ADVANCED ORBITAL MANUFACTURING SYSTEM

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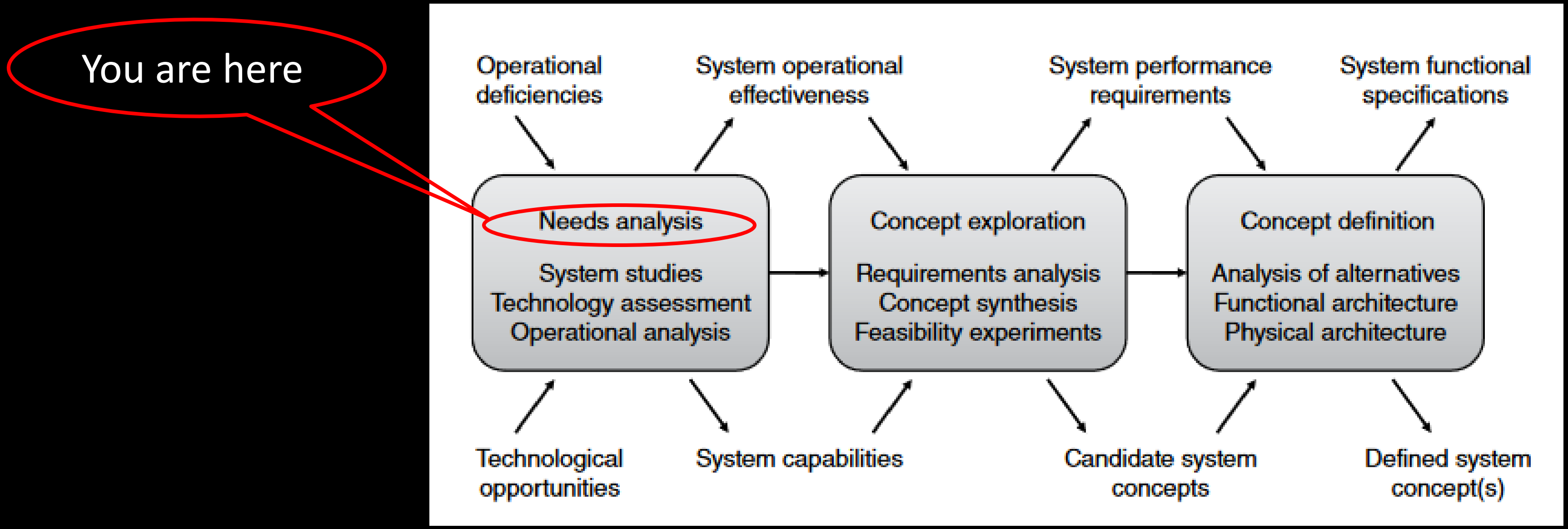
26 NOVEMBER 2024

OVERVIEW

- Introduction
- System Needs Analysis
- Requirements Analysis & Concept of Operations
- Functional Analysis
- Conceptual Design
- Trade Study
- Test and Evaluation Plan
- Risk Management
- A-Specification
- Capstone Wrap-up

BIOGRAPHY

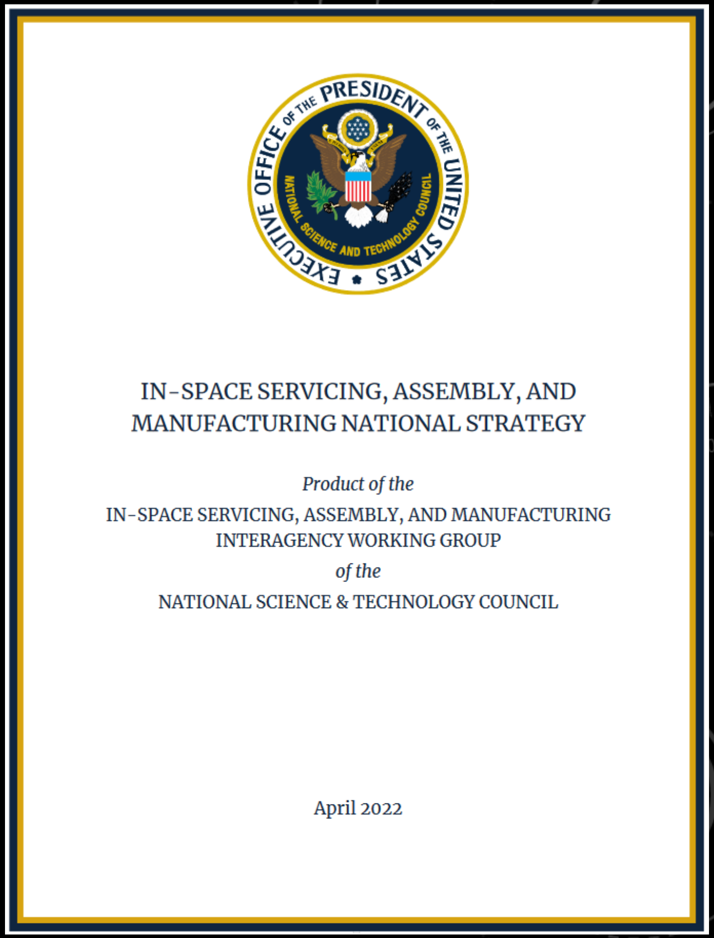
- **Education:**
  - SOON: MS in Systems Engineering from Johns Hopkins University.
  - BS in Mechanical Engineering from Rochester Institute of Technology.
- **Professional Experience:**
  - Senior Member of Technical Staff at Draper:
    - Developing interface control documents and subsystem requirements for VLEO satellite supporting DARPA's Otter program.
    - Using Model-Based Systems Engineering (MBSE) to design adaptable architectures for guidance systems in US Navy programs.
  - Technical Project Manager at Boston Engineering Corporation:
    - Developed EOD ROV and magnetic ballast tank inspection robot for US Navy.
    - Led the creation of automated quality assurance systems and anchoring software for autonomous vehicles.
  - US Air Force Officer:
    - Contributed to programs like Minotaur launch, Falcon 9 certification, and X-37B recovery.
- **Hobbies:**
  - Woodworking, collecting vinyl records, reading, banjo



SYSTEM NEED ANALYSIS

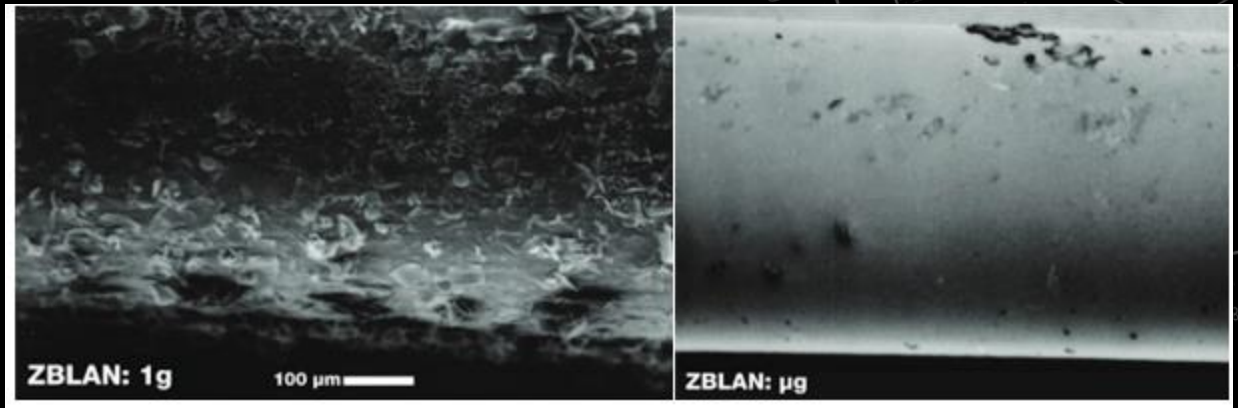
PROJECT OVERVIEW & SYSTEM NEED

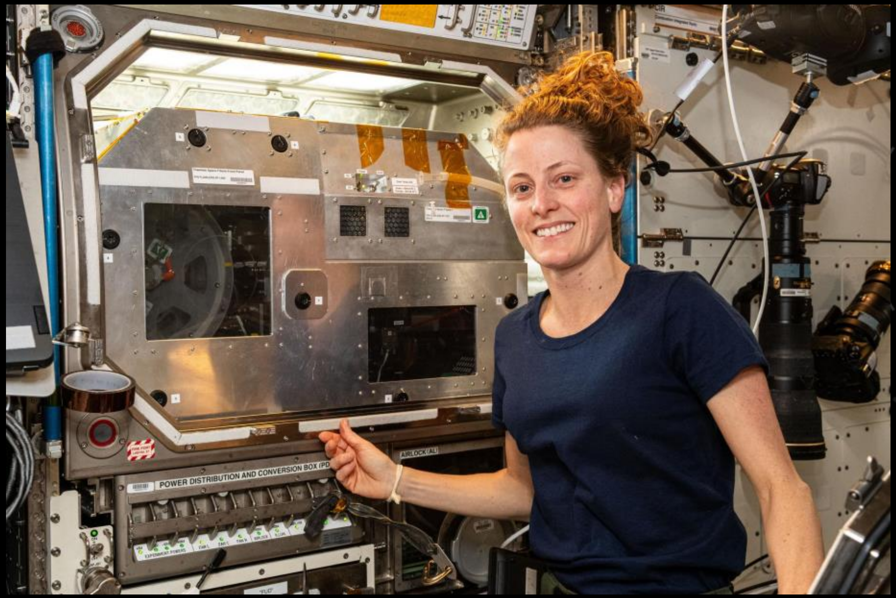
- Introduction to In-Space Servicing, Assembly and Manufacturing (ISAM):
  - U.S. ISAM National Strategy underscores ISAM's transformative potential for scientific innovation, economic growth, and space commercialization
  - Key Advantages:
    - Overcoming launch size constraints
    - Enhancing Flexibility via on-orbit upgrades
    - Cost savings through reduced structural mass
    - Decreasing ground based testing needs
    - Enabling structures unbuildable in Earth's gravity
- AOMS Objective:
  - A modular platform to enable large-scale in-space manufacturing of high-value products



ZBLAN FIBER PRODUCTION – AOMS INITIAL USE CASE

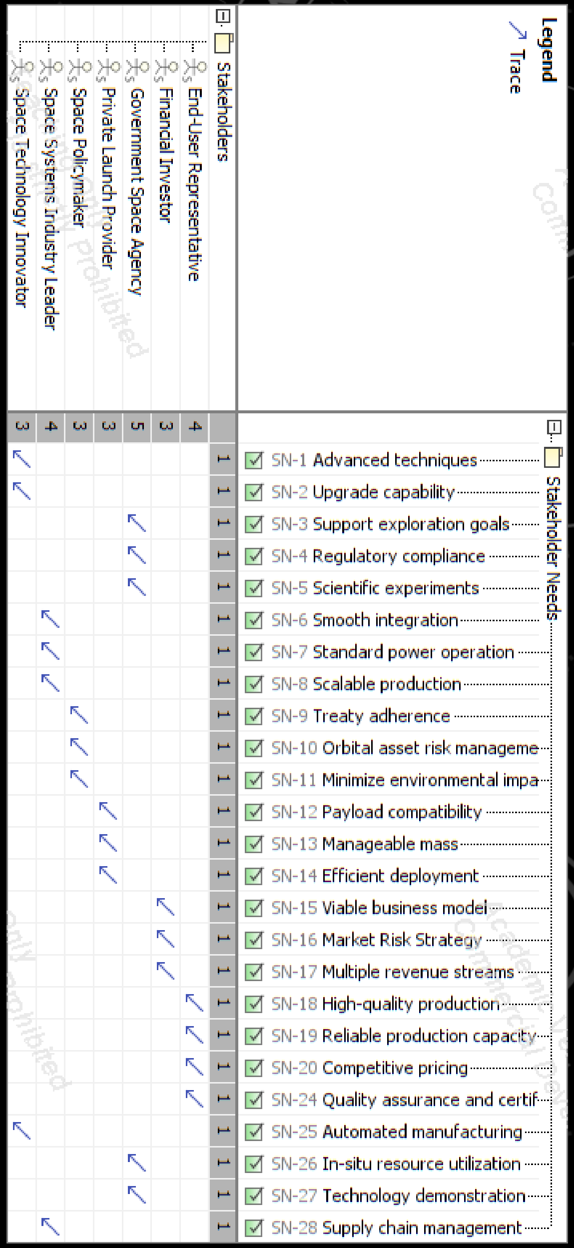
- ZBLAN is a heavy metal fluoride glass($\underline{Z}rF_4$-$\underline{B}aF_2$-$\underline{L}aF_3$-$\underline{A}lF_3$-$\underline{N}aF$) known for exception optical properties:
  - Attenuation as low as 0.01 dk/km (vs. 0.2 db/km for silica fibers)
- Microgavity benefits the production of ZBLAN by suppressing convection currents and sedimentation
  - Fibers produced in microgravity exhibit **10–100x better performance** compared to Earth-based manufacturing
- ZBLAN production has been proven onboard the ISS, and is a high TRL candidate for AOMS
  - Flawless Photonics produced more than 11km aboard the ISS in Mar 2024, with 7 runs exceeding 700m





STAKEHOLDER NEEDS ANALYSIS

- Stakeholder Groups:
  - End-Users: Require high-quality ZBLAN fibers for advanced applications.
  - Financial Investors: Demand economic viability and return on investment.
  - Regulatory Bodies: Enforce compliance with safety and operational standards.
  - Scientific Community: Seek innovative research opportunities enabled by AOMS
  - Commercial Partners: Focus on scalability and integration into market demands.
- Stakeholder Needs:
  - Technical Performance: Reliable and scalable ZBLAN production.
  - Economic Viability: Cost-effective operations and ROI.
  - Compliance: Adherence to regulatory and safety standards.
  - Innovation: Enable groundbreaking manufacturing processes.
- Traceability Matrix maps needs to stakeholders, Identifies shared interests and resolves competing priorities.
  - Guides requirement development and resource allocation.



