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Life Cycle Assessment in the Space Sector

Literature Review

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Abbreviations

A-LCA Attributional Life Cycle Assessment

AlSi Aluminium-Silicon

C-LCA Consequential Life Cycle Assessment

CDEP Concept Development and Evaluation Program

CSID Clean Space Industry Days

E-LCA Environmental Life Cycle Assessment

ELCD European reference Life Cycle Database

EPFL École Polytechnique Fédérale de Lausanne

ESA European Space Agency

EU European Union

GEO Geostationary Orbit

ILCD International reference Life Cycle Data system

JRC Joint Research Center

KPI Key Performance Indicators

LBM Laser Beam Melting

LCA Life Cycle Assessment

LCC Life Cycle Costing

LCI Life Cycle Inventory

LCIA Life Cycle Impact Assessment

LCSA Life Cycle Sustainability Assessment

LEO Low Earth Orbit

PBA Printed Boarded Assembly

PEEK PolyEther-Ether-Ketone

PEP Product Environmental Profiles

REACH Registration Evaluation and Authorization of Chemicals

RoHs Restriction of Hazardous Substances

S-LCA Social Life Cycle Assessment

SDG Sustainable Development Goals

SiC Silicon-Carbide

SSSD Strathclyde Space Systems Database

SWOT Strengths Weaknesses Opportunities and Threats

TRL Technology Readiness Levels

1 Introduction

Space offers vast benefits to humanity, which are harnessed through the use of satellites and space stations. In January 2023, 6718 operational satellites orbit the Earth [1] at different altitudes supporting many technologies like earth observation, communication, navigation or military. Nonetheless, the orbits such as Low Earth Orbit (LEO) or Geostationary Orbit (GEO) in which satellites travel represent a limited resource [2] as they are becoming increasingly crowded with satellites and debris [3] as illustrated in figure 1.1. If the population of orbital space debris exceed a critical threshold, the potential for collisions among objects, even without additional launches, could instigate a cascading effect. This, in turn, would lead to an increased accumulation of debris and a heightened risk of subsequent collisions, a phenomenon known as the "Kessler Syndrome" [4]. Thus, the use of space, emphasized by the lack of international environmental regulations [5], is compromising the overall sustainability – this term will be specify below – of space. This contradictory situation refers to the “space sustainability paradox” and highlights the need of an equilibrium between sustainability from space (i.e. “using space as a platform to directly or indirectly address global problems”) and sustainability of space (i.e. “managing of ecological or other sustainability impacts stemming from space sector activities to both the orbital and Earth environment”) [6].

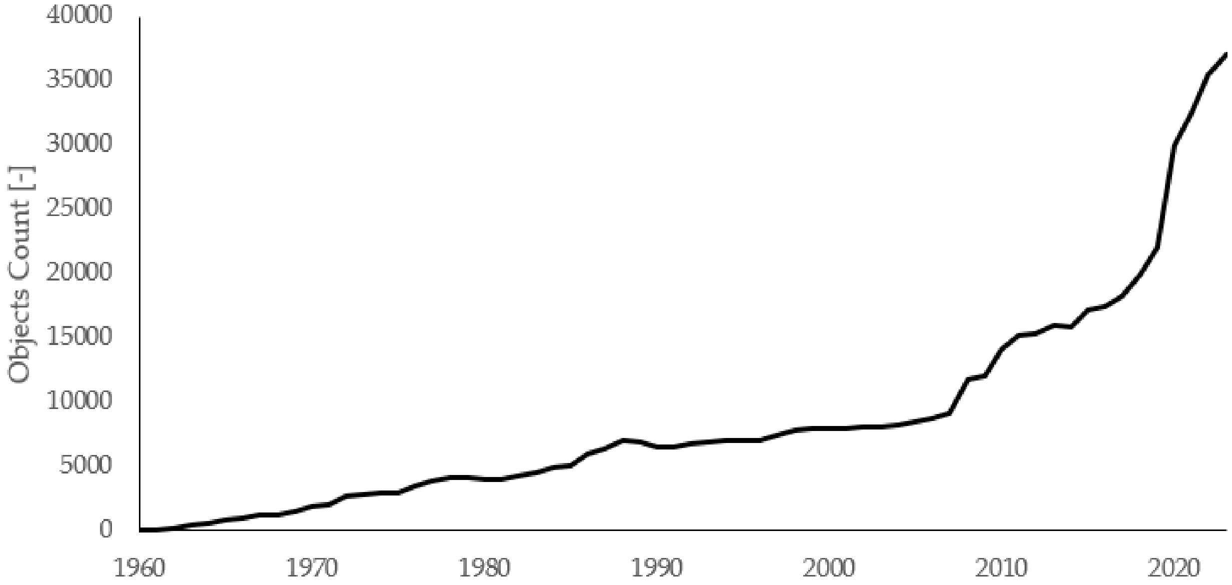


Figure 1.1: Evolution of number of objects in all orbits [7]

In order to face this issue, Life Cycle Assessment (LCA) has been identified as being the most appropriate tool to assess and reduce environmental impacts [5]. This method consists in evaluating the environmental impact of a product throughout its entire life cycle in four steps. This past few years, the community dealing with LCA in the space sector has continuously been growing supported by actors such as the European Space Agency (ESA) and industrial stakeholders. It is essential to emphasize that environmental considerations represent one of the three pillars of sustainability, alongside economic and social aspects. Life Cycle Sustainability Assessment (LCSA) serves as a comprehensive tool for evaluating the overall sustainability performance of a product [8]. It assesses environmental, economic, and social impacts throughout its entire life cycle, employing methodologies such as environmental life cycle assessment (LCA), Life Cycle Costing (LCC)), and Social Life Cycle Assessment (S-LCA) as shown in figure 1.2. For the purpose of this literature review, the focus will specifically delve into the environmental dimension.

Figure 1.2: The three dimensions of sustainability and LCSA (adapted from [8])

Therefore, the objective of this literature review aims to explore and summarize existing research to provide a comprehensive overview of studies dealing with LCA in the space sector. After presenting the concepts and the methodology of LCA, this review delves into the intricacies of space systems from an LCA perspective by examining their definition, regulatory framework and integration of LCA principles based on ESA guidelines. Subsequently, the methods outline the approach taken for this review by including the search strategy and criteria for document selection. The results section presents the key findings and the discussion and perspectives section critically analyses these results, offering insights and recommendations for future research in the field.

2 Life Cycle Assessment: Concepts and Methodology

In this chapter, the fundamental aspects of LCA are explored, delving into the definition and principles. Additionally, the methodology and necessary tools are presented by studying the four essential steps, the different types of LCA and the software and methods commonly employed in the process. To provide a comprehensive perspective on LCA's potential and challenges, a Strengths Weaknesses Opportunities and Threats (SWOT) analysis for general LCA is conducted, identifying its strengths, weaknesses, opportunities and threats. Contextualizing and describing LCA in this chapter will pave the way for a deeper understanding of its application and importance.

2.1 Definition and Principle of Life Cycle Assessment

A life cycle of a product undergoes consecutive and interlinked stages starting from raw material acquisition or generation from natural resources to final disposal or end-of-life management [9] as shown in figure 2.1.

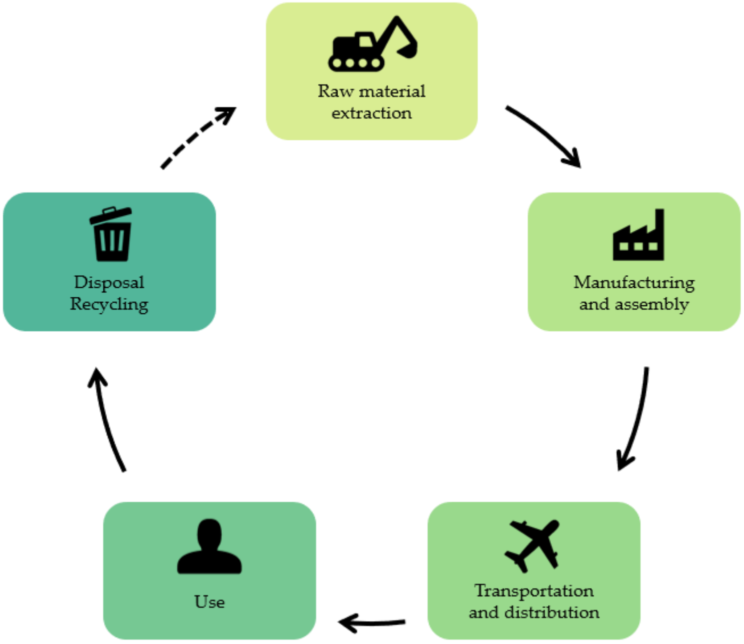
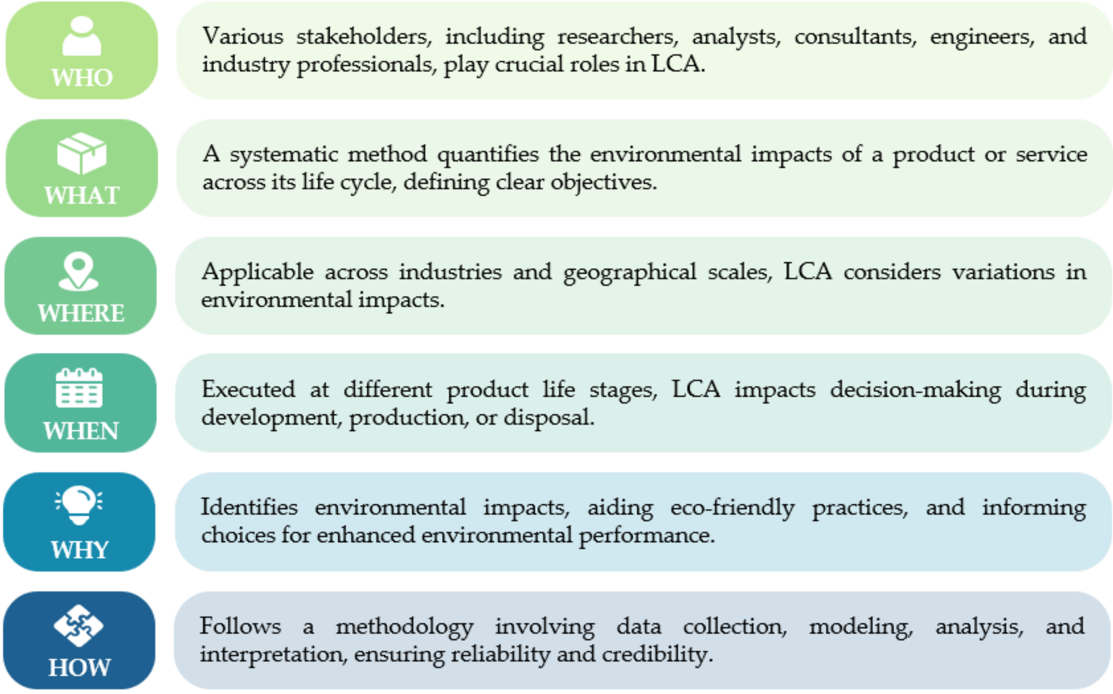


Figure 2.1: Product life cycle phases (adapted from [10])

LCA refers to a methodology used to assess the environmental impacts of a product, a process over a part or an entire life cycle. It quantifies the environmental inputs and outputs associated with each life cycle stage in order to provide insights into the potential environmental burdens and identify opportunities for improvement. It should be emphasized that LCA primarily focuses on evaluating environmental impacts. Nevertheless, social and economic impacts can be included in the scope of the so-called LCSA.

In the context of this literature research on LCA, the 5W1H method will be used (figure 2.2) and consists in answering the fundamental questions of Who, What, Where, When, Why and How [11]. By using this approach, the goal is to gain a deep understanding of LCA by exploring the key dimensions of stakeholders involved, the core principles and methodologies employed, the sectors and geographic contexts in which LCA is applied and the underlying reasons and motivations for conducting LCA.



WHO Various stakeholders, including researchers, analysts, consultants, engineers, and industry professionals, play crucial roles in LCA.

WHAT A systematic method quantifies the environmental impacts of a product or service across its life cycle, defining clear objectives.

WHERE Applicable across industries and geographical scales, LCA considers variations in environmental impacts.

WHEN Executed at different product life stages, LCA impacts decision-making during development, production, or disposal.

WHY Identifies environmental impacts, aiding eco-friendly practices, and informing choices for enhanced environmental performance.

HOW Follows a methodology involving data collection, modeling, analysis, and interpretation, ensuring reliability and credibility.

