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Meet-in-the-Middle Approach for Modeling Complex Systems #359

Kathryn Wesson Dassault Systemés & ERAU, Prescott

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Hello…

from Northern Arizona!

Kathryn Wesson

Industry Process Consultant / Dassault Systemes

Adjunct Professor College of Engineering / ERAU

c 928-273-6287

e Kathryn.wesson@3ds.com

Today's Agenda

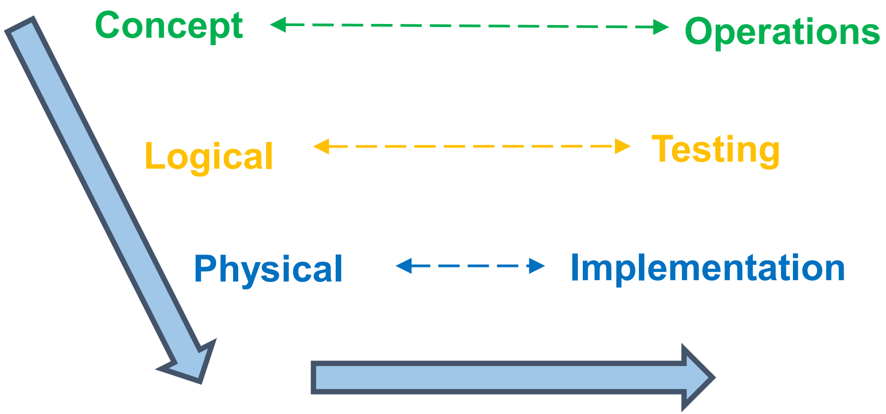
- Why is Everything Always Top-Down?
- Overview of this Research Project
- Top-Down Frameworks
- Meet-in-the-Middle
- Tailoring MagicGrid
- Modeling an SRM for Discovery
- Proposed Approach
- Including Safety & Reliability
- Research Findings
- The Way Forward

Systems Engineering Life Cycle

Why is everything always "Top-Down?"

- Historically systems modeling is approached with "**top-down**" methodologies
- All training material in industry is also "**top-down**"
- Sample Models and Guidance Material are "**top-down**"
- Very few initiatives today are being developed from Concept, "**top-down**"
- Most system development is an **upgrade to a system**, or V&V of a system in operation today.

Systems Engineering "Vee"



Project Research

- Collaboration with Dassault Systemes and Embry-Riddle Aeronautical (ERAU) Prescott, Arizona
  - Summer Research with the Undergraduate Research Institute (URI)
  - 5 Engineering Students of Varying Disciplines (Aerospace and Mechanical)
  - Students Pursuing Minors in Systems Engineering
- How to approach modeling an **As-Is/As-Built** system using current modeling methodologies.
- Literature review revealed little to no documentation, step-by-step guides, or guidance on how to approach an MBSE effort for an As-Built System
- This project defined several research questions
- Students were able to attack these challenges with little no bias on how to attack this challenge
- A scenario was created to create the mindset needed to support this work:
  - **Solid Rocket Motor w/ Igniter Trade Analysis for Upgrade**

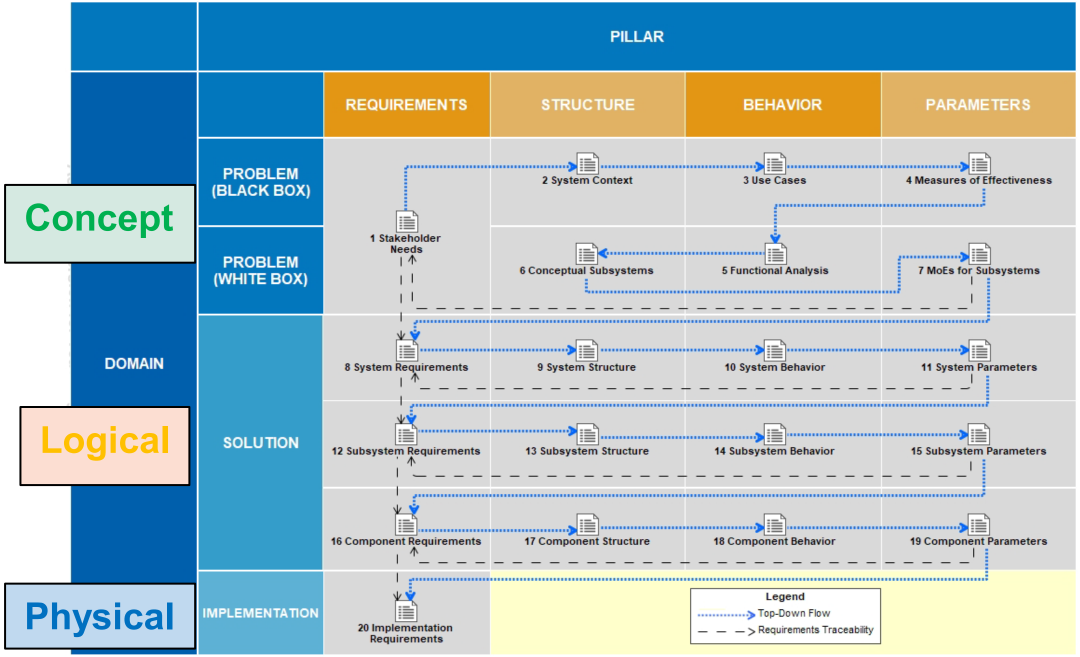
Research Questions:

- "Why do I need to conceptualize a system I already have?"
- "Why do I need a Conceptual and a Logical Domain if I already have a system?"
- "Why can't I just start importing physical data into a model?"
- "Why can't I go **Bottom-up/Reverse Engineer** the system into my model?

Research Questions were also formulated around observations of deployment of MBSE in industry.

Top-Down MagicGrid Framework V2

- Typically MBSE is attempted Top-Down using a framework such as MagicGrid
- Concept to Logical is most common
- It is not common to model the Physical Domain
- Except when you have an as-is/as-built system!
- No guidance on the Physical Domain, or attempting to Reverse Engineer into a model.
- Physical domain is historically captured in Documents, Databases, CAD models, and Software Repositories.



Meet-in-the Middle

Nothing Documented in Aerospace, Nuclear, or Missile Systems Yet!

- In systems engineering, traditional development processes often follow a top-down approach, progressing from conceptual design to physical implementation. However, when upgrading existing systems, a "meet-in-the-middle" strategy—integrating both top-down design and bottom-up analysis—can be more effective. This approach facilitates the alignment of new system requirements with existing system capabilities, enabling more seamless upgrades.
- **Documented Meet-in-the-Middle Approaches:**
  - **Human Systems Integration (HSI):** HSI is an interdisciplinary approach focusing on the interfaces between humans and technical systems. It emphasizes integrating human considerations into system design and upgrades, effectively combining top-down requirements with bottom-up human factors analysis. This integration ensures that system upgrades are user-centric and operationally effective. Wikipedia
  - **System of Systems Engineering (SoSE):** SoSE addresses the challenges of integrating multiple independent systems into a cohesive whole. It employs a meet-in-the-middle approach by considering both overarching system objectives (top-down) and the capabilities of constituent systems (bottom-up). This methodology has been applied in various domains, including defense and transportation, to achieve effective system upgrades. Wikipedia
  - **Scholarly Documentation of Successful Applications:**
  - Several scholarly articles have documented the successful application of meet-in-the-middle approaches:
  - **Railway Modernization:** Research published in the *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit* detailed the development of system models to facilitate the adoption of innovative technologies in Great Britain's railways. This study employed a meet-in-the-middle strategy by integrating top-down system requirements with bottom-up analysis of existing railway operations, leading to successful modernization efforts. Wikipedia
  - **City Waste Management Systems:** A novel methodology utilizing middle-out, model-based systems engineering techniques was applied to the development of city waste management systems. By balancing top-down policy directives with bottom-up operational data, this approach led to more effective and sustainable waste management solutions. Wikipedia
- These examples illustrate the efficacy of meet-in-the-middle approaches in upgrading complex systems by harmonizing new requirements with existing capabilities.

