Space Life Cycle Assessment: A Risk or Opportunity for the USA?

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Abstract

Life Cycle Assessment (LCA) is a standardized method of analysis which is used to scientifically quantify environmental impacts associated with products, processes, or services over their entire lifetime. Within the European space sector, the application and perceived importance of LCA has exponentially increased in recent years to the point that it is beginning to become entwined with the procurement process. As such, it is highly probable the technique will become a common element of space mission design within Europe before the end of the decade. In comparison, very little work on space LCA has been conducted within the United States of America (USA), meaning the country is beginning to lag behind others in its ability to account for the life cycle environmental impacts of its space operations. This could become a serious problem for United States (U.S.) original equipment manufacturers (OEMs) and suppliers in the near-term future due to misalignment or non-compliance with European procurement policies, with the potential to cause widespread supply chain disruption. Therefore, this work examines the extent to which the USA has fallen behind Europe on LCA of space assets and the risk this poses. However, the identified benefits of space LCA highlight the method could also act as an indispensable mechanism to further business success within the U.S. space sector beyond solely policy compliance. As such, a set of recommendations are outlined to encourage an intensification of research and development (R&D) on the concept within the U.S. space sector as a foundational principle to a sustainable global space economy.

Keywords: Life Cycle Assessment, United States, space missions, supply chain, risk management, environmental impacts

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Evaluación del ciclo de vida espacial: ¿riesgo u oportunidad para EE. UU.?

Resumen

La evaluación del ciclo de vida (LCA) es un método de análisis estandarizado que se utiliza para cuantificar científicamente los impactos ambientales asociados con productos, procesos o servicios durante toda su vida útil. Dentro del sector espacial europeo, la aplicación y la importancia percibida de LCA ha aumentado exponencialmente en los últimos años hasta el punto de que está comenzando a entrelazarse con el proceso de contratación. Como tal, es muy probable que la técnica se convierta en un elemento común del diseño de misiones espaciales en Europa antes de que finalice la década. En comparación, se ha realizado muy poco trabajo sobre LCA espacial dentro de los Estados Unidos de América (EE. UU.), lo que significa que el país está comenzando a quedarse atrás con respecto a otros en su capacidad para dar cuenta de los impactos ambientales del ciclo de vida de sus operaciones espaciales. Esto podría convertirse en un problema grave para los fabricantes de equipos originales (OEM) y proveedores de los Estados Unidos (EE. UU.) en un futuro cercano debido a la desalineación o el incumplimiento de las políticas de adquisición europeas, con el potencial de causar una interrupción generalizada de la cadena de suministro. Por lo tanto, este trabajo examina hasta qué punto los EE. UU. se han quedado atrás de Europa en LCA de activos espaciales y el riesgo que esto representa. Sin embargo, los beneficios identificados del LCA espacial resaltan que el método también podría actuar como un mecanismo indispensable para promover el éxito comercial dentro del sector espacial de los EE. UU. más allá del cumplimiento de las políticas. Como tal, se esboza un conjunto de recomendaciones para alentar una intensificación de la investigación y el desarrollo (I+D) sobre el concepto dentro del sector espacial de los EE. UU. como un principio fundamental para una economía espacial global sostenible.

Palabras clave: Evaluación del ciclo de vida, Estados Unidos, misiones espaciales, cadena de suministro, gestión de riesgos, impactos ambientales

空间生命周期评估：美国的风险还是机遇？

摘要

生命周期评估（LCA）是一种标准化分析方法，用于科学量化与整个生命周期内的产品、过程或服务相关的环境影响。在欧洲太空部门，LCA的应用和感知重要性近年来呈指数级增长，以至于其开始与采购过程交织在一起。照此，该技术极有可能在2030年之前成为欧洲太空任务设计的共同元素。相比之下，美利坚合众国（美国）在空间LCA方面开展的研究很少，这意味着该国在其空间操作的生命周期环境影响的解释能力方面开始落后于其他国家。由于与欧洲采购政策不一致或不合规，这可能在短期内成为美国原始设备制造商（OEM）和供应商的一个严重问题，并有可能导致广泛的供应链中断。因此，本文分析了美国在太空资产 LCA方面落后于欧洲的程度以及由此带来的风险。不过，已识别的空间LCA的优势强调了此法还能作为一种不可或缺的机制，以在美国空间部门内进一步取得商业成功，而不仅仅是政策合规。照此，概述了一系列建议，以鼓励在美国空间部门内加强此概念的研发（R&D），将其作为可持续全球空间经济的基本原则。

关键词：生命周期评估，美国，空间任务，供应链，风险管理，环境影响

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1. Introduction

The pursuit of sustainable supply chain management by companies around the world is placing an increasing responsibility on OEMs and suppliers to consider the environmental impact of their products. Despite this, space technologies have historically been exempted from key environmental legislation and regulations, meaning there has not been a specific requirement to account for supply chain impacts to date [1, 2]. However, growing interest in implementing LCA as a standard within the European space sector over the past decade has sharply brought this issue into focus. Pertinently, political priorities within the USA have not focused on ensuring environmental considerations as a necessary aspect for enabling space exploration and operations. As a result, European R&D on space LCA as a method for determining the environmental footprint of space technologies has vastly exceeded U.S. efforts. Europe is now in a position where space LCA could soon become a mandatory requirement of procurement contracts and the space mission design process, which would ultimately impact international trade on space products. The consequence to U.S. OEMs and suppliers is the need to diversify their operations outside of their main business function to comply with such changes or risk losing potential business and/or customers.

As such, this paper will use literature reviews to investigate the use of space LCA within Europe and the U.S. as a means for ensuring environmental stewardship, and the extent to which the U.S. is lagging behind Europe. It will then discuss the related risks that minimal environmental considerations may pose to U.S. OEMs and suppliers. Next, the paper will present a business case for implementing space LCA based on the expected potential benefits to the U.S. space sector. Finally, an evaluation on the overall findings will be provided, including the provision of a list of recommendations which outline a practical pathway for the implementation and adaptation of the LCA methodology in order to make it applicable to U.S. space operations.

