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THE STRATHCLYDE SPACE SYSTEMS DATABASE: A NEW LIFE CYCLE SUSTAINABILITY ASSESSMENT TOOL FOR THE DESIGN OF NEXT GENERATION GREEN SPACE SYSTEMS

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ABSTRACT

Life Cycle Assessment is an important environmental management technique that is increasingly being applied within the space industry to assess the environmental impacts of products over their life cycles. However, with a renewed focus on sustainability issues, the space sector may need to move to a more encompassing sustainability assessment. In this regard, the new open source Strathclyde Space Systems Database is the first Life Cycle Sustainability Assessment tool for space systems. The use of this database is demonstrated by comparing different monopropellants in two separate scenarios. From this it is clear that the added sustainability dimensions can dramatically assist decision-makers to select more sustainable products.

1. INTRODUCTION

Environmental Life Cycle Assessment (E-LCA) is an internationally standardised environmental management tool used to measure the environmental impacts of a product, process or service over its entire life cycle from raw material acquisition through production, use and end of life [1]. Its adoption within the space sector is a crucial first step for the industry to achieve environmental sustainability by using cutting-edge technological solutions with both the capability and practical application to mitigate the overall environmental impacts of space programmes and activities. Moreover, with Life Cycle Sustainability Assessment (LCSA) being predicted as the future of Life Cycle Assessment (LCA) [2], moving towards space-based LCSA is a logical next step for the space industry. This paper will present the methodology used in an open-source LCSA platform called the Strathclyde Space Systems Database (SSSD) under development at the University of Strathclyde for the design of space missions, outlining the integration of social and economic aspects with E-LCA.

2. SUSTAINABILITY & THE SPACE SECTOR

2.1. Background

Until recently, environmental impacts of space activities had often been omitted from key legislative or regulatory requirements, with the result that the environmental impact of the industry were often overlooked or ignored. For example, when the Montreal Protocol was introduced in 1987 it completely left out the space industry despite rocket propulsion being the only source of anthropogenic emissions to inject ozone destroying compounds directly into all layers of the atmosphere [3].

To address this issue, ESA decided to use E-LCA to gain a scientific quantification on the environmental impact of a space mission. This work began in 2009 when they conducted an internal concurrent design study called ECOSAT to consider the life cycle impact of satellite design, manufacturing, launch and operation of a space mission. This then led to further E-LCA studies of the Vega and Ariane 5 launch vehicles and four different types of satellite mission. After this ESA then released an E-LCA handbook for space systems and created their own E-LCA database and ecodesign tool called SPACE OPERA to be used in mission design. ESA have now reached a point where they are beginning to test E-LCA integration within the concurrent design process [4].

To further support this push, in 2017 the United Nations Committee on the Peaceful Use of Outer Space produced the ‘Guidelines for the long-term sustainability of outer space activities’ which is the first ever international sustainability guidelines for space activities [5]. Specifically, Guideline 27.3 suggests the use of E-LCA by stating that space actors “should promote the development of technologies that minimize the environmental impact of manufacturing and launching space assets”. However whilst E-LCA is an extremely useful tool to measure the environmental impact of a product, on its own it is not enough to accurately gauge how sustainable a product is. The reason for this is because the concept of sustainability encompasses not just the environment but also society and the economy. This notion is reiterated by Guideline 27.2 where it states that when conducting their space activities actors *"should take into account, with* reference to the outcome document of the United Nations Conference on Sustainable Development (General Assembly resolution 66/288, annex), the social, economic and environmental dimensions of *sustainable development on Earth"*. This clearly suggests that LCA of space systems should go beyond the traditional focus on the environment to include social and economic impacts as well. In this regard, the full sustainability spectrum can be considered (environment, society and economy). As can be seen in Figure 1, three life cycle perspective assessment types exist which can individually address each of these sustainability dimensions; E-LCA, Social Life Cycle Assessment (S-LCA) and Life Cycle Costing (LCC). Together, these form a single Life Cycle Sustainability Assessment (LCSA).

Figure 1. Dimensions of Sustainability & LCSA [6]

2.2. Life Cycle Sustainability Assessment

Life Cycle Sustainability Assessment (LCSA) is a new environmental management tool used to measure the environmental, social and economic impact of products, processes and services over their entire life cycle. This allows for an assessment to be made based on the traditional 'three pillar' interpretation of sustainability for products by combining E-LCA with S-LCA and LCC. Similar to E-LCA, S-LCA is an assessment type used to predict the social impacts of a product, process or service over its entire life cycle and LCC is an economic assessment used to determine the entire cost of a product, process or service over its entire life cycle [7, 8].

