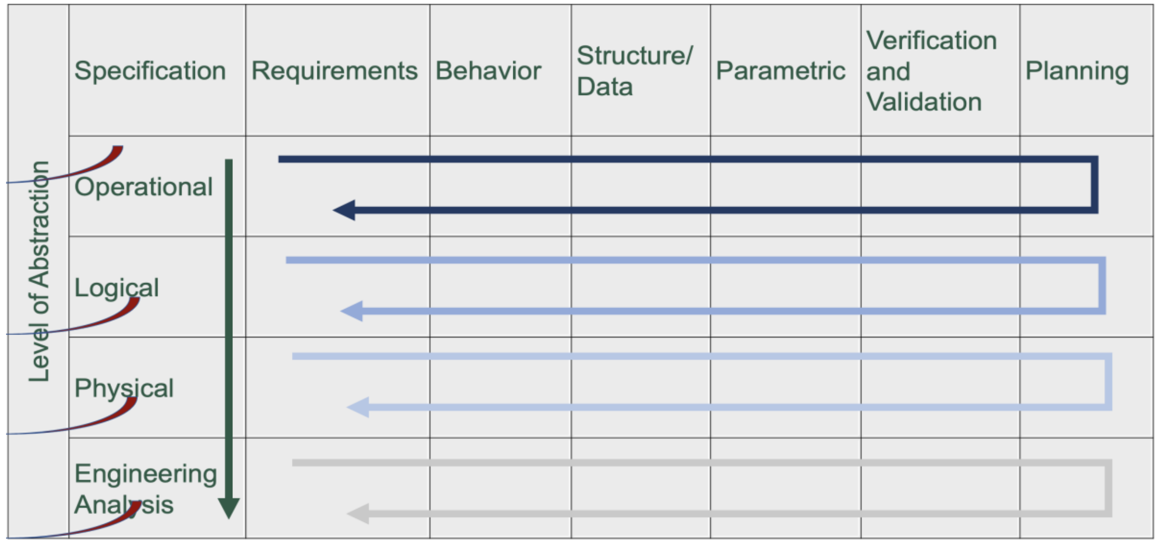


Figure . Automatic generation of refined requirements from the needs and requirements development framework

4. Model-based verification and validation for virtual prototyping (fifth column)
   - Introduce verification planning capabilities with the development of custom stereotypes

Research Publication

- Co-Author on a manuscript in the journal *Systems Engineering*.
  - Dustin S. Birch, P.E., Jayesh Narsinghani, Daniel Herber, Ph.D., Thomas H. Bradley, Ph.D., Human Factors Hazard Modeling in the Systems Modeling Language. *Systems Engineering*. 2021;

  (Evaluation of a standardized stereotype-based approach that enables a human factors hazard model methodology to be implemented within MBSE)
- Planned conference publication submissions:
  - Model-Based Requirements Development
  - System Requirement Verification with Linked Simulation Models

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Thank you

Colorado State University

Questions?