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Ecospheric life cycle impacts of annual global space activities☆

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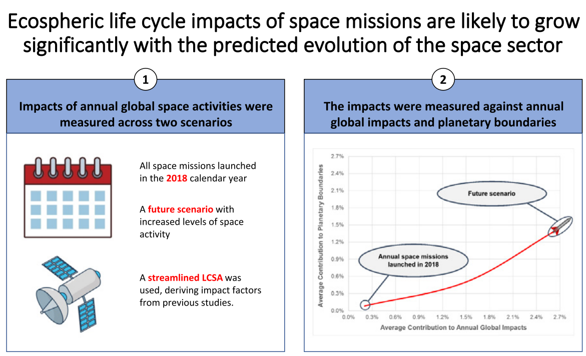
HIGHLIGHTS

- The life cycle impacts of space activities have been benchmarked for the first time.
- The versatility of a streamlined LCSA was shown to make this exercise more manageable.
- The impact of space activities will become more significant with projected trends.
- The future growth of the space sector will be constrained by environmental limits.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents a first-order approximation of ecospheric life cycle impacts from annual global space activities across two scenarios using a streamlined Life Cycle Sustainability Assessment (LCSA). The first scenario considers all space missions launched throughout the 2018 calendar year whilst the second is a futuristic scenario where affordable access to space significantly increases the prevalence of space operations. A new space-specific life cycle database and sustainable design tool called the Strathclyde Space Systems Database (SSSD) has been used to compile the inventory of each scenario and generate results across numerous impact categories. The results for each scenario are then compared against normalised values to portray their contribution towards annual worldwide impacts and their severity in terms of planetary boundaries. This allows the relative life cycle sustainability impacts of space activities to be benchmarked for the first time, forming a basis for evaluation and discussion. Overall, the study highlights that despite the relatively small footprint of the space industry at present, this will likely become much more meaningful in the future based on predicted trends. This places an added importance on addressing potential adverse life cycle impacts within the design process of future space technologies and products.

1. Introduction

1.1. Background

Until recently, environmental impacts of space activities had often been omitted from key legislative and regulatory requirements, with the result being that the environmental impacts of industry activities were traditionally overlooked. For example, when the Montreal Protocol on Substances that Deplete the Ozone Layer was introduced in 1987, it completely left out the space industry despite rocket propulsion being the only source of anthropogenic emissions to inject ozone destroying compounds directly into all layers of the atmosphere (Ross et al., 2009; Ross and Vedda, 2018). A key difficulty arising from neglecting such impacts from mainstream legislative and regulatory requirements was that the industry lagged behind others in terms of its ability to determine and account for its impacts.

However, renewed commitments in recent years by national and international bodies towards environmental problems and wider sustainability issues has allowed a range of mitigation measures and key issues to filter

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down and become embedded in a variety of sectors. In particular, the adoption of the Paris Agreement, 2030 Agenda for Sustainable Development, Guidelines for the Long-term Sustainability of Outer Space Activities and European Union Green Deal all increase the motivation and necessity for addressing the environmental and sustainability aspects of future space missions and technologies. Such strategies create a coordinated global approach towards achieving sustainability in which all sections of society must be fully engaged, including the space industry.

Nonetheless, despite a growing realisation for the need to quantify the environmental consequences of space activities, prior exclusions granted to the industry has meant that environmental and sustainability modelling techniques within the sector are only beginning to establish themselves. As a result, this means that to date, the environmental footprint of the global space missions remains relatively unknown.

1.2. Towards a sustainable space sector

One novel approach which has begun to emerge within the space sector as a method for addressing such concerns is environmental life cycle assessment (E-LCA). E-LCA is an environmental management technique used to assess environmental impacts of products, processes or services over their entire life cycle. The method is internationally standardised by the International Organization for Standardization (ISO) through the ISO 14040:2006 (International Organization for Standardization, 2006a) and 14044:2006 (International Organization for Standardization, 2006b) environmental management standards on E-LCA which provide a globally accepted framework to which all E-LCA studies should adhere. A particular advantage of life cycle approaches is that they go beyond traditional protocols for environmental footprinting given that they are able to track total impacts across entire supply chains. As such, the potential implementation of this method within the space industry could help scientifically quantify and reduce geocentric environmental impacts of space missions.

However, the novelty and unique characteristics of the space industry means that its application is not as straightforward as with other sectors (Boonen et al., 2018). This is due to the very unique environmental impacts of the sector in comparison to others which are not captured by conventional life cycle models. Traditional E-LCA models typically consist of common, mass-produced products and processes which make them virtually incapable of accounting for the complexities and specificities of the space industry. Space technologies have low production rates, long development cycles and use specialised/unique materials and industrial processes which also have to satisfy stringent safety and quality requirements. This means that they are subjected to significantly more research and testing than other products (ESA LCA Working Group, 2016). Ultimately, this means that in their current form, traditional E-LCA models are effectively incapable of providing results without large data gaps and/or uncertainties attached to provide any sort of meaningful analysis. Therefore, in order for the technique to begin to be properly applied to space projects, it is clear that the methodological rules and standards for E-LCA require adaptation. In this regard, since its conception in 2012, the European Space Agency (ESA) Clean Space Initiative has been pioneering the application of E-LCA within the space sector to assist industry in protecting the environment through the minimisation of life cycle impacts of space activities to Earth and space (Serrano, 2018).

1.3. Designing sustainable space missions

To coordinate research development and assist the European space industry to apply E-LCA, ESA developed a new framework in 2016 under the auspices of the Clean Space Initiative (Austin et al., 2015). The framework was designed to make E-LCA more applicable to space technologies and was developed based on the cumulative knowledge of environmental impacts acquired from the various studies that they conducted across the space, ground and launch segment of space missions, involving input from a variety of stakeholders.

The framework consists of a handbook, E-LCA database and ecodesign tool. The handbook was developed to adapt current ISO standards on E-LCA to be more space-specific, thus providing common methodological rules to be followed when performing space E-LCAs. As such, its purpose is to assist practitioners with the application of E-LCA within the space sector (ESA LCA Working Group, 2016). The E-LCA database contains specific datasets for performing E-LCAs of space missions. The use of these datasets enables space-specific E-LCAs to be applied properly for the first time by accurately measuring the environmental impacts of space systems (Boonen et al., 2018). The ecodesign tool integrates this process into mission design scenarios of future space missions. The purpose of the tool is to assist decision-makers assess, compare and lower the environmental impacts of preliminary design choices made during the mission design process (Deloitte Sustainability, 2017). Whilst the handbook is currently available to European stakeholders, the E-LCA database and ecodesign tool are currently only available under contract with no near-term release foreseen (ESA Clean Space Initiative, Personal communication).

