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MBSE approach for a preliminary architecture definition for a factory in space

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Abstract

The MBSE approach stands as one of the most widely employed methodologies in the definition of the activities and the operations integral to a space mission. It serves to create and use models to design, analyze and monitor the evolution of complex system such as, in the case of this study, a factory in space. In particular, this project starts from a mission statement and high-level primary and secondary objectives for an in-space manufacturing mission endeavouring to delineate all activities performed by the facility.

The needs to be fulfil by the concept are related to the recycling of materials starting from decommissioned components, the repairing process that broken systems and tools could need during their operative life and the final decommissioning of a space system with the associated safety measures. The strength point of this approach would be the possibility to avoid all the constraints related to the launch environment, which is the most demanding in terms of structural and thermal loads and, for this reason, is usually the main driver of the costs, weight and complexity of a space system.

Following the consolidation of stakeholder needs and operational activities, an extensive identification process involving entities, actors, roles, activities, and concepts was conducted. This phase considered diverse applications of the concept, ranging from the aforementioned in-orbit repair of decommissioned satellites to the futuristic prospect of a facility capable of manufacturing large structures for in-situ applications using recycled materials, since the model aimed for inclusivity across potential applications.

Once the operational analysis was consolidated, the further steps were the system analysis and the logical architecture, which have been carried out and defined at high-level. The physical architecture could be evaluated in the future, once the novel technologies and processes involved will reach an adequate level of readiness.

Keywords: MBSE, Space Factory, Additive,

Acronyms/Abbreviations

AM – Additive Manufacturing
ConOps – Concept of Operations
ISM – In-Space Manufacturing
ISS – International Space Station
LAB – Logical Architecture Breakdown
MBSE – Model Based System Engineering
OBC – On-board Computer
RTG – Radioisotope Thermoelectric Generators
SE – System Engineering
WAAM – Wire Arc Additive Manufacturing

1. Introduction

In the evolving landscape of space exploration, the concept of in-orbit manufacturing has emerged as a critical frontier, with notable advancements in the last decade. Even if some demonstrators have already been implemented in the International Space Station, mainly through Additive Manufacturing techniques, a crucial gap persists in the absence of a fully realized autonomous space factory design for future extra-planetary long-term missions.

Model-Based Systems Engineering (MBSE) is in this case a crucial tool that could lead to the development of complex architectures such as the one needed for a factory in space with the use of well-defined actors linked to the relative's operations and functionality. Central to this conceptualization of a space mission is the identification of an operational orbit or surface, which dictated the environmental challenges and boundaries of the project. The collaborative nature of the project underscores the importance of coordinating efforts among multiple stakeholders to achieve a cohesive and comprehensive vision.

2. Model-Based Systems Engineering (MBSE) in Complex System Design

Model-Based Systems Engineering (MBSE) leverages models throughout the lifecycle of complex systems, providing enhanced visualization and clear communication compared to traditional document-centric methods. By aligning closely with Systems Engineering (SE) principles in a model-centric framework, MBSE utilizes specialized languages and methodologies to streamline design processes and

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maintain a coherent data repository. This approach enhances data traceability and evaluates the impacts of system updates, leading to more consistent designs, especially for the intricate requirements of in-space manufacturing (ISM) systems.

An essential tool supporting MBSE is CAPELLA, an open-source solution offering advanced modeling techniques for the design and architecture of complex systems. Developed by Thales through the ARCADIA method, CAPELLA focuses on operational needs and system analysis in its initial stages, advancing to logical and physical solutions. ARCADIA enables diverse diagrammatic representations, ranging from scenarios to system architectures, and is widely used in Thales' global projects for its effectiveness in managing various aspects of system design.

MBSE's application during the conceptual design phase of complex systems, such as those involved in mission planning, is crucial for developing robust, efficient, and mission-aligned solutions. Specifically, for ISM, the multifaceted nature of space systems necessitates MBSE's ability to handle design complexities effectively. Key aspects demonstrating MBSE's critical role in the conceptual design phase include:

- Defining System Boundaries: MBSE helps establish clear definitions for the ISM system's scope, outlining its interactions with other systems and the environment. This clarity is essential for guiding the development process.
- Identifying Requirements: MBSE captures and manages the ISM system's requirements comprehensively, covering technical, operational, and stakeholder perspectives, ensuring all necessary requirements are integrated into the design.
- Conducting Trade-Off Analyses: MBSE allows for the evaluation of various design alternatives against the defined requirements, helping to identify the most viable and efficient design solutions that align with mission objectives.
- Simulating and Validating Concepts: Utilizing virtual models within the MBSE framework facilitates the simulation of the system's behavior under different scenarios. This capability is critical for validating the conceptual design against expected performance outcomes, ensuring the system's feasibility and reliability.
- Integrating MBSE with tools like CAPELLA enables the research team to iteratively refine the conceptual design. This iterative approach ensures that the final system design is not only technically feasible but also optimally aligned with broader goals of cost-efficiency, safety, and mission success. In conclusion, MBSE is fundamental in the conceptual design of complex systems, providing a structured and comprehensive approach to system development, essential for achieving desired outcomes in space mission projects.

The approach that has been followed rise into the Operational analysis layer in which the concept of the mission was designed as well as the expectations.
This allowed the engineers to agree on a common definition of the high-level concepts modelled as operation allocated in operational activities, which represent the different preliminary actors.
Once the concepts were settled, the functional architecture was modelled into the Capella's logical layer, in which the building blocks have been defined and the functions allocated into them. In the following pages the diagrams designed in Capella are showed with a clear decomposition of the Space factory in different modules along with the interactions with the support modules and the external actors. The functions are the green blocks inside with the data exchanged among to specify the interfaces to put in place.

