Evaluation of In-Space Manufacturing initiatives through comparative Life Cycle Assessment and Procurement Demand Modeling

M. Sc. in Engineering & Management

Major in Space Economy

M. Sc. thesis developed in collaboration with Thales Alenia Space Italia

Supervisors

Dr. Angioletta Rita Catalano

Prof. Paolo Claudio Priarone

Company Advisors

Dr. Lucia Grizzaffi

Dr. Elia Sindoni

Candidate

Giovanni Del Vecchio

Academic Year 2025–2026

To the family that supported me,
and to the horizons it opened to me.

To the city I left behind,
and to the one that welcomed me.

To the friendships that time has scattered,
and to those it has strengthened.

To the people I met along the way,
and to those I only crossed paths with.

To the days when I faltered,
and to those when I found my strength.

To the solitude that questioned me,
and to the sharing that gave me answers.

To every infinitesimal contribution,
guiding me toward what I was meant to be.

To each of you,
my gratitude.

Contents

List of Abbreviations

ADR Active Debris Removal

AHP Analytic Hierarchy Process

AI Artificial Intelligence

AM Additive Manufacturing

AP Acidification Potential

AP ammonium perchlorat

ASI Agenzia Spaziale Italiana

CE Concurrent Engineering

CRS Cosmic Ray Shielding

DARPA U.S. Defence Advanced Research Projects Agency

EFESTO Enhanced Factory for Extraterrestrial Space Technology Operations

EO Earth Observation

ESA European Space Agency

ESR Equipped Solid Rocket

ETS Engineering Test Satellite

FFF Fused Filament Fabrication

GEO Geosynchronous Equatorial Orbit

GNSS Global Navigation Satellite System

GWP Global Warming Potential

HEO Highly Elliptical Orbits

HST Hubble Space Telescope

IOS In Orbit Servicing

ISAM In space Servicing, Assembly, Manufacturing

ISAM In space Servicing, Assembly, Manufacturing

ISM In Space Manufacturing

ISO International Organization for Standardization

ISS International Space Station

LCA Life Cycle Assessment

LCE Life Cycle Engineering

LCI Life Cycle Inventory

LEO Low Earth Orbit

LLPM Lower Liquid Propulsion Module

MBSE Model Based System Engineering

MELiSSA Micro-Ecological Life Support System Alternative

MEP Mission Extension Pod

MEV Mission Extension Vehicle

MICS Made in Italy Circolare e Sostenibile

MRV Mission Robotic Vehicle

NASA National Aeronautics and Space Administration

NASDA National Space Development Agency of Japan

OOM On Orbit Manufacturing

OR Operations Research

ORUs Orbital Replacement Unit

OSAM On orbit Servicing, Assembly, Manufacturing

OST Outer Space Treaty

PLA Polylactic Acid

PM Particular Matter

PNRR Piano Nazionale di Ripresa e Resilienza

RPOD Rendezvous, Proximity Operations, and Docking

SDGs Sustainable Development Goals

SLR Systematic Literature Review

SMM Solar Maximum Mission

SMPCs Shape Memory Polymer Composites

SSO Sun Synchronous Orbits

STM Space Traffic Management

STS Space Transportation System

TAS-I Thales Alenia Space Italia

ULPM Upper Liquid Propulsion Module

UN United Nations

UNOOSA United Nations Office for Outer Space Affairs

VLEO Very Low Earth Orbit

WCED World Commission on Environment and Development

List of Tables

List of Figures

Chapter 1

Introduction

The progressive development of the New Space Economy is leading to the so called In-Space Manufacturing (ISM) initiatives, supported by both space agency and private companies. ISM capabilities represent the opportunity to reshape the strategic and economic foundations of the emerging in-space economy. The dependency of orbital manufacturing systems on Earth-based resupply mission remains one of the critical challenges to be addressed, with significant environmental, economic, and logistical impacts and implications. The thesis, developed in collaboration with Thales Alenia Space Italia, within the EFESTO research context, has firstly been oriented toward investigating how sustainability has been addressed within the space sector and ISM missions through a Systematic Literature Review (SLR). Supported by the rigorus SLR, the thesis aims to analyze the environmental impacts and Earth dependency of ISM initiatives through a comparative Life Cycle Assessment (LCA) based evaluation and Procurement Demand Modeling. The LCA-based evaluation has been conducted to investigate the environmental impacts associated with two alternative scenarios: (i) terrestrial production of the functional unit followed by launch, and (ii) in-orbit manufacturing supported by material resupply. The study integrates both primary data from additive manufacturing (AM) process (i.e. electric energy consumption) and secondary data related to the Ariane 6 launcher. A parametric procurement demand model has been developed to formalize the structural relationship between functional unit life-time, production scale, recycling efficiency, and quality decay. The demand model introduces substitution rate and effective efficiency factor as key system level parameters defining the procurement needs. Thus, the model explores a deeper definition of both, structuring the effect of learning curve and quality decay effects on the demand itself. The study, supported by LCA results and procurement demand model, contributes to providing a structured framework useful to be integrated into strategic long-term planning and decision-making processes for ISM systems.

The thesis has been structured into five main chapters. Chapter 2 provides the research context, introducing the technological and strategic evolution of ISAM and presenting the EFESTO project. Chapter 3 outlines the methodological framework adopted for the SLR, the LCA methodology applied in accordance with ISO standards and ESA guidelines, and the system dependency modeling approach. Chapter 4 presents the case study and data inventory, defining the goal and scope of the LCA w.r.t. the selected case study, thus detailing the selected antenna prototype, and describing both primary experimental data and secondary data inventories. Chapter 5 reports and discusses the results, including the findings of the systematic literature review, the environmental impact comparison between the analyzed scenarios, and the outcomes of the system dependency analysis, while Chapter 6 summarizes the conclusions.

Chapter 2

Research Context

The objective of this chapter is to provide an overview of the broad concept of In space Servicing, Assembly, Manufacturing (ISAM), describing the technological and strategic context within which the research of this thesis must be framed.

The research has been set at the intersection of the rapidly evolving New Space Economy and the increasing demand for sustainable solutions in outer space. Following this framework, ISAM has emerged as a key aspect to enable long-term and cost-effective operations beyond Earth. The chapter is composed by:

- Section 2.1, which explores historical and technological evolution of ISAM, ultimately focusing on In Space Manufacturing (ISM).
- Section 2.2, which introduces the EFESTO project, developed by Thales Alenia Space Italia (TAS-I), Turin, within which this thesis has been carried out, describing its objectives, structure, and specific positioning with respect to the project's tasks.

In doing so, the chapter provides the necessary background to understand how this research contributes to the vision of a self-sustaining in-space economy.

2.1 In-Space Servicing, Assembly, Manufacturing

The New Space Economy represents an established new phase of the global space sector characterized by the growing involvement of private actors, the reduction of launch and production costs, and the increasing integration between space technologies and terrestrial markets. Within the large concept of this, it is possible to observe that the use of space assets to support applications on Earth is predominant. However, the concept of an In-Space Economy is gaining increasing importance. This term refers to the set of activities carried out in space that generate value and benefits directly in space or, in other words, the production of goods and services intended for use within the space environment itself [Kulu, 2023] [European Space Policy Institute (ESPI), 2023].

One of the most prominent element within this context is the concept of ISAM defined as a suite of capabilities used in space, on the surface of celestial bodies, and during transit between these environments. ISAM capabilities support specific activities in the areas of servicing, assembly, and manufacturing. The term "in-space" refers to all the environment beyond Earth. Thus, it is worth to mention a general distinction in the literature that yields to specific concepts like On orbit Servicing, Assembly, Manufacturing (OSAM), which refers to specific environment, in this case to all orbit locations around Earth and Moon [Arney et al., 2024].

Space assets are generally characterized by high development and launch costs, as well as significant expenses for on orbit operations, both to activate and to maintain the system. This has led to the development of ISAM capabilities since the very beginning of the space era, for technological, operational, and economic reasons. Over the years, as missions became more complex, higher levels of capability were required. Looking at the history of space exploration, the progress of ISAM can be traced looking at specific missions that acted as milestones, highlighting when and why these capabilities were developed, and providing a first general view of the current state of the art [Arney et al., 2024].

At first, servicing missions were carried out by astronauts. Beginning in the late 1980s and continuing through the early 1990s, complex robotic systems were integrated with human activities, enabling a wide range of capabilities in servicing and assembly. On the other hand, uncrewed autonomous servicing and assembly have been developed only recently. Table 2.1 lists main historical achievements [United States Government Accountability Office, 2025] [Cavaciuti et al., 2022] [Arney et al., 2024].

Year(s)	**Agency / Missions**	**Key Milestone**
1964–1966	NASA / Gemini	RPOD demonstrations
1973–1974	NASA / Skylab	On-orbit repairs of critical components
1984	NASA / SMM	First repair of a satellite in space by STS; modular design was introduced, implementing ORUs to streamline the repairing process
1993–2009	NASA / HST	Multiple in-orbit servicin; a total of five missions by STS were performed
1997	NASDA / ETS-VII	First satellite with a robotic arm
1998-Present	ISS	On-orbit assembly, and continuous servicing through years, enabling technological growth of RPOD
2007	DARPA / Orbital Express	First autonomous robotic servicing mission included docking, refueling, and part replacement.
2019-Present	SpaceLogistics / MEV	First commercial satellite servicing for life extension in GEO

Table 2.1: Main historical in space servicing and assembly milestones.

Examples of crewed servicing missions are those performed by the Space Transportation System (STS) crew on the Hubble Space Telescope (HST), 1993, as Figure 2.1 presents. The success of a total of five mission demonstrated that repairing

Figure 2.1: Astronauts installing protective covers on the HST, Dec. 1993. Image Credit: NASA.

a satellite in orbit could be more cost-effective than replacing it entirely. However, the involvement of astronauts significantly increased both the cost and the risk of the operation. In light of these challenges, numerous programs and demonstration technologies that enable robotic, autonomous satellite servicing have been explored [United States Government Accountability Office, 2025].

As Table 2.1 shows, the first and only full commercial initiative in history is the one promoted by SpaceLogistics, a Northrop Grumman subsidiary. The Mission Extension Vehicle (MEV) missions, specifically MEV-1 and MEV-2, represent key milestones as the first successful commercial operations in satellite servicing. The objective of both mission was to service a spacecraft running out of fuel, providing attitude control and propulsion, allowing an extension of the spacecraft service lifetime. In 2020 and 2021, they docked with Intelsat's IS-901 and IS-10-02 satellites, not originally designed to be serviced, providing on-orbit life extension services of

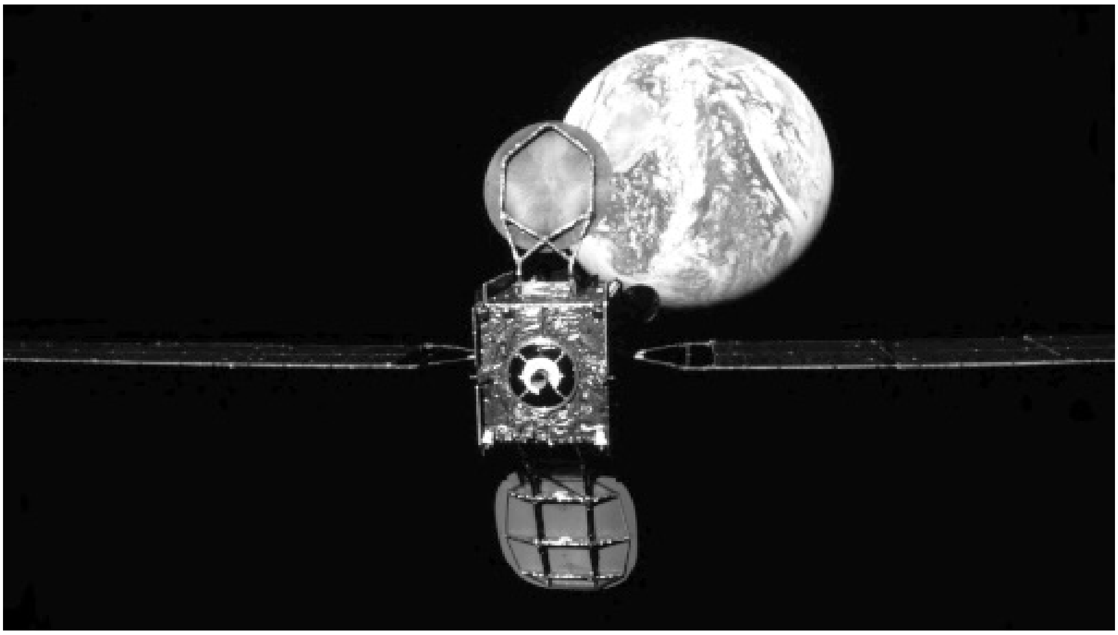


Figure 2.2: Photo of IntelSat-901 taken from the approaching MEV-1, Feb. 2020. Image Credit: Northrop Grumman.

about five years, giving opportunity to Intelsat to still generate revenues. Once a contract ends, the MEV can be disconnected and redeployed to support other clients. Missions resulted in significant savings for the client: an estimated $70 million investment, approx. $13–14 million per-year, avoided replacement costs between $200–400 million, demonstrating a strong return on investment for satellite operators [European Space Policy Institute (ESPI), 2023].

Building on these results, SpaceLogistics is now developing next-generation systems to broaden its services, including on-orbit repairs, upgrades, refueling, debris removal, and even in-orbit assembly and manufacturing, through the upcoming Mission Robotic Vehicle (MRV), a servicing spacecraft designed to perform in-orbit robotic operations in Geosynchronous Equatorial Orbit (GEO), and Mission Extension Pod (MEP), a small and attachable propulsion module designed to extend the operational life of a satellite by several years. Figure 2.3 presents the projected development of OSAM capabilities over the next years, based on forecasts by SpaceLogistics [Northrop Grumman Corporation, 2025].

TODAY
Life Extension Services
Mission Extension Vehicles (MEVs) docked with satellites to provide maneuvering and pointing control (for up to 15 years).

Launch in 2024
Robotic Satellite Servicing
Mission Robotic Vehicle (MRV) provides on-orbit augmentation, inspection and repair capabilities, as well as installation of Mission Extension Pods (MEPs).

2025+
Refueling and GEO Active Debris Removal
Mission Refueling Pods (MRPs) and Depots refuel compatible* spacecraft in GEO.

Removal of debris from vicinity of high value assets.

2030+
In-orbit Assembly and Manufacturing
Mission Assembly and Repair Vehicle (MARV) manufactures and assembles spacecraft in-orbit.

Figure 2.3: Future development of OSAM capabilities. Image Credit: Northrop Grumman.

It is clear how ISAM represents a significant area of current space development activities due to the wide range of critical functions it encompasses. All of these activities can promote a sustainable space environment, enhancing the performance, availability, resilience, and lifetime of space systems, enabling a possible sustainable framework for space activities, both economically and environmentally [European Space Policy Institute (ESPI), 2023].

Even if ISAM can still be considered in its early stages, even short-term progress in orbit can bring significant advantages: satellite servicing will likely focus on inspection, orbit modification, maintenance of legacy satellites, and refueling of satellites with limited servicing capabilities. In the longer term, demonstrations of more advanced functions could expand the market. These capabilities could also push beyond the demand for basic services, driven by the growing complexity of space systems and operations [Cavaciuti et al., 2022].

The challenges in developing ISAM capabilities are not only technical but also economic, specifically linked to issues of demand and supply. A clear example is the so-called "chicken-and-egg problem". Satellite operators are reluctant to design satellites to be serviceable until commercial servicing options are available, while potential providers hesitate to invest in such capabilities until a sufficient number of serviceable satellites exists to create a viable market. As a result, both sides wait for the other to act first, and satellites continue to be treated as disposable [European Space Policy Institute (ESPI), 2023] [United States Government Accountability Office, 2025].

There it follows, the role of State actors acting as first customer in this context appears pivotal, and it may provide an indication of the interest of some countries to develop such capabilities as well as to make some companies emerge in this market segment, enabling commercial services to both State actors and other companies in the future. This is has been observed lately in Europe for on-orbit demonstration missions. For example, in 2023, the Agenzia Spaziale Italiana (ASI) awarded a 235 millions euro contract to TAS-I to design, develop, and qualify an IOS mission, which will demonstrate in-orbit refuelling, component repair and replacement, orbital transfer, and atmospheric re-entry [European Space Policy Institute (ESPI), 2023].

In summary, despite the technical and economic challenges, demand for ISAM is steadily increasing, specifically for the great economic returns as MEV missions demonstrated recently. Past data support this trend: Figure 2.4 shows the number of deals and the total investment volume in ISAM from 2014 to 2019, highlighting constant growth in both metrics [European Space Policy Institute (ESPI), 2023].

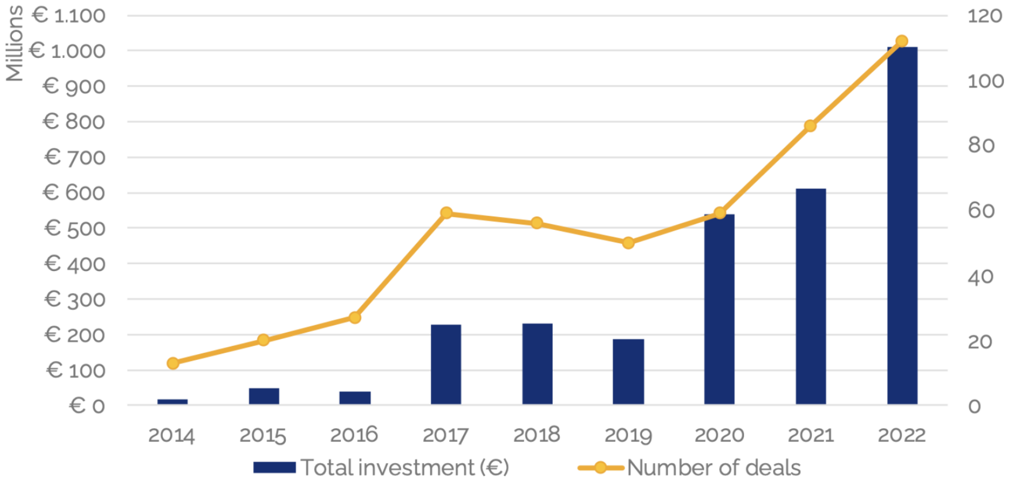


Figure 2.4: Total investment and number of deals in European space start-ups ISAM related [European Space Policy Institute (ESPI), 2023].

Figure 2.5 summarizes the main milestones in servicing, assembly, and manufacturing in space from the 1990s to those planned until 2030. It is clear that among the three main ISAM capabilities, manufacturing is the less developed, with demonstrations started only in 2014, with the 3D Printing in Zero G (3D Print) mission, a NASA and Made In Space partnership. This was the first demonstration of 3D printing in space using fused filament fabrication on the International Space Station (ISS), aiming to test additive manufacturing in microgravity, with the goal of enabling on-demand part creation for long-duration space missions [Arney et al., 2024].

ISM is a fundamental pillar of ISAM, and it has been defined as the transformation of raw or recycled materials into components, products, or entire infrastructures directly in space [Kulu, 2022].

NASA proposed to organize ISAM's capabilities into 11 capability areas: (1)

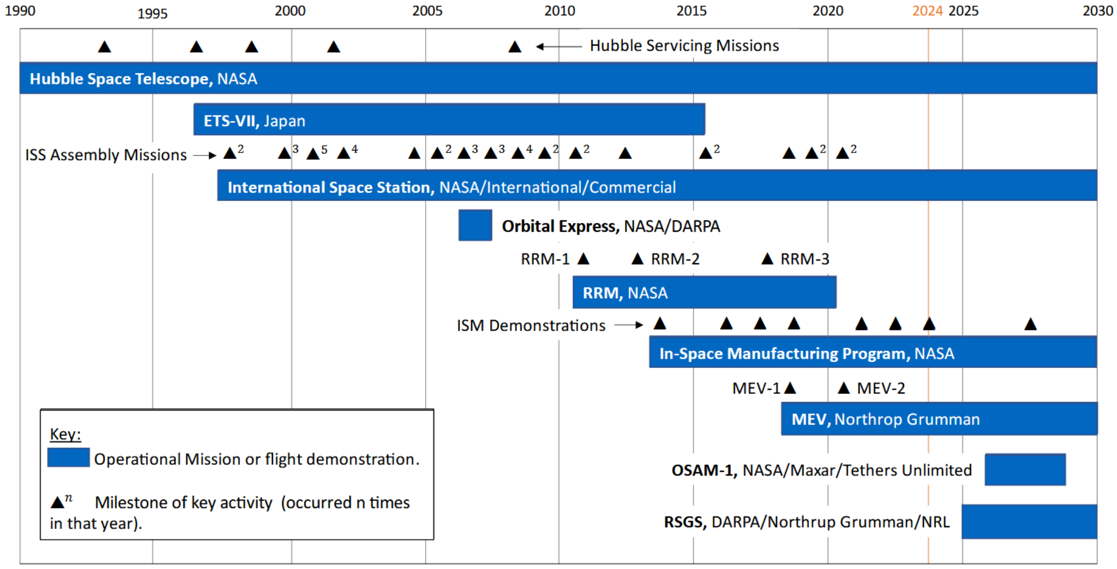


Figure 2.5: Timeline of ISAM capabilities w.r.t. operational missions and flight demonstrations [Arney et al., 2024].

Robotic Manipulation, (2) Relocation, (3) Planned Repair, Upgrade, Maintenance, and Installation, (4) Rendezvous, Proximity Operations, and Docking (RPOD), (5) Unplanned or Legacy Repair and Maintenance, (6) Refueling and Fluid Transfer, (7) Structural Manufacturing and Assembly, (8) Recycling, Reuse, and Repurposing, (9) Parts and Goods Manufacturing, (10) Surface Infrastructure, (11) Inspection and Metrology. Thus, ISM can be studied as a high-level, cross-cutting capability that connects to several of the mentioned areas. Moreover, ISM is both an enabling capability, fostering the realization of other in-space activities, and a dependent one, as its effective operation relies on complementary capabilities within the broader architecture [Arney et al., 2024] [United States Government Accountability Office, 2025].