A recent project conducted at the University of Strathclyde attempted to expand this framework towards Life Cycle Sustainability Assessment (LCSA) and integrate this within the concurrent design process based on a Life Cycle Engineering approach (Wilson, 2019). Rather than a model itself, LCSA is a framework of models designed to provide product-related information in the context of sustainability and allow integrated decision-making based on a life cycle perspective (Guińee, 2016). This is achieved by combining E-LCA, Social Life Cycle Assessment (S-LCA) and Life Cycle Costing (LCC) into a single framework. S-LCA can be used to predict the social and sociological aspects of products whilst LCC can be used to determine the entire cost of a product, process or service over its entire life cycle including both one time and recurring costs. Therefore this, a new LCSA tool called the Strathclyde Space Systems Database (SSSD) was developed for this purpose (Wilson and Vasile, 2017; Wilson et al., 2018). The aim of the SSSD is to advance current methodologies for E-LCA within the space sector by moving towards a more holistic approach of sustainability assessment for space systems which aligns with the global aspirations envisaged within the 2030 Agenda. To achieve this, the tool provides a mechanism for decision-makers to design sustainable space technologies and products based on multiple sustainability parameters/criteria. Therefore, the intention of this tool is not to compete with those developed by ESA, but to bridge the gap between the lack of life cycle databases for space systems and the public dissemination of the ESA tools.

1.4. Problem statement

Using life cycle methodologies to calculate the role of space activities against global footprints and ecological thresholds is a fundamental step towards understanding the space sector's contribution to global environmental change and sustainability. However, due to the novelty of this approach, coupled with confidentiality concerns surrounding the vast majority of space-specific E-LCA studies, the space sector has thus far been unable to scientifically account for the entirety its environmental, social and economic life cycle impacts stemming from nominal operations, leaving a fundamental gap in knowledge.

Given this situation, the main goal of this paper is to present a first-order approximation of ecospheric life cycle sustainability impacts from annual global space activities, based on a streamlined LCSA across two scenarios. The first scenario is based on all documented space activities occurring in 2018 whilst the second refers to a futuristic scenario where affordable access to space significantly increases the prevalence of space operations in the short to medium term future. This latter point was investigated due to the considerable efforts being made to provide affordable access to space, meaning that the prospect of mega constellations, space tourism and Moon/Mars colonisation could begin to establish themselves within the next couple of decades (Leach, 2014). The results for each scenario have been compared against normalised values to portray their magnitude and severity. In this regard, the contribution of selected impact categories have been measured against total annual worldwide impacts relative to

2010 (Sala et al., 2017) and planetary boundaries (Sala et al., 2016) to produce an ecological footprint of global space missions for the first time. As such, the results of this paper are then evaluated and discussed, with recommendations provided to further elaborate on these findings within future studies.

1.5. Outline

Section 1 outlines the historical context and gives an overview on the need for calculating the sustainability footprint of the space activities, as outlined within this paper. Section 2 goes on to present the theory and approach of the study by outlining the goal & scope definition according to the ISO 14040:2006 (International Organization for Standardization, 2006a) and ISO 14044:2006 (International Organization for Standardization, 2006b) standards and detailing the life cycle inventory, encompassing modelling assumptions for each scenario. Section 3 then provides life cycle sustainability results for each scenario, comparing these to normalised values to make them more understandable and interpreting them to find potential hotspots, including their root cause. After this, Section 4 evaluates and reflects on these findings whilst Section 5 provides a conclusion to the study.

2. Theory and approach

2.1. Goal & scope

As defined by the ISO 14040:2006 (International Organization for Standardization, 2006a) and ISO 14044:2006 (International Organization for Standardization, 2006b) standards, the goal and scope definition sets the purpose of the assessment and establishes criteria relating to the product system under study, to which all decisions within each stage of the LCA framework should relate. In this regard, the purpose of this study is to benchmark the relative significance of ecospheric life cycle sustainability impacts deriving from annual global space activities over two scenarios. The first scenario refers to the full life cycle impacts from all space missions launched throughout the 2018 calendar year, and takes into account the 114 recorded launches and the 452 satellites placed in orbit (Kyle, 2021; United Nations Office for Outer Space Affairs, 2021). The second scenario is a mid-term outlook which refers to the full life cycle impacts from scaling the first scenario to account for affordable access to space and the prospect of mega constellations, space tourism and Moon/Mars colonisation. Under this scenario, 750 launches are assumed in one calendar year with 5000 spacecraft being placed in orbit. It should be duly noted that the prospect of intercontinental suborbital point-to-point travel has been excluded from this analysis as it was considered to be less achievable in the mid-term future. Additionally, the study only measures the impact of space missions and does not represent the impact of the entire space industry. These impacts refer to Earth-based (ecospheric) impacts only, since the issue of space debris is considered to be outside the scope of study. This is because the position of ESA is to exclude these impacts from space LCA studies at present as they are considered to be addressed by the 'ESSB-HB-U-002 - ESA Space Debris Mitigation Compliance Verification Guidelines' (ESA LCA Working Group, 2016; ESA Space Debris Mitigation Working Group, 2015).

Importantly, the functional unit (FU) and system boundary of the study also needs to be defined under the goal and scope definition. The FU is a quantified performance of a product system for use as a reference unit. It defines what all inputs and outputs of the study should be related to and is particularly useful in comparative assessments. The system boundary specifies which unit processes are included as part of the product system. This is particularly important for clarifying which unit processes are included as inputs and outputs within the study. Within this study, the FU has been defined for both scenarios as 'one year of global space missions in fulfilment of their requirements'. This is relevant across the adopted system boundary, which covers the ground, launch and space segments outlined in Fig. 1 below. Although this system boundary is generally seen to be applicable to one space mission, within this study it refers to the sum of impacts deriving from all space missions within one calendar year.

The applied methodology is based on a streamlined LCSA which was adopted to make this exercise more manageable. Although these assessment types continue to follow the same standards and principles as LCSA, there are a number of differences. In particular, they are less accurate since their purpose is to reduce the time required to make an assessment (Vogtländer, 2012). This can be achieved in a number of ways including by limiting the scope, using generalised or qualitative data, removing upstream and/or downstream components or using specific impact categories (Airbus Corporate Answer to Disseminate Environmental Management System (ACADEMY), 2018). Within this methodology, the simplification lies in the use of generalised data and the fact that very specific evaluations have been used to represent very broad and complex industrial activities. The SSSD was selected as the calculation tool to compile the life cycle inventories and generate LCIA results across numerous impact categories.