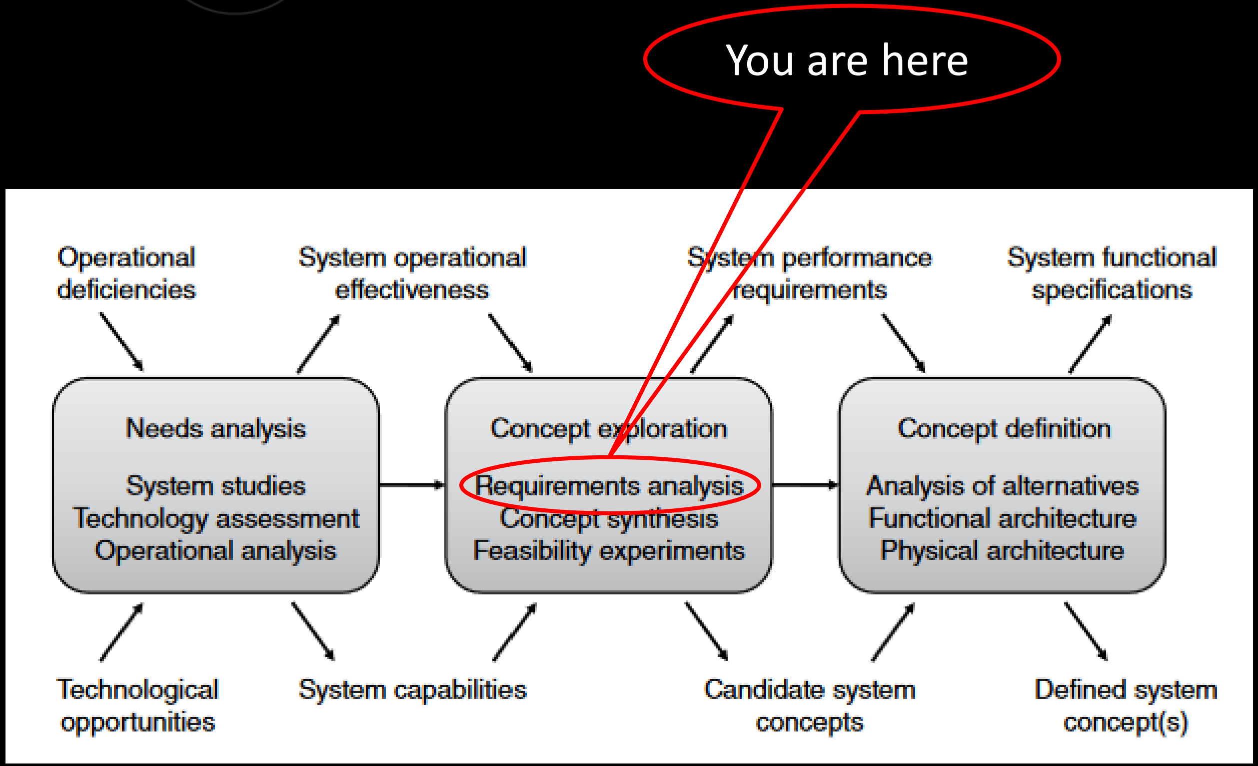
MISSION OBJECTIVES

- Mission Need:
  - Develop a scalable, upgradable orbital system to produce high quality materials in microgravity
  - Ensure regulatory compliance, environmental responsibility, and compatibility with existing space infrastructure
  - Support national space goals, scientific research, and commercial viability with sustainable operations

#	Name	Text
1	☑ Obj-1 High-Capacity ZBLAN Production	Establish a versatile manufacturing platform capable of producing high-quality ZBLAN optical fibers in microgravity, with a production capacity of up to 50 km per mission and a manufacturing rate exceeding 3 km per hour.
2	☑ Obj-2 Advanced Thermal Management	Implement advanced thermal management systems to ensure precise control over processing environments, with capabilities extending beyond 1000°C
3	☑ Obj-3 Autonomous Operations	Achieve a high degree of autonomous operations, minimizing the need for crew intervention through process optimization, quality control, and fault recovery systems.
4	☑ Obj-4 Efficient Material Management	Incorporate efficient material handling and storage systems, including potential recycling capabilities to manage raw materials, finished products, and waste
5	☑ Obj-5 Multi-Mission Support	Support secondary missions and scientific experiments without compromising primary production objectives
6	☑ Obj-6 Economic Viability	Demonstrate economic viability by achieving a positive return on investment within 5 years of full operational capability
7	☑ Obj-7 Regulatory Compliance	Comply with all relevant safety standards, international guidelines, and regulations while minimizing environmental impact
8	☑ Obj-8 Sustainable End-of-Life Plan	Develop and implement a comprehensive end-of-life plan that includes safe deorbiting or repurposing of at least 90% of the system's components

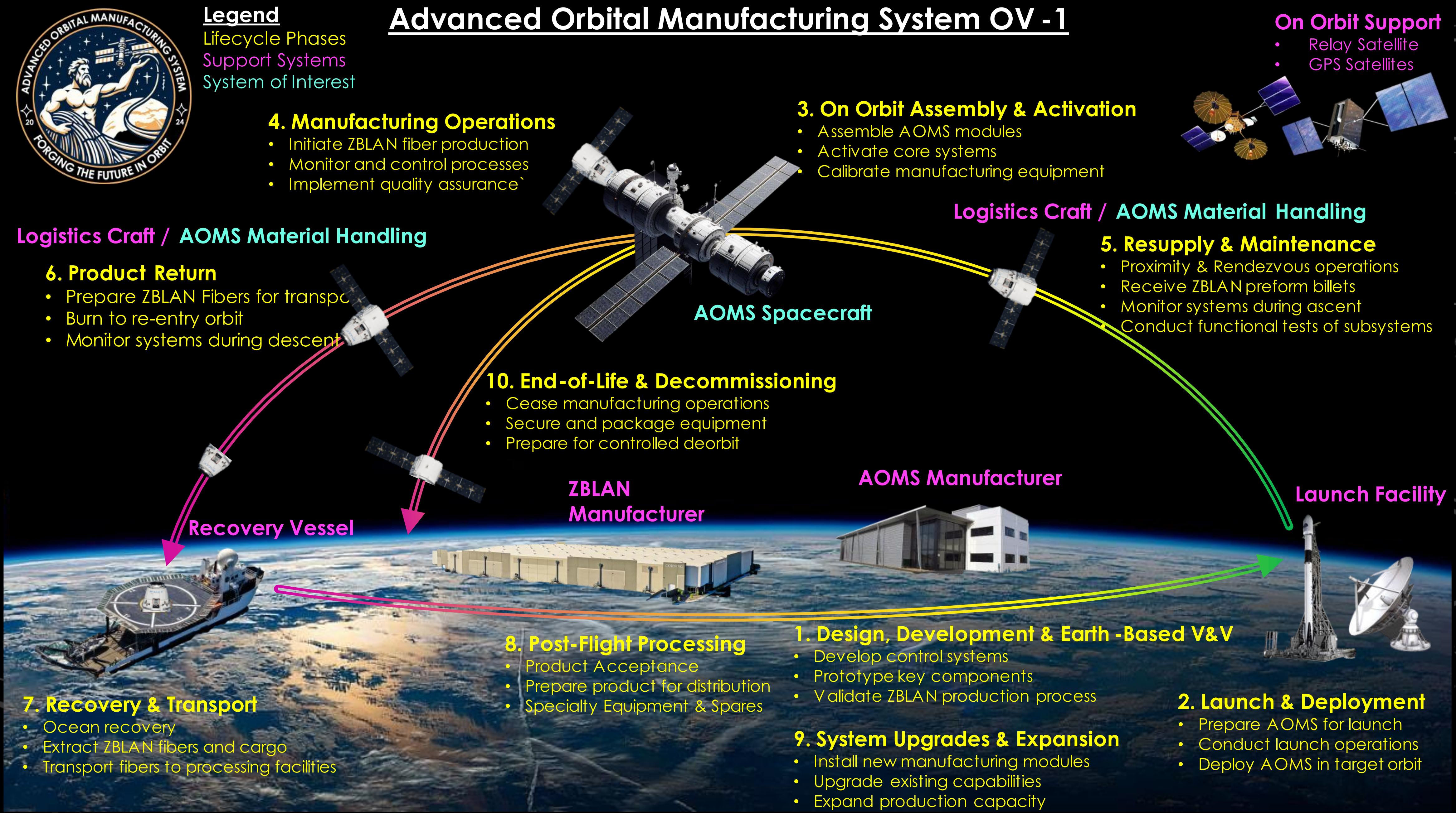
Legend
↗ DeriveReqt

Stakeholder Needs		SN-1 Advanced techniques	SN-2 Upgrade capability	SN-3 Support exploration goals	SN-4 Regulatory compliance	SN-5 Scientific experiments	SN-6 Smooth integration	SN-7 Standard power operation	SN-8 Scalable production	SN-9 Treaty adherence	SN-10 Orbital asset risk management plan	SN-11 Minimize environmental impact	SN-12 Payload compatibility	SN-13 Manageable mass	SN-14 Efficient deployment	SN-15 Viable business model	SN-16 Market Risk Strategy	SN-17 Multiple revenue streams	SN-18 High-quality production	SN-19 Reliable production capacity	SN-20 Competitive pricing	SN-24 Quality assurance and certification	SN-25 Automated manufacturing	SN-26 In-situ resource utilization	SN-27 Technology demonstration	SN-28 Supply chain management
Program Objectives		4	2	1	2	1	2	2	3	1	2	3	1	1	2	3	1	2	3	3	4	2	1	1	5	1
☑ Obj-1 High-Capacity ZBLAN Production	8	↙							↙							↙			↙	↙	↙	↙			↙	
☑ Obj-2 Advanced Thermal Management	4	↙						↙											↙						↙	
☑ Obj-3 Autonomous Operations	12	↙					↙	↙			↙				↙	↙			↙	↙	↙	↙	↙		↙	
☑ Obj-4 Efficient Material Management	12	↙	↙				↙		↙			↙	↙	↙	↙						↙			↙	↙	↙
☑ Obj-5 Multi-Mission Support	5		↙	↙		↙												↙							↙	
☑ Obj-6 Economic Viability	6								↙							↙	↙	↙		↙	↙					
☑ Obj-7 Regulatory Compliance	4				↙					↙	↙	↙														
☑ Obj-8 Sustainable End-of-Life Plan	2				↙							↙														



REQUIREMENTS ANALYSIS & CONOPS

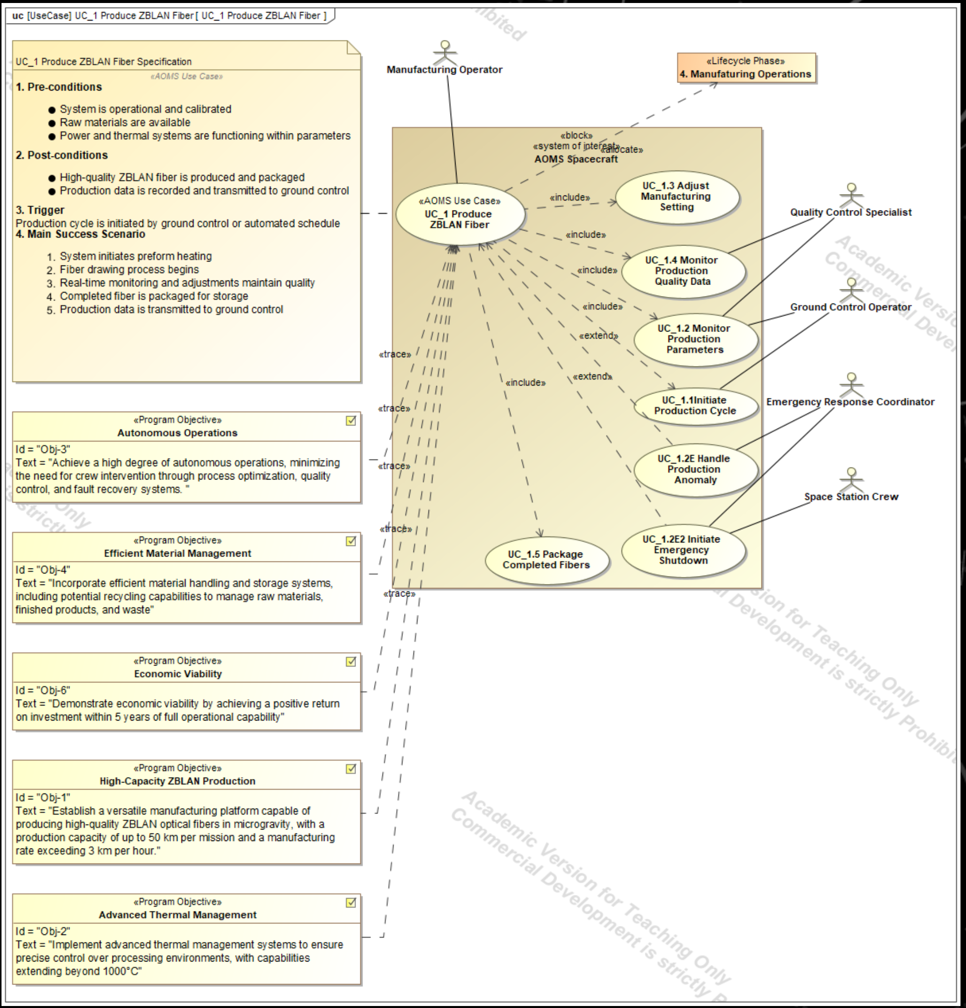
CONOPS



Legend
Lifecycle Phases
Support Systems
System of Interest`
Advanced Orbital Manufacturing System OV-1
On Orbit Support
• Relay Satellite
• GPS Satellites
4. Manufacturing Operations
• Initiate ZBLAN fiber production
• Monitor and control processes
• Implement quality assurance`
3. On Orbit Assembly & Activation
• Assemble AOMS modules
• Activate core systems
• Calibrate manufacturing equipment
Logistics Craft / AOMS Material Handling
5. Resupply & Maintenance
• Proximity & Rendezvous operations
• Receive ZBLAN preform billets
• Monitor systems during ascent
• Conduct functional tests of subsystems
Logistics Craft / AOMS Material Handling
6. Product Return
• Prepare ZBLAN Fibers for transpo
• Burn to re-entry orbit
• Monitor systems during descent
AOMS Spacecraft
10. End-of-Life & Decommissioning
• Cease manufacturing operations
• Secure and package equipment
• Prepare for controlled deorbit
ZBLAN Manufacturer
AOMS Manufacturer
Launch Facility
Recovery Vessel
7. Recovery & Transport
• Ocean recovery
• Extract ZBLAN fibers and cargo
• Transport fibers to processing facilities
8. Post-Flight Processing
• Product Acceptance
• Prepare product for distribution
• Specialty Equipment & Spares
1. Design, Development & Earth-Based V&V
• Develop control systems
• Prototype key components
• Validate ZBLAN production process
9. System Upgrades & Expansion
• Install new manufacturing modules
• Upgrade existing capabilities
• Expand production capacity
2. Launch & Deployment
• Prepare AOMS for launch
• Conduct launch operations
• Deploy AOMS in target orbit

