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Life cycle assessment as a tool for sustainable space activity in Aotearoa New Zealand

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Abstract

New Zealand's space sector is at the early stages of growth but already attracts 1.5% of global private investment in space and contributes NZD 1.75 billion per year in revenue to the national economy. Growth has in part been due to the country's desirable location for space operations due to a combination of geographic advantages, with its clear seas and skies and access to a wide range of launch angles, a skilled workforce, and strong government financial incentives.

There are however challenges to future space activities such as the risk to long-term access and use of Earth's orbital environment, specifically from space debris and a growing challenge to the whole-of-life of space operations, from the climate emergency and biodiversity crises. Consequently, there is increasing global motivation and urgency to quantify environmental consequences of space activities, which have historically been omitted from legislative and regulatory requirements. This paper provides a summary of the commercial development of New Zealand's space sector and where appropriate environmental regulation and legislation may have been overlooked, as well as outlining broader environmental concerns of space operations.

New Zealand's emerging space industry offers a unique opportunity to integrate international best practices for environment and sustainability at a foundational level, for example, the European Space Agency's Clean Space Initiative and their Life Cycle Assessment (LCA) Tool and Eco-design Framework. These types of tools provide valuable sources of information to support policy and business decisions.

This paper provides a case study for an environmental LCA for a New Zealand designed and launched CubeSat which is the most launched satellite type from New Zealand. The case study indicates how the LCA can be used to identify environmental hotspots during

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Abbreviations: APSS, Auckland Programme for Space Systems; ESA, European Space Agency; LCA, Life Cycle Assessment; LCIA, Life Cycle Impact Assessment; LCSA, Life Cycle Sustainability Assessment; LRE, Liquid Rocket Engines; MBIE, Ministry for Business, Innovation and Employment; NASA, National Aeronautics and Space Administration; NZ, Aotearoa New Zealand; NZSA, New Zealand Space Agency; OSHAA, Outer Space and High-Altitude Activities Act; OST, Outer Space Treaty; SRM, Solid Rocket Motor; SSSD, Strathclyde Space Systems Database

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the preliminary and detailed design phases as well as the launch event. Barriers and gaps in data collection have also been identified. As a result of this work, a set of recommendations have been made for further research requirements on the application of LCA to space activities.

Keywords: Space sustainability; environmental impact; Life cycle assessment; New space

1. Introduction

The global space sector has historically been driven by a combination of geopolitical factors, technology development and governmental regulatory frameworks (Peeters & Jolly, 2004). As public funding for the space sector has reduced over the last two decades, New Space and the increasingly commercialised space industry has brought a speed and agility that continues to transform the sector, by building younger, more efficient teams to generate cost-effective innovations, incentivised by a financial culture that is accepting of high market risk (Cornell, 2011). By 2000, 65 % of the space revenue in the US and 50 % in Western Europe was generated from privately funded activity. Meanwhile, international and national space legislation has lagged, including updates to the Outer Space Treaty (OST) with respect to commercialisation (Peeters, 2002) and environmental impact (Wilson, 2019). However, the public sector continues to have a key influence in the space economy through investments, operations, regulations and joint development of products and services (OECD, 2021).

Superimposed onto this is the increasing pressure on space agencies to consider broader societal aims (Robinson & Mazzucato, 2019), including social well-being and sustainable growth, as well as preservation of Earth's orbital environment (OECD, 2021; UN COPUOS, 2016). While space technology plays a critical role in helping monitor Earth's climate and environment, its own environmental impacts have historically not been understood or accounted for (Maury et al., 2020; Wilson, 2019).

These value tensions present a unique opportunity for space agencies and businesses who are early in their development to innovate and optimise their activities to support the delivery of positive outcomes for the four dimensions of sustainable development – society, environment, culture and economy (UN General Assembly, 2015) as well as mitigating risks and maximising benefits to their operations.

In this paper, we describe New Zealand's space sector development and present a case study of a CubeSat using the environmental life cycle assessment (LCA) methodology. Section 2 provides an overview of New Zealand's space sector ecosystem, its legislative environment and global context on emerging environmental concerns from space activities. Section 3 describes the LCA methodology and its relevance to space system design, including similar studies that have been performed in Europe and the United States of America (USA). Section 3 also describes the Strathclyde Space Systems Database (SSSD), developed at the University of Strathclyde as a life cycle sustainability assessment tool, that was used to perform a case study presented in Section 4. The case study of a 1U CubeSat designed, built and launched in New Zealand using up-to-date data from the SSSD highlights the importance of data collection and interpretation in order to understand its environmental impact.

In line with global efforts (Maury et al., 2020; Wilson, 2019), the broader aim of this research is to accelerate the adoption and integration of environmental LCA into industrial and research activity within New Zealand's space sector to account for and reduce its environmental impact.