2.2. Life cycle inventory analysis

The streamlined LCSA was conducted using the Strathclyde Space Systems Database (SSSD). The SSSD is a new LCSA developed at the University of Strathclyde which can be used to quantitatively and scientifically determine life cycle sustainability impacts of space missions during concurrent design activities, and use this information to lower adverse environmental, social and economic impacts. It is based on an attributional, process-based methodology which relies on physical activity data to develop a product tree derived from assessing all the known inputs of a particular process and calculating the direct impacts associated with the outputs of that process. Validated at ESA through a collaborative project in late 2018, the SSSD has already been used in the design of several space missions. It consists of 250 unique space-specific life cycle sustainability datasets, based on Ecoinvent and ELCD background inventories, which each contain environmental, costing and social data. The SSSD also includes several impact categories at midpoint-level. This is a problem-oriented approach which quantifies and translates the life cycle impacts into themes such as climate change, ozone depletion, acidification, human toxicity, social performance, costs, etc. The SSSD has been designed to align closely with several widely accepted international standards and norms (International Organization for Standardization, 2006a; International Organization for Standardization, 2006b; ESA LCA Working Group, 2016; Benoît and Mazijn, 2009; International Organization for Standardization, 2010; International Electrotechnical Commission, 2017; National Aeronautics and Space Administration, 2015; Valdivia et al., 2011; United Nations Environment Programme and Society of Environmental Toxicology &amp and Chemistry, 2011). A full methodological description of the SSSD is provided in 'Advanced Methods of Life Cycle Assessment for Space Systems' (Wilson, 2019), including a full description on the development of the social and economic models, including their inventories and impact assessment methods.

Within this analysis, the underlying assumptions for the LCI calculation of both scenarios are based on a literature review of space activities in 2018. Gathered LCI data was either used directly, using proxies supplied by the SSSD or by applying methods of extrapolation. In particular, mass-based emission factors for the average production and manufacturing of spacecraft were derived from two SmallSat space missions designed at the University of Strathclyde's Concurrent & Collaborative Design Studio in 2017 and 2019 called M̀IOS and NEACORE (Wilson, 2019). M̀IOS is a small satellite mission with a mass of less than 300 kg. With an expected mission duration of 2 years, it aims to collect data on the lunar micrometeorite and radiation environment as well as detect the presence of water/ice on the lunar South Pole in view of a future Moon base. In comparison, NEACORE is a low-cost interplanetary mission involving up to six 12 U CubeSats with a low thrust propulsion system. The mission aims to estimate the relative position, velocity and 2D shape of near-Earth objects, with an expected mission duration of between 3 and 6 years. Furthermore, the S-LCA data included in this analysis was generated using averaged values

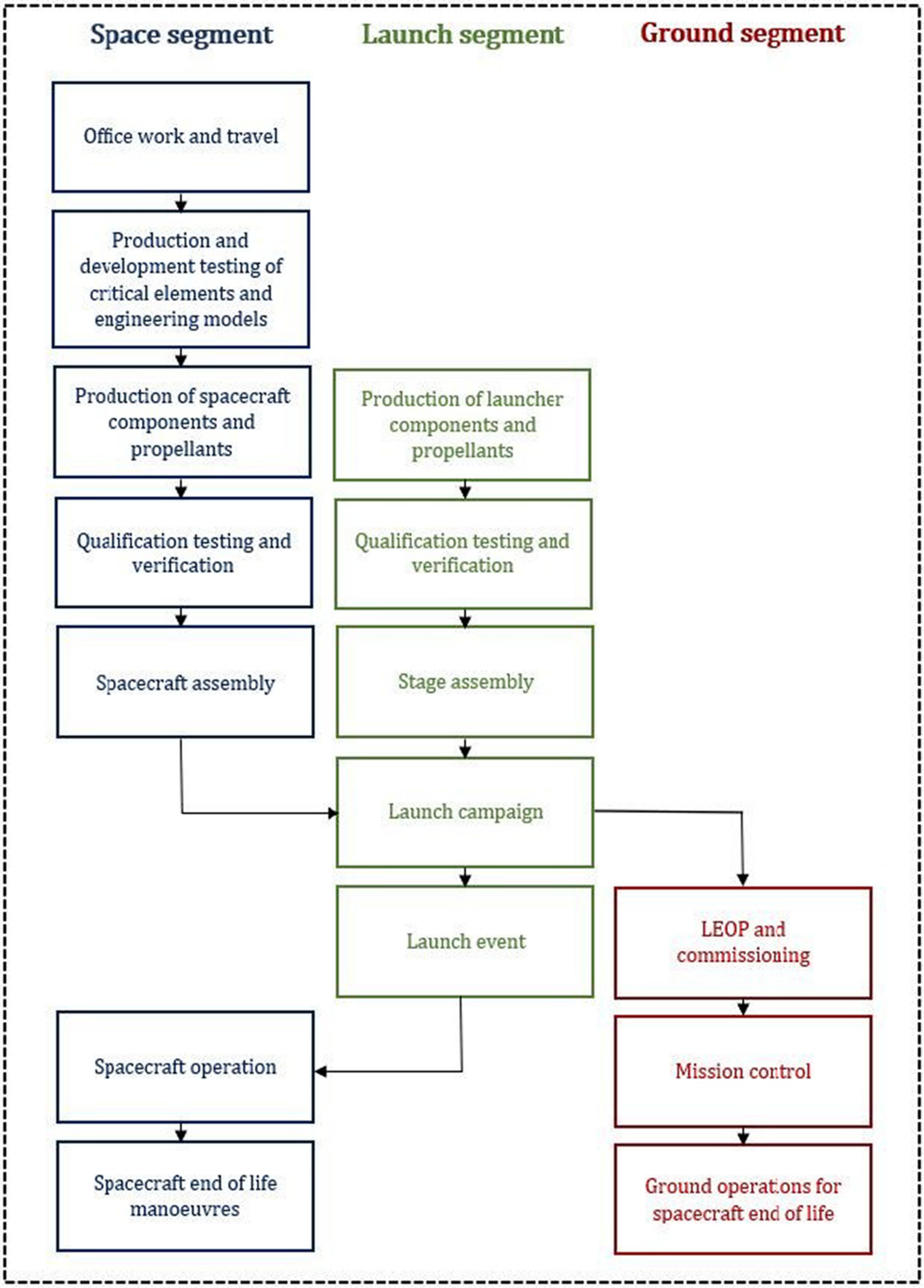


Fig. 1. System boundary of annual global space activities (adapted from ESA LCA Working Group, 2016).

from datasets contained within the SSSD based on a national-level perspective for the stakeholder categories of value chain actors (VCAs) and workers. The life cycle impact of all space missions launched in 2018 was calculated and used to represent the annual impact. It is within this context that LCI data began to be generated, as documented for scenario one below.