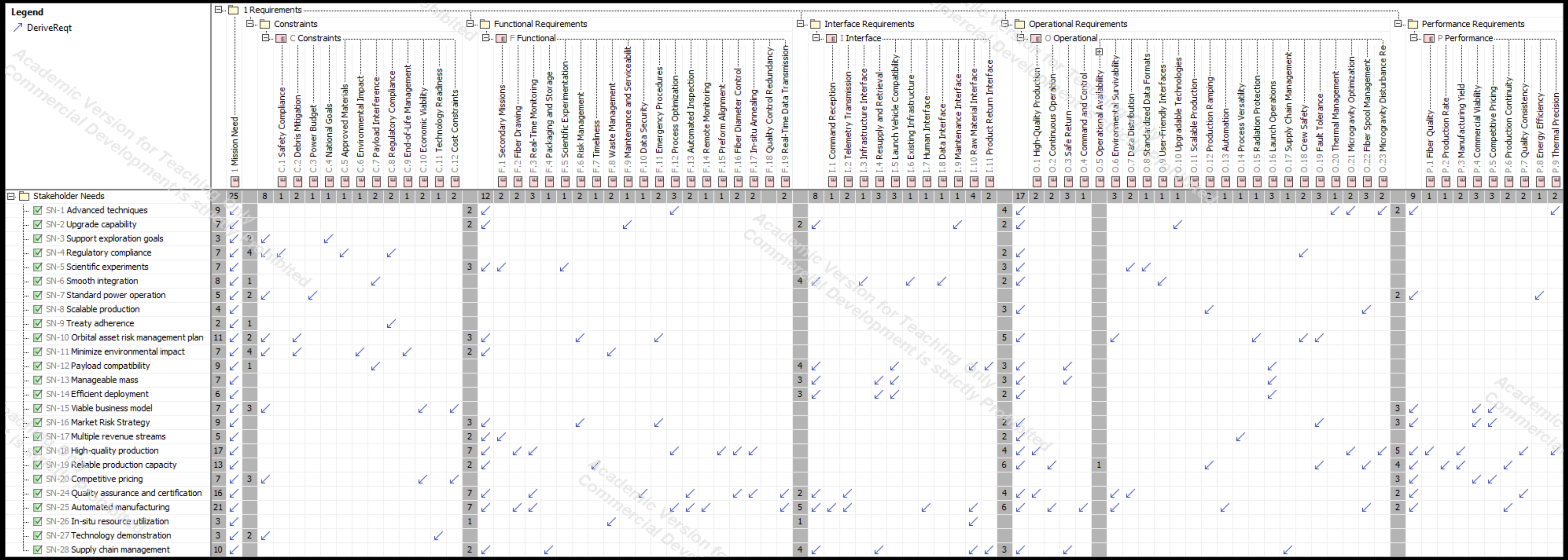
USE CASES & MISSION SCENARIOS

- Key Use Cases:
  - Produce ZBLAN Fiber: High-quality manufacturing in microgravity.
  - Scientific Research: Enable experiments in materials and fluid dynamics.
  - System Maintenance: Diagnostics, repairs, and in-orbit servicing.
  - Resource Management: Efficient resupply and product return.
  - Performance Analysis: Real-time monitoring and optimization.
  - Regulatory Compliance: Adherence to safety and space debris standards.
  - System Upgrades: Adaptability to new materials and processes.
- Operational Scenarios:
  - ZBLAN Fiber Production: Automated drawing, monitoring, and quality control
  - Multi-Material Research: Flexible setups for concurrent experiments.
  - Anomaly Response: Remote diagnostics and recovery protocols.
  - Resupply & Return: Coordinated material handling and inventory updates.



SYSTEM REQUIREMENTS DERIVATION

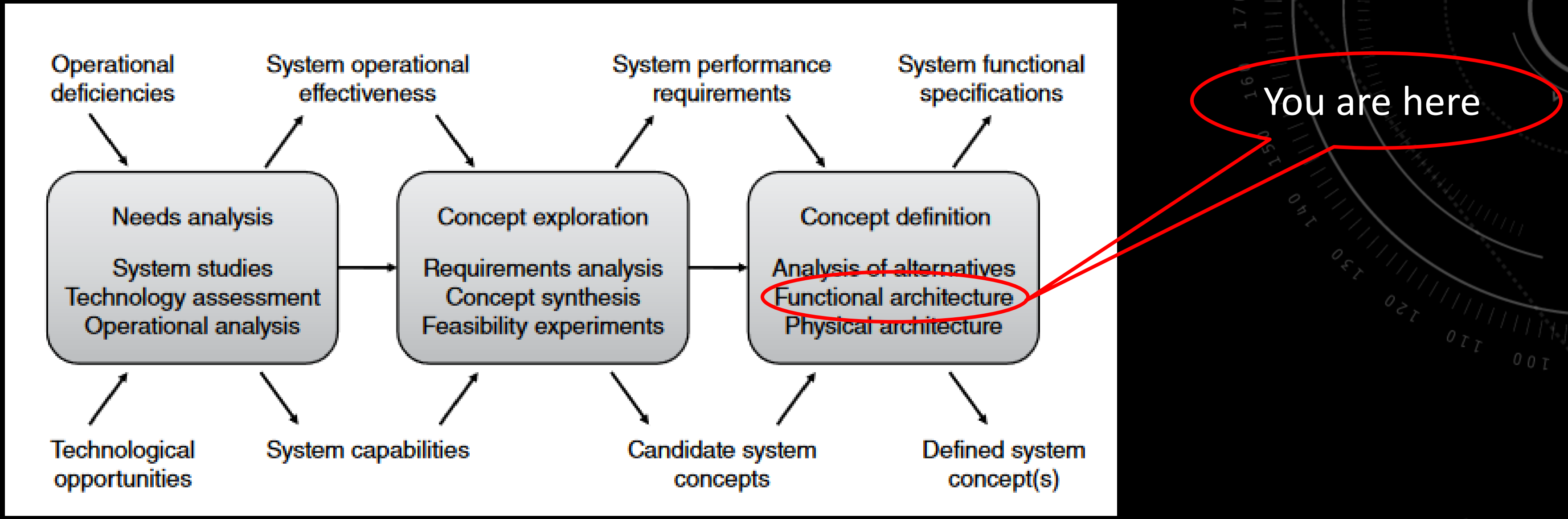
- Identified Stakeholder Needs: Gathered goals and expectations from end-users, investors, and regulators
- CONOPS & Lifecycle Analysis: Defined system lifecycle stages, ensuring coverage from design to end-of-life.
- Use Case Analysis: Mapped system behaviors and interactions
- Derive Requirements: Translate operational needs & performance targets into quantifiable, verifiable requirements
- Traceability: Aligned each requirement with stakeholder needs, ensuring validation and consistency



KEY PERFORMANCE PARAMETERS (KPPS)

- KPPs are critical success factors that are non-negotiable for system success. If unmet, the project cannot continue.
- AOMS KPPs:
  - High-Quality Production: <1 crystallization defect per km of ZBLAN fiber in microgravity.
  - Continuous Operation: 5 years of operation without human intervention.
  - Operational Availability: 95% operational availability.
  - Production Ramping: Scale production to 50 km per draw.
  - Automation: 95% autonomous operation, including auto-restart after breaks.
  - Fiber Quality: Attenuation of 0.05 dB/km or lower at 2.5 µm.
  - Production Rate: 500 meters of fiber per day.
  - Production Continuity: Auto-restart within 10 minutes, maintaining 90% of quality

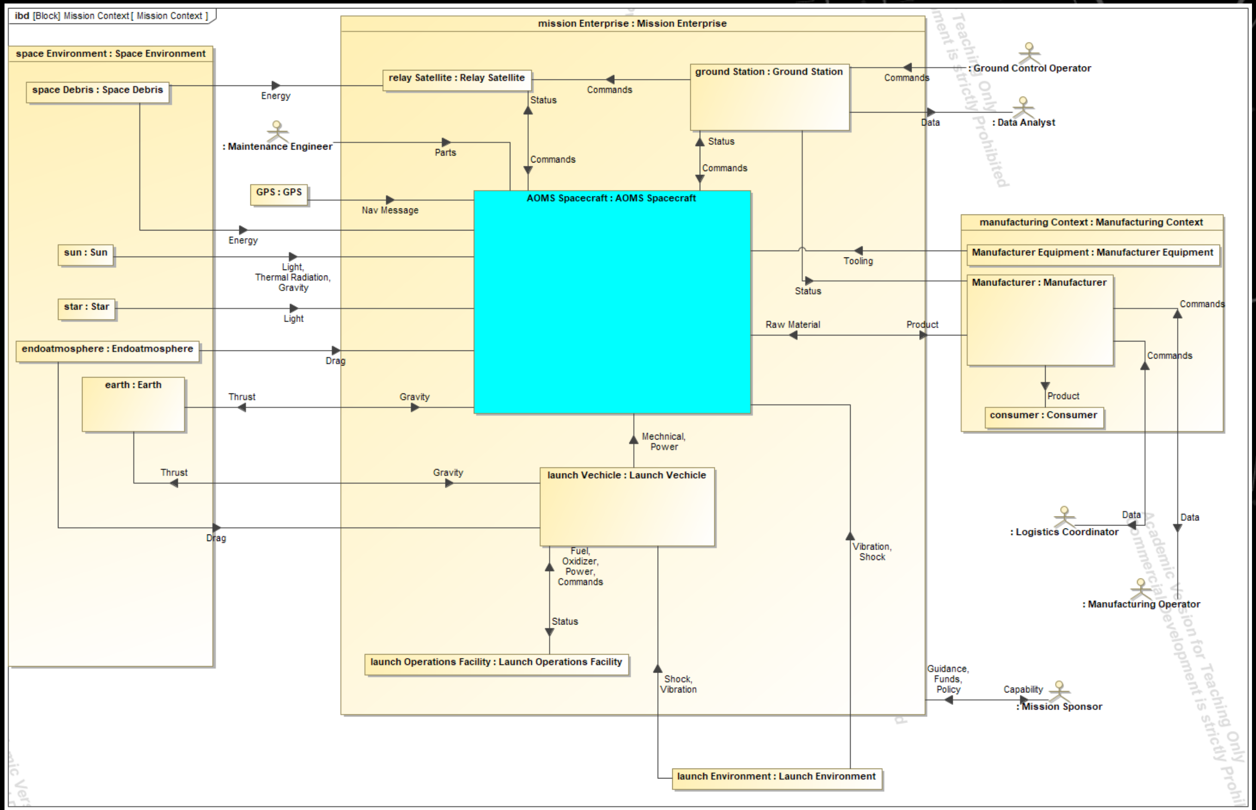
#	Name	Text	KPP
2	Operational Requirements		
3	O Operational	The system shall operate continuously and securely in the space environment, producing high-quality ZBLAN fibers while maintaining operational availability, autonomy, and microgravity conditions. It shall be capable of scaling production, handling multiple materials, and ensuring radiation protection.	false
6	O.21 Microgravity Optimization	The system shall maintain a microgravity environment with less than 10^-6 g during ZBLAN fiber production.	true
14	O.13 Automation	The system shall operate autonomously for at least 95% of its production time, including the ability to automatically restart fiber production after breaks.	true
15	O.12 Production Ramping	The system shall be capable of scaling production capacity from initial demonstration levels to full commercial production levels of up to 50 km of ZBLAN fiber per draw.	true
22	O.5 Operational Availability	The system shall maintain a minimum of 95% operational availability throughout its design life.	true
35	O.2 Continuous Operation	The system shall be designed to operate continuously in the space environment for a minimum of 5 years without requiring physical human intervention.	true
36	O.1 High-Quality Production	The system shall produce ZBLAN fibers with less than 1 crystallization defect per kilometer of fiber manufactured in microgravity	true
58	Performance Requirements		
59	P Performance	The system shall achieve superior performance metrics in ZBLAN fiber production, including fiber quality, production rate, yield, and consistency. It shall demonstrate commercial viability through competitive pricing and multiple revenue streams, while ensuring energy efficiency and rapid production recovery after interruptions.	false
63	P.6 Production Continuity	The system shall be capable of automatically restarting fiber production within 10 minutes of a production break, maintaining at least 90% of pre-break production quality.	true
66	P.3 Manufacturing Yield	The system shall achieve a manufacturing yield of at least 95% usable fiber.	true
67	P.2 Production Rate	The system shall maintain a production rate of at least 500 meters of ZBLAN fiber per day.	true
68	P.1 Fiber Quality	The system shall produce ZBLAN fibers with attenuation rates of 0.05 dB/km or lower at 2.5 µm wavelength.	true



FUNCTIONAL ANALYSIS

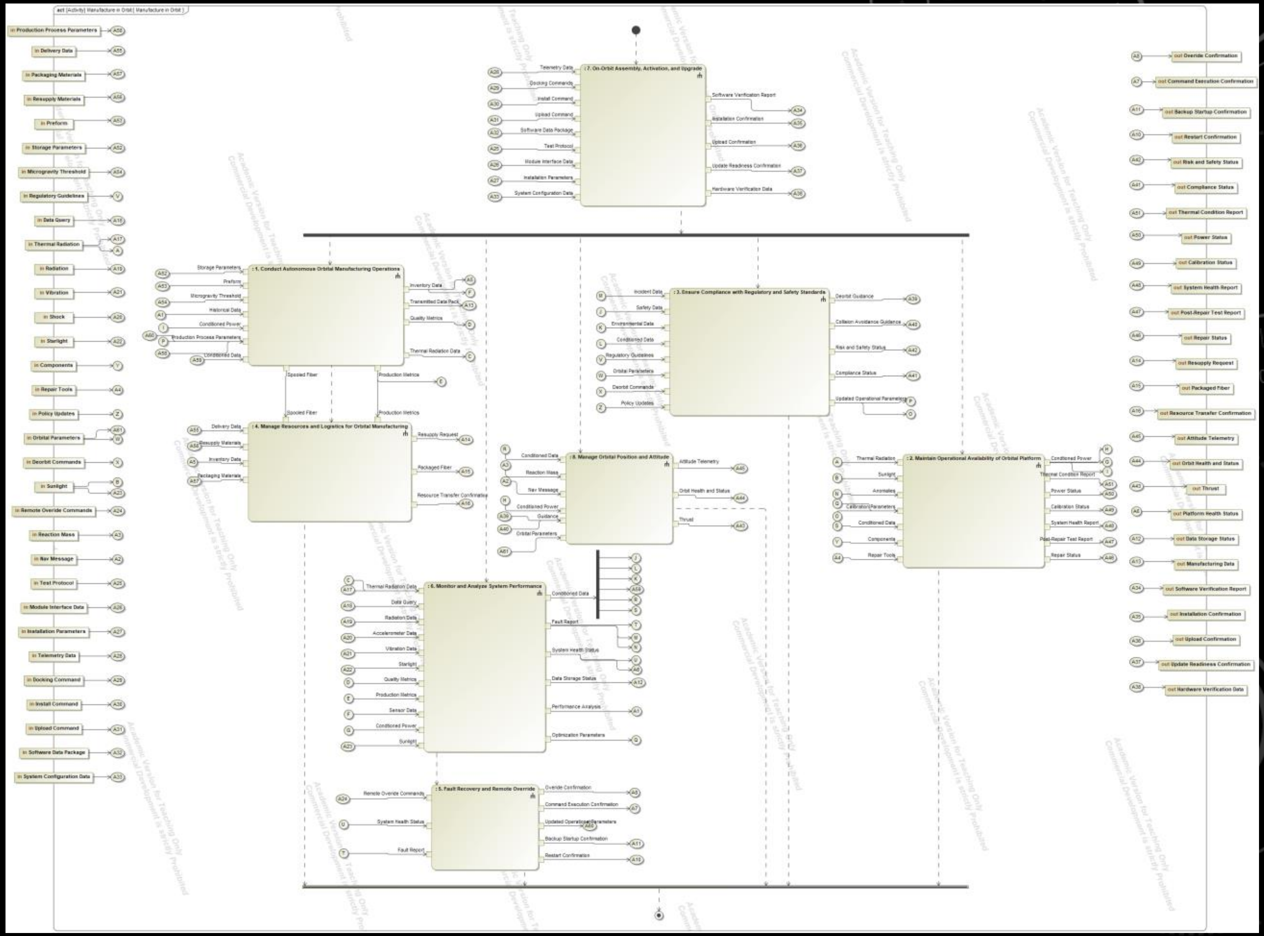
FUNCTIONAL ANALYSIS: CONTEXT DIAGRAM

- Purpose:
  - Shows high-level interactions between AOMS and external systems/entities.
- Key Elements:
  - AOMS as a Black Box: Focus on mission-level interactions, not internal components.
  - Inputs/Outputs: Displays flow of resources, data, and control signals to/from AOMS.
  - External Systems: Includes interactions with launch vehicles, ground control, and resupply capsules.
- System-Level View:
  - Illustrates how AOMS supports key objectives like fiber production and resource management.
- Foundation for Functional Analysis:
  - Serves as the basis for detailed functional decomposition and system design.