Focusing on area 9, i.e. "Parts and Goods Manufacturing", Figure 2.7 shows a timeline of demonstrated and in-development technologies. The first demonstrations began recently, in 2014, and since then it has already become possible to identify distinct categories of manufactured products, differentiated by the type of material employed and by the intended end-user [Arney et al., 2024].

A key distinction relies also on the materials that can be implemented specifically materials launched from Earth, and materials available in situ. Figure 2.6 illustrates a possible material system for OOM.

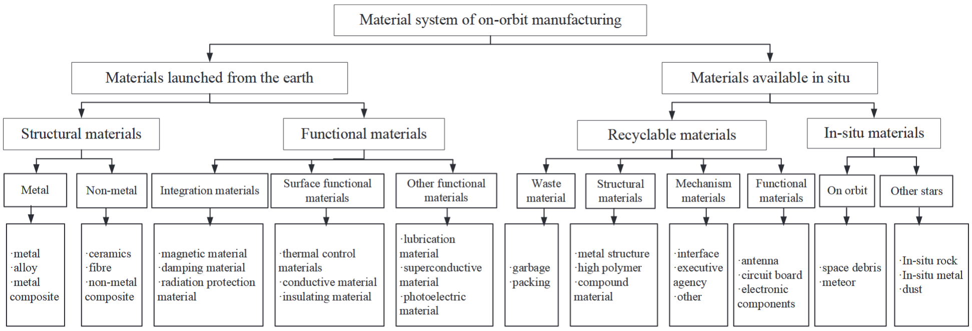


Figure 2.6: Material system of on-orbit manufacturing [Jiayong et al., 2023].

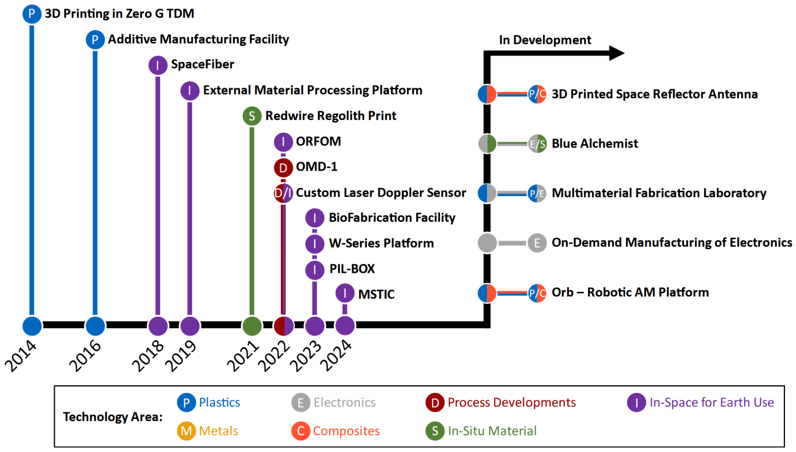


Figure 2.7: Demonstrated and in-development technogies w.r.t. Parts and Goods Manufacturing capability area [Arney et al., 2024].

2.2 Enhanced Factory for Extraterrestrial Space Technology Operations

EFESTO project is an initiative exploring the concept of a factory in space, supported by the Italian Piano Nazionale di Ripresa e Resilienza (PNRR) - Made in Italy Circolare e Sostenibile (MICS), within a partnership between Italian academia and industry. The main objective of MICS is research in the fields of sustainability and circular economy. The MICS program conducts research in eight areas called Spokes: (1) Digital Advanced Design: technologies, processes, and tools, (2) Eco-Design strategies: from materials to Product Service Systems, (3) Green and sustainable products and materials from non-critical and secondary raw sources, (4) Smart and sustainable materials for circular and augmented industrial products and processes, (5) Closed-loop, sustainable, inclusive factories and processes, (6) Additive Manufacturing as disruptive enabler of the Twin Transition, (7) New and consumer-driven business models for resilient and circular supply chains, (8) Digitally-oriented factory design and management through AI and data driven approaches. EFESTO is developed within Spoke 5, and correlated to Spoke 2 and 7 [MICS (Made in Italy Circolare e Sostenibile), 2024].

The project follows the evolving growing interest in ISM trend, considering it as a possible key enabler of a self-sustaining In Space Economy. Following Model Based System Engineering (MBSE) approach, the mission statement and objectives of EFESTO were defined [Sindoni et al., 2024]:

> *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 assembly, integration*

and deployment.

Three primary objectives were defined:

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

And three secondary objectives as well:

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

A trade-off study was carried out to select the most suitable orbit for the factory. Using the Analytic Hierarchy Process (AHP) method, the study identified GEO as the best option. However, since the results did not show a clear predominance of GEO over Low Earth Orbit (LEO), both possibilities remain open for further discussion. On the other hand, Sun Synchronous Orbits (SSO) and Highly Elliptical Orbits (HEO) were excluded [Sindoni et al., 2024].

The EFESTO research project is organized around four main tasks, each subdivided into three specific sub-tasks. Figure 2.8 shows the hierarchical structure of the tasks [Sassanelli et al., 2025].

The thesis has been developed within Task 4 Technical & Economic Feasibility, and Task 3 System Definition. More specifically, under Sub-Task 3.2 Manufacturing Process Definition, Sub-task 4.2 Electrothermal budget, and Sub-Task 4.3 Circularity Assessment. Task 4 aims to assess the practicality and viability, focusing

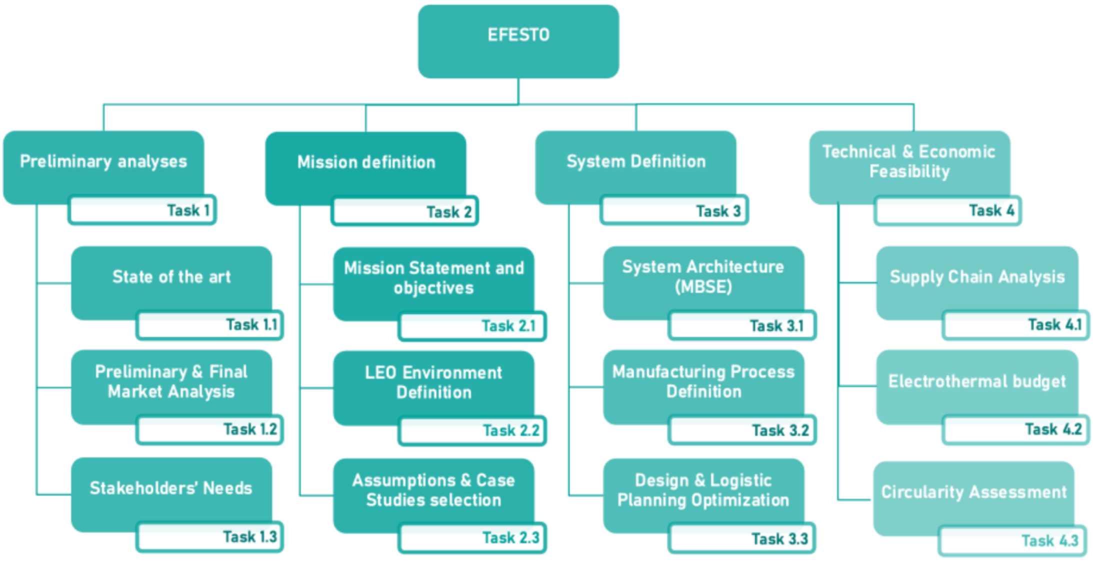


Figure 2.8: EFESTO research plan's main tasks [Sassanelli et al., 2025].

on defining a circular economic model and its indicator. The thesis work aims to provide LCA of a space product, evaluating the environmental benefits resulting from carrying out activities directly in orbit.

Chapter 3

Methodology

The scope of the thesis is to contribute to the EFESTO research project. Considering the space factory as a complex system, multiple technical and economic feasibility assessments are required to evaluate requirements, potential benefits, and critical aspects. Considering this, the following chapter aims to the describe the methodological frameworks adopted to address the research, illustrating the three methodologies applied:

- Section 3.1 - Systematic Literature Review Methodology, which defines the search strategy, selection criteria, and synthesis process adopted to address a structured review and to position the research within the existing literature.
- Section 3.2 - LCA-based Methodology, which presents the methodological principles, standards, and assumptions underlying the comparative LCA-based evaluation performed.
- Section 3.3 - Procurement Demand Modeling Approach, which presents the framework developed to study the dependency of the space factory from Earth.

3.1 Systematic Literature Review Methodology

The objective of the literature review is to focus on relevant scientific contributions addressing the relationship between space activities and the sustainability. Consequently, the review aims to analyze the current state of knowledge in this field, identify dominant research trends, and highlight existing gaps relevant to the scope and positioning of this thesis. Therefore, the literature has been framed along three complementary perspectives:

1. Studies investigating the role of space technologies in supporting sustainable development on Earth are examined.
2. Studies investigating the sustainability of the outer space environment itself.
3. Studies investigating the sustainability of space activities, focusing on environmental impacts associated with the design, manufacturing, launch, and operation of space systems.

Given the multidisciplinary nature of the topics addressed, a Systematic Literature Review (SLR) methodology has been adopted to conduct the literature review. Through this approach, the review aims to identify approaches, commonly adopted indicators, limitations of existing studies, and trends with respect to the above mentioned sustainability dimensions in the space sector. The insights derived from the literature review have been then used to identify research gaps and to position the present work within the broader research landscape.

The SLR is a structured methodology designed to identify, assess, evaluate, and synthesize existing research related to a specific topic. SLR has been conducted in three main steps:

1. Preliminary search and screening: An initial search query has been formulated and applied to a selected database. Titles and abstracts of the articles were screened to exclude works that were clearly irrelevant.
2. Refined screening: A second round of screening has been performed by reading the full text of the previously selected articles to assess their relevance.
3. Analysis and synthesis of results: Once the final set of relevant articles was identified, a qualitative analysis has been conducted. Key data from articles have been extracted and synthesized in relation to the research questions.

The review has been conducted using the Scopus database, limited to open-access articles in English, published from 2015 to 2025, accessed in July 2025. Other types of publications developed by organizations and institutions have been also included. Figure 3.1 presents the defined specific query used to explore the intersection between space and the environmental dimension of sustainability. More directly, the review aims to answer the following questions:

> *How is the relationship between space and sustainability defined?*
>
> *What are the main trends and issues emerging?*
>
> *Which dimensions of sustainability are most explored?*
>
> *Which standards have been applied, and what types of studies have been carried out w.r.t. the environmental dimension?*

The Scopus query returned a total of 383 results, 133 open-access articles. After screening titles and abstracts, 89 records were excluded for being out of scope. The full-text of the remaining 44 articles was analyzed, resulting in a final selection of 22 relevant contributions. Figure 3.2 shows the related PRISMA flow diagram. Articles have been excluded for the following reasons: (1) articles discussing sustainability but not in the space sector, (2) articles discussing space without any

```
TITLE-ABS-KEY( "sustainability" OR "sustainable development" OR
  "sustainable practices" OR "long-term sustainability" OR
  "environmental impact" OR "sustainable governance" OR
  "SDG" OR "sustainable design")
AND TITLE-ABS-KEY( "outer space" OR "space activities" OR
  "space missions" OR "space systems" OR
  "space operations" OR "space sector" OR
  "space economy" OR "new space economy" OR
  "space technologies" OR "space technology")
AND PUBYEAR > 2014 AND PUBYEAR < 2026
AND (LIMIT-TO(DOCTYPE, "ar"))
AND (LIMIT-TO(LANGUAGE, "English"))
AND (LIMIT-TO(OA, "all"))
```

Figure 3.1: Scopus query for sustainability and space-related literature

consideration of sustainability, (3) articles referring to specific technological research, but where sustainability was not sufficiently addressed, and (4) articles referring to specific sustainability research, but where space was not sufficiently addressed.

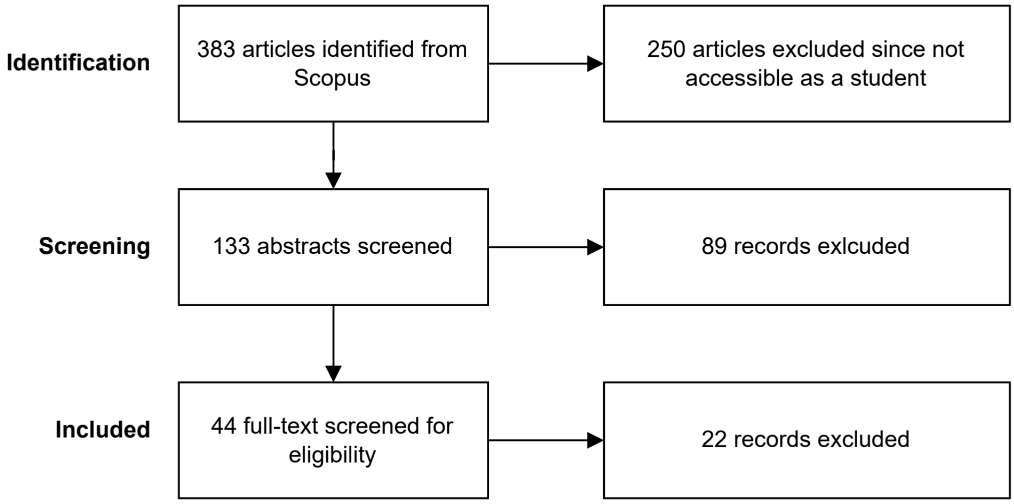


Figure 3.2: PRISMA SLR Flow Diagram.

3.2 LCA-based Methodology

LCA is a standardized methodology which offers the possibility to analyze the whole life cycle of a system or a product object of the study, covering a large range of impacts for which it performs a quantitative assessment. Following the main international references, i.e. ISO 14040/44, LCA can be defined as a technique for assessing the environmental aspects and potential impacts associated with a product by (1) compiling an inventory of relevant inputs and outputs of a product system, (2) evaluating the potential environmental impacts associated with those inputs and outputs, and (3) interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study [Hauschild et al., 2018] [International Organization for Standardization (ISO), 1997].

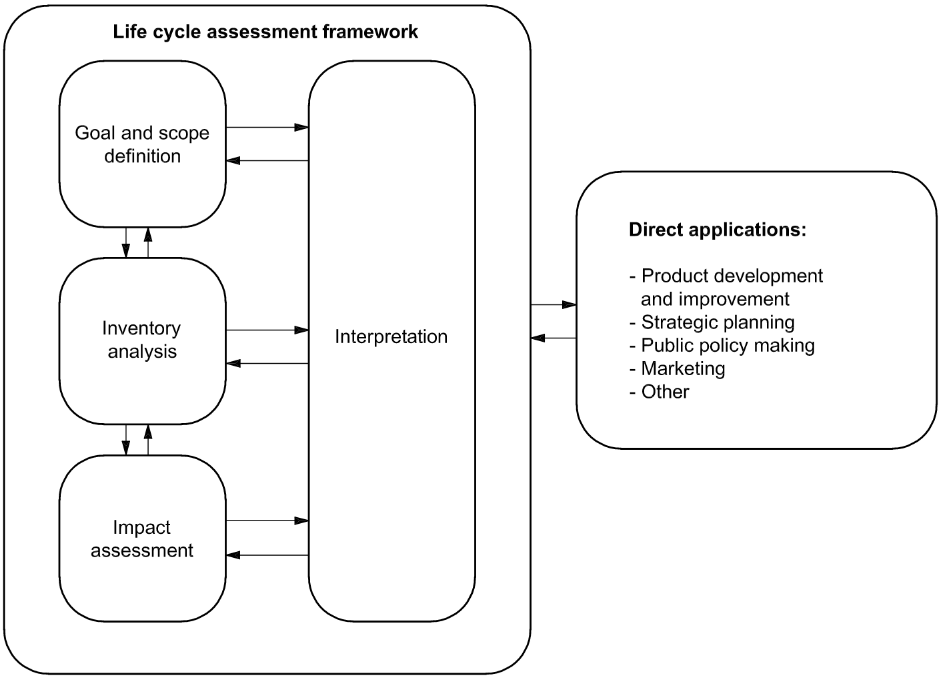


Figure 3.3: Phases of a LCA Framework [International Organization for Standardization (ISO), 1997].

As Figure 3.3 shows, LCA Framework consists of four separate phases:

1. Goal and Scope Definition: The goal of the study shall states the intended application, the reasons for carrying out the study, the intended audience, whether the results are intended to be used in comparative analysis. The scope has to includes the product system to be studied, system's functions, the functional unit, system boundaries, impact categories selected, data requirements, assumptions, and limitations.

2. Inventory Analysis: The inventory analysis shall include data collection and calculation procedures, and allocation of inflows and releases, to quantify relevant inputs and outputs of a product system.

3. Impact Assessment: The impact assessment shall evaluate the potential environmental impacts using the the inventory results. This involves associating inventory data with specific environmental impact categories and indicators;

4. Interpretation: The findings from inventory analysis and impact assessment are considered together to deliver results that are consistent with the defined goal and scope and which reach conclusions, explain limitations and provide recommendations in terms of decision-making.

When defining the system boundaries in a LCA, one of the main decisions concerns which life cycle phases to include in the analysis. Although LCA ideally encompasses the entire product life cycle, from material extraction to final disposal, there are cases where the focus is narrowed to specific phases. This results in three common boundary definitions:

- Cradle-to-Grave: Includes all phases of the product life cycle.

- Cradle-to-Gate: Includes the phases from raw material extraction to the point the product leaves the manufacturing facility (i.e. factory gate), therefore excluding use, transport, and disposal.

- Gate-to-Gate: Includes only on the manufacturing phase, ignoring material production, use, transport, and disposal phases.

The general LCA principles have been considered not sufficient in the space industry. ESA developed a tailored framework for evaluating the environmental impacts of space missions and programs, titled as the ESA Space System LCA Guidelines. This is the final result of ESA's Clean Space initiative, undertaken between 2016 and 2017, revised in 2021. These guidelines provide tailored rules, datasets, and tools that adapt the standards to the specific challenges of the space sector [Koffler, 2024].

Specific features of the space sector have defined the need to adapt the standards. Compared to other industries, the space sector is characterized by low production volumes, direct emissions into the upper atmosphere, specialized materials and processes not included in inventory databases, long development cycles, and extensive testing campaigns. As a result, methodological adaptations have been introduced throughout the LCA framework, including the redefinition of the functional unit, the selection of suitable environmental impact indicators, and the establishment of criteria for data collection and quality assurance [European Space Agency (ESA), 2023].

The life cycle of a space system is composed of different stages, involving various environments, segments, and mission phases. A space system can be defined as a complex and organized set of interconnected elements, technologies, and processes working together to perform a specific task in the space environment. It consists of four distinct segments: space, launch, ground, and support segments.

Figure 3.4 shows the breakdown of the space system [European Cooperation for Space Standardization (ECSS), 2023].

There have been defined different LCA levels depending on the system decomposition adopted in the analysis [European Space Agency (ESA), 2023]:

- Level 1 LCA: mission, or system-level assessment, based on a functional breakdown. This level focuses on the environmental performance of an entire space mission or of a major mission segments and is typically used for early design phases and strategic trade-off analyses.
- Level 2 LCA: element, or subsystem-level, assessment, based on a physical breakdown. This level focuses on specific hardware elements, components, or subsystems, enabling a more detailed comparison of technologies, materials, and processes.

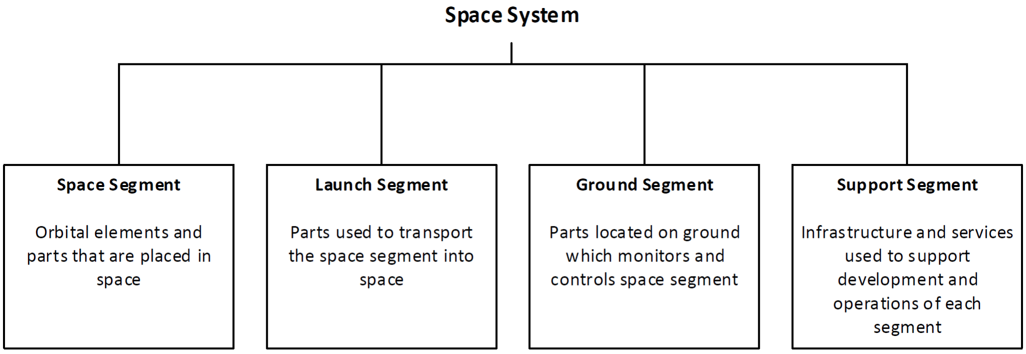


Figure 3.4: Space system and its four segments.

Considering the scope of the work, the thesis has been based on ISO 14040/44 frameworks and the ESA Space System LCA Guidelines, developing an equipment-level assessment, corresponding to a Level 2 LCA, focusing on space and launch segments' elements.

The analysis focuses on a single hardware element rather than a complete mission or system, enabling a detailed comparison between alternative scenarios. The choice of an equipment-level analysis is consistent with the exploratory nature of the study, and with the objective of isolating the environmental effects associated with manufacturing location and logistics. The comparative LCA has been defined on two scenarios established according to the location on which the production of the functional unit takes place, adopting a Cradle-to-Grave system boundaries.

Primary data have been collected for the manufacturing process through experimental measurements of energy consumption and material usage, while secondary data have been adopted from the literature and technical public documentations. Following ESA guidelines for equipment-level LCAs, a mass-based allocation approach has been applied to attribute launcher emissions to the functional unit.