2. Background

2.1 What is LCA?

LCA is a systematic method of analysis which compiles and evaluates the inputs, outputs, and potential environmental impacts of products, processes, and services over their entire life cycle. The method is internationally standardized through the International Organization for Standardization (ISO) 14040:2006 [3] and 14044:2006 [4] environmental management standards which provide an evaluation framework consisting of four stages outlined in Figure 1 below.

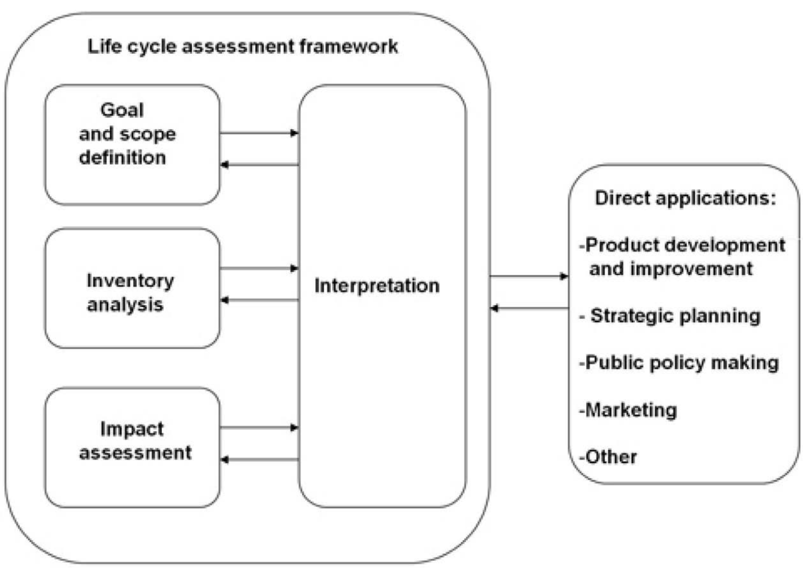

Figure 1: The ISO LCA Framework [3]

The first step is the goal and scope definition. This establishes both the purpose of the assessment and the criteria relating to the product system under study to which all decisions within each stage of the LCA framework should relate. Two of the most important features which need to be defined within this stage are the functional unit (FU) and system boundaries of the study. The FU is a quantified performance of a product system for use as a reference unit. This drives the data collection and analysis since it is what all inputs and outputs relate to within the study. The system boundary specifies which unit processes are included as part of the product system. Defining the system of study is particularly important for clarity relating to which unit processes are included as inputs and outputs within the study. Figure 2 shows a generic example of an LCA system boundary with typical inputs and outputs.

The second step is the life cycle inventory (LCI) analysis which requires data to determine quantification of inputs and outputs for a product and is built on the unit process. Data collection is one of the most challenging aspects of LCA, so for this reason, LCI databases are commonly used as an inventory of process input and outputs.

The third step is the life cycle impact assessment (LCIA) phase. This uses the LCI results to evaluate the magnitude and significance of the potential environmental impacts. This process involves associating inventory data with specific environmental impact categories and category indicators, thereby attempting to understand these impacts through either a midpoint or endpoint perspective.

Lastly, the interpretation phase considers the findings from the LCI and LCIA together. It should deliver results consistent with the goal and scope

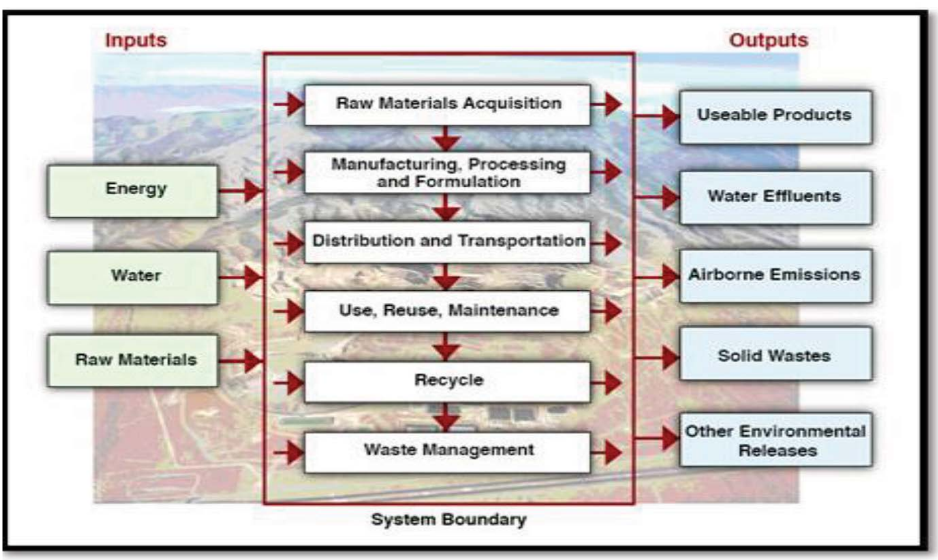

Figure 2: A generic system boundary of an LCA study (adapted from [5])

whilst providing a set of conclusions, limitations, and recommendations. As the LCA process is iterative, the inclusion of more detailed information leads to better model fidelity and application of the assessment.

In a similar manner to other sectors, the space industry generates pressures and causes damage on the environment. As specified by ISO 14040:2006 [3], LCA has several direct applications, including product development and improvement. As such, LCA can be used within the space sector as a mechanism to redirect the industry towards more sustainable activities by informing experts on the environmental impacts of their technologies. However, it can also be used to facilitate improvements during the concurrent design process of space missions via an approach called ecodesign [6]. Ecodesign is an environmental management technique which aims to improve the environmental performance of products and services by assessing their life cycle environmental impact at the design stage, without reducing their quality or performance [7]. This technique is based on principles of LCA, but distinctly different. It is standardized internationally through ISO 14062:2002, which describes the concepts and current practices relating to the integration of environmental aspects into product design and development [8]. The technique is extremely important to the product development process since, in most applications, current methods to lower environmental impacts of products only generate slightly modified or improved designs. Typically, these techniques are often applied late in the design process after many key decisions have already been made meaning too many constraints are already in place to significantly alter the design and lower adverse impacts. In contrast, adverse impacts are easier to modify the earlier into the design process they are identified. Therefore, the application of ecodesign has the potential to address this by informing decision-makers of life cycle environmental impacts of products during early design stages, which is vital if the environmental impacts of space missions are to be lowered [9].