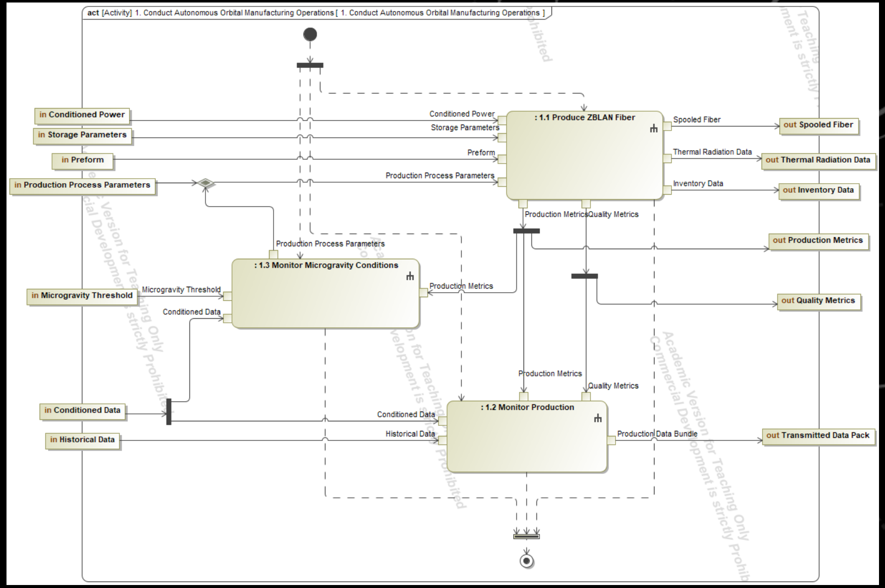
TOP LEVEL FUNCTION ACTIVITY DIAGRAM

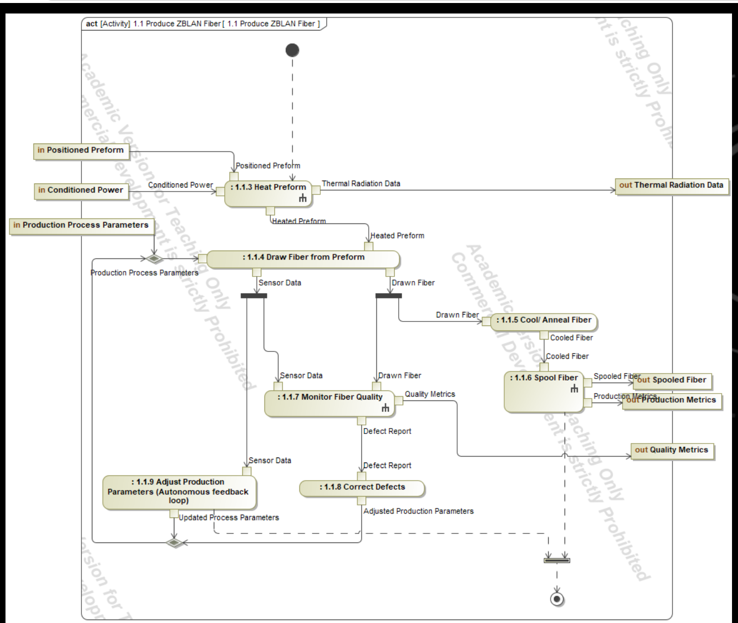
- Purpose:
  - Visualizes the primary operations and sequence of AOMS's core functions.
  - Key Functions:
  - 1. Autonomous Manufacturing Operations
  - 2. Maintain Platform Availability
  - 3. Regulatory Compliance
  - 4. Manage Resources & Logistics
  - 5. Fault Recovery & Remote Override
  - 6. Monitor System Performance
  - 7. On-Orbit Assembly & Upgrades
  - 8. Manage Orbital Position & Attitude
- Flow of Activities:
  - Control flows show sequence and dependencies, while object flows represent materials and data movement.
- System Overview:
  - Illustrates how AOMS integrates core functions, ensuring smooth operation from manufacturing to maintenance.



EXAMPLE DECOMPOSITION OF L0 FUNCTIONS TO L1

- Purpose of Decomposition:
  - Breaks down high-level functions into manageable tasks for easier design and implementation.
- Why Decompose?
  - Clarifies Operations and identifies specific actions.
  - Simplifies Complexity by breaking functions into smaller components.
  - Enables Design by providing clear tasks for development.
- Decomposition Example:
  - L0 Function: Conduct Autonomous Orbital Manufacturing Operations
  - L1 Functions: Produce ZBLAN Fiber, Monitor Microgravity Conditions, Monitor Production





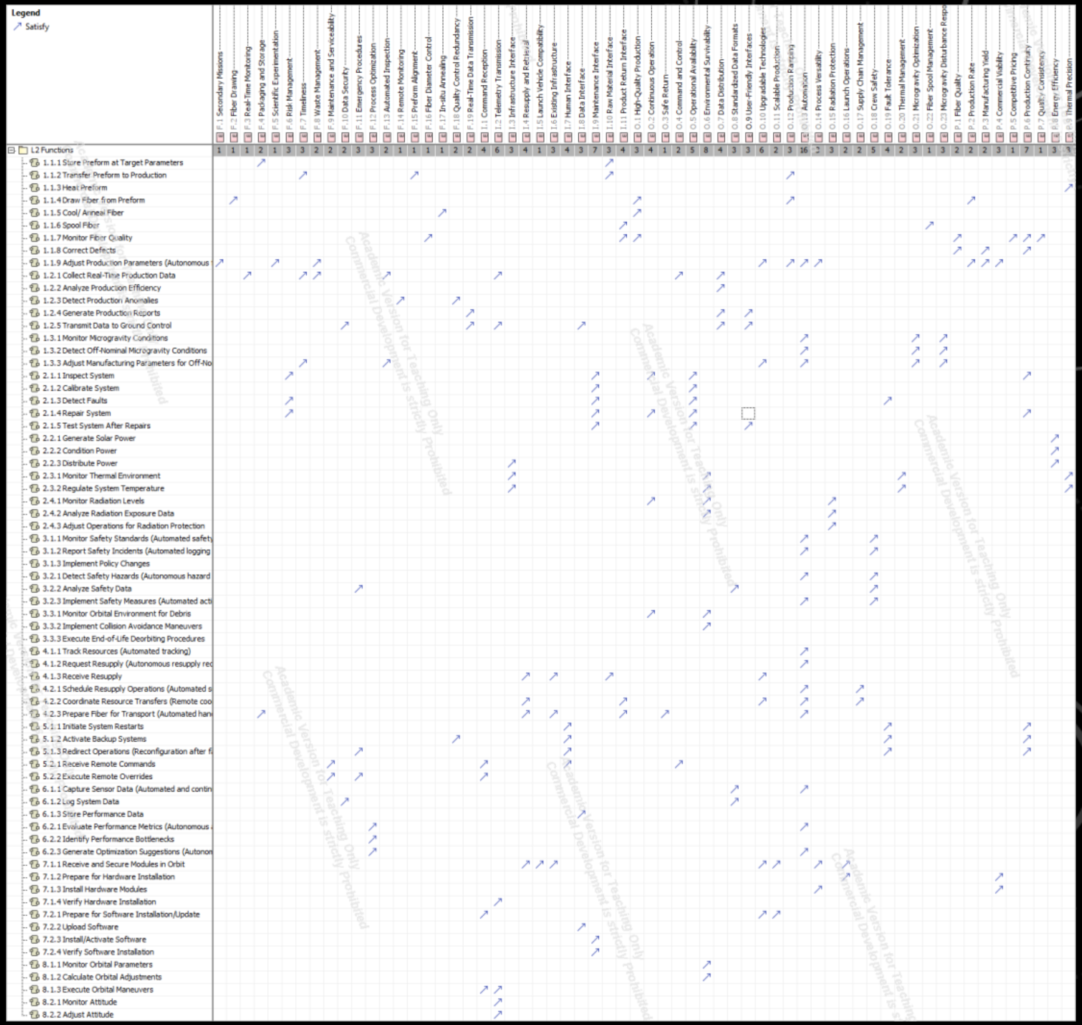
DECOMPOSITION TO L2/L3 & BINDING/COUPLING

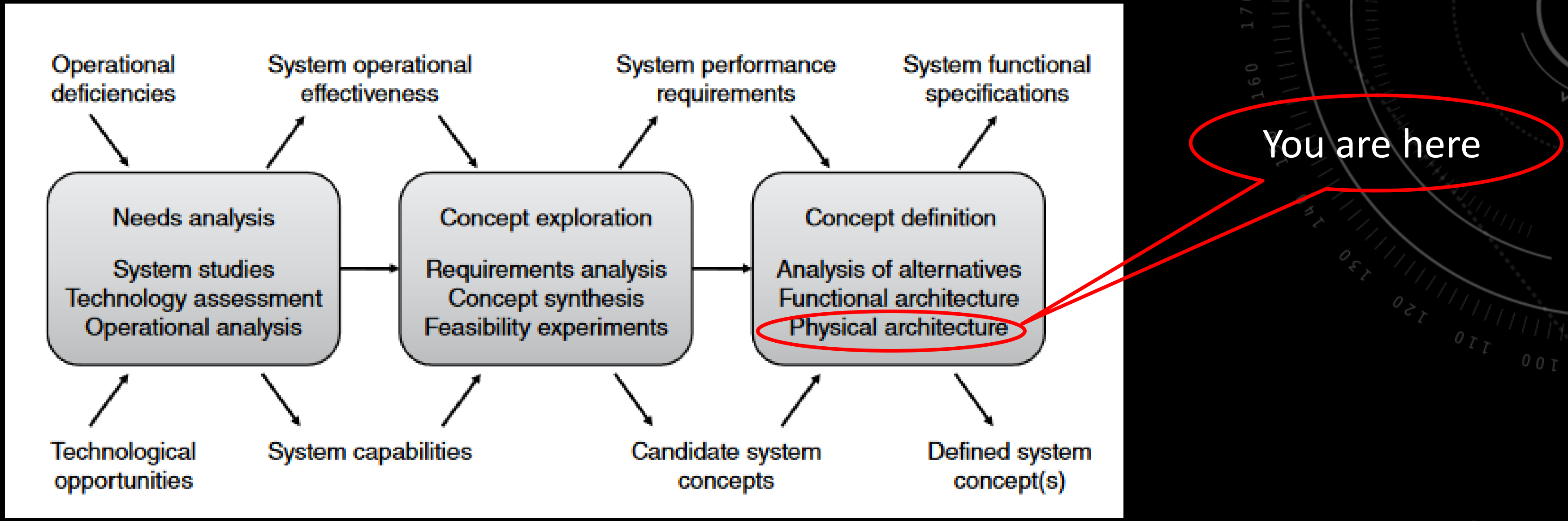
- Purpose:
  - Break down L0 functions into L1, L2, and L3 subfunctions to ensure the system is designed with acceptable risk.
- Process:
  - L1 Functions: High-level tasks (e.g., fiber production, thermal control).
  - L2 Functions: More detailed tasks (e.g., heating preform, monitoring microgravity).
  - L3 Functions: Specific tasks (e.g., adjust heating rate, measure fiber tension) for clear implementation.
- Binding and Coupling Considerations:
  - Tight Binding: Group related functions to reduce redundancy and increase cohesion.
  - Loose Coupling: Assign unrelated functions to separate subsystems to enhance flexibility and minimize interdependencies.