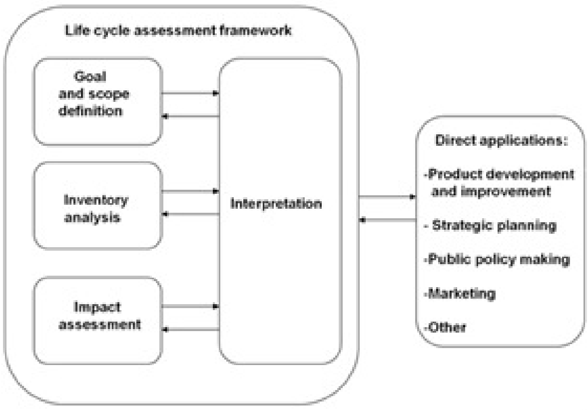


Figure 2. LCA Framework [1]

Klöpffer (2008) formalised efforts of linking environmental, societal and economic principles as they relate to product life cycle by creating a new kind of sustainability framework called LCSA [9]. This framework can either use the three assessment types as separate standalone entities or use S-LCA and LCC as impact categories within E-LCA. As such, LCSA closely aligns to E-LCA and for this reason follows the LCA framework as defined by ISO 14040:2006 and ISO 14044:2006 Standards. This as can be seen in Figure 2 above.

Although the possibility of encompassing more than just the environment in LCA of space missions has been briefly mentioned by some researchers [10, 11], to date there has been no serious effort made or work conducted on LCSA for space systems. However in an evaluation of the LCA evolution, Guinée et al (2011) predicted that LCSA to be the future of LCA [2]. As such, an eventual transition to this assessment type may be required in the future to allow the space sector to stay in line with the requirements of the environmental sector.

2.3. Ecodesign of Space Systems

Integrating E-LCA into the concurrent design process was first investigated by Chanoine et al (2014) who suggested that this could be facilitated by interfacing a space-specific ecodesign tool (such as SPACE OPERA) with the Open Concurrent Design Tool (OCDT) which is an ESA tool used to enable efficient multi-disciplinary concurrent engineering of space systems [12]. Figure 3 gives an overview of this process.

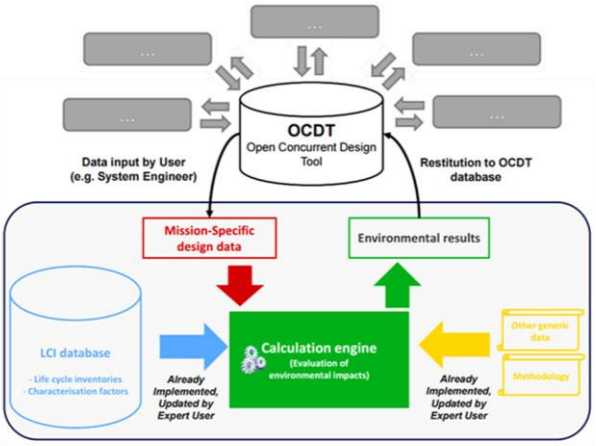


Figure 3. Connecting ecodesign with the OCDT (adapted) [12]

The first space-specific CDF study to include the ecodesign discipline (and to date the only study of this nature to have taken place) occurred in May 2017 for a Phase 0 space mission design. This was the High Accuracy Telescope for elephant Herd Investigation (HATHI) study, a mission tasked with remotely tracking African elephants to prevent poaching, run as part of the ESA Academy's third Concurrent Engineering

Workshop. The workshop was part of a training and learning programme provided by the ESA Education Office to give students a chance to learn about how ESA assesses the technical and financial feasibility of space missions through hands-on concurrent engineering training. As such, the ESA Clean Space Initiative saw this as an ample opportunity to test the current state of ecodesign and agreed with the ESA Academy that the inclusion of this discipline should be included as part of the HATHI mission which was then proposed to and executed by the corresponding author of this paper.