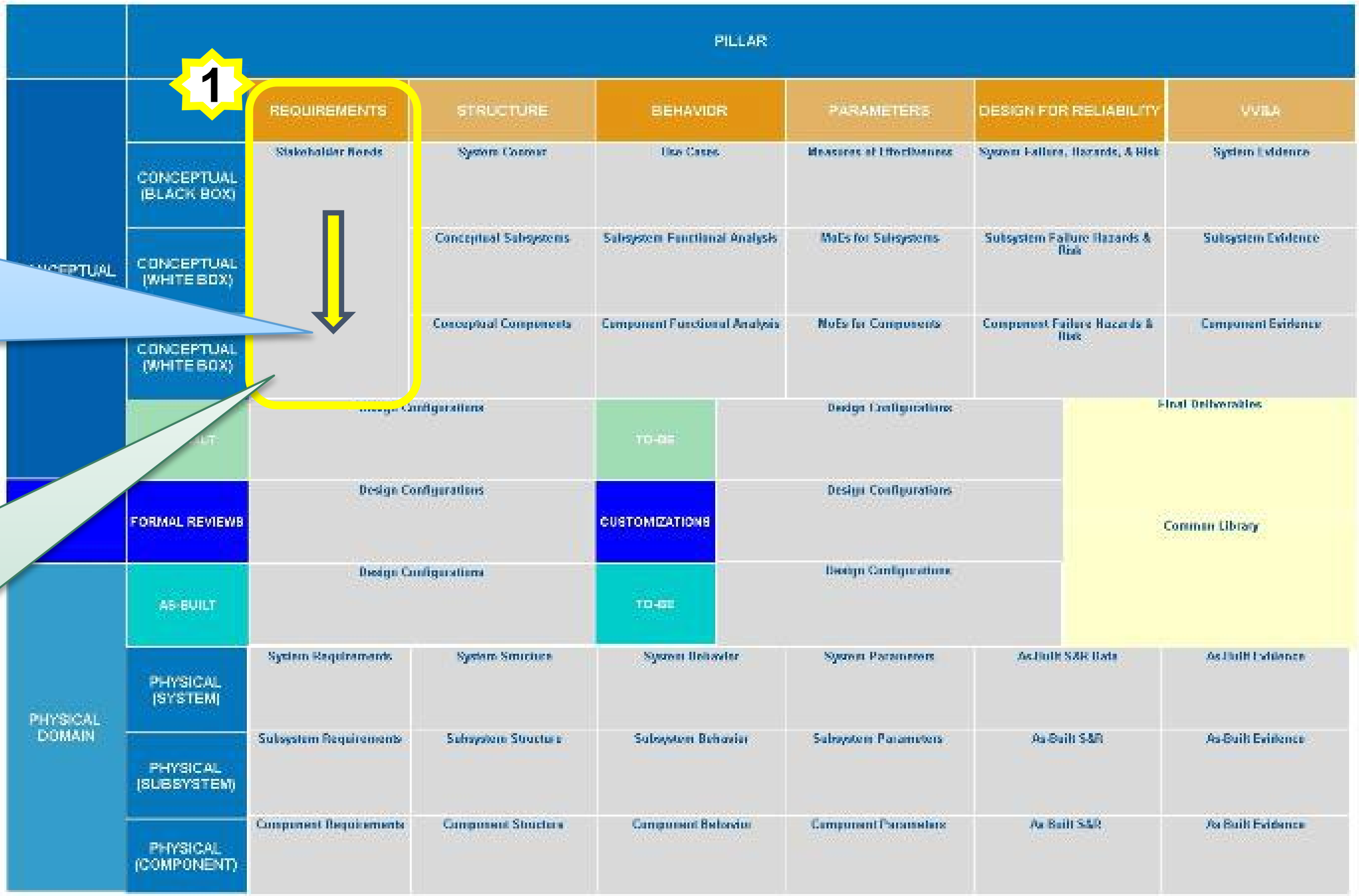
Meet-in-the-Middle Tailored MagicGrid

	PILLAR						
		REQUIREMENTS	STRUCTURE	BEHAVIOR	PARAMETERS	DESIGN FOR RELIABILITY	VV&A
CONCEPTUAL DOMAIN	CONCEPTUAL (BLACK BOX)	Stakeholder Needs	System Context	Use Cases	Measures of Effectiveness	System Failure, Hazards, & Risk	System Evidence
	CONCEPTUAL (WHITE BOX)		Conceptual Subsystems	Subsystem Functional Analysis	MoEs for Subsystems	Subsystem Failure Hazards & Risk	Subsystem Evidence
	CONCEPTUAL (WHITE BOX)		Conceptual Components	Component Functional Analysis	MoEs for Components	Component Failure Hazards & Risk	Component Evidence
	AS-BUILT	Design Configurations		TO-BE	Design Configurations		Final Deliverables
	FORMAL REVIEWS	Design Configurations		CUSTOMIZATIONS	Design Configurations		Common Library
PHYSICAL DOMAIN	AS-BUILT	Design Configurations		TO-BE	Design Configurations		
	PHYSICAL (SYSTEM)	System Requirements	System Structure	System Behavior	System Parameters	As-Built S&R Data	As-Built Evidence
	PHYSICAL (SUBSYSTEM)	Subsystem Requirements	Subsystem Structure	Subsystem Behavior	Subsystem Parameters	As-Built S&R	As-Built Evidence
	PHYSICAL (COMPONENT)	Component Requirements	Component Structure	Component Behavior	Component Parameters	As-Built S&R	As-Built Evidence

1 Establish Stakeholder Needs

Import Data via Plug-ins, Connectors, or Excel Import today.

Tomorrow, use AI technology to help with the heavy lifting.



Use the Blank MagicGrid Sample Model to Help Build Your Tailored Index.

