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Implementing Life Cycle Sustainability Assessment for Improved Space Mission Design

Andrew Ross Wilson[1*], Massimiliano Vasile[1], Christie Maddock[1], Keith Baker[2]

[1] Aerospace Centre of Excellence, Department of Mechanical & Aerospace Engineering, University of Strathclyde, James Weir Building, 75 Montrose Street, Glasgow, G1 1XJ, United Kingdom

[2] Built Environment Asset Management (BEAM) Centre, School of Engineering & Built Environment, Glasgow Caledonian University, Cowcaddens Road, Glasgow, G4 0BA, United Kingdom

*Corresponding author: andrew.r.wilson@strath.ac.uk

Abstract

Within the space sector, the application of Environmental Life Cycle Assessment (E-LCA) is beginning to emerge as a credible and compelling method for scientifically quantifying environmental impacts of space missions. However, E-LCA does not fully align with the concept of triple bottom line sustainability, whilst the combination of all three sustainability dimensions (environment, society and economy) within a single life cycle study has thus far never been attempted within the space industry. Moving towards a Life Cycle Sustainability Assessment (LCSA) is, therefore, a logical next step for the space sector to allow these three sustainability dimensions to be addressed. Consequently, this paper presents the underlying principles of a new LCSA framework for space missions and demonstrates its applicability for improving system-level design concepts based on the interaction between sustainability dimensions. The framework was formed based on a systematic literature review to analyse the background, issues and knowledge gaps related to life cycle methodologies, as well as context-specific sustainability aspects. The framework has been implemented within a life cycle database called the Strathclyde Space Systems Database (SSSD). Using the SSSD, the framework was tested on a mission concept called MÌOS to demonstrate how changes in the design for a circular economy and other sustainability-based principles will affect the functionality of the mission at system level. It is envisaged that this framework will enable engineers to create sustainable space systems, technologies and products that are not only cost-efficient, eco-efficient and socially responsible, but also ones that can easily justify and evidence their sustainability.

Keywords: Life Cycle Sustainability Assessment, Systems Engineering, Product Development, Space Systems

1. Introduction

Outer space is a key resource in the pursuit of sustainable development. In this regard, the orbital environment around Earth enables space missions to provide vital information which allows decision-makers to measure progress and set plans of action on a variety of environmental, societal, and economic issues. However, despite their practical application, the adverse impacts caused by space missions to the Earth environment over their entire lifetime is an aspect which is regularly overlooked, despite increasing calls for space environmentalism (Palmroth, et al., 2021; Lawrence, et al., 2022; Miraux, 2022; Wilson, et al., 2022).

To address this, the European Space Agency (ESA) Clean Space Office has been pioneering the application of Environmental Life Cycle Assessment (E-LCA) within the space sector to scientifically quantify and reduce geocentric environmental impacts of space missions since 2009 (European Space Agency, 2009). E-LCA is a technique used to assess the environmental impacts of products, processes or services over their entire life cycle. This technique is particularly useful in early mission design phases since around 80% of a product's environmental impacts are set by early design choices (European Commission, 2022). Adverse impacts are more difficult to address the further into the design process that they are identified since several key decisions and constraints will have already been put in place, restricting the possibility for design modification (Sheldrick & Rahimifard, 2013; Chanoine, et al., 2014).

Nevertheless, the use of E-LCA does not fully align with the concept of sustainability envisioned within the 2030 Agenda for Sustainable Development, which seeks to "balance the three dimensions of sustainable development: the economic, social and environmental" (A/RES/70/1). Despite this, the possibility of combining all three sustainability dimensions within a single life cycle study within the space industry has only briefly been suggested by some researchers (Viikari, 2004; Durrieu & Nelson, 2013; Maury, et al., 2017; Harris & Landis, 2019), with just one previous project having been initiated to investigate this further (Wilson, 2019). This is irrespective of the fact that 2030 Agenda for Sustainable Development (A/RES/70/1), Guidelines for the Long-term Sustainability of Outer Space Activities (A/AC.105/2018/CRP.20), and the European Union's Green Deal (Fetting, 2020) all increase the motivation and necessity for addressing the full spectrum of sustainability aspects within future space missions and technologies.

To address this, Life Cycle Sustainability Assessment (LCSA) could be used to assist industry introduce triple-bottom line (TBL) considerations into the space mission design process. LCSA refers to the combination of E-LCA, Social Life Cycle Assessment (S-LCA) and Life Cycle Costing (LCC) into a single framework (Klöpffer, 2008). S-LCA is an assessment type which can be used to predict the life cycle social and sociological aspects of products. LCC is an economic assessment which 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, 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 (Guinée , 2016).

The first and only attempt to apply LCSA to space missions is outlined in (Wilson, 2019). However, the specificities of the space sector mean that applying such an approach is not a straightforward endeavour (Wilson, 2022). For this reason, defining robust methodological guidance in the form of a space LCSA framework is required to tailor this technique to the context of space mission design. Such an approach may, therefore, promote industrial stakeholders to become fully transparent in their operations by allowing them to scientifically quantify the overall sustainability performance of space missions and mitigate any potentially significant impacts (or hotspots) before they occur.

As such, the aim of this paper is to feed LCSA into the decision-making process of space missions to drive change at system level whilst helping to create a truly sustainable space sector. To do this, a new framework will be presented which provides methodological guidance concerning the application of LCSA within the design process of early space mission design concepts. The framework has been developed to comply with several guiding principles, including the ESA E-LCA guidelines (ESA LCA Working Group, 2016), the United Nations Environment Programme (UNEP) / Society of Environmental Toxicology & Chemistry (SETAC) LCSA guidelines (Valdivia, et al., 2011) and the ISO 14040:2006 & ISO 14044:2006 standards amongst others. Consequently, this should provide a credible and compelling new method for streamlining decision-making in a more systematic and coordinated fashion, with the concept of sustainable development at its core. Finally, the proposed framework was applied retrospectively as part of a Phase 0/A concurrent engineering study which took place at the University of Strathclyde (Wilson & Vasile, 2022). This practical demonstration has been used as a case study to evidence the applicability of the developed framework, with the results highlighting how environmental, social and economic performance can collectively act as a decision parameter in the space mission design process for improved system performance.

2. Methodology

To fulfil the aim of this paper, the development of the space LCSA framework will principally be based upon a literature review. After this, the process for implementing the new framework will be described through a case study, demonstrating the appropriateness of its application for early space mission design concepts. The methods for completing each of these steps are outlined below.

2.1 Literature Review

The initial part of the literature review is designed to establish the guiding principles which will govern the formation of the space LCSA framework. This was based on known documents which were considered an authoritative or front-running source both for life cycle practices in general, life cycle practices as applied to space systems and space mission design in general. These were uncovered through prior knowledge, using simple searches of the Scopus database, Google Scholar and the British Standards Online Library (BSOL). The reference documents captured by this approach are reported in Table 1 and were selected to ensure that each sustainability dimension, including trade-offs and technical space-related considerations were fully captured by the space LCSA framework.

This was complimented by a more comprehensive literature to provide additional evidence to inform the development of the space LCA framework and assist in the formation of rules. This was achieved by searching for peer-reviewed reviewed journals, conference papers, books, reports, and standards based on a wide range of key terms including “life cycle assessment,” “social life cycle assessment,” “life cycle costing,” “life cycle sustainability assessment,” “multi-criteria decision analysis” and “space mission design” amongst others. Several sources were used for this purpose, including the Scopus database, Google Scholar, BSOL, the National Aeronautics and Space Administration (NASA) technical library’s public search engine TechDoc, proceedings published on conference websites, and various elements collected within the space industry from different sources. The reference section for each collected article was also searched in order to find additional research. In this regard, dozens of reference documents were uncovered. However, on review, only those considered to be most pertinent to the development of the space LCSA framework or those most reflective of general practice are reported in Table 2.

Collectively, the reference documents outlined in Table 1 and Table 2 were used only where considered appropriate during framework development, as reported in Section 3.