2. Mission Definition and Study Cases

The formulation of a mission statement and mission objectives to guide the implementation of automated processes within the planned facility is among the initial steps in the preliminary phase of a mission. In the case of EFESTO, this mission statement was developed to delineate the project's purpose and provide a clear direction for the team, stakeholders, and the general public. It was established subsequent to a high-level feasibility study of the mission and the identified needs, which was conducted collaboratively with all partners possessing competence and expertise from diverse fields. This collaborative approach enabled the team to attain a broader perspective, ultimately resulting in the creation of the following interdisciplinary and succinct mission statement:

EFESTO aims to be a factory in 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

The effectiveness of a mission statement lies in its ability to encapsulate the team's intent in a few sentences. In the subsequent section, the mission objectives will instead play the role of specifying the functionalities that

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the mission must achieve to fulfil the expectations outlined in the mission statement.

2.1 Mission objectives

The objectives of EFESTO were selected to create a baseline for the future verifiable requirements definitions and to better understand what the mission should accomplish, giving a priority hierarchy on the system drivers. In particular, the primary objectives include:

1. To recycle waste, dismissed satellites and broken components
2. To manufacture new components in orbit
3. To assemble large infrastructures in orbit

It is immediately evident that the primary focus of EFESTO is the in-situ manufacturing process, whether for repair or assembly purposes. It is important to note that the only hierarchy exists between the primary and secondary objectives. There is no prioritization within the primary objectives' order. The same applies to the secondary objectives, which are as follows:

1. To optimize the design of the recovered products;
2. To assemble components in orbit;
3. To manage non-recyclable waste.

2.2 External Actors

In the context of a space factory, that tries to be as autonomous as possible, several external actors could play critical roles in the development and operation of the facility. During this preliminary study phase, the involvement of external actors was limited to the minimum necessary to ensure the basic functionality and operability of the factory. These key external actors include:

- On-Ground Factory: it serves as the primary Earth-based support facility for the space factory. It is responsible for the initial fabrication and assembly of components (especially during the first operational mode of the factory where the only in-space capability will be the assembly system) conducting pre-launch testing, and ensuring that all modules or batches are ready for deployment. The on-ground factory also functions as the logistical hub, managing the supply chain for raw materials, replacement parts to be launched, and other resources needed for ongoing operations of the factory;

- Designer: is tasked with the comprehensive design and engineering of the components and systems to be manufactured in the factory. He is also in charge of the repairing evaluation and support. The designer is responsible for ensuring that the needs are met using the raw materials already presents in the factory or, if impossible, for submit the resupply request through additional batches. The presence of an on-ground design phase is crucial to assure the quality of the space-made components, but the aim is to integrate this role with an automated system that will work in the factory, hopefully trying to go towards a future self-standing design system.

- Space Tug: it is an orbital vehicle designed to transport modules, batches, or other cargo from one orbit to another. In the context of the space factory, the space tug plays a crucial role in the logistical chain by moving components from low Earth orbit (LEO) to the designated factory site, potentially located in a higher orbit (e.g. GEO) or at a specific location in space. The tug ensures that the various elements of the factory arrive at the correct locations and times, facilitating the assembly and expansion of the factory's capabilities over multiple missions.

- Waste Operator: it is responsible for managing and processing waste generated by the space factory. In a closed-loop system such as a space factory, effective waste management is essential to maintain sustainability and operational efficiency. The waste operator's role includes the collection, processing, and disposal of waste materials, ensuring optimal resource utilization.

In this phase of the study, the involvement of these external actors is conceptualized to provide a foundational framework for the space factory's operation. As the design matures and moves towards implementation, additional external actors may be identified and integrated into the broader operational model to enhance capabilities and support long-term objectives.

3. Batches Approach

Once the logical functions were defined and the subsystems of the space factory were connected through logical chains, a preliminary concept of operations (ConOps) began to take shape. Given the modular nature of the factory's design, it was essential to determine which modules could operate independently and establish the optimal sequence for their implementation before finalizing the ConOps configuration.

From this point forward, we will refer to these "modules" as "batches" to avoid any potential confusion. While "modules" typically refer to physical components, in this phase, the spatial allocation of volumes has not yet been determined. For example, a single "AM batch" could ultimately be split into two separate modules or

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combined with another batch, depending on volume and mass constraints during the design process.

Accordingly, five distinct batches (Service, Assembly, Qualification & Acceptance, Additive Manufacturing, Wire Manufacturing) were identified based on a provisional concept of operations that integrates the development of these batches with a phased launch schedule. EFESTO, the envisioned space factory, will be constructed incrementally through multiple launches from Earth, gradually expanding its capabilities in line with both the operational concept and available resources. This modular approach allows for flexibility in design and execution. However, at this stage of conceptualization, a high level of detail regarding the number of modules, their weight, volume, and specific subdivisions is not yet necessary. These factors will largely depend on the technologies chosen to meet the factory's requirements and the needs of its stakeholders.

Moreover, many processes must be adapted for the space environment before their specific applications within EFESTO can be properly defined. Thus, adopting a batch approach at this stage provides a more adaptable framework for conceptual development.