However, applying LCA to space missions can be difficult for a number of reasons including sector specificities and the proprietary nature of the manufacturing and production processes. Before it can be used within the space sector, there is a need to adapt the methodological rules contained within the ISO 14040:2006 standard to make them applicable for space LCA [10]. For this reason, the activities on space LCA which have taken place in Europe over the last decade have been vitally important for the advancement of the method. Following this approach, the application of the LCA methodology used by the European space sector could also allow more robust environmental assessments of U.S. space missions.

2.2 LCA in the European Space Sector

As a concept, space LCA/ecodesign can be traced back to a European Space Agency (ESA) concurrent design facility (CDF) study conducted in 2009 on a mission called ECOSAT [11]. This study was the first to investigate potential life cycle impacts of satellite design, manufacturing, launch, and operation of a space mission. Following on from this project, ESA decided to examine potential environmental impacts of launch vehicles, satellite missions and ground-based infrastructure more closely through a series of dedicated studies [12, 13, 14]. A direct output of this work was the formation of the ESA Clean Space Initiative which aims to make space sustainable for future generations by safeguarding the environment on Earth and in orbit [15]. Based on the knowledge acquired from various LCA/ecodesign studies conducted under the scope of the ESA Clean Space Initiative, a new space LCA framework was developed to streamline its application within the European space industry [16].

The framework consists of a handbook, LCA database, and ecodesign tool. The handbook provides the primary guiding principles which should be applied when conducting a space LCA at either system or component level [17]. They tailor the methodological rules contained with the ISO LCA standards to be more appropriate to the space sector without risking non-compliance and are orientated as closely as possible with the Product Environmental Footprint approach, thereby allowing the ESA to align more closely with the strategic goals of the European Commission. The ESA LCA database was developed because space is a unique domain, meaning its application is not straightforward. Environmentally extended input-output methodologies provide highly inaccurate results whilst process databases do not have sufficient coverage due to the unique materials used and environmental impacts of the space sector [17, 18]. As such, the ESA LCA database was created to act as a consolidated and centralized source of LCI datasets specific to space activities. It involved input from hundreds of world experts and contains over 1,000 datasets [19]. The ecodesign CDF tool is intended to integrate LCA into the space mission design process. This is because most environmental impacts are set by early design choices which are more difficult to modify with increased design definition. The tool addresses these impacts during early concept development where possible design modification is still high. Further technical improvements are required to convert this tool to a working version [9, 19, 20]. Furthermore, additional efforts have been made within the European space sector to elaborate and build on this framework [20, 21, 22]. A previous literature review on the topic identified the critical role that this has played in the context of the development of space LCA within the European space industry, particularly in terms of both its application and the development of good practice [23]. As far as is known, the ESA LCA framework continues to be the first and only framework for space LCA in existence, with nothing remotely similar having been developed elsewhere, including North America or Asia [22].

Although LCA is currently a voluntary practice within the Europe, several ESA projects already include mandatory contractual requirements on space LCA, including Ariane 6 and the Copernicus expansion missions [22]. Beyond this, as suggested in [22], the importance of public-sector procurement and research program expenses coupled with a limited number of large system operators and integrators in the sector may foster the generalization of such practices. Consequently, in the future, there is a distinct possibility this approach may grow to become an integral part of the development and procurement process across the entire European space industry. This is evidenced by a poll conducted as part of the ESA Clean Space Industrial Days 2021 which sought to gauge the opinion of industrial space LCA experts on whether mandatory LCA requirements should be set for ESA procurement contracts and missions [24]. As seen in Figure 3 below, all participants indicated their preference for mandatory LCA requirements to be implemented at ESA. Whilst this survey had a small sample size consisting only of space LCA experts, it can be said that the outcome still provides a strong indication of the potential future direction of the European space sector, where sustainable development is a core principle.

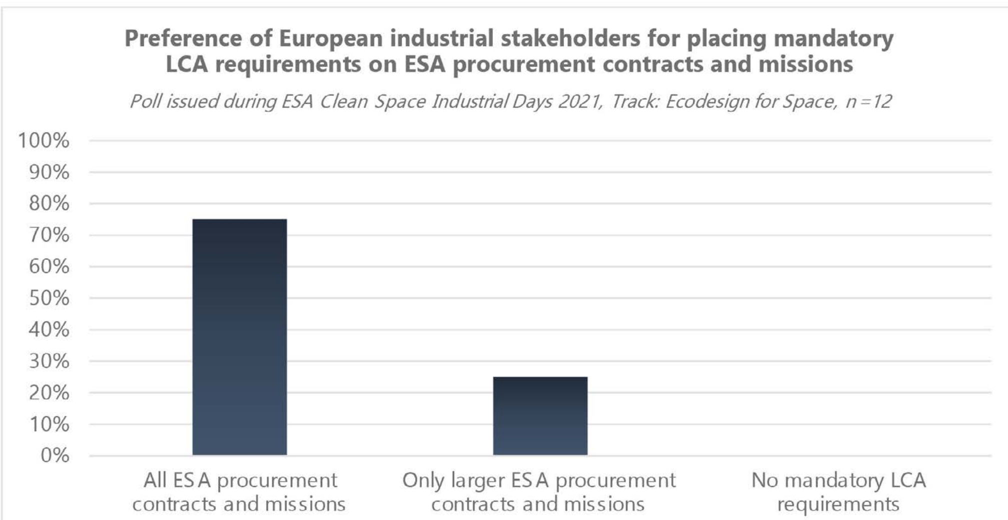

Figure 3: Poll on whether space LCA should be made a mandatory requirement at ESA (adapted from [24])

2.3 LCA in the U.S. Space Sector

Despite the COVID-19 pandemic, space activities in the USA have continued to increase in 2021 according to the U.S. Federal Aviation Administration/Commercial Space Transportation (FAA/CST) Office [25]. This amplifies the motivation for addressing adverse life cycle environmental impacts of U.S. space missions to allow for better ecodesigned products and good environmental stewardship. Regardless, despite the pioneering work on space LCA which has been conducted in Europe, the apparent interest in identifying, characterizing, and understanding environmental impacts in the USA is not as evident as expected. In this regard, space LCA studies in the U.S. have been rather limited to date, with only small-scale studies on ground facilities being conducted at NASA [26].