Stakeholder Needs

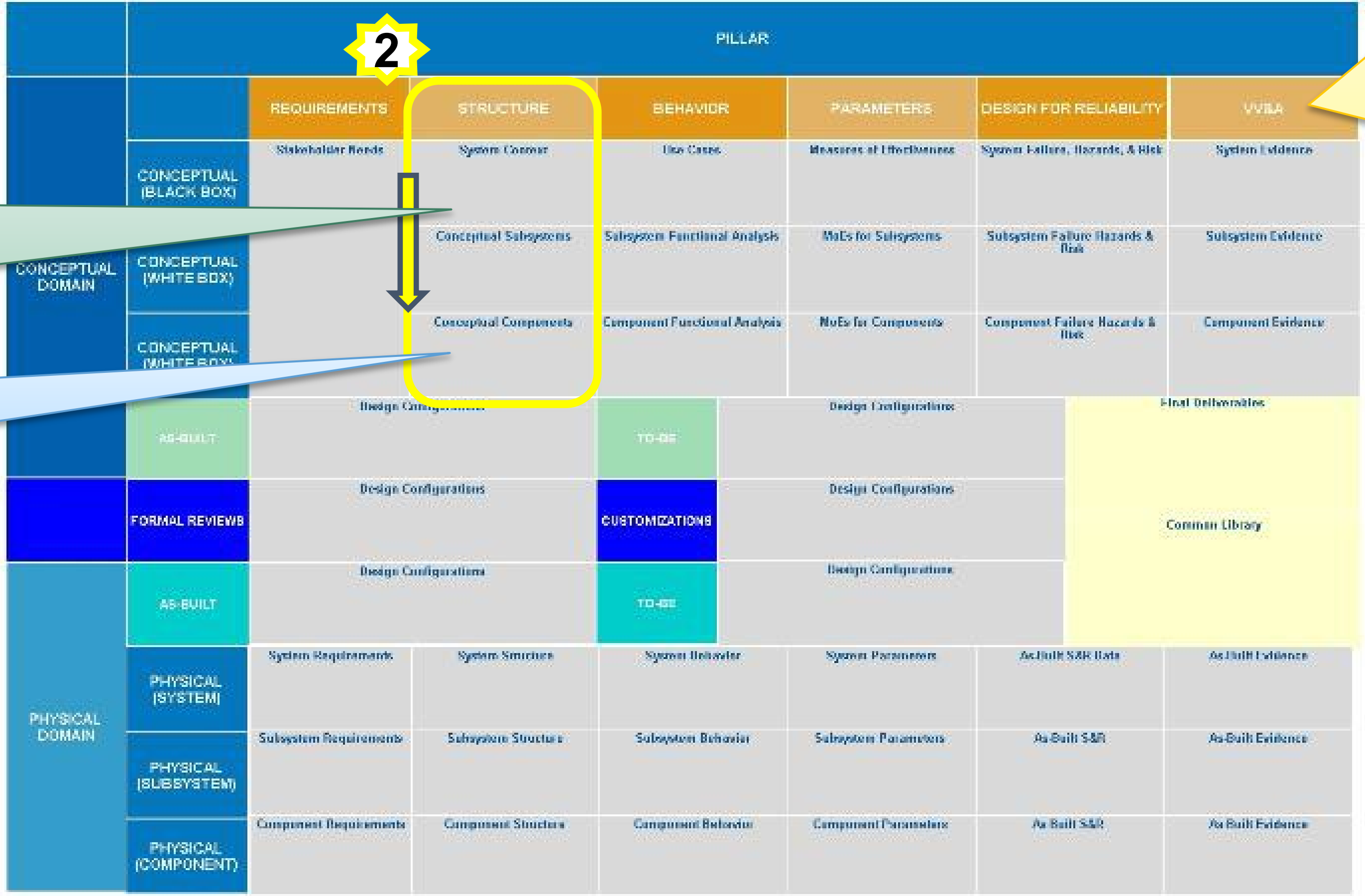
Why Populate Stakeholder Needs?

- Early VV&A, Completeness Checks
- Customer and Industry Compliance
- Requirement Development for Upgrades
- Traceability in a Source of Truth
- Assessment of Mission Level Changes
- Traceability and Evidence of Standards and Industry Design Constraints

2 Define the Conceptual Architecture

Define SysML Compliant Block Structure

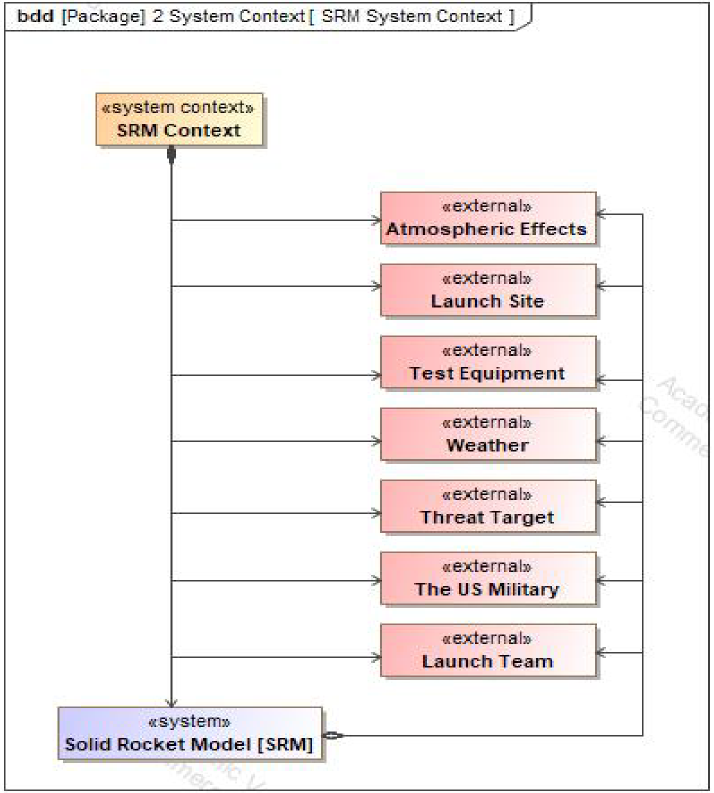
System, Subsystem, and Component Levels



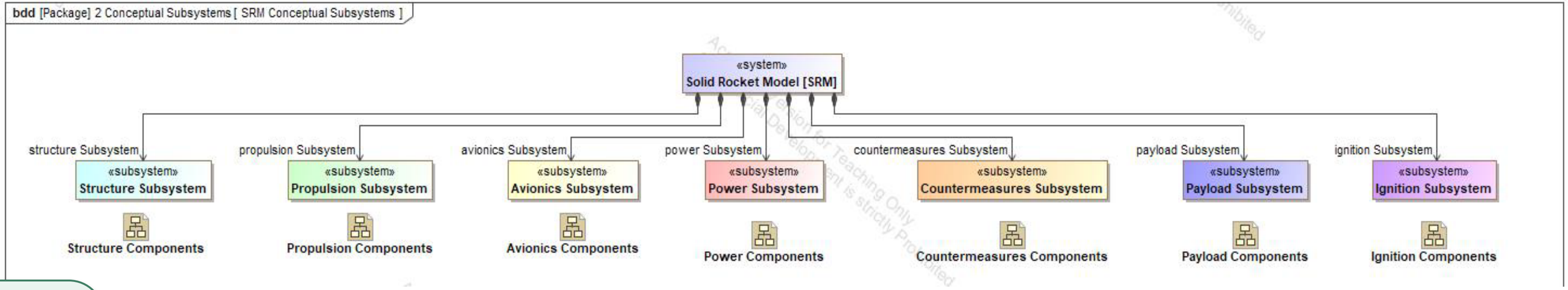
This Block Structure is Imperative to Establish the Rest of the Model and its Organization