Whilst the mission produced a highly complex design which was indeed feasible, the process highlighted the need to further optimise the ecodesign process. There were numerous technical problems with the tool leading to inaccurate results. A poor interface with the OCDT (no ecodesign parameters) led to results being conveyed after each iteration rather than during design sessions in real time. Additionally, ESA does not include impacts relating to end of life such as re-entry smoke particle generation within their SPACE OPERA tool due to a lack of data. They also assume no impact from the space segment during the operation phase despite the presence of a diffused atmosphere in LEO. This is where the release of mono-propellants occurs and the presence of atomic oxygen causes platform erosion which ultimately leads to the release of volatile oxidant products to the LEO domain. Evidently the released compounds from both of these processes have the potential to mix back into lower levels of the atmosphere to some degree.

As such, the SSSD seeks to address these downfalls whilst also moving the scope of the study from E-LCA towards LCSA.

3. THE STRATHCLYDE SPACE SYSTEMS DATABASE

3.1. Overview

The SSSD is a space-specific process database capable of determining the life cycle sustainability impacts of a variety of space systems. The main aim of the SSSD is to improve upon space E-LCA methodology by providing a robust open-source ecodesign platform which can be integrated into the concurrent design process and to move ecodesign within the space sector towards a more encompassing sustainability assessment. It is by no means intended to compete with or duplicate the SPACE OPERA tool created at ESA. As such, the SSSD should contribute to and advance the development of ecodesign and sustainability assessment within the space sector.

The SSSD (see Figure 4) is part of the Strathclyde design and optimisation toolbox available at the University of Strathclyde. This is linked to the Space Systems Toolbox in order to support design automation of complex space systems using one or multiple performance criteria. The optimisation and space systems toolboxes are part of the Strathclyde Mechanical and Aerospace Research Toolbox (SMART) that supports all Concurrent Engineering activities at the university. Thereby the LCSA tool fits into SMART and contributes to the evaluation of how green space systems are.

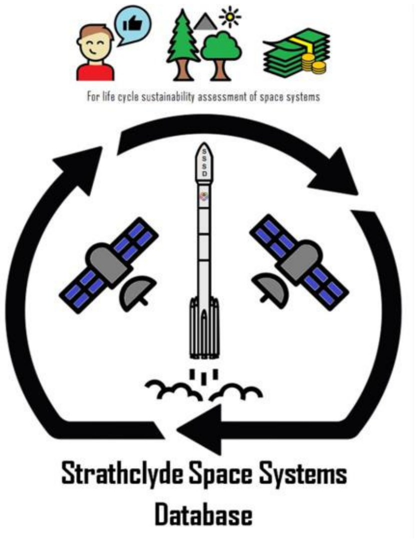


Figure 4. SSSD banner & logo

3.2. Methodology

The SSSD has been built as a ZOLCA file in openLCA which is an open source software used for life cycle assessment studies. It has been built to conform to the ISO 14040/14044 standards at all times and follow the ESA LCA space system guidelines as closely as possible with the view of improving the methodology used. It has been built on top of European Life Cycle Database and Ecoinvent processes which are purpose-built background inventories. Input data comes from a variety of sources including experimentation, analysis, research and work conducted at the University of Strathclyde, literature reviews, collaboration between various space organisations and entities and expert input. Each assessment type is based on several guiding documents as indicated in Table 1. The Life Cycle Impact Assessment (LCIA) methods used are at midpoint level and have come from a variety of sources including CML, IPCC, ReCiPe and USEtox. The selected impact categories, indicators and characterisation models closely resemble those used by ESA within their SPACE OPERA Ecodesign tool.

Assessment	Guiding Documents
E-LCA	ISO 14040:2006; ISO 14044L2006; ESA LCA Space Systems Guidelines
S-LCA	UNEP/SETAC S-LCA Guidelines; ISO 26000:2010; Sustainable Development Goals
LCC	ISO 15686-6:2017; IEC 60300-3-3:2017. Literature Reviews
LCSA	UNEP/SETAC LCSA Guidelines

Table 1. Guiding Documents for SSSD Implementation

In terms of E-LCA, the characterisation of a substance can be calculated using the following formula which allows the impact category result to be a single unit:

$$IR_c = \sum_s CF_{cs} \cdot m_s \tag{1}$$

Where IR_c is the indicator result for impact category c, CF_{cs} is the characterisation factor that connects intervention s with impact category c, and m_s is the size of intervention s.

The SSSD S-LCA calculates a range of social issues across five stakeholder categories of Consumer, Local Community, Society, Value Chain Actors and Worker. Under each stakeholder category there are a range of stakeholder subcategories and each of these have a range of several indicators. The indicators are based on the UNEP/SETAC S-LCA Guidelines and Sustainable Development Goals which were sorted into 23 broad categories and disseminated into indicators. Risk factors have been created by comparing the Life Cycle Inventory (LCI) results against a suggested evaluation scheme contained within each indicator's general description. The evaluation scheme puts the LCI result into bands and these bands are attributed a risk factor and score of up 100 which are; No risk (0), Very low risk (20), Low risk (40), Medium risk (60), High risk (80) and Very high risk (100).