2.2.1. Scenario one

In terms of the space segment, the LCI data for work-hours and travel were based on default SSSD values which were originally obtained from expert input during the HATHI study (Wilson, 2019). These figures were then multiplied by the number of space missions launched in 2018 as identified during the literature review. In this regard, according to UNOOSA's 'Online Index of Object Launched into Outer Space', 452 objects were placed into orbit in 2018 (Kyle, 2021; United Nations Office for Outer Space Affairs, 2021). Through the extrapolation of data contained within the Union of Concerned Scientists Satellite Database (Union of Concerned Scientists, 2021), it was found that the average mass of these objects was 617.41 kg per spacecraft. Therefore, based on these figures, it can be postulated that the total mass of spacecraft put into orbit in 2018 is 279,069.32 kg. The LCIA results relating to the manufacturing and production of the MIOS and NEACORE missions were then scaled to 1 kg and averaged before being multiplied by this figure to provide an approximation relating to the sustainability impacts of this activity. It was also estimated that an average of 5 spacecraft models would be created per space mission using a 1:1 mass ratio. In a similar manner to work-hours and travel, AIT (assembly, integration & testing) and spacecraft activities during the launch campaign were calculated based on SSSD default values using the number of space missions launched in 2018. The manufacturing and production of spacecraft propellants and pressurants including their management were based on averaged propellant mass to spacecraft dry mass ratio observed during the M̀IOS and NEACORE missions. This was then scaled to 452 spacecraft. All propellants and pressurants listed within the SSSD were applied within this analysis using the following breakdown: helium (30%), N_2 (10%), high performance green propellant (HPGP) (5%), hydrazine (30%), MMH (10%), MON-3 (10%) and chemical-electric propulsion systems using xenon (5%).

With regards to the launch segment, according to the 2018 Space Launch Report, 114 launches occurred in the calendar year of 2018 (Kyle, 2021). Of these, 111 were successful. A breakdown of these orbital launches by launcher type is provided in Fig. 2. The launchers indicated in orange mean that the SSSD contains specific data within it relating to that launcher type. This provides a 46.5% coverage. However, it should be noted that 33.33% of these successful orbital launches relate specifically to the Long March launcher for which the SSSD does not contain data. For each launcher where this is the case, the generic launcher processes were used as input based on the appropriate stage masses and propellant volumes for each launcher type found through a literature review.

The LCI of the launch segment was therefore calculated by scaling this data to the total number of launches per launcher type. This includes the manufacturing and production of each launcher and its propellants. AIT and the launch campaign were calculated based on SSSD default values using the total number of launches in 2018 to scale up these activities. The launch event was calculated using the same scaling method as the manufacturing and production activities within relevant SSSD launcher processes. For launchers not included within the SSSD, values obtained during the literature review were used within 'Launch event by propellant type' processes for the masses of the observed propellant types of each launcher. This also included the total mass disposed to the ocean from spent launcher stages. However, it is important to note that eleven out of the twenty Falcon 9 launches used reusable rocket stages (Kyle, 2021). This was also factored into the calculation.

Looking at ground segment, averaged values obtained during the M̀IOS and NEACORE missions were used to portray the use of ground stations and control centres during launch & early orbit phase (LEOP), commissioning, routine and ground operations at the end of life. A 10-year average mission lifetime was assumed for each space mission meaning that the M̀IOS and NEACORE were scaled to this reference. It was also assumed that none of the spacecraft were systematically salvaged after re-entry. According to ESA, about 20–40% of large spacecraft typically survives re-entry to reach Earth's surface (European Space Agency, 2019). As such, it was considered that 70% of spacecraft components would burn-up on re-entry whilst 30% impact water bodies. Since no data could be found on the number of planned re-entries for the 2018 missions, a 100% re-entry rate was assumed as a worst-case scenario.

2.2.2. Scenario two

The LCI of the second scenario considered the linear scaling up of space sector activities due to ease of access to space. Under this scenario, the analysis assumed 750 launches take place in one calendar year whilst 5000 spacecraft with an average mass of 1000 kg were placed in orbit with an average mission lifetime of 10 years. This means that a total mass of 5000,000 kg will be placed in orbit. Due to the prospect of mega-constellations encapsulating a large proportion of this mass (where the baseline is typically an electric propulsion), the following breakdown was assumed: helium (15%), N_2 (5%), HPGP (5%), hydrazine (15%), MMH (5%), MON-3 (5%) and chemical-electric propulsion systems using xenon (50%). A 50% reuse of launcher components was also considered which lessens the potential impact of production & manufacturing of launchers and disposal to the ocean. These guesstimates are aligned with observable trends relating to the potential future direction of space industry development (Leach, 2014). These figures were then applied within the first scenario, replacing the other previously stated figures and assumptions. Although this clearly does not provide a completely accurate overview of the potential activities that may occur due to mega-constellations, space tourism and Moon/Mars colonisation, it avoids attempts at predicting future space activities and the precise processes involved whilst continuing to scale up impacts to account for increased launches and space system development.

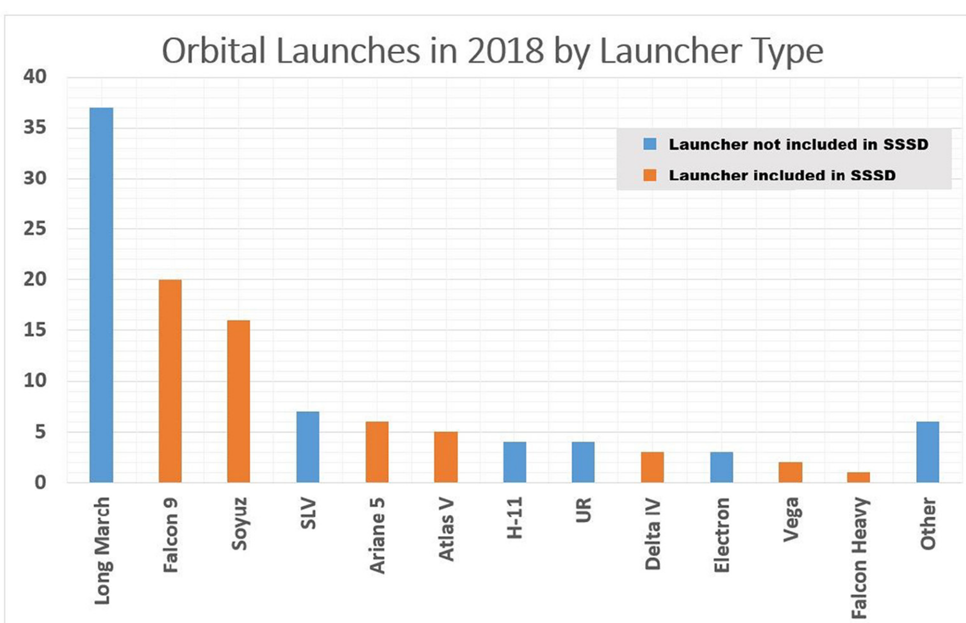


Fig. 2. Orbital launches in 2018 by launcher type (adapted from Kyle, 2021).