The environmental impact assessment focuses on a selected set of midpoint indicators. Each impact I-th for a given scenario s has been computed as sum of all contributions defined by the inventory and the energy demand. In general, the calculation has been expressed as the product between the inventory of elementary flows and the corresponding characterization factors:

$$I^{(s)} = E^{(s)} \times CF^{I} = \sum_{i=1}^{n} \left[E_i^{(s)} \times CF_i^{I} \right] \tag{3.1}$$

where $I^{(s)}$ represents the total impact of scenario s, $E^{(s)}$is the vector of elementary flows associated with scenario s, CF_i^I is the vector of characterization factors for the impact, while $E_i^s \times CF_i^I$ represents the weighted sum of the contributions from all the elementary flows. Selected impacts are introduced in Section 4.1.

3.3 Procurement Demand Modeling Methodology

The procurement demand model has been structured starting from the specific constraints of an in-space factory. Figure 3.5 illustrates the conceptual architecture defined for the hypothetical recycling in-orbit factory. The scheme highlights four main flows:

1. The forward flow from Earth to orbit, representing the procurement of feedstock material.
2. The in-orbit additive manufacturing phase, where feedstock material is transformed into functional components.
3. The use phase, leading to end of life.
4. The reverse flow through in-orbit recycling, where end-of-life components are processed to recover secondary feedstock material, partially closing the loop.

The objective of the analytical model is to quantify the mass flow required from Earth, i.e. the raw material procurement demand necessary to sustain the system's operations over time. This demand represents the fraction of material that cannot be internally satisfied due to incomplete recycling efficiency and associated system losses.

The demand has been initially defined under the following assumptions:

- The space factory aims to maintain a production demand of N equipment.
- Each equipment requires a mass m of feedstock material for manufacturing.
- Each equipment has a lifetime equal to L years.
- A replacement cycle occurs at the end of each lifetime period L.

Under these assumptions, the procurement demand is formulated under two complementary representations: (i) a continuous-time formulation and (ii) a discrete-time formulation, both analyzed in Chapter 5.

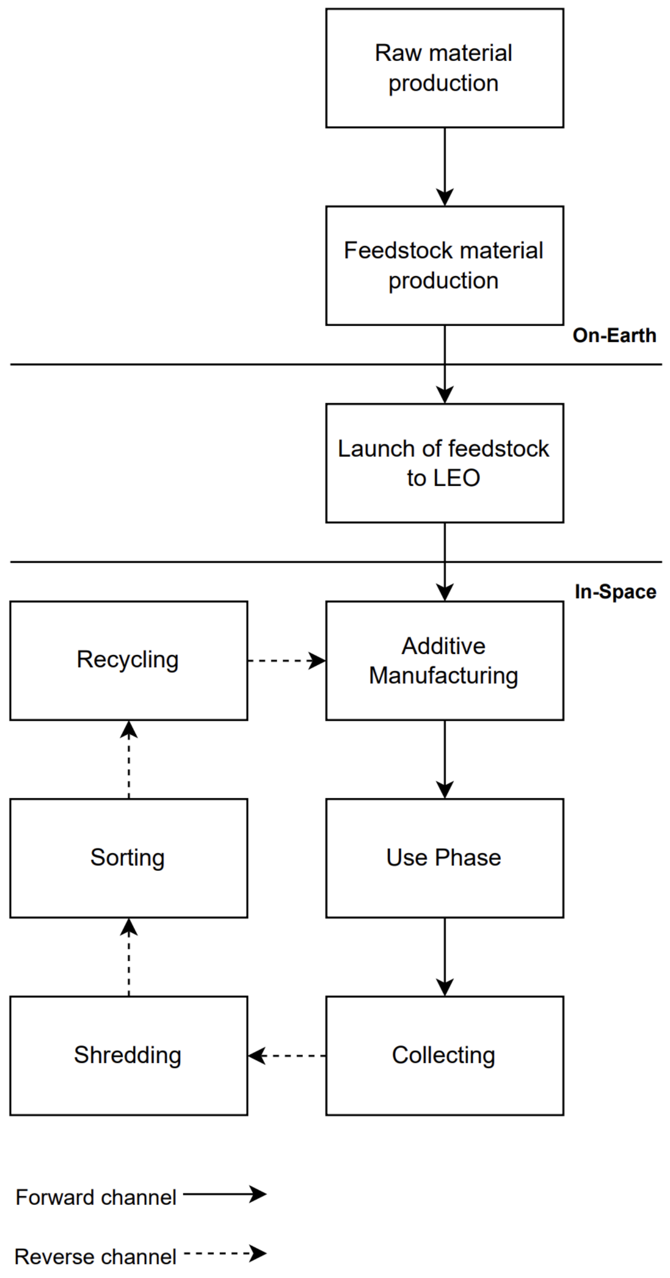


Figure 3.5: Conceptual model for in-space factory.

Chapter 4

Case Study and Data Inventory

The objective of the following chapter is to detail the case study selected for the comparative Life Cycle Assessment, describing in detail the construction of the data inventory supporting the analysis. The chapter defines the functional unit, system boundaries, assumptions, and data sources adopted to ensure methodological transparency and consistency with the frameworks introduced in Chapter 3. More specifically, the chapter has been structured as follows:

- Section 4.1 - Goal & Scope, which details the objective of the LCA study, the functional unit, the compared scenarios, the system boundaries, the selected impacts, and the main assumptions supporting the analysis.
- Section 4.2 - Antenna Description & Geometry, which introduces the selected horn antenna prototype, justifies the design and material choices.
- Section 4.3 - Additive Manufacturing Phase, which presents the experimentally data collected during the additive manufacturing phase.
- Section 4.4 - Launch Phase, which details the launcher configuration, propulsion system characteristics, and specifically launcher emission data used to model the transportation phase and complete the inventory.

4.1 Goal & Scope

The goal of the LCA study is to document the environmental impacts of producing horn antennas using AM processes, and to perform a comparative LCA between two different scenarios. The study has been carried out to support future decision-making processes in the space sector. It serves as an initial analysis aimed at promoting circular economy initiatives in the space industry. Thus, the target audience includes aerospace industry professionals, academic researchers, and policy research institutions.

The functional unit has been defined taking into account the selected component and its performance as follows:

> *The functional unit is 1 horn antenna, Yamacli model, printed in AM with Protopasta conductive PLA material, operating in the X-Band in LEO.*

The comparative LCA has been defined on two scenarios, established according to the location on which the production of the functional unit takes place:

- Scenario A: Transportation of the additive manufacturing feedstock to orbit through a launch vehicle, followed by in-orbit production of the functional unit.
- Scenario B: Terrestrial additive manufacturing of the functional unit, followed by orbital transportation of the finished product through a launch vehicle.

Thus, the study adopts the following specific system boundaries:

> *The study adopts cradle-to-grave system boundaries, starting from raw material production, until end-of-life.*

As illustrated in Figure 4.1, the system boundaries include raw material production, feedstock preparation, additive manufacturing, launch operations when required, use phase in Low Earth Orbit, and end-of-life. The grey shaded stages are identical in both scenarios, so that they do not contribute to the comparative assessment and are therefore excluded from the differential impact computation. The comparison calculations are consequently focused only on the processes that vary between the two pathways.

The environmental impact assessment specifically focuses on Global Warming Potential (GWP), Acidification Potential (AP), and Particular Matter (PM). These indicators have been selected because they represent the main impact categories associated with both additive manufacturing energy consumption and launch activities. In particular, GWP captures the contribution of greenhouse gas emissions to climate change, while AP and PM are particularly relevant for the space sector due to the presence of combustion products such as nitrogen oxides, hydrogen chloride, and particulate matter generated by launcher propulsion systems. Following Equation 3.1, the GWP, AP, and PM indicators have been calculated as the sum of all contributions defined by the inventory as follows:

$$GWP(s) = \sum_i \left[E_i(s) \times CF_{i\text{-}GWP}\right] \tag{4.1}$$

$$AP(s) = \sum_i \left[E_i(s) \times CF_{i\text{-}AP}\right] \tag{4.2}$$

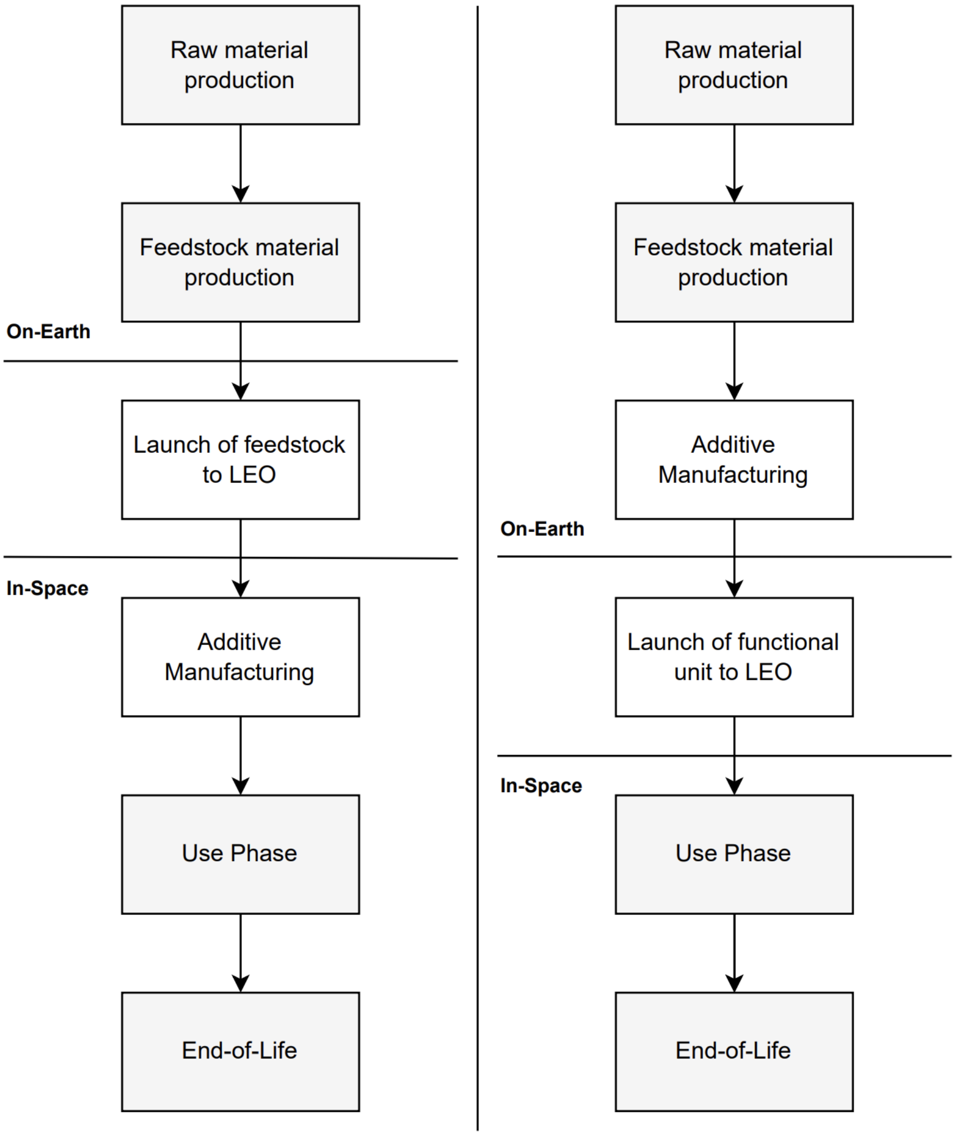
$$PM_{2.5}(s) = \sum_i [E_i(s) \times CF_{i-PM_{2.5}}] \tag{4.3}$$

Additionally, all indicators have been also expressed as sum of the impacts generated during the additive manufacturing and launch phases:

$$\text{Indicator}(s) = \text{Indicator}(s)_{AM} + \text{Indicator}(s)_{Launch} \tag{4.4}$$

Assumptions to support the study and scenario comparison have been listed:

- The functional unit shall be ready for orbital deployment and usage.
- The material and energy flows analyzed for the manufacturing phase on Earth, based on experimentally measured ground data, are considered representative also for equivalent manufacturing operations in space.
- The launcher emission impact has been allocated following a mass-based allocation approach.
- The energy mix associated with terrestrial manufacturing corresponds to the average electricity grid mix of European zone.
- The structural integrity and dimension of the antenna produced on Earth are assumed to be maintained during the launch phase.
- The packaging related to the launch phase has not been considered in the analysis to simplify the assessment.



Scenario A: production of the FU in-space. Scenario B: production of the FU on-Earth.

Figure 4.1: System boundaries and process flow for the comparative LCA-based evaluation of the functional unit.

4.2 Antenna Description & Geometry

The component selected for the study is horn antenna. This choice has been followed since this component meets the requirement of being accessible to an hypothetical space-tug, and is not located near critical subsystems such as propulsion, making it a suitable element to be assessed within a circular economy initiative in the next future [Sindoni et al., 2024].

Horn antennas are a type of directional antenna consisting of a flaring metallic waveguide that provides a gradual transition from the guided region to free space. Its main function is to match the impedance of the waveguide to that of free space, reducing reflections and maximizing transmission efficiency, while shaping the radiation into a directive beam. In space applications, horn antennas are widely used onboard satellites and space probes for different purposes. Horn antennas are usually made of conducting materials, typically metals, and is fed through a waveguide section. The most common geometries are pyramidal and conical horns [Thales Alenia Space Italia and CIM 4.0, 2024a].

From the previous analysis of the EFESTO project, the pyramidal geometry has been selected. For the design, one model from the literature has been considered, referred to here as model Yamacli. Figure 4.2 reports the model.

The studies on which this is based showed that manufacturing a horn antenna using 3D printing is fully functional and produces results comparable to a standard ones. A major advantage of this method is the significant reduction in weight, the printed antenna weighing about 10% of the conventional all-metal version. It has also been shown that PLA doped with carbon particles, thus conductive, can be used in fields such as mobile defense and telecommunications systems [Olivová et al., 2022] [Yamaçlı, 2022].

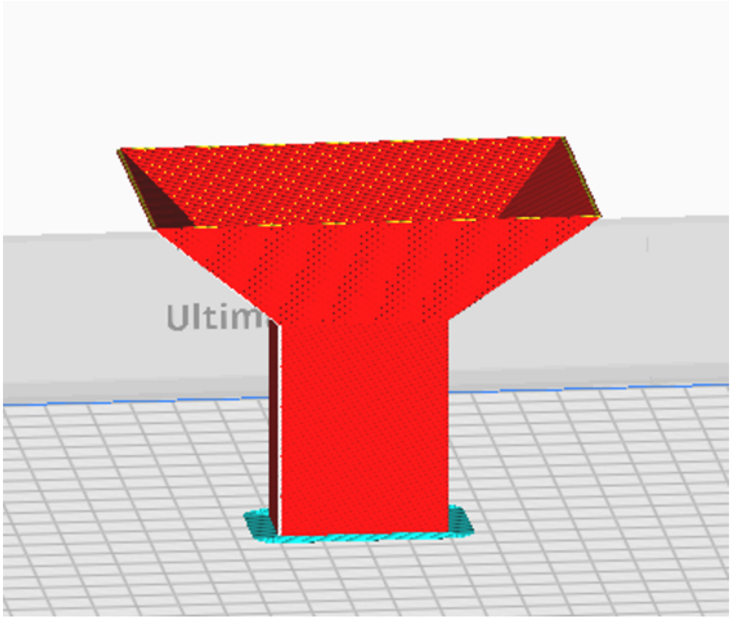


Figure 4.2: Yamacli Model designed with NX CAD, and CURA Slice softwares [Thales Alenia Space Italia and CIM 4.0, 2024b].

The material selection has been carried out by considering the antenna's function, constraints, and objectives. The function of the antenna is:

To guide and radiate an X-Band electromagnetic signal in LEO.

Several constraints must be satisfied by the selected material. The choice of antenna materials depends not only on communication performance but also on the need to meet various technical and environmental requirements. The main categories of constraints are summarized as follows:

- Geometry constraints: the selected material must be compatible with the chosen designs, namely the Yamacli antenna models.

- Radio-frequency constraints: the selected material must be suitable for communication within the X-Band frequency range.
- Environmental constraints: the selected material must be compatible with the LEO environment.
- Manufacturing process constraints: the selected material must be compatible with the current additive manufacturing processes available in space.

Usually, it is also necessary to ensure that the component can withstand the thermal and structural loads experienced during the launch phase into orbit. However, since ISM is independent of the launch phase, alternative materials can potentially be used while still ensuring the same function and performance. Therefore, requirements related to mechanical and thermal loads during launch can been excluded during the selection process [Sindoni et al., 2024].

The choice of the material has been guided by taking into account electrical properties [Thales Alenia Space Italia and CIM 4.0, 2024a]:

- Electrical conductivity σ, as a measure of the ability of the material to conduct electric current.
- Dielectric constant ε_r, as a measure of the degree of electrical insulation provided by the dielectric material.
- Dissipation factor $\tan\delta$, as a measures how easily a material introduces power losses during operation.

Three material alternatives to metal printing have been investigated:

1. Antennas printed with dielectric materials and then metalized. In this case, AM is mainly used to create the dielectric structure, followed by different metallization methods, e.g. conductive paint.

2. Antennas printed directly with conductive materials. In this case, commercial filaments that combine polymers with a percentage of conductive additives have been considered, e.g. conductive carbon black, graphene, copper.

In terms of process, the complexity and high cost of fully printing antennas in space using metallic materials led to the exploration of alternative solutions. Fused Filament Fabrication (FFF) was identified as the most suitable process, both for its lower cost and its realistic technological feasibility in in-space applications [Thales Alenia Space Italia and CIM 4.0, 2024a].

The printing process has been carried out using FFF with an Ultimaker S5 printer, and three material options have been initially investigated: standard PLA with metallization through Kontakt Chemie 35 conductive paint, and two different types of conductive PLA, namely the conductive PLA supplied by Multi3D and the one suppleid by Protopasta [Thales Alenia Space Italia and CIM 4.0, 2024b].

Material	**Supplier**	**Cost [EUR/kg]**	**Resistivity [Ω·cm]**
Standard PLA	Ultimaker	348	0
Conductive PLA	Multi3D	1980	0.006
Conductive PLA	Protopasta	200	15

Table 4.1: Investigated materials for antenna 3D printing [Thales Alenia Space Italia and CIM 4.0, 2024b].

Based on the availability and quality of data collected during the printing process, and considering the objectives of this study, the analysis has been restricted to a single material, specifically, the Protopasta conductive PLA.

The optimization of the printing parameters for the Yamacli antenna has been conducted through an iterative process, aimed to to guarantee the mechanical integrity and the surface quality. The final setup produced the most homogeneous surface finish, robust closure at all corners, and a general printing quality suitable for the finalized prototype, as Figure 4.3 shows [Thales Alenia Space Italia and CIM 4.0, 2024b].

Figure 4.3: Yamacli prototype antenna model manufactured using Protopasta conductive PLA with the identified printing parameters.

4.3 Additive Manufacturing Phase

Primary data have been collected for the additive manufacturing phase of the functional unit antenna prototype. Three separate printing jobs have been performed for the same Yamacli prototype in order to capture potential variations in energy consumption and material usage. The electrical power consumption has been measured using a Fluke power meter connected directly to the 3D printer. The instrument sampled the instantaneous power demand $P(t)$ at a constant sampling interval of $\Delta t = 0,25$ s. The acquired data have been exported to a tabular format, resulting in a discrete time series of power values P associated with their corresponding time instants t.

The evaluation of the electrical energy demand of the printing process has been carried approximating the value of the definite integral, i.e. estimating the area under the curve by subdividing the integration interval into smaller sub-intervals and approximating the area of each sub-interval. Given a function $f(x)$ defined over the interval $[a, b]$, the integral has been approximated as follows:

$$\int_a^b f(x)\,dx \approx \frac{h}{2}\left[f(a) + f(b) + 2\sum_{i=1}^{n-1} f(x_i)\right] \tag{4.5}$$

where $h = \frac{b-a}{n}$ is the width of each sub-interval. Considering our case, the total energy consumption can be computed as time integral of the power signal $P(t)$:

$$E = \int_{t_0}^{t_e} P(t)\,dt \approx \frac{\Delta t}{2}\left[P(t_0) + P(t_e) + 2\sum_{i=1}^{N-1} P(t_i)\right] \tag{4.6}$$

where $P(t_0)$ and $P(t_e)$ are the power values measured at the beginning and at the end of the process, $P(t_i)$ the intermediate power samples, Δt s the constant sampling interval, and N is the total number of acquired samples. Total energy consumption E_i of the i-th printing job ($i = 1, 2, 3$) are reported in Table 4.2. Figure 4.4 reported the measured power demand function profile of one job as an example. The average value has been adopted as the baseline demand for the AM process:

$$\bar{EC}_{AM} = 1646.04 \text{ [kJ/FU]} = 0,4572 \text{ [kWh/FU]} \tag{4.7}$$

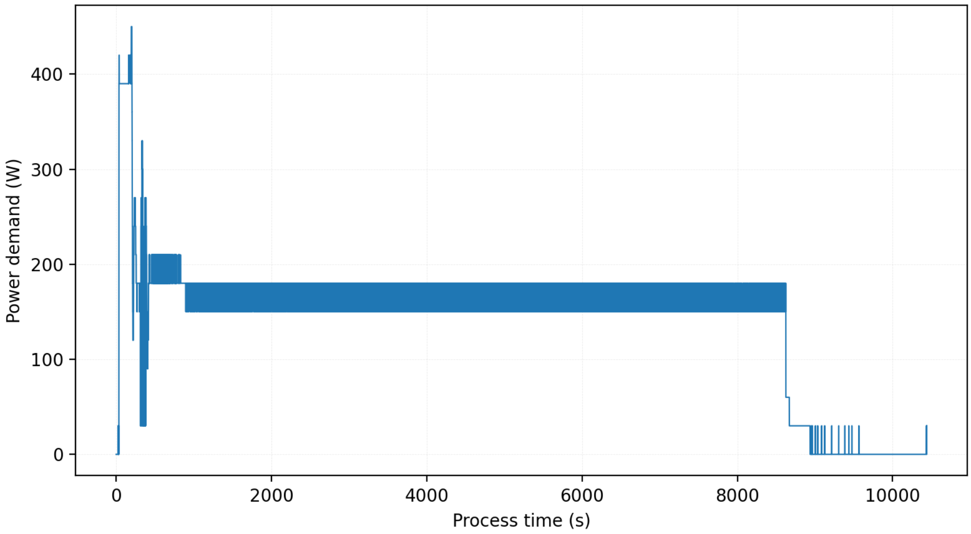


Figure 4.4: Power demand with respect to process time.