As shown in Equation 2, through the use of the appropriate risk factor, the impact category result can be calculated to a single score:

$$IR_c = \sum_s \frac{RF_{em_s}}{I_{xs} \cdot SS_{cs}} \tag{2}$$

Where IR_c is the indicator result for stakeholder category c, RF_{em_s} is the risk factor obtained from evaluation scheme e for the size of intervention s, I_{xs} is the total number of interventions contained within Stakeholder Subcategory x containing intervention s, and SS_{cs} is the total number of Stakeholder Subcategories contained within stakeholder category c containing intervention s.

The SSSD LCC calculates all costs associated with space systems and splits monetary flows into costs and revenues across all life cycle phases for a variety of impact categories. It takes into account exchange and inflations rates of 35 international currencies in relation to the value of the Euro in the year 2000. For this reason, LCC is much simpler to calculate and is represented by Equation 3:

$$IR_c = \sum_s (TI_{cs} - TC_{cs}) \cdot (CR_{ays_b}\,[1 - CP_{bys_z}]) \tag{3}$$

Where IR_c is the indicator result for cost category c, TI_{cs} is the total income that connects intervention s to cost category c, TC_{cs} is the total costs that connects intervention s to cost category c, CR_{ays_b} is the currency conversion rate which connects the exchange rate of currency a used by intervention s to currency b in year y, and CP_{bys_z} is the percentage of cumulative price change due to inflation of currency b in year y for intervention s relative to baseline year z.

4. CASE STUDY: MONOPROPELLANTS

In order to test the capabilities of the SSSD, a case study was conducted to investigate the life cycle impacts of two different types of monopropellant during the manufacturing and production process. This allowed for a direct comparison between the two products which also highlighted the influence that concurrent design has on the overall results.

In this case Hydrazine, the traditional and most commonly used type of monopropellant, was compared to LMP-103S which is a high performance green propellant and proposed alternative to hydrazine [13]. An E-LCA and LCC was conducted along with an S-LCA for the stakeholder categories of 'Worker' and 'Value Chain Actors'. Results were obtained for two scenarios; (1) the production and manufacturing process of 1 kg of each monopropellant, and (2) the impact of using each propellant for a fictitious mission within a Phase0/A concurrent design session. During this second scenario, other factors relating to mission design were also included within the scope of the assessment which have the potential to influence the overall result in relation to which monopropellant is selected.

4.1. Scenario 1: Hydrazine versus LMP-103S

The results from this scenario are considered to be 'direct' results. This means that no input from upstream or downstream processes were considered. Therefore a direct comparison was made for the same amount of hydrazine in relation to the same amount of LMP-103S for the production and manufacturing process (i.e. a direct comparative assessment).

4.1.1 Goal & Scope

This case study identified the relative sustainability impacts from the production and manufacturing process of two different monopropellants. In this instance, the goal was to compare a high performance green propellant (LMP-103S) to hydrazine in order to identify which mono-propellant has the lowest environmental impact. The results obtained will be used as a basis for choosing which monopropellant is a more sustainable choice for future space missions. The selected functional unit (FU) is the manufacturing and production of 1kg of mono-propellant. The system boundary included all relevant processes from raw material extraction through to the manufacturing and production of each monopropellant including transportation.

4.1.2 Life Cycle Inventory Analysis

The data used in this study came directly from SSSD and Ecoinvent processes. The process inputs were based on literature reviews and experimental data. The amount contrasted was set at 1 kg for both monopropellants as defined by the FU.

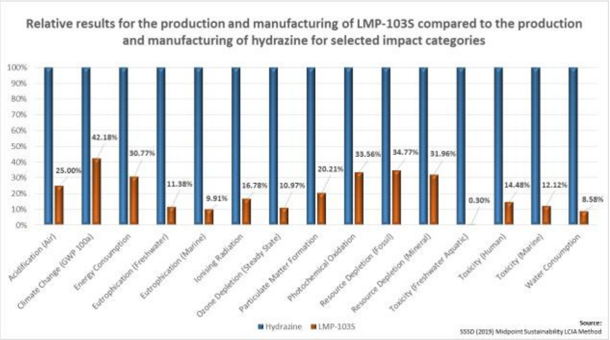
4.1.3 Life Cycle Impact Assessment

The selected E-LCA impact categories and classification/characterisation source can be found in Table 2 below. Single score S-LCA and LCC were also used as impact categories within the E-LCA.