3. Results and analysis

3.1. Life cycle impact assessment

The impact categories chosen for this study are presented in Table 1 below. These were selected on the basis that they are most relevant to the systems undergoing comparison and due to the constraints in place due to the normalisation procedures (outlined in Section 3.2). The applied LCIA methods across these impact categories, including model sources and reference units, are consistent with the recommendations of the ESA LCA handbook (ESA LCA Working Group, 2016). ESA mainly based the selection of their adopted methods on recommendations provided by the International Reference Life Cycle Data System (ILCD) and may look at moving towards the Product Environmental Footprint approach in the future. The ILCD was established in 2005 by the EC's Joint Research Centre (JRC) to harmonise European LCA methodology and provide a common basis for consistent, robust and quality assured life cycle data, methods and assessments (European Commission - Joint Research Centre, 2011). It should also be noted that the newly developed S-LCA and LCC impact categories have also been included as part of this analysis as single scores. A full methodological description on the development and use of these impact categories in the frame of the SSSD is provided in 'Advanced Methods of Life Cycle Assessment for Space Systems' (Wilson, 2019).

3.2. Normalisation procedures

Normalisation is an approach for making LCIA results more understandable by comparing them to reference values. A commonly used method in this regard is to relate impacts to annual consumption rates. The normalisation procedures applied as part of this study follow a global perspective since the impact of worldwide space missions have been measured. In reference to this study, the LCIA results of both scenarios can then be mapped against the annual worldwide impact of 2010 (Sala et al., 2017) and planetary boundaries (Sala et al., 2016). It can be argued that the contribution to planetary boundaries of global space missions is the most important performance indicator since it measures impacts with regard to safe operating thresholds/tipping points of the Earth system (i.e. the severity). However, assessing this against the contribution to worldwide impacts indicates where the impacts of space activities place in relation to the sum of all other anthropogenic activities (i.e. the contribution). Considering these together provides an outline of the relative performance of global space activities with regards to the significance of its sustainability impacts.

All eight of the E-LCA impact categories correlate with planetary boundaries and global normalisation factors (NFs) outlined from these reference sources (hence their selection). However, it should be noted that the planetary boundary defined for water consumption was considered to be impractically low, so the planetary boundary adopted for this impact category is based on the NF value proposed by Bjorn & Hauschild instead (Bjørn and Hauschild, 2015). Additionally, due to their novelty, NFs for S-LCA and LCC do not yet exist. This is based on the exact same method, but scaled up to represent worldwide impacts. In this regard, the NFs derived for S-LCA is based on the SDG Index (Lafortune et al., 2018) due to its similarities with the S-LCA approach adopted by the SSSD. The SDG Index frames the implementation of the 2030 Agenda for Sustainable Development by measuring and comparing the performance of 162 UN Member states towards achieving the SDGs. The index ranks each country on a scale of 0–100 (100 best, 0 worst) by aggregating ratings for each SDG (weighted equally) based on a variety of metrics. From this it was found that the average score across all Member States was 66 for 2018. In this regard, a score of 34 was used within this analysis to reflect the global average social impact of one work-hour of labour. This is because the scale of the SSSD is inversed in comparison to the SDG Index, meaning that the SSSD considers a score of 100 to be the worst and 0 the best. Additionally, from OECD data, it was found that the average annual working time for 2018 was 1734 work-hours (Organization for Economic Co-Operation &amp and Development, 2020). Therefore, it can be assumed that the typical social score of an average global employee is 58,956 per annum. This value is simply obtained by multiplying the derived score of 34 by the average annual working time of 1734 work-hours. Given that the World Bank reports that the global labour force in 2018 was 3.427 billion (World Bank, 2020a), then this creates an annual global social score of 2.02E + 14. In terms of the planetary boundary, the same methodology was followed, where a score of 100 was assumed rather than 34 to produce a maximum potential annual global social score which equates to 5.94E + 14. Finally, in terms of LCC, the NF used to represent annual worldwide impact is defined as the total global taxation in 2015 whilst the NFs applied to represent the planetary boundary is based on total worldwide GDP in 2016 (World Bank, 2020b; KPMG, 2015; United Nations Department of Economic &amp and Social Affairs - Population Division, 2017). An overview of these NFs and planetary boundaries can be found in Table 2.

An overview of the normalised results is provided in Fig. 3 below based on the LCIA results contained within Table 2. Fig. 3a provides the estimate for the life cycle sustainability impact of all worldwide space missions launched in the year 2018. In comparison, Fig. 3b provides this estimate for the future scenario, where 750 launches are assumed in one calendar year to deliver a total of 5000 spacecraft into orbit.

3.3. Interpretation

Based on these results, three categories of particular interest are air acidification, freshwater aquatic ecotoxicity and ozone depletion due to their impacts compared to NFs. In terms of air acidification, within Scenario 1, it can be seen that the production & manufacturing of launcher propellants is responsible for the greatest impact (38.81%). However, this shifts to the production & manufacturing of spacecraft propellants in Scenario 2 (68.03%) due to the amount of sulphur dioxide, nitrogen oxides and ammonia released as part of the cryogenic air separation process for the chemical-electric propulsion system. A similar result is found within the freshwater aquatic ecotoxicity impact category where the greatest impact for Scenario 1 came from the production & manufacturing of spacecraft components (68.68%), most notably due to the release of arsenic, mercury and dioxins to air from germanium production & manufacturing. However, Scenario

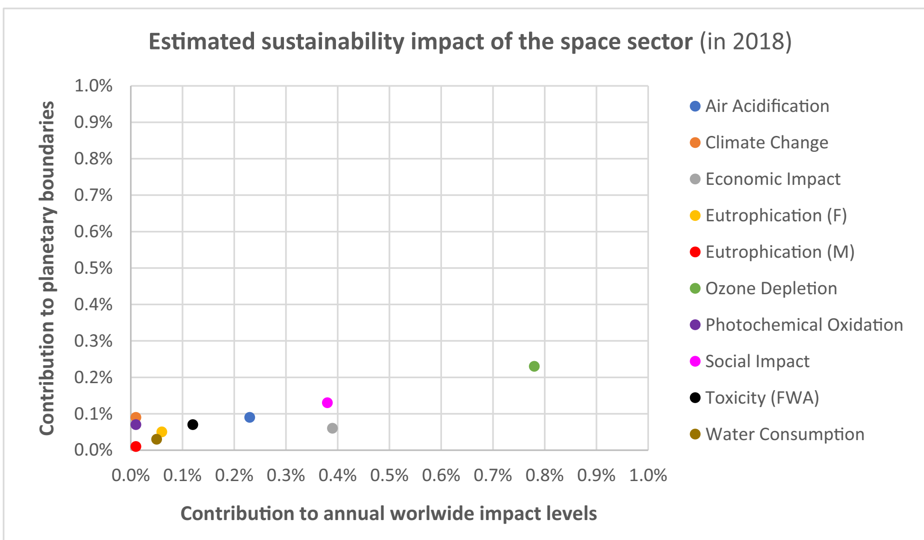
Table 1
SSSD LCIA results of both scenarios.