Name	Supporting L1 Functions	Supporting L2 Functions	Supporting L3 Functions
1. Conduct Autonomous Orbital Manufacturing Operations	1.1 Produce ZBLAN Fiber(context Manufacturing Subsystem) 1.2 Monitor Production(context Quality Assurance Subsystem)	4.1.4 Store Preform at Target Parameters(context Material Storage Unit) 1.1.9 Adjust Production Parameters (Autonomous feedback loop)(context Process Control CSC) 1.1.6 Spool Fiber(context Spool Tension Motor) 1.1.5 Cool/ Anneal Fiber(context Fiber Annealer) 1.1.4 Draw Fiber from Preform(context ZBLAN Fiber Drawing Unit) 1.1.7 Monitor Fiber Quality(context Spectroscopy Sensor) 1.1.3 Heat Preform(context Preform Heater) 4.1.5 Transfer Preform to Production(context Material Handling Robotics) 1.1.8 Correct Defects(context Process Control CSC) 1.2.1 Collect Real-Time Production Data(context Production Data Logging CSC) 1.2.5 Transmit Data to Ground Control(context High Rate Antenna) 1.2.4 Generate Production Reports(context Onboard Computer) 1.2.2 Analyze Production Efficiency(context Onboard Computer) 1.2.3 Detect Production Anomalies(context Process Monitoring Camera)	1.1.6.1 Hold Spool(context Spool Linear Stage) 1.1.6.2 Level Wind Spool(context Spool Stage Motor) 1.1.6.3 Measure Tension(context Tension Sensor) 1.1.7.1 Measure Fiber Diameter 1.1.7.2 Detect Defects 1.1.3.1 Hold Heater(context Heater Stage) 1.1.3.2 Rotate Heater Stage(context Heater Stage Motor) 1.1.3.3 Hold Preform(context Preform Holder) 1.2.5.2 Amplify High Rate Transmission(context High Rate Transmitter Amplif 1.2.5.1 Switch Signal Path(context Duplexer) 1.2.5.3 Transmit Low Rate Signal(context Low Rate Antenna) 1.2.5.4 Amplify Low Rate Transmission(context Low Rate Transmitter Amplifie

FUNCTIONS TO REQUIREMENTS

- Purpose:
  - Establishes bi-directional traceability between L2 functions and system requirements using the <<Satisfy>> relationship in SysML.
- Process:
  - Decompose Functions: Break down high-level functions into L2 functions.
  - Map to Requirements: Use the <<Satisfy>> relationship in SysML to trace L2 functions to the corresponding requirements.
  - Verify Completeness: Traceability ensures all requirements are covered and highlights any missing requirements, which are added to the System Specification.
- Importance:
  - Ensures Completeness: Guarantees that all functional requirements are met.
  - Identifies Gaps: Highlights missing requirements for inclusion in the System Specification.
  - Supports Validation: Confirms that system functions align with defined requirements.
  - Improves Traceability: Provides clear, traceable connections between design and requirements.

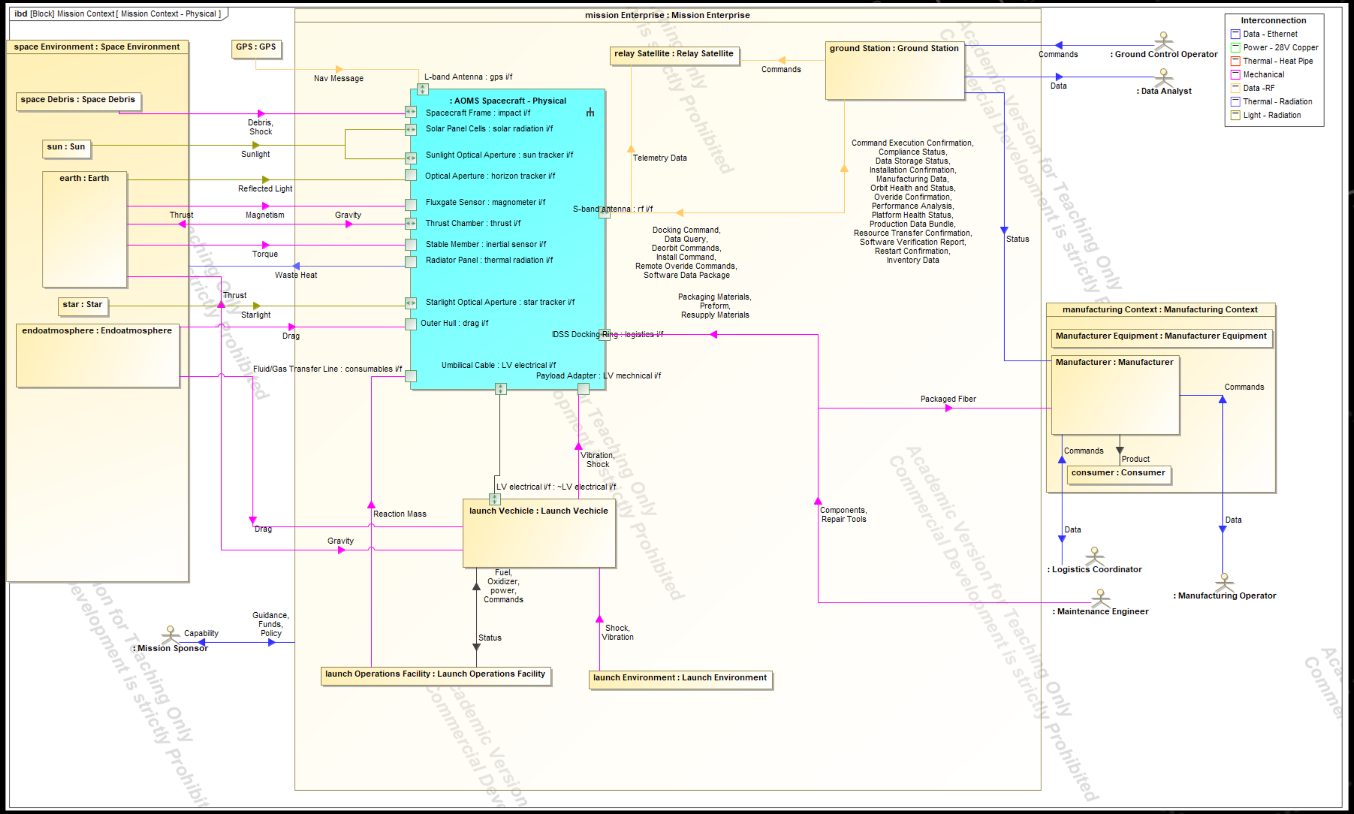




CONCEPTUAL DESIGN

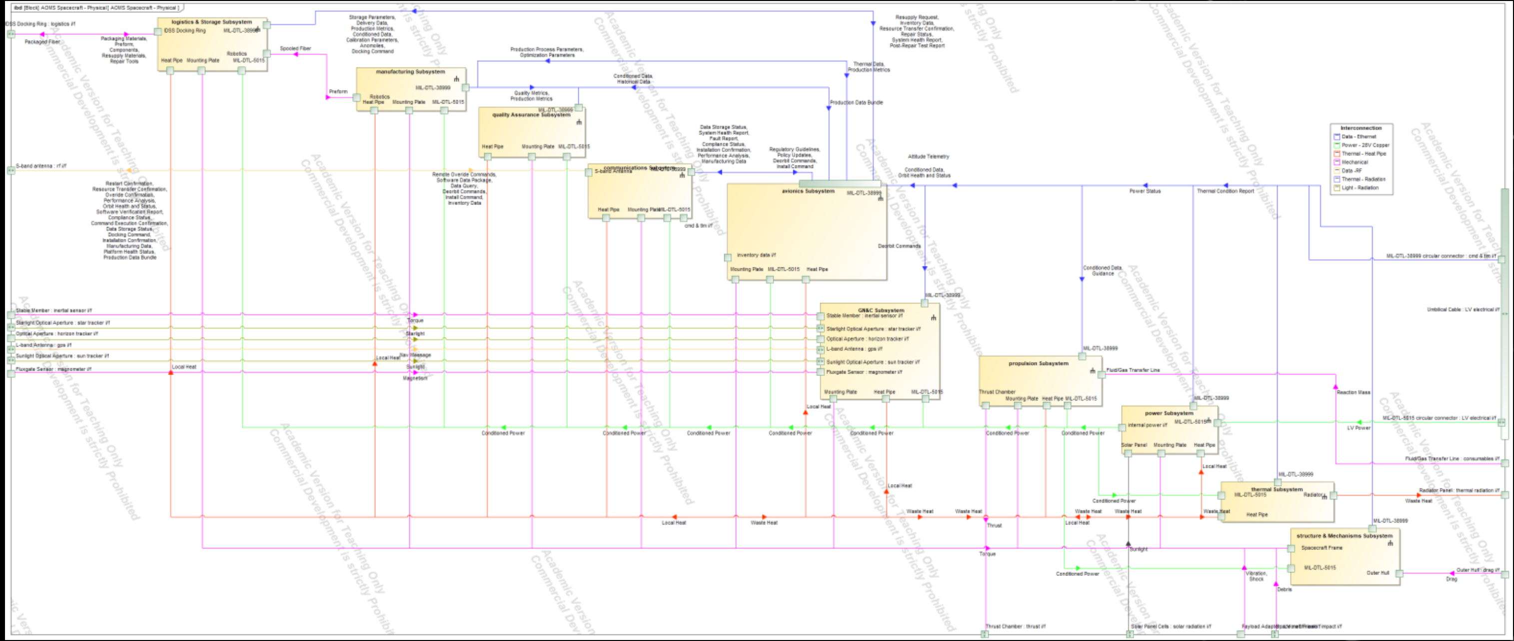
PHYSICAL CONTEXT DIAGRAM

- Purpose:
  - Shows AOMS's interactions with external entities, focusing on physical interfaces.
- Key Elements:
  - AOMS as the central system with external entities (e.g., launch vehicles, ground control, resupply capsules).
  - Inputs and Outputs: Labeled with implementation details (e.g., Ethernet for data, power cables for electricity).
- Difference from Functional Context Diagram:
  - The Physical Context Diagram focuses on physical interfaces (e.g., data cables, power connections) while the Functional Context Diagram focuses on functional interactions (e.g., commands, data flow).
  - This diagram emphasizes the hardware connections and physical resources used by AOMS.



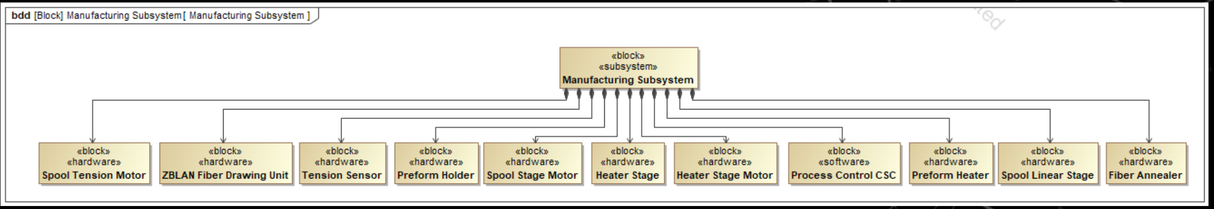
TOP LEVEL PHYSICAL INTERNAL BLOCK DIAGRAM (IBD)

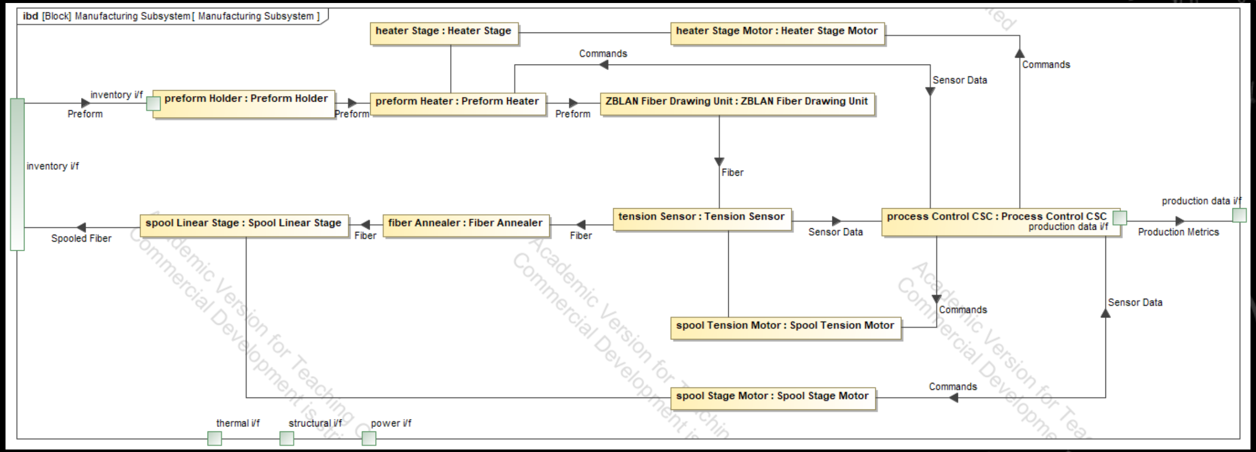
- Purpose:
  - Displays the top-level physical architecture of AOMS, showing subsystems and interfaces.
- Key Elements:
  - Subsystems: Main subsystems like ZBLAN fiber production and thermal control.
  - Interfaces: Connections such as cables, data links, and power cables.
- Focus:
  - Depicts the flow of material, energy, and data between subsystems.
- Importance:
  - Provides a high-level overview, ensuring subsystems are well-connected for seamless operation and guiding further design.



SUBSYSTEM PHYSICAL DECOMPOSITION (BDD & IBD)

- Purpose:
  - Shows the physical decomposition of the manufacturing subsystem, detailing components and their interactions.
- Key Elements:
  - BDD: High-level breakdown of physical components (e.g., fiber drawing mechanisms, heating units)
  - IBD: Illustrates physical connections and interfaces (e.g., power cables, data links, mechanical connections).
- Importance:
  - Provides a complete view of the subsystem's behavior and physical integration, guiding detailed design and integration.





TOP-LEVEL PHYSICAL N2 DIAGRAM

- Purpose:
  - Illustrates the interactions and data/material flows between subsystems at the top level.
- Key Elements:
  - Subsystems on the Diagonal: Represents the main subsystems (e.g., ZBLAN fiber production, thermal control).
  - Interactions/Flows: Shows what is transferred between subsystems (e.g., data, power, materials) and how they communicate.
- Focus:
  - Highlights the physical relationships and dependencies between subsystems, ensuring each subsystem supports the overall mission objectives.
- Importance:
  - Provides a clear overview of how subsystems interact physically and exchange resources, supporting system integration and functional completeness.

