Definition of a Space Factory through MBSE

Serena Brizio [1], Riccardo Cambertoni[1], Elia Sindoni [1], Lucia Grizzaffi[1], Brendan P. Sullivan[2]

[1] *Thales Alenia Space, Str. Antica di Collegno, 253, 10146 Torino TO, Italy*
[2] *Polytechnic University of Milan, Piazza Leonardo da Vinci, 32, 20133 Milano MI, Italy*

Abstract

In the context of in-orbit manufacturing, Thales Alenia Space (TAS) has implemented a typical space system engineering approach currently used internally for ESA and NASA projects, which includes the definition of a mission statement and mission objectives for a factory in space. Since the project was in partnership with different Italian universities, it was necessary to coordinate the workload among the entities. Then, a MBSE approach was settled to obtain a preliminary architecture of the Space Factory. The result shows a promising novel concept, even if future work is needed to define the technological roadmap for the manufacturing processes and the supply chain.

Keywords

MBSE, System Engineering, Space Factory, Recycling, In-orbit 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 the conceptualization of a space mission is the identification of an operational orbit or surface, which dictated the environmental challenges and boundaries of the project, as well as the definition of a mission statement and mission objectives. The collaborative nature of the project underscores the importance of coordinating efforts among multiple stakeholders to achieve a cohesive and comprehensive vision.

2. Mission Definition

The formulation of mission statement and mission objectives is a crucial step in the preliminary phase of the project to clearly identify what needs the mission is answering to. In other words, the mission statement ensures that all the actors (the stakeholders) are aware of what the main purpose of the mission will be and, especially in the early phase of the design, provides a clear direction for the team.

For the of the Enhanced Factory for Extraterrestrial Space Technology Operations (EFESTO), the mission statement was defined in a brainstorming session by TAS team, considering the feedback by partners with a wide range of different competence and expertise areas. This collaborative approach enabled the team to attain a broader perspective, ultimately resulting in the creation of the following interdisciplinary mission statement:

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EMAIL: serena.brizio@thalesaleniaspace.com (A. 1); riccardo.cambertoni-somministrato@thalesaleniaspace.com (A. 2); elia.sindoni@thalesaleniaspace.com (A. 3) ; lucia.grizzaffi@thalesaleniaspace.com (A. 4); brendan.sullivan@polimi.it (A. 5)
ORCID: N/A

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

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 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 important to note that hierarchy only 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. Environmental scenario

Understanding the environmental context is a fundamental step in the design and development of a space mission, as the environment deeply interacts with the system and influences its lifespan. In addition to its isolation, space is indeed a hostile environment for both human life and spacecraft, necessitating the implementation of adequate countermeasures to minimize its degrading effects. While there are some general commonalities, defining universal characteristics of the space environment is impossible. However, for the first factories in space, as in the EFESTO study, the options can be narrowed down to the Low Earth Orbit (LEO) region and the lunar surface. Due to its easier accessibility as well as the increasing of launches in the region [2] [3] and its strategical relevance [4], Low Earth Orbit was selected as the operational environment, facilitating the communication with the ground station and reducing the resupply costs. Other elements for the choice of LEO were the absence of lunar dust and a less challenging radiation environment, which would add several criticalities and consequently lead to a more complex system.

A satellite travelling in LEO will have to contend with various factors influencing its lifespan and performance in orbit, depending on the orbital parameters of the mission (e.g., altitude, inclination, eccentricity). However, all spacecraft will encounter residual atmosphere, (near) vacuum, microgravity conditions, micrometeoroids and debris, radiation, magnetic field disturbances and interactions, as well as a plasma and charged particle environment.

In accordance with the previously mentioned environmental constraints, some assumptions on the operational orbit were made to give boundary conditions to the other actors of the mission design. They are here summarized:

1. Operative environment: Low Earth Orbit (LEO);
2. Circular Orbit (e=0);
3. Altitude range [400÷900] km;
4. Waste, dismissed satellites and debris are already in the factory; the presence of an external service that transports them to the factory is taken for granted;
5. No constraints in terms of mass and volume (launcher) and power. Feasibility and optimization of the power and mass request will be assessed as next step;

6. The factory will be modular and will be designed with an incremental approach, enabling new functionalities with time;
7. CIMR (Sentinel 11), a future Earth-observation satellite, was selected as a reference platform for the study. The entire end-to-end process (from recycling to final deployment) of the space factory will focus on the study cases applied to this mission.

2.3. Tasks definition

Since the project is in partnership with different Italian universities, it was necessary to coordinate the workload among the entities, defining a task tree and selecting two study cases for evaluation based on criteria such as costs, power requirements, and the feasibility of the manufacturing process. Table 1 shows an extract of the Work Breakdown Structure (WBS) and it is comprehensive of a short description of the activities to be accomplished.

