FINAL REPORT

for the

Advanced Orbital Manufacturing System for ZBLAN Optical Fiber Production

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1 Executive Summary

The Advanced Orbital Manufacturing Station (AOMS) is a next-generation platform designed to enable large-scale, automated in-space manufacturing, with an initial focus on ZBLAN fiber production. This project explored the Concept Definition phase of the systems engineering lifecycle, including needs analysis, concept exploration, and concept definition, to develop a robust, scalable system model that supports commercial viability and operational success.

This report outlines the methodology and results of applying Model-Based Systems Engineering (MBSE) practices to AOMS, focusing on stakeholder-driven design, requirements development, functional decomposition, and early-phase trade studies. The design emphasizes modularity, automation, and integration with resupply capsules for streamlined operations and product retrieval. Leveraging frameworks like ISO 42010 for architecture development and insights from Sanford Friedenthal's Architecting Spacecraft with SysML, the project builds on industry best practices to align stakeholder needs with system capabilities.

The Concept Definition phase began with a comprehensive Needs Analysis, identifying the demand for microgravity-enabled manufacturing and aligning with U.S. ISAM National Strategy objectives. Foundational artifacts clarified the system's operational environment, interfaces, and preliminary architecture. A detailed Risk Assessment identified potential technical and operational challenges, informing mitigation strategies to enhance reliability and performance.

Key activities included developing a comprehensive set of requirements and tracing them to functions, identifying critical interfaces, and planning for validation and verification through detailed test cases. Functional Flow Block Diagrams and activity models captured the system's operations, while trade studies informed critical technology choices, such as the selection of the Deployable Panel Radiator, optimizing performance and cost-effectiveness. These efforts culminated in an initial architecture that balances technical feasibility, economic potential, and mission objectives.

The project's test plan outlines a phased integration approach, including subsystem testing and full-system qualification under operational conditions. This ensures all components meet defined requirements and function cohesively in the space environment.

Looking ahead, the project establishes a solid foundation for transitioning to the Preliminary Design phase. Recommended next steps include conducting a System Requirements Review (SRR), refining architecture models, and developing detailed engineering analyses. Simulations and prototypes will further validate the system design.

This project not only demonstrates the feasibility of the AOMS concept but also highlights the value of MBSE practices in developing complex space systems. It provides actionable insights for future space manufacturing initiatives and serves as a personal milestone in advancing my skills in systems engineering. Through a combination of technical rigor, creative problem-solving, and stakeholder-driven design, this project represents a meaningful step toward realizing the potential of in-space manufacturing while simultaneously marking a significant achievement in my academic and professional journey.

2 Project Objective and Approach

2.1 Project Objective

The development of In-Space Servicing, Assembly and Manufacturing (ISAM) capabilities has emerged as a national priority, reflecting the United States' commitment to maintaining leadership in space exploration and utilization. The White House's ISAM National Strategy, released in 2022, underscores the transformative potential of these technologies in advancing scientific innovation, economic growth and commercial development in space [1]. ISAM is poised to revolutionize space operations by enabling the inspection, repair, upgrade and construction of space assets directly in orbit, significantly expanding the performance and longevity of space systems.

A critical aspect of ISAM's importance lies in its ability to overcome current limitations in space technology deployment. Rocket fairing diameter limitations restrict the size and number of instruments that can be fielded in orbit for science and national security missions. In turn, these constraints place definite limits on the information that can be obtained from spaceborne payloads [2]. ISAM offers five key advantages that address these constraints:

1. Deployment of structures beyond Earth-launch size limitations
2. Enhanced flexibility and resilience through on-orbit payload modifications
3. Cost savings from reduced structural mass for launch
4. Reduced ground-based testing requirements
5. Creation of structures impossible to build in Earth's gravity

These advantages not only expand technological possibilities but also offer significant economic benefits. For instance, the on-orbit assembly of a large space telescope over three launches could potentially save $12.8 billion compared to traditional approaches [2].

The Advanced Orbital Manufacturing System (AOMS) aims to develop a comprehensive framework for manufacturing high-value products in microgravity environments. This system will integrate launch operations, space station modules, specialized manufacturing equipment, and supply chain management to enable efficient production of materials that benefit from microgravity conditions.

Recent experiments on the International Space Station have demonstrated the ability to produce more than seven miles (11.9 km) of optical fiber in a single month, with individual draws exceeding 2,296 feet (700 meters) [3]. This approach not only improves the quality of the fibers but also increases production efficiency, making it feasible to meet the growing demand for high-performance optical fibers in various industries. The telecommunications sector is facing exponential growth in bandwidth transmission. With almost half of the world's population not yet online and higher bandwidth applications like 5G networks, 4K streaming, and virtual reality on the horizon, the need for high performance fiber optics will not diminish [4]. With ZBLAN fibers, laser repeaters might only be needed after thousands of kilometers instead of hundreds of kilometers [5].

The economic potential of this project is substantial, with ZBLAN fibers currently selling for $175 to $1000 per meter [6]. Given that one kg of ZBLAN yields 2.2 kilometers of fiber, the potential revenue per kilogram ranges from $0.385 million to $2.2 million [6], far exceeding associated launch costs, which are projected to decrease to about $30 per kilogram by 2040 in a best-case scenario [7].

This approach positions AOMS as a pivotal system in advancing U.S. capabilities of space-based manufacturing and unlocking new possibilities for high-value products like ZBLAN optical fibers. It aligns with broader industry trends as the global space economy, valued at over $400 billion in 2022 [8], is projected to reach $1 trillion in annual revenue by 2040 [7], further contributing to the nation’s strategic goals of accelerating the emerging ISAM commercial industry and inspiring a future space workforce.

2.2 Project Approach

The approach to the development of the AOMS is grounded in a systems engineering methodology that follows an iterative process, emphasizing the importance of refining system concepts and requirements at each stage. In the Concept Definition lifecycle phase, this process consists of needs analysis, concept exploration, and concept definition to ensure the system's architecture and design meet the project's objectives while remaining adaptable to new insights and evolving requirements. The subphases of this lifecycle are further detailed in 3.2 Scope.

Throughout the lifecycle, a key aspect of the approach is the application of Model-Based Systems Engineering (MBSE) principles. MBSE tools are used to represent the system and its components in a visual and standardized format, allowing for better communication across teams and providing a clear understanding of the system's behavior and architecture. This iterative MBSE process ensures that all system elements are correctly integrated, verified, and validated as the project progresses.

Additionally, this approach includes ongoing stakeholder engagement and validation to ensure that the AOMS is aligned with both technical feasibility and market needs. Frequent reviews, assessments, and updates to the system concept will help to refine the design, ensuring that AOMS will be capable of achieving its goal of advancing space-based manufacturing while contributing to the broader national and commercial objectives of ISAM.

This approach ensures that the development of AOMS remains adaptable and capable of incorporating emerging technologies and lessons learned throughout the lifecycle, ultimately leading to a system that meets the project’s objectives in a cost-effective, efficient, and sustainable manner.

3 Significance and Scope of the Work

3.1 Significance

The AOMS is a groundbreaking project with the potential to significantly impact the future of space-based manufacturing. From the perspective of the products and results produced by the project, the AOMS will provide a revolutionary capability for in-space production of critical materials, with the first application focused on the production of ZBLAN fiber in microgravity. The significance of this work is immense, as it marks a step toward a self-sustaining space industry where high-value materials can be produced directly in space, reducing reliance on Earth-based manufacturing and launching complex supply chains.

From a student’s perspective, this project represents a unique convergence of systems engineering, space exploration, and advanced manufacturing technologies. It highlights the importance of integrating multiple engineering disciplines—such as power, communications, propulsion, and thermal systems—into a cohesive solution capable of operating in the challenging environment of space. The successful development and deployment of AOMS will provide valuable insights into the practical challenges of building scalable, automated manufacturing systems in orbit, paving the way for future in-space industries.

The ability to produce ZBLAN fiber, a material with unique optical properties, in space will enable advances in telecommunications and other industries dependent on fiber optics. The ZBLAN fiber produced by AOMS will support the broader goal of enhancing space infrastructure, enabling more efficient satellite communications, and contributing to the overall reduction of space mission costs by creating essential materials in orbit rather than launching them from Earth.

Beyond the immediate application of ZBLAN fiber production, AOMS holds the potential for further advancements in space-based manufacturing, with the possibility of scaling the system to produce a range of materials and products in space. This ability to adapt the AOMS for various manufacturing applications ensures that its impact will extend far beyond the project’s initial objectives, offering substantial benefits to future space exploration, scientific research, and commercial ventures.