Table 1: Selected reference documents which form the guiding principles for the proposed space LCSA framework

Article no.	Reference Document	Sustainability Pillar			Decision-Analysis for LCSA (Trade-Offs)	Technical Considerations (Space)	Description and Overview
		Environment (E-LCA)	Society (S-LCA)	Economy (LCC)			
1	A/RES/70/1*		x		x		The 2030 Agenda for Sustainable Development, comprising of the 17 Sustainable Development Goals (SDGs) and 169 targets.
2	A/RES/71/313*		x		x		A global indicator framework comprising of 232 indicators to facilitate the implementation of the 17 SDGs and 169 targets.
3	Benoît-Norris, et al. (2020)		x				A document which provides a technical framework for calculating the social life cycle impacts of products.
4	ECSS-S-ST-00-01C					x	An international standard controlling the definition of all common terms used in the ECSS Standards System.
5	ESA LCA Working Group (2016)	x				x	Guidelines outlining a methodology for adapting the ISO E-LCA standards to be more appropriate to space.
6	European Commission (2018)	x					A document providing instructions on how to develop PEFCRs for calculating the environmental profile of products.
7	Goedkoop, et al. (2020)		x				A handbook describing a methodology for assessing the positive and negative social impacts of products and services.
8	Hannouf & Assefa (2018)	x	x	x	x		A journal article which presents a decision-analysis framework for LCSA.
9	IEC 60300-3-3:2017			x			An international standard establishing a general introduction to the concept of life cycle costing and covers all applications.
10	ISO 14040:2006	x					An international standard which describes the principles and framework for E-LCA.
11	ISO 14044:2006	x					An international standard which specifies the requirements and provides guidelines for E-LCA.
12	ISO 26000:2010		x				An international standard which provides guidance on the underlying principles of social responsibility.
13	Klöpffer (2008)	x	x	x	x		A journal article which presents the LCSA concept for the first time, including suggestions on how results should be presented.
14	NASA (2015)			x		x	A guidance document covering the cost estimating methodology as applied at NASA.
15	Traverso, et al. (2021)		x				Additional guidance relating to Benoît-Norris, et al. (2020) by the provision of further information on stakeholder subcategories.
16	Valdivia, et al. (2011)	x	x	x	x		A publication presenting guidance on how to use and combine stand-alone life cycle techniques to start an overall LCSA.
17	Wertz & Larson (1999)			x		x	A book which provides a comprehensive overview and summary into the theory and practice of designing spacecraft elements.
18	Wilson (2019)	x	x	x	x	x	A PhD thesis presenting a pathway for transitioning space E-LCA towards space LCSA, which forms the basis for this work.

** Although these reference documents relate to all three sustainability dimensions, for the purposes of LCSA they are considered relevant for S-LCA and decision-analysis segments only.*

Table 2: Selected reference documents which provide additional evidence and assist in the formation of rules for the proposed space LCSA framework

Article no.	Reference Document	Overview and Relevancy to Space LCSA Framework
1	Benini, et al. (2014)	A technical report providing recommendations for normalisation methods and data for the PEF approach.
2	Benoît, et al. (2009)	A document which provides a technical framework for calculating the social life cycle impacts of products (now outdated)
3	Benoît-Norris, et al. (2013)	Additional guidance relating to Benoît, et al. (2009) by the provision of further information on stakeholder subcategories (now outdated).
4	Ciroth (2009)	A journal article discussing parameters that affect cost data quality.
5	Chanoine, et al. (2015)	A conference paper discussing the benefits and challenges of developing tools and integrating sustainability into the design of space activities.
6	Curran, et al. (2004)	A journal article which provides a literature review on the state of the art in engineering cost modelling as applied to aerospace.
7	Diaz-Sarachaga, et al. (2018	A journal article which analyses the suitability of applying the SDG Index for assessing the fulfilment of the 2030 Agenda.
8	ECSS-M-ST-10 Rev.1	An international standard describing key elements of coherent and integrated project planning in space projects and applications.
9	Finkbeiner, et al. (2010)	A journal article which paper explores the status of LCSA for products and processes and how to present results.
10	Gluch & Baumann (2004)	A journal article discussing the usefulness of LCC for environmental decision-making.
11	Hunt & van Pelt (2004)	A conference paper discussing the similarities and difference between NASA and ESA cost estimating methods.
12	ISO/TR 14062:2002	An international standard which describes the concepts and practices relating to ecodesign (now withdrawn).
13	Kayrbekova, et al. (2011)	A journal article discussing the applicability of ABC costing as an alternative to conventional LCC in engineering design.
14	Keller, et al. (2014)	A journal article providing results from a review on techniques, approaches, models, and conceptual tools for space program cost estimating.
15	Maier, et al. (2016)	A journal article outlining a methodological approach for LCSA of development cooperation projects based on the SDGs and life cycle thinking.
16	Mrozinski, et al. (2020)	A conference paper demonstrating a new method for parametric cost modelling for CubeSats.
17	Maury (2019)	A PhD thesis which sought to integrate space debris as an impact category within space E-LCA.
18	Pagotto, et al. (2021)	A book chapter which develops a framework for analysing sustainability impacts of the Australian food industry, based on a literature review.
19	Rebitzer & Seuring (2003)	A journal article providing an overview relating to the methodology and application of LCC.
20	Sala, et al. (2015)	A technical report outlining a state of the art and challenges for supporting product policies through S-LCA.
21	Sala, et al. (2018)	A technical report providing recommendations for a weighting approach for the PEF approach.
22	Shishko (2004)	A conference paper which discusses some potential approaches that can improve rigor and repeatability in the analogy costing process.
23	Sureau, et al. (2018)	A journal article which reviews the criteria and indicators proposed to assess social and socioeconomic impacts of products.
24	Swarr, et al. (2011)	A journal article providing guidance on environmental LCC via a code of practice.
25	Valdivia, et al. (2021)	A journal article which establishes principles for the increased application and use of LCSA.
26	Velasquez & Hester (2013)	A journal article which provides an overview on the wide variety of MCDA methods developed.
27	Watson, et al. (2006)	A journal article describing different cost estimation approaches as they relate to the aerospace supply chain.
28	Wilson & Vasile (2022)	A journal article demonstrating the use of LCE within the concurrent engineering process of space missions.
29	Wilson, et al. (2021)	A conference paper outlining the results of a scoping exercise designed to map the specificities of space E-LCA to the PEF approach.
30	Wulf, et al. (2018)	A journal article demonstrating the selection of LCSA indicators are selected based on the SDGs through a case study.
31	Zampori, et al. (2018)	A technical report providing guidance for interpreting the results of life cycle studies.

2.2 Case Study

The developed space LCSA framework described in this paper has been applied through a new tool called the Strathclyde Space Systems Database (SSSD). The SSSD can be used to facilitate LCSA of early space mission concepts and has already been used by actors across three continents. The tool contains over 250 validated space-specific Life Cycle Inventory (LCI) datasets and includes several integrated Life Cycle Impact Assessment (LCIA) methods. Further information on the development of the SSSD is outlined in Wilson (2019).

Therefore, to demonstrate the new space LCSA framework, a prospective LCSA was conducted on the Phase 0/A MÌOS concept using the SSSD. This means that although the overall concept is still at an early stage of development, the space mission will be modelled to represent a future, more-developed stage. The MÌOS concept was created within a concurrent engineering environment at the University of Strathclyde, although the LCSA took place retrospectively. Primary data was obtained based on data deposited to the engineering model used in the concurrent engineering study and mapped to relevant SSSD LCI datasets. Additional data was also collected for elements not covered in the engineering model using relevant calculation and/or extrapolation techniques, expert knowledge and default values contained within the SSSD.

The case study is intended to test the practicality of the space LCSA framework for reaching more sustainable designs of early space mission design concepts. The success of this framework will be measured by its ability to measure the sustainability performance of the MÌOS mission and then generate improvement opportunities to reduce its overall footprint. For this reason, the case study will neither focus on the development of the SSSD nor the LCIA results of the space mission per se, but rather, how the framework was implemented.

Whilst the focus of this case study is on LCSA, the framework may also be applied as part of the concurrent engineering process of space missions through Life Cycle Engineering (LCE). LCE is an engineering technique used to assess the environmental, social, economic and technical impacts of products, processes and services over their entire life cycle by finding a balance between societal needs, economic growth and minimising environmental impacts in product engineering. Evidently, this makes this approach particularly well-suited to concurrent engineering sessions which apply a model-based systems engineering approach. In such sessions, dedicated space LCSA tools (such as the SSSD) can be used to scientifically quantify the sustainability footprint of early space mission concepts as the design progresses, with the LCE expert advising subsystem experts on how to redesign elements that are particularly problematic to lower adverse impacts without compromising mission objectives and requirements. Therefore, the proposed principles of the newly defined space LCSA framework can be integrated into such tools to enable conformity. The process for this, including all necessary adaptations to the proposed space LCSA framework below, is outlined in Wilson & Vasile (2022) which is exemplified through three case studies on SmallSats using the SSSD.

3. Framework Development

The application of LCSA in the space sector can generally be broken down to two levels, each of which follow the ECSS space system breakdown from ECSS-S-ST-00-01. The first level follows a functional view and addresses system level activities, such as space systems, including the ground and launch segments. The second level represents equipment, components, materials or processes. Whilst in practice it is common for redesign activities to be conducted at equipment, component & material level, targeting specifically the space mission design process as the desired level of application therefore places the emphasis on system level assessments, which forms the basis for this framework.

The space LCSA framework has been designed for implementation from either an LCSA or LCE perspective. In this regard, it has been split into two parts according to the decision-analysis framework presented by Hannouf & Assefa (2018). The first is the modelling of each life cycle technique to understand the total environmental, social and economic impacts of space missions. The second focusses on its direct applications through a decision analysis technique called multi-criteria decision analysis (MCDA), which can be used to handle the multi-functional aspects of each sustainability dimension and assessment type to enable decision to be made. For this reason, the new space LCSA framework considers MCDA as a vital additional step within the decision-making process.

An overview of the new space LCSA framework is outlined in Figure 1 and was developed based on the reference documents outlined in Table 1 and Table 2. As such, the new framework should be seen as an extension of these guiding principles rather than an alternative to them. This will be further explained throughout the remainder of this section.