2. Aotearoa New Zealand's space sector

The New Zealand space sector began its rapid development with the establishment of the nation's space agency in 2016, following Rocket Lab's proposal to commence commercial space launches (Scott, 2020). The SpaceBase Directory identifies 231 unique organizations, at the time of writing, characterised by a mixture of start-up and well-established companies, educational and research institutions, and special interest groups (SpaceBase., n.d.). A 2019 survey conducted by 'Deloitte access economics' using the NZ Aerospace directory, which sought to better understand the NZ space economy, found the sector to be New Space driven. More than 60 % of respondents identified as commercial companies. The industry primarily consists of small, new businesses, commonly reporting annual turnover between NZD 200,000 and NZD 2 million and employing between 1 and 19 full-time equivalent employees. However, some well-established companies include 14 companies earning more than NZD 10 million per annum and 16 companies employing more than 200 + employees (Deloitte, 2019).

The recent development of the New Zealand space sector has largely been catalysed by the presence of Rocket Lab USA Inc with a subsidiary in New Zealand, that provides end-to-end space services. Their presence in New Zealand reflects the geographic advantages of the country for space operations, with its clear seas and skies and access to a wide range of launch angles, and strong government financial incentives (Deloitte, 2019).

Sub-sectors of the New Zealand space economy are shown in Table 1, with the significant sub-sectors being space manufacturing and space applications. The space manufacturing sub-sector renders the NZ space economy unique. It does not have a sizeable government-funded defence or aerospace sector that typically supports space manufacturing like in other nations. Meanwhile, the space applications sub-sector is largely driven by public demand for data (Deloitte, 2019).

NZ's space sector is estimated to generate NZD 1.75 billion per year in revenue (in 2019), representing 0.5 % of the New Zealand economy and 0.27 % of the global space economy. Rocket Lab alone attracts 1.5 % of global investments in New Space. The sector contributes NZD 1.69 billion to the New Zealand economy, comprising the direct contribution of NZD 897 million and indirect contribution of NZD 789 million. It also supports 5000 full-time equivalent employees across all the space sub-sectors, equivalent to 0.2 % of the total New Zealand workforce. Revenue by sub-sector (Table 2) is dominated by space applications (57 %), followed by space manufacturing (13 %) and ancillary services (13 %) (Deloitte, 2019).

The New Zealand Space Agency (NZSA), under the Ministry of Business Innovation & Employment (MBIE), has a distinctive commercial focus (Scott, 2020), indicating its primary functions to be developing space policy, regulation of the use of space from New Zealand, supporting rocket launches, and enabling space-related business, science and innovation (NZSA, n.d.).).

Since its founding in 2016, the NZSA has approved a total of 394 satellites for launch (NZSA, 2021). Fig. 1 shows the mass distribution of the 394 satellites approved to be launched from New Zealand as of 30 September 2021. About 92 % of them have a mass of less than 10 kg, primarily CubeSats. As of 10 Jan 2022, 109 satellites have been launched aboard the Electron rocket by the local launch provider Rocket Lab (Rocket Lab 2022a; Rocket Lab 2022b). The Electron is, to date, the only launch vehicle in New Zealand that has placed satellites in orbit, with others on the horizon (Dawn Aerospace, 2022; MBIE, 2021a, 2021b). Between 2016 and 2021, 81 missions have been approved to be launched from New Zealand. Fig. 2 shows that they predominantly originated from the USA (56 %), and were primarily for commercial organisations (59 %), followed by governmental (22 %) and educational (19 %) (NZSA, 2021). Some of the missions include multiple satellite payloads in a constellation arrangement.

Table 1
Primary sub-sectors of the New Zealand space economy (Deloitte, 2019).

Sub-sector	Respondents (n = 104)
Space manufacturing	25
Space operations	8
Space applications	29
Ancillary services	18
Research and development	15
Government	9

Table 2
New Zealand space economy revenue by sub-sector (Deloitte, 2019).

Sub-sector	NZD millions (2019 value)	Proportion of total revenue (%)
Space manufacturing	247	13
Space operations	150	9
Space applications	1,007	57
Ancillary services	221	13
Research and development	119	7
Government	10	1
Total	1,754	100

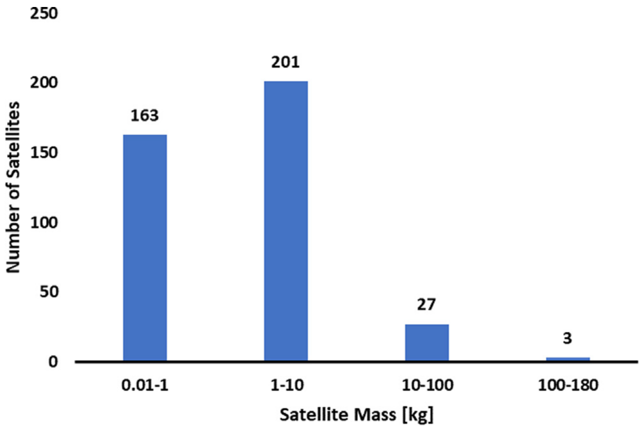

Fig. 1. Mass of satellites approved to be launched from New Zealand as of 30 September 2021 (New Zealand Space Agency, 2021).