3.2 Scope

The Concept Definition phase is a pivotal period in the systems engineering lifecycle where the foundational elements of the Advanced Orbital Manufacturing System (AOMS) for ZBLAN optical fiber production are established. This phase encompasses three distinct stages: Needs Analysis and Requirements Definition, Concept Exploration, and Preliminary Concept Definition. Each of these stages builds upon the previous one, refining the AOMS concept through iterative evaluation, analysis, and decision-making. The overall systems engineering lifecycle model is depicted below in Figure 1.

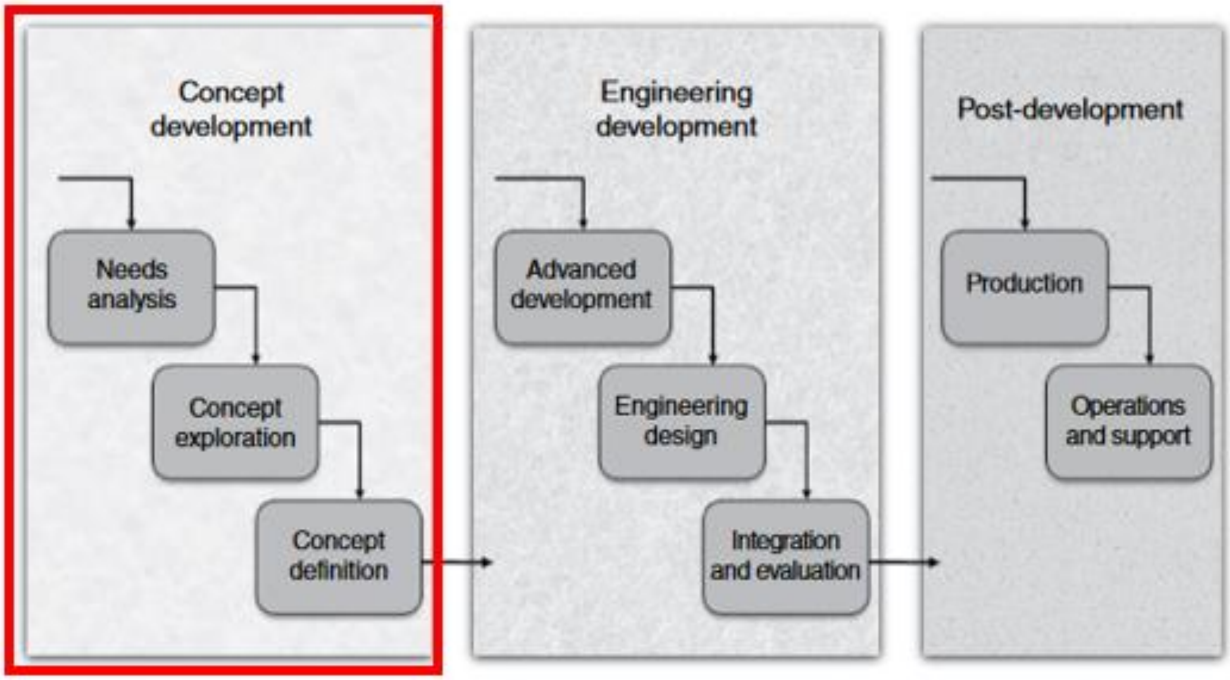


Figure 1: System Lifecycle model with relevant phase highlighted [9]

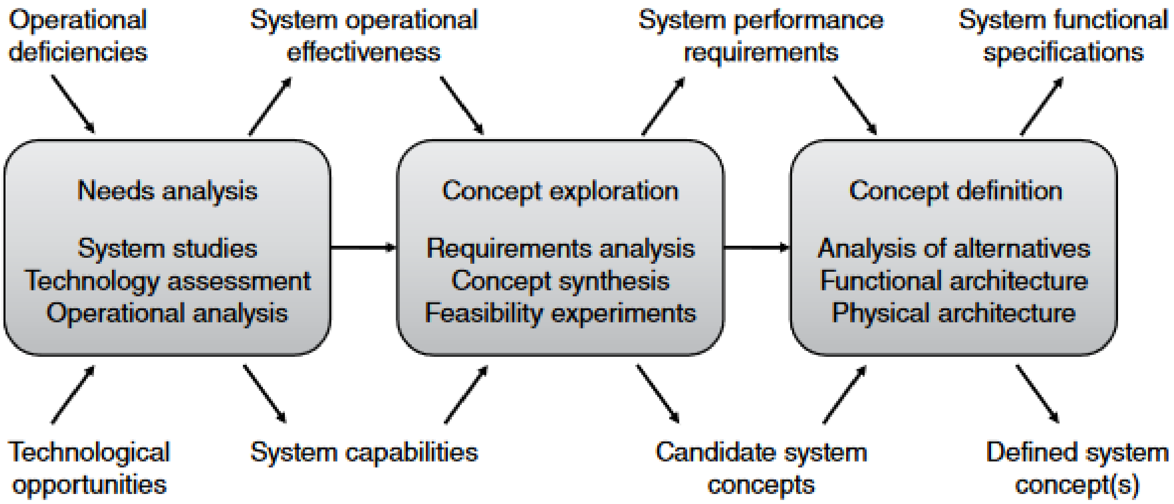


Figure 2: Concept Development Lifecycle Phase process model [9]

The concept development phase consists of three major subphases, each with distinct activities. This process model is illustrated in Figure 2. The following sections define each subphase in the context of the AOMS project, detailing the relevant activities and outputs.

1. **Needs Analysis and Requirements Definition**
   The Needs Analysis phase focuses on identifying and defining the need for the AOMS system. The first task is to answer key questions: "What capabilities are required to manufacture ZBLAN fiber in space?" and "What are the operational constraints and challenges that must be addressed?" This phase critically examines the current gaps in space manufacturing and assesses the technological feasibility of fulfilling these needs. It culminates in a description of the system's essential capabilities and operational effectiveness, which forms the basis for the system's early conceptual model. These outputs, while not formal requirements yet, set the direction for the system's development and will eventually evolve into more detailed performance specifications.

2. **Concept Exploration**
   The Concept Exploration phase shifts focus to exploring different potential design concepts that could satisfy the system's needs identified during the earlier analysis phase. This stage aims to answer: "What performance levels are required to meet the identified needs?" and "Is there a feasible approach to achieving this performance?" In this phase, a variety of system concepts are evaluated for their feasibility, considering factors like cost, complexity, and performance. Several candidate designs are developed and assessed using techniques such as trade studies, technology assessments, and expert judgment. The outcome of this phase is an initial set of system performance requirements and a list of candidate system concepts, which provide the foundation for the next phase of concept definition.

3. **Preliminary Concept Definition**
   Building on the exploration of potential concepts, the Preliminary Concept Definition phase works to select the most promising design for the AOMS. In this phase, various concepts are compared in terms of their performance, operational utility, risk, and cost. The goal is to identify the system concept that achieves the best balance of these factors, ensuring that the system will meet mission objectives while staying within technical and budgetary constraints. The output of this phase includes refined functional specifications and a detailed system architecture that outlines key subsystems and their interactions. This documentation provides a clear description of the selected concept, detailing both functional and physical perspectives of the system, and serves as a foundation for further development in the subsequent engineering design phases.

The work conducted during these three stages will produce a comprehensive set of documents and analyses that lay the groundwork for the system's detailed design and development. These outputs will ensure that the AOMS system is not only technically feasible but also optimized for its intended mission. By the end of the Concept Definition phase, the project will have a clear set of requirements, an initial concept design, and a well-understood system architecture, ready to transition to the next phase of detailed engineering and development.

4 Project Proposal

The development of this proposal followed a structured systems engineering approach, aligned with the Concept Definition phase of the system lifecycle. The process began with a comprehensive Needs Analysis, identifying the critical demand for advanced in-space manufacturing capabilities within the context of the United States' ISAM National Strategy. A systematic examination of stakeholder needs, operational requirements, and market trends informed the articulation of the project's objectives and scope.

Key activities included the creation of foundational artifacts such as the Context Diagram, Conceptual Block Diagram, and Work Breakdown Structure. These tools provided clarity on the system's operational environment, interfaces, and preliminary architecture. Concurrently, a detailed Risk Assessment was performed, identifying potential technical, programmatic, and operational risks alongside mitigation strategies.

To ensure feasibility and alignment with industry goals, significant effort was devoted to defining Measures of Effectiveness (MOEs) and selecting analytical tools to estimate system performance. The schedule and milestones were developed with an earned value management framework to track progress against cost and schedule baselines.