SYSTEM CONTEXT

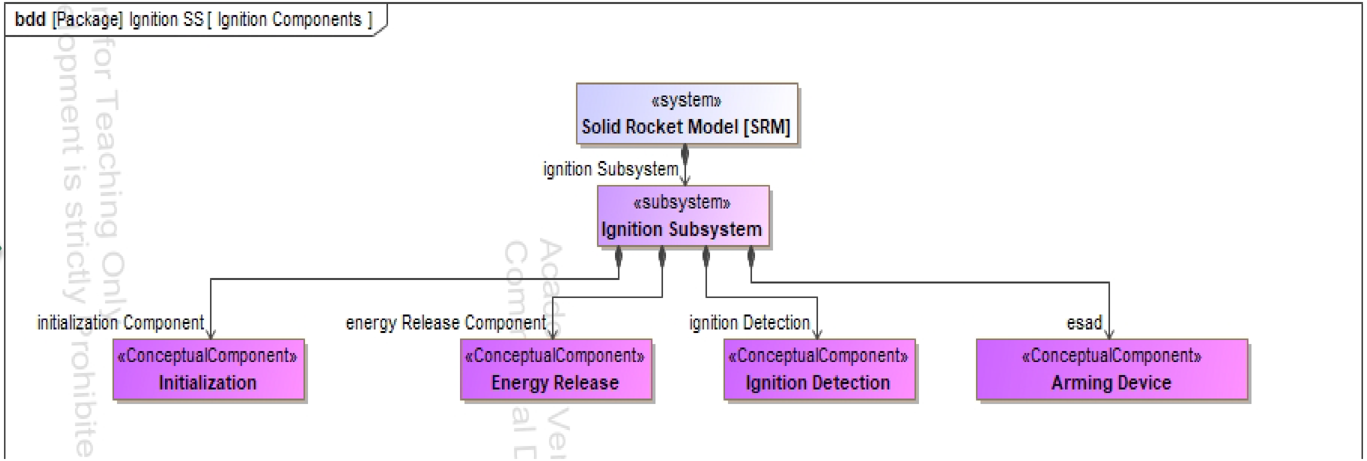
- The System Context establishes the initial blocks of the system and its external connections
- This set of blocks defines the Context of the System of Interest and the Package Structure
- It enables capture of the external interfaces and functionality of this system today (the as-built) as it interacts with the environment and other systems/entities



Conceptual Subsystems & Component Decomposition



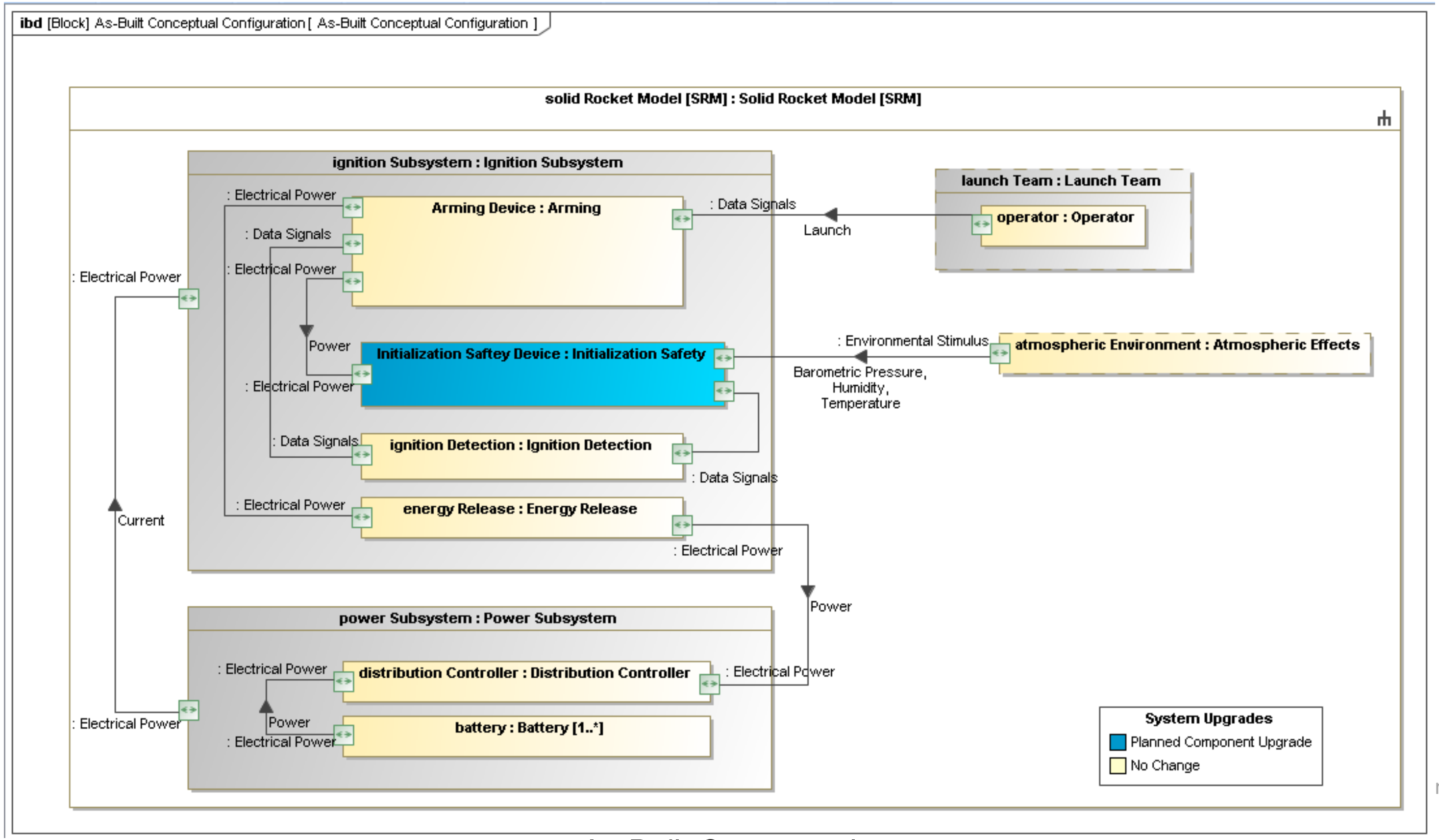
These Blocks help define package structure, libraries, and the further context of the System of Interest