Wider than this, research on the topic can be traced back to an academic project conducted at the University of Texas at Arlington which investigated the environmental impacts of one launch within the U.S. [27]. This study produced a comprehensive LCA for U.S. CST activities based on the ISO 14040:2006 framework, considering the overall launch campaign within a 14-day window. The research objectives were to develop a base case for U.S. launch campaign, generate a reproducible framework of current launch activities using the data libraries in SimaPro software and identify green technology options such as additive manufacturing and product substitution. As an outcome, a new tool called the Space Transportation Environmental Profile for Launch (STEP-L) was generated by applying the SimaPro results into an interactive dashboard of the launch campaign consumables, producing an impact assessment on the areas of human health, ecosystem quality, climate change, and resources.

Further studies on space sustainability are currently being conducted by the Landis Sustainability Research Group of the Colorado School of Mines. The group is attempting to adapt the ISO LCA framework for space applications [28, 29, 30]. However, despite having potential to act as a foundation for a U.S. space LCA framework, the work is embryonic and not well aligned with best practice according to the space LCA/Life Cycle Sustainability Assessment (LCSA) evolution in Europe [17, 20]. Despite this, the group's studies have been useful in advocating the concept within the U.S. space sector, including introducing it to educational degree programs [31].

Beyond these studies, no other material was uncovered in relation to space LCA studies within the USA. However, it should be noted that the uptake of LCA as a concept has been slower in the U.S. than in Europe. In that regard, the use of LCA in general is not ubiquitous within industry throughout the USA. This includes within the dairy sector and Department of Energy [32]. In comparison, the application of LCA within Europe is much more widespread and systematic as a method for capturing and quantifying environmental impacts from sectoral activities and operations. As lines become more blurred between commercial space, civil space, and national security on the how space will be explored and exploited, developing a standard for characterizing the environmental implications of those operations will become increasingly more important. The benefit to the U.S. commercial space sector for implementing space LCA to its operations and supply chain would be the quantification of environmental impacts and informing sustainability aspects such as climate change objectives. As such, there is a need for more R&D on space

LCA within the USA, with a priority on developing a focused framework/guidance and data collection.

2.4 Problem Statement

Within the European space sector, there is a distinct possibility that LCA could become a fundamental part of the development and procurement process of space missions before the end of the decade. Should this be the case, then there is an obvious risk to U.S. manufacturing due to the relatively limited amount of work on the topic within the USA, meaning the country is beginning to fall behind others. This could become a serious problem for U.S. OEMs and suppliers in the near-term future due to misalignment or non-compliance with European procurement policies, with the potential to cause widespread supply chain disruption. As a result, U.S. OEMs and suppliers in aerospace could be at risk of being cut-off by European consumers if they cannot accurately account for the life cycle impacts of their space products. In this regard, Peck [33] found that 91% of all reported disruptions occurred upstream in the supply chain and were outside the direct control of OEMs and suppliers, highlighting the importance for them to be able to adapt to environmental legislation/regulatory changes, tariffs/trade agreements, and wider economic conditions in order to limit supply chain vulnerability.

Based primarily on trade relations between the U.S. and European Union (EU), the remainder of this paper will investigate the consequences and opportunities for U.S. manufacturing given the extent of which the USA has fallen behind Europe on space LCA. Finally, a set of recommendations are outlined to minimize potential supply chain disruption and place the USA in a position where it can begin to champion LCA and reap its benefits.

3. Methods

3.1 A Comprehensive Review of Literature

A critical review of literature was selected as the most appropriate research method within this study. This was used to characterize the historical context of space LCA, potential supply chain risk should it become a mandatory reporting requirement within Europe, potential mitigation measures and the business case for the widespread implementation of space LCA in the USA. Several procedures were followed to ensure a high-quality literature review.

In terms of the historical context of space LCA, a comprehensive search of peer-reviewed reviewed journals, conference papers, books and reports were completed based on a wide range of key terms including "life cycle assessment," "ecodesign," "space," and "United States." Several sources were used for this purpose, including the Scopus database, Google Scholar, the British Standards Online Library (BSOL), the National Aeronautics and Space Administration (NASA) technical library's public search engine TechDoc, proceedings published on conference websites, and various elements collected within the space industry from different sources. The reference section for each collected article was also searched in order to find additional research. In this regard, dozens of papers on space and LCA work was uncovered, primarily by the ESA and other European countries, while only a few U.S. space LCA papers were found. The findings from this process were then synthesized to provide a general overview of information pertinent to the development of space LCA.

The types of supply chain risks and mitigation measures considered as part of this paper were obtained based on a literature review through the Scopus database, based on the terms "supply chain risks," "supply chain management," and "sustainable supply chain." In this regard, the findings of Peck [33], Ziaei and Amalnick [34], Treuner et al. [35], and Blass and Corbett [36] were considered to be the most relevant as they list common types of supply chain risks and associated management strategies. From these papers, the two issues which were considered most relevant and prominent to the space sector were financial impacts and misalignment to policy, agreements and/or mission statements. As such, in terms of the risks posed to U.S. OEMs and suppliers, relevant data and information on these two aspects were obtained from the websites of government and industry associations, including companies providing outlook reports on the global aerospace industry/market. These data sources were filtered to obtain information which focuses exclusively on financial aspects of the aerospace industry and EU–U.S. trade on aerospace products. To support this, various national and international policies, best practices, and mission statements pertinent to the USA from a space perspective were also identified based on a simple internet search.

Finally, a business case for implementing space LCA and/or ecodesign in the USA was outlined based on the list of potential benefits provided in [37] which are specified below:

- To comply with current and future legislation.
- To cut costs.
- To facilitate technological development and advance with the times.
- To respond to consumer demand for environmentally benign products (creating a competitive advantage).
- To create a more sustainable space sector.

Another search for literature was conducted on each of these benefits as an extension of the previous two literature reviews. In this regard, numerous documents relating to U.S. legislation, cost cutting, technological development, customer demands, and space sustainability from an LCA/ecodesign context were obtained based on a wide variety of search terms. On review, only those considered to be most relevant to the space sector or reflective of general practice were reported. As such, this referred almost exclusively to the experiences of other sectors primarily because of the limited amount of literature uncovered on the direct benefits of space LCA and/or ecodesign from a business perspective. The findings were then synthesized and related to the space industry to provide a general overview on the potential benefits to U.S. businesses that could be achieved through space LCA.