The completed proposal synthesizes these efforts, presenting a cohesive plan for the AOMS. Detailed documentation of the process and its outcomes is included in Appendix A.

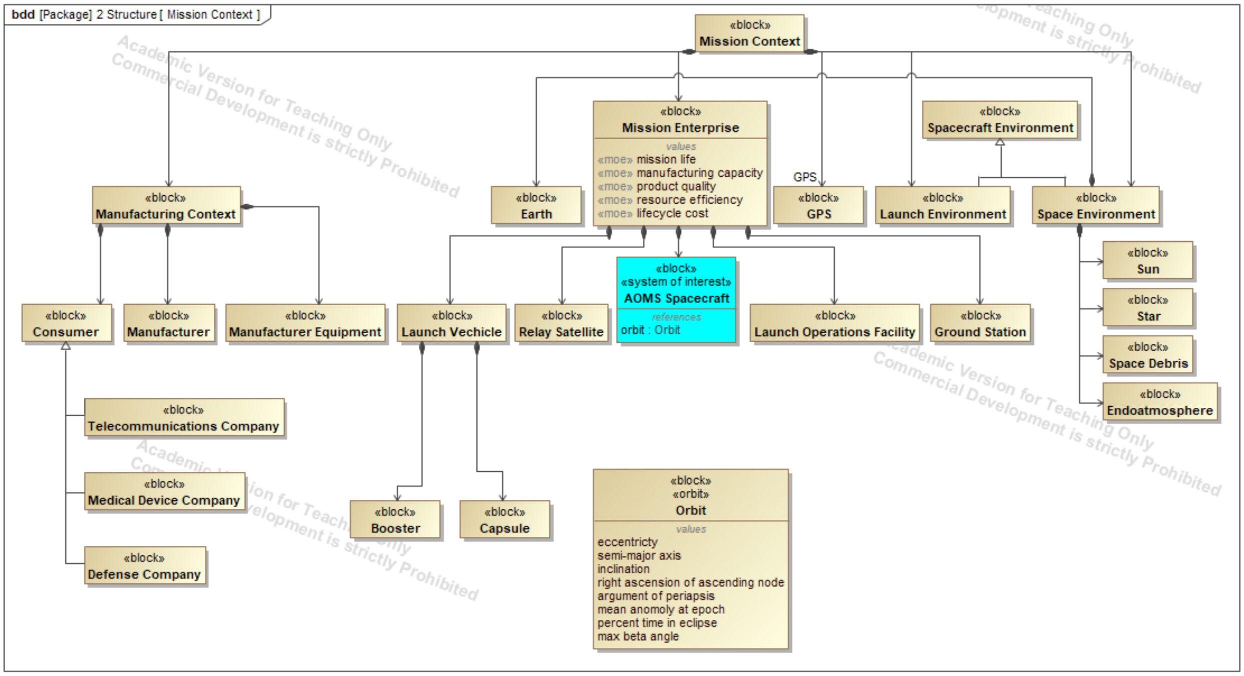


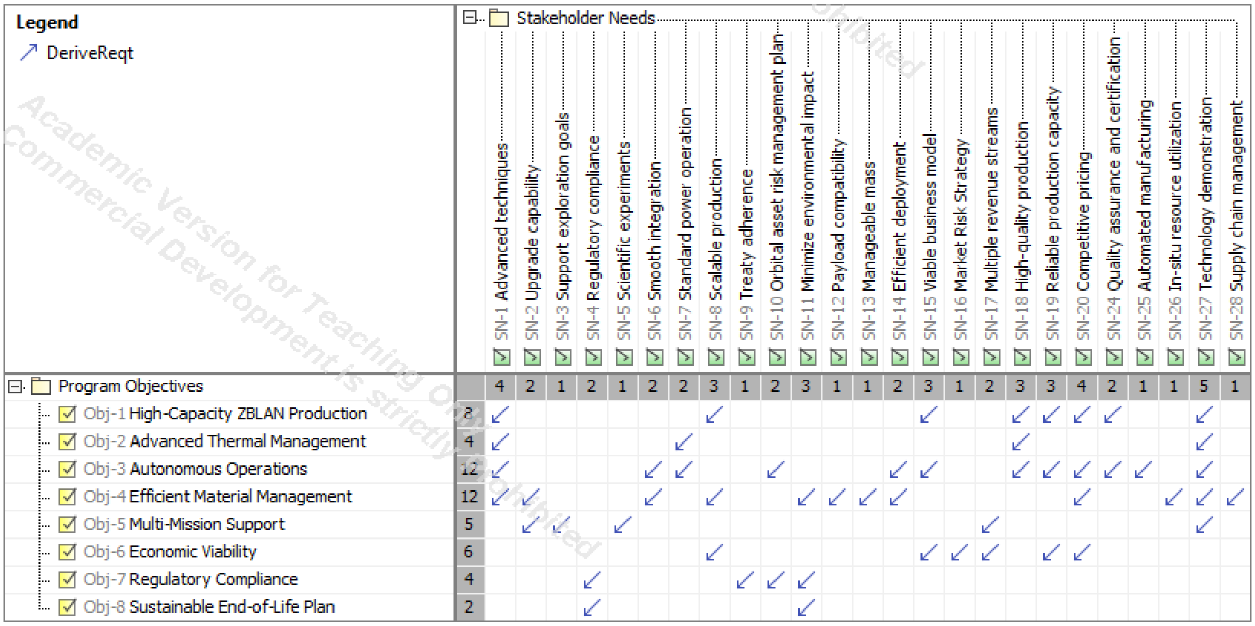
Figure 3: AOMS Mission Context Diagram

5 Requirements Analysis and Concept of Operations Report

The Requirements Analysis Report (RAR) for the AOMS was developed using a structured systems engineering approach to ensure the alignment of the platform's design and operations with stakeholder needs and mission objectives. The report begins with a Stakeholder Analysis, identifying key stakeholders and their interests in the project. This analysis is foundational, as it informs the subsequent requirements development process. Key stakeholders range from end-users requiring high-quality ZBLAN fibers, to financial investors focused on economic viability, and regulatory bodies concerned with compliance. A traceability matrix was created to map stakeholder needs to specific stakeholders, ensuring that all needs are addressed and potential conflicts are identified early. This matrix also serves as a tool to prioritize needs and allocate resources efficiently.

The Mission Needs & Objectives section synthesizes the stakeholder needs into a unified mission need, outlining the requirement for an orbital system capable of producing high-quality materials in microgravity using upgradable technologies. This system must be economically viable, regulatory-compliant, and able to scale production to meet increasing demand. The report includes a traceability matrix to align the AOMS program objectives with stakeholder needs, ensuring a balanced approach to development.

The Requirements Analysis section introduces the comprehensive requirements meta model, linking stakeholder needs, system functions, architectural elements, and verification methods. This meta model enables multi-directional traceability throughout the system lifecycle, ensuring consistency and supporting impact analysis.



Legend

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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				↙							↙														

Figure 4: Mission objectives traced to stakeholder needs

The Concept of Operations (CONOPS) section describes how the AOMS system will operate in Low Earth Orbit (LEO) with minimal human intervention once deployed. The operational phases include initialization, production monitoring, routine maintenance, resupply, and product retrieval. The CONOPS highlights how users will interact remotely with the system through telecommunication links, leveraging data from sensors, cameras, and diagnostic tools. The system's autonomous capabilities, such as fault detection and self-correction, ensure continuous and efficient production in orbit.

