Model-Based Conceptual Design of an In-Space Manufacturing System (ISM)

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Abstract
In-Space Manufacturing (ISM) represents a pivotal shift in the paradigm of space exploration and the exploitation of extraterrestrial environments. This paper introduces a model-based conceptual approach to the design of the Enhanced Factory for Extraterrestrial Space Technology Operations (EFESTO) system. Leveraging Model-Based Systems Engineering (MBSE) to integrate simulations and virtual testing, the architecture aims to support in the refinement of ISM systems throughout its entire development process, from conception to realization. With the advent of ISM as a cornerstone for future space missions, this study leverages MBSE to systematize the conceptual design of ISM systems, meeting the intricate demands of space environments. In particular, this work will explore how the MBSE approach can be used to investigate operational, economic, and legal aspects to assess the market viability of ISM, intending to meet the rigorous technical and safety standards of ISM, while also considering the commercial imperatives that will shape future human space activities. MBSE's rigor in the conceptual phase is the focal motivation, intending to reinforce the technical base for ISM systems that are both robust and adaptable.

Keywords
In-Space Manufacturing, Model-Based System Engineering, Factory in Space

1. Introduction

The journey from the historic launch of the Saturn V to the present has seen a decentralization in space endeavors, transitioning from government space agencies to a burgeoning private sector. The evolution of space technology, despite setbacks like the Soyuz 11 and Columbia disasters, continues to expand possibilities, with satellite technology becoming essential for global communications, navigation, and weather forecasting [1, 2].

The International Space Station (ISS), orbiting within Low Earth Orbit (LEO), stands as a testament to the practicality and strategic value of microgravity research [3, 4]. The ambition to expand our operational reach beyond LEO brings to light the limitations of current launch systems, particularly regarding cost and payload constraints. This realization has given rise to the Factory in Space (FIS) concept, also known in literature as In-Space Manufacturing (ISM), aiming to manufacture and assemble space components in situ [5]. Such a development could revolutionize space logistics by mitigating the constraints of Earth-based manufacturing.

This paper introduces a model-based conceptual approach of Factory in Space (FIS) system, pivotal for the progression of ISM. In particular, objectives include an MBSE Adaptation for ISM (to tailor

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MBSE methodologies to enhance simulation accuracy and risk assessment for ISM, ensuring comprehensive design evaluations) and a comparative design assessment (to methodically compare ISM design concepts using MBSE, determining each design's practicality, durability, and performance efficiency).
The paper is structured as follows. Section 2 provides the theoretical foundation grounding the research. Section 3 provides a system overview, from the operational environment, up to stakeholders and requirements. Finally, Section 4 discusses them and concludes the paper.

2. MBSE and CAPELLA: Conceptual Design of Complex Systems

MBSE employs models for the lifecycle of complex systems, enhancing traditional document-centric approaches with visualization and unambiguous communication [6, 7, 8]. MBSE mirrors the procedures of Systems Engineering (SE) within a model-centric framework. Its language and methodologies streamline the design process and maintain a coherent data repository. MBSE advances data traceability and system update impacts, yielding more consistent designs than traditional SE, particularly for managing the complexities of ISM systems [9].

CAPELLA, an open-source tool, underpins MBSE by offering robust modeling techniques for complex system design and architecture [10]. Developed by Thales using the ARCADIA method, CAPELLA emphasizes operational needs and system analysis in its initial phases, progressing to logical and physical solutions. ARCADIA, akin to SysML, enables diverse diagrammatic representations from scenarios to system architectures, and is employed across Thales' global projects for its efficacy in handling varied system design aspects [10, 11].