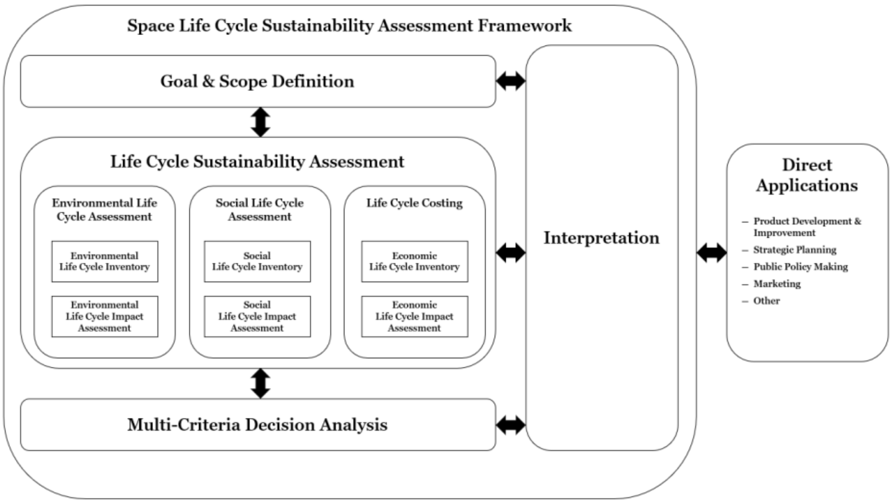

Figure 1: LCSA framework for the sustainable design of space missions (Wilson, 2019)

3.1 Goal & Scope Definition

The fulfilment of mission requirements and objectives as well as the role of the LCSA will ultimately inform the purpose of the goal & scope definition. Valdivia, et al. (2011) strongly recommends the use of a common goal and scope definition when conducting an LCSA, taking into account the different requirements of the three assessment types, including the functional unit (FU) and system boundary. The FU is a quantified performance of a product system for use as a reference unit and is what all inputs and outputs of the study should be related. The system boundary specifies which unit processes are included as part of the product system.

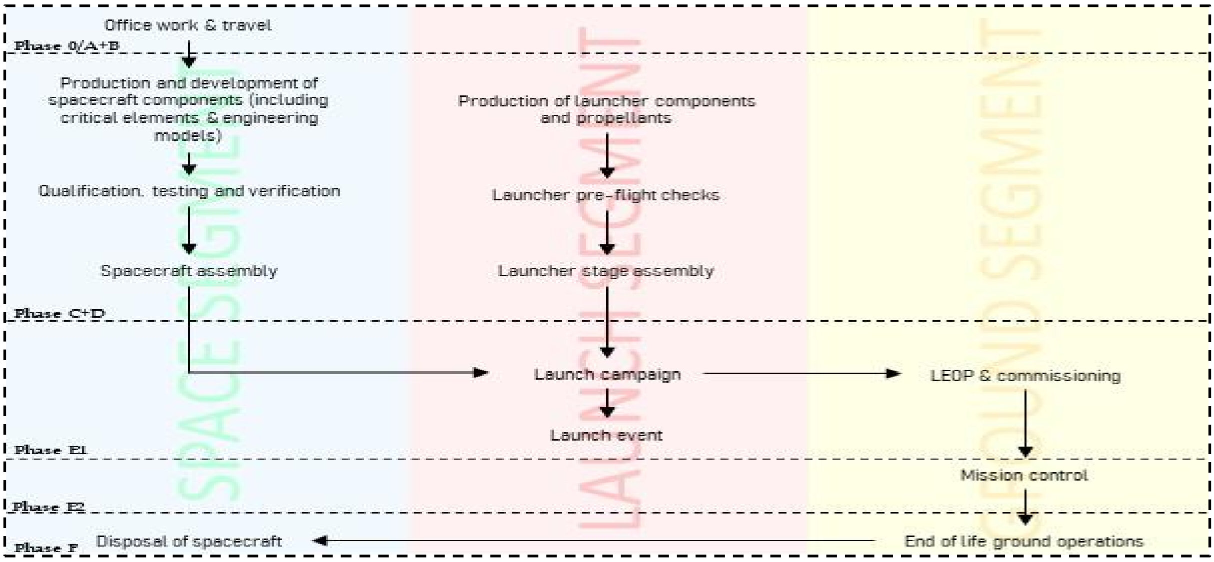

Figure 2: Generic system boundary of a typical space mission (adapted from ESA LCA Working Group, 2016)

The ESA space E-LCA guidelines, which are outlined further in the following subsection, provide excellent guidance on these aspects from an environmental perspective (ESA LCA Working Group, 2016). In this regard, as very few space missions serve an identical purpose or function, obtaining an FU which enables comparison based on the 'function' of a satellite is very difficult. As such, the guidelines provide a common, simplified FU which is defined as 'one space mission in fulfilment of its requirements'. Although this can be applied to multiple space missions, comparative assessments at system level are not recommended by the ESA guidelines because of the varying requirements and specifications of space missions, even of the same mission class. Efforts to create dedicated FUs for different mission classes are currently being investigated in a scoping exercise (European Commission, 2022), based on a recommendation made by Wilson, et al. (2021). The suggested system boundary of the ESA space E-LCA guidelines covers the sum of space segment, launcher segment, and ground segment across all phases (0/A to F) for both the payload and platform of the space mission in accordance with ECSS-M-ST-10 Rev.1. Infrastructure impacts may also be considered separately. A representative systems boundary diagram of a typical space mission is outlined in Figure 2.

However, careful attention should be paid to the system boundary, since each life cycle technique may have slightly different boundaries based on their relevancy to the overall assessment. Identical system boundaries should be applied to each of the three approaches whenever possible. Additionally, other small methodological differences can be considered within the goal & scope in order to determine how they might affect the study. For example, S-LCA may require the selection of an activity variable to measure the share of a given activity as it relates to each unit process and LCC may consider the use of a work breakdown structure (WBS) which adopts a life cycle actor perspective (e.g., supplier, manufacturing, user or consumer) to facilitate consistent data collection along the full life cycle. Furthermore, the scale of the relationship between the activity and unit process can massively impact the results and is therefore an important consideration within the goal & scope definition of an LCSA (Finkbeiner, et al., 2010).

3.2 Inventory Analysis & Impact Assessment

The LCI analysis and LCIA of each assessment type should be based on a combined approach using the most relevant methodologies in the context of LCSA when it is applied to early space mission design phases. When combining the three assessment types into a single framework, it is common practice for S-LCA and LCC to align with the principles and rules of E-LCA. This places an added importance of defining methodological rules for space E-LCA and tailoring both S-LCA and LCC to be consistent with this in order to produce scientifically robust and sound analysis.

3.2.1 Environmental Life Cycle Assessment

E-LCA is internationally standardised through the ISO 14040:2006 and ISO 14044:2006 standards and has been increasingly applied within the European space industry over the past decade to scientifically quantify environmental impacts of space missions over their entire life cycle. To help facilitate this, ESA released a consolidated set of guidelines in 2016 which act as primary guiding principles which should be applied when conducting a space E-LCA. The guidelines tailor the methodological rules contained within the ISO 14040:2006 and ISO 14044:2006 standards to be more appropriate to the space sector without risking non-compliance. They are also orientated as closely as possible with the Product Environmental Footprint approach to better align with the strategic goals of the European Commission and are available to European stakeholders upon request. As such, E-LCA shall be conducted in a manner which is consistent with the approach specified by these guidelines and its other associated adaptations/extensions such as Maury (2019) and Wilson, et al. (2021).

In particular, the ESA guidelines cover all aspects of space E-LCA, including the LCI and LCIA phases at the two levels defined by ECSS-S-ST-00-01, including primary and secondary data considerations, cut-off criteria, environmental indicators (including space applicable factors), results communication and more. It also provides a small number of simplistic LCI datasets which can be used in conjunction with dedicated space life cycle databases or software, such as the SSSD or ESA E-LCA Database. However, given the rigorous guidance provided by this source, the focus of the remainder of this subsection will be on tailoring S-LCA and LCC to align with E-LCA.

3.2.2 Social Life Cycle Assessment

Increased levels of public perception on social responsibility in recent years has placed an added pressure on organisational transparency and the justification of public budget spending. For this reason, whilst space S-LCA is still finding its feet, socio-economic impact assessments (SEIAs) have been applied more widely within the space sector. These are systematic methods of analysis which are commonly applied to evaluate socio-economic and cultural impacts of a proposed project or space mission. Comparatively, no space S-LCA studies are known to have ever taken place, besides those listed in Wilson (2019) and Wilson & Vasile (2022).

This means that there is currently an absence of guidance on space S-LCA guidance, despite clear need for quantifying the social impacts of space systems to ensure the development of socially responsible mission concepts. A dedicated project is about to get underway at University of Strathclyde which is hoped to produce detailed preliminary guidance on the topic, expanding on the principles developed by Wilson (2019). However, in the meantime, these foundational principles can be derived as part of this space LCSA framework.