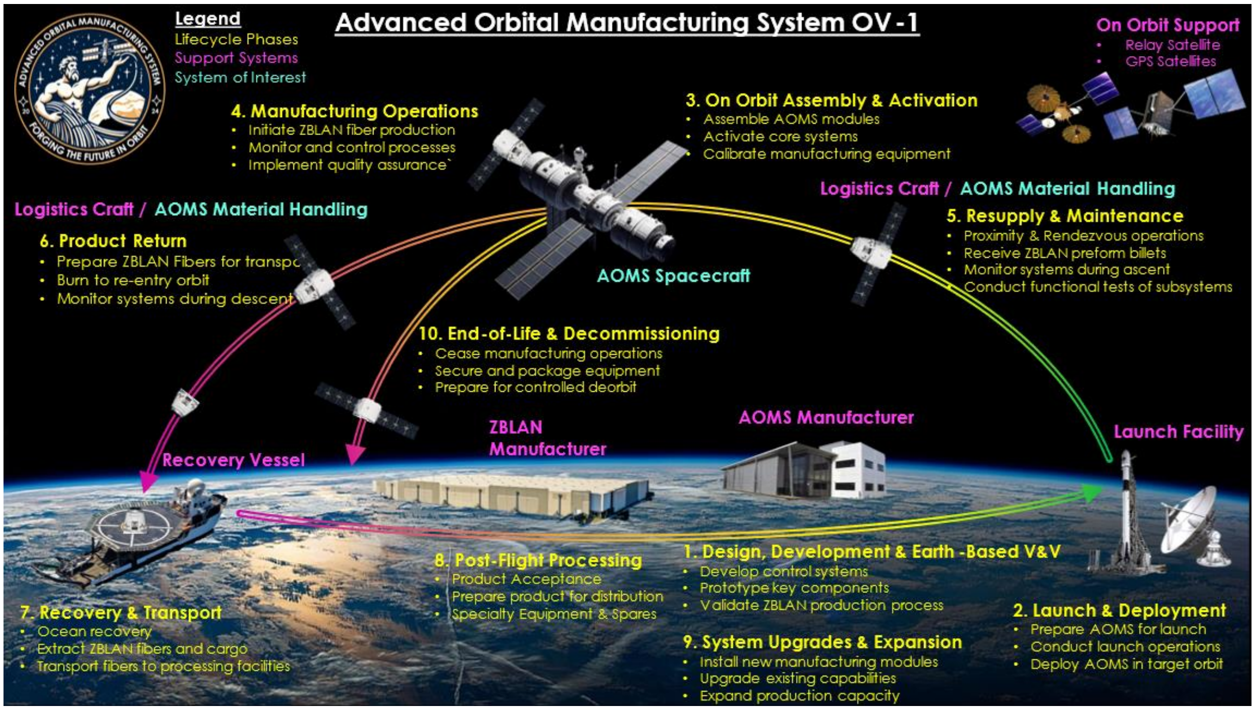


Figure 5: AOMS OV-1

By capturing detailed stakeholder needs, synthesizing mission objectives, incorporating a well-defined CONOPS, and implementing a robust requirements traceability framework, the RAR establishes a foundation for the design and development of the AOMS platform. This process ensures that the platform will meet the diverse needs of all stakeholders while supporting the technical, operational, and regulatory requirements necessary for successful deployment and operation in space. The detailed documentation of the requirements analysis process and its outcomes is provided in Appendix B, offering additional context and supporting information for the AOMS development.

6 Functional Analysis Report

The Functional Analysis Report (FAR) for the AOMS is a key component of the Concept Definition phase, breaking down the system's functions to ensure they are well understood and traceable to specific requirements. As an interim artifact in the systems engineering process, the FAR lays the groundwork for the system's design, identifying key functions and their interrelationships for successful implementation.

The FAR starts with a context diagram, which provides an overview of the system's inputs and outputs and defines interactions with external systems. This diagram serves as the foundation of the functional analysis, ensuring that the relationships between key components are well-defined.

Next, the system's functions are decomposed into eight core operational areas: (1) Conduct Autonomous Orbital Manufacturing Operations, (2) Maintain Operational Availability of Orbital Platform, (3) Ensure Compliance with Regulatory and Safety Standards, (4) Manage Resources and Logistics for Orbital Manufacturing, (5) Fault Recovery and Remote Override, (6) Monitor and Analyze System Performance, (7) On-Orbit Assembly, Activation, and Upgrade, and (8) Manage Orbital Position and Attitude. These functions are further broken down into sub-functions, defining specific tasks.

Each function uses verb-object syntax, ensuring consistency and clarity. For example, functions like "Conduct Autonomous Orbital Manufacturing Operations" and "Monitor and Analyze System Performance" are defined with specific inputs and outputs. Functional Flow Block Diagrams (FFBDs) and Activity Diagrams depict the sequence of operations, decision points, and parallel workflows within the system. N2 diagrams capture interfaces between functions, ensuring all inputs and outputs are logically structured. The FAR also includes a traceability matrix, linking each function to its corresponding requirements, verifying that all functional elements contribute to meeting project goals. By thoroughly decomposing the system's functions, the FAR provides a comprehensive foundation for the development of the AOMS system, ensuring that all stakeholder needs are addressed and that the system is positioned for successful deployment and operation in space.

Detailed documentation of the FAR is included in Appendix C, which captures the full scope of functional analysis, decomposition, and traceability, providing stakeholders with the necessary insights to proceed with the system's design and development.

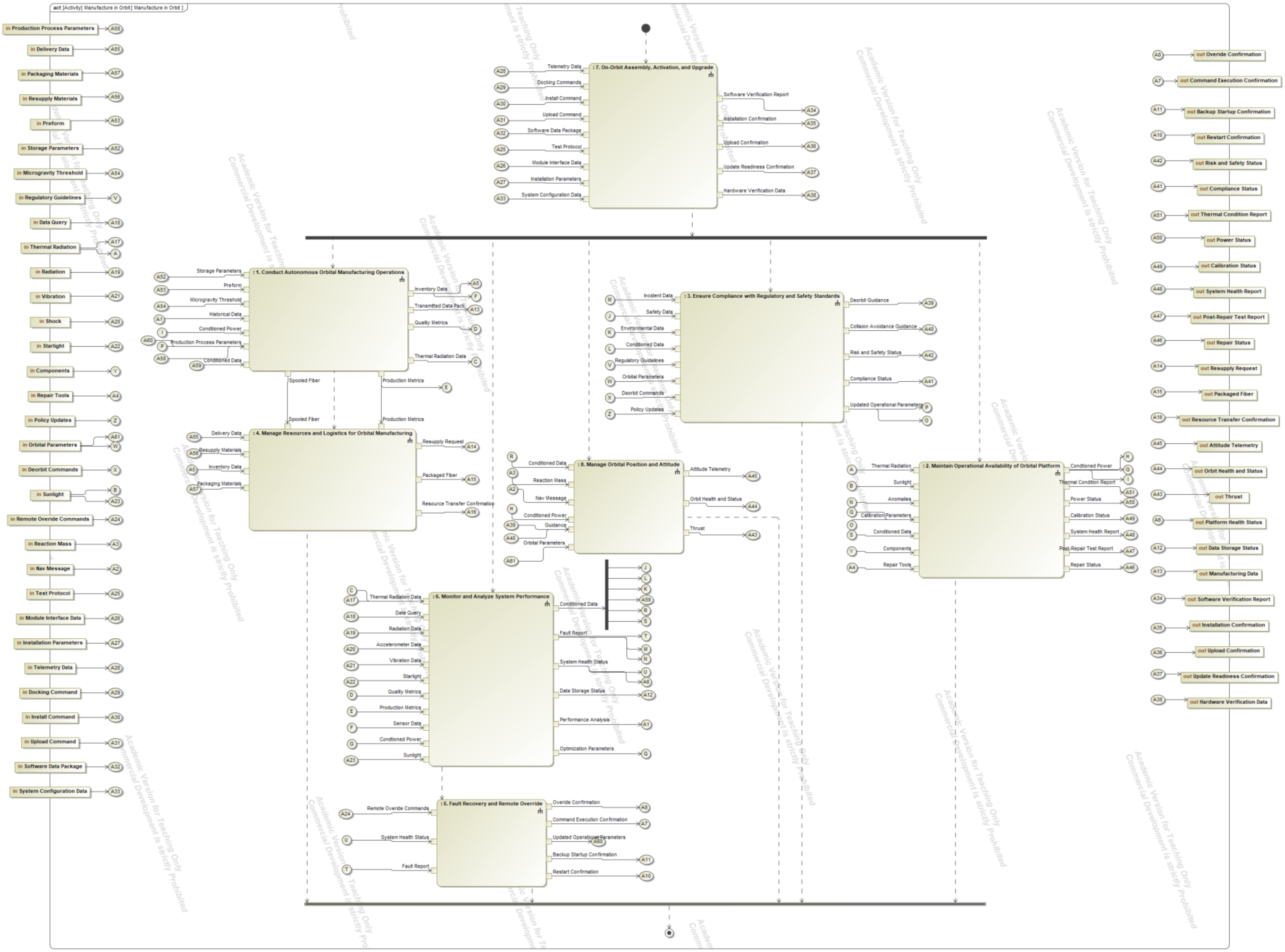


Figure 6: AOMS Top Level Activity Diagram

7 Trade Study Report

The purpose of this trade study was to evaluate and select optimal components for the AOMS system, focusing on critical and high-risk elements essential to the platform's success. A key focus was the thermal management system, which is crucial for thermal stability during ZBLAN fiber production. The study used a structured methodology combining Pair-Wise Comparison and Utility Curves to evaluate potential alternatives based on their ability to meet system requirements.