The total material flows and demand have been determined by considering the mass of the printed functional unit and the wasted material associated with supports, brim, and process losses. The average material demand has been considered: the average mass of the functional unit corresponds to approximately 97,84% w.r.t. total material input, while the wasted material accounts for about 2,16%. Table 4.2 summarizes the primary data related to the material, energy demand collected, and average values.

Job	**Tot. Material [g/FU]**	**FU [g/FU]**	**Waste [g/FU]**	**E [kJ/FU]**
1	14,9190	14,5954	0,3236	1836,73
2	16,6262	16,2797	0,3465	1502,04
3	15,4705	15,1278	0,3427	1599,35
avg.	15,6719	15,3343	0,3376	1646,04

Table 4.2: Material flows and energy consumption related to the AM process w.r.t. each job, and the corresponding average.

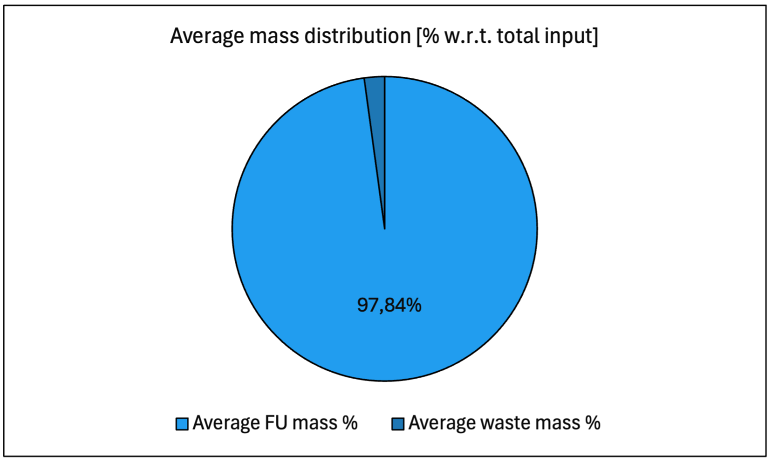


Figure 4.5: Average mass distribution w.r.t. the total material input used.

4.4 Launch Phase

Considering the transportation phase, the study considers the Ariane 6 launcher which adopts a modular architecture, allowing different configurations. The launcher consists of (i) two or four Equipped Solid Rocket (ESR) rocket boosters P120C to tailor launcher performance according to the mission needs, (ii) a cryogenic core stage, Lower Liquid Propulsion Module (LLPM), equipped with a Vulcain 2.1 cryogenic engine, and (iii) a cryogenic upper stage, Upper Liquid Propulsion Module (ULPM), equipped with a Vinci cryogenic engine. The study considers the Ariane 6 configuration with two lateral boosters, i.e. Ariane 62, which is optimized for launches to LEO and GTO. Figure 4.6 reports the launcher architecture in its two booster configuration [Ariane Group, 2021].

Considering P120C boosters, both make use of the same propellant based on a composite propellant consisting of ammonium perchlorate NH_4ClO_4 (AP) as oxidizer, aluminum (Al) as metallic fuel, and hydroxyl-terminated polybutadiene $(C_4H_6)_{50}(OH)_2$ (HTPB) as polymeric binder and secondary fuel, with a total propellant mass equal to 287,2 t. The percentage composition of each propellant component is known with respect to the total propellant mass, allowing the total mass of each element to be calculated. Considering the cryogenic liquid propulsion systems, both the LLPM and ULPM make use of the same liquid propellant combination based on liquid oxygen as oxidizer and liquid hydrogen as fuel. The total mass of cryogenic propellant for a single launch is equal to approximately 171 t, accounting for the combined contribution of the LLPM and ULPM stages. The oxidizer-to-fuel (O/F) ratio is approximate 6 for nominal operating conditions of both the Vulcain 2.1 and Vinci engines. Table 4.3 reports the corresponding total mass of each element for solid and liquid propulsion systmes [Ariane Group, 2021].

Propulsion	**Element**	**wt.-%**	**Q [t / Launch]**
Solid	NH_4ClO_4	69%	198.168
Solid	Al	19%	54.568
Solid	$(C_4H_6)_{50}(OH)_2$	12%	34.464
Liquid	LOX	85.8%	146.6
Liquid	LH_2	14.2%	24.4

Table 4.3: Solid boosters and cryogenic propellants composition quantities [Ariane Group, 2021].

Solid propellant is consumed through a surface-regressing heterogeneous combustion process occurring at high chamber pressure. The combustion is initiated by the thermal decomposition of ammonium perchlorate, which releases oxidizing species and chlorine-containing compounds that control the burning rate and enable the next gas-phase reactions. The AP decomposition can be represented as follows:

$$4NH_4ClO_4 \rightarrow 2N_2 + 4HCl + 6H_2O + 5O_2 \tag{4.8}$$

These products establish an oxidizer-rich environment at the propellant surface and enable the subsequent gas-phase combustion reactions. Simultaneously, the hydroxyl-terminated polybutadiene binder, which serves both as a structural matrix and as a secondary fuel, undergoes rapid thermal degradation under extreme heating rates. The complete oxidation of HTPB can be expressed as follows:

$$(C_4H_6)_{50}(OH)_2 \rightarrow 200CO_2 + 151H_2O \tag{4.9}$$

In the actual motor environment, HTPB first pyrolyzes into light hydrocarbon species, which then react with the oxidizer-rich stream derived from AP in a high-pressure diffusion flame. This diffusion-controlled combustion zone constitutes the

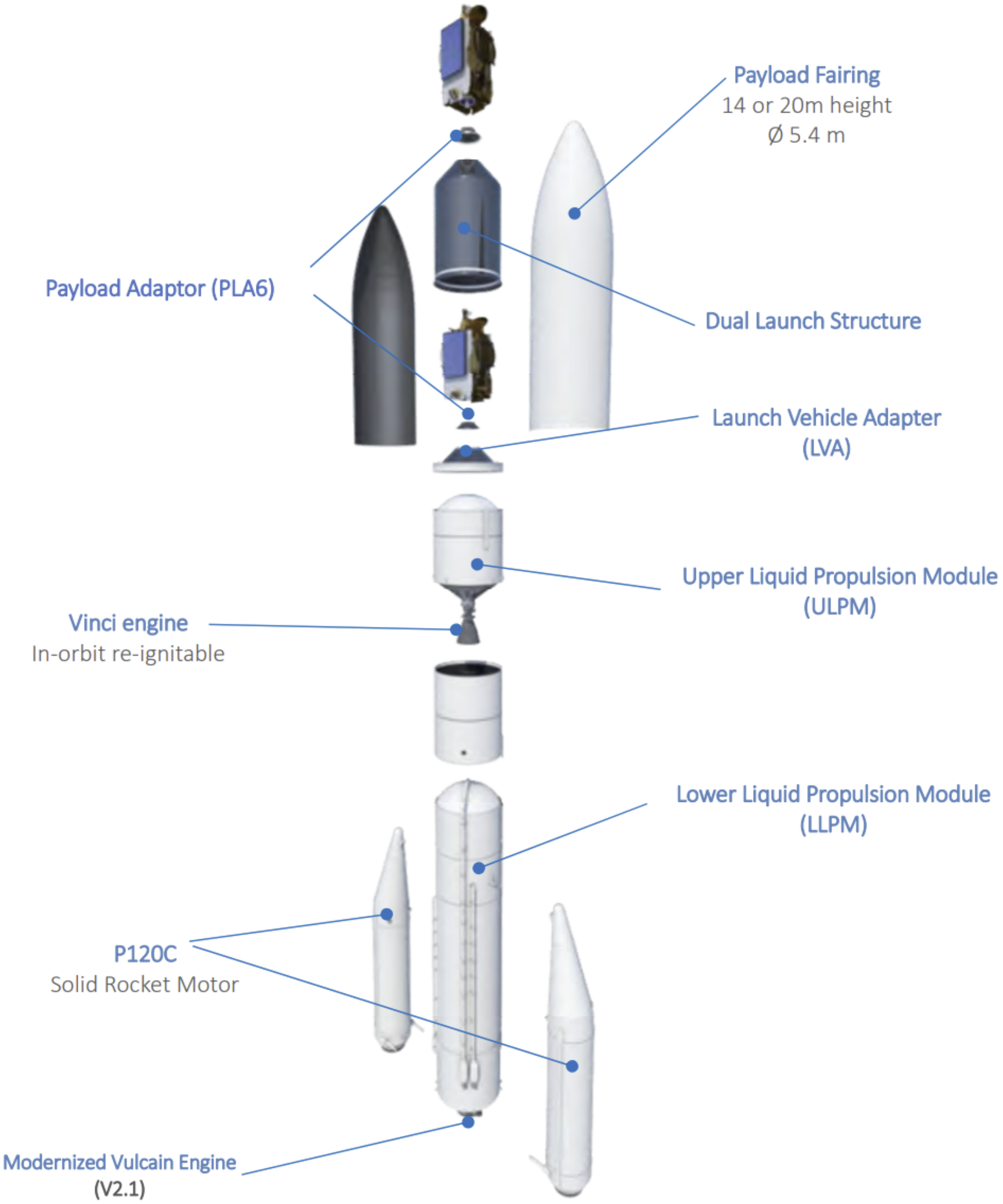


Figure 4.6: Ariane 62 configuration elements [Ariane Group, 2021].

main source of heat release sustaining the regression of the propellant surface. In parallel with the gas-phase reactions involving AP and HTPB, aluminum particles embedded in the propellant melt and oxidize. The oxidation of aluminum can be described by:

$$\mathrm{Al} + 0.8\mathrm{O}_2 \rightarrow 0.5\mathrm{Al}_2\mathrm{O}_3 \tag{4.10}$$

The resulting Al_2O_3 is present partly as liquid droplets and partly as solid particulate matter [Cai et al., 2008] [Fischer and Fasoulas, 2022].

Considering the liquid propulsion, its propellants are consumed through a homogeneous, gas-phase combustion process. Both propellants are stored at cryogenic temperatures and are injected into the combustion chamber, where they undergo rapid vaporization, mixing and ignition under high pressure conditions. The combustion process is governed by the exothermic oxidation of hydrogen, which represents the chemical reaction involved in the energy conversion process:

$$\mathrm{H}_2 + \frac{1}{2}\mathrm{O}_2 \rightarrow \mathrm{H}_2\mathrm{O} \tag{4.11}$$

The exhaust composition at the nozzle exit consists predominantly of H_2O, residual unburned hydrogen and minor species [Casalino et al., 2022] [Fischer and Fasoulas, 2022].

All combustion products are expelled through the nozzles and released directly into the atmosphere along the launcher trajectory. Chemical equilibrium calculations at the nozzle exit for solid and liquid propulsion are respectively reported in Figure 4.7 and Figure 4.8. Table 4.4 lists in details all the percentages.

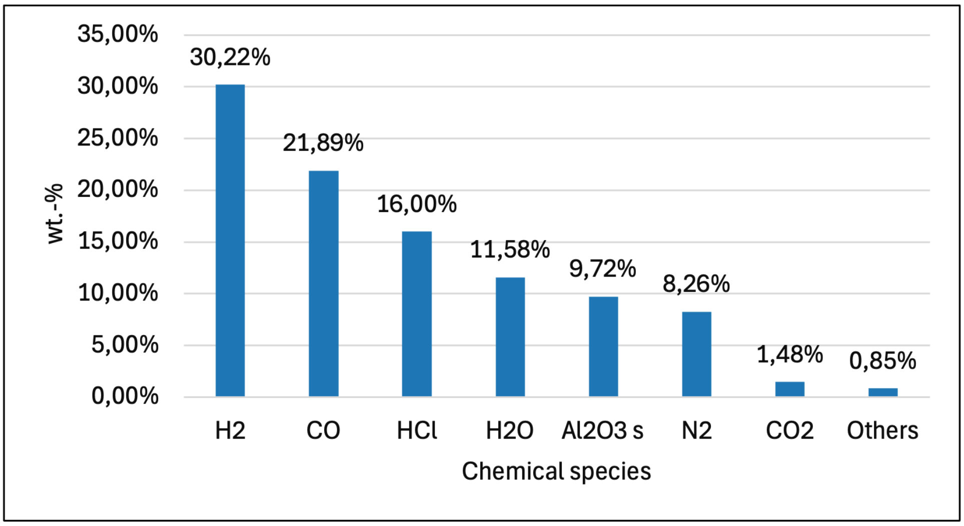


Figure 4.7: Exhaust composition at nozzle exit for solid propulsion.

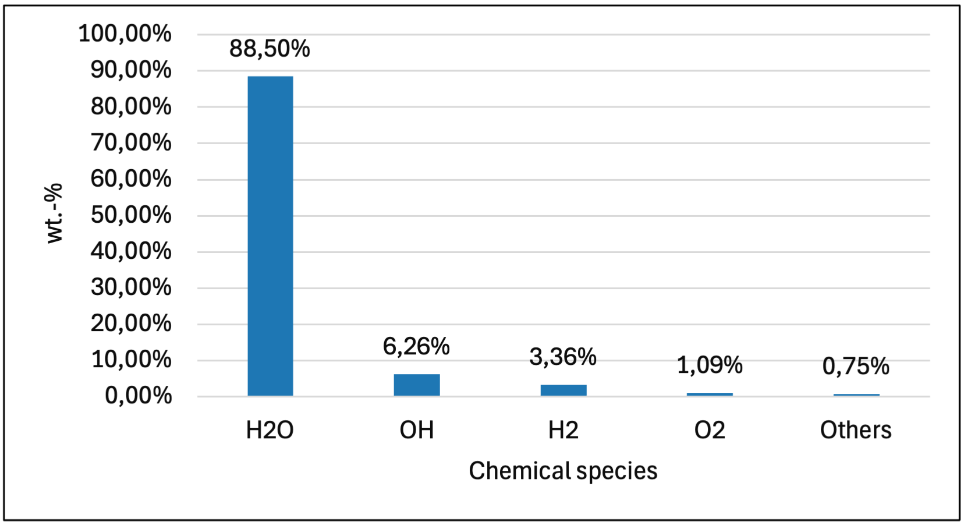


Figure 4.8: Exhaust composition at nozzle exit for liquid propulsion.

Propellants and their exhausts products have been allocated to the scenarios' payloads according to their masses, thus defining a specific allocation factors. Considering the payload mass of one functional unit or of its feedstock, these can be assessed as negligible compared to the total launcher capacity, so that only a fraction of the launcher's inventory has been attributed to the payload.

Propulsion System	**Element**	**wt.-%**
Solid	AlCl	0.01%
Solid	$AlCl_2$	<0.01%
Solid	$AlCl_3$	<0.01%
Solid	AlOH	<0.01%
Solid	$AlOHCl_2$	<0.01%
Solid	$Al(OH)_2Cl$	<0.01%
Solid	CO	21.89%
Solid	CO_2	1.48%
Solid	Cl	0.22%
Solid	H	0.58%
Solid	HCl	16.00%
Solid	H_2	30.22%
Solid	H_2O	11.58%
Solid	NO	<0.01%
Solid	N_2	8.26%
Solid	OH	0.04%
Solid	Al_2O_3 (s)	4.98%
Solid	Al_2O_3 (l)	4.74%
Liquid	H	0.25%
Liquid	HO_2	0.01%
Liquid	H_2	3.36%
Liquid	H_2O	88.50%
Liquid	H_2O_2	<0.01%
Liquid	O	0.48%
Liquid	OH	6.26%
Liquid	O_2	1.09%

Table 4.4: Exhaust composition for solid and liquid propulsion [Fischer and Fasoulas, 2022].

Following ESA guidelines for equipment level studies, a mass based allocation has been adopted, assuming that propellant consumption scales linearly with payload mass. The allocation factors have been defined as follows:

$$AF_s = \frac{m_{payload-s}}{m_{A62-LEO}} \tag{4.12}$$

where, $s \in \{A, B\}$ denotes the scenario, $m_{payload-s}$ is the mass of the item injected into orbit in scenario s, $m_{A62-LEO} = 10,350$ t is the maximum payload capacity of Ariane 62 for LEO. Allocation factors has been computed for both scenarios:

$$AF_A = \frac{\bar{m}_{feed-stock}}{m_{A62-LEO}} = 1,5141 \times 10^{-6} \quad ; \quad AF_B = \frac{\bar{m}_{FU}}{m_{A62-LEO}} = 1,4815 \times 10^{-6} \tag{4.13}$$

These values reflect that the payload in both scenarios contributes with a vary low share. Thus, the inventory associated to the functional unit in each scenario can be obtained by simple scaling:

$$LCI_{launch-s} = AF_s \times LCI_{launch-total} \ , \ s \in \{A, B\} \tag{4.14}$$

Thus, considering data reported in Table 4.3 and Table 4.4, it is possible to detail the inventory for each scenario, reported in Table 4.5 and Table 4.8.

Propulsion	**Element**	**wt.-%**	**Q_A [g / FU]**	**Q_B [g / FU]**
Solid	NH_4ClO_4	69%	300,0646	293,6007
Solid	Al	19%	82,6265	80,8466
Solid	$(C_4H_6)_{50}(OH)_2$	12%	52,1852	51,0610
Liquid	LOX	85.8%	221,9807	217,1989
Liquid	LH_2	14.2%	36,9463	36,1504

Table 4.5: Solid boosters and cryogenic propellants composition quantities allocated to scenarios' payloads through mass-based allocation factors.

Considering the output inventory in Table 4.8, CO_2 emissions have been considered direct GWP impact contributors, following a one-to-one relationship. CO contributes mainly through indirect effects, having a negligible direct GWP, but exerting significant indirect impacts by altering atmospheric chemistry. More in details, CO reacts with hydroxyl radicals OH, reducing their concentration, thus increasing the atmospheric lifetime of methane CH_4, and it promotes the formation of tropospheric ozone O_3, with an effect magnitude depending on the concentration of nitrogen oxides (NO_x). Table 4.6 summarizes the estimations found in literature, estimating the factor to range between 1.0 and 3.0.

$CF_{GWP\text{-}100}$	**Model / Effects**	**Literature Ref.**
1.0 gCO_2-eq./gCO	1D / CH_4 feedback	Daniel, Solomon, 1998
2.1 gCO_2-eq./gCO	2D / CH_4 feedback + O_3 prod.	Johnson, Derwent, 1996
3.0 gCO_2-eq./gCO	2D / CH_4 feedback + O_3 prod.	Fuglestvedt et al., 1996

Table 4.6: GWP-100 carbon monoxide (CO) indirect characterization factors estimation [Ramaswamy et al., 2001] [U.S. Environmental Protection Agency, 2002].

Regarding the acidification impact, this has been taken into account considering HCl emissions, while the particulate matter formation indicator has been computed considering aluminum oxide particles emissions modeled as primary $PM_{2.5}$ with a unitary characterization factor, for both solid and liquid exhaust products. Finally, the factors related to energy consumption in additive manufacturing phase have been assessed with respect to the Italian energy mix. Table 4.7 summarizes the characterization factors and respective literature references.

Indicator	**CF**		**Literature Ref.**
GWP	225	gCO_2-eq./kWh	[EU Environment Agency, 2025]
AP	2.22	gSO_2-eq./kWh	[Ghisellini et al., 2023]
$PM_{2.5}$	0.74	$gPM_{2.5}$-eq./kWh	[Ghisellini et al., 2023]
AP	2.22	gSO_2-eq./gHCl	[BIO Intelligence Service, 2005]
$PM_{2.5}$	1.00	$gPM_{2.5}$-eq./gAl_2O_3	[Huijbregts et al., 2016]

Table 4.7: Characterization factors for impact assessment.

Propulsion System	**Element**	**wt.-%**	$\mathbf{Q_A}$ **[g / FU]**	$\mathbf{Q_B}$ **[g / FU]**
Solid	AlCl	0.01%	0.0435	0.0426
Solid	$AlCl_2$	<0.01%	0.0435	0.0426
Solid	$AlCl_3$	<0.01%	0.0435	0.0426
Solid	AlOH	<0.01%	0.0435	0.0426
Solid	$AlOHCl_2$	<0.01%	0.0435	0.0426
Solid	$Al(OH)_2Cl$	<0.01%	0.0435	0.0426
Solid	CO	21.89%	95.1944	93.1438
Solid	CO_2	1.48%	6.4362	6.2975
Solid	Cl	0.22%	0.9567	0.9361
Solid	H	0.58%	2.5223	2.4679
Solid	HCl	16.00%	69.5802	68.0813
Solid	H_2	30.22%	131.4196	128.5886
Solid	H_2O	11.58%	50.3587	49.2739
Solid	NO	<0.01%	0.0435	0.0426
Solid	N_2	8.26%	35.9208	35.1470
Solid	OH	0.04%	0.1740	0.1702
Solid	Al_2O_3 (s)	4.98%	21.6568	21.1903
Solid	Al_2O_3 (l)	4.74%	20.6131	20.1691
Liquid	H	0.25%	0.6473	0.6334
Liquid	HO_2	0.01%	0.0259	0.0253
Liquid	H_2	3.36%	8.6999	8.5125
Liquid	H_2O	88.50%	229.1504	224.2141
Liquid	H_2O_2	<0.01%	0.0259	0.0253
Liquid	O	0.48%	1.2428	1.2161
Liquid	OH	6.26%	16.2088	15.8597
Liquid	O_2	1.09%	2.8223	2.7615

Table 4.8: Exhaust composition for solid and liquid propulsion under scenarios A and B.