Based on this, it is suggested that the S-LCA inventory is formed using mainly a burden-based approach in order to be more comparable with E-LCA and LCC, hence replicating their general methodologies. Although it can be contemplated that space missions may create a distinctly positive social impact (e.g., through environmental monitoring, catastrophe prevention, etc.), it can generally be considered that SEIAs are a more appropriate assessment type to capture such impacts. Regardless, due to the nature of S-LCA, an added emphasis is placed on creating an evaluation scheme that can handle both positive and negative social impacts in a consistent way (as discussed later in this section). This leans towards a risk-based approach (as the SOCA database) where positive impacts are represented by lower risk classes whilst neutral to negative impacts would have a higher risk class.

The LCI data can be collected across the six stakeholder categories and their associated subcategories as defined by Benoît-Norris et al. (2020), at either country-level, organisational-level or product-level (Sureau, et al., 2018). The applied perspective will depend on data availability and goal & scope definition. However, due to the unique nature of space systems and the fact that they are not commonly created within a mass production cycle, this disfavours a product-level approach, leaving either a country-level or organisational-level approach. Under each subcategory, a range of indicators are provided by Traverso et al. (2021). Similarly, Wilson (2019) produced a list of 105 new social which accords with the ISO 26000:2010 standard and are tailored to the specificities of the space sector and its supply chain. However, these were based on now outdated guidance (Benoît, et al., 2009; Benoît-Norris, et al., 2013) and needs updated according to Benoît-Norris et al. (2020) and Traverso et al. (2021). Additionally, in order to align with the 2030 Agenda for Sustainable Development, these indicators were developed based on the Sustainable Development Goals (SDGs), including their targets and indicators (A/RES/70/1; A/RES/71/313), in a similar manner to Maier, et al. (2016) and Wulf, et al., (2018). The indicators have been implemented within the SSSD and it is suggested that they are used as a basis for space S-LCA until more detailed guidance is issued. It should also be noted a new ISO standard is currently under development to define the principles and framework of the approach (ISO/AWI 14075).

Each of the 105 social indicators have been designed with an appropriate unit of measurement and evaluation scheme with relevant benchmarks on which to measure LCI results, similar to the method outlined by Goedkoop, et al. (2020). This allows social impacts to be defined by levels of risk, ensuring comparability. The benchmarks should have set uniformed intervals on which numerical levels of risk can be determined. This is a particularly advantageous approach since S-LCA results can be based on a mixture of qualitative and quantitative data. Making decisions based on qualitative data can add high levels of subjectivity into the analysis whilst basing decisions only on quantitative data could offer too narrow a view for proper decision making. By defining social aspects by levels of risk, all impacts (both qualitative or quantitative) can be measured based on these benchmarks and compared in a single unitary value (social risk). These datasets can then be combined with E-LCA processes using the number of man-hours accrued during the process under study as the activity variable. However, it is important that an external auditor validates the S-LCA datasets, particularly where the level of risk assigned could have been made through a qualitative assertion (Sala, et al., 2015).

In terms of LCIA methods, the stakeholder categories previously mentioned, or the SDGs shall be used as impact categories. Since the applied scoring mechanism uses a single common unitary value (i.e., social risk), the impact categories can therefore be aggregated to form a single score for S-LCA, thereby facilitating both options on which to evaluate LCSA results as proposed by Klöpffer (2008).

3.2.3 Life Cycle Costing

LCC already a fundamental element in the early definition phases of space concepts since cost is generally considered to be a major driver in terms of mission viability. For this reason, LCC is perhaps the most mature of the three life cycle techniques within the context of aerospace, with the cost estimating process for early-phase space mission concepts given in (Wertz & Larson, 1999). In this regard, costs can be broken down in three main phases: Research, Development, Test, and Evaluation (RDT&E); Production; and Operations and Maintenance (O&M). For each of these phases, a Work Breakdown Structure (WBS) is defined, dividing costs among the basic elements of a space architecture, namely the space, ground and launch segments, as well as management & systems engineering (program level costs).

According to Swarr, et al. (2011) and the IEC 60300-3-3:2017 standard, the LCI phase involves the collection and calculation of monetary data. Typically, dedicated cost estimating models will be used for this purpose. As outlined by NASA (2015), three cost estimating methods are mainly used during the space mission design process, with the choice of method dependent on concept maturity. The first is a parametric estimation approach, where simplistic statistical models, extrapolations, or cost-estimating relationships (CERs) are created based on historical cost data, correlating the cost of an element to physical, technical, and performance parameters that are known to strongly influence costs. Such techniques are often used during conceptual studies in early mission design stages where design details are scarce or there is limited mission definition. The second is a top-down analogy-based estimating approach, where the cost of a similar item is used as a baseline and is then adjusted for differences in size, complexity, technology readiness levels etc. The baseline item(s) and scaling method used can be based on expert judgement or more formal methods (e.g., Shishko, 2004; Mrozinski, et al., 2020). This technique is typically applied once a mission design is more adequately defined but there is still insufficient actual cost data to use as a basis for a detailed approach. Lastly is the grassroots methodology which is a bottom-up estimate of every activity in the project’s WBS, including overheads. It is applied when there is adequate project maturity which allows far more detailed cost data to be accumulated despite being a lot slower and more labour intensive. Depending on the design details available, these methods can be used at the system, subsystem, or component level.

In terms of this framework, parametric and analogous cost estimation techniques could be considered as most appropriate for early space mission design concepts. However, NASA (2015) states that none of these techniques are individually sufficient to accurately estimate the life cycle cost of a space mission. For this reason, several different cost models and techniques often need to be used in conjunction for this purpose. In comparison to NASA, ESA applies a mixture of in-house build cost estimation relationship (CER) tools based on excel and commercially available cost estimation tools (Hunt & van Pelt, 2004).

Despite this, besides the three phases outlined by Wertz & Larson (1999), when applied as part of the space LCSA framework, there is a need to ensure complete coverage of system boundary. To achieve this, another interesting cost estimating methodology which could be incorporated is activity-based costing (ABC). ABC is an approach whereby costs of organisational activities are identified and assigned to products, processes, services and activities according to the actual consumption of each. According to Curran et al., the implementation of this technique is based on activity pools which are a collective set of activities (Curran, et al., 2004). Each activity pool is then allocated to a specific cost driver as a base (i.e., the amount of an activity used). All overhead costs are then determined and calculated per cost driver. As such, the method assigns more indirect costs elements into direct costs compared to conventional costing approaches and evidently aligns closely with the E-LCA modelling approach. Besides this, one of the main advantages of using this method is that the number of cost pools used to assemble overhead costs can be expanded. As such, new bases on which to assign costs are produced (i.e., FUs as cost drivers) which allows the nature of several indirect costs to be altered in a way which makes them more traceable to certain activities. Although this is a far more labour-intensive approach, the method can often lead to a significantly more thorough and informative costing analysis (Keller, et al., 2014).

Therefore, due to its applicability during conceptual studies, a parametric and/or analogous methodology is proposed for LCC using an ABC estimating approach. This is more in line with the life cycle methodology than the conventional LCSA approach and allows grouped LCI datasets to be generated using specialised life cycle modelling software which has been explicitly developed to handle life cycle activity-related data of products (Watson, et al., 2006). This is because the method allows other overhead elements which are not typically included within space systems cost engineering models (e.g., cost of heating and/or electricity consumption during design work) to be considered. As such, a more complete cost model can be developed which better aligns with the current LCC methodology whilst covering the sum of space, launch and ground segment for the system boundary under study. As such, the main difference between the LCC approach proposed by this framework and cost analyses which typically occur during space mission design studies is the complete number of cost pools used to assemble overhead costs which leads to a more detailed assessment being conducted. Additionally, when applied within concurrent engineering, this approach can also be seen to be more resource efficient since it requires just one discipline expert to cover three assessments and eliminates the need for a separate cost expert (Kayrbekova, et al., 2011).

However, appropriate aggregation of costing data is extremely important in cases where co-products are produced. This is because some expenses, particularly overheads, cannot always be directly related to a product (Kayrbekova, et al., 2011). Additionally, since costs might occur for different actors, it is also important to differentiate and select which costs and cost bearers are included within the assessment (Gluch & Baumann, 2004). For this reason, caution must be exercised when calculating the LCI or using cost models. According to Ciroth, another important consideration during this phase involves the selection of an appropriate discount rate (Ciroth, 2009). Discount rates are used to convert future costs associated with a product system into a net present value, thus accounting for future inflation rates. Cost data might also be gathered in different currencies over different time periods (Swarr, et al., 2011). LCI data will therefore need to refer to a common currency at present value using appropriate exchange and discount rates.

Lastly, like S-LCA, whilst the LCIA phase is not strictly required within LCC, it has been considered as a mandatory requirement within this framework to make the results comparable to those of E-LCA and S-LCA. As such, all monetary values should be aggregated into economic cost categories, life cycle stages, activity types or cost elements. Since this methodology uses a single unitary value, it is also recommended that a single score is generated and integrated as an impact category within E-LCA for the same reasons as stated for S-LCA (Rebitzer & Seuring, 2003).