Three thermal alternatives were considered: the ISS Heat Rejection System Radiator (HRSR), Alpha Radiator, and Deployable Panel Radiator (DPR). Criteria such as heat rejection capacity, system mass, deployment efficiency, and redundancy were weighted and evaluated using utility functions. Sensitivity analysis was conducted to ensure the robustness of the results.

The DPR emerged as the optimal choice, outperforming the other alternatives in heat rejection, mass efficiency, and deployable area, while meeting mission reliability standards. The thermal management system, along with other selected components, provides a balance of performance, reliability, and feasibility, ensuring the system meets all critical needs. The full details of the trade study, including the data tables, utility functions, and sensitivity analysis, are provided in Appendix D.

Table 1: Trade Study Results

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		

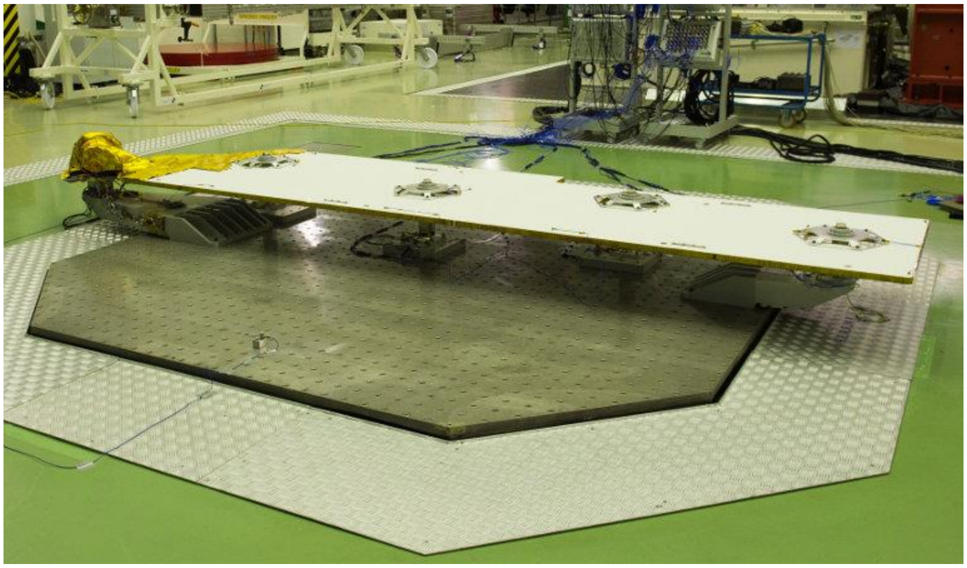


Figure 7: Deployable Panel Radiator on shaker table

8 Conceptual Design Report

The Conceptual Design Report (CDR) for the AOMS outlines the process and findings from the Concept Definition phase, validating the system's design feasibility and ensuring alignment with the defined functional requirements. The CDR focuses on ensuring that the physical architecture of the system effectively supports its intended functions while maintaining flexibility for further design implementation. The allocation of top-level functions to subsystems follows the guidance provided by the Functional Analysis Report, ensuring that each function is mapped to a specific subsystem or component with well-defined, consistent interfaces.

AOMS consists of 12 major subsystems, including power, thermal, communications, software, propulsion, and manufacturing elements. These subsystems are described in detail, with each subsystem's components and their roles in the system's operation outlined. The CDR provides physical component hierarchies and block diagrams, which illustrate the system’s structure, subsystem breakdowns, and how each subsystem interfaces with both other subsystems and external entities such as resupply capsules and ground control. The interfaces are categorized into internal interfaces (those between subsystems) and external interfaces (to support operations like remote control, resupply, and product retrieval). These interfaces are described in terms of the data, energy, and materials exchanged between subsystems, with detailed explanations of their implementation, such as power cables, data links, and mechanical connections.

To ensure full traceability and system coherence, the CDR includes traceability matrices linking functions to physical elements and interfaces. These matrices validate that all system functions have corresponding physical implementations and interfaces, and that all subsystems are interconnected in a way that supports the system's operational goals. The detailed interface descriptions ensure that all components work seamlessly together, whether interacting internally or with external entities. This structured and methodical approach helps ensure the system’s performance and integration capabilities.

The CDR serves as a high-level validation of the AOMS design, confirming that the system’s architecture is not only feasible but also aligned with the mission’s objectives, particularly the goal of enabling ZBLAN fiber production in microgravity. This report sets the stage for the next phases of system development by providing a clear roadmap for design refinement, subsystem integration, and testing. The CDR’s findings and analyses are supplemented by a comprehensive set of diagrams, matrices, and interface descriptions, which provide additional technical depth and clarity regarding subsystem interactions. These details, including the full descriptions of physical and functional interfaces, are contained in Appendix E, supporting the report's conclusions and offering an in-depth view of the system's design and operation.

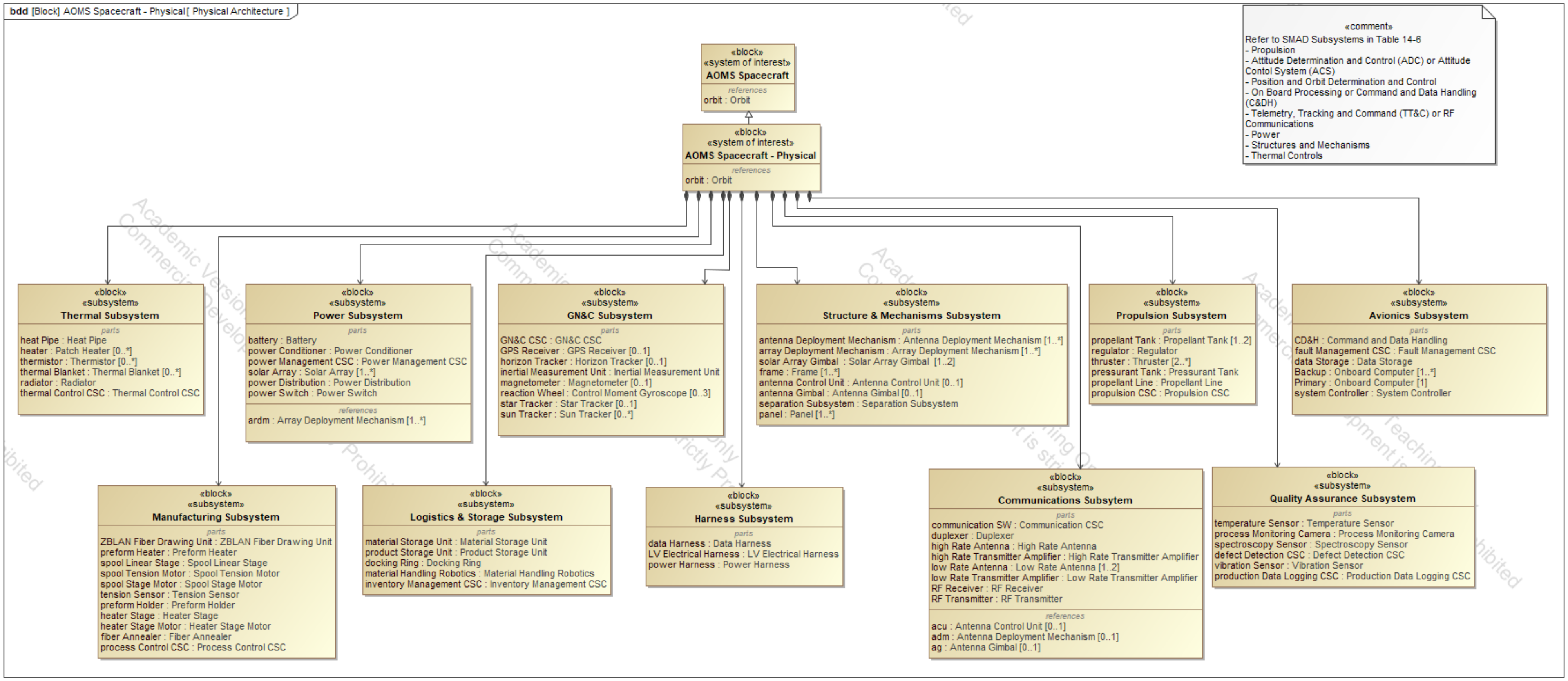


Figure 8: AOMS Physical Decomposition

9 Risk Management Report

The Risk Management Report for the AOMS outlines the structured methodology for identifying, assessing, and mitigating risks throughout the system's lifecycle. AOMS follows a proactive and adaptive risk management approach, ensuring that potential risks are identified early, assessed based on their likelihood and impact, and continuously monitored. A risk assessment matrix is employed to evaluate risks on a scale of 1 to 5, where 1 indicates the lowest likelihood or consequence and 5 represents the highest. This allows the project to prioritize high-likelihood, high-consequence risks that could impact system performance, safety, and mission success.