3.1 Service

The service facility will encompass all critical functions required for initiating the operational phase of the space factory. This essential component is designed to generate electrical power using solar panels, Radioisotope Thermoelectric Generators (RTG), or nuclear generators, contingent upon the finalized power budget. Currently under evaluation, the power budget's preliminary assessments suggest that approximately 3000 square meters of solar panels will be necessary, a surface area comparable to that of the International Space Station (ISS). Beyond power generation, the service module will include a comprehensive power distribution system, interfaces for seamless integration with other modules, and an On-Board Computer (OBC) to monitor instrumentation status. Additionally, a power storage system is critical for the factory, with batteries selected based on peak power demands and eclipse durations, which are influenced by orbit selection and the temporal distribution of processes. These logical components may not reside within a single physical module nor be deployed simultaneously from Earth. Instead, the functionalities and capacities of the service module will expand incrementally in tandem with the factory's evolutionary growth.

3.1 Assembly

The assembly module will be the first segment of the space factory to become fully operational following the implementation of the service facility. This module includes a secondary storage facility to house components awaiting assembly and final products pending their qualification phase. A self-sustaining docking interface is essential for this module, influencing the overall architecture of the factory. Inputs from the ground will be received through this docking interface, where they will be sorted in the assembly module and then distributed as needed. To facilitate these operations, a robotic arm or a general moving system will be employed for transferring components from the docking port to the storage facility and for assembling products from these components. This phase enables the factory to assemble components sent from Earth. The advantage of this approach is that hardware does not need to endure launch loads in its final configuration. Instead, components can be stored in the launcher in an optimal configuration, minimizing the risk of structural failure. This results in lighter components, which simplifies the design phase and broadens material selection options.

3.3 Qualification and Acceptance

The final logical component required in the initial configuration to deliver a deployable product is the qualification and acceptance module. This module can be launched together with the service and assembly batches or separately, but it must be operational from the outset. Within this module, two primary functions will be performed: qualifying the final product and conducting acceptance tests.

Qualification involves a series of thorough inspections and evaluations to ensure that the product meets all design specifications and performance requirements. This process includes detailed examinations of the product's structural integrity, material composition, and operational capabilities. Advanced diagnostic tools and methodologies will be employed to detect any potential defects or deviations from the required standards. Additionally, environmental testing will simulate the harsh conditions of space, such as extreme temperatures, vacuum pressure, and radiation exposure, to verify the product's durability and resilience.

Acceptance testing follows the qualification phase and focuses on verifying that the final product is fully functional and ready for deployment. This includes a comprehensive series of tests designed to confirm that all systems operate correctly under expected conditions. Functional tests will assess the performance of the product's components and subsystems, ensuring they work together seamlessly. Performance tests will measure the product's operational efficiency, stability, and reliability. Furthermore, redundancy tests will evaluate the product's fail-safe mechanisms and backup systems to ensure it can handle unexpected failures or anomalies.

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These processes ensure that the assembled products meet all required standards and specifications before deployment, confirming their readiness for operational use. This rigorous testing phase is crucial for validating the integrity and functionality of the products, thereby guaranteeing their reliability and performance in space. The qualification and acceptance module thus plays a vital role in the overall mission success, ensuring that only products that meet the highest standards of quality and reliability are deployed.

3.4 Additive Manufacturing

By incorporating a fourth batch, a new operational mode is established, centered around additive manufacturing. This module will employ Wire Arc Additive Manufacturing (WAAM) technologies for both repairing components and directly manufacturing metal parts. In this phase, design inputs can either be received from Earth and applied as-is or be integrated and optimized by an in-situ system.

Additive manufacturing has been chosen as the optimal technology for EFESTO due to its numerous advantages. This approach allows for the efficient use of materials, significantly reducing waste compared to traditional subtractive manufacturing methods. The ability to produce complex geometries that are often impossible or cost-prohibitive to achieve with conventional manufacturing techniques is another key benefit. This capability is particularly valuable in a space environment, where the optimization of every component can lead to substantial improvements in performance and efficiency.

Furthermore, additive manufacturing provides unparalleled flexibility to adapt designs on-site. This means that the factory can respond quickly to new requirements or changes in mission parameters, enabling rapid prototyping and customization of parts as needed. The integration of WAAM technology allows for the production of high-strength metal components, which are essential for the demanding conditions of space operations. WAAM is particularly suited for creating large, structural components due to its ability to deposit material at high rates while maintaining excellent mechanical properties.

In addition to manufacturing new parts, the additive manufacturing module will play a crucial role in repairing existing components. This capability is vital for maintaining the factory's operational readiness and extending the lifespan of its equipment. By repairing worn or damaged parts on-site, the factory can avoid the delays and costs associated with sending replacement parts from Earth. This not only enhances the sustainability of space operations but also ensures that the factory remains fully functional even in the face of unforeseen challenges.

The design process in this module will leverage advanced computational tools and machine learning algorithms to optimize the manufacturing parameters and improve the quality of the produced parts. These tools will enable real-time monitoring and adjustments during the manufacturing process, ensuring that each component meets the stringent standards required for space applications.

Overall, the incorporation of additive manufacturing into the EFESTO space factory represents a significant advancement in its operational capabilities. By combining the benefits of efficient material use, complex geometry production, on-site adaptability, and robust repair functions, this module will enhance the factory's ability to create and maintain the essential components needed for its mission. This comprehensive approach ensures that the factory can meet the evolving demands of space exploration and industrialization, positioning EFESTO at the forefront of space manufacturing technology.