3.3 Multi-Criteria Decision Analysis

Before the significance of the LCIA results can be interpreted, it is important that decision-makers are able to understand the severity and trade-offs between sustainability dimensions. As such, a systematic and structured decision-analysis technique is required to assist decision-makers to evaluate and improve the sustainability performance of a product. However, the plethora of impact categories across the three different assessment types creates difficulties for decision-makers in terms of their ability to handle such plentiful and diverse forms of data (Valdivia, et al., 2021). Three options are generally available for presenting results and making decisions:

- **Option 1:** Results of each assessment are presented separately using their own impact categories.
- **Option 2:** Results of S-LCA and LCC are added as impact categories within E-LCA.
- **Option 3:** Results are presented as a single sustainability score.

Option one is perhaps the most scientific and provides most depth but can be overwhelming due to the amount of impact categories. Option two is generally more advised to simplify decision making, particularly if the S-LCA and LCC impact categories have been developed using common units. Despite this, when applying E-LCA within concurrent design, ESA found that the high number of impact categories included within the assessment significantly complicated decision-making due to the iterative nature of the process (Chanoine, et al., 2015). Additionally, neither of the first two options adequately address the interaction between the sustainability dimensions or the burden-shifting effect which occurs during system redesign, which implies an obvious risk of cherry-picking and sub-optimised decision-making.

For this reason, Option three presents a more credible decision-analysis technique to enable trade-offs between sustainability dimensions. Despite this, it is considered only to be appropriate for the identification of hotspots and not for results presentation (with the exception of within concurrent engineering studies because the technique simplifies the decision-making process and reduces the learning curve of engineers who may have limited time within such studies).

In relation to Option three, a commonly used technique is MCDA which is frequently applied within decision-making to address problems with conflicting goals, handle diverse forms of data and reach conclusions, particularly when there could be multiple perspectives as with sustainability issues. It is increasingly being applied to LCSA studies to address the multidimensional results of LCSA and is recognised by many researchers as a critical component of LCSA. As documented by Velasquez & Hester (2013), various methodological approaches exist for MCDA, but of particular relevance to LCSA is the multi-attribute value theory (MAVT) approach. This quantitatively compares a set of attributes or criteria by calculating their performance with respect to a given objective. In this respect, the MAVT approach can be used to assign real numbers to different alternatives in order to produce a preference order on the alternatives consistent with decision-maker value judgements. The technique is particularly useful when assessing trade-offs between conflicting criteria and combining dissimilar measurement units. The MAVT approach is typically based on the following weighted sum formula:

$$v(a) = \sum_{i=1}^{I} wi\ vi(a) \qquad (1)$$

Where *v(a)* is the overall score of product *a* on sustainability dimension *v*, *wi* is the weighting factor for impact category *i*, *vi(a)* is the score reflecting the performance of product *a* on impact category *i*, and *I* is the total number of impact categories.

In this regard, a score reflecting performance for each impact category should be calculated through the sum of normalisation and weighting procedures when applied to LCIA results. Normalisation is the magnitude of impact relative to reference information whilst weighting expresses the relationship between normalised impacts and politically determined goals or targets. To align with the approach adopted within the ESA E-LCA guidelines, the recommended method for E-LCA is to apply normalisation and weighting values for E-LCA developed by the European Commission (Benini, et al., 2014; Sala, et al., 2018), whilst new factors for S-LCA and LCC as single score impact categories are outlined in Wilson & Vasile (2022).

Supplementary weighting factors are also suggested by Wilson & Vasile (2022) for each impact category with respect to its parent assessment type to reflect their respective sustainability dimension. This is used to determine the relative contribution of each impact category in terms of a single score. In this case, the most dominant political framework for sustainability currently in existence can be used to reflect this. This allows the three dimensions of sustainability to be appropriately balanced according to the level of concern given to each with respect to the contents of 2030 Agenda. In this respect, Diaz-Sarachaga, et al. (2018) groups the 17 SDGs and their associated 169 targets into environmental, social, economic and governance categories, and uses the Delphi methodology to highlight the percentage of goals/targets dedicated to each sustainability dimension. Based on this study, it was found that the weighting factor for the environment was 18% in comparison to 53% for social/governance and 29% for the economy. Equation 1 can then be used again, based on *v(a)* for each assessment type and the above weighting factors to obtain an overall single sustainability score.

Lastly, it should be noted that although normalisation and weighting procedures are listed as optional elements according to the ISO 14040:2006 and ISO 14044:2006 standards. Regardless, their use in MCDA is considered vital to the space LCSA framework, with a distinct overlap in relation to the interpretation phase.

3.4 Interpretation

In terms of interpretation, the ESA E-LCA guidelines state that environmental hotspots should be identified during this phase (ESA LCA Working Group, 2016). This is a critical element of decision-analysis process, with common techniques to determine hotspots including contribution analyses, dominance analyses, influence analyses or anomaly analyses (Zampori, et al., 2018). However, in accordance with this framework, MCDA is considered as the foundation for hotspot analysis. Building upon the LCSA decision-analysis framework proposed by Hannouf & Assefa (2018), it has been considered that the interpretation phase within this framework should consist of the following steps (which should be repeated with each iteration of analysis):

- **Hotspot identification:** Informed by the relative contribution to the MCSA single score result.
- **Objective identification:** A set of objectives are proposed to address the defined hotspots.
- **Solution generation:** A range of possible solutions should be sought in line with these objectives.
- **Solution evaluation:** All identified solutions are analysed in order to determine their effectiveness.
- **Trade-off analysis:** Trade-offs are evaluated collectively for all solutions to determine which delivers the most optimal sustainability performance in relation to the sustainability dimensions and technical requirements.
- **Implementation / recommendations:** The selected solution can then be recommended or implemented within the system design model.

Although the process is the same, it is important to consider the potential of the above steps for generating solutions depending on the study application (LCSA vs LCE). Once a hotspot is defined in an LCSA study, it can be investigated further at subsystem level. An example of this is presented in Wilson (2019) for a battery module. In this analysis, when using MCDA to determine hotspots, it was found that social aspects and costs were the most dominant sustainability dimensions. It went on to show the respective trade-offs concerning the implementation of potential improvement measures, exemplified by addressing the social hotspot of health & safety by looking into methods for introducing more stringent health & safety training for employees and the net impact across all sustainability dimensions. In comparison, when addressing hotspots during concurrent engineering sessions through LCE, only system level improvements are possible due to time constraints. This means either reducing the quantity of the hotspot or replacing / phasing out the hotspot entirely is possible in real-time. This is discussed further in Wilson & Vasile (2022), which also provides additional guidance on the adaptation of this framework to facilitate LCE within concurrent engineering sessions of space missions.

The interpretation phase should also seek to provide a set conclusions, limitations and recommendations whilst addressing uncertainties and data quality where possible. However, uncertainty and data quality are aspects which are currently lacking in space LCA. This is seen by many as being a priority issue needing to be addressed in the near future. Although critical reviews are required for E-LCA in the case of a comparison, according to (the now outdated) ISO/TR 14062:2002, they are not an essential component of ecodesign. If these standards are to be followed for LCSA, this also means that a critical review is not strictly required for LCE but is perhaps advisable. This could be conducted by independent experts between space mission design sessions or when a final design is reached, particularly if the results are intended for public disclosure.

3.5 Direct Applications

Another important consideration of this framework is how the outcomes of space LCSA studies will be used. This places a need for the findings to be passed to the relevant decision-makers (Valdivia, et al, 2021). As outlined in the ISO 14040:2006 and ISO 14044:2006, numerous direct applications for life cycle studies exist. However, from the early application of E-LCA within the space sector, perhaps the most common is for engineers to receive the input from the LCSA expert to update and improve the design through reiteration. This can either be initiated between design sessions through LCSA, or by applying this framework within the concurrent engineering process by adapting it towards LCE, as specified by Wilson & Vasile (2022). Regardless, according to Wilson (2019), the multitude of possible applications of the LCSA approach for space systems makes it a powerful tool for the space industry to:

- Comply with current and future legislation,
- Cut costs,
- Facilitate technological development and advance with the times,
- Respond to consumer demand for sustainable products (creating a competitive advantage), and
- Create a more sustainable space sector.

4. Framework Implementation

The applicability of this framework will be tested on a Phase 0/A SmallSat concept called MÌOS which was designed at the University of Strathclyde in September 2017 as part of the ESA Academy's First Concurrent Engineering Challenge. MÌOS stands for Moon Ice Observation Satellite, which is a derivation of the Scottish Gaelic word for month, and less commonly, moon. The mission has an aim of collecting data on the lunar micrometeorite and radiation environment as well as detecting the presence of water and ice content on the lunar South Pole in view of a future moon base.

Table 3: Mission objectives and requirements for the MÌOS space mission design concept

MIS-OBJ-01	The mission shall make pictures of South pole areas with high expected water/ice content, with a resolution of 10m/pixel.
MIS-OBJ-02	The mission shall observe the lunar radiation and micrometeorite environment.
MIS-OBJ-03	The mission shall observe the water/ice content of the Lunar South pole.
MIS-R-01	The mission shall consist of a single satellite or a single plane constellation.
MIS-R-02	The mission shall stay in Lunar orbit for 2 years.
MIS-R-03	The mission shall be launched using an Ariane shared GTO.
MIS-R-04	The mission shall be compatible with any launch date.
MIS-R-05	The total combined mass of the whole system shall be 300 kg.
MIS-R-06	The mission should use commercial off-the shelf (COTS) components.
MIS-R-07	The mission shall have an end-of-life disposal manoeuvre.
MIS-R-08	The mission shall use direct to earth communication.
MIS-R-09	Applicable documents: CDF margin philosophy.