Figure 2.2: The 5W1H for the LCA methodology

The principle of LCA is rooted in a system perspective (system-of-systems) and in a holistic approach. That is, it recognizes that a product is part of larger interconnected system. It analyzes the interactions and interdependencies between different life cycle stages providing a comprehensive perspective on the environmental impacts [12]. Moreover, LCA adheres to principle of transparency and consistency in its methodology and data sources. It requires clear documentation of assumptions, methods and data collection procedures, ensuring that the assessment is transparent and replicable. Consistency enables comparative analysis, facilitating the comparison of different alternatives to identify opportunities for improvement. Furthermore, LCA is characterized by an iterative process [13] within and between its phases. Through these principles, LCA supports informed decision-making, fosters sustainability and promotes the adoption of environmentally responsible practices.

2.2 Methodology and Tools

2.2.1 The Four Steps

While LCA can be performed using various approaches, its methodology is standardized by the International Organization for Standardization under ISO 14040 and 14044 [14]. It is carried out in four successive and distinct phases that are connected, as the outcomes of one phase will inform how other phases are completed as shown in figure 2.3.

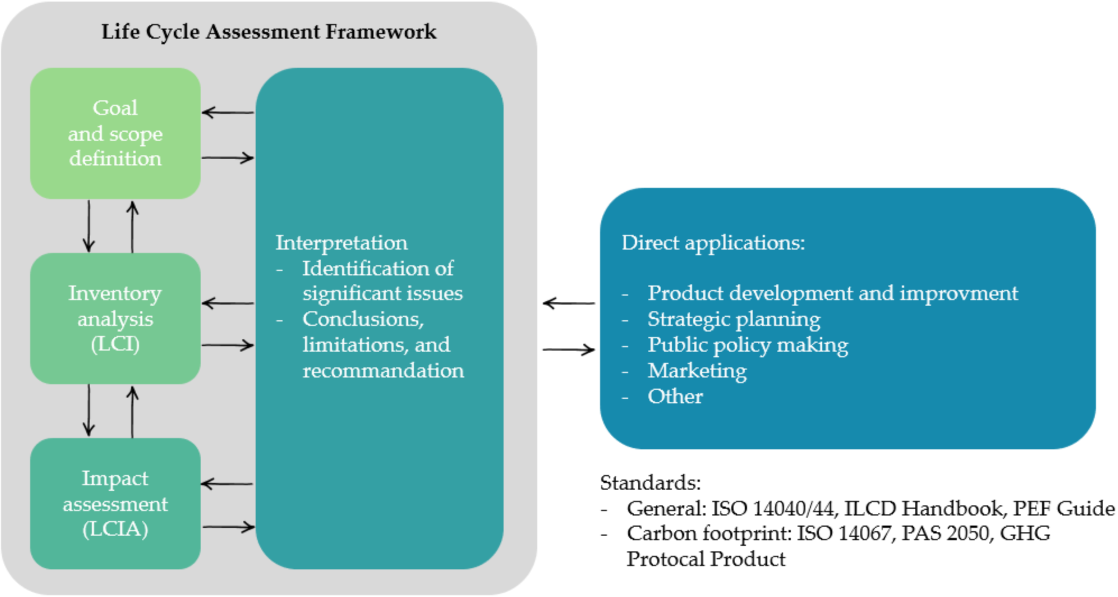


Figure 2.3: Stages of an LCA (adapted [15])

An LCA begins by defining the goal and scope, followed by the inventory analysis. It then continues to the impact assessment and ultimately concludes with the interpretation phase. After completing these steps, an uncertainty and sensitivity analysis can be performed in order to study the reliability of the results and understand how variations in data and assumptions impact the overall conclusions. This step is essential since it ensures the credibility and transparency of the results. However, this analysis will not be discussed in this literature research. Accordingly, the four phases as explained in the ISO documents will be described in the following.

2.2.1.1 Goal and Scope

The initial phase of any LCA consists in defining explicitly the targets and boundaries: a critical step given its substantial influence on results [16]. Unfortunately, this phase often receives insufficient attention [17, 18].

The goal in LCA must be clearly stated to prevent unintended use or misinterpretation of results. It should encompass aspects like the intended application, reasons for the study, intended audience and limitations due to methodological choices [19, 13]. This goal definition shapes the scope, guiding work in both second phase Life Cycle Inventory (LCI) and third phase Life Cycle Impact Assessment (LCIA), with the flexibility to be redefined or revised throughout the study.

The scope encompasses various elements, including the product system, functional unit, reference flow, system boundaries, selected impact categories, methodology of impact assessment and data requirements. It must be clearly defined to ensure the study's relevance and adequacy in addressing goals. Given that LCA is iterative, aspects of the scope may require modification as data is collected to meet the study's original goals. To go into a little more detail, some of the items included in the scope will be explained. A functional unit quantifies a product's performance and serves as a reference for comparisons. For example, lighting 10 square meters with 3000 lux for 50,000 hours with daylight spectrum at 5600 K [20]. Reference flow measures inputs needed from a process to fulfill the defined functional unit, such as 15 daylight bulbs of 10,000 lumens with a lifetime of 10,000 hours in the given example [20]. The system boundary establishes what is being analyzed, with options like cradle-to-cradle, cradle-to-grave, or gate-to-gate approaches [17, 21] and serves to delimit the consideration of the interaction with other systems. The assessment should include geographical/spatial and temporal boundaries. Data types, such as energy consumption, material inputs/outputs, emissions and waste generation, are identified based on availability, quality and required detail.

2.2.1.2 Life Cycle Inventory

The second phase, Life Cycle Inventory (LCI) or inventory analysis, involves the collection, calculation and allocation of data related to inputs, outputs and emissions at each stage of a product's life cycle. This step demands the utmost efforts and resources in an LCA, making it the most time-consuming phase [17].

Figure 2.4: The four groups of data during data collection

The data collected is categorized into four groups (figure 2.4): inputs, such as energy or raw material, outputs, including products, co-products and waste, releases, encompassing emissions to air or discharges to water and soil and finally a last category with other environmental aspects. After collecting all the required data, calculation procedures are done following these steps: first a check on the data validity is performed. After, the quantitative input and output data for each unit process in relation to an appropriate flow is determined. The flows of all unit processes are then related to the reference flow resulting in all system input and output data being referenced to the functional unit. If it cannot be avoided by dividing unit processes or expanding product systems accordingly, inputs and outputs have to be divided between processes shared with other product systems. Afterwards, allocation is used to distribute resources and environmental impacts among different products originating from the same production process. This enables a more accurate assessment of the environmental footprint of each studied product in the LCI.

2.2.1.3 Life Cycle Impact Assessment

LCIA is the stage where the inputs and outputs of elementary flows, previously collected and documented in the inventory, are transformed into impact indicator results associated with human health, the natural environment and resource depletion [19].

The ISO 14040/14044 standards [14] outline necessary and optional steps for the LCIA phase. Mandatory steps are the selection of impact categories, category indicators and characterization models (in practice typically done by choosing an already existing LCIA method). Second the classification by assigning LCI results to impact categories according to their known potential effects (in practice typically done automatically by LCI databases and LCA software). Lastly, the characterization where the calculation of category indicator results in quantifying contributions from the inventory flows to the different impact categories (in practice typically done automatically by LCA software). Optional steps are normalization by expressing LCIA results relative to those of a reference system, weighting by prioritizing or assigning weights to each impact category and grouping by aggregating several impact indicators results into a group.

Table 2.1 [22, 21, 23] provides descriptions of impact categories together with their unit. Beyond these environmental impact categories, various parameters and indicators, presented in table 2.2 [22, 23], are available to report on resource use, waste types and the output flows of materials and energy.

Table 2.2: Other parameters and indicators [22]

Impact category	**Unit**
Primary energy consumption potential	MJ
Gross water consumption potential	m^3
Mass left in space	kg
Mass disposed in the ocean	kg
$Al_2 O_3$	kg

While LCIA is predominantly automated by LCA software in practice, practitioners must have a solid understanding of the principles, models and factors to ensure the insight that is needed for a qualified interpretation of the results [13].

2.2.1.4 Interpretation

In LCI, the focus is on assessing the results of the LCA to achieve the objectives outlined in the goal definition [19]. The primary purposes are to meet the needs derived from the study goal and derive robust conclusions and recommendations.

This interpretation involves three key activities: first the identification of significant issues, encompassing key processes, parameters, assumptions and elementary flows. Then, the evaluation of these issues in terms of their sensitivity or influence on the overall LCA results. This includes

Table 2.1: Summary of environmental impact categories (from [22, 23]

Impact category	**Unit**	**Description**
Climate change	kg CO_2-eq	Indicator of potential global warming due to emissions of GHG to the air: (1) fossil resources, (2) bio-based resources and (3) land use change
Ozone depletion	kg CFC-11-eq	Inidicator of emissions to ar that causes the destruction of the stratospheric ozone layer
Acidification	kg mol $H+$	Indicator of the potential acidification of soils and water due to the release of NO_x and SO_x
Eutrophication - freshwater	kg PO_4-eq	Indicator of the enrichment of the freshwater ecosystem with nutritional elements, due to nitrogen and phosphorus compounds emission
Eutrophication - marine	kg N-eq	Indicator of the enrichment of the marine ecosystem with nutritional elements, due to the emission of nitrogen compounds
Eutrophication - terrestrial	mol N-eq	Indicator of the enrichment of the terrestrial ecosystem with nutritional elements, due to the emission of nitrogen compounds
Photochemical ozone formation	kg $NMVOC$-eq	Indicator of emissions of gases that affect the creation of photochemical ozone in the lower atmosphere (smog) catalysed by sunlight
Depletion of abiotic resources - minerals and metals	kg Sb-eq	Indicator of the depletion of natural non-fossil resources
Depletion of abiotic resources - fossil fuels	MJ, net calorific value	Indicator of the depletion of natural fossil fuel resources
Human toxicity - cancer, non-cancer	CTUh	Impact on humans of toxic substances emitted to the environment. Divided into non-cancer and cancer-related
Eco-toxicity (freshwater)	CTUe	Impact on freshwater organisms of toxic substances emitted to the environment
Water use	m^3 world eq. deprived	¨Indicator of the relative amount of water used, based on regionalized water scarcity factors
Land use	-	Measure of the changes in soil quality (biotic production, erosion resistance, mechanical filtration)
Ionising radiation, human health	kBq U-235	Damage to human health and ecosystems linked to the emissions of radionuclides
Particulate matter emissions	Disease incidence	Indicator of the potential incidence of disease due to particulate matter emissions

assessing completeness and consistency in handling significant issues within the LCI/LCA study. Finally, the utilization of the evaluation results in formulating conclusions and recommendations from the LCA study. In cases involving comparisons of two or more systems, additional considerations are integrated into the interpretation process to enhance the overall assessment.

2.2.2 Types of Life Cycle Assessment

There are different modeling approaches within the LCA methodologies, which are used to understand and quantify the environmental impacts of a product throughout its entire life cycle. They represent distinct ways to analyze and assess the environmental aspects of a product. Among them, there are two main approaches that are widely used: attributional and consequential LCA [24]. Other approaches exist, for example, decisional LCA proposed by [25], yet their application scope and the number of case studies are notably limited compared to the other two [26].

Attributional LCA focuses on analyzing the environmental impacts of a product or process at a specific point in time. It looks at the direct consequences of specific activities and processes related to the product without considering broader system interactions. In contrast, consequential LCA considers the broader system-level effects resulting from choices and decisions. It contemplates the complex interactions and cascade effects in the environmental system due to changes in production, consumption and management.