The initial risk assessment identified five key risks related to AOMS operations, each with a Likelihood x Consequence (LxC) rating. These risks include microgravity manufacturing process instability, fiber pulling process continuity, remote quality control system reliability, thermal management system inefficiency, and material handling automation errors. Specific mitigation strategies have been devised for each of these risks, including real-time monitoring, process optimization, automated inspection, and emergency procedures. These strategies are aligned with AOMS's system functions and supported by physical components in subsystems. Each risk mitigation approach is integrated with subsystems, which undergo testing, including Thermal-Manufacturing Integration Tests and End-to-End Production Cycle Tests.

The final risk assessment shows a reduction in risk severity due to the successful implementation of mitigation measures. The final risk status and mitigation strategies are detailed in the final assessment tables, which provide the necessary information to track the effectiveness of control measures and ensure system reliability during AOMS's operational phases.

The risk management process is integral to ensuring the successful deployment of AOMS, with detailed tracking of risks and the implementation of strategies to minimize disruptions. The risk mitigation framework is closely aligned with system requirements, and ongoing risk monitoring is planned throughout the project's lifecycle. Further details on the risk management strategies, test cases, and physical implementations can be found in Appendix G.

Table 2: AOMS Risk Summary

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.

10 Test Plan

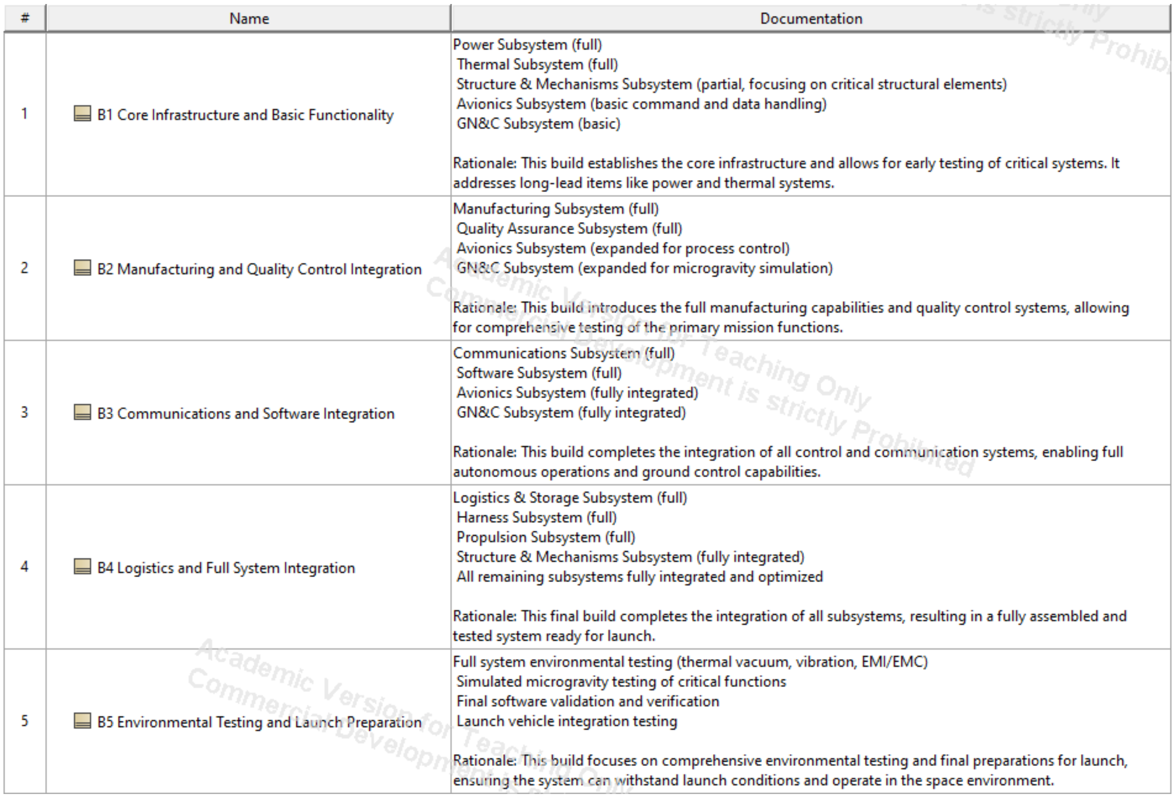
The test plan for the AOMS outlines the structured approach to verifying that each subsystem and the overall system meet the specified requirements outlined in the A-Spec. The plan ensures that AOMS is thoroughly evaluated across various stages of integration, from individual subsystems to the final system in its operational environment.

The testing will be conducted through a series of integration builds, each focused on progressively integrating critical subsystems. The first phase of testing will assess the core infrastructure and basic functionality of the system. Following this, subsequent builds will integrate Manufacturing, Quality Assurance, Communications, Software, Logistics & Storage, Harness, and Propulsion subsystems, ensuring comprehensive testing at each stage. Each build will include a set of defined test cases targeting the specific functionalities and interactions of the integrated subsystems.

Integration test cases will be planned and executed for each build to verify the subsystem interactions, while qualification test cases will be carried out after full system integration. Qualification testing will verify the system's compliance with environmental conditions, including thermal vacuum, vibration, and electromagnetic interference (EMI) testing, simulating launch conditions and the space environment.

The test plan is designed to ensure that AOMS can meet its mission objectives, with each subsystem's functionality verified in both isolated and integrated contexts. This comprehensive approach guarantees that AOMS will be fully prepared for launch and operations in space. The full set of test cases and detailed procedures is included in Appendix F.

Table 3: AOMS Build Descriptions



#	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.

11 A-Specification Report

The A-Spec for the Advanced Orbital Manufacturing System (AOMS) was developed as an output of the Concept Definition phase, synthesizing previous analysis and design work into a detailed set of specifications. This document serves as the foundation for guiding the development of the system, translating mission needs into measurable, testable performance criteria. It builds on the Requirements Analysis Report (RAR), refining and adding more specific and quantified requirements. The A-Spec emphasizes the importance of measurable requirements, with 70% of the system's specifications being quantitative, ensuring the system can be objectively assessed during development. In developing the A-Spec, care was taken to ensure that the requirements focused on performance rather than prescribing specific solutions. This approach allows for design engineers to explore the best methods for meeting the system's performance objectives. The A-Spec ensures sufficient trade space for engineers by promoting creative solutions without restricting practical design decisions.

The A-Spec also introduces key performance parameters (KPPs) that are measurable and aligned with the system's mission goals, such as ensuring high fiber quality, continuous operation, and scalability in production. These KPPs ensure the AOMS meets its operational and mission objectives. Overall, the A-Spec represents a significant evolution from the RAR, with the addition of more precise requirements and performance metrics. It serves as a detailed guide for future development, ensuring the AOMS can meet its mission of in-space manufacturing while providing enough flexibility for design engineers to implement the most effective solutions. The A-Spec can be found in full in Appendix H.

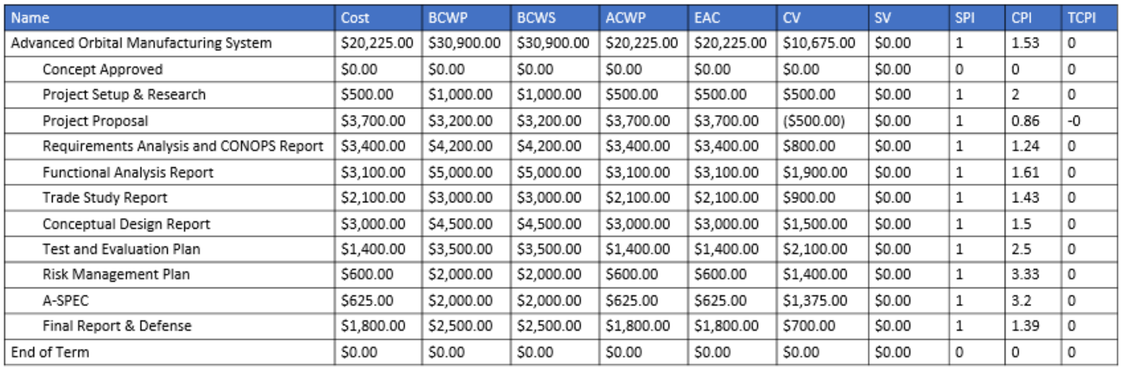
Table 4: AOMS Key Performance Parameters

Name	Text
O.1 High-Quality Production	The system shall produce ZBLAN fibers with less than 1 crystallization defect per kilometer of fiber manufactured in microgravity
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.
O.5 Operational Availability	The system shall maintain a minimum of 95% operational availability throughout its design life.
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.
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.
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.
P.2 Production Rate	The system shall maintain a production rate of at least 500 meters of ZBLAN fiber per day.
P.3 Manufacturing Yield	The system shall achieve a manufacturing yield of at least 95% usable fiber.
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.