3.5 Wire Manufacturing

To manufacture wire, the factory must implement at least three distinct logical functions: a disassembly system, a melting facility, and a casting facility. The disassembly system will be responsible for separating different components of a system and isolating the various materials. This process is critical for ensuring that the materials are prepared in a form suitable for further processing. Once disassembled, the materials will be transferred to the melting facility. Here, the materials will be melted down to create pure fused metals and, if necessary, alloys. This step is essential for achieving the required material properties and ensuring the quality of the final product. Finally, the melted metals will be processed in the casting facility, where they will be formed into wires suitable for additive manufacturing. This casting process will involve precise control to ensure the wires meet specific dimensions and material standards required for the subsequent manufacturing phases. Together, these three logical functions will form an integrated system that enables the efficient and high-quality production of wires, essential for the factory's additive manufacturing operations.

3.6 Additional Batches

During the operational life of the factory, it is crucial to recognize that the system will not be entirely self-sufficient until all the batches are fully implemented. This incremental approach means that, particularly in the

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initial stages, the factory will rely on external inputs to maintain its operations and meet its production goals.

For instance, at the very beginning of its operations, the factory will depend on input components shipped from Earth for assembly and subsequent deployment. These components will arrive pre-manufactured, ready for final assembly within the factory's facilities. This dependency on Earth-supplied components will persist until the factory's internal manufacturing capabilities are fully established and operational.

Similarly, the wire required for additive manufacturing processes will need to be sourced from Earth until the wire manufacturing facility is implemented and operational within the factory. The wire manufacturing facility, once active, will allow the factory to produce its own wire from raw materials, reducing dependence on Earth and enhancing operational autonomy.

This phased implementation strategy extends to other critical systems as well. Initially, the factory's power generation, storage, and distribution systems may require supplementary energy sources or components from Earth until they are fully functional and capable of meeting the factory's demands independently. As each new module and system comes online, the factory's reliance on Earth will decrease, gradually moving towards a self-sustaining operational state.

The incremental nature of the factory's implementation requires meticulous planning and coordination. Each phase must be carefully synchronized to ensure that the necessary support systems are in place before the next phase begins. This includes ensuring that the service facility is fully operational to support the initial assembly processes, followed by the establishment of the qualification and acceptance module to validate the assembled products.

Moreover, the factory's logistical operations must be adapted to accommodate the phased implementation. Efficient scheduling and management of shipments from Earth are essential to ensure that components, materials, and other necessary inputs arrive on time and in the required quantities. This logistical framework must also be flexible enough to adapt to changing requirements and unforeseen challenges.

As the factory progresses through its operational phases, continuous monitoring and optimization will be necessary to address any emerging issues and improve efficiency. The incremental implementation approach allows for the gradual integration of new technologies and processes, facilitating a smoother transition towards full operational capability.

In summary, the operational dependency and incremental implementation of the factory are fundamental aspects of its development strategy. By methodically phasing in each batch and system, the factory can progressively build towards a fully self-sufficient operation. This approach ensures that each phase is supported by the necessary infrastructure and resources, enabling the factory to achieve its long-term goals of sustainable and autonomous space manufacturing.

4. Operational Configurations

Once the batch division and function allocation are defined, the next step is to select an operational configuration that allows the space factory to remain functional even when certain batches are not yet deployed. This incremental approach maximizes the factory’s operability and flexibility, enabling it to adapt to changing conditions and launch schedules.

By implementing batches strategically, each batch (or combination of batches) can support specific operational modes that evolve over time. This prevents periods of complete inactivity due to missing functions and allows the factory to continue operating despite potential delays between batch launches. These delays could range from weeks to years, depending on factors like launcher availability and the readiness of each module. This approach ensures that the factory remains productive by adapting its operations based on available capabilities, thereby maintaining continuity and making efficient use of resources. For instance, a batch dedicated to additive manufacturing (AM) can begin production independently while waiting for subsequent batches to expand the factory’s capabilities.

By adopting a modular batch strategy, the space factory can incrementally increase its operational capabilities, reduce downtime, and enhance resilience against schedule disruptions, leading to a more efficient and scalable deployment process.

4.1 First configuration

The first operational configuration of the space factory will be composed of three primary modules: the Service, Assembly, and Qualification batches. This initial setup will be essential for establishing the fundamental capabilities needed to support the factory's

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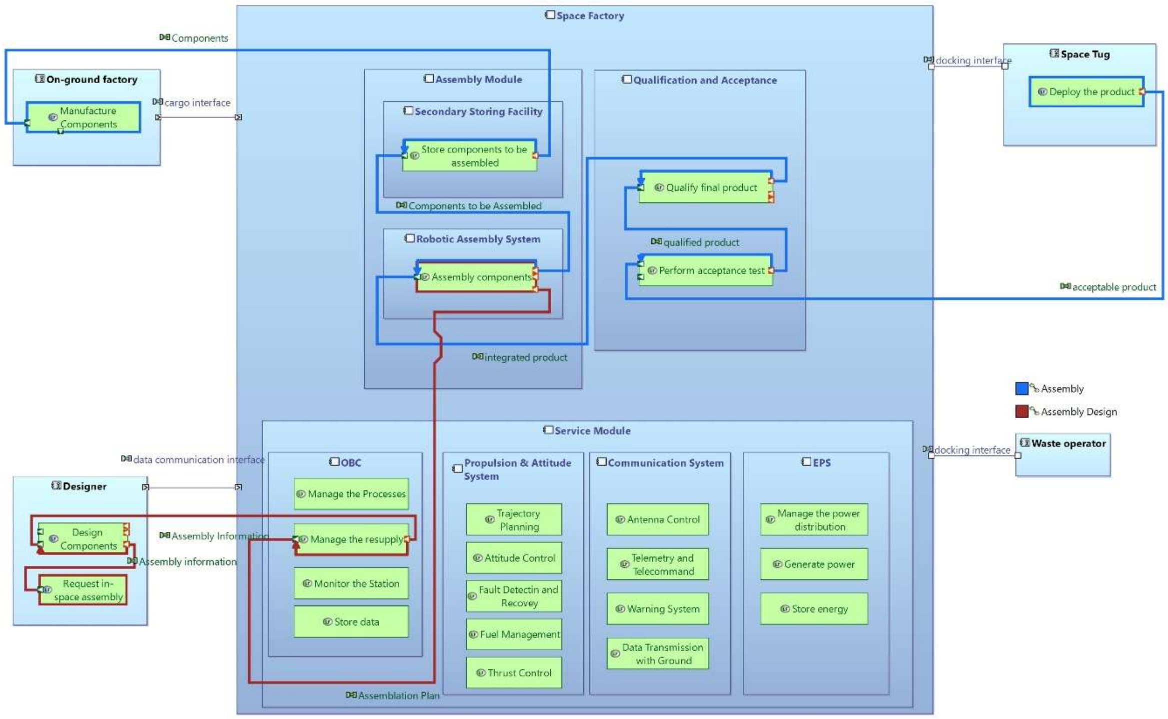