Conceptual System Decomposition

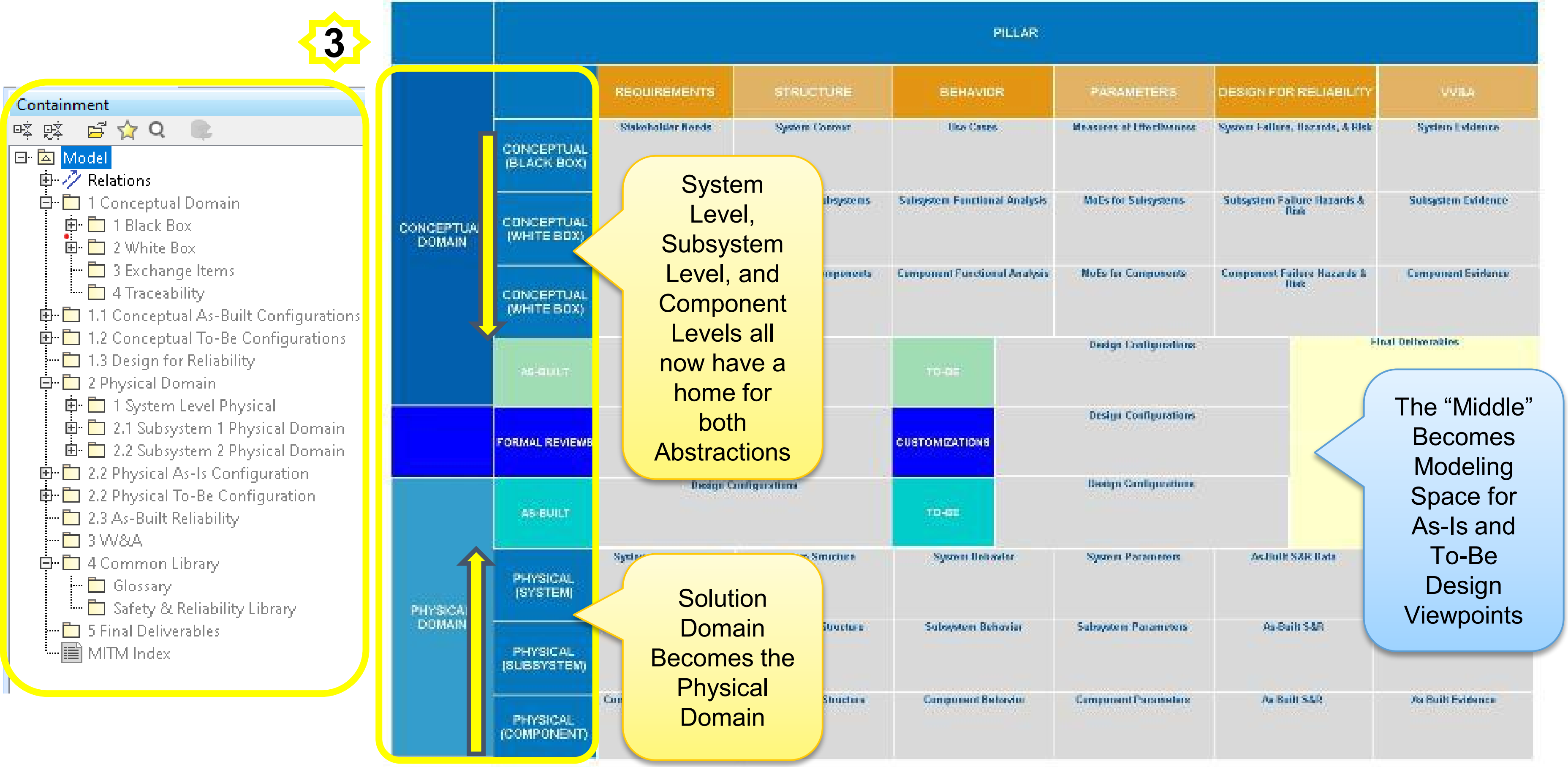
Conceptual Configuration

Planned upgrade for the Ignition Safety Device to New Technology

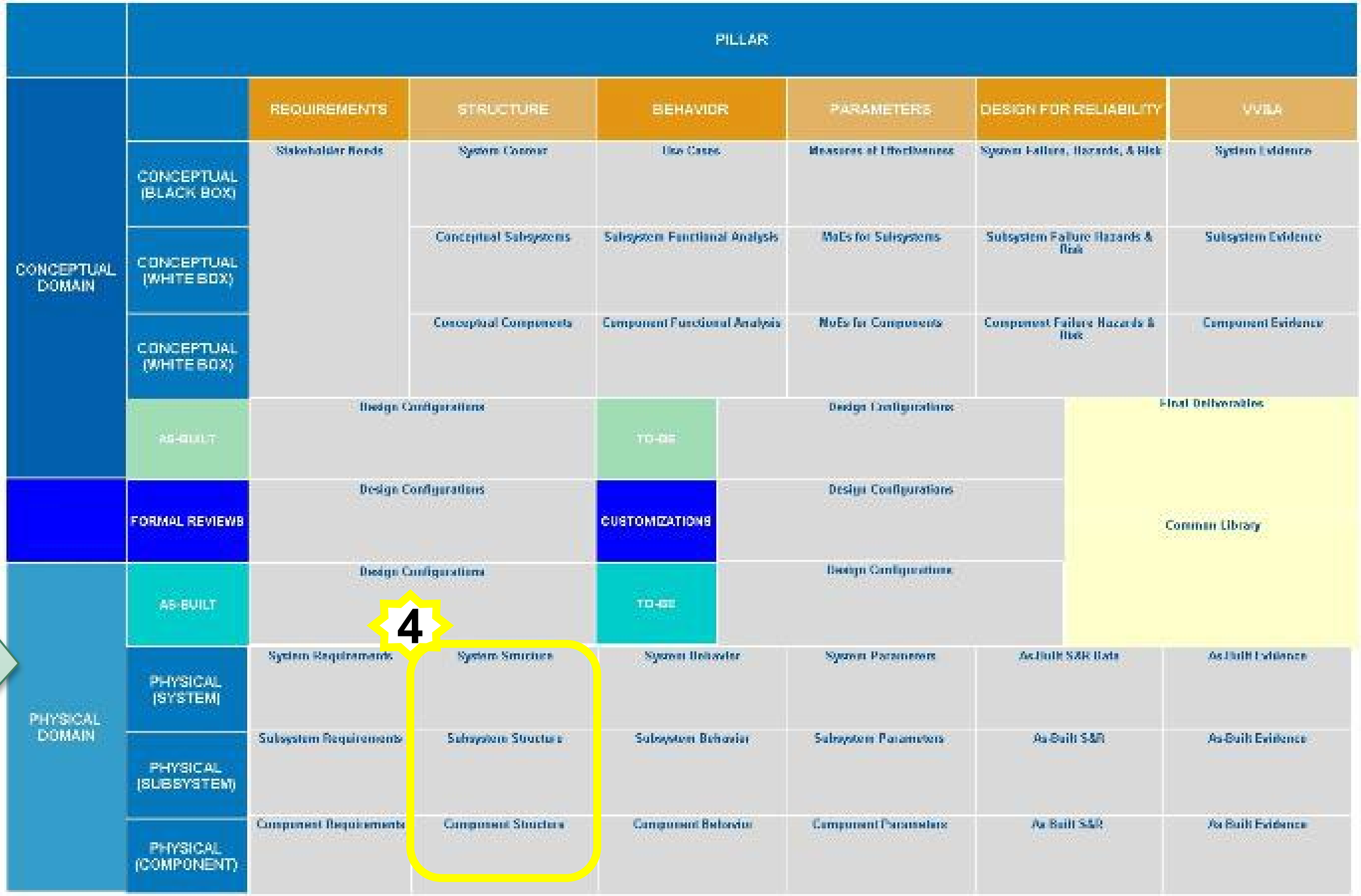


As-Built Conceptual

3 Use Conceptual Architecture to “Inform” Package Structure



4 Define the Physical Architecture

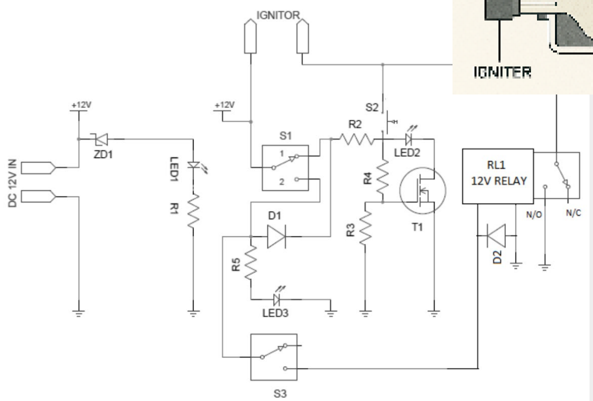


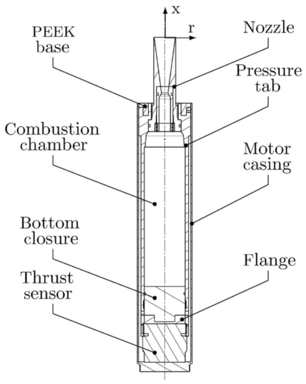
The Physical set of Blocks Provide an Architecture of “Great Detail” of the system as it is today.

Think of the Block Architecture as a place to store data at this Abstraction Level.

Physical Domain Data in SysML

- The **<u>Physical Domain</u>** is not typically modeled in **"Top-Down"** model development
- Why?