The rapid growth observed in the sector in recent years corresponds to the commencement of Rocket Lab's commercial operations in which the majority of approved missions are for small satellites, Rocket Lab's target market (Schneider, 2018).

2.1. Legislative environment

The New Zealand space sector is regulated by the Outer Space and High-altitude Activities Act 2017 (OSHAA) which came into force in December 2017 and is administered by the NZSA within MBIE. The act enforces regulations through licenses and launch permits for launch facilities, high-altitude vehicles, and payloads. To be granted a license or permit, applicants must satisfy the following requirements:

- the technical capability to safely conduct the proposed activity — for example, a safe launch, or safe operation of the payload
- an orbital debris mitigation plan that meets any prescribed requirements
- that the proposed activity is consistent with New Zealand's international obligations.

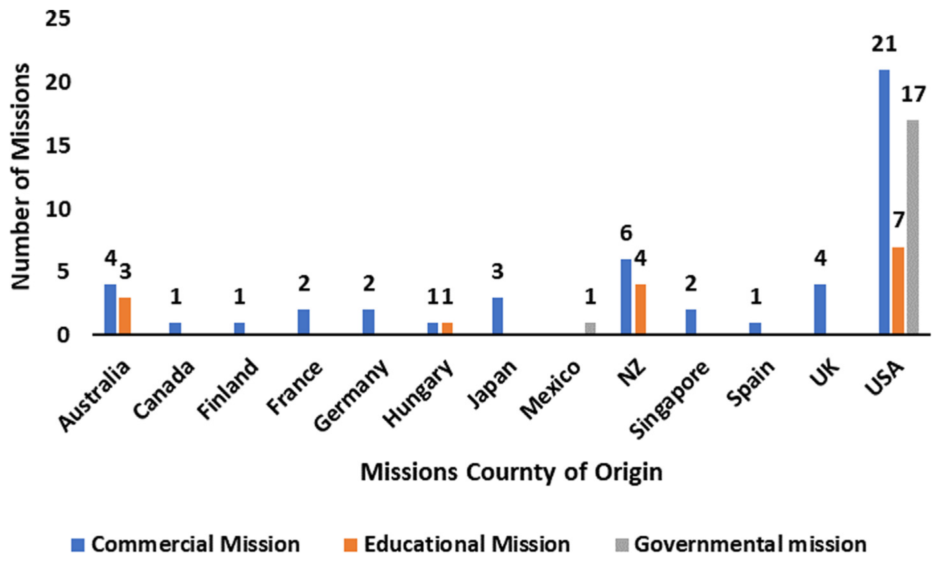

Fig. 2. Country of origin and mission type of satellites approved to be launched from New Zealand as of 30 September 2021 (New Zealand Space Agency, 2021).

The legislation also allows for the recognition of overseas licences and permits as satisfying some of the New Zealand requirements. OSHAA relies on existing New Zealand legislation such as the Resource Management Act, indicating all actors must comply with all other applicable New Zealand legislative requirements such as resource consent, health and safety and environmental requirements (OSHAA, 2017). In October 2016, the Economic Exclusion Act was amended to permit the deposition of material on the seabed from space launch vehicles (Ministry for the Environment, 2012), following an analysis from the National Institute of Water and Atmospheric Research (NIWA). The NIWA report considered 10 repeated launches to present a low risk to the marine environment, 100 launches to present a moderate risk, while 1000 launches could lead to high risk, depending on whether the debris is scattered or deposited in the same general area (Lamarche et al., 2017).

Analysis of the legislative framework created for the emerging space sector in New Zealand indicates that the New Zealand Government has taken a regulatory-state intervention approach, seeking to guide the market with ‘light touch’ interventions (Borroz, 2020). Evidence of the regulatory-state intervention approach can be seen on the NZSA website indicating one of its core missions is the removal of barriers to business: “Our laws minimise unnecessary prescription, by including detailed requirements in regulation. Compliance costs are also minimised, by enabling overseas licenses to satisfy New Zealand requirements.” (NZSA, n.d.).).

Another feature of the regulatory-state intervention approach is the preference to support established businesses with competitive business cases. The most prominent example of this is the joint agreement between the New Zealand Government and Rocket Lab to facilitate the development of a national space industry (NZSA, 2016). Moreover, for Rocket Lab to launch from New Zealand a Technology Safeguard Agreement (TSA) had to be signed with the United States. The TSA imposes an obligation on New Zealand for the secure transfer, use and management of US space launch technologies. The majority of these obligations on the New Zealand Government are to ensure compliance by Rocket Lab and third parties, such as Rocket Lab contractors (Hutchison et al., 2017). Atypical of a regulatory-state intervention approach, the NZSA refrains from providing specific monetary support. However, MBIE, within which NZSA operates, has provided funding to space initiatives, such as LeoLabs, an American space debris management firm (MBIE, 2021a, 2021b).