12 Schedule Assessment

This section evaluates the project's schedule and cost performance using Earned Value Management (EVM) metrics. The assessment compares planned versus actual performance at key milestones, providing insight into the project's current standing in terms of schedule adherence and cost efficiency. Trend charts offer a visual representation of the project's evolution, with a specific focus on significant deviations and corrective actions. The table below summarizes the EVM results for the AOMS project:

Table 5: AOMS EVM Metrics



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

12.1 Schedule Performance

The Schedule Variance (SV) and Schedule Performance Index (SPI) metrics highlight the project's performance in terms of timeline adherence. Initially, during the Project Setup & Research phase, considerable effort was invested to establish the project's foundation, leading to delays in early milestones. This is reflected in the negative SV seen in August and September 2024, as the project was behind schedule. This phase was intensive and necessitated adjustments to initial estimates.

However, by late October 2024, schedule performance recovered showing an improvement in SV and SPI, as tasks progressed at a faster pace than originally planned. The recovery in schedule performance suggests that the delays incurred early on were offset by an accelerated pace in subsequent phases, supported by the efficiencies gained through MBSE and ongoing risk mitigation. The project's schedule began to stabilize with October showing positive signs, even though some scope and complexity challenges in the Conceptual Design Review (CDR) and Final Report & Defense (FAR) led to delays in those specific reports. Despite these delays, November and December continued to show positive SPI, indicating that the project was able to keep up the momentum towards the latter phases despite fluctuations in the schedule towards the end.

12.2 Cost Performance

From a cost perspective, the project maintained a relatively stable performance, with several early cost variances (CV) resulting in higher-than-expected expenditures. These early cost overruns were primarily attributed to the intensive effort required for Project Setup & Research, proposal drafting, and initial setup tasks, all of which required substantial time investment.

However, the application of MBSE and continuous risk updates as the project progressed helped realize significant cost savings, particularly in areas such as the Risk Management Report, A-spec, and Test Plan. The ability to trace requirements and streamline the review process through MBSE led to reduced costs during the later stages of the project.

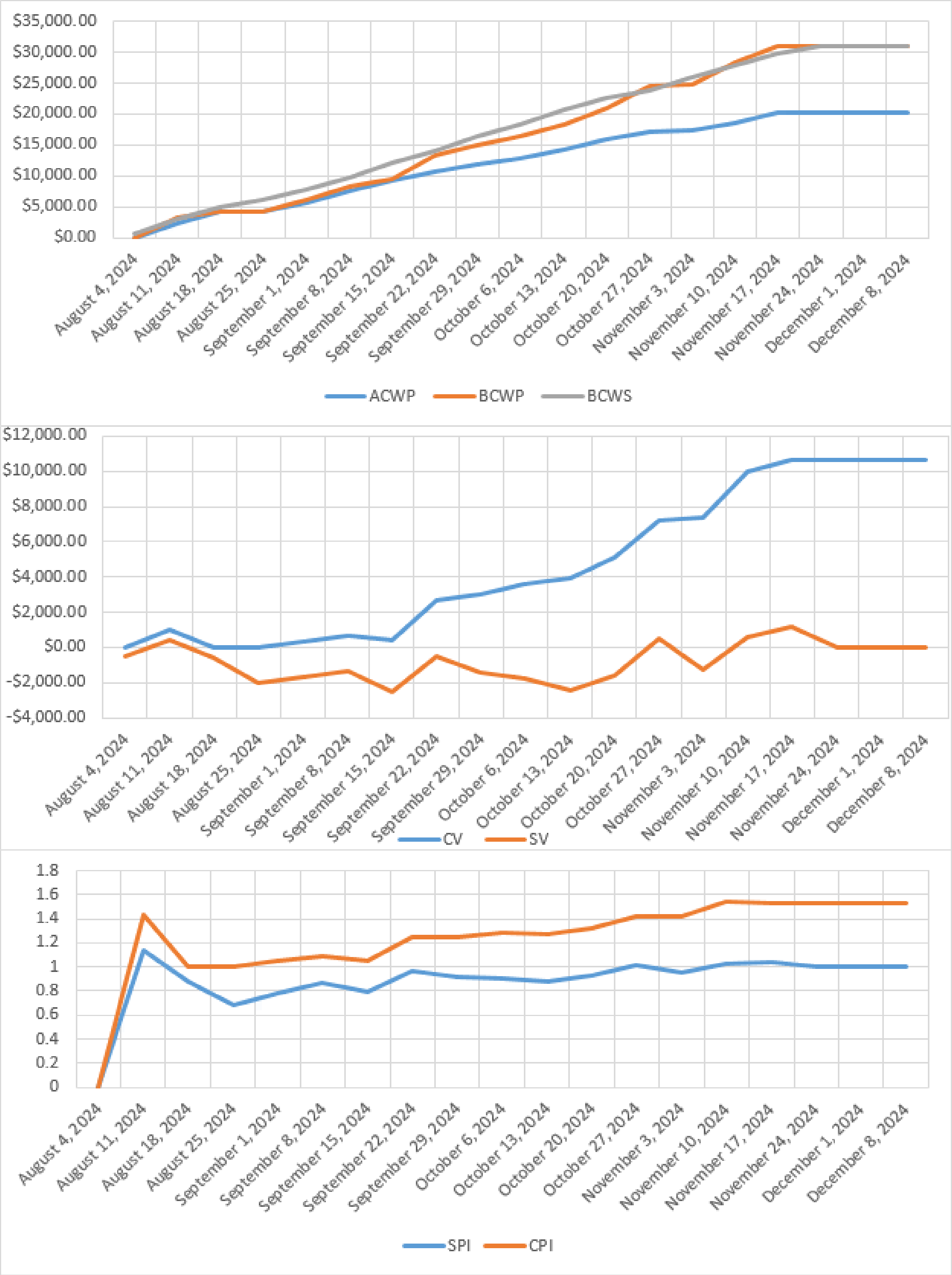


Figure 9: AOSM EVM trends over time

13 Lessons Learned

Lesson Learned: Choose a topic that excites you, even if it's outside your usual area of expertise.

Pursuing a topic I was genuinely passionate about made the entire capstone experience more fulfilling and motivating. With the project's long duration, maintaining inspiration over time was a significant challenge. My love of sci-fi novels and space kept my enthusiasm alive, while parallel activities—like being a STEM pen pal for a 7th grader and helping them explore microgravity science projects for a NASA science fair competition—helped me stay connected to the broader significance of my work. Designing a mission logo and patch added a personal and creative touch, making the process even more engaging. These connections and activities were instrumental in keeping me focused and inspired throughout the journey.

Lesson Learned: Consult Reference Architectures – Insights from Sanford Friedenthal's Work

Consulting established reference architectures can be a powerful approach to ensuring a system design aligns with proven best practices. One valuable resource I consulted was Sanford Friedenthal's reference architecture detailed in *"Architecting Spacecraft with SysML"*. This resource follows a model-based systems engineering (MBSE) approach and applies it to the example FireSat system outlined in the latest edition of the Space Mission Analysis and Design (SMAD) [10].

By leveraging Friedenthal's reference architecture, I was able to follow a structured and industry-recognized MBSE process that closely mirrors the steps and methodologies employed in real-world spacecraft development. This architecture provided an invaluable framework for organizing and modeling key elements of the AOMS project, guiding me through system decomposition, stakeholder requirements alignment, and ensuring consistency in functional allocation across subsystems.

Friedenthal's work highlights how reference architectures are indispensable in navigating the complexities of system design, especially for space missions, where integration and reliability are paramount. By consulting this reference, I was able to refine my approach to requirements traceability, model integration, and validation, making sure that each design decision could be traced back to established best practices and verified against system goals.

This approach proved essential in understanding how to organize the system model, maintain consistency across elements, and communicate complex ideas to both technical and non-technical stakeholders. Consulting Friedenthal's architecture not only helped ensure that the system was being developed according to a proven methodology but also empowered me to identify potential issues early in the design phase, reducing risks and improving overall system quality.