Chapter 5

Results & Discussion

The objective of this chapter is to present and discuss the results obtained. The chapter integrates all the findings of the Systematic Literature Review, the comparative Life Cycle Assessment conducted on the selected case study, and the system dependency modeling analysis. Thus, the chapter has been structured as follows:

- Section 5.1 - SLR Results, which presents the outcomes of the Systematic Literature Review and positions the thesis within the research landscape. The section is articulated into:
    - Section 5.1.1 - Descriptive Results, which provides the characteristics of the selected articles, including distribution by country, subject area, and publication year.
    - Section 5.1.2 - Thematic Synthesis of Findings, which analyzes the selected contributions according to three thematic categories, i.e. (i) space for sustainable development on Earth, (ii) outer space sustainability, and (iii) sustainability of space activities.
    - Section 5.1.3 - Identified Gaps, which highlights the main gaps emerging

from the literature, and clarifies the contribution of the thesis.

- Section 5.2 - LCA-based Results, which presents the environmental impact assessment of the two alternative scenarios. The section is structured into:
  - Section 5.2.1 - Impact Assessment, which reports the Life Cycle Impact Assessment results using the selected midpoint indicators, quantifying the environmental impacts associated with each scenario.
  - Section 5.2.2 - Scenarios Comparison, which provides a comparative interpretation of the results, analyzing the relative contributions, and highlighting environmental trade-offs between terrestrial and in-orbit production alternatives.
- Section 5.3 - Procurement Demand Model Analysis, which presents the results of the analytical model developed to evaluate the dependency of the ISM system on Earth-based material procurement. The section has been structured under:
  - Section 5.3.1 - Continuous-Time Formulation Analysis, which analyzes the procurement demand under continuous-time assumptions and discusses the its main parameters.
  - Section 5.3.2 - Discrete-Time Formulation Analysis, which presents the analysis within a discrete-time setting, reflecting periodic replacement cycles and operational dynamics.
  - Section 5.3.3 - Resupply Policies, which proposes possible different resupply strategies and their implications on long-term dependency on Earth-based inputs.

5.1 SLR Results

5.1.1 Descriptive Results

Considering the initial set of 383 retrieved publications, it is possible to provide a descriptive analysis of the results, contextualizing the literature.

Figure 5.1 shows the analysis of scientific publications by country. China and the United States lead, and Europe is well represented, with Italy in third place, showing the commitment that European space agencies and research institutions have dedicated to these topics in recent years. India among the top ten highlights the growing interest in space activities also in emerging economies.

Figure 5.2 shows the distribution by disciplinary area, which clearly highlights the multidisciplinary nature of the topic. More specifically, Engineering is the most relevant field, accounting for about one quarter of publications, followed by Social Sciences (18%) and Environmental Sciences (10%). Significant shares also come from Earth and Planetary Sciences (8%), Physics and Astronomy (6%), and Energy Sciences (6%).

Figure 5.3 shows the analysis by year, up to 2025. Initial focus to these topics had started to appear in the early 1990s, even if the trend observed in the last decade highlights a unique expanding focus compared to previous periods. Interest in the topic remained quite low until 2018, with low than fifteen articles per year, and then grew steadily, reaching a new peak every year.

Taking into account the final 22 selected articles, these reflect almost the same distribution considerations mentioned above in terms of subject area, as Figure 5.5 shows. On the other hand, they differ in the country, reported in Figure 5.4. Specifically, Italy has the highest number of contributions in the set, together with the United Kingdom, France, and other European countries. This likely reflects the commitment, already mentioned and discussed later on, of European institutions and research centers to space sustainability concerns.

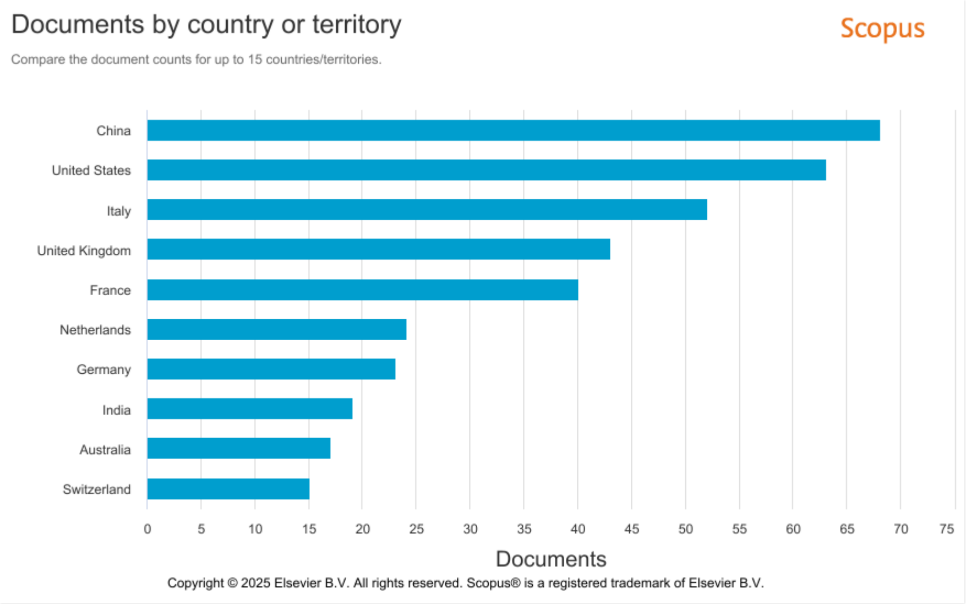


Figure 5.1: Distribution of scientific publications by country based on the Scopus query results.

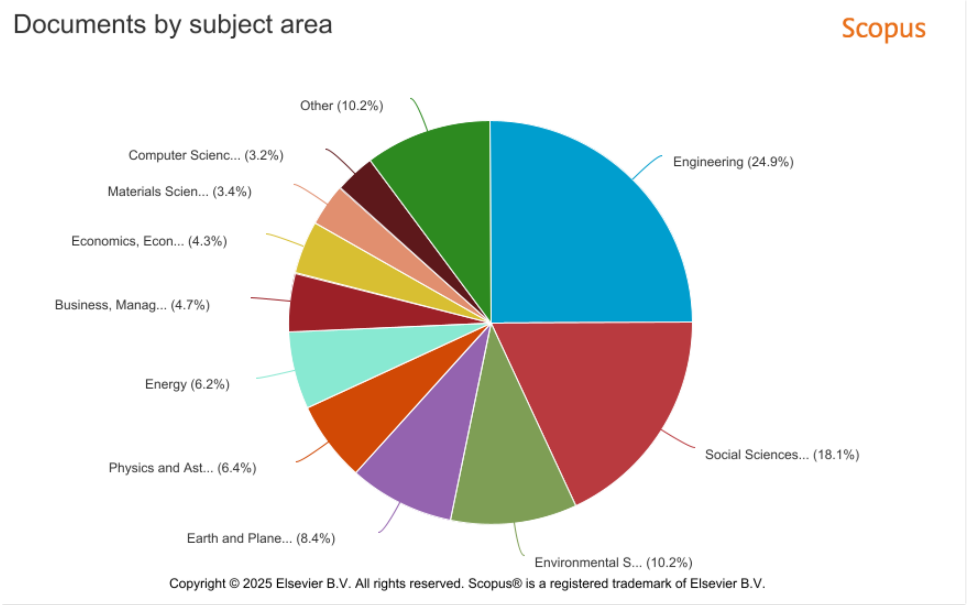


Figure 5.2: Distribution of scientific publications by subject area based on the Scopus query results.

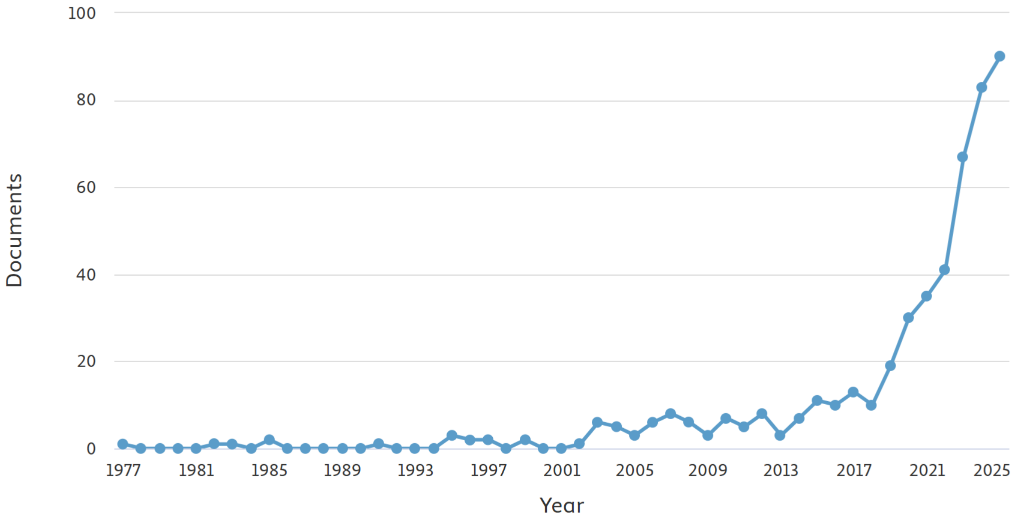


Figure 5.3: Annual number of publications related to space and sustainability from 1977 to 2025, based on the initial Scopus query results.

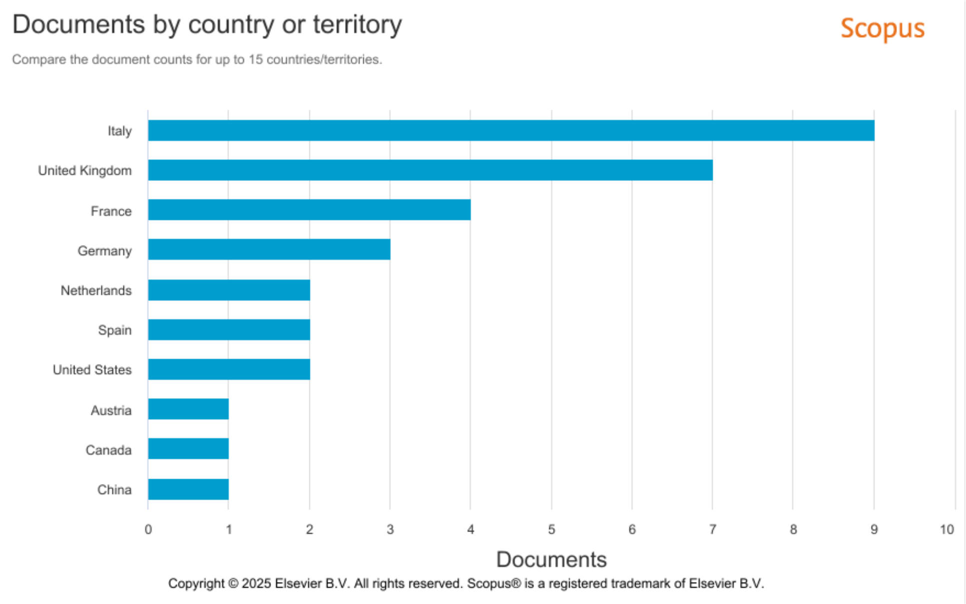


Figure 5.4: Distribution of scientific publication by country based on the final 22 selected articles.

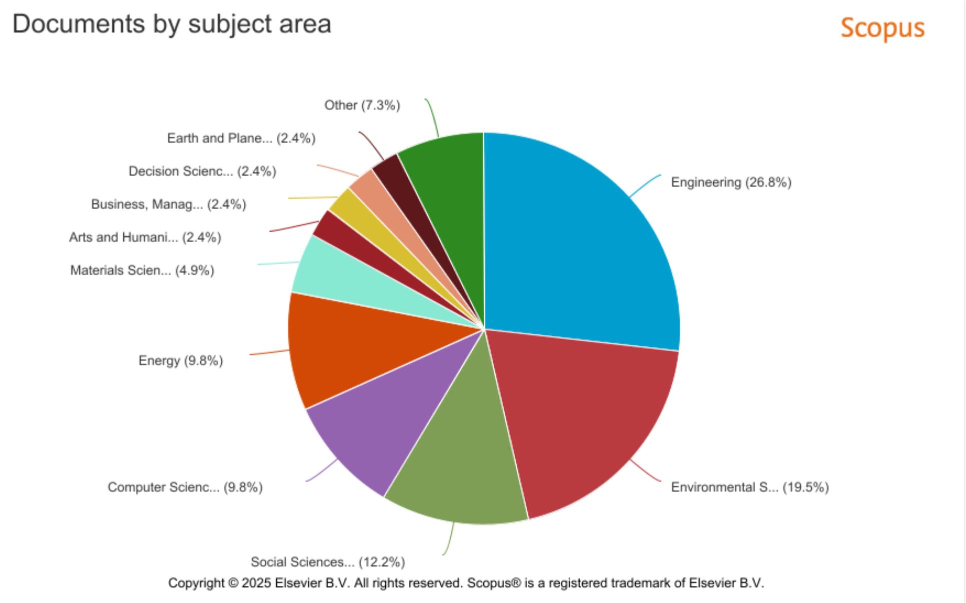


Figure 5.5: Distribution of scientific publication by subject area based on the final 22 selected articles.

5.1.2 Thematic Synthesis of Findings

The sustainable development concept, introduced in 1987 by the World Commission on Environment and Development (WCED), has been developed within three key dimensions, namely environmental, economic, and social, also referred to as Triple Bottom Line [Purvis et al., 2019]. Since then, the concept has been developed across a wide range of sectors and applications, becoming a pivotal element for governmental and academic debates, ultimately leading to the global call for action represented by the SDGs, promoted by United Nations (UN) in 2015.

Given the strategic importance of space activities, sustainability has also emerged as a critical concern in the space domain. As a result of this strategic concern, it is widely acknowledged that the sustainability of space activities must be addressed both on Earth and in space. Moreover, space assets themselves play a key role in supporting sustainability initiatives, both directly and indirectly [IAF Industry Relations Committee, 2024].

Space sustainability refers to the responsible use of space to ensure the long-term viability of space activities, considering multiple dimensions. In the space industry, it is increasingly clear that sustainability is a multifaceted concept — one that begins on Earth and extends into orbit, covering the entire life cycle of space operations. Three dimensions have been identified i.e. sustainability on Earth through space activities, sustainability on outer space environment, sustainability of space activities on Earth [Wilson and Vasile, 2023b].

The 22 selected articles have been organized following the three mentioned thematic categories and dimensions, in turn also defining the following paragraphs.

Space for Sustainable Development on Earth

It is agreed that space activities and technologies strongly support sustainable development on Earth, specifically those related to our planet observation and satellites' services which enable space-derived products and services for sustainability initiatives. One method of measuring their impact is to link them to the 17 SDGs. It can be observed that key space technologies and related research activities (e.g. Earth Observation (EO), Global Navigation Satellite System (GNSS), communication, human spaceflight, microgravity research, etc.) are important tools to the achievement of these goals. However, these technologies alone are not enough: many were created for other purposes, not strictly designed to support specific SDGs. Because of this, there are several economic, political, and technological barriers that need to be correctly addressed. Moreover, space projects also need high initial investments, and using services coming from space solutions to support SDGs might be difficult due to costs, limited access, and the need for international cooperation. Considering this context, governments, international organizations, and policies are still very important to make easier the use space technologies for sustainable development [Wood et al., 2024].

Considering the European area, there's a growing interest in applying space technologies as a support technology to other industries, and to support sustainable development. ESA Business Applications programme is a clear example of this trend. ESA provides financial and managerial support to develop private commercial space-based services which, even if developed in space, define products and services used on Earth. An analysis of more than 603 commercial satellite projects, supported by the programme between 2014 and 2022, shows that the initiative plays an important role with respect to the SDGs. Table 5.1 shows the SDGs most frequently impacted [Paravano et al., 2024].

SDG	**N. of Projects**	**Percentage**
SDG 3 - Good Health & Well-being	136	22%
SDG 11 - Sustainable Cities & Communities	105	17%
SDG 2 - Zero Hunger	78	12%

Table 5.1: Most impacted SDGs by commercial satellite-based applications supported by ESA Business Applications [Paravano et al., 2024].

However, there are important gaps in academic studies on the intersection of the space industry and sustainability. Most academic research focuses on space rather than on impacts on Earth, with environmental sustainability being the most frequently addressed topic. There's limited focus on the environmental impacts of space activities on Earth — in terms of debris falling back, pollution from rocket launches, resource extraction for space missions, etc. Similarly, the social dimensions of sustainability in space missions and exploration are rarely considered, in terms of equity, inclusion, and social impact: literature mainly focuses on policy, international cooperation, regulation, and discussion on the social impact of space-derived technological applications, services, or data on human communities on Earth [Valente et al., 2025].

An underlying topic of sustainability is the concept of the circular economy. Considering the nature of human space missions, manned space projects have the potential to support circular economy models. In space, resources are extremely limited and must be reused efficiently. A clear example is ESA's Micro-Ecological Life Support System Alternative (MELiSSA) project, initiated in 1989, designed to recycle waste, water, and air. The system was originally developed for long-duration space missions, but then it was also applied on Earth, showing how these projects can inspire sustainable practices, especially in regions where reducing waste and reusing materials is essential [Paladini et al., 2021].

The link between space and sustainability becomes clear when looking at the numerous opportunities for technology transfer, both past successes and current ones. Taking advanced materials and micro-nanotechnologies as an example, research in space has driven the development of key sustainable technologies, such as Shape Memory Polymer Composites (SMPCs) and Cosmic Ray Shielding (CRS) materials. These smart materials are designed to be lightweight, durable, and multifunctional, which helps reduce the use of resources and supports long-term missions. Produced on Earth, intended as materials for space applications, tested in real space conditions, these materials also show strong potential for Earth applications, especially in extreme or resource-scarce environments. As such, innovations developed for space can directly contribute to sustainable solutions on Earth, showing how space technologies can be a powerful driver of environmental sustainability [Santo, 2022].

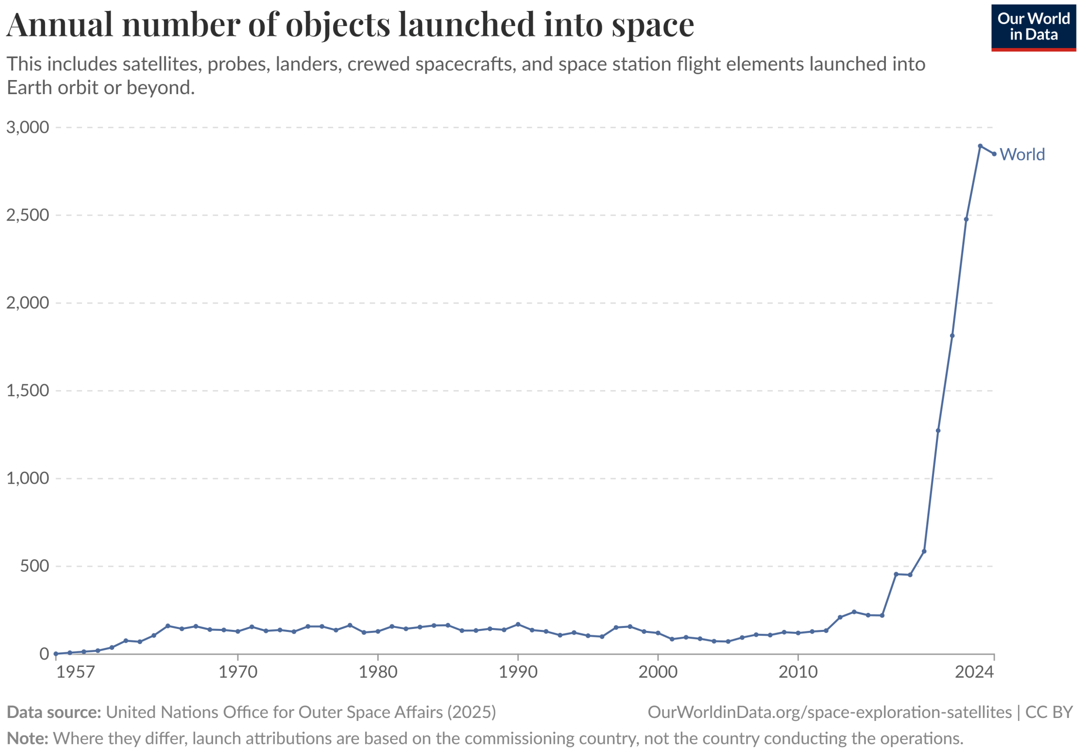
Outer Space Sustainability

Observing the rapid growth of commercial space activities, alongside the emergence of a clearer and increasingly defined Space Economy, it has become evident in recent years that Earth's orbits must also be regarded as a domain for sustainability. Several gaps remain, especially from a legal and regulatory point of view, but already many space agencies and industry players have already launched a number of initiatives to better address this challenge [IAF Industry Relations Committee, 2024].

By analyzing international space law, specifically the Outer Space Treaty (OST) and the Liability Convention, it emerges that the current legal frameworks are not sufficient to address the environmental risks related to space activities. Following the interpretative approaches of the Vienna Convention on the Law of Treaties, it becomes clear that the existing legal frameworks are inadequate to ensure sustainability in orbit, and that further political and legal developments must be properly developed to support sustainability challenges [Cinelli and Campodonico, 2024].

Sustainability of outer space is currently addressed in three main dimensions: Space Traffic Management (STM), space debris mitigation, and space resource activities. STM and space debris are closely related topics, for which space policies have been demanding solutions and regulations, and are considered the most urgent to tackle. On the other hand, space resource utilization, is a long-term challenge, perceived as moderately urgent, and mainly addressed in terms of the permissibility of space resources by private actors and states [Bartóki-Gönczy et al., 2024].