  - CAD models, Numerical Models, Prototypes, and Software Repos are more effective at communicating physical design
  - These were likely made before the MBSE effort was implemented
  - What does the system design look like before SysML?
    - Documents!
- The Physical Domain is what most projects want to import into a SysML Model
  - The Wiring Diagrams
  - Bill of Materials (BOMs)
  - System Design Documents (SDDs)

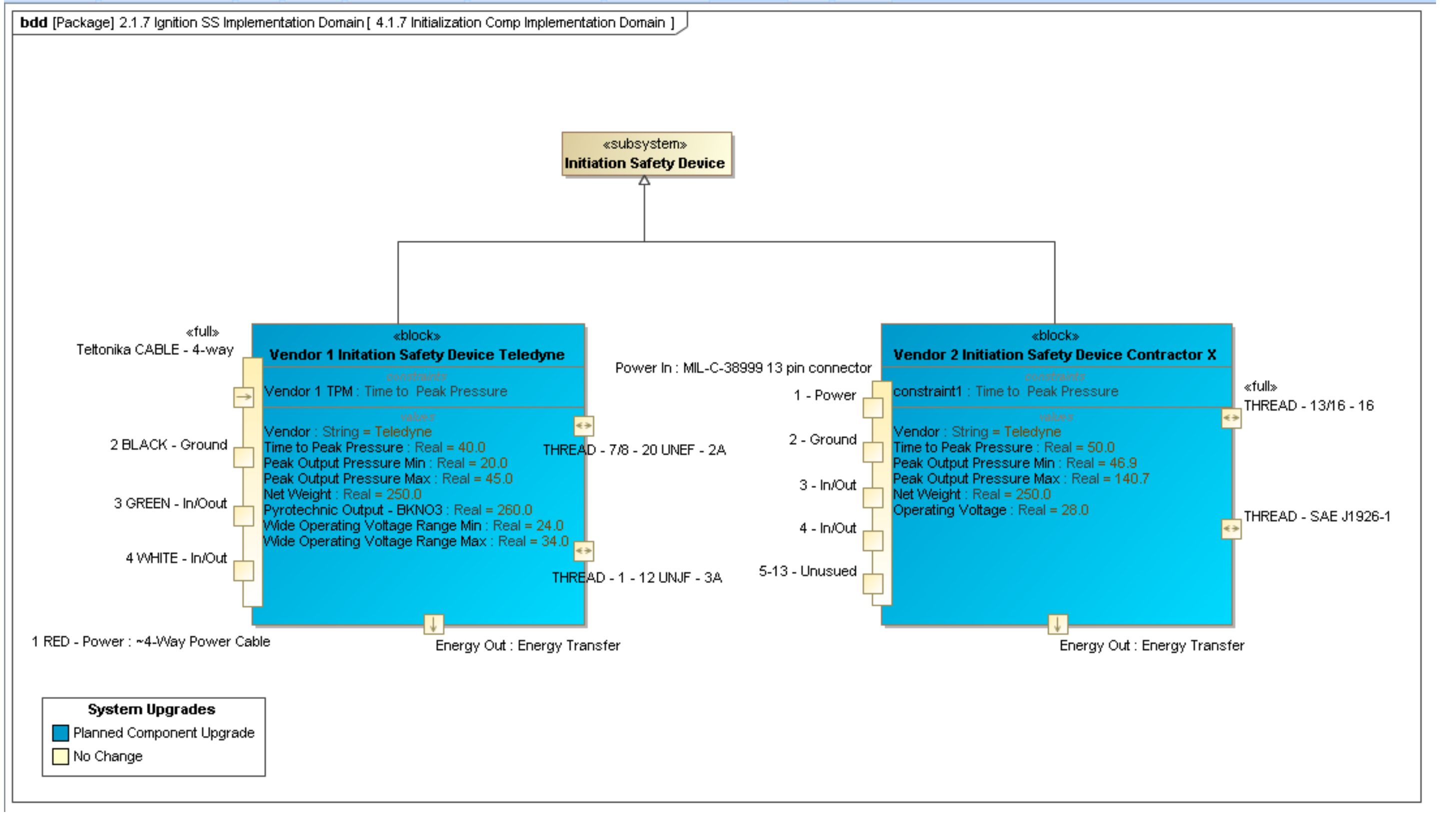




Part	Quantity	Price
Drill motor	1	$99.00
PLA filament ~400 g	1	$10.00
NinjaFlex filament ~20 g	1	$1.60
12-V DC motor 200 rpm	1	$14.99
Caster bearings	3	$2.99
Speed controller	1	$8.45
Power supply	1	$15.84

Physical Configuration – to-Be (Proposed)

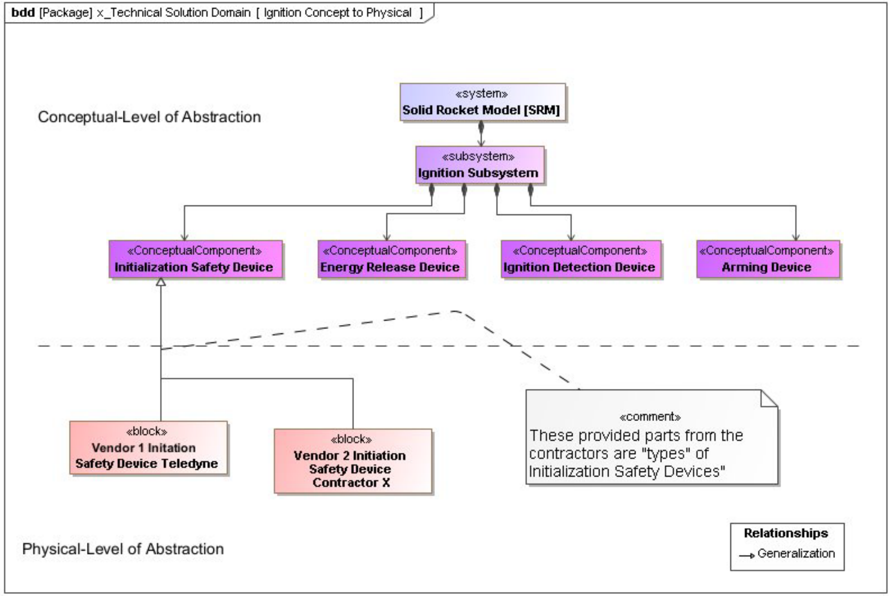
Which vendor provided component will be implemented into the new To-Be Design?