Figure 1 - First configuration

core functions and to prepare for more advanced operations in subsequent phases.

4.1.1 Service batch

The Service batch serves as the backbone of the operational configuration, providing critical support infrastructure to the other modules. This includes fluidic interfaces, data handling, thermal control, and, most importantly, energy distribution. The energy distribution system will supply power not only for the various manufacturing processes but also for maintaining the station's operational environment, ensuring the survival and functionality of the space factory.

One of the significant advantages of this initial configuration is the ability to ship components from Earth in a disassembled state. This approach offers several benefits, primarily in terms of cost and structural constraints. By sending components in a packed, disrupted form, the factory can leverage lighter materials and explore more innovative configurations. This is particularly beneficial in space operations, where launch loads are a major design consideration. These loads, which arise from acoustic forces and vibrations caused by rocket engines and atmospheric drag, dictate the need for robust and often heavy structural components when hardware is launched from Earth. However, by circumventing these launch loads, the space factory can adopt lighter and potentially more efficient design solutions.

4.1.2 Assembly batch

In this phase, the Assembly batch will enable the factory to receive inputs directly from Earth. This will likely occur through a docking system that is equipped with a sophisticated robotic arm capable of handling and manipulating incoming materials. Given that the system is designed to operate without a human crew, there will be no need for a pressurized environment at this stage. This uncrewed design reduces the complexity of the space factory and eliminates the associated safety concerns that come with human presence. However, provisions could be made for future expansion; should the need arise for human-rated components or operations, a pressurized environment could be introduced as an independent module. This modular approach allows for flexibility and scalability, potentially enhancing the operational capabilities of the space factory—referred to as EFESTO.

4.1.1 Qualification batch

The Assembly process will require a sophisticated robotic system to ensure precise and reliable construction and assembly of components in space. This system will likely comprise at least one robotic arm, equipped with various sensors, including position and thrust sensors, and a control system capable of receiving commands from ground-based operators. The control system will also monitor operations in real-time, ensuring that assembly procedures are executed accurately and efficiently.

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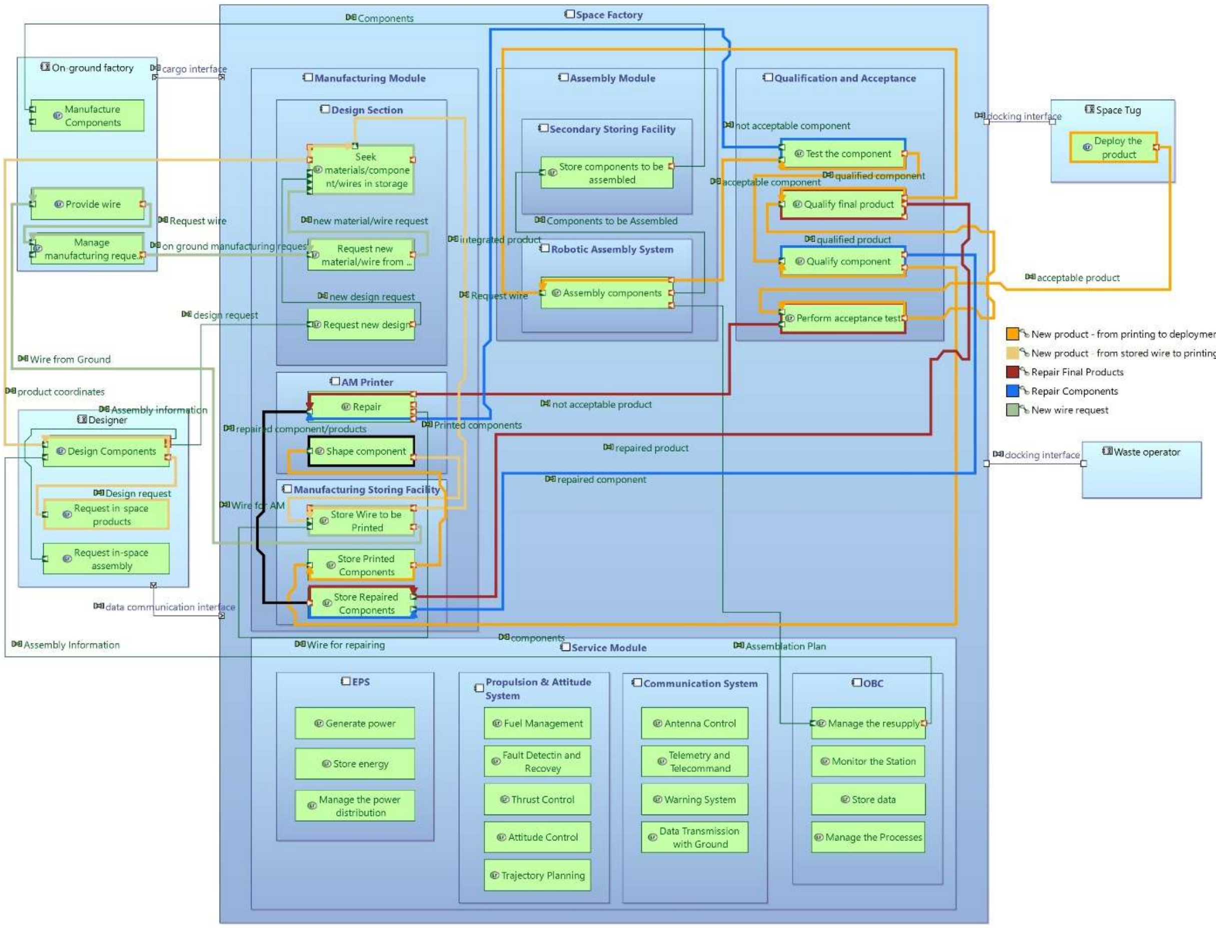