Forecast of the future of New Zealand’s space economy from this legislative analysis suggests that due to a business-friendly approach with relatively low barriers (including the approval of international permits and licences), the New Zealand space sector will attract more international business. However, the lack of direct funding and preference for established firms is likely to select for existing commercial companies with competitive business cases. This may lead to a New Space economy that generates barriers for latecomers and limited diversity within the sector (Borroz, 2020).

2.2. Environmental concerns

Other critiques of OSHAA suggest the legislation is short-sighted with regards to the environment, albeit from a marketing and communications perspective (Scott, 2020). Rocket Lab’s 200–300 kg payload launch vehicle, Electron, uses 10 LOx/RP-1 kerosene-fuelled Liquid Rocket Engines (LRE). There is a lack of new research on the environmental impact of space launches, and minimal research into the impact of LREs, with most research focusing on Solid

Rocket Motors (SRM) (Dallas et al., 2020). Limited information is available on the environmental impact indicators associated with space launches, including ozone depletion, climate change, ecosystem toxicity, and human toxicity (Dallas et al., 2020; Ross et al., 2010).

In an environmental impact statement for their planned 2020 Mars missions, the National Aeronautics and Space Administration (NASA) noted the need for considerable further research into the global impact of LREs on the ozone layer (NASA, 2014). Global ozone loss from rocket launches will become more concerning as the number of rocket launches increases (Dallas et al., 2020). There is minimal research on the cumulative impact of kerosene-based LREs and the analysis by Lamarche et al. (2017) suggests that impacts will become more concerning with increased launches. Rocket Lab is currently capable of launching up to 120 Electron missions per year from its private launch site at Complex 1 on the Māhia Peninsula, with plans to build a larger launch vehicle with 26 times the payload capability of Electron.

A modelling study considering the collative impacts of 1000 hydrocarbon-powered rockets engineered per year indicated that the estimated topical stratospheric ozone would decline while polar stratospheric ozone would likely increase due to black carbon (Ross et al., 2010). Black carbon is emitted from kerosene-fuelled engines while SRMs also emit alumina particles, both of which contribute to global warming. The same study concluded that after a decade, the cumulative black carbon emissions would result in radiative forcing comparable to current subsonic aviation (Ross et al., 2010). Although the toxicity effect of kerosene-based LREs on the ecosystem and humans has not been studied, the impact of both is currently assumed to be low (Dallas et al., 2020). Green technology recommendations by Neumann (2018), including replacing kerosene-based fuels with methane, indicate a modest 1–2 % reduction to the impact indicators related to climate change, human toxicity and ecosystem toxicity.

The emerging New Zealand space sector appears to be an ecosystem supported by a monoculture of one essential business, Rocket Lab, and the above analysis of the legislative framework (Borroz, 2020) suggests this circumstance is unlikely to change. While New Zealand has adopted a legislative framework to encourage the growth of the space sector, appropriate environmental regulations, and legislation may be lacking.

Environmental policy changes are underway in New Zealand, most significantly a national goal for net zero carbon has been set for 2050 with legislated emissions budgets being developed to meet those goals, with adaptation measures to respond to the continued impacts of climate change (Ministry for the Environment, 2022). These changes apply to all parts of society and the economy, including the emerging space sector.

Space infrastructure is essential to the sustainability of humanity; 26 of the 50 variables used to assess Earth's climate are monitored via satellite observations (OECD, 2021). As any foreseeable sustainable future requires space missions, it is imperative that the environmental impact of these necessary missions is fully understood. While the space industry is by far not the largest emitter of greenhouse gases in New Zealand (Ministry for the Environment, 2021), the growing sector offers an opportunity to integrate sustainable thinking and eco-design from its foundation, while the industry is still evolving. Doing so will remove the inefficiency of retrospectively redesigning and retooling established infrastructure, supply chains and business practices, while mitigating the risk of disruption to business operations in the future.

3. LCA and its applications

LCA is an internationally standardised methodology that takes a holistic approach in determining and evaluating the environmental impacts of a product or process over its entire life cycle - from raw materials extraction through to end of life (Hellweg & Canals, 2014; International Organisation for Standardisation [ISO 14040], 2006a, ISO 14044, 2006b). The inputs and outputs in each stage of a product's life cycle associated with their potential environmental impacts such as raw materials and energy extraction, air emissions, wastes, co-products and other releases are shown in Fig. 3.

LCA is an iterative process and has four phases, illustrated in Fig. 4: (i) Goal and scope definition, (ii) life cycle inventory (LCI); (iii) life cycle impact assessment (LCIA) and (iv) interpretation. The goal and scope definition phase identifies the purpose of the LCA, system boundaries, functional unit, assumptions and expected outputs. It also outlines the level of detail of the LCA which depends on the goal of the study. The next phase is the LCI where the identifiable inputs and outputs in the life cycle stages are quantified. It is the breakdown of all the known input and output data. Using the LCI data, the quantified materials and energy are linked to the potential environmental impacts in the LCIA phase such as for example global warming, human toxicity and ocean acidification. The final phase is the interpretation that involves the analysis and discussion of the LCI and LCIA results, presentation of findings and conclusions (SAIC & Curran, 2006).