Impact Category	Source	Reference Unit	LCIA Results	
			Scenario One	Scenario Two
Air Acidification	CML (2002) (Guińee and Lindeijer, 2002)	kg SO_2 eq.	2.68E + 07	6.10E + 08
Climate Change (GWP100)	IPCC (2013) (Myhre et al., 2013)	kg CO_2 eq.	5.96E + 09	1.20E + 11
Economic Impact (CY:2000)	Wilson (2019) (Wilson, 2019)	EUR (2000)	4.38E + 10	5.28E + 11
Eutrophication (Freshwater)	ReCiPe (2008) (Goedkoop et al., 2009)	kg P eq.	2.92E + 06	1.03E + 08
Eutrophication (Marine)	ReCiPe (2008) (Goedkoop et al., 2009)	kg N eq.	5.50E + 06	1.11E + 08
Ozone Depletion (Steady State)	WMO (1999) (World Meteorological Organization, 1999)	kg CFC-11 eq.	1.25E + 06	8.26E + 06
Photochemical Oxidation	ReCiPe (2008) (Goedkoop et al., 2009)	kg NMVOC	1.95E + 07	3.71E + 08
Social Impact	Wilson (2019) (Wilson, 2019)	social score	7.72E + 11	8.53E + 12
Toxicity (Freshwater Aquatic)	USEtox (2017) (Rosenbaum et al., 2008)	PAF.m^3.day	9.77E + 10	2.66E + 12
Water Consumption	ReCiPe (2008) (Goedkoop et al., 2009)	m^3	3.58E + 10	1.20E + 12

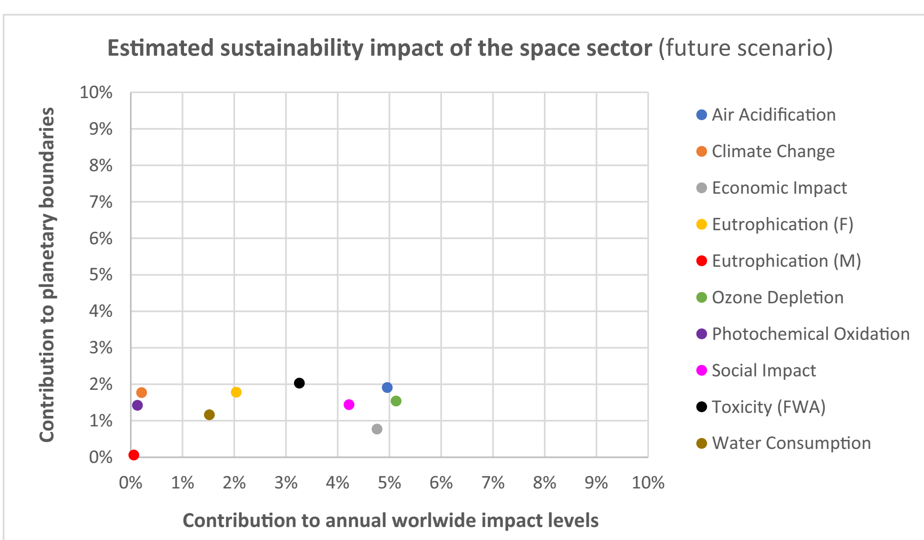
Table 2
Applied normalisation factors for space activities impact analysis (Wilson, 2019; Sala et al., 2017; Sala et al., 2016; Bjørn and Hauschild, 2015; Lafortune et al., 2018; Organization for Economic Co-Operation &amp and Development, 2020; World Bank, 2020a; World Bank, 2020b; KPMG, 2015; United Nations Department of Economic &amp and Social Affairs - Population Division, 2017).

Impact Category	Unit	Annual Worldwide Impact	Estimated Planetary Boundary	Overall Robustness
Air Acidification	kg SO_2 eq.	1.23E+10	3.20E+10	High
Climate Change	kg CO_2 eq.	5.79E+13	6.79E+12	V. High
Economic Impact	EUR (2000)	1.11E+13	6.84E+13	N/A
Eutrophication (F)	kg P eq.	5.06E+09	5.79E+09	Med to Low
Eutrophication (M)	kg N eq.	1.95E+11	2.00E+11	Med to Low
Ozone Depletion	kg CFC-11 eq.	1.61E+08	5.38E+08	Med
Photochemical Ox.	kg NMVOC	2.80E+11	2.62E+10	Med
Social Impact	social score	2.02E+14	5.94E+14	N/A
Toxicity (FWA)	PAF.m^3.day	8.15E+13	1.31E+14	Low
Water Consumption	m^3	7.91E+13	1.04E+14	Med to Low

Note: Annual worldwide impacts refer to 2010 levels except for economic and social impacts which refer to 2016 and 2018 levels respectively. Due to the nature of their formulation, economic and social planetary boundaries are also based on 2016 and 2018 levels.



(a)



(b)

Fig. 3. Estimated Sustainability Impact of Annual Global Space Activities.

2 also sees production & manufacturing of spacecraft propellants produce the greatest impact (47.76%) due to the release of chromium VI along with copper, nickel, vanadium and zinc ions to groundwater during the cryogenic air separation process for the chemical-electric propulsion system. As such, it can be determined that the cryogenic air separation process could be a considerable environmental hotspot for future space missions, which draws similarities to the findings of Pettersen et al. (Pettersen et al., 2017; Pettersen et al., 2016). For ozone depletion, the impact comes almost entirely from ClO_x, NO_x, HO_x and HCl emissions of the launch event (99.97% for Scenario 1 and 99.88% for Scenario 2), particularly due to from the combustion of the solid propellant.

In terms of social and economic impacts, the majority of the S-LCA score was generated within Phase C + D (83.34% in the first scenario and 87.71% in the second scenario). This is primarily due to the high levels of organisational involvement within this phase which would clearly drive an organisation's S-LCA score. In terms of LCC, the total cost of Scenario 1 was 4.38E+10 EUR 2000 which increased to 5.28E+11 EUR 2000 in Scenario 2. This is primarily due to additional research & development activities together with increased levels of production & manufacturing in line with new space developments as part of Scenario 2. Additionally, the relative share of costs across Phase E1 and Phase E2 fell from 17.96% to 10.76% between Scenario 1 and Scenario 2. This is mainly due to cheaper access to space, which is envisioned as part of Scenario 2 in addition to the fact that a proportionally smaller workforce is required for satellite operations per mission.

4. Evaluation and reflection

4.1. Discussion

As a basis for evaluation, the environmental impact categories of climate change and ozone depletion will be discussed further due to the widespread scientific interest in regulating these impacts. Additionally, social and economic impacts will also be discussed due to the novelty of considering them from a life cycle perspective within the space sector.