Figure 2 - Second configuration

This phase of the project lays the groundwork for subsequent expansions and operational enhancements. By focusing initially on robotic assembly and remote operation, the space factory can achieve a high degree of operational efficiency and flexibility. The uncrewed nature of the configuration simplifies the design and reduces potential risks, while the modularity of the system ensures that future upgrades -such as the introduction of a human-rated pressurized module- can be integrated with minimal disruption.

The first configuration is, therefore, a crucial step in the operational roadmap of the space factory, setting the stage for future development and demonstrating the feasibility of automated, uncrewed manufacturing processes in a space environment. This approach not only optimizes resource use and operational safety but also aligns with the broader goals of sustainable and scalable space infrastructure development.

4.2 Second configuration

The second operational configuration introduces increased complexity to the space factory system with the integration of the Additive Manufacturing (AM) batch. This configuration marks a significant evolution in the factory's capabilities by incorporating advanced manufacturing processes, including 3D printing, which expands the range of possible operations and enhances the versatility of the factory.

4.2.1 Additive Manufacturing Batch

The Additive Manufacturing batch includes the installation of an AM printer and its associated design section. This new module is designed to facilitate in-situ manufacturing by utilizing materials stored on-site, which have been shipped from Earth. In future phases, the factory will aim to source materials from decommissioned satellites, further enhancing its sustainability and reducing dependency on Earth-based supply chains. However, during this phase, a complete recycling loop has not yet been established, so additional supplies of wire for additive manufacturing will need to be shipped from Earth and stored in a dedicated facility. These materials will be cataloged in the On-Board Computer (OBC) database and will be selected as needed by the design section.

Functional Chain and Design Workflow

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The introduction of the AM batch enables a new functional chain, beginning with a request from Earth for a new component. The design process for this component could be carried out entirely by human designers on Earth, with the design data transmitted to the space factory. Alternatively, a more autonomous approach could be implemented, where the system receives only the required component specifications and outputs the optimal design configuration. While incorporating artificial intelligence to fully automate the design process is a possibility, it may be overly ambitious at this stage to eliminate human intervention entirely. The design section will handle these requests by selecting the appropriate materials, locating the necessary components in storage, and then retrieving the optimal wire or other material via an automated system to be fed into the 3D printer.

Once the material selection and preparation are complete, the next functional chain begins with the printing of the component. After printing, the component will undergo a qualification process followed by a testing phase. The specifics of the testing facility depend heavily on the type of instrumentation or components the space factory aims to produce. For now, this facility is defined as a logical component, pending further development and clarification of the factory's manufacturing capabilities. Integration testing with the satellite systems is not anticipated at this stage.

4.2.2 Component Qualification and Testing

A crucial decision in this phase is the separation of qualification processes for individual components versus integrated systems comprising multiple components. As previously outlined, single components will undergo testing after their production. However, for integrated systems, acceptance tests will be performed prior to final deployment, which will be managed by the space tug. It is important to note that any activities following the transfer of the system to the space tug are considered beyond the scope of this preliminary study.

4.2.3 Repair and Maintenance Capabilities

The implementation of additive manufacturing also introduces the capability to repair damaged components in space, aligning with one of the primary objectives of the space factory. This capability is not only applicable to structural failures, such as fractures in support ribs or frames, but could potentially extend to other types of repairs, including coatings or even microchip issues, although these might require a different type of printer. The ability to conduct repairs on-site would significantly extend the operational life of satellites and reduce the risk of mission failure due to critical component malfunctions. Components like antennas, which are essential but vulnerable to radiation, micrometeoroids, debris, atomic oxygen, and other environmental hazards, could benefit greatly from this capability.

By enabling both the creation of new components and the repair of existing ones, the additive manufacturing capability enhances the factory's flexibility and resilience, allowing it to respond dynamically to the needs of space missions. This second configuration, therefore, represents a substantial advancement in the operational capabilities of the space factory, moving it closer to its goal of supporting long-term, sustainable space operations.