Over the last few decades, LCA has been widely used by industry and governments where it is valuable for identifying environmental hotspots in product and service design. It is also used for corporate and government environmental management, through strategic, goal-setting policy development. However, in corporate settings, there can be a focus on only those impacts needed to reach required environmental and sustainable goals, e.g., carbon emissions profiles (Stewart et al., 2018).

In industry, for example, LCA is used in (i) product and process development, (ii) market strategy (e.g. eco-labelling), (iii) determination and evaluation of environmental performance, (iv) selection of suppliers, and (v) planning (da Luz, et al., 2018; Ekvall et al., 2007;

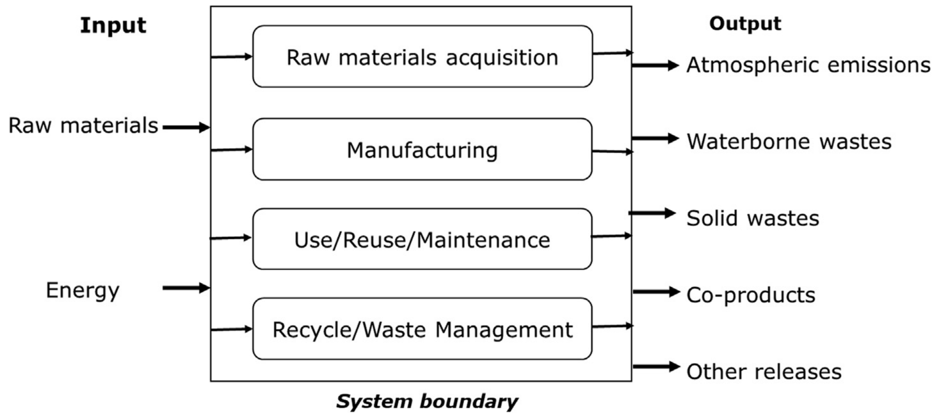

Fig. 3. Life Cycle Stages (Adapted from US EPA, 1993).

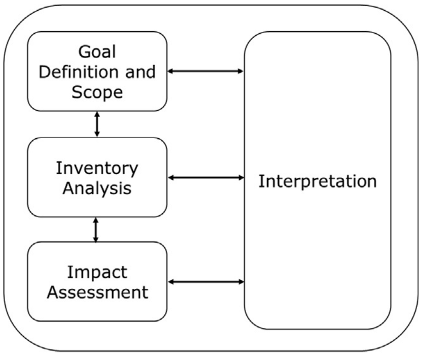

Fig. 4. Phases of LCA (adapted from ISO 14040:2006).

Hermann et al., 2007; Jenssen & de Boer, 2019; Peano et al., 2015; SAIC & Curran, 2006). Whilst in the government sector, LCA is used to develop and implement policies for example those related to new technologies such as electric vehicles (Owsianiak et al., 2018).

In New Zealand, a few companies such as New Zealand Post and Tetra Pak Oceania have applied LCA to their product designs. New Zealand Post compared the use of low-density polyethylene and New Zealand-made recycled plastic as a material for courier bags. Between the two courier bags, New Zealand-made recycled plastic has a lower carbon footprint (Riordan & Vickers, 2021). Tetra Pak Oceania also applied LCA to assess the environmental impact of their packaging materials. They found that beverage cartons have the least manufacturing and importation emissions among different types of packaging in Australia and New Zealand (Warmerdam & Vickers, 2021).

3.1. Eco-design

LCA can estimate the environmental impacts of a product or system throughout its life cycle. Using an LCA report, designers can be strategic in reducing the environmental impact of a product from the raw material extraction through until the end of life phase. This approach is referred to as eco-design, and it can be applied as early as the design phase of the product where minimisation of the environmental impacts is the primary goal. Eco-design can lead to lower production costs, identification of new product opportunities and improvement of environmental compliance (Knight and Jenkins, 2009).

In 2012, the Okala Ecodesign Strategy Guide suggested eight ways to incorporate eco-design into a product, service or system that considered all stages of the life cycle. Companies should design for: (i) innovation, (ii) reduced material impacts, (iii) manufacturing innovation, (iv) reduced distribution impacts, (v) reduced behaviour and use impacts, (vi) system longevity, (vii) transitional system and (viii) optimised end of life (Belletire et al., 2012). However, these strategies may not all be applied to a product, service or system but designers should consider them. Automotive companies such as the BMW Group, General Motors, Volkswagen and Toyota have applied eco-design principles to their products. For example, BMW Group has required their suppliers to not use banned materials in any components or stages of car manufacturing. Moreover, only recycled materials are used for some parts of the car manufacture e.g., recycled plastics and polyurethane foam (Ramirez, 2012).