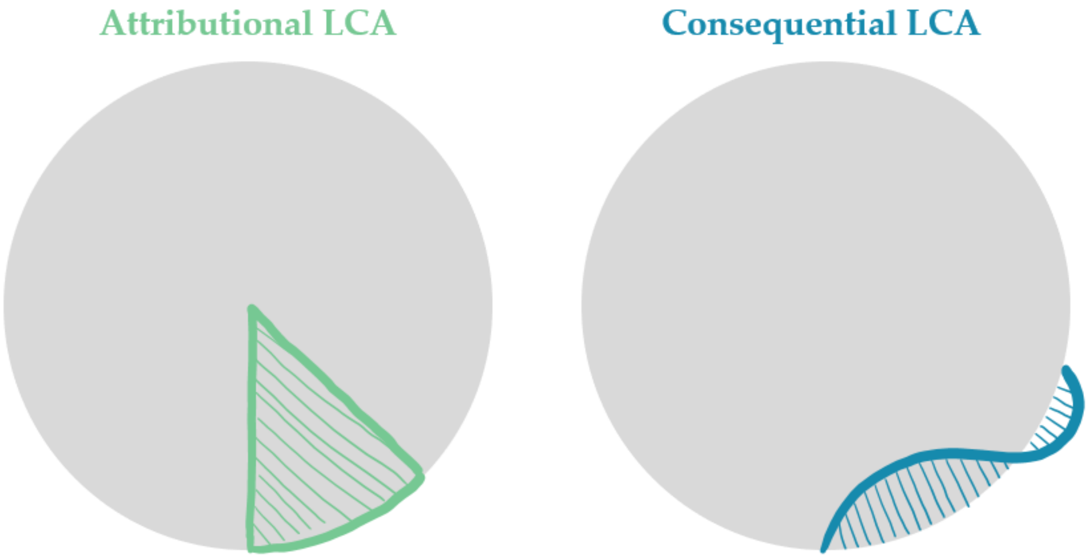


Figure 2.5: Attributional VS consequential LCA [27]

To summarize, the attributional approach focuses on each piece individually, whereas the consequential approach helps see the bigger picture and how changes in one part can affect the whole picture. Figure 2.5. also shows the difference of both approaches where the circles represent the total global environmental exchanges. Appendix A shows a comparative table between attributional and consequential LCA.

2.2.3 Tools Used to Conduct Life Cycle Assessment

Within the framework of an LCA, three essential components are required. The LCI database serves as a comprehensive source of data, offering insights into the environmental inputs and outputs of a product. Simultaneously, LCI tools are employed to structure and analyze this data, facilitating the creation of an LCI. Following this, LCIA tools play a crucial role in assessing environmental impacts based on the compiled inventory. Together, these components form the foundation for conducting a comprehensive and insightful LCA.

2.2.3.1 LCI Databases

LCI database is a repository of data containing information on the environmental inputs (e.g., raw materials, energy, water) and outputs (e.g., emissions, waste, products). The database provides a wide range of data to cover different life cycle stages. Obtaining data from the LCI database can be done through two alternatives: Primary source (foreground data) involves collecting data directly from the entity, ensuring accuracy but requiring substantial resources. Secondary source (background data) utilizes existing LCI databases, a common practice. The most used databases are presented in the table below.

Table 2.3: Example of LCI databases

Name	Description
Ecoinvent	One of the most widely used and comprehensive LCI databases. It provides data on environmental impacts of materials, processes and products across different life cycle stages and can be used by almost every LCA method.
Sphera	Sphera, formely known as GaBi, offers a wide range of LCI datasets, including data on energy consumption, emissions, waste generation and other environmental indicators. These datasets cover various industries and sectors and is both LCA software and an LCI database. The database is often used in conjunction with Sphera software but can also be used in OpenLCA.
ELCD	ELCD comprises LCI data from EU business associations and other sources for key materials, energy carriers, transport and waste management [28]. It was discontinued in 2018 but the data can still be downloaded.
SimaPro database	SimaPro, a widely used LCA software, comes with its own database containing various LCI datasets for performing LCA studies.

2.2.3.2 LCI Software Tools

An LCI tool is a software application or platform used to collect, organize and analyze data related to the environmental inputs and outputs of products. LCI tools facilitate the creation of comprehensive inventories by allowing users to input data on raw materials, energy consumption, emissions, waste generation and other relevant parameters associated with the entire life cycle. These tools can come with built-in databases, as mentioned before this is the case for SimaPro and Sphera. The most used LCA software are presented in the table below.

Table 2.4: Example of LCI software

Name	Description
Brightway	Open-source LCA software tool and provides a flexible and customizable platform for creating and managing LCIA calculations. Brightway is known for its transparency, user-friendliness and robustness. It is widely used in academia and research for conducting LCA in various industries.
OpenLCA	Open-source LCI software tool. It offers a user-friendly interface and extensive databases of materials and processes. OpenLCA enables users to build complex life cycle models and conduct LCIA with a range of impact assessment methods. The software is accessible to both beginners and experienced LCA practitioners.
SimaPro	Commercial LCI software tool that provides comprehensive capabilities for LCI but also for LCIA. It offers a large database of materials and processes, making it convenient for users to build detailed life cycle models. SimaPro is widely used in industry and academia and is known for its powerful LCIA functionalities and user support.
Umberto	Commercial LCI software tool. It allows users to create detailed life cycle models and assess the environmental impacts of products and systems. Umberto is particularly popular in industries that require detailed and specialized LCA analyses, such as manufacturing and engineering.

2.2.3.3 LCIA Methods and Tools

During the LCIA phase, the LCI data (i.e. emissions and resources consumptions) are converted into impact categories [28]. Indicators are quantifications of impact categories and provide a more detailed and quantitative representation of environmental or social performance within a specific impact category. In order to have a comprehensive picture of the impacts associated with a product, midpoint and endpoint impact categories are used (Figure 8 adapted from [22]). Midpoint impact categories are intermediate impact categories, whereas endpoint impact categories represent the ultimate environmental impacts that affect human health, ecosystems and resources and are more related to overall well-being of human societies and the environment.

The ISO 14040/44 standard [14] offers no specific guidance on the choice of LCIA methods, emphasizing the importance of a thoughtful selection process due to the varying suitability of methods [13]. Broadly, LCIA methods fall into two categories [12]: resource-based methods focus on evaluating the consumption of natural resources, particularly non-renewable ones such as fossil fuels, metals and minerals, throughout a product's life cycle. Emission-based methods center around the release of pollutants, including nitrogen oxides, sulfur oxides and water pollutants like nutrients and heavy metals, into the environment during the product's life cycle.

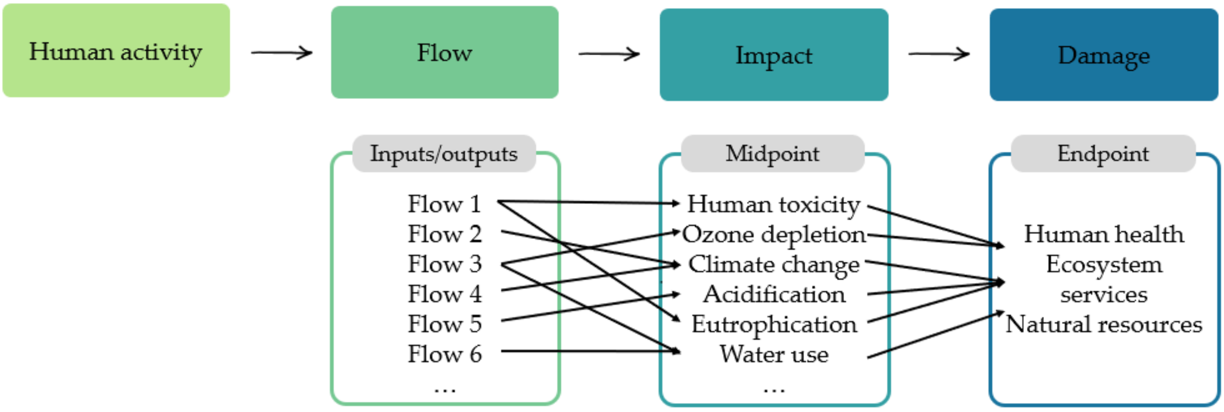


Figure 2.6: LCIA with midpoint and endpoint (adapted from [22])

Since the inception of LCIA methods in 1984, various approaches have been utilized, with examples including RECIPE, IMPACT 2002+ and CML. The careful choice of an LCIA method is crucial to ensure a comprehensive and accurate assessment of a product's environmental impact.

2.3 Strengths, Weaknesses, Opportunities and Threats

To provide the reader with a comprehensive understanding of LCA, a SWOT analysis to assess its strengths, weaknesses, opportunities, and threats. It helps identifying internal (strengths and weaknesses) and external (opportunities and threats) factors that can influence the success or effectiveness of this methodology.

- **Strengths:**
  - Comprehensive analysis: LCA provides a holistic view of a product's environmental impact throughout its entire life cycle.
  - Standardization and Recognition: LCA follows international standards (e.g. ISO 14040 and ISO 14044), providing a framework and principles for this methodology.
  - Decision-making support: Based on scientific methodologies the LCA approach enables an informed, profound, traceable and objective decision-making process with regard to ecological factors.
  - Environmental awareness: LCA raises awareness about the environmental consequences of products and processes, encouraging eco-friendly practices and responsible consumption.
- **Weaknesses:**
  - Complexity and costs: LCA can be a complex and costly process, requiring a significant amount of data, expertise and time.
  - Data challenges: gathering accurate and relevant data for LCA can be time-consuming and resource-intensive, especially for complex assets and supply chains.

  - Subjectivity in impact assessment: LCA relies on impact assessment methods that may involve subjective choices, leading to potential variations in results.
  - Limited scope: LCA primarily focuses on environmental impacts and may not capture all relevant social and economic aspects of sustainability.

- **Opportunities:**
  - Innovation and optimization: LCA identify opportunities for product and process optimization, leading to eco-friendly innovations and efficiency improvements.
  - Product labeling and certifications: LCA can be used to develop eco-labels and certifications, guiding industry, stakeholders and consumers towards more sustainable choices.
  - Policy support: LCA provides robust data for policymakers to design effective environmental regulations, incentives and eco-friendly policies, promoting sustainable practices across industries.

- **Threats:**
  - Incomplete data: LCA heavily relies on available data. Data gaps or uncertainties can affect the accuracy and reliability of the results.
  - Greenwashing: Misuse of LCA results for marketing without genuine commitment to sustainability may lead to greenwashing and erode trust in LCA outcomes.
  - Complexity and resource intensity: The complexity of LCA can be a barrier for small businesses and industries with limited resources, hindering its widespread adoption.

To conclude, LCA is a powerful tool for understanding and improving the environmental performance of a product. While it has numerous strengths and opportunities to promote sustainability, addressing its weaknesses and threats is crucial for maximizing its impact and credibility. Transparency, standardization and ongoing research and development can further enhance the effectiveness of LCA as a sustainable decision-making tool.

3 Space Systems: A Life Cycle Assessment Perspective

In this chapter, we delve into the environmental considerations of space exploration through an LCA perspective. We begin by defining a space system and exploring the regulatory framework governing space activities. The core focus is on integrating LCA principles into space systems analysis, guided by the ESA Guidelines. ESA guidelines, crafted under the Clean Space Initiative, provide a specialized framework for evaluating the environmental impacts of space missions. These guidelines offer tailored rules, datasets, and tools, adapting international standards for LCA to the unique challenges of the space sector. This exploration extends to two levels of breakdown — functional and physical — providing a concise yet comprehensive perspective on assessing the environmental impact of space missions.

3.1 Definition of a Space System

A space system refers to a complex and organized set of interconnected elements, technologies and processes working together to perform a task in the space environment. It can be broken down into four distinctive segments [29], that have their own activities, impact and environmental characteristics (figure 7.1).

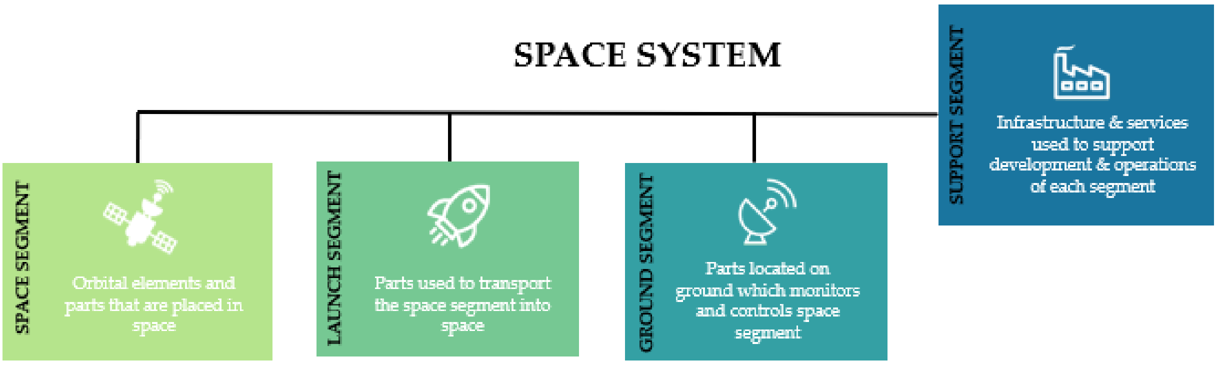


Figure 3.1: Definition of a space system and its four different segments (from [30])

The life cycle of a space system [31] is adjusted from figure 2.3 and presented in **??**. In the existing literature, one can also come across, not life cycle phases, but rather mission phases [6]. These are very similar to the life cycle phases described above, albeit with a more exhaustive breakdown.