3.2 Limitations and Bias

Perhaps the greatest limitation of this research is the assumption that space LCA will become a mandatory reporting requirement within Europe and that this requirement will uniformly affect all supply chain actors, including those located outside of Europe. Although this will certainly not be the case, the potential benefits outlined as part of the results can be seen to justify the advancement of R&D of the topic within the USA.

Additionally, whilst the potential risks to U.S. OEMs and suppliers due to inaction on space LCA have been presented succinctly within this paper, this is based on a high-level perspective. Risks stemming from changes in procurement policies will impact each organization differently. In this regard, some OEMs and suppliers will be able to adapt better and faster towards change than others. As such, it could be argued that this paper only presents a surface level analysis. Therefore, regardless of the presented findings, it should be emphasized that organizations will still need to determine the business case of implementing space LCA within their own company.

Furthermore, in terms of the potential business case for space LCA in the USA, the majority of the reported benefits are based on observations from other sectors. These do not necessarily reflect the nuances of the space industry. In this regard, a number of factors such as the novelty of space LCA and the confidential nature of numerous studies (beyond the work of the ESA) has meant there is very little information available on the direct benefits of space LCA to the space sector to date. This is problematic as the space sector itself is a unique domain. In this regard, monetary flows are vastly different than in other sectors as the industry does not fulfil the requirements of a completely free market due to state financing plans and limited players. Therefore, the cited benefits may not be completely applicable or relevant and should only be seen as an indicative gauge to the potential advantages of implementing space LCA.

Finally, in terms of bias, the focus of this paper has been exclusively on Europe and USA. This was ultimately due to the significance of these regions to space LCA. In this regard, the world-leading work on space LCA conducted within Europe was considered inescapable in relevance to this topic, whilst the USA is the largest space fairing nation with arguably the most to gain or lose from space LCA. This is not to overlook or diminish the importance of the work on space LCA that has been conducted in other geographical regions.

4. Results

4.1 Consequences of Inaction on Space LCA

Within the U.S., the amount of financial capital at risk due to the potential influence of changes to the European procurement process due to mandatory space LCA reporting requirements is underpinned by the landscape of the global aerospace market, particularly as it relates to EU–U.S. trading. Despite its small size, the satellite industry has a very high leverage effect on global trade. In this regard, the space sector plays a critical role in many of the services we take for granted and is becoming increasingly pivotal to developing solutions to some of the greatest global challenges, including climate change and the COVID-19 pandemic. In 2020, global revenues from the aerospace sector were reported to be $697 billion [38], with the satellite industry providing $271 billion [39]. The USA is currently the leading net satellite exporter globally, with European countries providing the largest single destination market amongst U.S. manufacturers [40]. Consequently, the U.S.'s largest export to the EU in 2019 was aerospace products and parts, at $35.7 billion [41], demonstrating the significant scale of the USA–Europe aerospace trade relationship, which involves entire supply chains from multi-national corporations to small businesses.

From a European perspective, Figure 4 highlights that 67.2% of all EU aerospace products and parts were supplied by the USA in 2020. This trade was estimated to be worth €22.4 billion to the U.S. economy. Comparatively, Figure 5 shows that EU exports of aerospace products and parts to the U.S. equated to around €11.3 billion. As a result, Europe suffered from a €11.1 billion trade deficit on aerospace products and parts with the USA. However, this deficit was more than compensated by the trade surplus on aerospace markets with other countries [40]. In this regard, the EU trade balance for aerospace products and parts in 2020 was €19.4 billion, where Canada acted as the only other country that the EU had a trade deficit with (at €116.8 million) [42]. As such, the EU–U.S. trade imbalance on aerospace products and parts is not a specific concern to the EU, as they are somewhat reliant on the U.S. for aerospace imports. Additionally, the EU recognizes that the aerospace market is global, so are working to keep markets and trade open through different instruments [43]. This is particularly important in the wake of the recent 17-year dispute that was resolved over subsidies to aircraft makers, which further improved transatlantic trade and diplomatic relations between the U.S. and EU [44].

Despite this, it is generally accepted that trade deficits reduce the number of domestic jobs and the income of domestic workers, pushing many into lower income brackets. As such, if U.S. OEMs and suppliers are unable to fulfil European requirements due to changes in their procurement policies, it is a distinct possibility that Europe may begin to develop such technologies internally or outsource to existing trade partners. In that regard, work on space LCA has already begun in other countries. Not only does this directly threaten the multibillion-dollar U.S. export trade with the EU on aerospace products, but also adds further competition to U.S. OEMs and suppliers on the global aerospace market. This competition should not be disregarded, particularly if the technologies to be developed have been sustainably sourced in line with the aims of the 2030 Agenda for Sustainable Development, given that it is consistently reported that upwards of 50% of consumers would be willing to pay more for sustainable products [45, 46, 47]. This is particularly relevant to U.S. small and medium enterprises (SMEs), as these make up over half of all U.S. jobs, with nearly 300,000 exporting to foreign markets and 95,000 to the EU [48, 49]. According to the U.S.–EU Transatlantic Trade and Investment Partnership (TTIP) [50], non-tariff barriers can disproportionately burden thousands of SMEs. Compliance with such measures can be challenging and resource intensive since these barriers can take the form of requirements applied at the border or behind-the-border. Although now obsolete, a central shared goal of the TTIP was to yield greater openness and transparency, reduce unnecessary costs and administrative delays, promote enhanced regulatory compatibility, while achieving the levels of health, safety, and environmental protection that each side deems appropriate and meeting other legitimate regulatory objectives. Furthermore, the TTIP aimed to ensure regulations were developed in ways that led to more efficient, cost-effective, and compatible regulations through, for example, use of impact assessments and the application of good regulatory practices. As such, the introduction of space LCA in the USA seems to be a natural fit, where the U.S. space sector can learn from what has already been done on the topic in Europe and lessen the financial risk to OEMs and suppliers, supporting a path towards a new or better TTIP agreement.