Inputs		Packaging Materials Preform Components Resupply Materials Repair Tools		Remote Overide Commands Software Data Package Data Query Derorbit Command Docking Command Install Command		Nav Message Reflected Light Inertial Reference Torque Magnetism Starlight Sunlight	Reaction Mass		Sunlight	Drag Debris Shock Vibration	Outputs
	Manufacturing Subsystem	Spooled Fiber	Production Metrics Quality Metrics		Production Metrics Thermal Data Production Data			Waste Heat			
	Preform	Logistics, Storage, & Repair Subsystem			Inventory Data Post Repair Test Report			Waste Heat			Packaged Fiber
			Quality Assurance Subsystem								
				Communications Subsystem	Deorbit Commands Install Command Policy Updates Regulatory Guidelines			Waste Heat			Restart Confirmation Resource Transfer Confirmation Overide Confirmation Performance Analysis Orbit Health and Status Software Verification Report Data Storage Status Installation Confirmation Inventory Data Manufacturing Data Platform Health and Status Production Data Bundle Compliance Status Command Execution Confirmation
	Optimization Parameters Production Process Parameters	Anomolies Calibration Parameters Conditioned Data Delivery Data Docking Command Production Metrics Storage Parameters	Condtioned Data Historical Data	Compliance Status Data Storage Status Fault Report Installation Confirmation Performance Analysis System Health Report	Avionics Subsystem	Deorbit Command	Conditioned Data	Waste Heat			
					Conditioned Data Orbit Health & Status	GN&C Subsystem		Waste Heat		Torque	
					Attitude Telemetry		Propulsion Subsystem				Thrust
	Local Heat	Local Heat	Local Heat	Local Heat	Local Heat Thermal Condition Report	Local Heat	Local Heat	Thermal Subsystem	Local Heat		Waste Heat
	Conditioned Power	Conditioned Power	Conditioned Power	Conditioned Power	Conditioned Power Power Status	Conditioned Power	Conditioned Power	Conditioned Power Waste Heat	Power Subsystem	Conditioned Power	
										Structure & Mechanisms Subsystem	

COMPONENT-FUNCTION TRACEABILITY & CONSIDERATIONS

- Purpose:
  - Map L2/L3 functions to specific components, ensuring all system functions are implemented and traceable to the physical architecture.
- Process:
  - Used the <<Allocate>> relationship in SysML to establish traceability between functions and components.
  - Identified gaps where functions lacked associated components, leading to the addition of new functions or refinement of existing ones.
- Design Considerations:
  - Avoided gold plating by ensuring each function was allocated to the appropriate component without redundancy.
- Outcome:
  - Gaps in tracing highlighted the need for new or refined functions, ensuring comprehensive functional coverage.

Legend
↗ Allocate

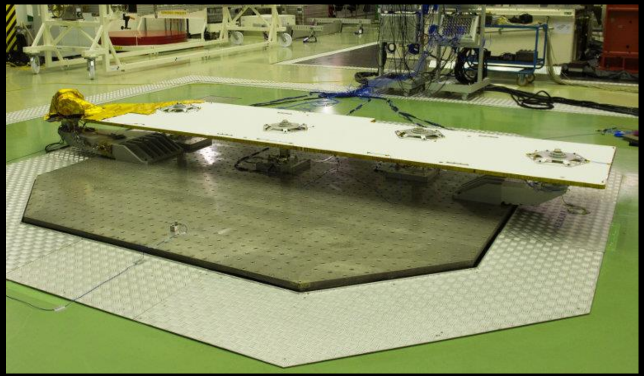
L2 Functions		1.1.3 Heat Preform(context Preform Heater)	1.1.4 Draw Fiber from Preform(context ZBLAN Fiber Dra	1.1.5 Cool/ Anneal Fiber(context Fiber Annealer)	1.1.6 Spool Fiber(context Spool Tension Motor)	1.1.7 Monitor Fiber Quality(context Spectroscopy Sensc	1.1.8 Correct Defects(context Process Control CSC)	1.1.9 Adjust Production Parameters (Autonomous feedb	1.2.1 Collect Real-Time Production Data(context Produc
Structure [Manufacturing]		1	1	1	1				
Fiber Annealer	1			↙					
Heater Stage									
Heater Stage Motor									
Preform Heater	1	↙							
Preform Holder									
Spool Linear Stage									
Spool Stage Motor									
Spool Tension Motor	1				↙				
Tension Sensor									
ZBLAN Fiber Drawing Unit	1		↙						

Name	Allocated L1 Functions	Components	Allocated L2 Functions
Logistics & Storage Subsystem	4.1 Manage Resources(context Logistics & Storage Subsystem) 4.2 Manage Logistics(context Logistics & Storage Subsystem) 2.1 Perform System Maintenance(context Logistics & Storage Subsystem)	Product Storage Unit Material Handling Robotics Inventory Management CSC Docking Ring Material Storage Unit	4.1.4 Store Preform at Target Parameters(context Material Storage Unit) 4.2.5 Store Manufactured Product(context Product Storage Unit) 4.2.4 Secure Docking Connection(context Docking Ring) 4.1.5 Transfer Preform to Production(context Material Handling Robotics) 4.1.3 Receive Resupply(context Material Handling Robotics) 4.2.3 Prepare Fiber for Transport (Automated handling and packaging)(context Material Handling Robotics) 4.1.1 Track Resources (Automated tracking)(context Inventory Management CSC) 4.1.2 Request Resupply (Autonomous resupply request)(context Inventory Management CSC) 4.2.1 Schedule Resupply Operations (Automated scheduling)(context Inventory Management CSC) 4.2.2 Coordinate Resource Transfers (Remote coordination)(context Inventory Management CSC)

TRADE STUDY

TRADE STUDY PROCESS AND RESULTS

- Purpose:
  - Evaluate and select optimal components for AOMS, focusing on high-risk elements, particularly the thermal management system.
- Methodology:
  - Used Pair-Wise Comparison and Utility Curves to assess thermal alternatives based on heat rejection, mass, efficiency, and redundancy.
  - Conducted sensitivity analysis for robustness.
- Thermal Alternatives:
  - ISS Heat Rejection System Radiator (HRSR)
  - Alpha Radiator
  - Deployable Panel Radiator (DPR)
- Results:
  - DPR selected as the optimal solution, excelling in heat rejection, mass efficiency, and deployable area while meeting reliability standards.



Criteria	Requirement(s)
Heat Rejection Capacity	O.20.1: The thermal management system shall achieve a heat rejection capacity of at least 10 W/kg (threshold) under normal operating conditions, with an objective of 60 W/kg or greater.
Redundancy	O.20.2: The radiator system shall have a mass penalty for achieving N+2 redundancy not exceeding 300 kg, with an objective of 40 kg or less.
Radiator System Mass	O.20.3: The total mass of the radiator system shall not exceed 2800kg (threshold) and 200kg (objective).
Radiator Deployed Area	O.20.4: The total deployed area of the radiator system shall not exceed 200m² (threshold) and 50m² (objective) while meeting the required heat rejection capacity.

Criteria	Wt.	ISS HRSR			Alpha Radiator			Deployable Panel Radiator		
		Raw Score	Utility Value	Weighted Utility Value	Raw Score	Utility Value	Weighted Utility Value	Raw Score	Utility Value	Weighted Utility Value
Heat Rejection (W/kg)	0.58	10.78	0.02	0.01	54.82	0.90	0.52	55.97	0.92	0.53
Mass (kg)	0.17	1487.75	0.03	0.01	273.60	0.82	0.14	288.00	0.79	0.14
Deployed Area (m2)	0.15	106.70	0.52	0.08	48.48	0.84	0.13	36.96	0.91	0.14
Redundancy (N+2) Penalty (kg)	0.10	270.50	0.11	0.01	45.60	0.98	0.10	72.00	0.88	0.09
Operational Utility Function (Weighted Sum)		0.103			0.884			0.891		

TEST AND EVALUATION PLANNING

INTEGRATION APPROACH & TESTING

- Integration Approach:
  - Structured integration with progressive subsystem testing across multiple builds to ensure functionality at each stage.
- Build Sequence:
  - Build 1: Core infrastructure, power, thermal subsystems.
  - Build 2: Manufacturing and Quality Assurance integration.
  - Build 3: Communications and Software integration.
  - Build 4: Logistics, Harness, Propulsion, final integration.
  - Build 5: Environmental testing (thermal vacuum, vibration, EMI) and final validation.
- Qualification Testing:
  - Verifies system meets performance criteria for space conditions, using inspection, analysis, demonstration, and physical testing.

#	Name	Documentation	Test Components	Test Inputs	Test Outputs	Pass/Fail Criteria	Verifies
1	TC-B1-001 Power-Thermal Integration Test	Verify integration of Power and Thermal subsystems	Test Operator Data acquisition system AOMS Spacecraft - Physical Load bank Power supply simulator Thermal chamber Thermal load simulator Thermal sensors	in Power load scenarios in Thermal load scenarios	out Power Consumption Data out Thermal Regulation Data	Power distribution within 5% of expected values Thermal control within ±5°C of target	C.3 Power Budget O.20 Thermal Management
2	TC-B1-002 Structure-Power-Thermal Integration Test	Verify structural integrity with integrated power and thermal systems	AOMS Spacecraft - Physical Power supply simulator Strain gauges Structural test rig Test Operator Thermal chamber Vibration table	in Structural Load Simulations in Power and Thermal Cycling Commands	out Structural Integrity Data out Power and Thermal Performance Data	No structural failures Power and thermal systems maintain performance within specs	C.5 Approved Materials O.6 Environmental Survivability
3	TC-B1-003 Basic Avionics-GN&C Integration Test	Verify basic integration of Avionics and GN&C subsystems	ADCS simulator AOMS Spacecraft - Physical Command and telemetry simulator GN&C test bench Orbital simulator Test Operator	in Simulated Orbital Parameters in Basic Command Sequences	out GN& Calculations out Avionics Response Data	Avionics processes all commands correctly GN&C calculations within 1% of expected values	O.4 Command and Control F.7 Timeliness

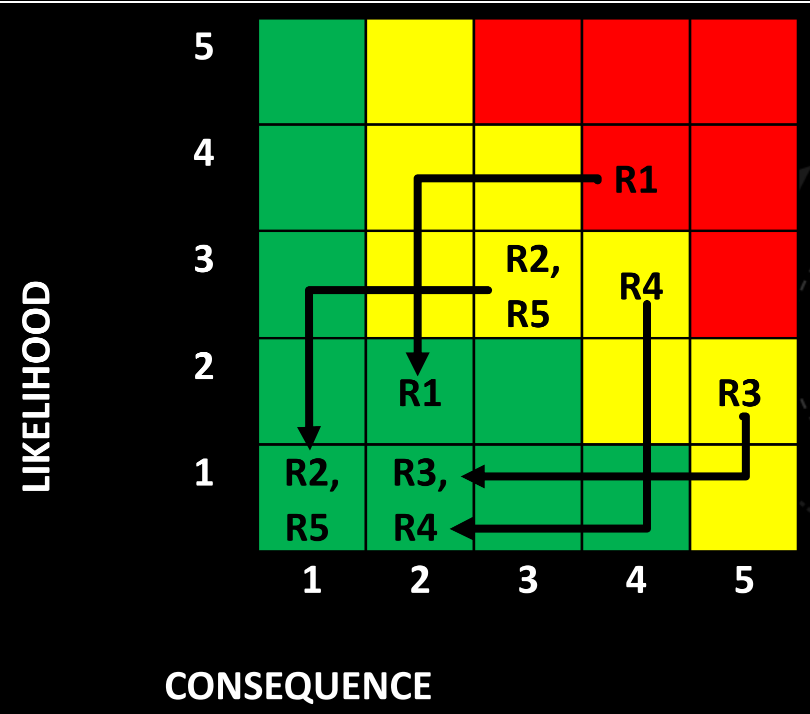
#	Name	Documentation
1	B1 Core Infrastructure and Basic Functionality	Power Subsystem (full) Thermal Subsystem (full) Structure & Mechanisms Subsystem (partial, focusing on critical structural elements) Avionics Subsystem (basic command and data handling) GN&C Subsystem (basic) Rationale: This build establishes the core infrastructure and allows for early testing of critical systems. It addresses long-lead items like power and thermal systems.
2	B2 Manufacturing and Quality Control Integration	Manufacturing Subsystem (full) Quality Assurance Subsystem (full) Avionics Subsystem (expanded for process control) GN&C Subsystem (expanded for microgravity simulation) Rationale: This build introduces the full manufacturing capabilities and quality control systems, allowing for comprehensive testing of the primary mission functions.
3	B3 Communications and Software Integration	Communications Subsystem (full) Software Subsystem (full) Avionics Subsystem (fully integrated) GN&C Subsystem (fully integrated) Rationale: This build completes the integration of all control and communication systems, enabling full autonomous operations and ground control capabilities.
4	B4 Logistics and Full System Integration	Logistics & Storage Subsystem (full) Harness Subsystem (full) Propulsion Subsystem (full) Structure & Mechanisms Subsystem (fully integrated) All remaining subsystems fully integrated and optimized Rationale: This final build completes the integration of all subsystems, resulting in a fully assembled and tested system ready for launch.
5	B5 Environmental Testing and Launch Preparation	Full system environmental testing (thermal vacuum, vibration, EMI/EMC) Simulated microgravity testing of critical functions Final software validation and verification Launch vehicle integration testing Rationale: This build focuses on comprehensive environmental testing and final preparations for launch, ensuring the system can withstand launch conditions and operate in the space environment.

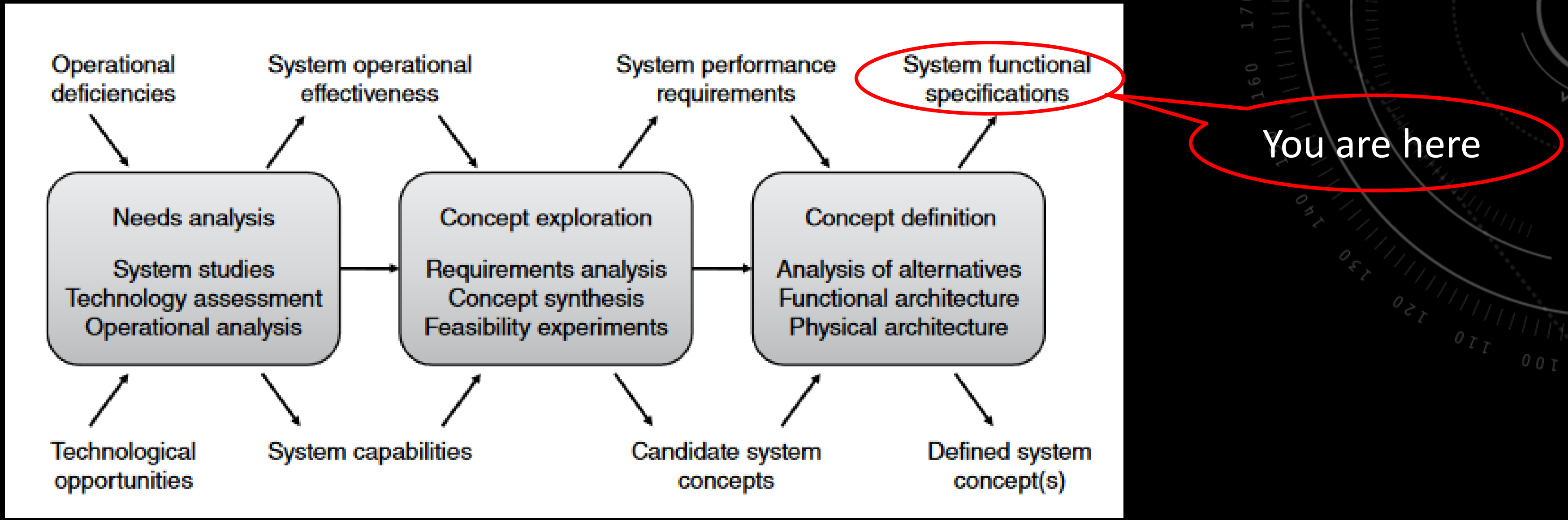
RISK MANAGEMENT

RISK MANAGEMENT

- Structured Methodology:
  - Identifies, assesses, and mitigates risks throughout AOMS's lifecycle.
  - Proactive and adaptive approach ensures early identification and continuous monitoring.
- Risk Assessment Matrix:
  - Evaluates risks on a scale of 1 to 5, prioritizing high-likelihood, high-consequence risks.
  - Focus areas: System performance, safety, and mission success.
- Mitigation Strategies:
  - Real-time monitoring, process optimization, automated inspection, and emergency procedures.
  - Integrated into subsystems, with testing such as Thermal-Manufacturing Integration and End-to-End Production Cycle Tests.
- Risk Reduction Outcome:
  - Successful mitigation measures reduced risk severity.
  - Ongoing monitoring to track effectiveness and ensure system reliability during operations

ID	Risk Description	Initial LxC	Final LxC	Impact Summary
1	Microgravity Manufacturing Process Instability	4 X 4	2 X 2	Variations in microgravity conditions could disrupt ZBLAN fiber production, impacting quality and equipment.
2	Fiber Pulling Process Continuity	3 X 3	1 X 1	Interruptions in fiber pulling can lead to production delays and quality issues, reducing operational efficiency.
3	Remote Quality Control System Reliability	2 X 5	1 X 2	Quality control malfunctions could allow undetected defects, compromising product quality and yield.
4	Thermal Management System Inefficiency	3 X 4	1 X 2	Inadequate thermal control could lead to temperature fluctuations, impacting fiber quality and system performance.
5	Material Handling Automation Errors	3 X 3	1 X 1	Errors in automated material handling could cause contamination, waste, and damage, reducing production quality and efficiency.