The mission objectives and requirements which drove the design are outlined in Table 3. The final baseline design had a total wet mass of 286.04 kg including mass margins and the launch adapter. According to the mission requirements, this was 13.96 kg within budget. The total mission duration is 913 days, consisting of a single satellite in a frozen lunar orbit with a maximum eclipse time of 160 minutes. It is sun pointing for most of the lunar orbit with a minimum altitude of 82 km and maximum altitude of 119 km at the Lunar South Pole. The mission concept uses a narrow-angled camera for taking pictures of the water/ice content and a wide-angled camera for the radiation/micrometeorite environment. The configuration of the components can be viewed in Figure 3. At the final design review, it was concluded that MÌOS was a solid and sound design concept which satisfied all mission requirements with no major design flaws.

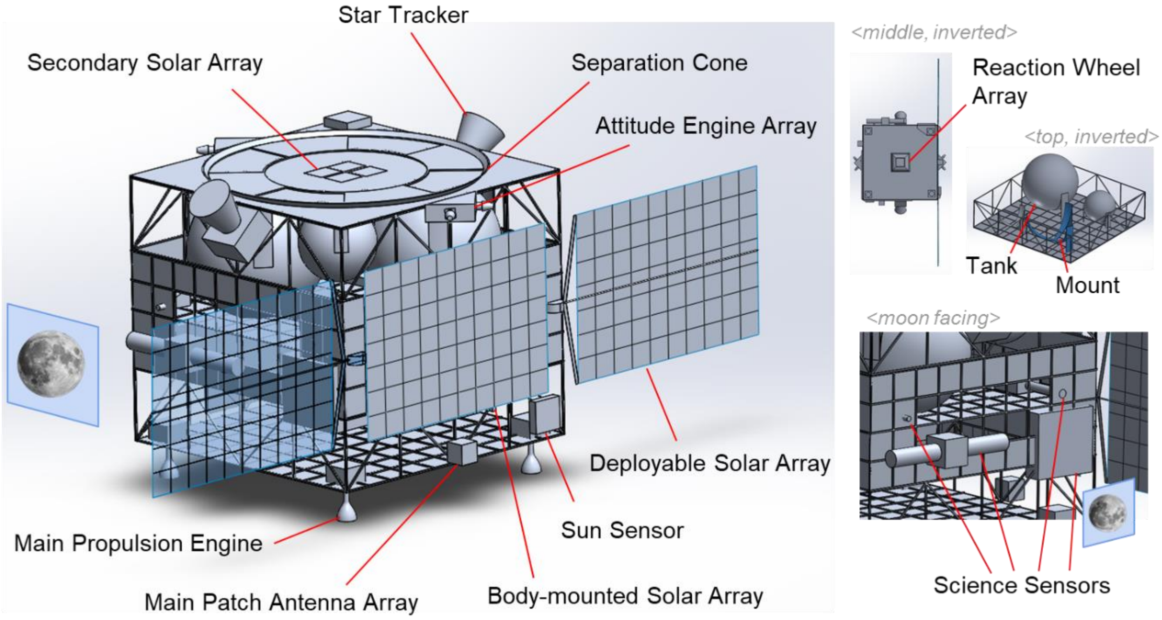

Figure 3: Configuration of the MÌOS space mission design concept

Therefore, to demonstrate the applicability of the LCSA framework, a post-CDF LCSA study will be performed on this design concept. As part of this case study, the life cycle sustainability impacts of the MÌOS baseline design will firstly be investigated and then compared to an adaptation of the same model where two predetermined ‘sustainable design’ options will be implemented. The first of these options targets the most substantial hotspot identified within MÌOS baseline design according to the most greatly impacted sustainability dimension according to MCDA. The second was to investigate the possibility of replacing the propellant with a high-performance green propellant (HPGP) to test if there is a case for this switch within future design sessions of the MÌOS mission. The collective influence of these options on LCIA results will be investigated at system level.

4.1 Baseline Design

The goal of this study was to inform decision-makers of the most prominent sustainability impacts of the MÌOS concept before any further iterations/design sessions occur. The FU was set as “the MÌOS mission in fulfilment of its objectives and requirements”. The system boundary covers the sum of the space, ground and launch segment across all phases of the space mission, consistent with the system boundary diagram found in Figure 2. However, it should be noted that there are no environmental impacts stemming from the deorbiting manoeuvre (besides ground station work) as the MÌOS mission was designed to crash into the moon at the end of its life, hence nothing returns to Earth.

The SSSD was used to calculate both the LCI and LCIA results. Validated at ESA through a collaborative project in late 2018 (Wilson, 2018), the SSSD has already been used in the design of several space missions. It consists of 250 unique foreground space-specific life cycle sustainability datasets which each contain environmental, costing and social data, building upon Ecoinvent and ELCD E-LCA background inventories. A process-based methodology is used which relies on physical activity data to develop datasets derived from assessing all the known inputs of a particular process and calculating the direct impacts associated with the outputs of that process. 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 five E-LCA impact categories selected as part of this study relate to the five impact categories identified by ESA as being most problematic (Serrano, ESA, personal communication, 2018). These are climate change, mineral resource depletion, ozone depletion, freshwater aquatic ecotoxicity and human toxicity. Additionally, the SSSD aligns closely with a variety of widely accepted international standards and norms, which are used as the basis for this coordinated, overarching space LCSA framework (Wilson, 2019).

In terms of data collection, primary data was collected directly from the mass budget and subsystem information contained within the MÌOS engineering model which was used within the concurrent engineering process. This was then mapped to the relevant SSSD processes. For all other elements of the MÌOS life cycle which was not pertinent to data contained in the engineering model, default values contained in the SSSD as well as well-judged estimations were used based on expert input. In particular, to fulfil MIS-R-03, it was assumed that the mission would be launched with the other three other missions, meaning that MÌOS was attributed a 25% share of total launch segment impacts.

For the social impacts, 31 different stakeholder groups were identified including the University of Strathclyde, ESA, ArianeGroup plus 28 other entities. These were then matched to SSSD S-LCA datasets which were obtained using freely-available averaged national-level data and integrated in E-

LCA datasets to represent these stakeholders based on their country of operation. This was considered appropriate since Siebert et al. (2018) states that “an organisation’s conduct is highly influenced by national and regional socioeconomic conditions”. The activity variable was based on detailed working hours for each process (already contained within the SSSD). The overall social impacts were calculated as a single score for all stakeholders for the stakeholder categories of ‘worker’ and ‘value chain actors’.

For LCC, a new parametric-analogous hybrid cost model which adopts an ABC estimating approach was integrated into the SSSD E-LCA datasets. This ABC approach treats each activity of a space mission defined by the system boundary within the ESA E-LCA guidelines as cost pools. In particular, this mainly estimates future costs based on historical trends, with the analogous part adjusting these parametric costs for complexity, technological and physical differences in a similar manner to Saint-Amand & Ouziel (2015) and Ouzeil & Saint-Amand (2015) for technology readiness levels (TRLs). The costs were calculated as a single score, taking into account relevant pre-defined cost categories.

The results of this process can be seen in Table 4. However, as can be seen the high number of impact categories makes it difficult to determine which impact categories or sustainability dimension is most important to address. As such, the normalisation and weighting factors outlined in Wilson & Vasile (2022) was used to create a single sustainability score through MCDA. This creates an ‘importance factor’ of each sustainability pillar, relating to the severity of impact magnitude per EU citizen. More specifically, the five environmental impact categories selected for this study were normalised based on the approach recommended for the Product Environmental Footprint method (Benini et al., 2014) which related to the EU-27 domestic inventory in 2010 per EU citizen. The normalised values were then multiplied by the JRC recommended weighting set (Sala et al., 2018) which was reformulated to 100% based on the impact categories used. For the Social Impact category, the normalisation method was based on the percentage of global companies which have not set quantitative targets linked to their societal impact for at least one KPI in 2016 (PwC, 2017). This was then multiplied by the total number of active EU-28 entities to generate a total social score for all EU entities (Eurostat, 2018). This was again multiplied by the total number of hours in one year to produce an annual social score before being divided by the EU-28 population in 2016 to produce the average share of total European organisational social impact per EU citizen (Eurostat, 2021). It is recognised that this approach has a very low level of robustness and work is ongoing to create a better normalisation procedure. or Whole Life Cost, the normalisation factor was based on the average tax rate of EU-28 nations per citizen in 2015 to the value of the euro in the year 2000 (European Commission, 2015). The weighting factors for both Social Impact and Whole Life Cost were given a value of 100% since they each represent an individual sustainability dimension. Finally, the generated values for the environmental, social and economic dimensions were multiplied by another weighting factor based on the relative importance of each sustainability dimension. As previously mentioned, this was based on indicators dedicated to each dimension within the 2030 Agenda for Sustainable Development (as specified by Diaz-Sarachaga et al. (2018)) which gave a split of 18% to the environmental dimension, 53% to society dimension and 29% to the economic dimension. Based on this approach, it found that the final importance of impact magnitude per EU citizen for the entire sustainability score is 1.66E+05 which is composed of 1.50E+05 environmental impact, 1.22E+04 social impact and 4.04E+03 economic impact. An overview of these results can be seen in Figure 4.