In parallel, besides monetary consequences due to inaction, there is also a risk of non-compliance with various policies and best practices, which has the potential to cause international tension if the U.S. is seen to not be aligning with their own commitments. Largely based on the 2030 Agenda for Sustainable Development [51], the "Guidelines for the Long-Term Sustainability of Outer Space Activities" [52] were released by the United Nations Committee on the Peaceful Use of Outer Space (COPUOS) in 2017. These act as the first ever international sustainability guidelines for space activities. Of particular relevance is paragraph 27.3, which states that space actors "*should promote the development of technologies that minimize the environmental impact of manufacturing and launching space assets.*" The action expressed in this sentence is clearly aligns with the LCA approach. Although these guidelines are voluntary, they represent best practice on space sustainability and is something that the USA helped to develop as a Member State of COPUOS. Therefore, it could create repercussions both internally and globally if the USA is seen not to be abiding by these guidelines.

Drawing upon these guidelines, the "National Space Policy of the United States of America" [53] has a goal of strengthening U.S. leadership in space by leading the enhancement of safety, stability, security, and long-term

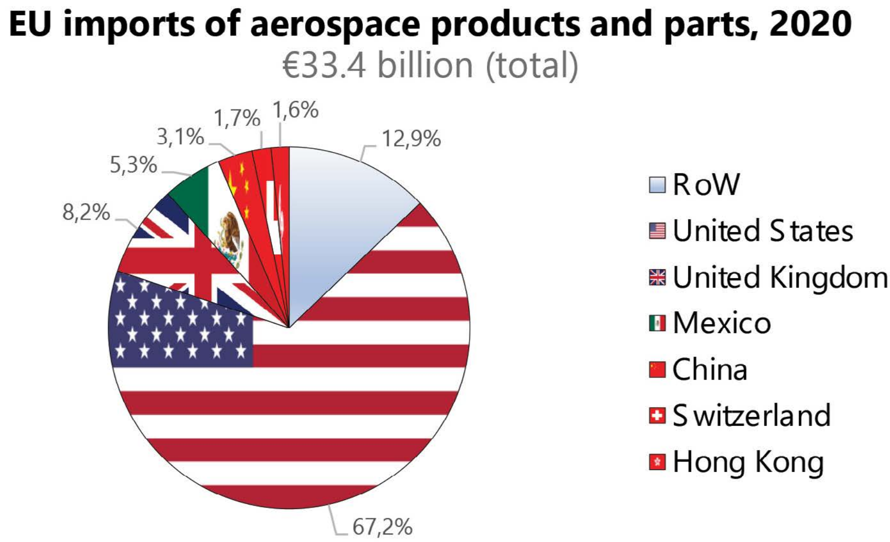

Figure 4: EU imports of aerospace products and parts in 2020 (adapted from [42])

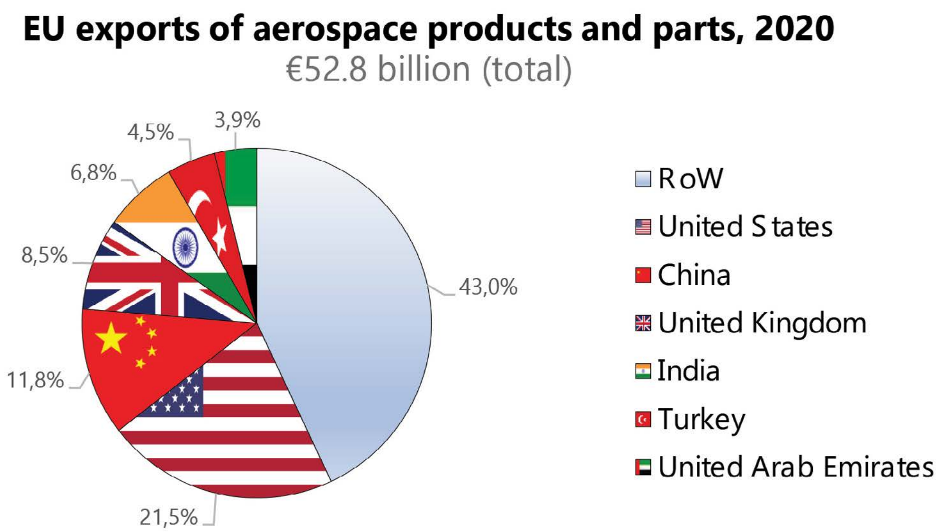

Figure 5: EU exports of aerospace products and parts in 2020 (adapted from [42])

sustainability in space by promoting a framework for responsible behavior in outer space, including the pursuit and effective implementation of best practices, standards, and norms of behavior. Additionally, in relation to procurement, the policy aims to strengthen and secure the U.S. space sector by incentivizing suppliers and manufacturers which are key to the U.S. space-related science, technology, and industrial bases to remain or return to the U.S. In this regard, the policy goes on to state that to improve space system development and procurement, efforts will be made to improve processes and effectively manage and secure supply chains. In order to fulfill the commitments of this policy, it is clear that the implementation of space LCA should be pursued to act as an enabler to a sustainable U.S. space economy. This is echoed in the mission statement of NASA [54], which is to:

> "*Lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and bring new knowledge and opportunities back to Earth. Support growth of the nation's economy in space and aeronautics, increase understanding of the universe and our place in it, work with industry to improve America's aerospace technologies and advance American leadership.*"

Therefore, as demonstrated, the use of space LCA has high relevancy to the strategic direction of the U.S. space sector. It could contribute towards the continued alignment of the country with their current national and international commitments and goals whilst also contributing towards a more sustainable economy. This is particularly pertinent given the scale of U.S. international aerospace trade and may ultimately translate into further global partnerships for space sustainability. Thus, meeting the goals set out in the Guidelines for the Long-Term Sustainability of Outer Space Activities, U.S. National Space Policy, and NASA mission statement to be a leader in space sustainability while strengthening partnerships can be seen to be of critical importance to the future direction of the U.S. space sector, something for which space LCA could play a leading role.

4.2 Advantages of Acting on Space LCA

Besides the avoidance of potential supply chain disruption, there are numerous other advantages stemming from the implementation of LCA within the U.S. space sector. This includes (but is not necessarily limited to) the ability of companies to comply with current and future legislation, cut costs, facilitate technological development, respond to consumer demands, and contribute to a more sustainable space sector [37]. These benefits will provide the basis for further discussion within this subsection.