SYSTEM SPECIFICATION (A-SPEC)

SYSTEM SPECIFICATION (A-SPEC)

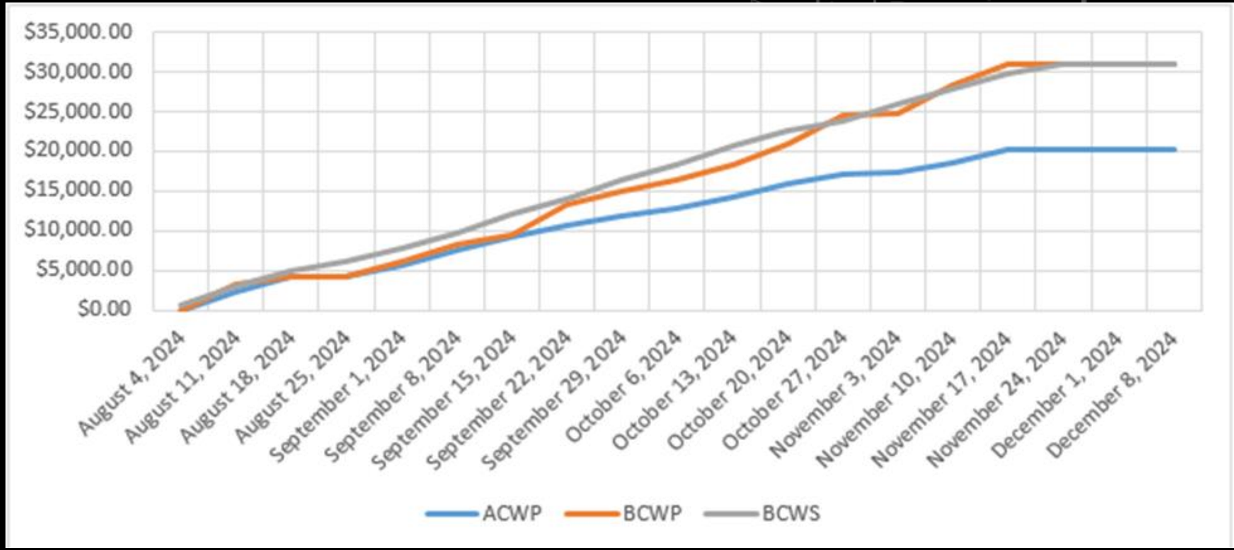
- Purpose:
  - The A-Spec (System Specification) defines the functional and performance requirements for the AOMS system, ensuring all subsystems meet mission objectives.
- Key Elements:
  - Requirements Hierarchy: Organized by operational, performance, functional, and constraint requirements, aligned with the needs identified in earlier phases.
  - Key Performance Parameters (KPPs): Critical, non-negotiable requirements that are essential for mission success.
  - Verification Methods: Each requirement includes defined methods for verification, ensuring compliance (e.g., inspection, test, analysis).
- Outcome:
  - Provides a comprehensive blueprint for the AOMS system, aligning design, testing, and validation with mission goals.

Report	Total	Quantitative	% Quantitative	Binary	Qualitative
Requirements Analysis Report	95	42	44%	28	19
Functional Analysis Report	101	47	46%	28	20
Trade Study Report	108	60	56%	28	20
Concept Design Report	108	60	56%	28	20
Test and Evaluation Plan	108	60	56%	28	20
System Specification	108	76	70%	32	0

CONCLUSION: SCHEDULE ANALYSIS, LESSONS LEARNED, & RECOMMENDATIONS

EARNED VALUE MANAGEMENT ANALYSIS

- Schedule Performance:
  - Schedule Variance (SV) and Schedule Performance Index (SPI) tracked milestones against planned timelines.
  - Initial delays during Project Setup & Research reflected negative SV in August and September 2024.
  - By October, schedule recovery was evident, with faster-than-expected progress in later phases, driven by MBSE efficiencies.
  - Despite some delays in CDR and FAR reports, positive SPI was maintained in November and December.
- Cost Performance:
  - Early cost overruns due to intensive Project Setup & Research efforts.
  - Application of MBSE and risk management strategies helped reduce costs, leading to savings in later stages, particularly in A-Spec and Test Plan development.



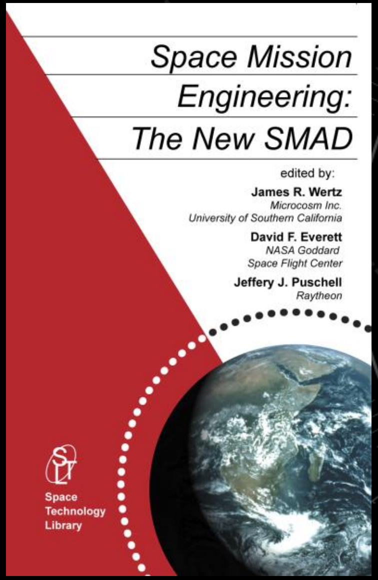
Name	Cost	BCWP	BCWS	ACWP	EAC	CV	SV	SPI	CPI	TCPI
Advanced Orbital Manufacturing System	$20,225.00	$30,900.00	$30,900.00	$20,225.00	$20,225.00	$10,675.00	$0.00	1	1.53	0
Concept Approved	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	0	0	0
Project Setup & Research	$500.00	$1,000.00	$1,000.00	$500.00	$500.00	$500.00	$0.00	1	2	0
Project Proposal	$3,700.00	$3,200.00	$3,200.00	$3,700.00	$3,700.00	($500.00)	$0.00	1	0.86	-0
Requirements Analysis and CONOPS Report	$3,400.00	$4,200.00	$4,200.00	$3,400.00	$3,400.00	$800.00	$0.00	1	1.24	0
Functional Analysis Report	$3,100.00	$5,000.00	$5,000.00	$3,100.00	$3,100.00	$1,900.00	$0.00	1	1.61	0
Trade Study Report	$2,100.00	$3,000.00	$3,000.00	$2,100.00	$2,100.00	$900.00	$0.00	1	1.43	0
Conceptual Design Report	$3,000.00	$4,500.00	$4,500.00	$3,000.00	$3,000.00	$1,500.00	$0.00	1	1.5	0
Test and Evaluation Plan	$1,400.00	$3,500.00	$3,500.00	$1,400.00	$1,400.00	$2,100.00	$0.00	1	2.5	0
Risk Management Plan	$600.00	$2,000.00	$2,000.00	$600.00	$600.00	$1,400.00	$0.00	1	3.33	0
A-SPEC	$625.00	$2,000.00	$2,000.00	$625.00	$625.00	$1,375.00	$0.00	1	3.2	0
Final Report & Defense	$1,800.00	$2,500.00	$2,500.00	$1,800.00	$1,800.00	$700.00	$0.00	1	1.39	0
End of Term	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	0	0	0

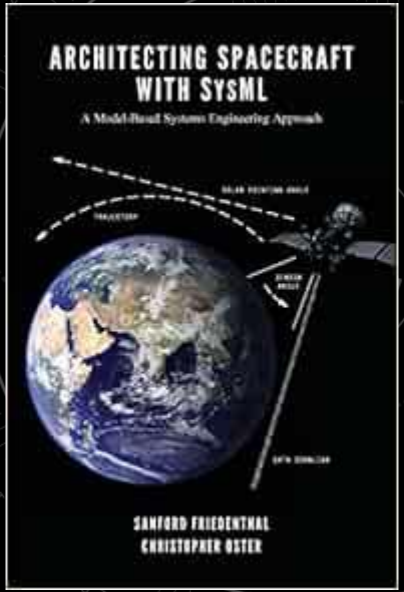
RECOMMENDATIONS

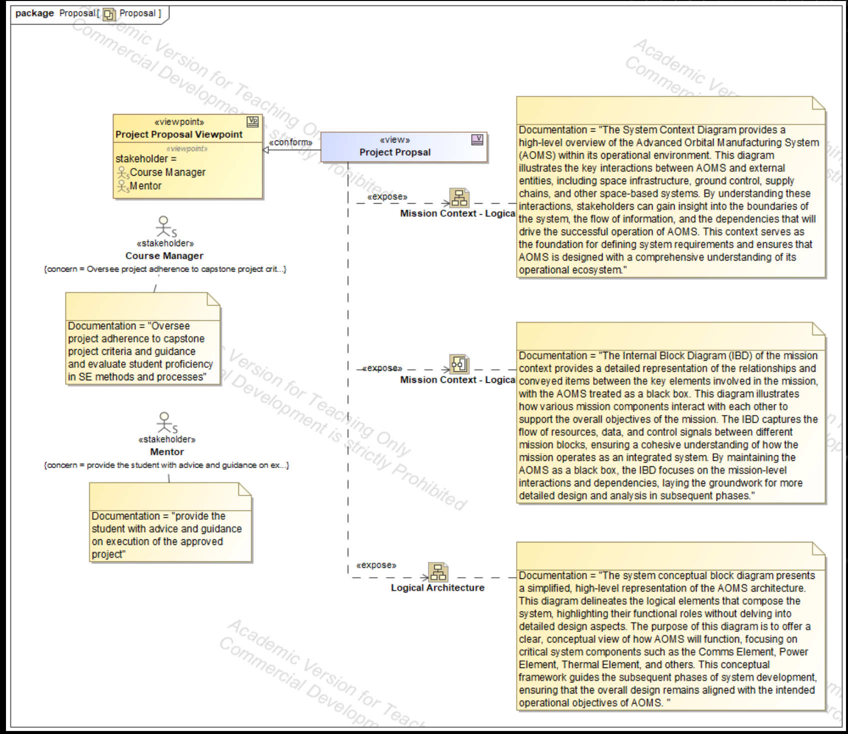
- Consider a Student Mentoring Program:
  - Implement a mentoring system where past students provide granular feedback to those currently working on projects.
  - Benefits:
    - Support for navigating challenges and refining approaches.
    - Guidance on best practices, common pitfalls, and effective strategies for systems design, requirements, and verification.
    - Reduced advisor workload and more peer-supported learning.
- Consider Integrating MBSE into T&E Course:
  - Incorporate MBSE tools like MagicDraw into the Test & Evaluation (T&E) course.
  - Benefits:
    - Enhances simulation and visualization of test cases.
    - Ensures tests align with system requirements and interactions.
    - Provides hands-on experience with tools used in industry, improving system validation and verification.

LESSONS LEARNED

- Passion-Driven Projects:
  - Choosing a topic you're passionate about keeps you motivated through long project phases.
  - Activities like STEM mentoring and designing a mission patch help connect with the significance of the work.
- Consult Reference Architectures:
  - Sanford Friedenthal's reference architecture ensured best practices and improved system design
- Stakeholder Engagement:
  - Continuous feedback, especially from experts like Lynn Harper, refines system requirements and aligns them with real-world needs and market demands.
- Meta Models & Model Organization:
  - Meta models clarify relationships and ensure consistency, enhancing communication and reducing errors.
  - ISO/IEC/IEEE 42010:2022 provided guidance on structuring viewpoints, ensuring clarity and improving report generation.
- Harnessing Metachain Navigation:
  - Using metachains and generic tables streamlines requirement-tracing and aids in visualizing dependencies.
- Requirements Tracing to Functions:
  - After initial tracing, evaluate if the right functions and requirements are identified.
  - Avoid forcing relationships that aren't fully accurate, as this can cause inconsistencies.
  - Functional decomposition and activity diagrams are crucial to ensure meaningful relationships. Careful tracing avoids compromising system integrity.