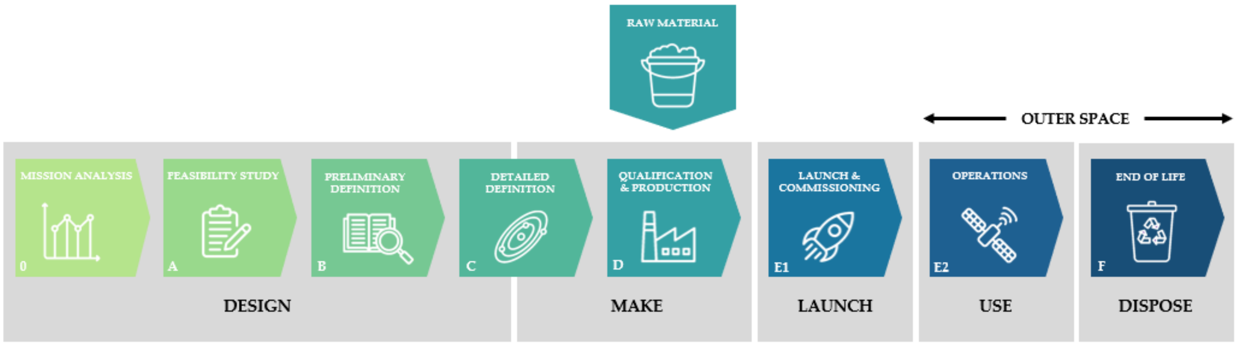


Figure 3.2: Life cycle (in grey) and mission phase (in color) of a space mission (adapted from [30])

3.2 Regulatory Framework for Space Activities

There are no strict agreements or rules at the United Nations level that directly impose legally binding obligations on industrial actors in the space sector regarding environmental protection. However, this does not mean that the space industries are not regulated at all in terms of the environment. Indeed, environmental regulations applicable to the space sector vary from one country to another and may arise from general international or national laws, specific nationals' laws for the space industry and voluntary protocols or agreements between governments and countries.

First of all, general international or national laws are related to environmental protection and product safety regardless of the sector or the industry. It includes among other things the Registration Evaluation and Authorization of Chemicals (REACH) and the Restriction of Hazardous Substances (RoHs) regulations. REACH, implemented by European Union, aims to regulate the production and use of chemical substances and their potential impacts on both environment and human health whereas RoHs aims to restrict the use of certain hazardous substances in electrical and electronic equipment.

Specific national laws for the space industry further contribute to this regulatory landscape, with countries like France, Belgium, the United Kingdom and the Netherlands implementing legislation to ensure environmental protection in space activities. Here are few examples [32, 33]:

- France: Law No. 2008-518 of June 3, 2008 includes provisions regarding environmental protection. It requires space operators to take measures to prevent any environmental damage by establishing plans to minimize risks.
- Belgium: Law on the Activities of Launching, Flight Operation or Guidance of Space Objects, as a signatory of the Moon Agreement, possesses the most advanced legislation regarding the protection of space environment [34]. They have the strictest rules in terms of environmental protection of space.
- United Kingdom: The Space Industry Act of 2018 includes provisions on environmental protection. It mandates space operators to minimize the environmental impacts of their space activities and to consider environmental considerations when planning launches.

- Netherlands: The Space Activities Act of 2018 addresses the environmental aspects of space activities and requires space operators to take measures to minimize environmental impacts and risks associated with their activities.

Finally, voluntary protocols and agreements also play a role, with space-specific treaties and guidelines. Five space-specific treaties were established between 1960 and 1980 to regulate space activities. Among these treaties, only two mention environmental protection: Outer Space Treaty (1967) and the Moon Agreement (1968). These treaties emerged during the Cold War. During this time, the primary concern of international space politics was not environmental protection, but rather preventing the escalation of armed conflicts between the United States and the Soviet Union, both competing in space exploration [35], into space. The published also two guidelines. This committee is part of the . The guidelines were developed by experts from various member countries of , with the aim of promoting the sustainable and responsible use of outer space:

- The “Space Debris Mitigation Guidelines”, published in 2007, primarily address the mitigation and management of space debris, which refers to non-operational human-made objects in space. These guidelines focus on preventing the creation of new debris and minimizing the generation of additional fragments.

- The "Guidelines for the Long-term Sustainability of Outer Space Activities" were published in 2018 and provides a broader framework for the sustainable conduct of activities in outer space. While they encompass space debris mitigation, they also cover a wide range of other aspects, including the preservation of the space environment, the management of space traffic and the responsible use of space resources. These guidelines aim to ensure that space activities are conducted in a manner that sustainable.

Another voluntary protocol is the Product Environmental Footprint. It is a specific methodology developed by the European Commission in order to assess the environmental impacts of product. The latter was developed by European Commission to harmonize LCA across European industries [36, 37] and is not specific to space

As environmental concerns surrounding the space sector grow, driven by evolving legislations, regulations and public expectations, the need for dedicated approaches becomes evident [38]. The unique characteristics of the space domain, including low production rates, specific environmental impacts not traditionally considered in LCAs, specialized materials and long development cycles [39], necessitate the development of dedicated databases and methodological rules for LCA in space projects. Recognizing this, ESA has established guidelines to guide good practices in LCA for the space sector, acknowledging the importance of proactive measures in this emerging field.

3.3 Life cycle Assessment and Space Systems

ESA’s Clean Space initiative, undertaken between 2016 and 2017 and currently under revision since 2021, aims to comprehensively address the environmental impact of space activities. This initiative is driven by the [**ESA**] and focuses on understanding and mitigating the pollution associated with space endeavors. The primary objectives of this effort include establishing methodological rules for conducting space-specific LCA and defining guidelines to ensure a consistent and harmonized approach to LCA within the European space sector [40]. By doing so, ESA seeks to identify alternatives to reduce the environmental impacts of space activities.

The initiative encompasses the development of a handbook, initiated in the first framework and currently being revised in 2021 [41, 40]. The handbook serves as a comprehensive guide, covering the general methodology of LCA, addressing the specificities and challenges of applying LCA to the space sector and providing guidelines for conducting space-specific LCAs. Additionally, it emphasizes effective communication of LCA results.

The handbook is structured to accommodate two main types of LCAs in the space sector, known as Level 1 and Level 2 as shown in figure 3.3 [22]. At Level 1, the focus is on a functional breakdown, covering entire space missions or specific segments such as space, launch, or ground components. At Level 2, a physical breakdown is performed, considering equipment, components, or materials/processes. To achieve these objectives, the initiative adapts the ISO standardized methodology of LCA (ISO 14040 and ISO 14044ES) to provide a common and standardized approach within the space sector. This involves performing dedicated studies to compile space-specific LCA datasets. For a detailed understanding of each step in the LCA process for both Level 1 and Level 2 of a space system, Annex 1 of the ESA Handbook provides a summary of key elements that should be included in each step [22]. Detailed descriptions of all four LCA steps — Goal and Scope, LCI, LCIA and Interpretation — for each level can be found in appendix 7 and **??**.

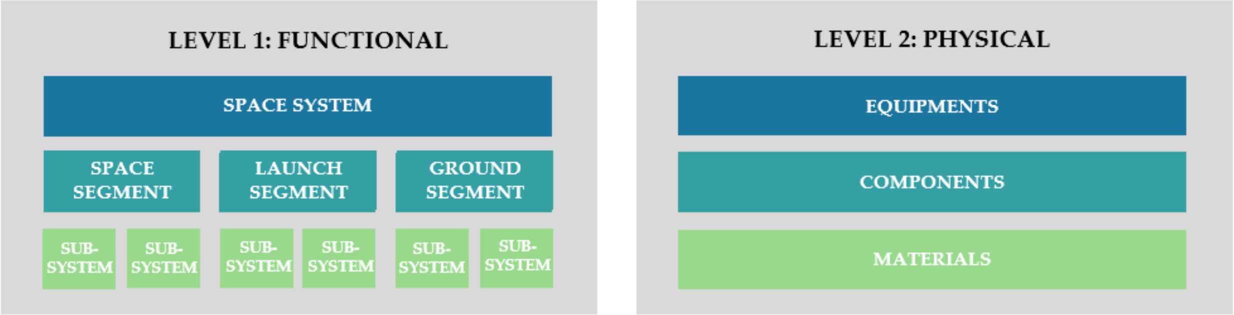


Figure 3.3: Space sector LCA activity breakdown and level definition (adapted from [22])

4 Literature Review Approach

The goal of this literature review is to offer an overview of current research addressing environmental assessment within the space sector. This is achieved through a three-step process: first, identifying effective search terms by analyzing the results yielded by various terms; second, conducting a statistical analysis to discern the evolution and trends of paper topics; and finally, selecting and categorizing papers based on subjects.

4.1 Search Strategy

A three-step methodology was employed for the review. Firstly, a comprehensive search was conducted in databases and conference websites to identify scientific publications addressing LCA in the space sector. Then, the snowballing method was applied, utilizing references from the initially identified documents to broaden the scope of potential publications. Finally, the selection process in the third step focused on documents that actively conducted LCA within the context of space-related activities.

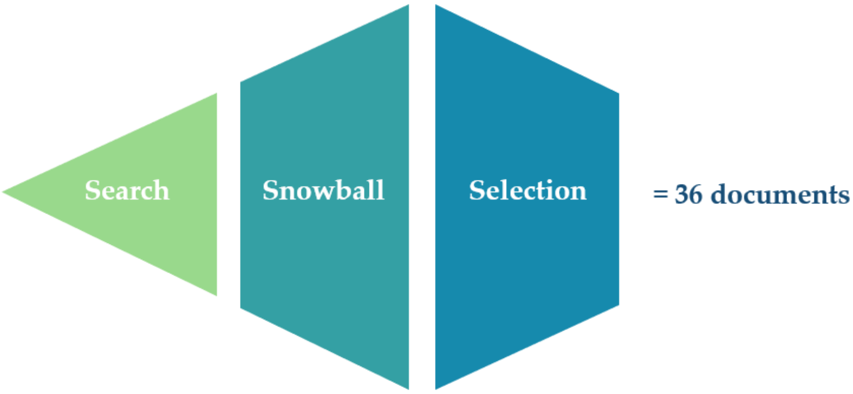


Figure 4.1: Search strategy for the selection of documents

4.1.1 Initial Search Strategy

In this phase, the identification of publications related to LCA in the space sector involves using prominent scientific databases, specifically Scopus and Web of Science. The choice of these databases is grounded in their status as two of the largest academic research databases, encompassing a broad spectrum of disciplines, thus ensuring a multidisciplinary coverage Rahn.26112021. The initial step entails defining research terms crucial for recognizing publications addressing LCA in the space sector. These terms, associated with LCA and the space sector, are compiled, categorized based on frequency and then refined. Subsequently, a comprehensive list of publications is generated by combining terms related to LCA and space, followed by a meticulous sorting process to determine their relevance for this literature review.

4.1.1.1 Databases

Life Cycle assessment related search terms

In order to find the most suitable terms related to LCA, multiple terminologies were searched. Table 4.1 shows the most used search terms.

Table 4.1: Life cycle assessment search terms

Search Term	Scopus	Web of Science	Sum
life cycle	250,142	139,596	389,738
life cycle assessment	36,499	33,642	70,141
LCA	38,551	25,593	64,144
life cycle analysis	19,189	4,415	23,604
life cycle engineering	710	327	1,037

Life cycle has too many hits and is not precise enough to target publications addressing LCA. The term life cycle assessment, together with its abbreviation, is the most successful term and thus, will be applied to this literature search. To extend the search terminology related to LCA, synonyms of this methodology are investigated. Table 4.2 shows the most used terms.

Table 4.2: Life cycle assessment synonyms

Search Term	Scopus	Web of Science	Sum
enviromental impact	240,594	53,954	294,548
environmental sustainability	32,066	14,260	46,326
carbon footprint	28,187	12,067	40,254
environmental assessment	27,829	9,724	37,583
ecodesign	5,329	1,142	6,471

The terms environmental impact, environmental sustainability, carbon footprint and environmental assessment are not the most used terms. However, they are not enough specific to focus on LCA. Therefore, to refine the research, the term ecodesign was selected for his frequent use in the space sector. The final search terms related to LCA are:

Search Term
life cycle assessment OR *LCA* OR *life cycle analysis* OR *ecodesign*
→ 64,536 publications in Scopus (11/2023)

Space related search terms

In order to find the most suitable terms related to space, multiple terminologies were searched. Table 4.3 shows the most used search terms.