Firstly, there is a need to comply with current and future legislation within the USA. In particular, Title 51 of the U.S. Code (51 U.S.C.) [55], entitled National and Commercial Space Programs, incorporates environmental compliance with air and water quality laws based on the National Environmental Policy Act (NEPA), including developing environmentally friendly aircraft. Despite this, the Federal Communications Commission (FCC) has ruled that this does not apply to activities in space since space is not an environment under NEPA. However, other general space policies and legislation, including the Department of Defense regulations on space operations [56], emphasizes that the minimization of space debris should be seen as a particular area of prioritization for environment protection. Regardless of this, the main environmental priority for FAA/CST on commercial space operations is ensuring the NEPA is fully complied with for each launch [57]. However, this law primarily focuses on developing environmental assessments (EAs) for launch activities and operations which are permitted at launch facilities. The FAA/CST is responsible for conducting the EAs in collaboration with the rocket launch partner. However, EAs do not require a cradle-to-grave understanding/quantification of environmental related impacts [58]. In addition to the NEPA, CST activities must ensure compliance with other Federal laws and requirements, including but not limited to the Clean Air Act, the Clean Water Act, the U.S. Department of Transportation Act, Section 4(f), etc. [57]. NASA also follows similar NEPA and related environmental regulations for its space operations with other federal laws [59]. However, NASA adds the several additional regulations to those of the FAA/CST, including the Executive Order 13834, Efficient Federal Operations, the Resource Conservation and Recovery Act (RCRA), the Safe Drinking Water Act (SDWA), Hazardous Waste Management, etc. [60]. Conversely, although these compliance driven efforts suggest that environmental implications are clearly identified and regulated within the U.S. space sector, a system-level life cycle perspective is notably absent. The U.S. sustainable supply chain has also lagged in reducing their supply chain emissions and have been encouraged by EPA to begin reducing greenhouse gases (GHGs) [61]. So, even in the supply chain area, environmental impacts are managed with similar environmental laws, but are still not providing the full understanding of the environmental implications from cradle-to-grave. In this regard, LCA (in general) has huge potential to assist in on these issues and contribute to these legislative/policy instruments. Therefore, there is a distinct opportunity for the U.S. space sector to lead by example through the implementation of space LCA.

Furthermore, as reported by Wilson et al. [22], recent privately funded spaceflights have acted as a catalyst for heightened public interest in quantifying the environmental footprint of the space sector. With this in mind, it is anticipated that this could propel the use of space LCA and place an added emphasis on the supply chain to deliver sustainable space technologies to satisfy consumer demands, thereby allowing OEMs and suppliers to retain current customers and attract new business. Consequentially, modest price increases (if unavoidable) may not necessarily be negative to businesses since it is consistently reported that >50% of consumers are willing to pay more for sustainable products (as previously outlined). The net effect of this to OEMs and suppliers from a financial perspective is demonstrated by a survey which was conducted in 2013 by Pôle éco-conception and Management du Cycle de Vie [62]. The survey measured the impact of developing environmentally friendly products on company profitability across France, Quebec, and the EU (see Figure 6). Although responses were significantly heterogeneous across each geographical location, it was found that 96% of EU companies (excluding France) that had implemented LCA/ecodesign experienced a neutral or positive effect on company profits. This compares to only 4% who stated that a reduction in profits had been experienced. Additionally, the survey also showed that for a large majority of the respondents, the LCA/ecodesign approach generated significant benefits other than financial. The four types of impact most often mentioned are an improvement in the image or awareness (86%), increased motivation and pride of employees (41%), increased/better relationship with customers (36%), and a greater ability to develop new products (32%). This evidences the fact that LCA/ecodesign has potential to create a competitive advantage for businesses.

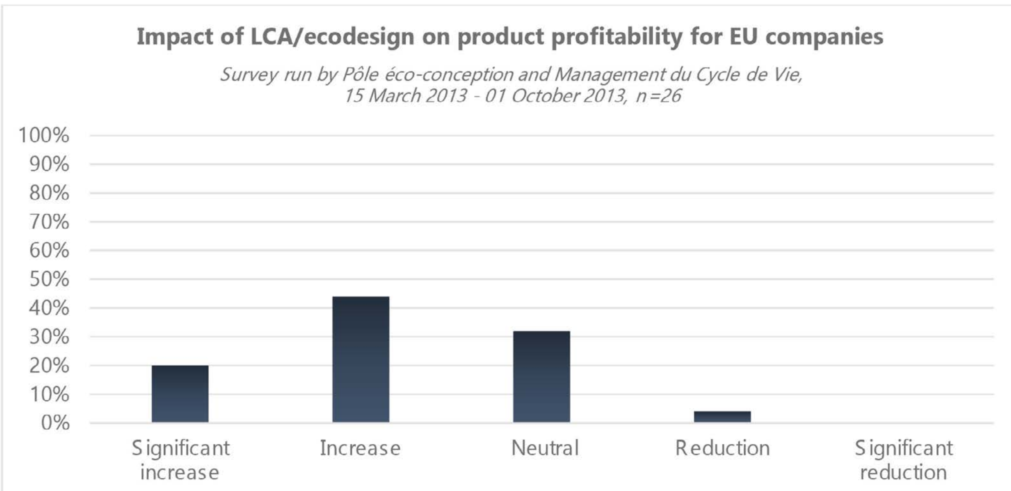

Figure 6: Survey on product profitability through LCA/ecodesign in the EU (adapted from [62])

Besides the additional profit which may ensue from developing sustainable space technologies due to improved company reputation, LCA and ecodesign can also be used to cut costs. Typical savings of 10-20% are consistently reported based on LCA [63,64], with the average profit margin of ecodesigned products being around 12% above the margin of conventional products [62]. Based on the latter, assuming an average net profit margin of 10% on the cost of all EU aerospace imports from the USA outlined in Figure 4, then U.S. manufacturers may be able to save slightly more than $2.5 billion in annual costs through the use of LCA/ecodesign. These savings can also be used directly to create new jobs. In this regard, the Aerospace Industries Association reports average industry wage and benefits of $102,900 [65] with the U.S. Small Business Administration stating that a general rule of thumb is that the cost of an employee is typically up to 1.4 times the salary, depending on certain variables [66]. Therefore, when used to support the advancement of

LCA/ecodesign for European purposes only, then this means that upwards of 10,000 new jobs could be created, leaving well over $1 billion worth of cost savings remaining. However, it should be noted that further cost savings and job creation opportunities could be supported if LCA was developed further beyond regulatory compliance with Europe. Therefore, space LCA should not solely be seen as a necessity for policy compliance, but also as a cost saving opportunity.