3.2. Eco-design for space activities

Similarly, eco-design has also been applied in the space sector. It is one of the four branches of ESA's Clean Space initiative where eco-design is defined as 'the development of tools to monitor and evaluate the environmental impact and legislation compliance of programmes' (Wormnes et al., 2013). According to ESA, environmental performance should be integrated at an early design stage as well as throughout the mission's design. This will allow designers to have more choices to improve the environmental performance of space missions (Chanoine et al., 2015). However, there are limited LCA studies in the space sector due to (i) low production rates; (ii) sector-specific environmental impacts not being considered in traditional LCA (e.g. space debris); (iii) most of the materials and processes used in space sector being specialised and (iv) research and development requiring a much longer time than the use phase (Austin et al., 2015). With all these challenges and limitations on the application of LCA and eco-design for the space sector in mind, ESA has developed a framework to evaluate the environmental impact of the space sector (ESA LCA Working Group, 2016). The framework consists of a LCA handbook, a LCA database and an Eco-design tool. While the LCA handbook is available upon request, the LCA database is currently only available under contract to European stakeholders and the Eco-design tool is still under development (ESA LCA Working Group, 2016).

The Strathclyde Space Systems Database (SSSD) is a life cycle sustainability assessment (LCSA) tool that was designed at the University of Strathclyde (Wilson, 2019) to bridge this gap. Thus, it is in close agreement with the guidelines set out in ESA's LCA handbook and incorporates new and relevant data from the ESA LCA database. The SSSD allows for the evaluation of economic, social, and environmental aspects of a product or system in a sole study. It also enables the integration of life cycle concerns into the design process of space missions and the advancement of the environmental LCA methodology for space towards a comprehensive LCSA.

The SSSD has been used to evaluate the environmental impact of monoproprellants namely hydrazine and LMS-03S in two scenarios i.e. direct results and direct contribution to the overall impact. In the direct results, the environmental impacts of 1 kg of each monopropellant were compared using their manufacturing and production processes where the LMS-03S contributes less environmental impact than hydrazine. Similarly, when the direct contribution is considered, based on the functional unit (one space mission in fulfilment of its requirements), LMS-03S is a better propellant than hydrazine in terms of environmental impact. However, due to lack of mass production of the new green propellant, LMS-03S, it is about 3.5 times the cost of hydrazine per functional unit (Wilson et al., 2018). On the other hand, SSSD was also used to determine the environmental impact of the 3U payload with an integrated 3D phase array antenna after the trade-off analysis of its design with two more advanced and expensive designs without compromising the purpose of the design (Jenkins et al., 2020). Moreover, LCSA and SSSD were recently used to estimate the annual ecospheric life cycle impacts of global space activities (Wilson et al., 2022). Although the application of LCSA and SSSD has been limited, these recent studies and the increasing environmental concerns of space activities discussed in Section 2.2 indicate that this area of research is attracting global attention.

The SSSD is based on the Allocation at Point of Substitution (APOS) version of the Ecoinvent and ELCD database and is implemented in openLCA (Ecoinvent, 2022; GreenDelta GmbH, 2022). It contains a variety of representative processes and methods relevant for space systems that can be readily applied for the LCI and LCIA phases (Wilson, 2019). To the best of the authors' knowledge, the SSSD is the only space systems LCA database accessible to actors outside of ESA member states. It hereby offers the possibility for members of the New Zealand space sector to estimate the environmental impact of an arbitrary space mission by utilising the implemented datasets. Therefore, it was selected to conduct an initial case study on the environmental impact of a typical New Zealand satellite.

4. Case study: Streamlined LCA of a CubeSat

A streamlined LCA, which is a simplified version of full LCA, was performed to focus on identifiying the significant stages and main impacts associated with a CubeSat mission, so that key issues may be explored in the future. In addition, due to the lack of database and studies on the environmental impact of space activities in New Zealand, a full LCA was not possible. The preliminary results of this study aim to provide baseline information on the environmental impact of a CubeSat that could potentially raise attention in New Zealand and globally regarding the limited information on environmental issues associated with CubeSat design and more broadly with space activities. This may eventually lead to more in-depth studies on the environmental impact of space activities, particularly in New Zealand. For products and processes to be comparable in LCA, functional unit and system boundaries such as time, geographic location and technology should be similar among them. Some of the relative impacts are compared to a similar CubeSat LCA study by Jenkins et al. (2020) performed at the University of Strathclyde. However, a more comprehensive comparison of the CubeSat mission in this study with other existing CubeSats would not be appropriate due to the temporal, geographical and technological differences among them.

4.1. Goal and scope definition

The goal of this case study is to demonstrate the suitability of space systems LCA using the SSSD for application in New Zealand's space sector to identify environmental hotspots. As shown in Fig. 1, most satellites launched from New Zealand are CubeSats. Hence, this high-level case study focuses on this satellite type. Under this premise, the functional unit (FU) was set to *'One generic 1U CubeSat mission from New Zealand to Low Earth Orbit with a mass of 1 kg'*. Technical inputs were collected from members of the Auckland Programme for Space Systems (APSS) (C. Mattson, personal communication, September 12, 2021; J. Mace, personal communication, September 18, 2021, F. Moynihan Lavey, February 21, 2021). APSS is an interdisciplinary CubeSat program for undergraduate students at the University of Auckland (Auckland Programme for Space Systems, 2022). Its first CubeSat, Te Waka Āmiorangi o Aotearoa APSS-1, was a standard CubeSat with the form factor of 1U (a cube with an edge length of 100 mm). It was launched into a circular low earth orbit (500 km) in November 2020 on a Rocket Lab Electron (Rocket Lab, 2020). Communication was not established after deployment (Keall, 2020).