Lesson Learned: Prioritize Stakeholder Engagement for Refining Needs and Requirements

Engaging with stakeholders and gathering real feedback is a crucial part of refining system requirements and ensuring the project's success. My collaboration with Lynn Harper, Strategic Integration Advisor to NASA, highlighted the importance of bridging the gap between conceptual designs and real-world needs. She played a vital role in helping refine the needs and requirements for AOMS, ensuring alignment with both NASA's goals and the market demands for in-space manufacturing.

In space-related projects, just developing technology or manufacturing in space is not enough to close the business case; it's the quality of the solution and its market fit that matter. Regular feedback and alignment with stakeholders, like Ms. Harper, empower the design process, validate assumptions, and help prioritize features or capabilities that will have the most impact. This reinforces the idea that stakeholder engagement should be an ongoing effort throughout the project lifecycle.

Lesson Learned: The Value of Meta Models for Organization and Stakeholder Communication

Meta models are essential for maintaining organization and clarity in system model development. They define the structure and relationships between elements, ensuring consistency and traceability across the system. Meta models also help communicate complex systems to stakeholders who may not be familiar with SysML, providing a simpler way to align technical teams and non-technical users on system design and requirements.

Additionally, they guide development by specifying appropriate relationships between model elements, preventing inconsistencies and errors. By offering a clear framework for model development, meta models ensure that the system evolves in a structured way, aligning with both stakeholder needs and system requirements.

Lesson Learned: Harnessing Metachain Navigation and Generic Tables

Metachain navigation and generic tables are powerful tools in model-based systems engineering (MBSE), enabling the visualization and documentation of complex relationships between model elements in a structured way. To ensure consistency and maintainability when navigating metachains, it's essential to follow a well-defined meta-model. This serves as a guiding framework for applying relationships consistently across the system model, minimizing the risk of errors or ambiguity.

Adhering to the meta-model allows you to unlock the full potential of metachain navigation, providing valuable insights and validating relationships, especially for tasks like tracing requirements to functions, analyzing dependencies, and generating custom reports. Generic tables enhance this by offering dynamic views tailored to specific stakeholder needs or analysis objectives.

Effective use of these tools improves the clarity, accuracy, and efficiency of the modeling process. To maximize their value, it's crucial to invest time in understanding and consistently applying the meta-model throughout the project.

Lesson Learned: Organizing Model Content with Viewpoints

Organize model content into viewpoints to maintain clarity and streamline report-building processes. Grouping model elements based on viewpoints simplifies navigation when producing reports and ensures all related content is centralized. Consulting ISO/IEC/IEEE 42010:2022 for guidance on defining viewpoints and mapping them to stakeholder concerns is invaluable. Establishing viewpoints aligned with this standard is a critical first step toward automating report generation using the Velocity Templating Language (VTL).

Lesson Learned: Requirements tracing to functions marks the transition from theory to actionable design—this is where the real work begins.

After the initial tracing pass, there may be functions and requirements without clear relationships. At this point, it’s crucial to evaluate whether the right functions have been identified or if additional requirements are necessary. Don’t let the desire for completeness compromise accuracy; forcing relationships that are “good enough” leads to inconsistencies and missed opportunities for deeper engagement. Functional decomposition and activity diagrams are challenging but essential prework for this step. Sloppy or rushed tracing can undermine the integrity of the system and is difficult to correct later, so investing time in ensuring precise and meaningful relationships between requirements and functions is vital to the success of the systems engineering process.

14 Evaluation and Next Steps

The AOMS project has provided invaluable insights into the systems engineering process, offering a practical application of the methodologies and principles associated with the Concept Definition phase. This phase encompassed activities such as needs analysis, concept exploration, and requirements development. From a personal perspective, the project represents a significant milestone, allowing me to deepen my understanding of system modeling, risk analysis, and stakeholder-driven design. The foundation laid during this phase will be critical as the project transitions to subsequent stages of development.

The next step in the project lifecycle is advancing into the Engineering Development stage, which encompasses the Advanced Development, Engineering Design, and Integration and Evaluation phases. The Advanced Development Phase will focus on identifying and reducing development risks while refining the system design. Key activities will include validating design concepts, resolving unknowns, and ensuring the practicality of meeting system requirements. Outputs will include a validated development model and system design specifications, laying the groundwork for detailed engineering.

In the Engineering Design Phase, the system design will evolve into detailed engineering specifications, supported by design reviews and rigorous testing of components. Reliability, maintainability, and other specialty engineering considerations will be central to ensuring the system meets its operational goals. Additionally, refined test and evaluation (T&E) plans will be developed, building on the foundational T&E framework established earlier in the lifecycle.

Finally, the Integration and Evaluation Phase will integrate engineered components into a functioning whole, and evaluate system performance in a simulated or operational environment. The primary goals will be to validate component compatibility, confirm interface integrity, and finalize the system production specifications.

While these formal lifecycle steps guide the technical progression of the AOMS project, I have also identified personal aspirations that extend beyond the established systems engineering process. One of these goals is to leverage the Cameo simulation toolkit to develop an executable system model. Although not strictly part of the next lifecycle phase, creating such a model would allow me to simulate system operations, validate subsystem interactions, and refine requirements in a virtual environment.

Additionally, I aim to use this project to develop reusable VTL templates for report generation. These templates could standardize documentation practices and streamline reporting across future phases, adding efficiency and consistency to the project lifecycle. By integrating these personal goals with the formal systems engineering process, I hope to enhance both the technical quality of the project and my own professional skill set.

15 Recommendations

Consider a mentoring program where students who have successfully completed the project provide more granular feedback to those currently in progress. This would create a valuable support system for students, helping them navigate challenges and offering perspectives from individuals who have already gone through the process. Such a program could provide students with more detailed guidance on best practices, common pitfalls, and strategies for successfully managing their projects. By offering feedback at different stages, mentors can help refine students' approaches, especially when it comes to systems design, requirements development, and verification processes. This approach would also help to alleviate the workload on advisors, allowing them to focus on the more strategic aspects of student development while providing a more structured and peer-supported learning experience.

Consider integrating MBSE into the T&E course, which currently stands out as the only course in the curriculum that does not utilize Model-Based Systems Engineering (MBSE) tools. Incorporating MBSE tools, such as MagicDraw, into the T&E course would greatly enhance the students' ability to simulate, visualize, and refine test cases in alignment with the rest of the systems engineering lifecycle. Using MagicDraw for test case creation and simulation would allow students to apply MBSE principles to their testing efforts, ensuring that tests are directly tied to system requirements and providing a clearer path to verification. Additionally, it would enable students to identify system interactions and dependencies early in the testing process, improving the overall effectiveness of the T&E phase and ensuring a more holistic approach to system validation. Integrating these tools into the course would align the T&E process with modern engineering practices, giving students hands-on experience with the same tools they would encounter in industry and providing better insights into how test cases can be used to validate and refine system models throughout the development process.

16 Appendices

16.1 Appendix A

“Project Proposal for the Advanced Orbital Manufacturing System for ZBLAN Optical Fiber Production”, dated 20 August 2024

16.2 Appendix B

“Requirements Analysis Report (RAR) And Concept of Operations (CONOPS) for the Advanced Orbital Manufacturing System for ZBLAN Optical Fiber Production”, dated 11 September 2024

16.3 Appendix C

“Functional Analysis Report (FAR) for the Advanced Orbital Manufacturing System for ZBLAN Optical Fiber Production”, dated 27 September 2024

16.4 Appendix D

“Trade Study Report for the Advanced Orbital Manufacturing System for ZBLAN Optical Fiber Production”, dated 7 October 2024

16.5 Appendix E

“Concept Design Report (CDR) for the Advanced Orbital Manufacturing System for ZBLAN Optical Fiber Production”, dated 25 October 2024

16.6 Appendix F

“Test and Evaluation Plan (TEP) for the Advanced Orbital Manufacturing System for ZBLAN Optical Fiber Production”, dated 1 November 2024

16.7 Appendix G

“Risk Management Report (RMR) for the Advanced Orbital Manufacturing System for ZBLAN Optical Fiber Production”, dated 11 November 2024

16.8 Appendix H

“System Specification (A-Spec) for the Advanced Orbital Manufacturing System for ZBLAN Optical Fiber Production”, dated 18 November 2024

16.9 Appendix I

“Oral Presentation for the Advanced Orbital Manufacturing System for ZBLAN Optical Fiber Production”, dated 24 November 2024

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