The application of MBSE in the conceptual design phase of complex systems, such as an in mission planning plays a pivotal role in ensuring the development of robust, efficient, and mission-aligned systems. In the specific context of ISM, the multidisciplinary nature of space systems necessitates the utilization of MBSE to navigate the intricacies of system design effectively. The following aspects underscore the instrumental role of MBSE in the conceptual design phase:

- Define System Boundaries: MBSE facilitates the establishment of clear definitions for the ISM system's scope, delineating its interactions with other systems and the surrounding environment. This clarity is crucial for setting the direction of the development process.
- Identify Requirements: through MBSE, the ISM system's requirements are captured and managed comprehensively, encompassing technical, operational, and stakeholder perspectives. This ensures that all necessary requirements are considered in the design process.
- Perform Trade-Off Analyses: MBSE enables the evaluation of various design alternatives against the defined requirements. This process is essential for identifying the most viable and efficient design solutions that meet the mission's objectives.
- Simulate and Validate Concepts: the use of virtual models within the MBSE framework allows for the simulation of the system's behavior under different scenarios. This capability is vital for validating the conceptual design against expected performance outcomes, ensuring the feasibility and reliability of the system.

By integrating MBSE with tools like CAPELLA, the research team is equipped to iteratively refine the conceptual design. This iterative process ensures that the final system design is not only technically feasible but also optimally aligned with the broader objectives of cost-efficiency, safety, and mission success. In summary, MBSE serves as a cornerstone in the conceptual design of complex systems, offering a structured and comprehensive approach to system development that is indispensable for achieving the desired outcomes in space mission projects.

3. System Conceptual Design

Confined to Low Earth Orbit (LEO), the Enhanced Factory for Extraterrestrial Space Technology Operations (EFESTO) project will be designated to reclamation of space-borne materials for the purpose of autonomously performing in-orbit manufacturing processes with a notable automation threshold of 95%. Its functions aim to be versatile, and capable of adjusting to at least three different manufacturing methods, and aims to use resources with 90% efficiency. Modular interfacing mechanisms are integral to EFESTO, enabling seamless integration with other spaceborne systems and terrestrial command structures. The system shall be engineered to support scalable expansion, with the potential to increase capacity by up to 50% within a five-year post-deployment period. The systems design parameters shall explicitly exclude launch vehicle operations, interplanetary travel, and terrestrial manufacturing processes. Furthermore, the system shall not be accountable for the generation of primary raw materials.

EFESTO aims to be a factory in Low Earth Orbit, able to provide the whole production chain of new components and large space infrastructures, from the recycling of waste to the final in-situ assembling and deployment

3.1.Operational Environment

The operational environment for the system is shall be restricted to LEO. Here, the environment is characterized by a set of unique and challenging conditions at an altitude ranging from approximately 400 to 900 kilometers above Earth (Table 1). The ISM system will be exposed to a harsh mix of extreme temperatures, microgravity, and a higher flux of ionizing radiation from the Van Allen belts compared to Earth's surface. The temperature in LEO can vary dramatically, from +250 degrees Fahrenheit (+121°C) in direct sunlight to -250 degrees Fahrenheit (-157°C) in the shadow of Earth, necessitating robust thermal control systems to protect sensitive electronics and materials. The presence of a residual atmospheric drag, although thin, also affects the system, gradually decreasing its orbit over time and demanding periodic adjustments to maintain altitude. Furthermore, the microgravity environment impacts fluid behavior, influencing the design of mechanical fluid management systems in the system. Collectively, these conditions define the operational context for LEO space systems, guiding the engineering and operational strategies to ensure mission success and safety.

Table 1. LEO environment: parameters and description

Parameter	Description
Atmospheric Pressure	Negligible, vacuum conditions prevail within modules (roughly 10–700 nPa)
Atmospheric Drag	Despite the low atmospheric density, atmospheric drag is a relevant factor for station-keeping and orbit maintenance.
Propulsion	The manufacturing system must include propulsion capabilities or regular boosts from auxiliary vehicles to counteract orbital decay.
Attitude	Adjustable - Controlled to optimize solar power and communication links. Approx. 51.6 degrees.
Altitude	400 to 900 km above Earth's surface.
Solar Radiation Level	Average of 1361 W/m^2, varies with solar cycle.
Debris	1 to 10cm at 13 km/s.