The standardisation of CubeSats sizes ranging from 1U to 12U suggests that apart from their payloads, most CubeSats of the same form factor will be similar in design (The CubeSat Program, 2020). Therefore, it seems plausible to create proxies for these satellite types that can facilitate the estimation of the environmental impacts of the majority of launched satellites from New Zealand. This study could serve as a first step towards creating such a proxy for designing and launching a 1U CubeSat from New Zealand.

The ESA handbook on Space Systems Life Cycle Assessment defines the phases and system boundaries of a space mission (ESA LCA Working Group, 2016). However, due to limited data availability, not all these phases could be modelled, hence the need for a streamlined LCA. This example mission was constrained to the phases illustrated in Fig. 5. As the commissioning of APSS-1 failed, there was no operational phase. Hence, the ground segment as well as the utilisation phase E2 were excluded from this study. Additionally, all travel and testing activities for the launch and the space segment were neglected, since the travel distances were relatively short and no energy consumption data during testing was recorded.

4.2. Life cycle inventory

APSS provided inputs specifically for phases A + B and C + D as well as the end-of-life scenario. Data for phase E, particularly launcher data, was gathered from publicly available information (Rocket Lab, 2022c). The model inputs related to office work, CubeSat components and the launch vehicle are summarised in Table 3, Table 4 and Table 5. Also, to account for varying payloads across different CubeSat missions, the payload was modelled as a generic electronic unit. The APSS CubeSat had no propulsion system. The manufacturing of one prototype (identical to the final CubeSat) was considered. According to the Orbital Debris Mitigation Plan for APSS-1, it was assumed that the 1U CubeSat will completely disintegrate during re-entry (N. J. Rattenbury, personal communication, September 15, 2021).

Fig. 5. System boundaries of a generic CubeSat mission.

Table 3
Input Office hours.

Phase	Personnel hours
A + B	8700
C + D	6900
Total	15,600

Table 4
Input CubeSat components.

Component	Mass (kg)
Antenna	0.115
Battery	0.104
Electronic Unit	0.229
GaInP/GaAs Solar Module	0.198
Power Distribution Unit	0.104
Satellite Structure	0.12
On-Board Computer	0.13
Total	1.00

Table 5
Input Launch Vehicle.

Payload capability to LEO	300 kg
Fuel/oxidiser	RP-1/LO$_x$
Estimated total fuel/oxidiser mass	11000 kg

4.3. LCIA and interpretation

LCIA was conducted within the openLCA software using the midpoint impact categories included in the SSSD (Wilson, 2019). Fig. 6 shows the relative results of the study.

For most impact categories, office work in the phases A + B and C + D is a major contributor in this simplified model. Impacts related to the manufacturing of spacecraft components are relatively small across many categories. This is likely a result of the low mass of only 1 kg of CubeSat. However, some categories such as mineral resource depletion, human and marine toxicity are dominated by the spacecraft-related manufacturing. This is mainly due to the germanium usage within the solar modules.

Similarly, the launch event solely dominates the categories Al_2O_3 (alumina) emissions and ozone depletion due to the direct exhaust gas emission to the atmosphere.