Table 1
Task Definition

Task	Task Manager	Task description
Preliminary analyses	PoliMI	This task gathers the preliminary analyses needed to better understand the context, in particular the market one, where EFESTO will operate, individuating the main actors and the potential customers of a space factory and defining the stakeholders' needs and their priority. Understanding the state of the art of the technologies that could be foreseen in a space factory implementation is also a crucial point of this activity.
Mission definition	TAS	This task defines the goal of the space factory, clarifying its main objectives and the boundaries of the study. The study case selection is also foreseen within this activity and a general presentation of the selected operative environment.
System definition	TAS	This task goal is to coordinate the activities needed for the definition of EFESTO at a high level.
Supply chain analysis	Sapienza	This task consists in evaluating the advantages of relocating part of the activities (manufacturing, assembling and integration) in orbit, studying the on-ground supply chain with or without EFESTO. An economic estimation of the advantages of an in-orbit factory should also be foreseen.
Electrothermal budget	UniPD	This task aims to assess the feasibility of EFESTO from a thermal and power point of view. Indeed, to enable all the manufacturing and recycling processes the platform will need to supply high levels of power and both to provide and dissipate high temperatures. For the preliminary estimation of the power budget, a bottom-up approach is proposed, starting from the study cases previously selected.
Circularity assessment	PoliBA	This task aims to define a circular economic model applied to EFESTO concept and his building block process chain. It will be important to underline the environmental benefits of locating the activities directly in orbit and to understand how the life cycle of a space product or of a single component would be extended by the factory with respect to the current averaged target missions' duration.

2.4. Study cases

The selection of study cases was carried out considering various factors that could influence the design process of the space factory. Primarily, the reference mission had to have a significant contribution from Thales Alenia Space, ensuring that all required documentation could be obtained without compromising industrial intellectual properties or internal information. Furthermore, the chosen mission should have an operational orbit within the same altitude range selected in the environmental definition phase for coherence. Concerning the specific component, the objective was to define objects that are, generally speaking, more fragile, not safety critical for the mission and not placed near dangerous subsystems such as propulsion. All these considerations led to the choice of the Copernicus Imaging Microwave Radiometer (CIMR), a mission focused on responding to high-priority requirements from key Arctic user communities and, in particular, the first study case focuses on its antennas

A feasibility study should be carried out for the S band (from 2 to 4 GHz) helix antennas (Figure 1), generation 3 (G3). The evaluation should encompass not only material recycling but also repairing and in-orbit manufacturing of new antennas. While made of aluminium alloy, the specific composition can be assessed through the optimization of the in-orbit manufacturing process. The material choice for antennas is generally influenced not only by communication performance but also by the need to withstand launch thermal and structural loads, depending on the satellite's configuration inside the fairing, or by the availability on-ground. In this case instead, the flexibility of decision-making is a benefit offered by a space factory.

The second selected study case aimed to involve both metallic materials and polymers, leading to the choice of thermal blankets (Figure 2), despite potential challenges in their in-orbit manufacture. Thermal blankets are crucial elements in a space system, ensuring the survival of spacecraft internal instrumentation under the demanding thermal loads of the space environment. Initiating a preliminary study for repairing such a component is fundamental for the extension of the operational life of a space system. The material and design of thermal blankets can vary based on the supplier, application, and needs. Partners are expected to choose the best solution in terms of materials, manufacturing processes, and required power. The goal is to understand the type and quantity of materials that can be reused starting from a 1m x 1m thermal blanket and determine the feasibility of manufacturing it in orbit.

Figure 1: S-band TTC Antennas from Beyond Gravity Sweden AB

Figure 2: COOLCAT 2 NF from Beyond Gravity Austria GmbH

3. Model Based System Engineering (MBSE) approach

The MBSE consists of a set of tools and methods applied to System Engineering that allows the definition of a preliminary design since the early phase of a mission. In the case of EFESTO, it has been used a Thales MBSE tool called Capella, which allows different levels of analysis following the maturity of the project. Since EFESTO is at its early stages, the first three levels of analysis were developed, namely the Operational Analysis and the System and Logical ones. In the Operational Analysis the entities involved and what is expected from them were defined, the System Analysis defined the perimeter of the system, the interfaces between system and external actors and the system level functions.

The third level of analysis, the Logical Architecture, deepens the building block of platform, including inside more detailed functions. Regarding the semantics of the diagram, the blue/light blue boxes correspond to the system perimeter, the sub-system/building blocks and the external actors. Otherwise, the green boxes are the functions that the component is supposed to perform in this context. A function is an action or a set of actions that describe what is the expectation of a system (high level approach) and of components within the system.

In the two pictures below is possible to highlight the evolution of model, from a high-level perspective, in this case the system level (Figure 3), with high level function allocated into the system perimeter. It is also possible to see the interface definition between the space factory and the external actors, from a very high perspective in the system architecture, and more detailed in the logical architecture (Figure 4).