4.3 Third configuration

In the third operational configuration of the space factory, the process extends beyond just receiving components and final products for repair from ground-based sources or directly from a space tug. In this phase, the factory is equipped to accept a broader range of inputs: not only the failed objects themselves but also comprehensive information related to these objects, such as their functions, materials, designs, and specific parts requiring repair. This configuration introduces enhanced capabilities in detection, sorting, and storage, marking a critical step toward achieving a closed-loop recycling process in space.

Until this stage, the factory lacked the ability to autonomously handle the inputs from the space tug. By integrating advanced detection functionalities, the space factory, codenamed EFESTO, will gain the capability to autonomously process components and systems that are unknown to ground controllers. EFESTO will be able to categorize these components based on their material properties and intended applications. This categorization process will involve detailed identification of the shape and material composition of each incoming object. Once identified, EFESTO will store these components in a designated storage area, simultaneously updating a comprehensive database that records the properties and characteristics of each item. This database will be crucial in the subsequent operational configuration, facilitating the closure of the recycling loop by ensuring all materials can be efficiently repurposed or recycled.

Specifically, after the shape and material identification process is complete, the ground-based staff will assess each component to determine the feasibility and practicality of repair. If deemed viable, the ground team will send a repair request back to the space factory. At this juncture, there is potential for optimizing the repair process or even fully automating

decision-making and design processes. Upon receiving a repair request, the design module within EFESTO will search the storage for the most suitable wire or material required for 3D printing. Subsequently,

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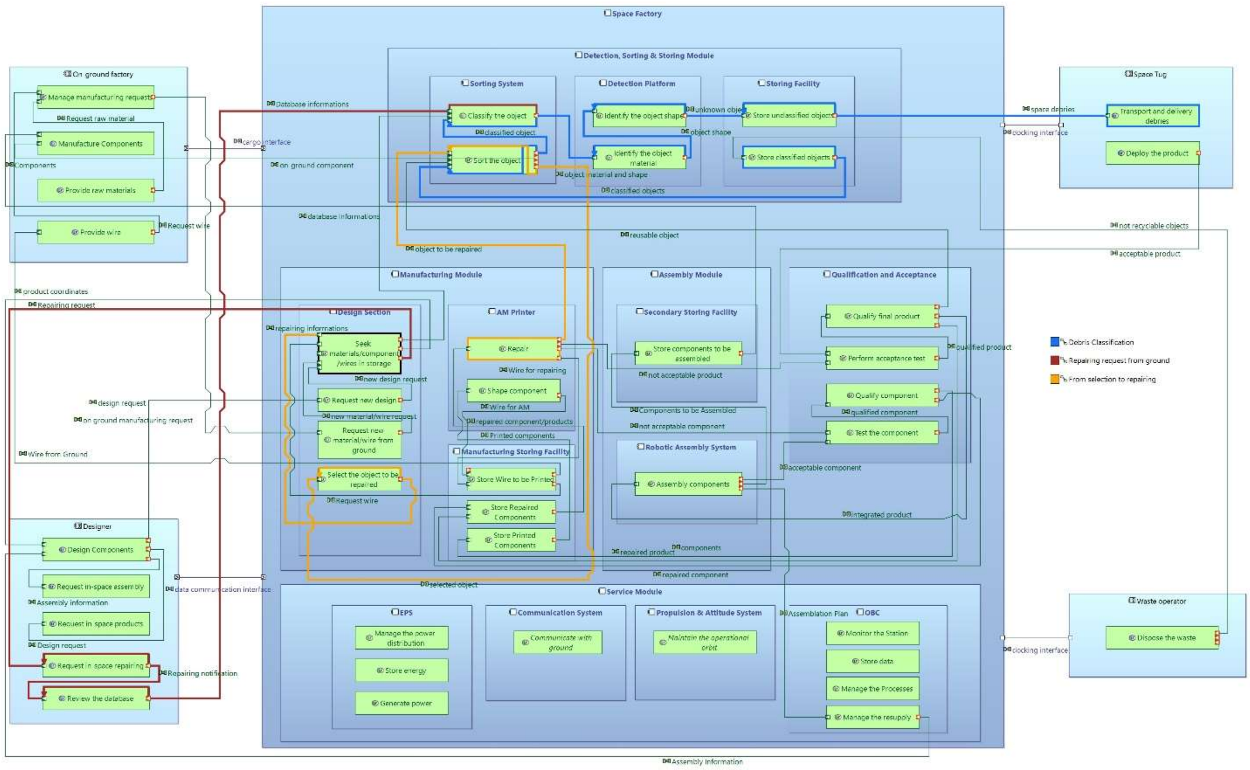

Figure 3 - Third configuration

the repair can be executed in the additive manufacturing facility, effectively closing the recycling loop and enhancing the sustainability of space operations.

This configuration not only streamlines the repair process but also sets the foundation for a more sustainable and autonomous operation. By automating material identification and categorization, and by storing detailed data on each component, EFESTO ensures that every part can be repurposed or recycled, thus significantly reducing waste and enhancing the efficiency of space operations. This step towards automation and recycling also reduces the dependency on ground-based resources and interventions, thereby optimizing the overall operational workflow of the space factory.