Table 4.3: Space search terms

Search Term	Scopus	Web of Science	Sum
Satellite	541,254	307,523	848,777
Space missions	18,691	7,551	26,242
Launcher	13,668	4,809	18,477
Space systems	10,276	2,947	13,223
Space sector	1,236	227	1,463

The most frequent term is satellite, space missions and launcher. The term space sector is also selected since some publications dealing with LCA and space were identified during an upstream research. The final search terms related to space are thus:

Search Term
Satellite OR *space mission* OR *launcher* OR *space sector*
→ 593,702 publications in Scopus (11/2023)

LCA and space search terms

For this literature review, the following search terms are used:

Search Term
(*life cycle assessment* OR *LCA* OR *life cycle analysis* OR *ecodesign*) AND (*satellite* OR *space mission* OR *launcher* OR *space systems*)
→ 196 publications in Scopus (11/2023)

After reviewing and comparing all documents from both Scopus and Web of Science, this search resulted in a total of 196 publications. In order to narrow this number, abstracts of each of these 260 publications were studied. As a result, 215 publications were disregarded because they did not focus on LCA. Many publications contained the abbreviation LCA, which had a different meaning. The remaining number of relevant publications therefore stands at 45.

4.1.1.2 Conferences

In the pursuit of publications addressing LCA in the space sector, a targeted approach involves identifying relevant content presented at conferences with a sustainability focus in the space industry. The selected conferences for this purpose include ESA Clean Days Industry Days, the International Astronautical Conference and the CEAS Conference. To ensure the latest insights and developments are captured, a specific focus is placed on the last seven years, reflecting the rapidly evolving nature of space LCA. This timeframe ensures that the retrieved documents are pertinent, providing an up-to-date perspective on the subject. Following this approach yielded a total of 36 documents that contribute valuable insights to the exploration of LCA in the space sector.

4.1.2 Snowballing

Out of the 80 documents, 44 from databases and 36 from conferences, the snowball method was employed, using the reference lists of publications to uncover additional relevant works. This method, as suggested by Wohlin [42, 17], serves as an alternative approach in systematic literature studies, expending the scope of the results to 84.

4.2 Statistics

The evolution in time of publication regarding LCA in the space sector is shown in figure 1.1. The initial set of LCA studies took place in Europe between 2011 and 2015 [5] and was followed by the release of the ESA Handbook in 2016 and the LCI database for ESA funded projects in 2017. Since then, the number LCA studies published in the space sector has increase over the years. A gap in the year 2019 and 2020 can be observed, which coincide with the absence of the ESA Clean Space Industry Days (ESA CSID) conference. The ESA CSID is a yearly conference, organized since 2016, focused on sustainable space missions that brings together space professionals to discuss advancements in ecodesign, end-of-life management, active debris removal and in-orbit servicing. It serves as a platform for sharing knowledge, presenting developments and fostering collaboration towards a more sustainable European space sector [43].

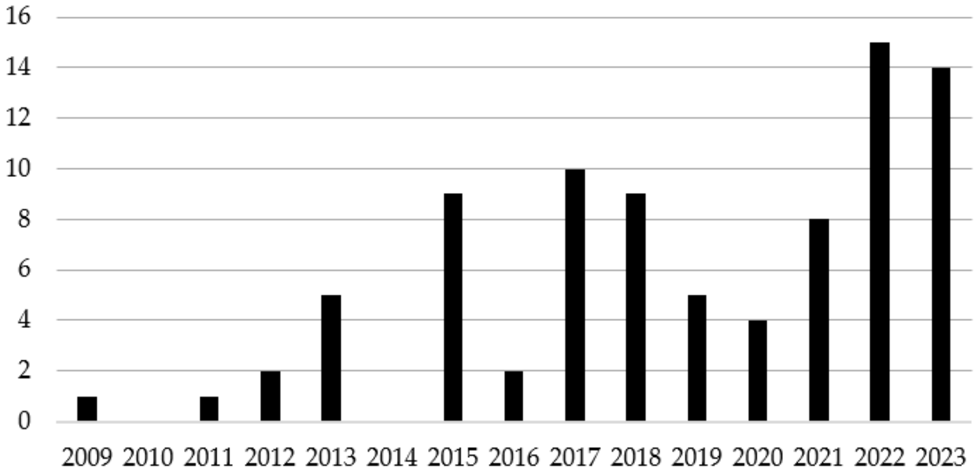


Figure 4.2: Evolution of publications per year

4.3 Selected Documents

Out of the 84 documents collected in the previous part (collection in databases and conference and then snowballing), a final screening within this document list was conducted. A total of 48 documents were deemed out of scope and disregarded. The reason for this was that these papers didn't have a concrete reference to LCA applications or were addressing a limited scope.

Of the 36 documents, 70% are from conference proceedings (25) whereas 30% are journal papers (11). Furthermore, the distribution based on geography indicates that Europe significantly leads in the application of LCA within the space sector [5].

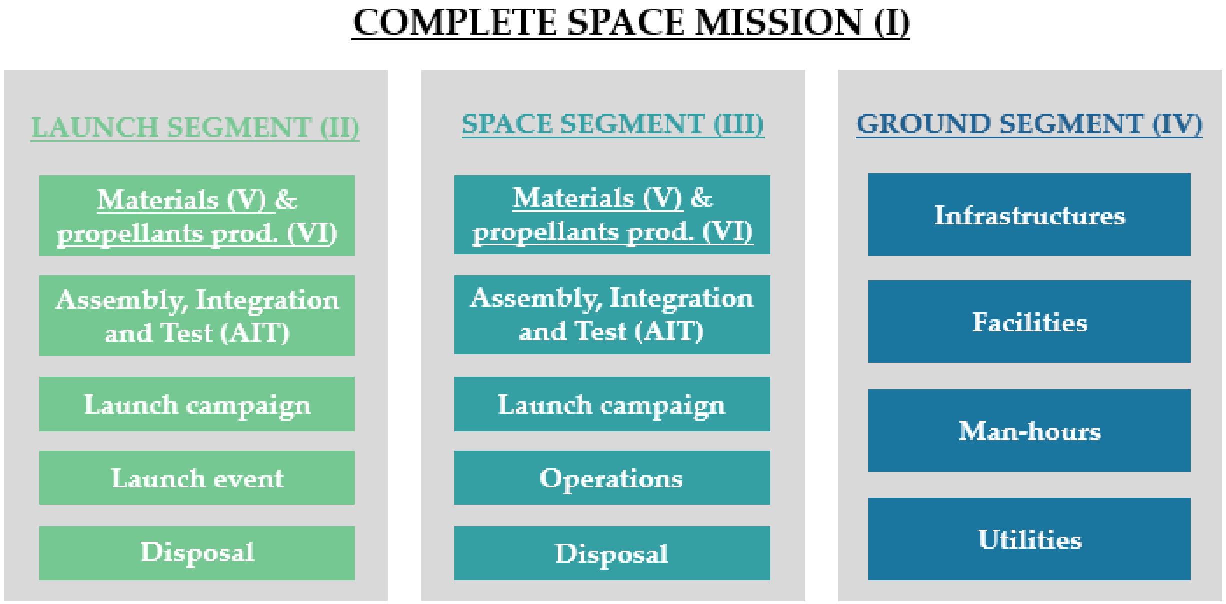


Figure 4.3: Goal and system boundaries of the selected LCA studies with 6 clusters (from [5, 22])

The six clusters from [5], as described in figure 4.3, are also adopted and applied here to guide the identification and classification of the goal and system boundaries for each LCA study, these 36 documents have been categorized accordingly. The six clusters are the following: (I) complete space mission, (II) launch segment, (III) space segment, (IV) ground segment, (V) materials and process, (VI) propellants production. The distribution of the LCA studies documents according to the clusters related to the LCA applications within the space sector is given in the figure 4.4, where more than half the documents represent LCA studies on the complete space mission or on the launch segment. Table 4.4 and 4.5 show the complete list of the selected documents.

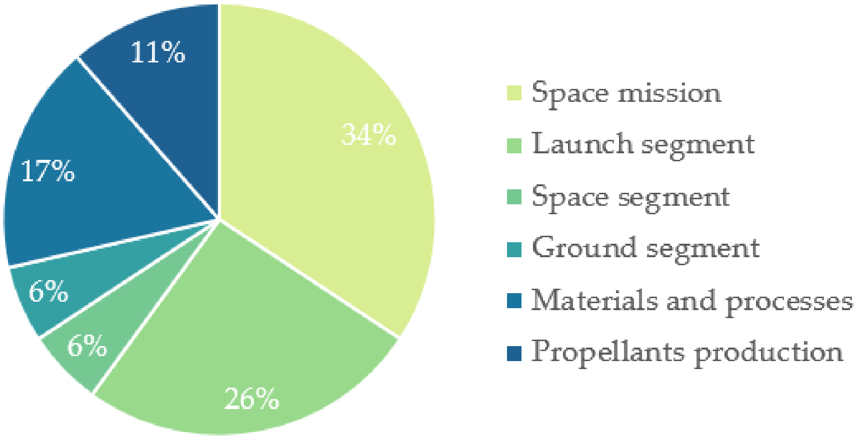


Figure 4.4: Repartition of the LCA studies according to the six clusters

Table 4.4: Selected documents according to their year, type (JP=journal paper, CP=conference proceedings) and clusters (1/2)

Reference	Title	Type	Cluster
Belliers et al. (2022)	Impact of life cycle assessment considerations on launch vehicle design	JP	II
Blondel-Canepari et al. (2023)	Single-Score Methodology for Space LCA	CP	VI
Bouilly et al. (2021)	Comparing alternative materials for optical instrument structural parts	CP	V
Brun-Buisson et al. (2022)	Study in the field of ultra-green launch space transportation systems	CP	II
Cauwe et al. (2022)	Life Cycle Assessment of eco-design options for printed circuit boards and electronic assembly	CP	V
Chanoine (2017)	Environmental impacts of launchers and space missions	CP	I
Colin et al. (2021)	Ground Segment Life Cycle Assessment	CP	IV
De Santis (2021)	Ground Segment Life Cycle Assessment – Methodological and Quantitative	CP	IV
Deroo et al. (2023)	Comparative life cycle sustainability assessment of novel monopropellant systems	CP	VI
Fischer et al. (2022)	A Comprehensive Approach to Life Cycle Assessment of Space Transport Systems	CP	II
Fischer et al. (2023)	Comparison Study on the Environmental Impact of Different Launcher Architectures	JP	II
Gallice et al. (2018)	Environmental impact of the exploitation of the ariane 6 launcher system	CP	II
Gandra et al. (2021)	Development of linear friction welding to add external features to spacecraft and launchers systems	JP	V
Guiliani (2023)	Overview of Life Cycle Assessment and EcoDesign Activities for Large Space Missions at Thales Alenia Space	CP	III
Harris et al. (2019)	Life cycle assessment of proposed space elevator designs	JP	III
Julienne (2023)	Laser beam melting for the manufacturing of rocket engine parts: a study of the environmental impacts	CP	VI
Maury et al. (2017)	Towards the integration of orbital space use in Life Cycle Impact Assessment	JP	I
Maury et al. (2020)	Space debris through the prism of the environmental performance of space systems: the case of Sentinel-3 redesigned mission	JP	I

Table 4.5: Selected documents according to their year, type (JP=journal paper, CP=conference proceedings) and clusters (2/2)

Reference	Title	Type	Cluster
Maury et al. (2019)	Assessing the impact of space debris on orbital resource in life cycle assessment: A proposed method and case study	JP	I
Mio et al. (2022)	A life cycle assessment of alternative materials for a CubeSat manufacturing	CP	V
Miraux et al. (2022)	Ecodesign of a launch service based on a semi reusable minilauncher	CP	II
Orbex (2022)	Ultra-Green Launch and Space Transportation Systems Study	CP	II
Richard-Noca et al. (2018)	EPFL's first steps toward the EcoDesign of the CleanSpace One mission	CP	I
Ross-Wilson et al. (2018)	The Strathclyde Space Systems Database: Life Cycle Sustainability Results of the MÌOS Mission	CP/JP	I
Parsons et al. (2019)	Can citric acid be used as an environmentally friendly alternative to nitric acid passivation for steel? An experimental and Life Cycle Assessment (LCA) study	JP	V
Schabedoth et al. (2021)	Life cycle of propellants Environmental benchmark of current "green" propellants	CP	VI
Thiry et al. (2017)	Lessons learned from the Sentinel 3 LCA and Applications to a GreenSat	CP	I
Tormena et al. (2022)	Environmental Impact of Propellants	CP	VI
Udriot et al. (2013)	Rapid Life Cycle Assessment Software for Future Space Transportation Vehicles' Design	JP	II
Val (2022)	Life Cycle Assessment of the Eurostar Neo Battery Pack	CP	V
Vercalsteren (2018)	Greensat: ecodesign of the proba-v mission	CP	I
Vercalsteren et al. (2023)	Key learnings when applying an iterative LCA approach during the different development phases of a space mission	CP	III
Verkammen (2023)	A consensus-based single-score for life cycle assessment of space missions	CP	III
Wilson et al. (2017)	Integrating life cycle assessment of space systems into the concurrent design process	JP	I
Wilson et al. (2020)	A process-based life cycle sustainability assessment of the space-based solar power concept	JP	I

5 Results

5.1 Goal and Scope

5.1.1 Goal and System Boundaries

Space missions (I) and space segment (III) LCA initiated the Clean Space Initiative with the objective of developing more environmentally friendly space missions. To assess the impacts of their missions, ESA delegated the responsibility of conducting LCAs for the launchers Vega and Ariane 5 ECA/ES, as well as four entire space missions, to other companies [38]. Each of the eight documents performed an LCA covering all stages, from manufacturing to disposal. One study deviates by examining two mission segments rather than the usual four. Specifically, [44] concentrated on the space segment and ground segment. In the case of space segment, in each of the three studies, the system boundaries taken into account were cradle-to-gate (disposal phase is excluded).