In terms of interpretation, the MCDA results clearly indicate that E-LCA should be considered to be the most important sustainability dimension to address for the baseline design of the MÌOS concept. The majority of this impact came from mineral resource depletion (59.98%) which is directly attributable to the use of germanium in solar cells. A contributing factor for this result could be the fact that the CML 'reserve base' horizon was used for this impact category (as recommended in the ESA E-LCA guidelines), a choice which leads to germanium being particularly impactful. Other high scoring impact categories were human toxicity (20.18%) and ozone depletion (19.71%). The former result is largely due to the manufacturing and production of the launcher propellants and dioxins released during the production & manufacturing of the germanium substrate for the solar arrays. The latter result was almost entirely due to the launch event.

In comparison, from a social perspective, it is clear that by far the largest social impact comes from the 'Working Hours' stakeholder subcategory (which produces 29.30% of total social impact). This was based on a survey conducted as part of this research at the University of Strathclyde which found that the working hours of PhD students and academics within the Department of Mechanical & Aerospace Engineering was generally higher in real-terms than reported by the university. Whilst at ESA during the ESA LCI Validation Project (Wilson, 2018), similar working patterns were also observed. This trend led to the establishment of a factor which was applied to average working times reported by each country based on OECD data (OECD, 2022). As such, it was found that a very high-risk factor was assigned to most countries associated with the MÌOS concept which was the primary reason for this score. The highest VCA stakeholder subcategory was 'Promoting Social Responsibility' which produced

9.25% of the total social impact. This score was based on information contained within a report titled 'Global trends in sustainability reporting' which highlighted the low number of reporting instruments identified by country (KPMG International, 2019). In terms of how this affects the SDGs, it was found that the top 5 most affected SDGs represents 79.41% of the total social score which are SDGs 8, 10, 12, 16, 17.

Additionally, it can be seen that the majority of costs arise from labour in term of work-hours (6.89E+07 EUR 2000). This was closely followed by the launch segment (3.61E+07 EUR 2000) which relates almost entirely to acquisition of the Ariane 5 ECA launcher. The third most impacting cost element was transportation (9.30E+06 EUR 2000) due to the shipping of both the spacecraft and launcher components to the ESA launch site in Kourou, French Guiana and the air travel involved for staff/expert participation in space mission design sessions and launch event activities.

4.2 Alternative Design

Given the MCDA results, it was considered that the germanium substrate of the solar array is the most prominent sustainability hotspot. For this reason, the first sustainable design option is to target the germanium substrate used within the solar array. The baseline design uses a triple-junction GaInP/GaAs/Ge solar cell with a mass of 18.84 kg (including mass margins) and conversion efficiency of 30%. The second sustainable design option is to replace hydrazine with LMP-103S which is a HPGP. This is because hydrazine is particularly toxic and now contained on the candidate list of substances to be regulated under the EU's regulation concerning the REACH regulations (European Chemicals Agency, 2022). In this regard, LMP-103S is a flight proven HPGP which is marketed as being much less toxic than hydrazine and also non-carcinogenic. More specifically, LMP-103S has a 6% higher specific impulse than hydrazine and is 24% more dense based on values based on observations from the PRISMA mission which was launched on 15 June 2010 (Dinardi, 2013). As such, it exhibits a 30% higher density impulse, meaning that 56.9 kg of the propellant is required in comparison to 61.2 kg of hydrazine in the MÌOS mission.

The executed sustainable design measures led to a 21.71% downsizing of the solar array and the replacement of the hydrazine propellant with LMP-103S. This latter option was implemented since it would lead to a 7% reduction in the amount of propellant required, despite the fact that kg to kg LMP-103S was found to perform environmentally worse than hydrazine on almost every impact category, a result confirmed by GreenSat project (Thiry, et al., 2019). This impact was primarily due to ammonium dinitramide production and in particular, the influence of nitric acid (from the production of potassium dinitramide), isopropanol and pentane. The combination of these two sustainable design measures led to waterfall mass savings of 5.05% and a reduction in MCDA score by 15.66% (see Figure 4). On average, the alterative design of the MÌOS concept generated average environmental savings of 8.65% across the five impact categories, a 0.91% better social performance and a reduction of 6.62E+04 EUR 2000 in costs. The direct savings in social impact occur mainly due to the use of LMP-103S in comparison to the risk associated with workers handling hydrazine. Additionally, as LMP-103S is produced in Sweden and hydrazine is produced in Germany, the workers category of LMP-103S scored significantly better for this activity, particularly relating to wellbeing of staff (36.71%) and working hours (33.33%). In terms of costs, the reduction of mass meant that due to the linear nature of CERs, a cost reduction was also achieved.

Overall, it is hypothesised that the environmental savings were almost entirely due to the reduction of the solar array mass. Actually, it is suspected that the replacement of hydrazine with LMP-103S actually suppressed the improvement measures. Proving this would be extremely challenging since tracing the full indirect impacts to a single sustainable design option is not a straightforward procedure. This is due to the interrelated nature of design decisions and the chain reaction that they can put into motion. For example, changes to the centre of mass caused by the redesign led to a reduction in the mass of the reaction wheels by 8.25%. As such, it is difficult to determine which sustainable design option primarily drove this change since both created reductions in system mass. However, despite the implementation of this sustainable design solution, it can be seen that the environment is still the driving force behind the LCSA results.

This study has demonstrated the importance of considering each sustainability pillar, even when targeting just one dimension. Moreover, the results suggest how imperative it is that system level technical considerations are also taken into account when designing sustainable space systems. In this regard, a space system component which performs worse environmentally, socially and/or economically at face value may actually be the more sustainable option if it provides an optimised performance at system level through redesign. Therefore, it can be concluded that completely replacing technologies without considering the complete system level performance is an inattentive and poor sustainable design choice.

Going forward, the results of this exercise can now be used to address the hotspots across the supply chain. In this regard, technological improvements can now be targeted, which includes advanced manufacturing technique refinement (similar to the efforts that ESA are undertaking) (Zimdars & Izagirre, 2017) and/or the development of lightweight spacecraft materials and structures (NASA, 2012). In particular relation to the MÌOS mission, it is recommended that either the solar array size is reduced further, or the germanium substrate is directly replaced, whilst additional efforts are made to minimise the other identified environmental hotspots within future design iterations. Additionally, whilst other HPGPs could be investigated for use within the MÌOS mission, switching propellants from hydrazine to LMP-103S should not considered as a sustainable design solution.

Table 4: LCSA results of the MÌOS mission for the baseline and alternative design

Sustainability Dimension	**Impact Category**	**Unit**	**Method**	**LCIA Results**	
				Baseline Design	**Alternative Design**
Environment	Climate Change	kg CO_2 eq.	IPCC (2013)	1.12E+07	1.12E+07
	Freshwater Aquatic Ecotoxicity	PAF.m^3.day	USEtox	6.93E+07	6.92E+07
	Human Toxicity	cases	USEtox	1.88E+03	1.47E+03
	Mineral Resource Depletion	kg sb eq.	CML (2002)	2.58E+05	2.03E+05
	Ozone Depletion	kg CFC-11 eq.	WMO (1999)	2.17E+04	2.17E+04
Society	Social Impact	Social risk	Wilson (2019)	7.70E+08	7.63E+08
Economic	Whole Life Cost	€ (CY:2000)	Wilson (2019)	1.19E+08	1.19E+08

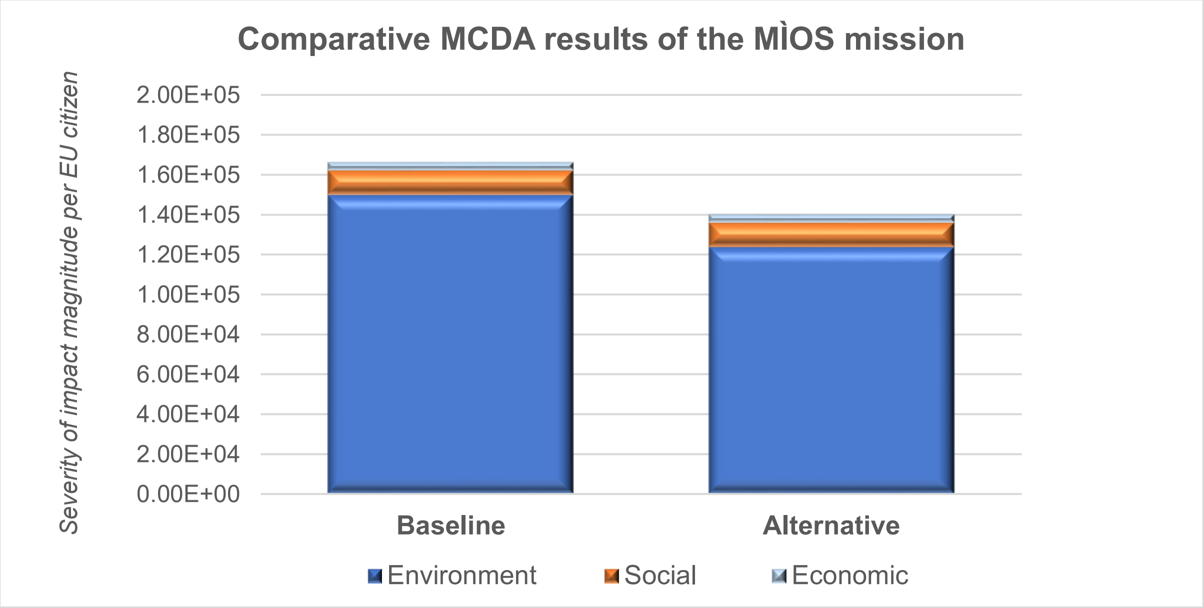

Figure 4: Comparative MCDA results of the MÌOS mission for the baseline and alternative design