4.3 Final configuration

The final configuration model is depicted in the Logical Architecture Breakdown (LAB) shown in the accompanying figure. This model integrates all the functionalities required to fulfill the objectives of the EFESTO mission. A critical addition to this configuration is the wire manufacturing module, which enables EFESTO to recycle decommissioned satellites effectively. This module was incorporated at this stage because it relies on outputs from the additive manufacturing (AM) facility and requires the detection and sorting batch to provide the necessary input materials. Manufacturing wire from objects shipped from Earth would not be efficient, as the wire could be launched directly. The wire manufacturing module is the most complex subsystem in the configuration, consisting of three distinct logical components: the disassembly unit, the melting unit, and the casting facility. Starting with the **disassembly unit**, this capability is designed to separate the various materials within decommissioned components and cut them into smaller pieces suitable for the melting process. This task is particularly challenging because most space systems currently in orbit were not designed for easy disassembly or material separation; rather, they were built for maximum durability. Consequently, separating different materials within the same component will often be nearly impossible, making this stage one of the most critical and complex in the entire recycling process.

Following disassembly, the next stage is the melting phase, which aims to convert the separated materials into molten metal. This phase involves melting small metal chips or spheres, and the technology chosen for melting in a microgravity environment is crucial for ensuring efficient process exchanges. As of now, such a process has not been implemented in microgravity, making the selection of an appropriate technology somewhat speculative. However, in collaboration with the University of Padua, the idea of utilizing a levitating

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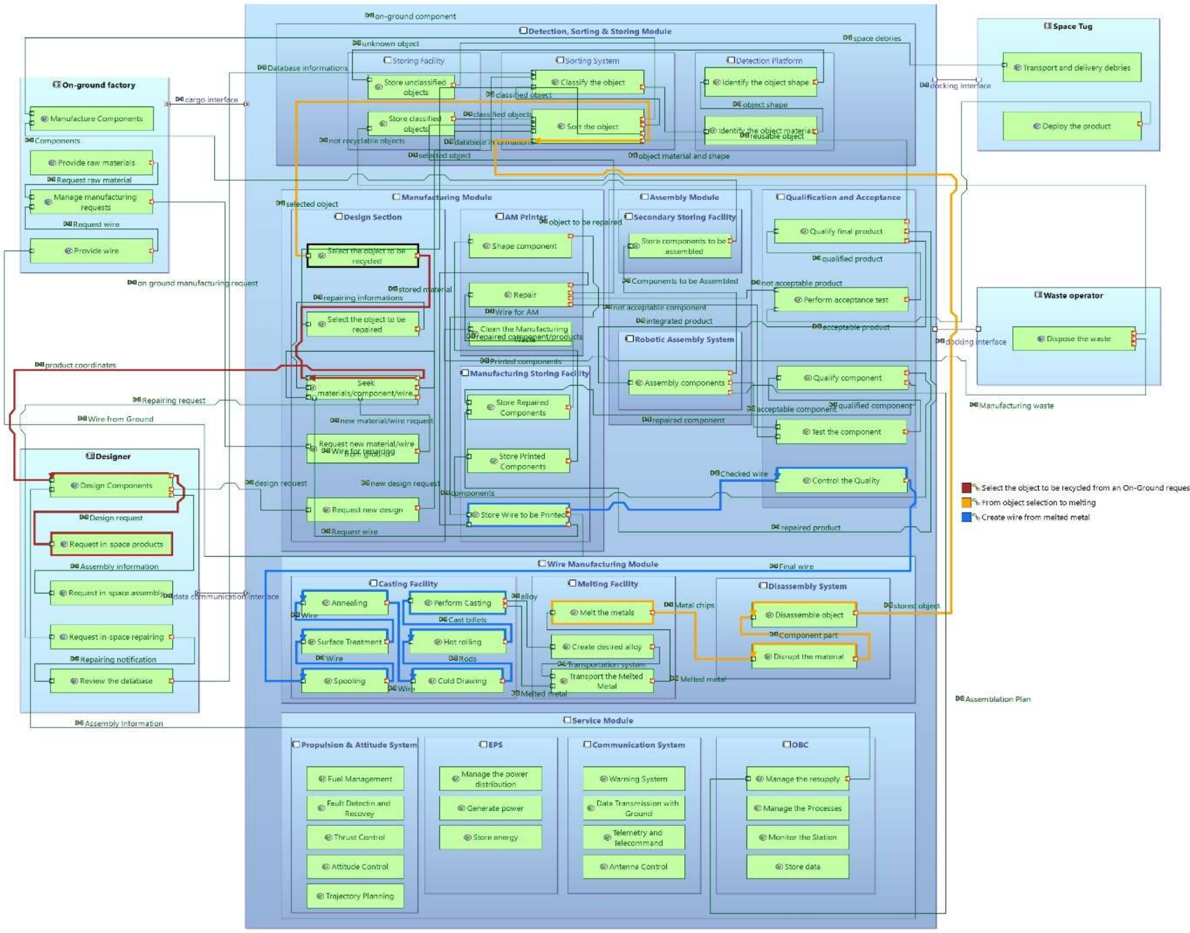

Figure 4 - Final configuration

melting process is being explored. This technology employs magnetic forces to levitate and melt the metal, thereby reaching the necessary melting temperatures without the need for physical containment of the molten material. Additionally, the use of induced magnetic fields minimizes the influence of gravitational forces, reducing the impact of the microgravity environment and making the technology highly suitable for space applications.

The same induced magnetic forces used in the melting process could potentially transport the molten metal to the casting batch. The casting process for wire production intended for additive manufacturing applications has yet to be fully adapted for use in space. It is assumed that similar processes used on Earth can be applied in microgravity, although significant modifications will be necessary. Future work will focus on refining these processes to address the unique challenges posed by the space environment, ensuring the reliability and functionality of wire production in orbit. By integrating these components into the final configuration, the EFESTO mission will be equipped with the capabilities necessary to recycle decommissioned satellites effectively, thereby advancing sustainable practices in space and supporting ongoing manufacturing needs.

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