In terms of climate change, 84.90% of the total LCIA result for 2018 came from the production & manufacturing of spacecraft and launcher components and propellants (which includes their management, handling and storage). This impact was primarily due to the CO_2 released during heat and electricity consumption. Overall, this analysis estimates that total global contribution of space missions towards climate change is just 0.01% of total emissions for the 2018 scenario and 0.21% for the future scenario. For reference, this equates to 54 days and 1082 days of daily averaged GHG emissions in Scotland for 2017 (Scottish Government, 2019). Whilst this would indicate that the overall impact is insignificant in comparison to other sectors, in comparison to the global aviation industry (which currently accounts for between 2 and 3% of all anthropogenic CO_2 emissions) (Wilkerson et al., 2010), this is a particularly alarming result. In this regard, the International Civil Aviation Organization reported that 38 million flights departed in 2018 (International Civil Aviation Organization, 2018). This compares to just 114 launches in the same year (Kyle, 2021), indicating that the impact per launch vehicle is several orders of magnitude greater than that of an aircraft. The influence on planetary boundaries is much greater, with a 0.09% contribution for the 2018 scenario and 1.77% for the future scenario. This highlights the urgent need for addressing climate change since more CO_2e is currently being emitted than the planet can cope with to restore its natural equilibrium. The breach of this planetary threshold outlined in Table 2 reaffirms the high urgency of addressing this impact category. Despite this, Ross and Sheaffer (2014) suggest that the radiative forcing caused by annual rocket launches alone contribute about one fourth of the relaxed forcing attributed to global aviation. This was primarily driven by black carbon and aluminium oxide as exhaust products, which the SSSD does not characterise as part of the climate change impact category due to insufficient data. However, the large uncertainty attached to Ross & Sheaffer's finding means there is an urgent need to verify this result. Should it prove to be accurate, the amplification is enormous and would make black carbon and aluminium oxide not only non-negligible, but a dominant factor in the life cycle of space missions.

Additionally, 99.97% of the observed ozone depletion impact in 2018 comes from the launch segment during Phase E1 due to HCl and oxygen radicals. This is due to chemical reactions on the surface of ice crystals which can convert chlorine containing compounds such as HCl into more reactive forms, priming severe ozone destruction, whilst recent findings suggest that NO_x radicals from human activity can cause twice as much ozone depletion than the next leading ozone-depleting gas. As a result, contrary to the WMO assessment on ozone which predicts that rocket launches have a small effect on total stratospheric ozone (causing much less than 0.1% loss) (World Meteorological Organization, 2018), this analysis estimates that total annual ozone destruction caused by global launches in 2018 could be on the order of about 0.78% of total emissions which leads to a 0.23% contribution to the planetary boundary. The WMO report goes on to suggest that modern space industry developments could lead to a more significant increase in launcher exhaust emissions than reported in previous assessments. In this regard, under the future scenario, this analysis estimates an impact of 5.13% of total emissions which leads to a 1.54% contribution to the planetary boundary. However, it is important to note that existing gaps in knowledge relating to the chemical, radiative and dynamical impacts of launcher exhaust products on the global stratosphere meant that CFs with regards to altitude of emissions could not be formulated within the SSSD. This omission limits the confidence level of these ozone predictions. It is expected that the significance of these impacts would considerably decrease with the application of altitude-dependant CFs.

The S-LCA results indicated that the 2018 scenario would contribute 0.30% of the total 2016 worldwide social score and 0.22% of the maximum potential social score. In comparison, the future scenario would contribute 3.32% of the total 2016 worldwide social score and 2.43% of the maximum potential social score. Of this impact, 83.34% arose during Phase C + D for the 2018 scenario, rising to 87.71% for the future scenario. This was due to a 50% launcher reuse considered as part of this scenario meaning less production & manufacturing time was being spent on launchers, which came into the system boundary during Phase E1. Overall, it was found that the total social score achieved was primarily due to the number of organisations which were involved in the supply chain to manufacture, produce and test spacecraft components. In particular, the large influence of US-based organisations within the space sector defined this result. This is because at a national-level, US-based organisations scored the 7th worst out of the 10 countries where LCI data was gathered. Primarily, this was due to the high social scores obtained for the stakeholder subcategories of fair competition and equal opportunities/discrimination. For example, the high score within this latter point was primarily reached because of the large gender pay gap present in the country. According to the Bureau of Labor Statistics, an average woman's unadjusted annual salary falls between 78% and 82% of that of the average man's (O'Brien, 2015; United States Bureau of Labor Statistics, 2014). This therefore attributed the maximum score for this social indicator. However, these S-LCA results are clearly the most contentious out of all the other impact categories since specific organisational data has not been used.

When considering LCC, it was found that the total costs associated with the 2018 scenario was 0.39% of global taxation in 2015 and 0.06% of worldwide GDP. In terms of the future scenario, it was found that the total costs would equate to 4.76% of global taxation in 2015 and 0.77% of worldwide GDP. These results were then compared to global satellite industry revenues for 2018 as reported by the Satellite Industry Association (Satellite Industry Association, 2019). Within this report, it was found that the global space economy was worth $360 billion of which 77% was related to the satellite industry. When excluding satellite service revenues from this analysis, it was found that the total revenues for satellite manufacturing, the launcher industry and ground equipment, was $151 billion. This equates to 9.36E+10 EUR (2000). In comparison to 2015 worldwide GDP, this equates to 0.14%. This is comparable to the result generated within this analysis for the 2018 scenario since this figure reflects costs, whilst the result obtained from the Satellite Industry Association document reflects revenues. As such, a higher value was expected to be obtained within this document to reflect profit margins which in this case averages at 29.03% for the space sector. However, it should be noted that the GNSS ground segment equipment contributed 61.83% of satellite manufacturing, the launcher industry and ground equipment revenue within the Satellite Industry Association report. In this regard, it can be determined that this operation has a large influence on results and the fact that this was not specifically considered within the analysis due to the generalisation of the LCI may be what is causing this high profit margin. Despite this, the similarity and clear correlation between the figures contained within this analysis and the Satellite Industry Association report adds credibility to the general accuracy of the generated results.