STM refers to the set of practices aimed at dealing with the growing congestion of orbital environments, particularly in LEO, where effective coordination is crucial to avoid collisions, while space debris mitigation concerns all the challenges posed by orbital debris, defined as "*all man-made objects, including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional*" (UNOOSA). Figure 5.6 illustrates how the recent space industry commercialization trends are reflected in terms of annual number of objects launched into outer space, while Figure 5.7 shows how few key actors are responsible for the majority of cataloged space debris objects.


Annual number of objects launched into space

This includes satellites, probes, landers, crewed spacecrafts, and space station flight elements launched into Earth orbit or beyond.

Data source: United Nations Office for Outer Space Affairs (2025) OurWorldinData.org/space-exploration-satellites | CC BY

Note: Where they differ, launch attributions are based on the commissioning country, not the country conducting the operations.

Figure 5.6: Number of objects into outer space annually, 1957-2023, UNOOSA.

Current estimates indicate a total mass of approximately 11,500 tons, including around 36,500 debris objects larger than 10 cm, about 1 million between 1 and 10 cm, and roughly 130 million in the 1 mm to 1 cm range. Space debris emerges as a socio-technical risk, simultaneously product and threat of space infrastructures, closely tied to orbital sustainability and the governance of global commons [Bartóki-Gönczy et al., 2024] [Clormann and Klimburg-Witjes, 2022].

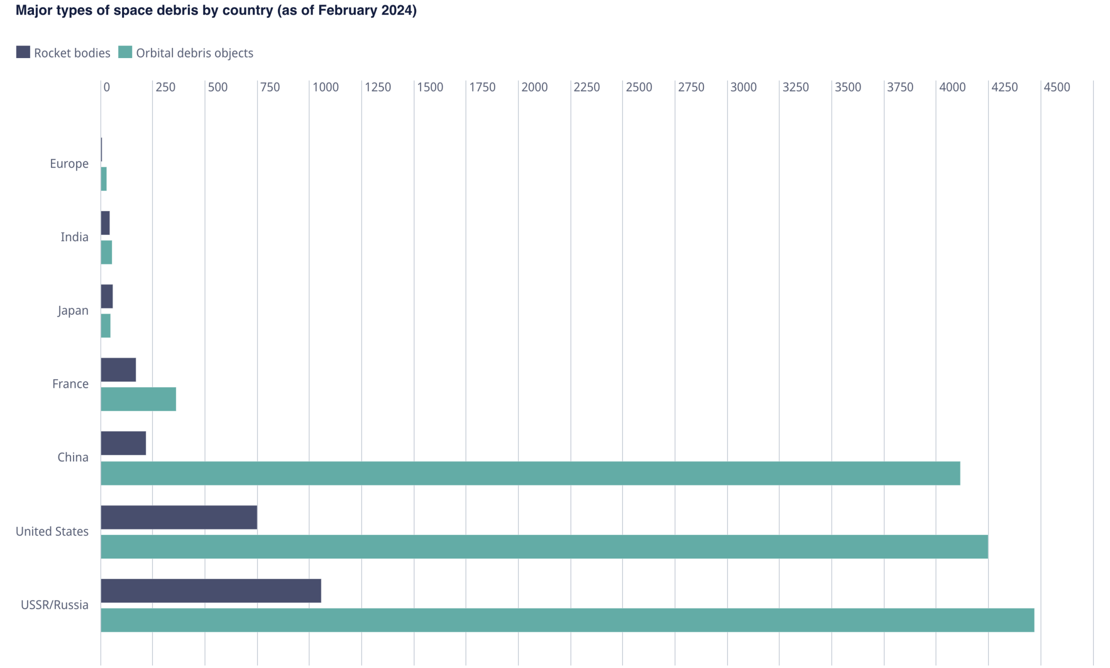


Figure 5.7: Major types of space debris by country and type, as of Feb. 2024, US Space-track website.

A well-known contribution in this domain is the concept of the Kessler Syndrome, introduced in 1978, which describes the potential for an uncontrollable cascade of collisions, defining a scenario where impacts between satellites and debris generate additional fragments that, in turn, trigger further collisions. Over time, such a chain reaction could saturate Earth's orbital environment with debris, making the use of satellites or the launch of new missions increasingly difficult, if not impossible [Kessler and Johnson].

The problem of space debris has been also addressed in terms of dynamic games, modeling the strategic interactions between operators, proving that sustainable use of space is possible. Cooperation slightly reduces satellite launches and yields higher overall profits, even if the difference with competition is small. In both cases debris neutrality can be achieved if Active Debris Removal (ADR) is financed, but costs are higher under non-cooperation. Also a taxation schemes, based on debris generated or satellites launched, can cover ADR expenses while keeping firms profitable [Bernhard et al., 2023].

Mitigation measures developed in the last 30 years have had positive effects, but these were reduced by negative factors such as major collisions, periods of very low solar activity, and the strong increase in launch rates in the mid-2010s. Key indicators to measure the orbital environment status, like total mass, collision cross-section, debris impact risk, and collision rate, must be developed and agreed internationally to support an effective coordination on mitigation strategies. The 2020s are seen as a decisive decade: without effective international actions, LEO could pass limits that would make long-term space operations unsustainable [Pardini and Anselmo, 2021].

Artificial Intelligence (AI) integrated with ADR technologies, inspection and capture procedures for non-cooperative objects, multi-target missions, In Orbit Servicing (IOS), quantum computing technologies, and re-entry services are all key elements to be developed in a long-term roadmap to ensure the safe use of outer space. In addition, the new opportunities offered by the use of new orbits such as Very Low Earth Orbit (VLEO), already started to be used, and cislunar space also require international collaboration, strong regulatory frameworks, and the training of future space professionals to guarantee the long-term sustainability of space activities [Rossi et al., 2024].

One suggestion to consider is treating orbital space depletion as the tenth planetary boundary and using it as an evaluation tool for missions and operations, together with other indicators, to measure space sustainability policies and actions [Wilson and Vasile, 2023b].

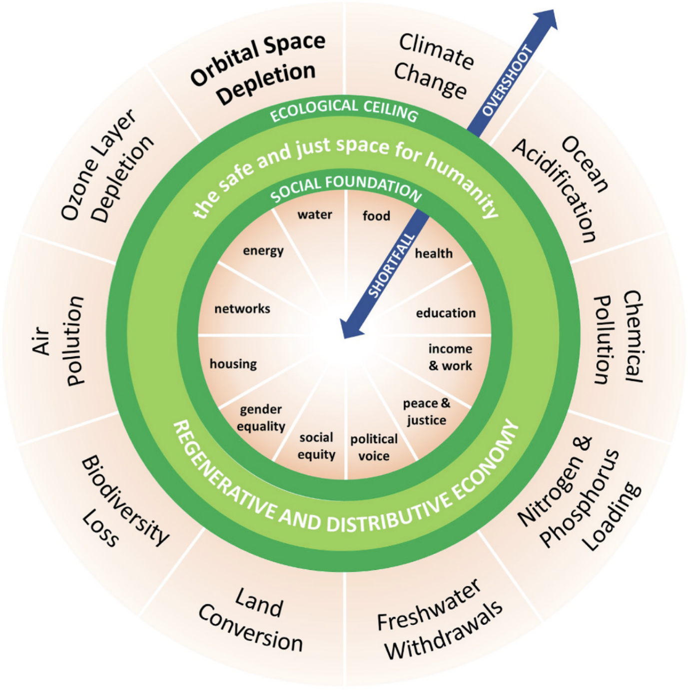


Figure 5.8: The doughnut of social and planetary boundaries depicting orbital space depletion as the 10th planetary boundary [Wilson and Vasile, 2023b].

Sustainability of Space Activities

Considering current and planned space programs, some studies have analyzed how and to what extent the space programs development and actuation impact Earth's environment. However, only a limited number of studies have addressed the direct effects of space activities on Earth's environmental sustainability, leaving room for further research in this field [Valente et al., 2025].

Space sector has often benefited, due to its specific nature, from regulatory and legislative exceptions in terms of environmental protection. This has led the industry to be unable to properly account for its environmental impacts. ESA was the first to carry out studies on the environmental effects of space activities, starting in 2009, focusing on LCA as the most suitable methodology. Even though many studies have been conducted and several standards established, the global evolution of the environmental impacts of the space sector is still less considered, especially when looking at multinational programs planned up to 2050 [Miraux et al., 2022].

Considering the nature of space activities, LCA has been adapted within the sector to account for issues not typical of standard applications. Specifically, space activities are the only human ones that cross all layers of the atmosphere during launch and re-entry. Therefore, they interact with the natural environment at different atmospheric levels and also at the orbital level, as mentioned in the section above. This has led the space industry to adopt LCA standards, while also promoting the development of new indicators useful for the sector itself [Maury et al., 2019].

Environmental impacts were neither considered as a parameter to minimize nor as a factor in decision-making. The number of publications linking space mission planning with risks, sustainability, and supply chain is very limited. However, there is a clear growing interest in the development of optimization models, or more generally Operations Research (OR) models, to create decision-making tools able to evaluate and select space missions in a multi-objective framework, aiming for sub-optimal solutions that are still aligned with current sustainability goals [Sawik, 2023]. It has also been shown that the integration of Life Cycle Engineering (LCE) practices within space mission design is possible, and it has been validated as effectively applicable in combination with the Concurrent Engineering (CE) approach as well [Wilson and Vasile, 2023a].

Considering the development and use of LCA practices, Europe can be considered the leader in the field. ESA made the first contribution in 2009, with a first complete LCA study, highlighting the need for a common standardized approach for the European space industry; since then has invested significant efforts in this direction. The work of ESA has focused mainly on three pillars: the Space System LCA guidelines, a dedicated Life Cycle Inventory (LCI) space database and an eco-design platform called OPERA. It is worth noting that no similar public initiatives have been observed in the United States or Asia. From a temporal perspective, the first LCA studies were carried out in Europe between 2012 and 2015. In 2016, ESA released the LCA handbook, followed by the LCI database in 2017. Since then, the number of studies has grown, covering different segments of the sector, as Figure 5.9 shows [Maury et al., 2020].

In general LCA studies show heterogeneous goals and scope definitions; some focus on large-scale systems or mission segments, while others concentrate on specific materials/processes. A key limitation is the access to suitable databases, due

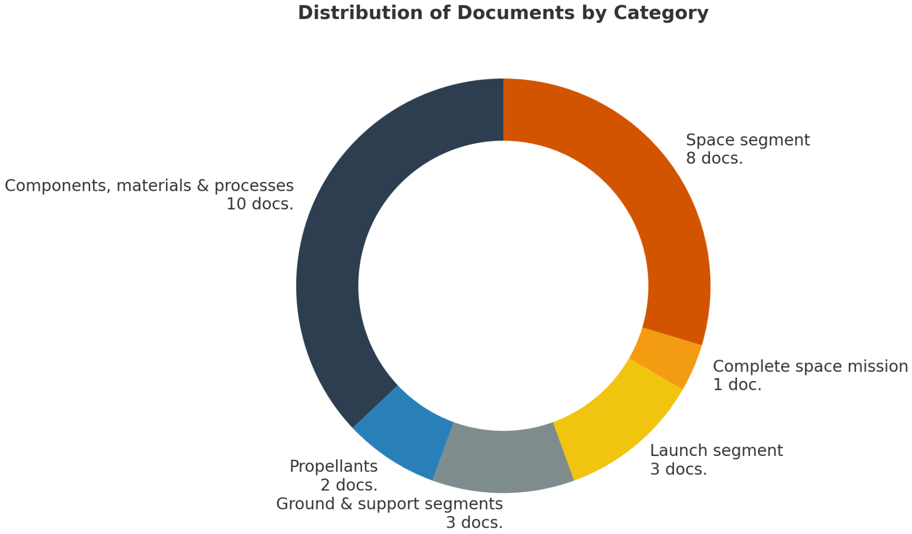


Figure 5.9: Distribution of 27 LCA studies, selected and reviewed in 2020, with respect to six clusters within the space sector [Maury et al., 2020].

to the unique properties of materials used in space. Although ESA has made important progress in promoting LCA and in developing dedicated databases for the sector, there is still a need to improve the analytical framework and standardization, especially to address challenges such as emissions of ozone-depleting substances and the proliferation of space debris, which have been recognized as major issues in recent years [Maury et al., 2020].

5.1.3 Identified Gaps

Building on these considerations extracted from the review, it is possible to respond directly to the initial questions mentioned.

How is the relationship between space and sustainability defined? The relationship between space and sustainability has been defined as a set of practices and principles that aim to ensure responsible space activities and sustainable use of space resources. It is a multidimensional concept, and the literature specifically distinguishes three main dimensions: sustainability development on Earth through space, sustainability of outer space environment, and sustainability of space activities on Earth.

What are the main trends and issues emerging? Space sustainability has become a central research theme, driven by the growth of the space economy and the need to align space activities with SDGs. The literature highlights a number of positive trends, but also reveals critical issues that remain unresolved. In terms of trends: growing alignment of space technologies with the SDGs, focus on orbital sustainability, integration of LCA methodologies into system and mission design. In terms of issues: lack of robust international regulatory frameworks, high economic and technological barriers, limited consideration of Earth-based environmental impacts from launches and manufacturing.

Which dimensions of sustainability are most explored in the space context? According to literature review findings, the environmental dimension dominates, economic aspects are addressed only in specific contexts, and the social dimension remains largely underexplored. This imbalance reveals important opportunities for future research. However, sustainability studies have been mostly focused on the orbit environment and less on environmental impacts on Earth.

Which standards have been applied, and what types of studies have been carried out considering the environmental dimension? The environmental dimension is the one that has developed the most from a methodological point of view. However, the literature shows that studies are still fragmented. The main standards and methods used are LCA, in general LCE approaches integrated in systems and design methods, applied on specific components/materials or segments. Indicators to effectively describe the orbital environment have also been developed. In this context, ESA is the institution that has worked the most to standardize these practices the sector.

The review shows that, although space sustainability is widely discussed, the focus remains primarily on orbital sustainability and, to a lesser extent, on the environmental dimension of missions on Earth. The thesis positioning relies on the following key points:

- To focus on hardware production on-orbit: The thesis aims to focus on a specific case study, selecting a common component used in space sector as a critical subsystems for spacecrafts, in line with EFESTO research objectives.
- To focus on ISM: The thesis aims to focus on ISM as a possible element to enable and support sustainable and circular economy initiatives in space for space, in line with EFESTO research objectives.
- To compare alternative pathways: The thesis aims to provide a comparison study developed by two scenarios, namely an Earth-based manufacturing plus launch scenario, and a in-orbit Additive Manufacturing (AM) scenario,

addressing both AM technologies applied to space and environmental advantages.

- To adopt LCA for space: The thesis aims to apply established assessment tools to a space-specific problem, providing quantitative evidence of environmental trade-offs.
- To model the raw material demand from Earth following an analytical approach, in order to highlights key system dependency's parameters.
- To support decision-making: The thesis aims to provide results that can inform industry and institutions on the potential benefits and limitations of ISM for future space programs, taking into account environmental sustainability.

5.2 LCA-based Results

5.2.1 Impact Assessment

Table 5.2 reports GWP results for both scenarios, with respect to the different CO characterization factors assumed. Table 5.3 and Table 5.4 report respectively AP and PM results for both scenarios.

CF_{CO-GWP}	0.0	1.0	2.1	3.0	gCO$_2$-eq./gCO
$GWP(A)_{AM}$	0.0000	0.0000	0.0000	0.0000	gCO$_2$-eq.
$GWP(A)_{Launch}$	6.4362	101.6306	206.3445	292.0194	gCO$_2$-eq.
$GWP(A)$	6.4362	101.6306	206.3445	292.0194	gCO$_2$-eq.
$GWP(B)_{AM}$	102.8775	102.8775	102.8775	102.8775	gCO$_2$-eq.
$GWP(B)_{Launch}$	6.2975	99.4413	201.8994	285.7288	gCO$_2$-eq.
$GWP(B)$	109.1750	202.3188	304.7769	388.6063	gCO$_2$-eq.

Table 5.2: GWP-100 for scenarios A and B under different CO CF value.

$AP(A)_{AM}$	0.0000	gSO$_2$-eq.
$AP(A)_{Launch}$	61.2306	gSO$_2$-eq.
$AP(A)$	61.2306	gSO$_2$-eq.
$AP(B)_{AM}$	0.0010	gSO$_2$-eq.
$AP(B)_{Launch}$	59.9116	gSO$_2$-eq.
$AP(B)$	59.9126	gSO$_2$-eq.

Table 5.3: AP values for scenarios A and B.

$PM_{2.5}(A)_{AM}$	0.0000	gPM$_{2.5}$-eq.
$PM_{2.5}(A)_{Launch}$	42.2700	gPM$_{2.5}$-eq.
$PM_{2.5}(A)$	42.27000	gPM$_{2.5}$-eq.
$PM_{2.5}(B)_{AM}$	0.0003	gPM$_{2.5}$-eq.
$PM_{2.5}(B)_{Launch}$	41.3594	gPM$_{2.5}$-eq.
$PM_{2.5}(B)$	41.3597	gPM$_{2.5}$-eq.

Table 5.4: PM-2.5 values for scenarios A and B.

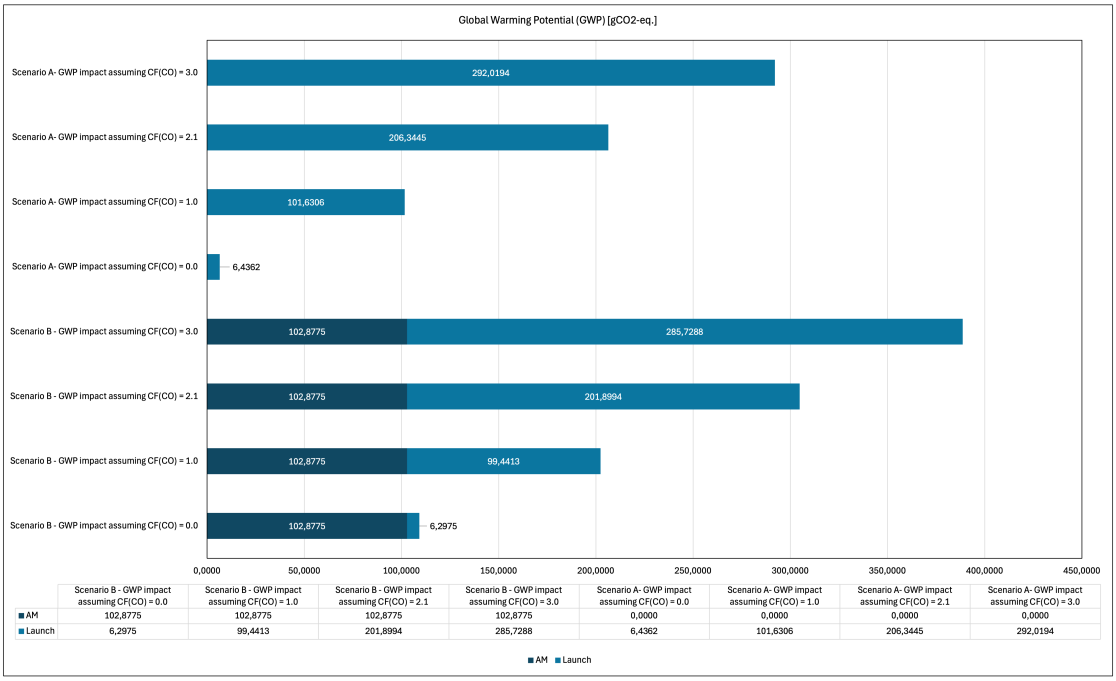
5.2.2 Scenarios Comparison

Three graphs have been reported to compare Scenario A and Scenario B. All the graphs breakdown the AM and launch contributions.

Figure 5.10 reports GWP-100 graphical comparison. It is clear that Scenario B results are higher in CO_2-eq. emissions compared to Scenario A. More specifically, the electricity consumption required for terrestrial AM increases the GWP of Scenario B. An important aspect is the influence of carbon monoxide on launch contribution to GWP: including a characterization factor for CO significantly amplifies the total GWP. This affects the absolute values, and the importance of launch w.r.t. the total emissions, but does not change the relative ranking between the two scenarios.

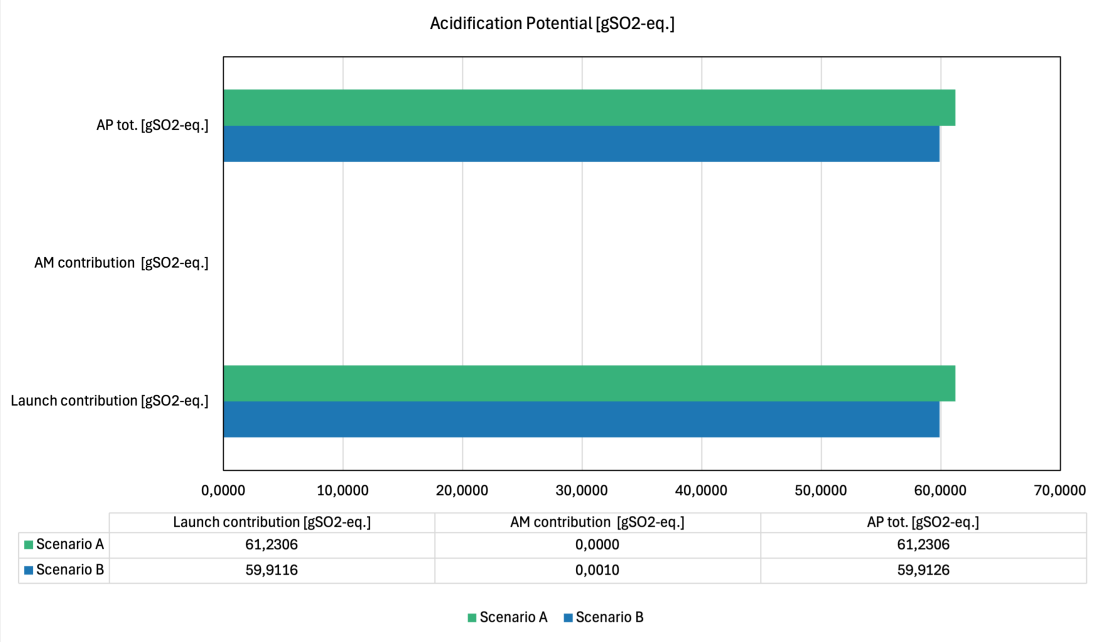
Figure 5.11 clearly shows that acidification impacts are only driven by launch emissions, specifically by hydrogen chloride released from solid rocket propulsion. Scenario A presents slightly higher AP values due to the higher feedstock mass, while the additional contribution from terrestrial electricity generation during the manufacturing phase in scenario B is negligible. The results suggest that, in this case, ground-based manufacturing in scenario B provides a measurable environmental benefit of about 2% reduction, aligned with the mass saving opportunity during the launch.