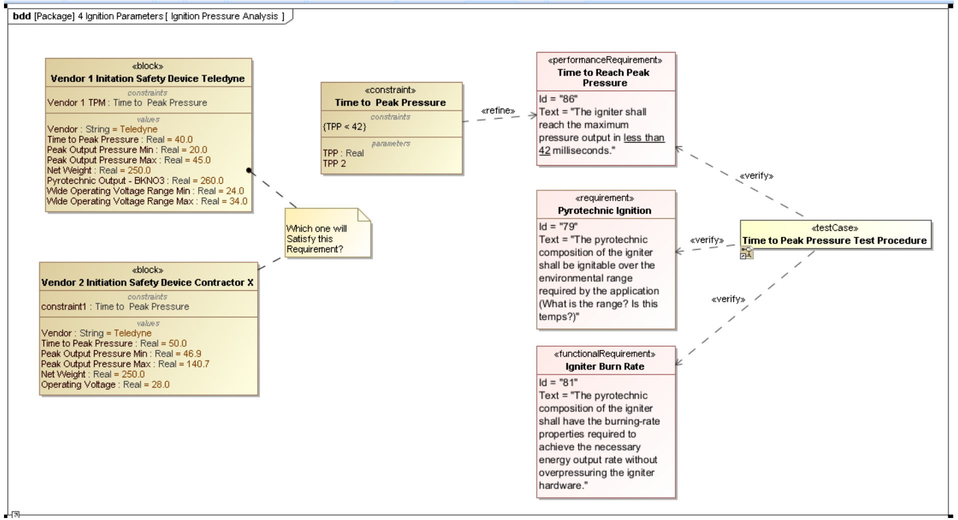
Igniter Upgrade Example Physical Domain - Trades

UPGRADED INGNITER SCENARIO

Design, Trades, and **Early** VV&A

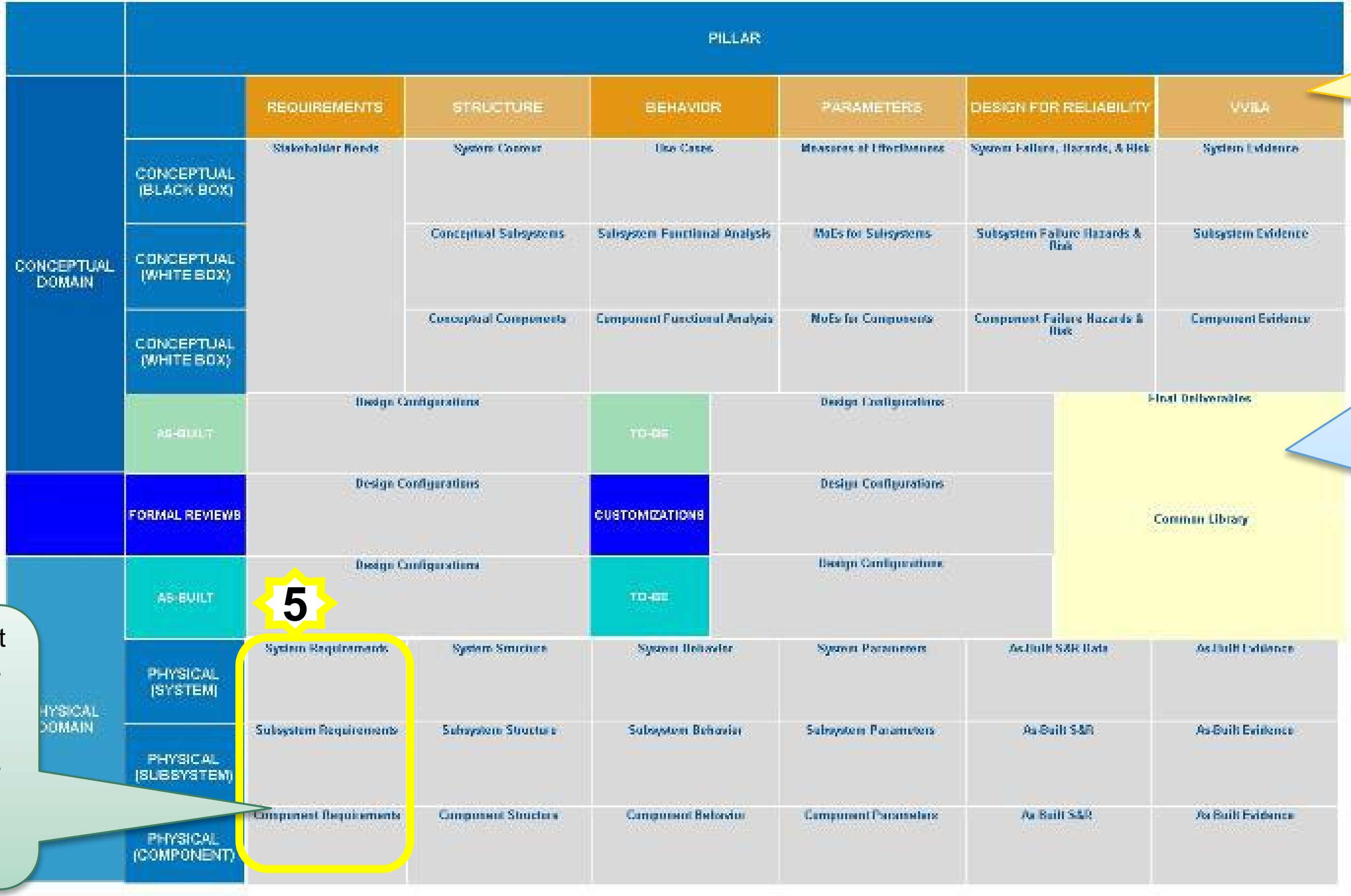


Physical Design Domain - Ignitor



Early V&V of New Design

5 Import System Requirements (As-Built Requirements into the Physical Domain)



Use the Model as your "Source of Truth!"

Utilize the MBSE Tool for Requirements Documentation Output for the Upgraded System.

Import As-Built Requirements to Manage New Requirements Development, Traceability , and VV&A

Identify Your Modeling Needs/Outputs

Establish the Focus of the Modeling Effort. What needs to be output from the model? What needs to be upgraded?