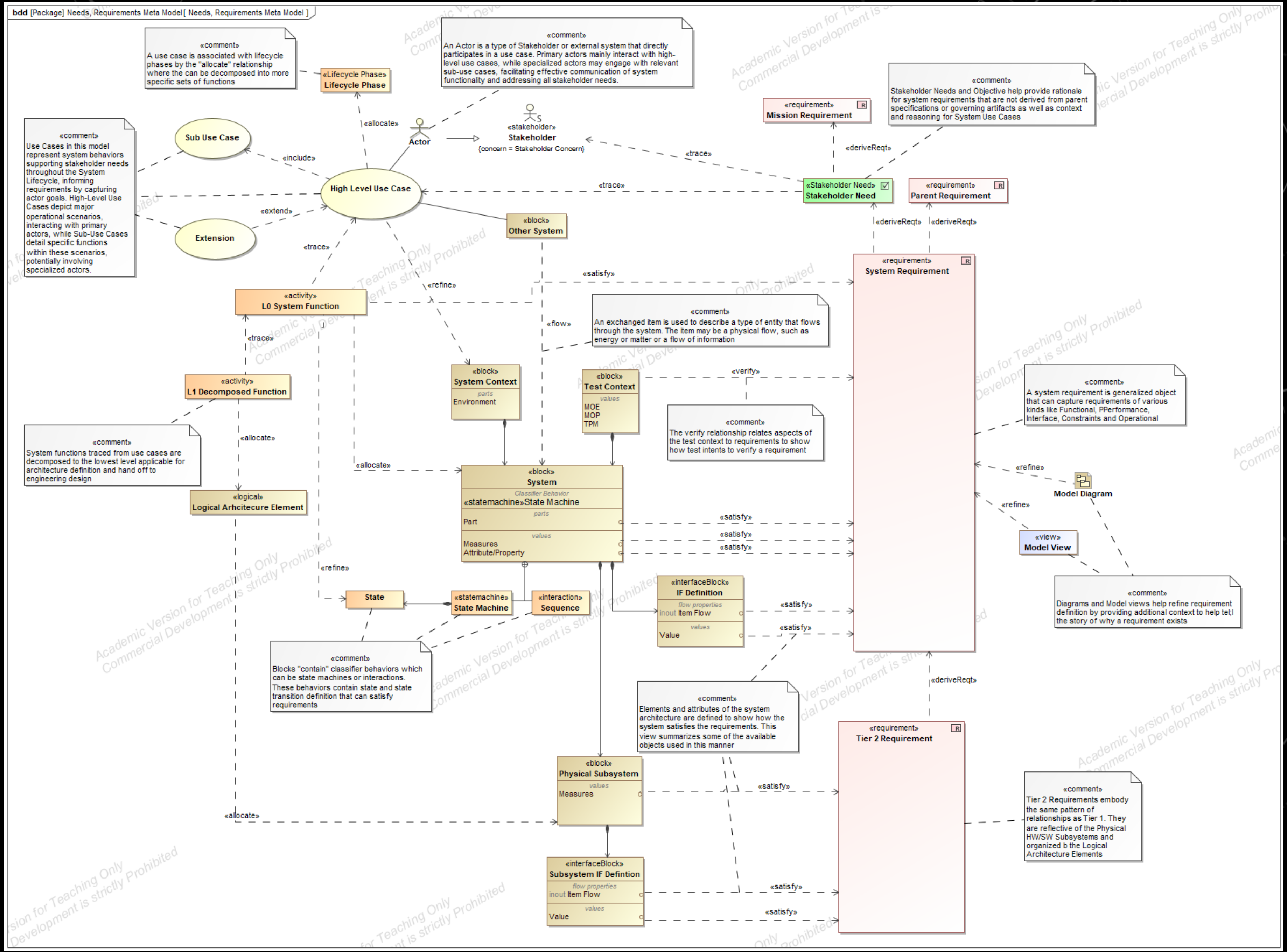




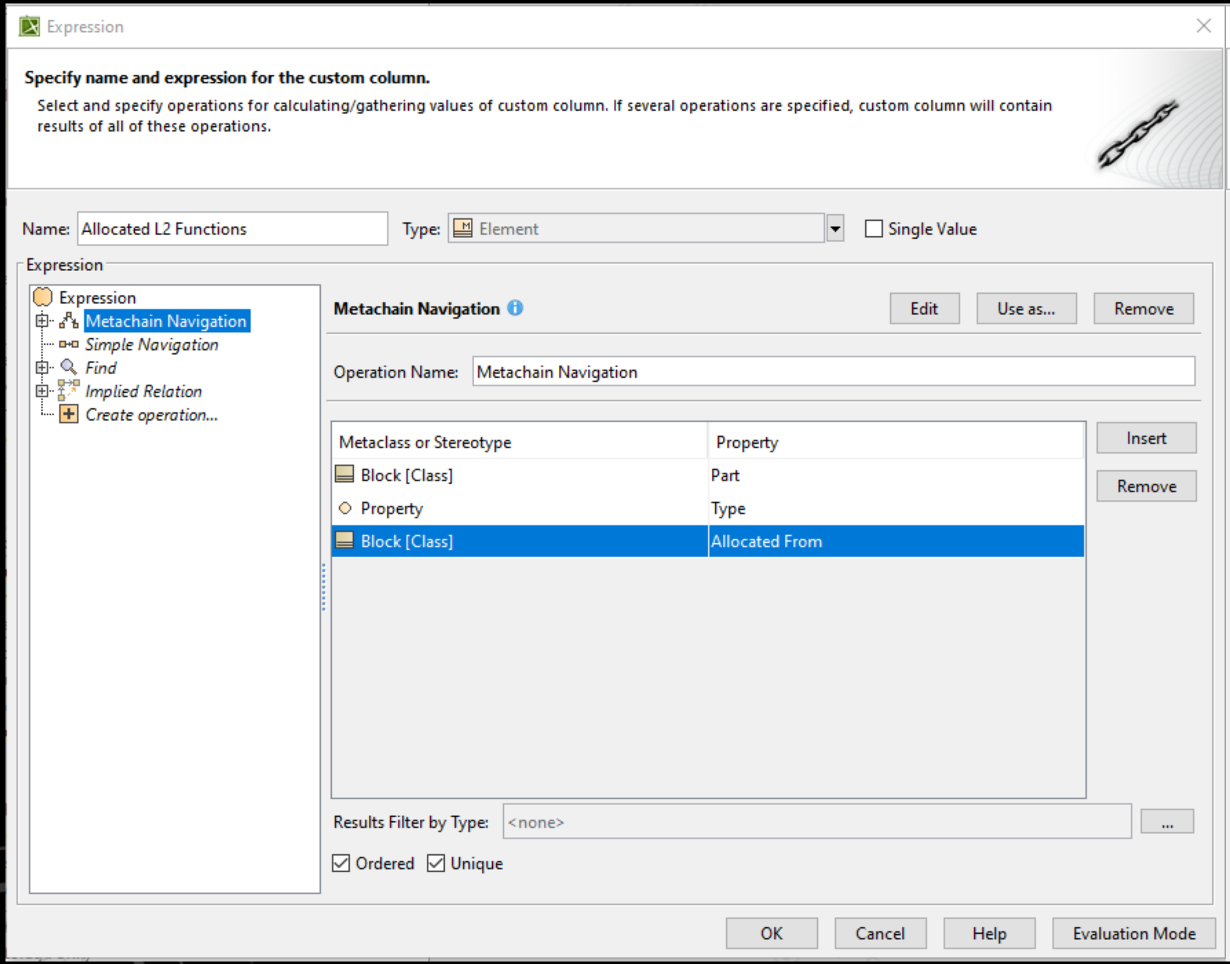


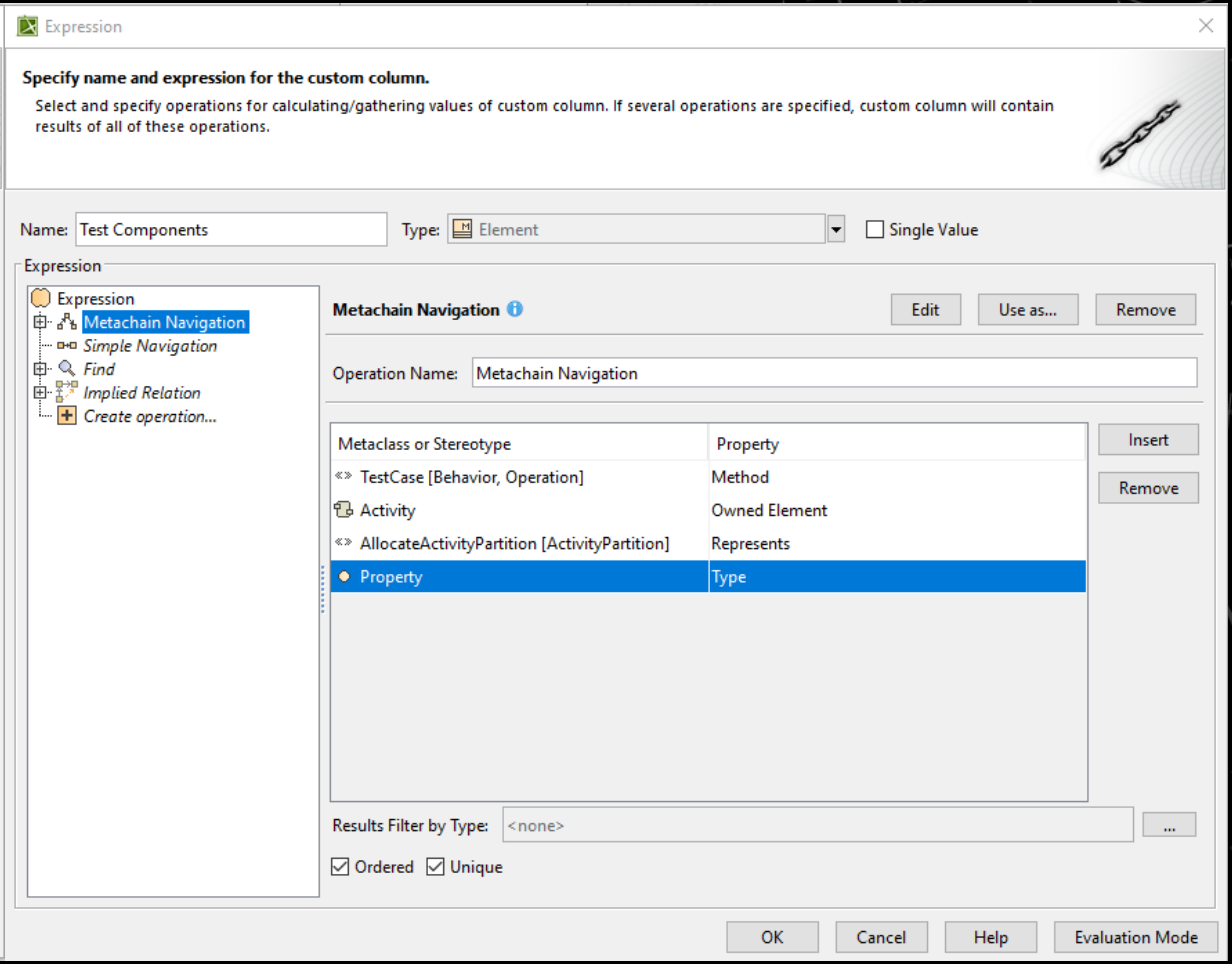
THANK YOU!

META MODEL


bdd [Package] Needs, Requirements Meta Model[Needs, Requirements Meta Model]
«comment»
A use case is associated with lifecycle phases by the "allocate" relationship where the can be decomposed into more specific sets of functions
«Lifecycle Phase»
Lifecycle Phase
«comment»
An Actor is a type of Stakeholder or external system that directly participates in a use case. Primary actors mainly interact with high-level use cases, while specialized actors may engage with relevant sub-use cases, facilitating effective communication of system functionality and addressing all stakeholder needs.
«comment»
Stakeholder Needs and Objective help provide rationale for system requirements that are not derived from parent specifications or governing artifacts as well as context and reasoning for System Use Cases
«requirement»
Mission Requirement
«comment»
Use Cases in this model represent system behaviors supporting stakeholder needs throughout the System Lifecycle, informing requirements by capturing actor goals. High-Level Use Cases depict major operational scenarios, interacting with primary actors, while Sub-Use Cases detail specific functions within these scenarios, potentially involving specialized actors.
Sub Use Case
«allocate»
Actor
«stakeholder»
Stakeholder
{concern = Stakeholder Concern}
«trace»
«deriveReqt»
«include»
High Level Use Case
«trace»
«Stakeholder Need»
Stakeholder Need
«requirement»
Parent Requirement
«extend»
Extension
«block»
Other System
«deriveReqt»
«deriveReqt»
«trace»
«requirement»
System Requirement
«refine»
«satisfy»
«activity»
L0 System Function
«flow»
«comment»
An exchanged item is used to describe a type of entity that flows through the system. The item may be a physical flow, such as energy or matter or a flow of information
«trace»
«verify»
«block»
System Context
parts
Environment
«block»
Test Context
values
MOE
MOP
TPM
«activity»
L1 Decomposed Function
«comment»
A system requirement is generalized object that can capture requirements of various kinds like Functional, PPerformance, Interface, Constraints and Operational
«comment»
The verify relationship relates aspects of the test context to requirements to show how test intents to verify a requirement
«comment»
System functions traced from use cases are decomposed to the lowest level applicable for architecture definition and hand off to engineering design
«allocate»
«allocate»
«refine»
«block»
System
Classifier Behavior
«statemachine»State Machine
parts
Part
values
Measures
Attribute/Property
Model Diagram
«logical»
Logical Arhcitecure Element
«refine»
«satisfy»
«satisfy»
«satisfy»
«view»
Model View
«refine»
State
«statemachine»
State Machine
«interaction»
Sequence
«interfaceBlock»
IF Definition
flow properties
inout Item Flow
values
Value
«satisfy»
«satisfy»
«comment»
Diagrams and Model views help refine requirement definition by providing additional context to help tel;l the story of why a requirement exists
«comment»
Blocks "contain" classifier behaviors which can be state machines or interactions. These behaviors contain state and state transition definition that can satisfy requirements
«comment»
Elements and attributes of the system architecture are defined to show how the system satisfies the requirements. This view summarizes some of the available objects used in this manner
«deriveReqt»
«requirement»
Tier 2 Requirement
«block»
Physical Subsystem
values
Measures
«satisfy»
«allocate»
«comment»
Tier 2 Requirements embody the same pattern of relationships as Tier 1. They are reflective of the Physical HW/SW Subsystems and organized b the Logical Architecture Elements
«interfaceBlock»
Subsystem IF Defintion
flow properties
inout Item Flow
values
Value
«satisfy»
«satisfy»
Academic Version for Teaching Only
Commercial Development is strictly Prohibited

META CHAINS


Expression
Specify name and expression for the custom column.
Select and specify operations for calculating/gathering values of custom column. If several operations are specified, custom column will contain results of all of these operations.
Name: Allocated L2 Functions
Type: Element
Single Value
Expression
Expression
Metachain Navigation
Simple Navigation
Find
Implied Relation
Create operation...
Metachain Navigation
Edit
Use as...
Remove
Operation Name: Metachain Navigation
Metaclass or Stereotype
Property
Block [Class]
Part
Property
Type
Block [Class]
Allocated From
Insert
Remove
Results Filter by Type: <none>
...
Ordered
Unique
OK
Cancel
Help
Evaluation Mode


Expression
Specify name and expression for the custom column.
Select and specify operations for calculating/gathering values of custom column. If several operations are specified, custom column will contain results of all of these operations.
Name: Test Components
Type: Element
Single Value
Expression
Expression
Metachain Navigation
Simple Navigation
Find
Implied Relation
Create operation...
Metachain Navigation
Edit
Use as...
Remove
Operation Name: Metachain Navigation
Metaclass or Stereotype
Property
TestCase [Behavior, Operation]
Method
Activity
Owned Element
AllocateActivityPartition [ActivityPartition]
Represents
Property
Type
Insert
Remove
Results Filter by Type: <none>
...
Ordered
Unique
OK
Cancel
Help
Evaluation Mode