4.2. Limitations

In terms of limitations, a significant weakness of this study is that the potential radiative forcing and ozone destruction caused by black carbon and aluminium oxide from rocket propulsion has not been captured by this analysis. This is because the SSSD classified these exhaust products as entirely independent impact categories due to the large uncertainty attached to their potential impact at different altitudes. In this regard, the exclusion of black carbon and aluminium oxide was mainly due to the high uncertainty surrounding these exhaust products. In particular, the Product Environmental Footprint Category Rules (PEFCR) guidelines state that "the GWPs for near term GHGs are not recommended for use due to their complexity and high uncertainty. Near term GHGs refer to substances that are not well-mixed once emitted to the atmosphere because of their very rapid decay" with black carbon given as a specific example (European Commission - Joint Research Centre, 2018). This is also the case for re-entry smoke particles (RSPs) generated during the re-entry event of spacecraft since RSP generation is not yet widely appreciated and the impact is generally considered insignificant at present. However with the prospect of future mega-constellations being proposed, it is becoming an area that requires much further study, as such constellations may produce a constant 'rain' of objects which may lead to RSP generation becoming a more significant concern due to its greater impact on climate or ozone, with NO_x emissions being a particular area of concern (Ross, Personal communication; David, 2017; Larson et al., 2017). Very few attempts have been made to characterise the amount or composition of RSPs since the fraction of re-entering mass that forms RSPs is highly variable from object-to-object and depends on various factors such as materials, mass and entry velocity. Further studies into re-entry impacts are under way (Combes et al., 2015; Bianchi and Grassi, 2018). Despite this, it is theorised that each of these emissions (black carbon, aluminium oxide, RSPs) could have a significant influence on climate change and ozone depletion, including other environmental impact categories, making this a major exclusion to the study. Based on this, further research is required to develop robust, altitude-dependent characterisation factors to gain a better understanding into the role and influence of these emissions in the future.

Another notable exclusion from the study was space debris impacts. This was because the Earth environment and orbital environment were considered to be separate issues. Although orbital impacts were outside the scope of the study, it should be noted that the exclusion of space debris does not mean that there is zero impact on the orbital environment. On the contrary, space debris is one of the greatest sustainability challenges facing future space activity and as such, work into integrating this as an impact category within space LCA has already been attempted by Maury (2019). Therefore, a similar study on orbital impacts could compliment this analysis in the future.

Additionally, it is important to note that the prospect of intercontinental suborbital point-to-point travel has been excluded from this analysis as it was considered to be less achievable in the mid-term future. However, it is recommended that this is thoroughly investigated within longer-term outlooks, as the realisation of this prospect could increase annual launch rates by several orders of magnitude. Given the findings of this analysis, if inter-continental suborbital point-to-point travel is left unmitigated its impact is likely to be considerable. In this regard, there is a distinct possibility that the generated CO_2 emissions could greatly surpass those generated by the entire aviation industry, with just a few thousand flights per year.

In terms of the SSSD, the LCI datasets contained within the database are mainly based on secondary sources. This was mostly driven by a lack of available or reliable data and a lack of willingness of companies to contribute data, due to fear of being seen as the 'black sheep' of the industry. Additionally, due the novelty and lack of scientific research on some topics, some flows were absent from SSSD LCI datasets meaning that placeholder flow indicators or proxies had to be used instead. Additionally, the only stakeholder impact categories included within the SSSD for S-LCA are value chain actors and workers, meaning that potential meaningful impacts to consumers, society and local community have been overlooked. Finally, the normalisation procedures used for the E-LCA impact categories are not completely comparable to those which are used for within S-LCA and LCC. This may has ramifications with regard to the significance levels of these impacts as a basis for comparison within Fig. 2.

Based on the normalised results, it can be considered that a major limitation of this approach is the omission of the human toxicity and mineral resource depletion from Fig. 3, despite these representing two of ESA's five hotspot impact categories (ESA Clean Space Initiative, Personal communication). This is a considerable exclusion since the M̀IOS and NEACORE studies have demonstrated the significance of these impact categories towards space LCA studies through multi-criteria decision analysis (Wilson, 2019). The reason for this is because no planetary boundary value is available for either of these impact categories. This is primarily due to gaps in knowledge caused by incomplete emissions accounting and issues associated with modelling exercises which has meant that assigning an unequivocal level of pressure due to human activities was not possible and hence a measurable ecological threshold could not be determined (Sala et al., 2016). Although defining planetary boundaries for both of these environmental issues is still a topic of discussion, without such a threshold, a NF could not be provided for either impact category. Therefore, the statistical power of this approach could be considered to be reduced since the proportion of impact categories excluded from the analysis has the distinct possibility to produce larger standard errors. Whilst this may limit confidence levels of the analysis by overlooking particularly meaningful impacts, it was an unavoidable feature of this modelling approach.

However, the main drawback of this analysis was its generalisation. In particular, specific spacecraft and components were not analysed due to a lack of data and time constraints. To overcome this, averages were taken from the M̀IOS and NEACORE mission which may not be the most representative choice for representing the sustainability impacts of all space missions in 2018.

Additionally, European manufacturing and production processes have been used to represent all spacecraft manufacturing which is over-simplistic. This is because the LCI datasets contained within the SSSD are mainly European-focussed. Finally, the production & manufacturing of lunar/mars modules or different launchers were not considered within the future scenario. This was mainly driven by a lack of data within the SSSD.

Despite this, since a streamlined LCSA was adopted, these limitations and methodological choices were deemed acceptable for this analysis in order to provide a first-order overview of annual life cycle sustainability results from space activities. As such, a more detailed analysis is recommended in the future, should more data become available.

4.3. Recommendations

Given the novelty of this research topic, further development is required in order to advance this study from a first-order approximation to a second-order approximation. Three high-level recommendations have been provided as a basis for future research in order to address the limitations listed in Section 4.2 and further consolidate/advance this work:

1. More research into E-LCA/LCSA of space systems is required at a general level, but with a particular focus on filling some of the data gaps outlined by this study.

2. The results of this analysis should be improved through the integration of new data into future estimates, including using different satellite types as a basis for analysis with a view of eventually moving away from a streamlined analysis towards a full LCSA.
3. The provided estimate should be expanded by calculating the impact of the entire space sector as opposed to just space activities, including the upstream, downstream and midstream segments.

5. Conclusions

Overall, this study has provided the space sector with a better insight into the consequences of its operations, suggesting that its future growth will be constrained by environmental limits. Although further research is needed to develop and expand on this analysis, it can be concluded that whilst the industry's contribution to adverse sustainability impacts is minimal at present, these impacts may become more meaningful with the scaling up of space activities in the near-to-medium term future. In such an event, scientifically quantifying and reducing environmental, social and economic impacts of space missions will become an increasingly more important subject within the industry and will likely become a fundamental component of space mission design. For this reason, we predict that the use of space-specific E-LCA/LCSA will become ever more prevalent within this process throughout the decade.

CRediT authorship contribution statement

Andrew Ross Wilson: Conceptualization, Methodology, Data curation, Software, Visualization, Investigation, Writing – original draft. **Massimiliano Vasile:** Supervision, Writing – review & editing. **Christie A. Maddock:** Supervision, Writing – review & editing. **Keith J. Baker:** Supervision, Writing – review & editing.

Declaration of competing interest

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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