As Figure 5.12 reports, also particulate matter formation is driven by emissions from the launch phase. Scenario A shows slightly higher $PM_{2.5}$-eq values, which is linked to the higher payload mass involved. Similarly to the acidification results, Scenario A would lead to a increase of about 2% in particulate matter impacts.



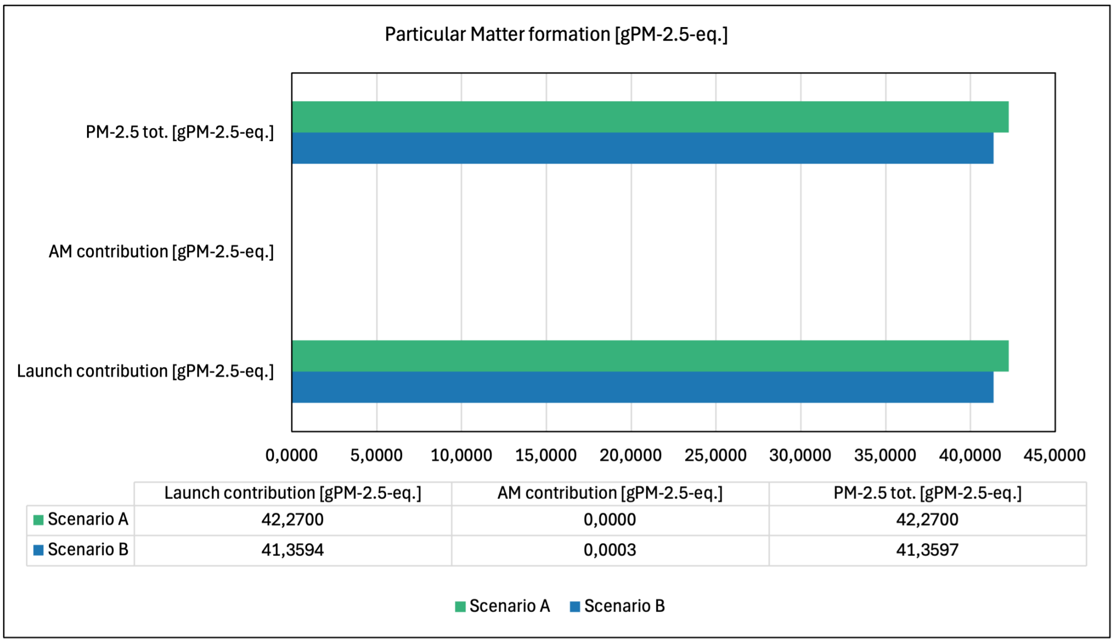
	Scenario B - GWP impact assuming CF(CO) = 0.0	Scenario B - GWP impact assuming CF(CO) = 1.0	Scenario B - GWP impact assuming CF(CO) = 2.1	Scenario B - GWP impact assuming CF(CO) = 3.0	Scenario A- GWP impact assuming CF(CO) = 0.0	Scenario A- GWP impact assuming CF(CO) = 1.0	Scenario A- GWP impact assuming CF(CO) = 2.1	Scenario A- GWP impact assuming CF(CO) = 3.0
■ AM	102,8775	102,8775	102,8775	102,8775	0,0000	0,0000	0,0000	0,0000
■ Launch	6,2975	99,4413	201,8994	285,7288	6,4362	101,6306	206,3445	292,0194

Figure 5.10: GWP-100 results and graphical comparison between scenarios A and B under different carbon monoxide characterization factor values.



	Launch contribution [gSO2-eq.]	AM contribution [gSO2-eq.]	AP tot. [gSO2-eq.]
🟩 Scenario A	61,2306	0,0000	61,2306
🟦 Scenario B	59,9116	0,0010	59,9126

Figure 5.11: AP results and graphical comparison between scenarios A and B.



	Launch contribution [gPM-2.5-eq.]	AM contribution [gPM-2.5-eq.]	PM-2.5 tot. [gPM-2.5-eq.]
🟩 Scenario A	42,2700	0,0000	42,2700
🟦 Scenario B	41,3594	0,0003	41,3597

Figure 5.12: PM-2.5 graphical comparison between scenarios A and B.

5.3 Procurement Demand Model Analysis

5.3.1 Continuous-Time Formulation Analysis

The continuous-time representation has been introduced as function of the substitution factor r, the efficiency factor η, and raw material mass m required to produce one item, which is assumed to be costant:

$$D(t) = r\, m\, \big(1 - \eta(t)\big) \tag{5.1}$$

which basically denotes the average mass of new raw material required per unit time.

The substitution rate r has been introduced as the average number of antennas that must be replaced per year to maintain the system in a operational state. It has been defined as:

$$r(N, L) = \frac{N}{L} > 0 \tag{5.2}$$

where N is the total number of antennas required by the system and L is the average operational lifetime of a single antenna. As shown in Figure 5.13, r exhibits a hyperbolic dependence on L, indicating that lifetime improvements have a non-linear impact on replacement needs. On the other hand, r increases linearly with N, confirming proportional demand growth with system size.

Figure 5.14 shows the demand D as a function of the substitution rate r, for three different values of η. From Equation 5.1, the first-order partial derivative

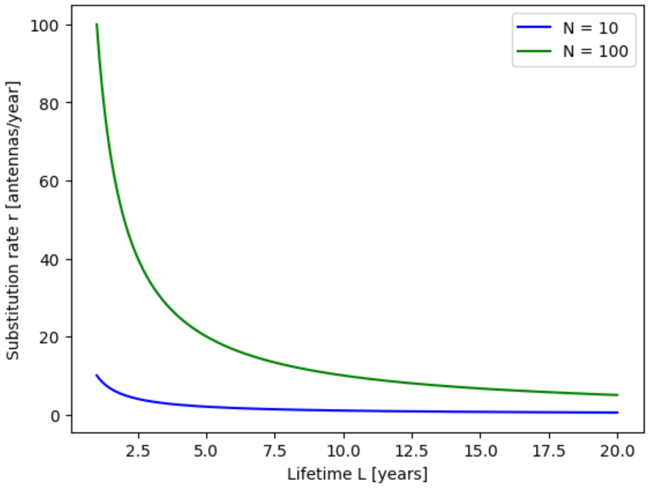


Figure 5.13: Substitution rate r as a function of the antenna lifetime L for different level of antennas N.

w.r.t. r and the mixed second-order derivative w.t.r. r and η can be computed:

$$\frac{\partial D(r,\eta)}{\partial r} = m(1-\eta) > 0 \quad ; \quad \frac{\partial^2 D(r,\eta)}{\partial \eta\, \partial r} = -m < 0 \tag{5.3}$$

These shows the demand D increases w.r.t. the substitution rate r, and the slope of the $D(r)$ relationship decreases as η reduces.

The efficiency factor $0 \leq \eta \leq 1$ represents the fraction of material that can be effectively recovered and reused through in-orbit recycling and manufacturing processes. It can be seen as the product of the efficiencies associated with each individual operation involved in the overall process:

$$\eta = \prod_{i=1}^{n} \eta_i \tag{5.4}$$

where η_i denotes the efficiency of the i-th processing step.

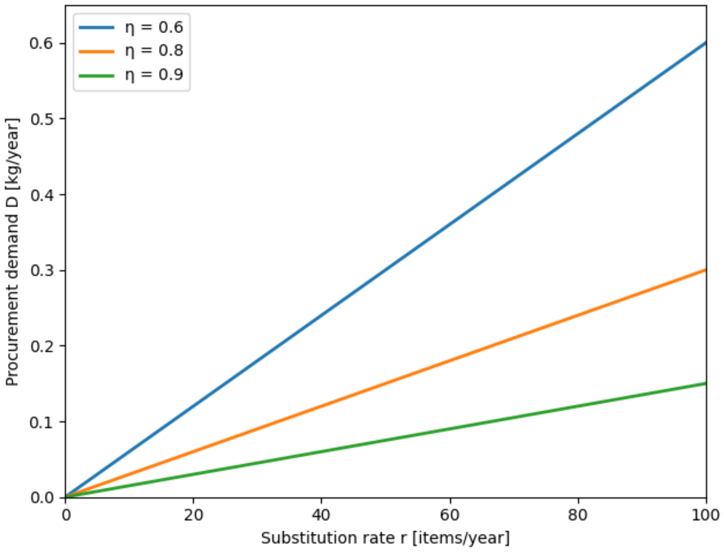


Figure 5.14: Procurement demand D as a function of the substitution rate r for different fixed effective efficiency factors η, with need mass per item fixed at $m = 15$g.

Considering one single efficiency factor η_i, this can be further modeled as a time-dependent function capturing the progressive maturation of technologies, driven by process optimization and the accumulation of operational experience in the orbit environment:

$$\eta_i(t) = \eta_{\max,i} - (\eta_{\max,i} - \eta_{0,i})e^{-kt} \tag{5.5}$$

where $0 < \eta_{\max} < 1$ represents the technological ceiling, $0 < \eta_0 < 1$ represents the initial efficiency level, and $0 < k < 1$ represents the learning rate, so that:

$$\dot{\eta}_i(t) = k(\eta_{max,i} - \eta_{0,i})e^{-kt} > 0 \quad \forall \quad t \geq 0 \tag{5.6}$$

$$\ddot{\eta}_i(t) = -k^2(\eta_{max,i} - \eta_{0,i})e^{-kt} < 0 \quad \forall \quad t \geq 0 \tag{5.7}$$

$$\lim_{t\to\infty} \eta(t) = \eta_{max} \tag{5.8}$$

$$\lim_{t\to\infty} \dot{\eta}(t) = \lim_{t\to\infty} \ddot{\eta}(t) = 0 \tag{5.9}$$

As Figure 5.15 shows, the efficiency factor function $\eta_i(t)$ exhibits a monotonic growth over time, asymptotically approaching the technological ceiling $\eta_{\max,i}$. The positive first derivative $\dot{\eta}_i(t)$ captures the progressive slowdown of efficiency improvements, while the negative second derivative $\ddot{\eta}_i(t)$ indicates diminishing marginal gains from learning. Both derivatives tend to zero, confirming the efficiency stabilization once technological maturity is reached.

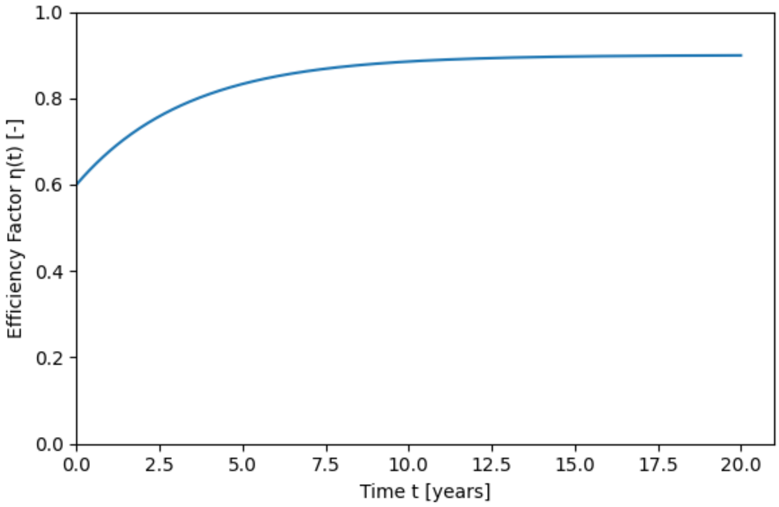


Figure 5.15: Efficiency factor function $\eta(t)$, assuming $\eta_0 = 0.6$, $\eta_{max} = 0.9$, and $k = 0.3$ year^{-1}.

The overall system efficiency η can be expressed as the product of the time-varying efficiencies associated with each of the n individual processing steps, each characterized by its own i-th parameters, leading to:

$$\eta(t) = \prod_{i=1}^{n} \eta_i(t) = \prod_{i=1}^{n} \left[\eta_{\max,i} - (\eta_{\max,i} - \eta_{0,i})e^{-kt}\right] \tag{5.10}$$

where $n_{max,i}$ and $\eta_{0,i}$ denote the maximum achievable and the initial efficiency levels of the i-th operation, and k represents the learning rate, assumed to be common to all operations for simplicity.

Considering the procurement demand, Figure 5.16 shows D as function of the effective efficiency factor η. For a fixed substitution rate r, improvements in the efficiency factor lead to a reduction in the required procurement demand. As discussed in the previous section, the efficiency factor η primarily mitigates the demand relationship associated with substitution needs. Formally:

$$\frac{\partial D(r,\eta)}{\partial \eta} = -r\,m < 0 \quad , \quad \frac{\partial^2 D(r,\eta)}{\partial r\,\partial \eta} = -m < 0 \tag{5.11}$$

The negative first derivative with respect to the efficiency factor indicates that improvements in recycling and reuse efficiency directly reduce the required external procurement for a given substitution rate, confirming the role of efficiency as a primary mitigation lever for the demand. The negative mixed second derivative exhibits that efficiency gains become increasingly valuable in scenarios characterized by higher substitution rates.

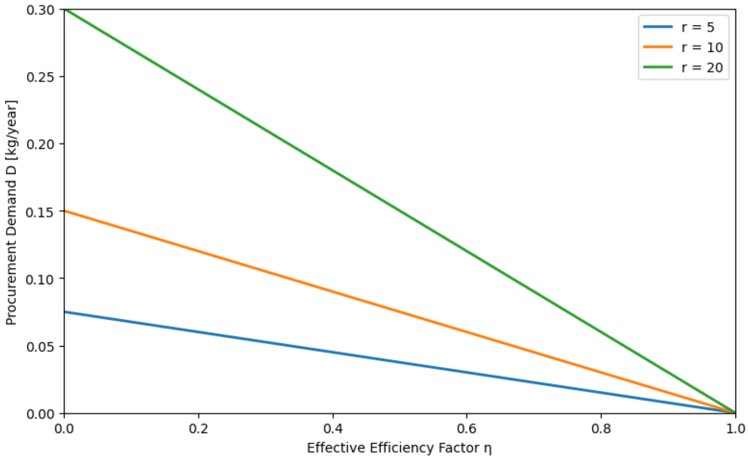


Figure 5.16: Procurement demand D as a function of the efficiency factor η for different fixed substitution rates r, with need mass per item fixed at $m = 15$g.

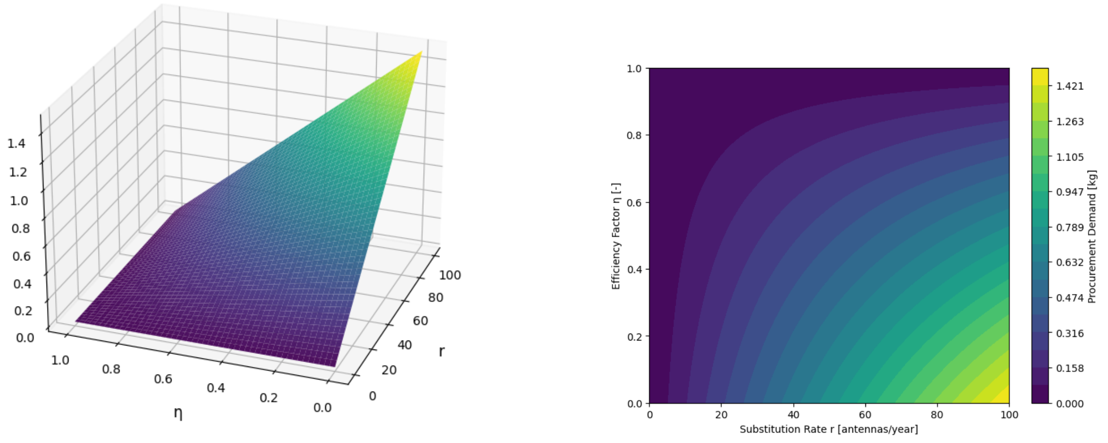
Based on these results, and assuming for simplicity only one efficiency factor to model, the procurement demand function can be interpreted within a system-level perspective:

$$D(t) = \frac{N}{L} m \left[1 - (\eta_{max} - (\eta_{max} - \eta_0)e^{-kt}\right] \tag{5.12}$$

The qualitative behavior can be assessed considering the partial derivatives:

$$\frac{\partial D}{\partial N} > 0\,, \quad \frac{\partial D}{\partial L} < 0\,, \quad \frac{\partial D}{\partial \eta_{\max}} \leq 0\,, \quad \frac{\partial D}{\partial \eta_0} < 0\,, \quad \frac{\partial D}{\partial k} \leq 0\,, \tag{5.13}$$

which indicate that an increase in system scale leads to a higher procurement demand, whereas all parameters governing system efficiency contribute to its reduction. The function $D(N, L, \eta_{\max}, \eta_0, k, t)$ therefore provides a coherent framework to assess long-term procurement requirements under different scenarios. It captures the trade-off between production scale expansion, technological maturation, and recycled material quality. As Figure 5.17a and Figure 5.17b show, procurement demand increases with system size and substitution rate, while it progressively decreases as the effective efficiency improves over time.



(a) $D(r, \eta)$ surface representation

(b) $D(r, \eta)$ filled contour representation

Figure 5.17: Graphical representations of the procurement demand function.

5.3.2 Descrete-Time Formulation Analysis

From an operational perspective, replacement events occur at specific time instants that correspond to the end of each equipment lifetime. Let k denote discrete time in years. Thus, the procurement demand has been modeled as an impulse function occurring at multiples of the lifetime L:

$$D(k) = \begin{cases} m\,N\left(1-\eta(k)\right), & \text{if } k = nL,\ n \in \mathbb{N}^{+} \\ 0, & \text{otherwise} \end{cases} \tag{5.14}$$

$$\eta(k) = \eta_{\max} - (\eta_{\max} - \eta_0)e^{-hk} \tag{5.15}$$

or, in compact form:

$$D(k) = m\,N\left(1-\eta(k)\right) I_{k\in A} \tag{5.16}$$

where the indicator function is:

$$I_{k\in A} = \begin{cases} 1 & \text{if } k \in A = \{L, 2L, 3L, \dots\} \\ 0 & \text{otherwise} \end{cases} \tag{5.17}$$

Within this formulation, the demand $D(k)$ represents the instantaneous mass of new material required in year k, which might be directly satisfied with a corresponding resupply mission in the k-th year. This structure enables the formulation of decision-oriented problems concerning launch frequency, recycling performance improvement, and long-term autonomy policies. Dependency from Earth can be assessed once assumptions on system performances and policies are defined. The following Section 5.3.3 explores possible applicable policies.

5.3.3 Resupply Policies

Let us assume the system is required to maintain exactly N operational items every k year. Each item is characterized by a fixed useful lifetime L, assumed to be independent of the number of recycling cycles experienced by the material used for its production. Under these assumptions, replacements occur at every cycle, i.e. at every L years. At each cycle, all N items reach their end-of-life and must be substituted. Recalling Equation 5.14, and considering $\eta(k)$ modeled as an increasing learning function of the cycle index k, the procurement demand becomes a decreasing sequence, s.t. the procured mass from Earth will decrease until a max efficiency is reached, and from there it would be constant.

Within this framework, the resupply policy consists of scheduling one launch every L years, with payload mass equal to $D(k)$. Such a rigid periodic policy does not necessarily represent the optimal strategy in terms of Earth-dependency minimization. Although in-space manufacturing reduces the mass of finished products transported from Earth, the system remains structurally dependent on scheduled terrestrial resupply. In this configuration, in-space manufacturing acts primarily as a mass-reduction mechanism rather than as a fully autonomous enabler capability.

Let us relax the assumption of a fixed number N of operational items, assuming that it is possible to be operative also with a lower number of item, in order to avoid immediate resupply from Earth. Within this assumption, the system produces only the number of antennas that can be manufactured using the recycled material available at each cycle. This type policy implies that Earth independence is achieved under a progressive reduction in the number of operational items. In other words, the system trades production capacity for autonomy, operating only with internally recycled material until a minimum threshold is reached.

Let N_0 denote the initial number of antennas placed in operation at $k = 0$. At each recycling cycle, the number of producible antennas depends on the effective recycling efficiency $\eta(k)$. Table 5.5 reports the evolution of the operational fleet, while the generic recursive formulation can be expressed as follows:

$$N_n = N_0 \prod_{i=1}^{n} \eta(i\,L) \tag{5.18}$$

Cycle (n)	Year (k)	Fleet Size (N)
0	0	N_0
1	L	$N_1 = N_0\,\eta(L)$
2	$2\,L$	$N_2 = N_1\,\eta(2L)$
3	$3\,L$	$N_3 = N_2\,\eta(3L)$
...	...	...
n	$n\,L$	$N_n = N_{n-1}\,\eta(nL)$

Table 5.5: Evolution of the item fleet size under the variable N policy.