- **6 Use the Conceptual Domain to:**
  - Model the As-Built System for Gap Checking and Requirements Completeness
  - Use the Model for Design for Reliability (Top-Down)
  - Construct As-Built and To-Be Design Configurations from the Conceptual Abstraction Level
    - To upgrade a system evidence must be presented in formal review from the model.
  - Utilize Parametric, Queries, and Validation Rules to Analyze "Deltas" Between As-is and To-Be
- **7 Use the Physical Domain to:**
  - Import Inventory Lists, Bill of Materials (BOMS), or Logical and Functional Physical Data from 3DX
  - Construct As-Built and To-Be Design Configurations from the Physical Abstraction Level
  - Perform new item level analysis for Design, Safety, Reliability, and Risk
    - To upgrade a system evidence must be presented in formal review from the model.

Note:

- The basic modeling data which has been constructed up to this point will support further SysML analysis where it is desired in the program.

6 & 7 Populate Model with Data that Supports the Upgrade of the System

Conceptual Model Top-Down "Discovery" Identify Gaps!

Physical Domain Trade Analysis and Early Verification of Upgrades

8 Design for Reliability (FMEA, Hazards, Risk, and Safety Requirements Analysis)

Use DfR for analysis of new system upgrades.

Cameo Safety & Reliability Analyzer Plug-In Coupled with Customizations for Your Domain

8 Design for Reliability

Failure Analysis of Ignition Subsystem

Criteria

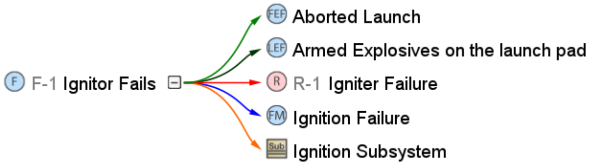
Element Type: FMEA Item ... Scope (optional): FEMA Elements ... Filter:

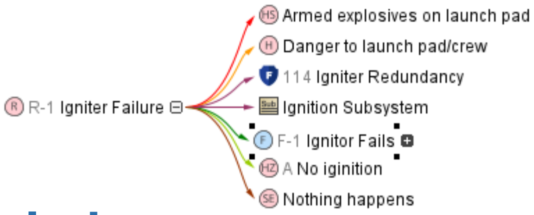
#	Id	Name	Classification	Failure Mode	Item	Local Effect Of Failure	Final Effect Of Failure	SEV	Mitigation	Requires Hazard Analysis	Hazard Analysis Reference
1	F-1	Ignitor Fails	electrical	Ignition Failure	Ignition Subsystem	Armed Explosives on the launch pad	Aborted Launch	5	114 Igniter Redundancy	true	R-1 Igniter Failure
2	F-2	Hard Start	mechanical	Ignition Failure	Solid Rocket Model [SRM]	Too high thrust	Uncontrolled Launch	3	117 Controlled Ignition 118 Fuel Grain Control	true	R-2 Total System Failure
3	F-3	Soft Launch	mechanical	Ignition Failure	Solid Rocket Model [SRM]	Insuficient thrust	Failed launch	3	116 Complete Ignition 118 Fuel Grain Control	true	
4	F-4	Rapid Unscheduled Disassembly	mechanical	Ignition Failure	Energy Release	Too high thrust	Explosion	5	118 Fuel Grain Control 117 Controlled Ignition	true	

Criteria

Element Type: Safety Analysis Item ... Scope (optional): Failures ... Filter:

#	Id	Initiating Cause	FMEA Reference	Hazard	Sequence Of Event	Hazardous Situation	Harm
1	R-1	Igniter Failure	F-1 Ignitor Fails	A No ignition	Nothing happens	Armed explosives on launch pad	Danger to launch pad/crew
2	R-2	Total System Failure	F-2 Hard Start	B Over ignition	To much dV	Uncrontolled launch	Loss of rocket





FMEA & Risk Analysis

9 Populate Viewpoints and Output Design Evidence from the Model

Bring Configurations into the "Middle" for Finalization and Formal Review.

Research Findings & Recommendations

Research Questions

1. "Why do I need to conceptualize a system I already have?"
2. "Why do I need a Conceptual and a Logical Domain if I already have a system?"
3. "Why can't I just start importing physical data into a model?"
4. "Why can't I go **Bottom-up/Reverse Engineer** the system into my model?

Research Answers

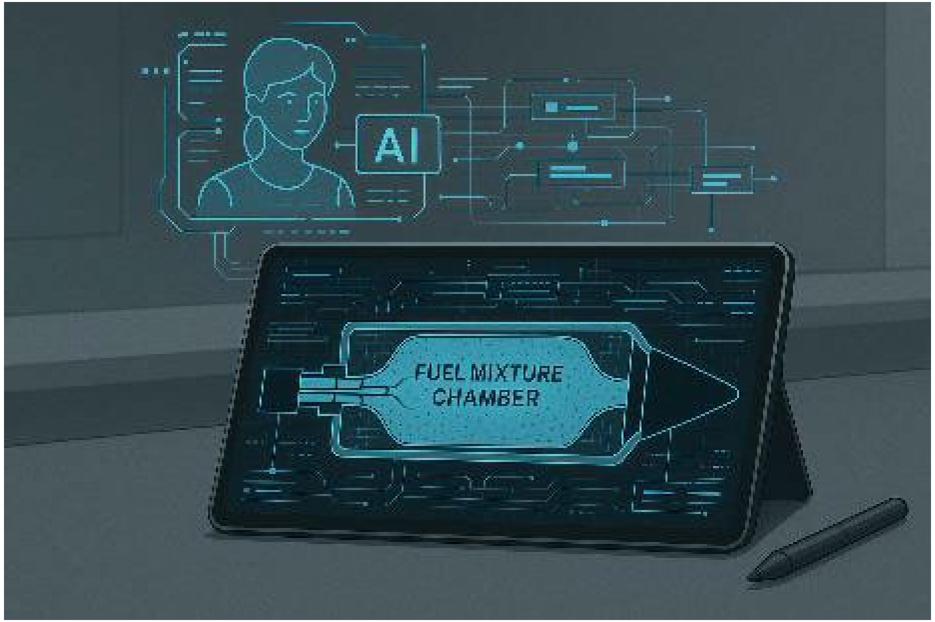
1. You need to document, understand, and use the Conceptual Architecture to Inform the Model Organization.
2. The Logical Domain should be transformed into the Physicall Domain, A "Solution" already exists.
3. No Framework today addresses the Physical Domain in SysML Modeling. You need to Organize the Physical Domain in a way effectively employ Reuse, Language Constructs, and Compliant SysML View Points.
4. SysML was developed with Top-Down model development in mind, there is little defined in the physical domain to support an efficient "way up."

Recommendations

- Gain full understanding of the Levels of Abstraction
- Identify Scope of Modeling Effort and Data Sources
- Tailor A Framework to Manage the levels of abstraction
- Create a new place in the model to manage viewpoints, model evolution, and analysis of the upgraded system.
- Stand up Modeling Plan and Configuration Management early to mange modeling workload and outputs

What is The Way Forward?

- SysML V2 Transition
- Utilize Generative AI Technology for Rapid Model Development



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