5. Evaluation & Discussion

Several commonalities and differences exist between the three assessment types of E-LCA, S-LCA and LCC. Therefore, it is important to synthesise these in terms of the main drivers, applied methodologies and data requirements in order to better understand the benefits and drawbacks of addressing them within a single space LCSA framework.

Firstly, the drivers of each assessment are distinctly different. Although E-LCA is mainly driven by environmental impact mediums, S-LCA is primarily based on principles of social responsibility outlined within ISO 26000:2010, whilst LCC is commonly steered by predefined financial factors typically based on mission requirements and/or a WBS. As such, this makes the strategy and methodological choices which are determined during the goal and scope definition an extremely important element of the LCSA process to align these drivers.

In this regard, the space LCSA framework aims to follow a common goal and scope in order to reduce the effort required in impact modelling. Since current practice dictates that E-LCA is used as the baseline methodology on which S-LCA and LCC should be applied, there is a need to tailor these assessments to E-LCA. In terms of S-LCA, selecting activity variables which best accords with reference flows of processes can be extremely challenging if an organisational perspective is adopted. However, this is necessary to relate organisational social impacts to processes. This becomes even more challenging if new social indicators need to be created since a scoring mechanism will also be required based for both quantitative and qualitative inventory data. Therefore, linking social inventory data to activity variables and then relating activity variables to quantitative references is extremely important for inventory relevancy but may limit what could be considered appropriate to reflect this relationship. In terms of LCC, the creation of costing flows is a lot simpler since they adopt a product-based perspective like E-LCA. However, it is important to define the cost bearer which should generally be viewed from the perspective of the organisation responsible for designing the space mission as a baseline.

In terms of data requirements, LCI data acquisition for compilation within a database may also be extremely challenging for all three assessment types meaning that stakeholder buy-in is particularly important for compiling an accurate and relevant LCI. Despite the varied and diverse LCI data requirements, a well-developed sustainable design tool should look to minimise the amount of additional data which engineers are required to provide in space mission design sessions. Therefore, should dedicated environmental, social and economic datasets be developed in accordance with the proposed space LCSA methodology, then integrating these within the same dataset should sufficiently achieve this since all of the LCI data refers to a common quantitative reference. The SSSD has been created to simply this process based on the methodological guidance offered by this framework, eliminating the need for background data collection.

The outputs of each assessment type are based on the LCIA methods outlined in Section 3. Although life cycle hotspots will mostly depend on the goal and scope definition, it is hypothesised that within E-LCA, the spacecraft, launcher and propellant production & manufacturing will produce the greatest impact across most impact categories. In comparison, it is thought that in S-LCA it will mostly be affected by activities with high levels of organisational involvement (typically during spacecraft and launcher production & manufacturing) whilst LCC will mostly be influenced by costs from labour, launcher acquisition and satellite operations.

Finally, it should also be noted that the impacts of each assessment are considered to be self-contained before MCDA is applied (i.e., no direct interactions between assessment types). However, the importance of MCDA should not be understated since its ability to address the multidimensional results of LCSA is vital to the decision-making process. Ultimately, despite the subjectivity such an approach introduces to results (as demonstrated by Wilson & Vasile (2022)), addressing each assessment type within a single framework offers numerous benefits. Assuming that the space LCSA framework is followed and that stakeholder buy-in can be achieved for LCI data collection, then aggregating these three assessments allows for complex environmental, social and economic and social data to be organised in a structured and common form to generate a more comprehensive overview of life cycle sustainability impacts of space missions.

6. Conclusion

This paper has outlined the potential for using LCSA as a method for designing sustainable spacecraft and presented a methodological framework for its application within the space mission design process. The framework provides a credible and compelling new method for streamlining the decision-making process in a more systematic and coordinated fashion, with the concept of sustainable development at its core. This was demonstrated on the Phase 0/A MÌOS space mission design concept to scientifically identify and reduce adverse sustainability impacts over its entire life cycle through system redesign. As such, it is hoped that this proposed framework will contribute to the global sustainability agenda by assisting engineers to design space missions that are not only cost-efficient, eco-efficient and socially responsible, but also ones that can easily justify and evidence their sustainability.

6.1 Limitations

The approach is not without its challenges. Since the solution is principally a burden-based approach, stakeholder buy-in may be difficult to achieve in the first instance as organisations may not want to participate in data collection or any other activity which could be seen to damage their reputation. However, shifting public perceptions may force organisations to think this protective stance, with 80% of citizens in EU Member States thinking that businesses and industry are not doing enough to protect the environment, according to a recent Eurobarometer survey.

Moreover, the use of E-LCA, S-LCA and LCC indicators and normalisation/weighting methods within the space systems design process is still not consensual given the current lack of a standardised method and commonly agreed quantitative metrics. This particularly relates to S-LCA due to the novelty of the approach when applied to space system. As such, the proposed method outlined by this framework may need to be further elaborated on in the future. For this reason, an international protocol may need to be established to govern the harmonisation of LCSA/LCE for space technologies.

Lastly, it should be noted that whilst the most dramatic life cycle impacts and optimisation activities associated with space systems engineering are obtained in the early stages, decisions that affect the environment, society or costs continue to be amenable to the systems approach even as the end of the system lifetime approaches. Although the presented case study of this paper was a Phase 0/A study, users of the new space LCSA framework must consider the concept's stage of design at the point of study to ensure that the most appropriate method is applied. For example, in LCC, whilst CERs or analogous costing is mostly applicable to early space mission concepts such as the MÌOS example, grassroots costing is more applicable to more adequately defined concepts.

6.2 Expected Outcome

The novelty of this newly proposed space LCSA framework lies in the adaptation of the current E-LCA, S-LCA, LCC and MCDA methods to the application to space missions. In particular, this relates to the calculation of sustainability impacts in a manner which is most relevant to industrial practice whilst enabling traceable decision-making (i.e., the provision of best practice in LCSA when applied to space). This is very relevant given the complexity of space missions as a product system.

Overall, the framework has been established as a voluntary tool with a goal of assisting industry to integrate LCSA into the design process of early space mission concepts and concurrent engineering. As such, it is not the intention of the framework to dictate which methodologies should be applied within a space LCSA study, but instead provide robust and systematic methodological guidance based on best practice. This was defined from literature reviews with reference to both the LCSA methodology and current practice within the space industry. The implementation of this framework is currently supported through the SSSD, as outlined by Wilson (2019). As such, this new space LCSA database should be seen as an extension of this framework.

Through its use, the framework can be used to illustrate how design decisions targeting a specific sustainability dimension may affect the others, since an environmentally friendly design does not necessarily mean that it is socially responsible or economically viable. In this regard, the LCSA results can be fed into the decision-making process at either system level (e.g., redesign activities) or strategic level (e.g., making changes to the procurement process) to drive internal change and create a truly sustainable space sector. This can help to lower ecological burdens, avoid potential supply chain disruption, and reduce costs, all whilst demonstrating the interaction of each sustainability dimension.

The application of the developed space LCSA framework has already been exemplified within this paper using MÌOS as a case study. However, the adoption of the technique within industry is not difficult to envisage. E-LCA is already a requirement for all future Copernicus missions, and it is reported that it may become a mandatory element of the space mission design process at ESA in the future (Wilson & Neumann, 2022). Such a scenario would provide an ideal opportunity for LCSA to also be integrated as a complimentary tool to E-LCA (at least on an experimental basis). Not only would this help to advance the methodology, but it would also ensure the widespread knowledge/application of the approach at all levels within the space sector.

As a result, it is expected that this approach will be used by industry for the design of next generation sustainable space systems, allowing conclusions to be reached based on the interactions of each sustainability dimension during the mission design process. It will therefore allow the space industry to streamline future decision-making and monitoring in a more systematic and coordinated fashion which accords with best practice.

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Data Availability

Data, associated metadata, and calculation tools are available from corresponding author Andrew Ross Wilson (andrew.r.wilson@strath.ac.uk). Requests for access to the Strathclyde Space Systems Database (SSSD) can be sent for consideration to the authors.

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