To preserve system performances, a minimum acceptable items fleet size N_{min} has been introduced, defined as a fraction of the initial configuration:

$$N_{\text{min}} = \alpha\, N_0 \tag{5.19}$$

with $0 < \alpha < 1$. The system is operates without resupply need as long as:

$$N_n = N_0 \prod_{i=1}^{n} \eta(i\,L) \geq \alpha\, N_0 \rightarrow \prod_{i=1}^{n} \eta(i\,L) \geq \alpha \tag{5.20}$$

Therefore, the resupply mission is triggered at the first cycle n^* such that the minimum operational constraint is violated. Figure 5.18 graphs an example, considering the time window from $k = 0$ to $k = 100$, assuming $N_0 = 100$, $N_{min} = 50$, $\eta_0 = 0.6$, $\eta_{max} = 0.8$, and $h = 0.35$. It is clear that the fleet decreases at each recycling cycle according to the effective efficiency $\eta(n)$, and it is restored to N_0 only when the minimum operational threshold N_{min} is violated.

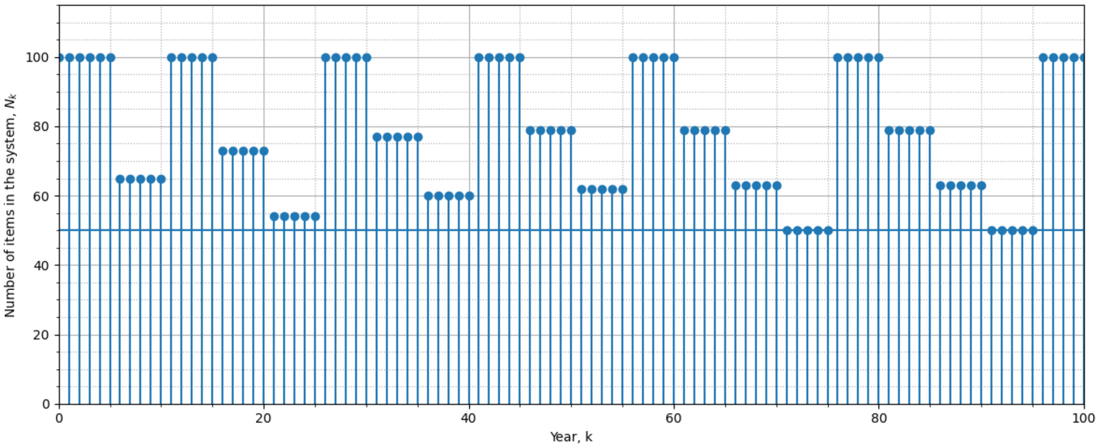


Figure 5.18: Impulse representation of the N evolution under the minimum threshold policy.

Assuming a variable lifetime L, specifically assuming a decreasing L w.r.t. the number of recycling cycles to model a possible quality decay effect over time, the policy logic does not change. The trigger condition for resupply missions remains governed by the minimum operational threshold N_{min}. However, introducing a variable lifetime affects the temporal mapping of the recycling cycles. If $L(n)$ decreases over successive cycles, replacement events occur more frequently in time, and the resupply is anticipated in terms of years. Consequently, the entire profile becomes compressed along the time axis, as degradation and resupply events take place earlier and more frequently.

Chapter 6

Conclusions

The progressive development of the New Space Economy is progressively shifting attention from the use of space assets for terrestrial applications toward the establishment of an autonomous in-space economy. Within this context, ISM emerges as a key enabler for long-term space sustainability. Following this, the thesis has investigated ISM from two perspectives, i.e. the environmental benefits associated with in-space manufacturing initiatives, and the system dependency of an orbital factory w.r.t. Earth-based resupply missions.

The comparative LCA-based study has demonstrated that the environmental profile of ISM initiatives is influenced by launch-related emissions. The two analyzed scenarios, i.e. in-orbit manufacturing supported by feedstock resupply (Scenario A) and terrestrial manufacturing followed by launch (Scenario B), exhibit comparable results with respect to Acidification Potential (AP) and Particulate Matter formation ($PM_{2.5}$), while showing significant differences in terms of Global Warming Potential (GWP-100). Assuming the highest carbon monoxide characterization factor reported in the literature, i.e. $CF_{\text{GWP-100}}(\text{CO}) = 3$ $\text{gCO}_2\text{-eq./gCO}$, the launch phase remains the dominant contributor in both scenarios. This conclusion regarding the relative importance of the launch phase is not affected by the assumption on the carbon monoxide characterization factor. However, the overall magnitude of the impacts changes accordingly. Scenario B, which represents the traditional pathway, consistently results in higher overall impacts due to the additional terrestrial manufacturing stage.

Beyond the LCA comparison, the procurement demand model developed provides a system interpretation of Earth dependency. The model highlights that resupply demand is not only a function of production scale, but is intrinsically linked to system characteristics. Thus, dependency from Earth emerges as a systemic property of the in-orbit production architecture.

From a decision-making perspective, the procurement demand formulation represents a key element for possible strategic planning policies. The introduction of additional variables, such as launcher capacity and availability, lead times, heterogeneous launch providers, orbital storage limitations, stochastic lifetime distributions, inventory policies, budget constraints, and environmental targets, naturally leads to a constrained optimization problem. A possible formulation may be expressed as the minimization of cost and emissions associated with resupply missions, which in turns represent possible extensions of the presented work. The objective minimization function shall be followed by equation constraints such as budget constraints, in-orbit inventory constraints, and others already mentioned above. Depending on the optimization modeling objectives, appropriate assumptions and structure can be accordingly defined, and thus turn the decision-making objective under different appropriate classes of operations research problems, also leading to structured multi-criterion decision analysis.

Within this perspective, the LCA results can be directly embedded into the optimization framework, transforming environmental indicators into decision variables. Environmental performance thus becomes not only an assessment outcome, but a controllable parameter in strategic planning policies.

Overall, this thesis contributes to frame in-space manufacturing initiatives under a system analysis. By integrating environmental assessment with procurement demand modeling, the thesis establishes structured pillars on which decision-oriented frameworks capable of supporting future research and strategic developments can be modeled. After the study, it is clear that achieving sustainability in space does not depend only on reducing emissions per launch, or improving manufacturing efficiency, but rather on design the entire Earth-orbit material flows under a circular production system perspective. In this context, ISM initiatives represent a promising pathway toward in-space economy; however, their effective implementation requires a balanced consideration of environmental, logistical, economic dimensions, and trade-offs, coherently addressed within an integrated systems framework.

Bibliography

Ariane Group. Ariane 6 user's manual, issue 2. Ueser's manual, 2021.

Dr Dale Arney, John Mulvaney, Christina Williams, Wilbert Ruperto-Hernández, Jessica Friz, Christopher Stockdale, John Nelson, and Rafael Rivera-Vargas. In-space Servicing, Assembly, and Manufacturing (ISAM) State of Play. 2024. URL `https://ntrs.nasa.gov/api/citations/20240012414/downloads/ISAM_State_of_Play_2024_final.pdf`.

Balázs Bartóki-Gönczy, Mónika Ganczer, and Gábor Sulyok. Space sustainability: Current regulatory challenges. *Hungarian Journal of Legal Studies*, 65(2):260–281, December 2024. ISSN 2498-5473, 2560-1067. doi: 10.1556/2052.2024.00552. URL `https://akjournals.com/view/journals/2052/65/2/article-p260.xml`. Publisher: Akademiai Kiado Zrt.

Pierre Bernhard, Marc Deschamps, and Georges Zaccour. Large satellite constellations and space debris: Exploratory analysis of strategic management of the space commons. *European Journal of Operational Research*, 304(3):1140–1157, February 2023. ISSN 0377-2217. doi: 10.1016/j.ejor.2022.04.030. URL `https://linkinghub.elsevier.com/retrieve/pii/S0377221722003447`. Publisher: Elsevier BV.

BIO Intelligence Service. A study to examine the costs and benefits of the elv directive. Final report, European Commission, 2005.

Weidong Cai, Piyush Thakre, and Vigor Yang. A Model of AP/HTPB Composite Propellant Combustion in Rocket-Motor Environments. *Combustion Science and Technology*, 180(12):2143–2169, October 2008. ISSN 0010-2202, 1563-521X. doi: 10.1080/00102200802414915. URL `http://www.tandfonline.com/doi/abs/10.1080/00102200802414915`.

Lorenzo Casalino, Andrea Ferrero, Filippo Masseni, and Dario Pastrone. Emission-Driven Hybrid Rocket Engine Optimization for Small Launchers. *Aerospace*, 9 (12):807, December 2022. ISSN 2226-4310. doi: 10.3390/aerospace9120807. URL `https://www.mdpi.com/2226-4310/9/12/807`.

Alec J Cavaciuti, Joseph H Heying, and Joshua Davis. IN-SPACESERVICING,ASSEMBLY, ANDMANUFACTURINGFORTHE NEWSPACEECONOMY. 2022.

Claudia Cinelli and Camilla Campodonico. The duty of state to protect the orbital environment. *Journal of Space Safety Engineering*, 11(2):318–321, June 2024. ISSN 2468-8967. doi: 10.1016/j.jsse.2024.02.006. URL `https://linkinghub.elsevier.com/retrieve/pii/S2468896724000363`. Publisher: Elsevier BV.

Michael Clormann and Nina Klimburg-Witjes. Troubled Orbits and Earthly Concerns: Space Debris as a Boundary Infrastructure. *Science, Technology, & Human Values*, 47(5):960–985, September 2022. ISSN 0162-2439, 1552-8251. doi: 10.1177/01622439211023554. URL `https://journals.sagepub.com/doi/10.1177/01622439211023554`. Publisher: SAGE Publications.

EU Environment Agency. Greenhouse gas emission intensity of electricity generation, country level. `https://www.eea.europa.eu/en/analysis/`

`indicators/greenhouse-gas-emission-intensity-of-1-1751032678/greenhouse-gas-emission-intensity-of-electricity-generation-country-level`, 2025. Accessed: 2026-01-03.

European Cooperation for Space Standardization (ECSS). Ecss-s-st-00-01c rev.1: Glossary of terms. Standard, European Space Agency (ESA), 2023. Issued on 11 October 2023. Accessed October 2025.

European Space Agency (ESA). Esa space system life cycle assessment (lca) guidelines. Technical report, European Space Agency, 2023. Accessed October 2025.

European Space Policy Institute (ESPI). On-orbit servicing, assembly, and manufacturing: State of play and perspectives on future evolutions. Report 87, European Space Policy Institute (ESPI), October 2023. URL `https://www.espi.or.at/reports/on-orbit-servicing-assembly-and-manufacturing-full-report-87`.

Jan-Steffen Fischer and Stefanos Fasoulas. Review of the environmental impact of space transportation systems towards a full life cycle assessment. In *Proceedings of the 73rd International Astronautical Congress (IAC)*, Paris, France, September 2022. International Astronautical Federation (IAF). Paper IAC-22-D2.IP.10.x68113.

Patrizia Ghisellini, Renato Passaro, and Sergio Ulgiati. Environmental assessment of multiple “cleaner electricity mix” scenarios within just energy and circular economy transitions, in italy and europe. *Journal of Cleaner Production*, 388: 135891, 2023. ISSN 0959-6526. doi: 10.1016/j.jclepro.2023.135891.

Michael Z. Hauschild, Ralph K. Rosenbaum, and Stig Irving Olsen, editors. *Life Cycle Assessment: Theory and Practice.* Springer International Publishing, Cham, 2018. ISBN 978-3-319-56474-6 978-3-319-56475-3.

doi: 10.1007/978-3-319-56475-3. URL `https://link.springer.com/10.1007/978-3-319-56475-3`.

Mark A. J. Huijbregts, Zoran J. N. Steinmann, P. M. F. Elshout, Geert Stam, Francesca Verones, M. D. M. Vieira, Anne Hollander, Michiel Zijp, and Rosalie van Zelm. Recipe 2016: A harmonized life cycle impact assessment method at midpoint and endpoint level. Technical Report RIVM Report 2016-0104, National Institute for Public Health and the Environment (RIVM), Bilthoven, The Netherlands, 2016.

IAF Industry Relations Committee. Space sustainability: A view from the global space industry. White paper, International Astronautical Federation (IAF), 2024. URL `https://www.iafastro.org/assets/files/Activities/IRC_White_Paper_2024_Space%20Sustainability%20-%20A%20View%20from%20the%20Global%20Space%20Industry.pdf`.

International Organization for Standardization (ISO). Environmental management – life cycle assessment – principles and framework (iso 14040:1997). `https://www.iso.org/standard/23129.html`, 1997. Accessed October 2025.

Yan Jiayong, Liu Baorong, Yang Kai, Liu Hanliang, Zhang Bin, Zhang Lixin, and Wang Cunyi. Research of Materials and Manufacturing Technology System for On-orbit Manufacturing. *E3S Web of Conferences*, 385:01015, 2023. ISSN 2267-1242. doi: 10.1051/e3sconf/202338501015. URL `https://www.e3s-conferences.org/10.1051/e3sconf/202338501015`.

Donald J Kessler and Nicholas L Johnson. The Kessler Syndrome: Implications to Future Space operations.

J. Koffler. Lca in the space sector: Literature review. Dlr internal report, German Aerospace Center (DLR), 2024. Accessed October 2025.

Erik Kulu. In-Space Manufacturing - 2022 Industry Survey and Commercial Landscape. 2022.

Erik Kulu. In-Space Economy in 2023 - Statistical Overview and Trends. *th International Astronautical Congress*, 2023.

Thibaut Maury, Philippe Loubet, Mirko Trisolini, Aurélie Gallice, Guido Sonnemann, and Camilla Colombo. Assessing the impact of space debris on orbital resource in life cycle assessment: A proposed method and case study. *Science of The Total Environment*, 667:780–791, June 2019. ISSN 0048-9697. doi: 10.1016/j.scitotenv.2019.02.438. URL `https://linkinghub.elsevier.com/retrieve/pii/S0048969719309507`. Publisher: Elsevier BV.

Thibaut Maury, Philippe Loubet, Sara Morales Serrano, Aurélie Gallice, and Guido Sonnemann. Application of environmental life cycle assessment (LCA) within the space sector: A state of the art. *Acta Astronautica*, 170:122–135, May 2020. ISSN 00945765. doi: 10.1016/j.actaastro.2020.01.035. URL `https://linkinghub.elsevier.com/retrieve/pii/S0094576520300552`.

MICS (Made in Italy Circolare e Sostenibile). 5.04 efesto – factory on the space – shaping the scenario. `https://www.mics.tech/en/projects/5-04-efesto-factory-on-the-space-shaping-the-scenario/`, 2024. Accessed: 14 September 2025.

Loïs Miraux, Andrew Ross Wilson, and Guillermo J. Dominguez Calabuig. Environmental sustainability of future proposed space activities. *Acta Astronautica*, 200:329–346, November 2022. ISSN 0094-5765. doi: 10.1016/j.actaastro.2022.07.034. URL `https://linkinghub.elsevier.com/retrieve/pii/S0094576522003800`. Publisher: Elsevier BV.

Northrop Grumman Corporation. Spacelogistics: Space logistics services. `https://www.northropgrumman.com/what-we-do/space/space-logistics-services`, 2025. Accessed: 13 September 2025.

Jana Olivová, Miroslav Popela, Marie Richterová, and Eduard Štefl. Use of 3D Printing for Horn Antenna Manufacturing. *Electronics*, 11(10):1539, May 2022. ISSN 2079-9292. doi: 10.3390/electronics11101539. URL `https://www.mdpi.com/2079-9292/11/10/1539`. Publisher: MDPI AG.

Stefania Paladini, Krish Saha, and Xavier Pierron. Sustainable space for a sustainable Earth? Circular economy insights from the space sector. *Journal of Environmental Management*, 289:112511, July 2021. ISSN 0301-4797. doi: 10.1016/j.jenvman.2021.112511. URL `https://linkinghub.elsevier.com/retrieve/pii/S0301479721005739`. Publisher: Elsevier BV.

Alessandro Paravano, Matteo Patrizi, Elena Razzano, Giorgio Locatelli, Francesco Feliciani, and Paolo Trucco. The impact of the new space economy on sustainability: an overview. *Acta Astronautica*, 222:162–173, September 2024. ISSN 0094-5765. doi: 10.1016/j.actaastro.2024.05.046. URL `https://linkinghub.elsevier.com/retrieve/pii/S009457652400300X`. Publisher: Elsevier BV.

Carmen Pardini and Luciano Anselmo. Evaluating the impact of space activities in low earth orbit. *Acta Astronautica*, 184:11–22, July 2021. ISSN 0094-5765. doi: 10.1016/j.actaastro.2021.03.030. URL `https://linkinghub.elsevier.com/retrieve/pii/S0094576521001430`. Publisher: Elsevier BV.

Ben Purvis, Yong Mao, and Darren Robinson. Three pillars of sustainability: in search of conceptual origins. *Sustainability Science*, 14(3):681–695, May 2019. ISSN 1862-4065, 1862-4057. doi: 10.1007/s11625-018-0627-5. URL `http://link.springer.com/10.1007/s11625-018-0627-5`.

V. Ramaswamy et al. Global warming potentials. In *Climate Change 2001: The Scientific Basis*, chapter 6, pages 385–390. Cambridge University Press, 2001. Indirect GWP of carbon monoxide.

Alessandro Rossi, Noelia Sánchez-Ortiz, Emmanuelle David, Roberto Opromolla, and Dmitriy Grishko. Future activities in the near-earth space in the face of ever-increasing space traffic. *Acta Astronautica*, 225:891–897, December 2024. ISSN 0094-5765. doi: 10.1016/j.actaastro.2024.09.063. URL `https://linkinghub.elsevier.com/retrieve/pii/S0094576524005654`. Publisher: Elsevier BV.

Loredana Santo. Space sustainability, advanced materials and micro/nanotechnologies for future life in outer Space. *Emergent Materials*, 5(1):237–240, February 2022. ISSN 2522-5731, 2522-574X. doi: 10.1007/s42247-022-00373-z. URL `https://link.springer.com/10.1007/s42247-022-00373-z`. Publisher: Springer Science and Business Media LLC.

Claudio Sassanelli, Brendan P. Sullivan, Elia Sindoni, Riccardo Cambertoni, Raffaele Carli, Angioletta Rita Catalano, Francesco Lucchini, Francesco Costantino, Fabrizio Dughiero, Mariagrazia Dotoli, Salvatore Digiesi, Idiano D'Adamo, Luca Settineri, and Sergio Terzi. The Enhanced Factory for Extra-Terrestrial Space Technology Operations: Conceptualization and Scenarios' Definition. In *Springer Proceedings in Mathematics & Statistics*, pages 139–150. Springer Nature Switzerland, Cham, 2025. ISBN 978-3-031-80784-8 978-3-031-80785-5. doi: 10.1007/978-3-031-80785-5_11. URL `https://link.springer.com/10.1007/978-3-031-80785-5_11`. ISSN: 2194-1009, 2194-1017.

Bartosz Sawik. Space Mission Risk, Sustainability and Supply Chain: Review, Multi-Objective Optimization Model and Practical Approach. *Sustainability*, 15(14):11002, July 2023. ISSN 2071-1050. doi: 10.3390/su151411002. URL `https://www.mdpi.com/2071-1050/15/14/11002`. Publisher: MDPI AG.

Elia Sindoni, Riccardo Cambertoni, Serena Brizio, Brendan Patrick Sullivan, Farouk Abdulhamid, Lucia Grizzaffi, Angioletta Rita Catalano, Claudio Sassanelli, Salvatore Digiesi, and Sergio Terzi. EFESTO: A Modular Space Factory to Enhance Sustainability and Outposts Autonomy. In *IAF Space Systems Symposium*, pages 80–92, Milan, Italy, 2024. International Astronautical Federation (IAF). doi: 10.52202/078372-0009. URL `http://www.proceedings.com/078372-0009.html`.

Thales Alenia Space Italia and CIM 4.0. Manufacturing in-space. Internal report, not public, 2024a.

Thales Alenia Space Italia and CIM 4.0. Progress report. Internal report, not public, 2024b.

United States Government Accountability Office. In-space servicing, assembly, and manufacturing: Benefits, challenges, and policy options. Technology Assessment GAO-25-107555, U.S. Government Accountability Office, July 2025. URL `https://www.gao.gov/assets/gao-25-107555.pdf`.

U.S. Environmental Protection Agency. Greenhouse gases and global warming potential values. Technical Report EPA 430-R-02-003, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, DC, April 2002. Excerpt from the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2000.

Marianna Valente, Federico Caviggioli, and Lara Agostini. Space Economy and Sustainability: A Systematic Review. *Sustainable Development*, February 2025. ISSN 0968-0802, 1099-1719. doi: 10.1002/sd.3383. URL `https://onlinelibrary.wiley.com/doi/10.1002/sd.3383`. Publisher: Wiley.

Andrew Ross Wilson and Massimiliano Vasile. Life cycle engineering of space systems: Preliminary findings. *Advances in Space Research*, 72(7):2917–2935, October 2023a. ISSN 0273-1177. doi: 10.1016/j.asr.2023.01.023. URL `https://linkinghub.elsevier.com/retrieve/pii/S027311772300039X`. Publisher: Elsevier BV.

Andrew Ross Wilson and Massimiliano Vasile. The space sustainability paradox. *Journal of Cleaner Production*, 423:138869, October 2023b. ISSN 0959-6526. doi: 10.1016/j.jclepro.2023.138869. URL `https://linkinghub.elsevier.com/retrieve/pii/S0959652623030275`. Publisher: Elsevier BV.

Danielle Wood, Minoo Rathnasabapathy, Keith Javier Stober, and Pranav Menon. Challenges and progress in applying space technology in support of the sustainable development goals. *Acta Astronautica*, 219:678–692, June 2024. ISSN 0094-5765. doi: 10.1016/j.actaastro.2024.03.064. URL `https://linkinghub.elsevier.com/retrieve/pii/S0094576524001899`. Publisher: Elsevier BV.

Serhan Yamaçlı. Implementation of a Lightweight and Portable Horn Antenna Using 3-D Printing Technology. *Journal of Advanced Research in Natural and Applied Sciences*, 8(3):370–379, September 2022. ISSN 2757-5195. doi: 10.28979/jarnas.1039348. URL `http://dergipark.org.tr/en/doi/10.28979/jarnas.1039348`. Publisher: Canakkale Onsekiz Mart University.