Through these design considerations, the ISM system in LEO will be capable of sustainable operation, addressing the challenges posed by the space environment while leveraging its unique conditions to enable innovative manufacturing processes not possible on Earth.

3.2.Stakeholders

Recognizing the role and interests of the various stakeholders in the definition of the conceptual design, the following entities have been identified as having a vested interest in the system's development, deployment, and operation. The stakeholders of EFESTO span a spectrum of public and private sector organizations, each with distinct priorities and expectations from the system (Table 2).

The conceptual design of the system is predicated on a holistic approach that considers the various operational scenarios, system requirements, and technical constraints identified [13, 14, 15]. Four key stakeholders have been specified based: product designer, on-ground manufacturing, space tug, and waste operator. Two of the identified stakeholders (product designer and on-ground manufacturing) are expected to continue to operate from their base on Earth. In contrast, the other two (space tug and waste operator) would be based in LEO and are closely related to space debris operations. The designer is responsible for providing final product design guidelines and artifacts (3D models, g-codes, etc.). The on-ground manufacturing is responsible for providing materials and products to the factory for assembly and manufacturing. The space tug is responsible for delivering recaptured debris to the factory. The waste operator is responsible for the disposal of non-recyclable waste from the factory.

Table 2. EFESTO Primary Stakeholders

Stakeholder	Description
Customer	As the primary clients and benefactors of the ISM **International Space Agencies** are direct customers. They have a high degree of influence and interest in the systems success as it aligns with their goals for sustainability and cost-efficiency in space operations.
Product	**Commercial Space Firms**: Are end-users of the ISM, interested in the operational efficiencies and cost reductions it can provide. Their influence is moderate to high depending on their market share and investment in space activities.
	Research Institutions: Are users who utilize the ISM for scientific research and development. They have a specialized interest in the system's capabilities and a moderate level of influence.
	Product designers: are responsible for conceptualizing and creating the technical models required for the production/assembly of components and structures.
Business and Regulatory	**Environmental Advocacy Groups**: Can act as regulators or influencers, ensuring that ISM activities adhere to environmental standards and contributes positively to space sustainability. They might have less direct influence but hold significant interest in the project's environmental impact.
	Defense and Security Organizations: Have a strategic interest in ISM and can influence its design and use to ensure it meets security and defense requirements.
Supplier and Material	**On-Ground Factories**: Are suppliers providing the primary raw materials and components necessary for ISM construction. They have a vested interest in the integration of their products with the ISM and the feedback it provides for improving manufacturing processes.
	System Designers: As the creators of the ISM, the designers supply the intellectual property and technical know-how. Their ongoing involvement is crucial for the system's success and evolution.
	Space Tug Operators: Provide essential services that support ISM operations. They are operational stakeholders with a significant interest in the coordination and success of the system's material positioning and structural adjustments.
	Waste Management Operators: Are responsible for the environmental aspect of the ISM’s operation, they are interested in how the system processes recycled and non-recyclable waste.

3.3. High-level System Requirements

The development of the ISM system is based on the Copernicus Imaging Microwave Radiometer (CIMR) and is subject to a complex array of requirements and technical considerations [12]. These must be carefully evaluated to ensure that the system can operate effectively in the space environment and meet the needs of stakeholders. The high-level system requirements as shown in Table 3 for the ISM encompass a broad spectrum of operational and include but are not limited to, technical, and safety considerations based on stakeholder specifications, and the operating environment:

Table 3. EFESTO High-level Requirements

Requirement Emphasis	Requirement
Operational Efficiency	The system shall achieve an automation level of 95%, capable of self-adjustment to at least three distinct manufacturing processes with a resource utilization efficiency of 90% as measured by the ratio of effective output to total input.