Launch segment (II) ESA, with the support of BIO Deloitte in 2011, conducted a study on the European launchers Vega, Soyuz and Ariane 5 ES/ECA [45, 39]. The assessment focused on one launch each from the Kourou launch pad, covering the production and assembly stages of the launcher, launch campaign and launch event. In 2018, and for the first time in the space industry, an LCA study has been conducted during the early development of Ariane6 launcher [46], with the aim of offering a comprehensive environmental profile of the launcher during its initial production phase [5]. Special attention was also given to the assessment of the environmental impacts of microlaunchers and reusable launchers [47, 48].

Ground segment (IV) Ground segments can be classified into five mission families which are the following: science, navigation, earth observation, communications and CubeSat. Furthermore, a ground segment can be divided into four major components (also named building blocks): mission operations center (MOC), science operations center (SOC), data processing center (DPC) and ground station (GS) [49]. De Santis' and Colin's study has been conducted to assess the environmental impacts of these activities. The system boundaries of the study encompass infrastructure and building construction as well as operational phases including transportation phases and facilities.

Materials and process (V) Every document examined specific components, materials or processes for the space applications. Half of the documents used LCA to compare two alternatives materials or processes [50, 51, 52] while the other half focus on identifying hotspots to reduce environmental impact [53, 54, 55]. The system boundaries for each study focused on a cradle to gate scope, which is managed by the manufacturer and therefore by the one conducting the LCA.

Propellants production (VI) Launch system propellants impact the environment throughout their entire life cycle, contributing significantly to pollution during production, transport, storage and most notably, the launch event. The launch event stands out as the only human activity directly causing pollution across all atmospheric layers [56]. The term "green propellants" has been frequently used in the space sector. However, it doesn't necessarily refer to "environmentally friendly propellants" but rather alternative rocket fuels that are less toxic and emit fewer ozone-depleting molecules [57]. The term green propellant in the space industry generally denotes fuels that meet environmental and toxicity standards, but the absence of agreed-upon standards has led to diverse perspectives on what qualifies as green [58]. While most studies have done cradle-to-gate approach, recent study expend it to cradle-to-grave including all stages of the lifecycle of the propellants, i.e. extraction of raw materials, production, transport, loading and launch, as well as the treatment of waste from the production, logistics and fueling stages [59].

5.1.2 Functional Unit

Space mission (I) and space segment (III) Deciding on a functional unit for space missions has been an ongoing discussion in space LCA. Most of the time, each mission is designed for a specific purpose like Earth observation or telecommunications, making it challenging to find a unit for easy comparisons based on the satellite's function [5]. Therefore, the purpose of space mission LCA is not to perform comparisons between different missions but rather to identify the hotspots of the environmental impacts of the mission [22]. The functional unit defined by ESA's Handbook and used in most of the studies dealing with space mission LCA and space segment LCA is "one space mission in fulfilment of the mission's requirements". Out of the 11 documents dealing with LCA for space mission and segment, 9 used this functional unit [60, 5, 61, 44, 62, 63, 64, 65]. For the 2 other documents, the functional unit was not mentioned [66, 67].

Launch segment (II) According to ESA's Handbook, the functional unit for launch segment is suggested as "to place a payload of X tons maximum [in single launch configuration and Y tons maximum in dual launch configuration] into orbit Z". This latter unit is largely used in the 9 documents dealing with the launch segment and enables a comparison between the environmental performance of launchers within the same mission domain [5]. For example, the ESA's contractual requirement for the environmental impact study mentions a comparison between the Ariane 5 and the new Ariane 6 launcher [46].

Ground segment (IV) For both Colin's study [68] and De Santis' study [49] on Ground Segment LCA, the following unit was used: "the fulfilment of requirements of Ground Segment for one year for the following mission types". This is also the one recommended by the ESA's Handbook. In the case of De Santis' study, the mission type was defined as navigation, Earth observation, science, telecommunications or CubeSat.

Materials and process (V) [5] The units used for materials, surface treatment, or processes are usually aligned with engineering and ecodesign perspectives. For materials, the unit can be the weight of materials used, formed, or removed [53]. In surface treatment, the unit can be an area, such as per square meter [52]. For processes like welding, a suitable unit is length.

Propellants production (VI) According to [69], in order to compare two types or propellants for a specific propulsion system [58], the functional unit that should be used is the specific impulse which quantify the efficiency of the propulsion system. The three studies related to LCA of propellants have not been using this functional unit but “one monopropellant system in fulfilment of the propulsion system requirements set for a case study of a 150kg Earth observation spacecraft” [70] or have not been specified.

5.2 Life Cycle Inventory

5.2.1 Primary Data

In collecting primary data for space LCAs, studies supported by industrial stakeholders play a crucial role, particularly in ESA-funded studies. System integrators like Thales Alenia Space [61], Deimos for ground station-related studies [49] and QinetiQ [71] are actively involved in gathering specific data through questionnaires, with a focus on various space missions.

For European launchers, Chanoine’s [72] reveal that 40 companies were contacted and 15 participated in data collection, covering all aspects of the launcher, including consumptions and emissions. This process involved two iterations, conducted in 2018 and 2020, providing valuable insights into the space industry [46, 73].

Iterative data collection, as highlighted by [46], involves questionnaires filled by key stakeholders, as mentioned before, such as Thales Alenia Space, Deimos and QinetiQ. Deloitte’s approach is applied to the ground segment, including operations and maintenance data for ground stations like Kiruna (Sweden) and Cebreros (Spain), covering electricity, fuel, water, waste and more [68].

Data is sourced both internally [74, 51, 52, 67] and externally. External sources originate primarily from three main channels:

- Primes, subcontractors [65, 51] or suppliers [51, 53].
- Existing LCA models like Ariane6 models or Themis study (Brun-Buisson and Guillemin 2022), ground segment LCA [68], European Union (EU) preparatory LCA studies [68] and Product Environmental Profiles (PEP) [68].
- Existing databases:
  - Space related: ESA LCA database [74, 49, 73, 46, 65, 5, 53, 59, 75, 71] encompassing more than 1600 entries [76], Strathclyde Space Systems Database (SSSD) [77, 70, 78], NASA Concept Development and Evaluation Program (CDEP) reference system report and preliminary materials assessment report [66].
  - Non-space related: EPFL Sustainable Campus [67] and European Life Cycle Database [62].

However, the space sector faces challenges due to the low availability of representative data, necessitating an intensive data collection process [5]. Complicated systems, like launches and complete space missions, involve numerous companies, highlighting the importance of meticulous data gathering [5]. The unique requirements of the space sector result in scarce literature on processes and precursors, introducing uncertainties in data collection [79]. The confidential synthesis routes for materials contribute to uncertainties, primarily concerning reactants, reaction yields and the use of solvents or metal catalysts [5]. Additionally, the highly variable Technology Readiness Levels (TRL) pose challenges in collecting data for potential alternatives at an industrial scale [79, 5].

5.2.2 Secondary Data

Conventional commercial databases are used in almost all the studies for secondary data [5]. Among these databases, the most well-known and widely used is ecoinvent [77, 46, 53, 48, 52, 67, 62]. Another database used for secondary data is the ELCD [77].

However, these databases encounter difficulties in accurately representing the specificities of the space sector [5]. This is where the database developed by the ESA plays an important role. It was first developed in 2016 to compile space specific materials, processes, propellants and equipment and was based on literature review and public information. In 2019, the database was aligned and datasets coming from ESA contracts and missions conducted between 2016 and 2019 were integrated [80]. In addition, the SSSD was designed to complement this database. Its primary goal is to enhance space LCA methodology and fill the gap in process-based life cycle databases for space systems [81]. Finally, literature and scientific publications have been consulted for secondary data as well [51, 52, 55].

5.3 Life Cycle Inventory Analysis

In the context of space LCA, a predominant reliance on multicriteria analyses is evident across various studies, with ESA-funded studies adopting indicators based on International reference Life Cycle Data system (ILCD) 2011 methods as outlined in the ESA Handbook [22]. ESA considers the following midpoint indicators as a priority [50]: climate change, ozone depletion, human toxicity, freshwater ecotoxicity and resource use minerals metals. Of the 36 examined documents, 14 extended beyond these 5 indicators.

Certain studies stand out for their distinct focuses. For example, only one study focused on a single midpoint indicator that is climate change [77]. Further, only two studies integrate both midpoint and endpoint categories [57, 51]. This could be explained by the fact that the ESA handbook emphasizes midpoint indicators rather than endpoint indicators, arguing, among other reasons, that they are more robust, that most impact categories have an LCIA method recommended by Joint Research Center (JRC) and that they are a requirement in existing environmental communication programs [22].

Addressing the unique demands of the space sector, Maury's work introduces specific midpoint indicators, such as the degradative use of orbital resources [5], later incorporated by Udriot et al. Udriot's study further integrates a second "space indicator" encompassing layered atmospheric launch emissions [75]. This expanded LCIA framework is designed to overcome methodological limitations, particularly in addressing disposal and end-of-life considerations highlighted by [72].

In four studies, a single score emerges as a key analytical tool, achieved by assigning weights to individual midpoint indicators. This approach, undertaken by [57, 72, 65, 61, 82], facilitates direct comparisons and aids decision-making, especially in the design phase, as emphasized by [75]. Blondel's study [57] grouped and weighted 17 midpoint indicators into five endpoint categories, subsequently consolidated into a single score through a comprehensive questionnaire process among space LCA experts involving over 60 responses. Additionally, studies exploring single scores across Environmental Life Cycle Assessment (E-LCA), S-LCA and LCC dimensions, as illustrated by [77, 70, 62], broaden the scope by incorporating new impact categories such as social performance and costs.

Finally, to enhance the analysis, ESA recommends the inclusion of flow indicators ([22], described in Table 2.2) from the ecoinvent database, covering cumulative energy demand and water consumption. These flow indicators also address substances regulated by the REACH legislation and the EU critical raw material list.

5.4 Results and Interpretation

Space mission (I) and space segment (III) Throughout the lifecycle of a space mission, environmental impacts vary across different phases. In the feasibility and preliminary definition (Phase A+B): noteworthy contributors include office work and business travel [63]. This phase has the biggest contribution for six out of seventeen impact categories (table 2.1), that are climate change, air acidification, particulate matter, gross water consumption, abiotic resource depletion and primary energy consumption [65]. The primary sources of impact in this phase are identified as energy and water consumption [65].

In the detailed definition and qualification/production (Phase C+D): main contributors on mineral resource depletion in this phase due to the use of scarce materials [63]. Office work, driven by the energy consumption of design buildings and business travel, plays a substantial role [63]. Significant contributors in this phase include raw material extraction, production, testing and transport of spacecraft models [63, 61]. Predominance of this phase is observed in nine out of seventeen impact categories [65].

In the launcher-related activities (Phase E1b): this phase emerges as the main contributor to various environmental impacts, encompassing material extraction, dry-mass and propellant production, launch campaign and launch event [63, 61, 71].

In the use phase (Phase E2): this phase covers ground facilities during the routine phase, including ground stations, control centers and payload data handling stations. The main contributor to freshwater eutrophication potential is the electricity consumption of control centers (in the case of Earth Observation missions) or ground stations for broadcast (in the case of communication missions) [63]. Significant impacts on toxicity indicators for both missions are attributed to the fossil share of electricity consumption [63]. The end-of-life impact is noteworthy during this phase [63].