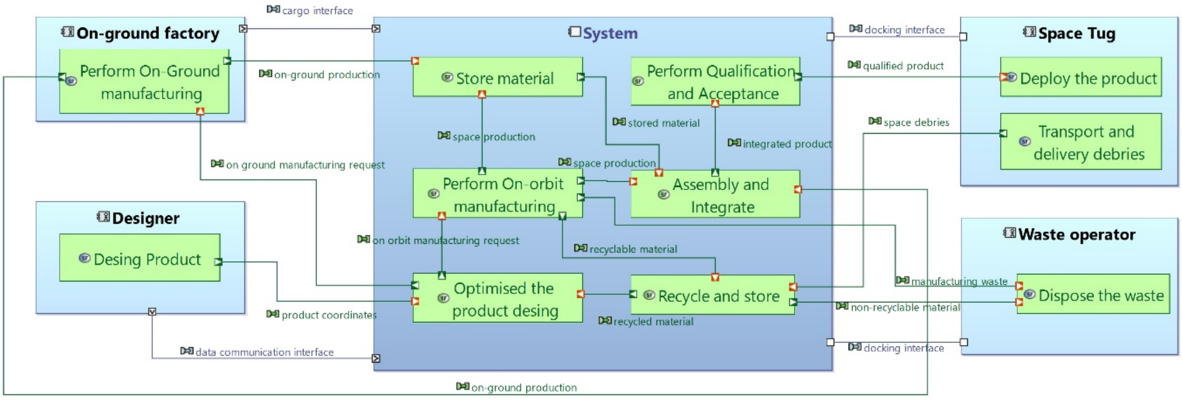

Figure 3: System architecture diagram

In the case of EFESTO, it was useful to define the major building blocks that constitute the space factory such as the design, the recycling, the manufacturing, the qualification and the storage, with the functions of each domain associated inside and the data/components exchanged among functions.

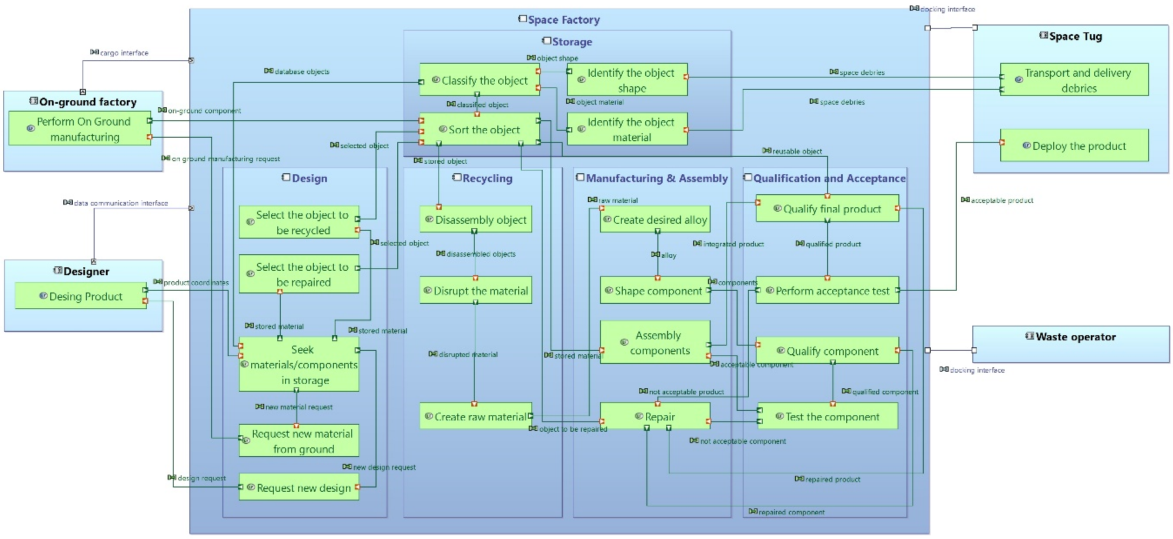

Figure 4: Logical architecture diagram

The first step of the recycling/repairing process is the resupply of components and materials. This would be done in two ways: the input will come from Earth as components to be assembled in space (for structural load reasons, mainly related to the launch) or from space as decommissioned systems. Once entered into the space factory, they will be categorized and stored, based on the material composition.

Regarding the creation of new components from scratch, the baseline envisions the possibility of developing the initial design on the ground and then sending the request to the space factory. Upon receiving the new component coordinates, the system will seek the needed materials in the database created thanks to the detector and provide clearance to proceed with manufacturing or not. If not, new coordinates should be provided from the ground to replace the missing material, but an in-orbit design optimizer could offer suggestions based on the availability status of the factory.

The process of repairing would be approached in a similar way, with a difference in the qualification and acceptance section, where the repaired objects will follow a distinct process. A space tug will also be required for the functions of transport and delivery, both for the input objects of the factory and for the deployment of the output systems.

4. Conclusions and Future work

The study unveiled a promising concept of operations, underpinned by a robust functional chain implementing mature or near-mature technologies. Despite the advancements, the work emphasizes the need for further investigation and definition of the technological roadmap for manufacturing processes and the supply chain. While the results present a groundbreaking concept, the study acknowledges the necessity of future endeavours to refine the proposed solutions and address potential challenges in the mission's execution.

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Declaration on Generative AI

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

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