	The system shall incorporate an intelligent design optimization software that can increase the functional efficiency of the recovered products by at least 20% compared to their original state.
	The system shall facilitate the assembly of components in orbit, reducing assembly time by 30% compared to manual assembly benchmarks established during initial trials.
Scalability and Flexibility	The system design shall provide modular interfaces for technology upgrades, allowing for a 50% increase in production capacity without significant architectural changes, within a period of five years from initial deployment.
Quality, Reliability and Maintenance:	The system shall be capable of manufacturing new components with a dimensional accuracy within 99.5% of specified tolerances and achieving a structural integrity score of no less than 95% compared to equivalent Earth-manufactured components.
	The system shall achieve a reliability rating of 0.999 (Mean Time Between Failures of 10,000 hours) and shall be designed for maintenance simplicity, with critical components replaceable within a Mean Time To Repair of less than 1 hour, under simulated space conditions.
	The system shall incorporate predictive maintenance algorithms capable of forecasting potential system failures with an accuracy of 90%, and self-diagnosing critical system components with a fault detection capability of 95% accuracy, thus enabling preemptive maintenance scheduling and minimizing unplanned downtime.
Resource Utilization and Recycling Efficiency	The system shall utilize in-situ materials for at least 75% of its manufacturing mass and reduce the reliance on Earth-based resupply missions by 85%, as measured by mass, within the first two years of operation.
	The system shall demonstrate the capability to recycle and repurpose at least 85% by mass of the designated waste, dismissed satellites, and broken components encountered, converting them into usable raw materials or components for further manufacturing processes.
	The system shall provide a solution for the management of non-recyclable waste, ensuring that at least 95% of such material is safely contained or repurposed to prevent orbital debris.

The system requirements in Table 3 and the following technical considerations form the foundation upon which the conceptual design of the ISM system will be developed. They guide the design process to ensure that the system is not only technically sound but also practical and aligned with the strategic objectives of space exploration and commercial exploitation.
Technical considerations are pivotal to the ISM system's feasibility, encompassing:

- Microgravity Environment: manufacturing processes must be adapted to operate in microgravity, which affects material handling, heat transfer, and assembly operations.
- Radiation and Extreme Temperatures: the system components must withstand the harsh conditions of space, including radiation exposure and temperature extremes.
- Miniaturization and Integration: the ISM system should leverage miniaturization to optimize the use of space and ensure integration with other systems and modules.
- In addition, safety and reliability are paramount in the design of any space system:
- Safety Protocols: the system must incorporate robust safety measures to protect both the manufacturing processes and the crew from potential hazards.
- Redundancy and Fail-Safes: critical components should have redundant systems in place to maintain functionality in case of failure.
- Quality Assurance: rigorous testing and quality assurance protocols must be established to ensure the integrity of manufactured components.
- Finally, legal considerations are also a crucial part of the technical framework:
- Space Law Compliance: the ISM system must adhere to international space laws and regulations regarding the use of space and celestial bodies.
- Intellectual Property Rights: the system should respect intellectual property rights and ensure that manufacturing in space does not infringe on existing patents or copyrights.**Error! Reference source not found.**

4. Discussion and Conclusions

The modular inspiration drawn from the ISS informs the FIS design, validating MBSE's applicability for incremental ecosystem development. While the logistics within the space factory remain undefined, the model's preliminary status will render detailed specificity premature.

The MBSE methodology's adoption allows for an expansive, interconnected view of the FIS ecosystem, empowering stakeholders to scrutinize design alternatives and their ramifications. This strategic approach promises better resource and responsibility distribution and the streamlining of the ecosystem. While a design standpoint, structural robustness against LEO's harsh conditions is crucial, technology limitations within FIS should guide design compromises, balancing structural integrity and manufacturability. This consideration is pivotal for FIS product design, potentially driving a paradigm shift in FIS's long-term realization. Nonetheless, the preliminary Capella model is not without its limitations. Assumptions like pre-captured decommissioned components, and the omission of logistical and launch constraints, restrict the model's thoroughness. Also, including ground manufacturing contradicts the essence of FIS. Future research will investigate the interplay between FIS's orbital elements, such as the space tug and waste operators, focusing on space debris — a topic ripe for technological innovation, as current technology does not provide clear solutions for the capture and utilization of space waste. Clarifying the role of space debris within the FIS context is essential, as it significantly influences the ecosystem's model and operations.

Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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