In terms of technological development, R&D on space LCA and ecodesign can be used to help identify and understand potential alternative design options that could lead to improved or optimized technologies (e.g., 3-D additive manufacturing to minimize environmental damage from resource depletion). In this regard, Blass and Corbett [36] found that the number of similarities between LCA and the supply chain management communities means it is only natural for them to seek inspiration from one another. For instance, LCA can aid in identifying critical raw materials, modifying manufacturing processes and developing sustainable supply chain contracts to enable the capability needed for future space missions. This is very important as certain raw materials such as germanium or beryllium are scarce, expensive, and/or difficult to source [20]. Examples of technological improvement areas needed for U.S. space operations where space LCA would be beneficial includes advanced manufacturing techniques (similar to the efforts that ESA are undertaking) [67], the development of lightweight spacecraft materials and structures [68] and other novel R&D efforts including launcher reusability [69].

Above all else, the application of space LCA within the USA has the potential to contribute to the development of a more sustainable space sector. Understanding the environmental impacts of U.S. space sector activities are of major importance to the U.S. space industry and its actors in order to address adverse environmental consequences stemming from its operations. In this regard, the Aerospace Industries Association [65] reported that in 2020, the space subsector led industry growth, which is expected to continue both in end-product development and supply chain needs. Assuredly, developing capabilities in space LCA will require a substantial and sustainable shift in the industry, but is vital for improving national security, life quality, protecting the ecosystem and preserving natural resources for future generations. As such, the USA faces a unique crossroads where the country can either choose to lead by example on space LCA or continue to fall behind others, threatening their global image as a responsible space fairing nation.

5. Discussion

5.1 Evaluation of Findings

This paper has shown that the growing importance of space LCA amongst European industrial stakeholders and national agencies present numerous threats and opportunities to the U.S. space sector. It has quantified the extent to which these threats and opportunities may impact the U.S. space sector in the near-term future based on a literature review. The results highlight the relevance of space LCA to national and international goals of the U.S. space industry, including maintain and improving international trading relations. As well as preserving the USA's global image as a responsible space fairing nation, developing a space LCA framework also has the potential to protect OEMs, suppliers and SMES from potential risk to changes in U.S.–EU aerospace procurement process. However, besides only mitigating risks to the U.S. economy, it is also clear that space LCA offers numerous benefits to companies, each with the potential to increase business. As such, a business case for pursuing space LCA within the USA has been presented. This included the ability of companies to comply with current and future legislation, cut costs, facilitate technological development, respond to consumer demands, and contribute to a more sustainable space sector.

Therefore, in order to help mitigate potential risks and respond to opportunities, a properly managed supply chain with the ISO 14040:2006 standard at its core is vital. Although this would require a huge cultural shift within the U.S., the appropriateness of the LCA concept to the space sector has already been demonstrated through several European studies, reaffirming its importance as a tool for scientifically quantifying and reducing adverse life cycle environmental impacts of space missions. As such, with appropriate adaptation, LCA could be successfully tailored for implementation within the U.S. space sector. For instance, the development of a national space LCA framework to guide its evolution from an American context, in a similar manner to the ESA's approach could act as a crucial first step. Undoubtedly this would be a laborious and costly endeavor considering that the ESA had spent over €20 million in studies to develop the ESA LCA framework between 2009 and 2018 [16]. However, the advantages of its application in Europe have been undeniable. Based on the lessons learned and implementation strategies from ESA, the U.S. could invigorate the integration and application of the LCA method into the space sector. However, at present, it is clear the U.S. is falling behind others on this front and must catch up if they do not wish to lose the space race on LCA.

5.2 Recommendations

Development of space LCA in the USA must be pursued if a sustainable space economy is to be realized. To enable this vision, four high-level recommendations have been outlined to advance space LCA practices further within the U.S. These are outlined below and collectively seek to minimize potential supply chain disruption and place the USA in a position where it can begin to champion LCA and reap its benefits for sustainable space operations:

- Create a set of guiding principles for the application of LCA for space technologies in the USA.
- Build a tailored database and eco-design tool suited for U.S. space

technologies, with a focus on developing datasets relating to production, manufacturing, materials, and processes.

- Develop a consortium of interested parties, included but not limited to U.S. space companies and suppliers, who are able to support the establishment of a space LCA framework within the country and provide relevant information and/or input to enable the first two recommendations.
- Integrate LCA as part of NASA and DoD contracts, including those issued to U.S. space manufacturers, launch providers and their major suppliers.

6. Conclusion

Since the beginning of the space age, the USA has been a leading space nation. However, 65 years' worth of space operations has led to the degradation of both Earth's orbit and environment. Space LCA could be a vital tool for quantifying and mitigating this impact, ensuring that the U.S. does not suffer irreparable damage to its image as public awareness into the space sector's environmental footprint continues to grow. In this regard, the extent to which the USA has fallen behind Europe on space LCA has been clearly defined. A serious risk to U.S. OEMs, suppliers and SMEs was identified under the assumption that LCA reporting requirements will become mandatory for space assets in Europe—a scenario which is a distinct possibility of occurring before the end of the decade. This threat has been quantified in terms of the EU-U.S. trade on aerospace products and parts due to potential non-compliance with European procurement policies. Despite this, several associated benefits of using space LCA were also presented, reinforcing that notion that the concept is a key ingredient for business success and should be used for more than merely compliance purposes. This strengthens the business case for R&D on the concept within the USA to allow the U.S. space sector to become fully accountable for its entire operations. As such, this paper should be seen as a call to action for the USA to begin transitioning towards a circular space economy, igniting the space race on LCA.

Disclaimer

The views expressed in this paper are those of the authors and do not necessarily reflect the views of the organizations they represent. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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