In addition, [5] compared two scenarios in the context of the GreenSat project that aims to replace hydrazine propellant in Sentinel-3B. The study showed that the baseline scenario, involving 120 kg of hydrazine, has a 2.3 times higher impact compared to the GreenSat scenario, which uses 165 kg of LMP-103s. In the same study, it was shown that 87% of the impact in the GreenSat scenario is attributed to the utilization phase, primarily due to a shorter post-mission disposal lifetime. Finally, according to LCSA conducted by [66], costs were identified as the most critical sustainability dimension for the silicon option, while the environment was most critical for the gallium arsenide option [5]. Social impacts were determined to be insignificant, but specific Sustainable Development Goals (SDG) were adversely impacted, mainly related to labor practices and economic inequalities.

Launch segment (II) Stage production (dry mass production) and the production of propellants and consumables stand out as the most impactful steps in terms of environmental considerations for both Ariane 5 and Vega, with the exception of ozone depletion, primarily caused by the launch event and boat fuel consumption during.

In assessing the major contributors to climate change, studies on Ariane 5 [72], Ariane 6 [46] and Vega [76] consistently highlight the significance of stage production, assembly stage and propellant manufacturing. The environmental impacts in these areas are primarily attributed to the consumption of electricity and heat. The transportation stage, particularly maritime transport, emerges as a noteworthy contributor to various environmental impacts, including climate change, terrestrial acidification, marine eutrophication and photochemical oxidation. The structure of the boosters and the main cryogenic stage in stage production plays a pivotal role in impacting metal depletion, human toxicity and freshwater ecotoxicity, primarily due to the use of stainless steel [76]. Ozone depletion, on the other hand, is predominantly influenced by the launch event, with emissions of alumina and chlorine identified as key contributors [76]. A significant insight into the climate change impact reveals that solid propellant, constituting 87% of the lift-off mass, plays a crucial role in influencing this environmental aspect. The detailed examination of these stages and processes helps to identify specific areas that significantly contribute to the overall environmental footprint of space launch systems

Ground segment (IV) The most comprehensive study on the ground segment is conducted by De Santis and Colin [68, 49]. According to Colin's findings focused on Kiruna-1, the largest contributor to its environmental footprint is the infrastructure, summing up to 50%. Visitor and business travels contribute around 25% to climate change impacts and the extraction of metals for electronic circuits, stainless steel in the antenna and lead-acid batteries are major contributors to toxicity and mineral resource depletion. Cables account for 11% of impacts on mineral resource depletion.

Differences between stations are linked to antenna size and weight, with Cebreros impacted more due to a heavier antenna. Mineral resource depletion and toxicity are influenced by batteries, cables and electronic equipment. Green electricity certificates offset the climate impact of electricity consumption, but travel-related emissions from visitors and staff remain notable.

Materials and process (V) [50] conducted a comparison of alternative materials for optical structural parts, revealing that Aluminium-Silicon (AlSi), in contrast to Silicon-Carbide (SiC), had a higher overall environmental impact. The study identified specific impacts of SiC, including blank machining which important amount of materials, sintering at 2000°C, isostatic pressing outside France and final machining with diamond. Potential improvements for SiC involve transitioning to less impactful energy sources and increasing the Buy-to-Fly ratio, which is the weight ratio between the raw material sed for a part and the weight of the finished part. For AlSi, impacts stem from raw material extraction, non-recyclability, additional steps like surface treatment and process steps with electricity mix from Germany and the Netherlands. Improvements for AlSi focus on managing raw material impact, specifying recycled aluminum use and certification.

In [54], an environmental assessment compared a reference Printed Boarded Assembly (PBA) with eco-design options, such as eliminating reflow SnPb finish, standardizing plastic packages and solder mask use and adopting lead-free solder. Parametric LCI approaches significantly improved quantification of the reference PBA's environmental impact. Eliminating certain processes and using plastic packages reduced overall impacts, but lead-free solder assembly and solder mask use increased environmental impact.

[83] environmental assessment of alternative linear friction welding manufacturing routes demonstrated potential reductions in raw material usage, material waste and environmental impact for satellite fuel and cryogenic tanks.

Laser Beam Melting (LBM) metal additive manufacturing is frequently regarded as one of the more environmentally friendly processes. When comparing equal masses, LBM manufacturing in aluminum or stainless steel is found to have a lower environmental impact than in titanium or inconel [51]. Across all materials assessed, the primary contributors to the environmental impact of the LBM process are the argon gas and the powder used. However, when incorporated into a product LCA, no broad generalizations can be drawn regarding the relative environmental impact of the LBM process compared to casting.

[53] conducted a comparison between aluminum and PolyEther-Ether-Ketone (PEEK) for CubeSat manufacturing. The results indicated that the laser sintering process for PEEK CubeSat requires more energy compared to metalworking for aluminum. This leads to higher greenhouse gas emissions and a greater impact on climate change. Additionally, impacts related to raw material extraction (ecotoxicity, eutrophication, resource depletion) were higher for aluminum-based CubeSats. In conclusion, [53] found that, as a general preliminary trend, an aluminum CubeSat exhibits worse environmental performance than one made from PEEK. [53] concluded that no single material excels across all impact categories. Consequently, a trade-off based on Key Performance Indicators (KPI) and specific needs would be necessary.

Both [84, 52] conducted studies on citric acid passivation, recently proposed as an environmentally friendly alternative to stainless steel passivation processes in various industrial sectors, including aerospace. The findings from both studies suggest that citric acid passivation is generally more favorable than nitric acid passivation, especially if electricity consumption and acid quantities in both treatments are minimized through the reuse of the passivation bath.

In her study on the Eurostar neo battery, Val revealed significant findings. Cells emerged as the major contributor, accounting for 50% or more of the relative impact across various categories.

Within cells, the cathode, driven by nickel and lithium, stood out with the highest environmental impact, followed by the anode featuring foil copper and silicon. Examining other module components, contributions from module welding and protection/insulation were noteworthy. Alternative scenarios were explored, with the fourth scenario proving the most promising. This combination involves cells supplied by a French supplier, module manufacturing using renewable energy sources (such as wind farms) and a 50% reduction in gold on electronic parts (harness, electronic board). In the assessment of , Val found they constitute approximately 15 wt% of the battery pack. These insights provide valuable considerations for sustainable battery development.

Propellants production (VI) Reducing the mass and consumption of propellants in launch vehicles is crucial for environmental impact [5]. Propellant mass constitutes a significant portion, reaching 87% of the lift-off mass for Ariane 5 ESA [46]. About two-thirds are released in the stratosphere, impacting climate change and ozone depletion. All cycle phases indirectly affect the troposphere and emissions during launch contribute to air acidification and human toxicity.

Propellant production is a major contributor to the launcher's environmental profile, considering energy consumption and materials/chemicals used. Raw material impacts, such as hydrocarbon extraction affecting climate change and bio-based propellant influencing water and land use,require further research. Production processes for solid, liquid and bio propellants vary, but all are requiring significant energy consumption [56].

Transporting solid and liquid propellants adds to energy consumption, impacting climate change. On one hand, cryogenic propellants, stored at low temperatures, affect atmospheric emissions or energy consumption for cooling. On the other hand, solid propellants, stored at atmospheric temperature, require a humidity-controlled environment, also leading to consumption of energy [56].

Schabedoth favors LCH4 and APCP propellants for climate change, while RP1 and LCH4 are preferred for ozone depletion [85]. However, determining truly "green" propellants remains challenging without a comprehensive LCA [57], which should consider the complete low atmospheric impact [56].

6 Discussion and Perspectives

The escalating public awareness of the pressing need to address the environmental impacts of human activities has led to a tightening of environmental legislation and increased public scrutiny [63]. The implementation of the Green Deal has notably expanded the EU's regulatory framework, with ongoing revisions to the RoHs directive and REACH regulations aligning with the EU's Chemical Strategy for Sustainability [86]. Concurrently, initiatives like the Sustainable Product Initiative and acts addressing the European Circular Economy Plan pose challenges, increasing the risk of obsolescence for qualified space materials, processes and technologies within the European market. Notably, EU Space law is evolving to manage space debris effectively.

Recognizing LCA as a science-based methodology is instrumental in enhancing environmental reporting for corporate social responsibility, sustainability management practices and compliance with regulatory requirements. LCA has become an integral part of a continuous loop encompassing framework development, its application in projects, subsequent research and development efforts and the adoption of greener technologies, ultimately culminating in ecodesign systems.

In recent years, emphasis has been placed on harmonizing LCA approaches and practices within the European space sector. The overarching objective was to establish a unified framework for use by national space agencies and industries in spacecraft design [5]. This Section provides an overview of the current status of LCA in the space sector, delineating each of the four key steps. Then, it outlines the challenges and opportunities in this domain.

6.1 Current Status of Life Cycle Assessment and its Suitability for Space Application

Goal and scope In light of the space industry's innovation-driven shift, there is a growing need for a comprehensive sustainability assessment. The complexity of comparing environmental footprints among conventional, Earth/space hybrid and stand-alone space systems underscores the relevance of LCA as the most suitable tool for this task [35]. As the space sector extends beyond Earth, there is a call for future LCA studies to consider outer space exploration and its associated environmental impacts, though limited work has been undertaken in this direction. Nevertheless, the challenge lies in setting boundaries, as the system expands beyond Earth and while including the entire universe within the current LCA framework is impractical, careful consideration is needed in defining appropriate boundaries.

LCI In the space industry, involving companies is crucial for strong environmental assessments using LCA. However, there's a challenge because there aren't many scientific articles on this topic. Collecting data is also tough due to complex supply chains and confidentiality in the space sector [5].

ESA started improving its LCA database in 2016, aiming to understand the environmental impact of space materials, propellants and more. With over 1600 entries, this database was created by researching literature and public information, making it shareable with ESA partners. ESA continued refining the database in 2019, combining datasets from ESA contracts and missions. While there's progress, ongoing efforts are needed [76, 44] to make data collection more effective and address gaps. [63] also points out that there's still room for improvement in environmental datasets.

In parallel, the ESA Handbook offers helpful practices, like a mass-based cut-off rule and a focus on critical materials. Maury et al. recommends specific steps for collecting data about the end-of-life stage and recycling. These insights guide the ongoing journey of improving LCA in the ever-changing world of space exploration.

LCIA Identifying environmental hotspots involves comparing the significant impacts of a given category to a benchmark or other categories [37]. For ESA, environmental hotspots in space missions were found by analyzing average results across missions, with key categories being climate change, aquatic toxicity, human toxicity, resource depletion and ozone depletion [87].

Space missions pose challenges for LCA due to their unique impact across the atmosphere and beyond natural ecosystems [56]. Addressing gaps, new impact categories with specific reference units are proposed by Maury and Udriot, using "space-specific" indicators [35].

To aid decision-making, a single score, adapted to space priorities, was assessed alongside multi-criteria results [57]. Significant impacts, such as atmospheric effects during launch, climate change and chemical toxicity, are emphasized [5].

Considering sustainability, space debris, end-of-life factors and atmospheric re-entry are crucial [5]. The ESA Clean Space Initiative suggests incorporating social and economic aspects into life cycle considerations, introducing them as new impact categories in the future [37].

Results Improving results in LCA requires an iterative, step-by-step approach. ESA is actively applying LCA in projects, with ongoing iterations for initiatives like Copernicus and Galileo [87]. Design choices heavily influence environmental impacts, emphasizing the need to consider these impacts early in the design process for effective mitigation. Continual assessment of environmental performance during mission design guides choices toward more eco-friendly solutions. Furthermore, in LCSA, discussions are underway about incorporating social and economic aspects as impact categories or having separate scores for each aspect: environmental, economic and social [60, 70]. Opportunities for LCA implementation and development in the space industry are presented by tools and methodologies developed in Europe, as highlighted by [82, 50, 88, 75].

6.2 Challenges and Opportunities for the Use of Life Cycle Assessment

In the context of space-related activities, applying LCA principles encounters a spectrum of challenges. Determining the appropriate system boundaries and functional unit for LCA is intricate. he complexities of data management in LCA, including issues of access, confidentiality and data reliability, were thoroughly explored as part of the ongoing challenges. Assessing the environmental impact of testing activities, analyzing the ecological footprint of space infrastructure and evaluating the consequences of research and development activities underscored the need for a balanced approach. Additionally, understanding the environmental impact of office-related tasks and studying the effects of spacecraft demises on the Earth's atmosphere present significant considerations. Investigating the impact of launch events on the Earth's atmosphere, exploring the ecological implications on the deep sea and addressing the challenges associated with space debris further contribute to the intricacies of implementing LCA in the space sector. These challenges collectively show the need for comprehensive and nuanced approaches to sustainability in the use of space.