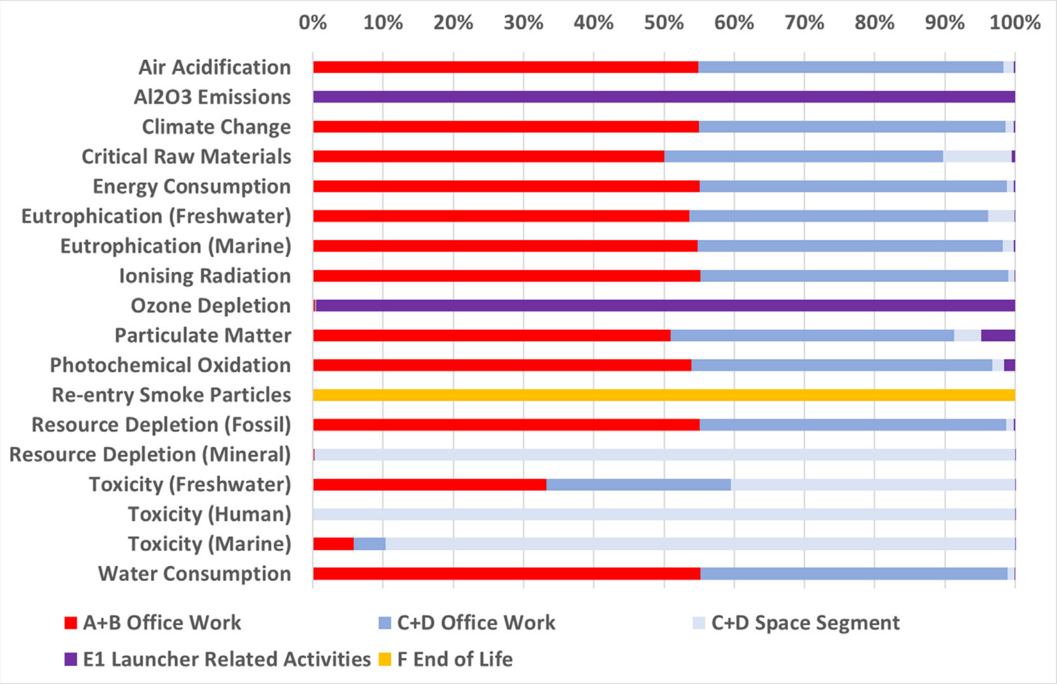

Fig. 6. Baseline results of one generic 1U CubeSat mission from New Zealand to Low Earth Orbit with a mass of 1 kg.

As expected, re-entry smoke particles only occur during the end-of-life phase.

Note that some phases and activities could not be considered in this study due to a lack of data. One example is the manufacturing and testing of the launch vehicle which would likely shift the results significantly by contributing to phase C + D. In a similar study by Jenkins et al. (2020), phase C + D was the largest contributor across most impact categories (except ozone depletion, Al_2O_3 emissions, disposal to ocean and re-entry smoke particles that, similar to the current study, are only associated with launch and end-of-life, respectively). In contrast, the E2 utilisation phase was found to rarely be the largest contributor of any impact category. However, this depends on the mission's duration as the amount of personnel hours and ground station usage, etc. would scale with the operational lifetime of the satellite.

For more accurate and comprehensive results, data input from industry would be required, especially for the manufacturing of the launch vehicle and spacecraft components. While APSS provided details on purchased parts, manufacturers rarely disclose all processes and associated environmental impacts involved in producing these components due to (i) the proprietary nature of the data, (ii) lack of awareness among suppliers of LCA guidelines such as ISO 14040, (iii) lack of data infrastructure that would allow for transparent collection of inputs. The authors acknowledge that the competitive spacecraft and launch vehicle market may not allow for transparency of data. However, the usage of de-identified or aggregrated data could result in misleading conclusions and reduced credibility of the LCA methodology in the space sector (Wilson, 2022).

5. Conclusions and recommendations

In this paper, we have summarised the development of the commercial space sector in New Zealand, catalysed by the formation of launch provider Rocket Lab and enabled by the NZSA. With many companies being small and new, spread across key sub-sectors such as space applications and space manufacturing, the current focus is on economic and technological development. As the sector continues to grow and attract international investment, we propose that all dimensions of sustainable development should be considered - social, environmental, cultural, and economical, commencing with the environmental impacts. As developed by ESA, the LCA handbook outlines common methodological rules to be followed when performing space LCAs. Wilson (2019) expanded these guidelines to advance the methodology towards space LCSA and integrate this into the space mission design process through the development of the SSSD. This platform can be used to perform LCA and/or LCSA on space-related products, processes, and systems.

We performed a streamlined LCA case study on the APSS CubeSat launched from New Zealand and identified environmental hotspots as well as gaps in relevant data collection. The case study, while limited by data inputs, offers a sound approach to calculate the environmental impact of a space component derived from international best practices. Future work will include the integration of the LCA approach into new CubeSat missions at the University of Auckland as well as the recording of all testing and travel data. Data from the launch provider will be sought to refine the E1 Launcher Related Activities phase and E2 utilisation phase. In addition, the ground segment will be included through inventory data collected in collaboration with the Auckland Space Institute – *Te Pūnaha Ātea* mission control centre.

We recommend two main areas for future space systems LCA research:

- More accurate modelling and experimental data of direct emissions from launch segments into the stratosphere. In particular, the heating effect of black carbon on the atmosphere and subsequent acceleration of ozone loss from hydrocarbon-based fuels is not well-understood.
- Improved estimation of energy consumption from the research and development components of the design process (Phases A + B and C + D). These phases are likely to be highly variable, depending on the product and type of business, therefore need a flexible and accessible data collection framework supported by contractors and suppliers.

With respect to the adoption and integration of environmental LCA into New Zealand's space sector, we recommend more research on understanding the awareness of sustainability issues among New Zealand space businesses and policymakers and the associated risks to current and future operations. Specifically, we need to understand what support structures are needed to enable a more sustainable supply chain and improve LCI data availability from suppliers.

Ultimately, the adoption of environmental LCA into industry practice and legislation in New Zealand will allow for better informed decision-making and the identification of opportunities for innovation to improve not only environmental outcomes but also broader social, cultural, and economic ones. This is particularly important to meet the net-zero emissions goals and adapt to the continued impacts of climate change.

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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