The European tools and methodologies [82, 50, 88, 75] developed in recent years offer a significant opportunity for implementing and advancing the use of LCA within the industry. These tools facilitate the identification of environmental hotspots along a company's supply chain, enhancing knowledge of upstream and downstream activities. LCA, when applied to facility management, serves as a powerful tool for mapping utility flows (e.g., electricity, water, waste) and identifying areas for improvement, following a Lean and Green approach. Furthermore, in the space industry, LCA serves as a proactive process to anticipate future risks arising from public concerns and legislation. Notably, it addresses current environmental issues such as plastic marine debris. Although the LCA method has challenges at lower TRL, incorporating LCA during the early design stage shows potential for making space systems more sustainable. This early inclusion of environmental performance criteria fosters a rethinking of design practices toward more efficient systems.

7 Conclusion

In conclusion, despite challenges in applying LCA to the space sector, the opportunities it offers for comprehensive sustainability assessments, early integration in design phases and harmonization of practices are crucial for advancing environmental responsibility in space exploration. As the space industry evolves, addressing these challenges and capitalizing on opportunities becomes essential to promote sustainable practices in space activities.

This paper examines the current use of environmental LCA in the space sector, revealing a lack of existing peer-reviewed literature. The majority of LCA work in the space sector is predominantly from Europe, particularly the ESA within its Clean Space initiative, contributing to the emergence of a common LCA framework in Europe. Despite the limited number of publications, there has been a significant increase in their quantity. The reviewed LCA case studies exhibit diverse goal and scope definitions, ranging from large-scale systems like launch segments and space missions to space-specific materials or processes. The application of LCA in the space sector faces challenges, notably in completing the LCI phase, where foreground data collection is crucial and currently challenging. Establishing a space-specific database for background data, addressing the unique properties of materials and chemicals used, is imperative and has been initiated at the European level by the ESA through the space LCI database. The review suggests the need for future research to enhance the application of LCA and life cycle management at the industrial level, assessing the environmental performance of space missions. This implementation could support coherent ecodesign actions across the entire value chains of space systems. However, methodological limitations persist in the LCIA phase, with ozone-depletion-related impacts and issues arising in the orbital environment due to space traffic management and space debris proliferation being crucial concerns that demand integration into LCA studies for a more sustainable design of space systems

Appendix A: Attributional VS Consequential LCA

	Attributional	Consequential
Objectives	Evaluation of the environmental performance of a system within a specific time frame, considering existing conditions and without any changes or interventions	Assessment of the environmental consequences of a change implemented in a system over a time period and at a given time horizon
Goal	Reporting, benchmarking, environmental communication (labelling)	Support decision making, environmental communication, benchmarking
Functional unit	Virtual reference unit (e.g. 1 electric vehicle) at a given time horizon (e.g. 2020).	Actual magnitude of the change (ex. additional 500'000 electric vehicles), over a time period (e.g. 10 years) and at a given time horizon (e.g. 2010-2020)
Scope	Include all the processes affected by the change, even if they are not directly or indirectly required (solicited) by the FU, i.e. are linked to the studied system (product, service, socio-economic system) by a technological cause-effect chain. The processes not affected by the change, even if they are solicited by the FU, are not included	Include all the processes linked to the studied system (product, service, socio-economic system) by a technological cause-effect chain.
Type of inventory data	The datasets reflect the average technological interactions between the inventory processes. These are average data at a given time horizon	The datasets reflect technological and market interactions between the inventory processes following the change, i.e. are marginal data (eventually average marginal data)
Inventory data sources	Average data specifically for the studied product. LCI databases for the average background data	Datasets to be built ad hoc depending on the market information.
Types of LCIA	All	All
Comparability between LCA studies	Mandatory	Not strictly mandatory as the C-LCA study is dependent on the socioeconomic context and modelling approach adopted. Prospective scenarios for a same study should be comparable as they are considering the same socio-economic context. However, two independent studies carried out to address the same question are probably not comparable.
Reliability of results	Uncertainty and sensitivity analyses are mandatory (also through prospective scenarios). The reliability depends on the modelling approach chosen.	Uncertainty and sensitivity analyses are mandatory. The reliability mainly depends on the inventory data quality (see decision tree).

Appendix B: 4 LCA Steps for Level 1 of a Space System

		Space mission	Space segment	Launch segment	Ground segment
Goal and Scope	**Goal**	Assess in a quantitative and objective manner the environmental impacts over its entire lifecycle. The mission under study must be specified			
	Scope	Encompasses a mission description, including the employed launcher and defines the model philosophy. This philosophy delineates the core principles that steer the formulation of the LCA model			
	Functional unit	One space mission in fulfillment of its requirements	One space mission in fulfillment of its requirements	One launch of [name of the launch	To fulfil the ground segment requirements of the specification of the mission in study
	System boundaries	See Appendix D	See Appendix D (space segment and infrastructures)	See Appendix D (launch segment and infrastructures)	See Appendix D (ground segment and infrastructures)
	Impact categories	Impact indicators at midpoint level are considered (Table 2.1). Additional parameters, i.e. flow indicators (table 2.2), are also considered as well as a list of materials identified by EU as CRM and substances included in REACH is recommended			
LCI	**Data**	Rules apply for each type of activity involved in the life cycle			
	Cut-off criteria	Material/sub-assembly that meets these requirements can before excluded: (1) Less than 5% of total mass of considered component (2) No data available (3) No particularly high environmental or health risk (4) Not included in REACH or CRM}			
	Data quality	For foreground processes, specific data need to be used, or if not available then generic data. For background data, generic data or proxies need to be used.			
	Data collection	Specific and generic data are collected when available. Otherwise, generic LCI datasets are used from either industrial federations or generic databases (i.e. ecoinvent)			
	Multifunctionnality	When it is necessary to allocate the inputs and outputs of a process to several co-products, the mass criteria is used. Concerning the end-of-life process, no environmental benefit of recycling or energy recovery can be allocated to the system under study: (1) Impacts of transport to waste management plan and impacts of incineration and landfill are accounted for (2) For material recycling, the cut-off at recycling method can be used}			
LCIA		The inventory flow is classified and characterized using ILCD classification data and characterization factors			
Interpretation		The interpretation of result includes: (1) Assessment of data quality (2) Identification of environmental hotspots (3) Uncertainty (4) Conclusions; recommendations; limitations and improvement potential			

Appendix C: 4 LCA Steps for Level 2 of a Space System

			Equipment	Material	Process
Goal and scope	**Functional unit**		One piece/kg of equipment X at the output gate	One kg of material X at the output gate	Processing of one unite (kg/m2/m3/etc.) of material X
	System boundaries	**Inclusions**	Upstream activities: extraction and transport of raw materials, production and transport of base materials. Core activities: production and transport of auxilaries and utilities, manufacturing processes of material, testing and waste treatment (water and solid)	Upstream activities: extraction and transport of raw materials. Core activities: production and transport of auxilaries and utilities, manufacturing processes of material, testing and waste treatment (water and solid)	Core activities: production and transport of auxilaries and utilities, manufacturing processes of material and waste treatment (water and solid)
		Infrastructures	The infrastructures are included in the assessment but accounted for as separated LCI		
		Exclusions	R&D and design activities as well as supporting activities like administrative activities or finance are excluded from the system boundaries		
	Impact categories		Impact indicators at midpoint level are considered (table 2.1). Additional parameters, i.e. flow indicators (table 2.2) are also considered as well as a list of materials identified by EU as CRM and substances included in REACH is recommended		
LCI	**Data**		For upstream activities, specific data are used and for core activities, either specific or generic data depending on the type of processes. If generic LCI datasets are used, they are sought in priority from either industrial federations or generic databases (i.e. ecoinvent		
	Cut-off criteria		Material/sub-assembly that meets these requirements can bforee excluded: (1) Less than 5% of total mass of considered component (2) No data available (3) No particularly high environmental or health risk (4) Not included in REACH or CRM		
	Data quality		For foreground processes, specific data need to be used, or if not available then generic data. For background data, generic data or proxies need to be used		
	Multifunctionnality		When it is necessary to allocate the inputs and outputs of a process to several co-products, the mass criteria is used. Concerning the end-of-life process, no environmental benefit of recycling or energy recovery can be allocated to the system under study: (1) Impacts of transport to waste management plan and impacts of incineration and landfill are accounted for (2) For material recycling, the cut-off at recycling method can be used		
LCIA			The inventory flow is classified and characterized using ILCD classification data and characterization factors		
Interpretation			The interpretation of result includes: (1) Assessment of data quality (2) Identification of environmental hotspots (3) Uncertainty (4) Conclusions, recommendations, limitations and improvement potential		

Appendix D: Systems Boundaries of a Space System

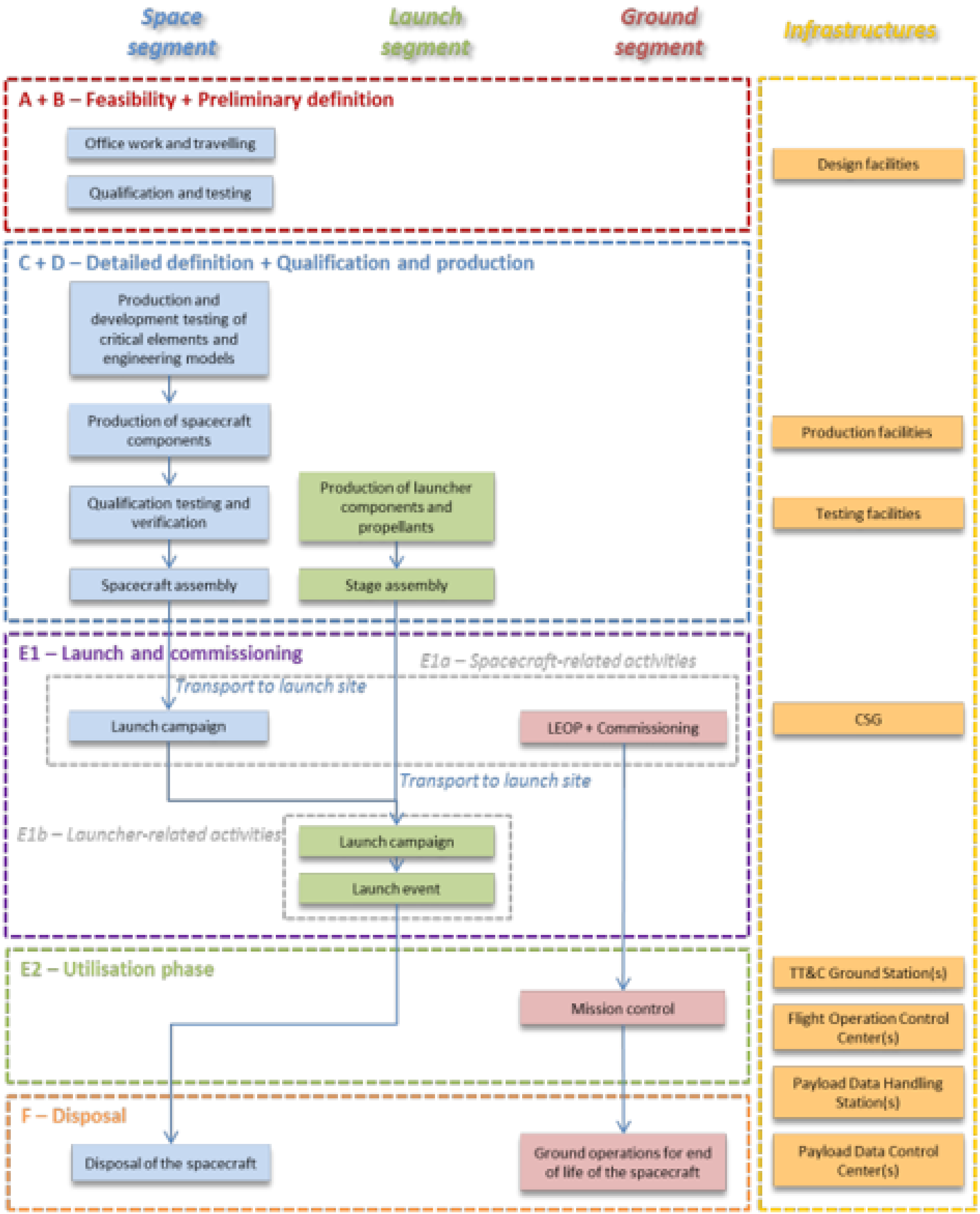


Figure 7.1: Systems Boundaries of a Space System (from [22])

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