Impact Category	Unit	Source
Air Acidification	kg SO_2 eq.	CML
Climate Change	kg CO_2 eq.	IPCC (2013)
Economic Impact	EUR 2000	SSSD (2019)
Energy Consumption	MJ	CED
Eutrophication (FW)	kg P eq.	ReCiPe Midpoint (H)
Eutrophication (M)	kg N eq.	ReCiPe Midpoint (H)
Ionising Radiation	kg U-235 eq.	ReCiPe Midpoint (H)
Ozone Depletion	kg CFC-11 eq.	CML
Particulate Matter	kg PM10 eq.	ReCiPe Midpoint (H)
Photochemical Ox.	kg NMVOC	ReCiPe Midpoint (H)
Resource Dep. (F)	MJ Fossil	CML
Resource Dep. (M)	kg Sb eq.	CML
Social Impact	Single Score	SSSD (2019)
Toxicity (FW)	PAF.m^3.day	USEtox
Toxicity (H)	cases	USEtox
Toxicity (M)	kg 1,4-DB eq.	CML
Water Consumption	m^3	ReCiPe Midpoint (H)

Table 2. Selected E-LCA impact categories

The results from the comparison (shown in Figure 5 below) clearly show that LMP-103S has a significantly lower environmental impact than hydrazine across every impact category including the toxicity categories which have often been considered as one of the major drawbacks of using hydrazine. As such, this comparison has evidenced LMP-103S's green marketing claim by proving quantitatively that it is indisputably a more environmentally friendly option for production and manufacturing than hydrazine.


Relative results for the production and manufacturing of LMP-103S compared to the production and manufacturing of hydrazine for selected impact categories

Source:
SSSD (2019) Midpoint Sustainability LCIA Method

Figure 5. SSSD LCIA environmental comparative results

The S-LCA scored for Hydrazine was 18.96 and 14.67 for LMP-103S whilst the LCC scored 144.62 EUR 2000 for hydrazine and 722.04 EUR 2000 for LMP-103S. The reason for this variation in social score is primarily due to the risks involved with workers handling hydrazine which is highly toxic. Additionally, LMP-103S is exceptionally more expensive than hydrazine as LMP-103S is not yet being mass produced. Mass production is expected to significantly reduce this cost in the future.

4.1.4 Interpretation

This study shows that the production and manufacturing of LMP-103S has a significantly lower environmental impact than hydrazine. For this reason, it is recommended that this monopropellant is used as an alternative to hydrazine for future space missions where the environmental impact of the mission is to be taken into account.

4.2. Scenario 2: Hydrazine versus LMP-103S in the MÌOS Mission

The above results shown in Section 4.1 can be considered as a 'direct' contribution to the overall impact. However, when designing space systems there are a variety of different parameters that need to be considered. Differences in these parameters may force design alterations elsewhere in the space system. For example, the relative performance of each monopropellant may vary which could force the need for more or less propellant and also require a larger or smaller propellant tank to store it. This kind of change can vastly alter the overall result obtained and therefore can be considered as an 'indirect' contribution to the overall impact.

As such, the Moon Ice Observation Satellite (MÌOS) mission created by a team of students at the University of Strathclyde during the ESA Concurrent Engineering Challenge at the Concurrent & Collaborative Design Studio (CCDS) was used to test this as hydrazine was used as a propellant. The purpose of this mission was to observe the water/ice content of the Lunar South pole in addition to the lunar radiation and micrometeorite environment. In this design, the life cycle impacts of using LMP-103S as a replacement for hydrazine was tested.

4.2.1 Goal & Scope

This case study identified the relative sustainability impacts from the use of two different monopropellants in the MÌOS mission. As in Section 4.1.1, the goal was to compare LMP-103S to hydrazine in order to identify which mono-propellant has the lowest environmental impact. The results obtained will be used as a basis for choosing which monopropellant is a more sustainable choice for future space missions. The selected FU is one space mission in fulfilment of its requirements. The system boundary included all relevant processes from raw material extraction through to the manufacturing and production for each monopropellant and all spacecraft components used in the design relating to each monopropellant including transportation.

4.2.2 Life Cycle Inventory Analysis

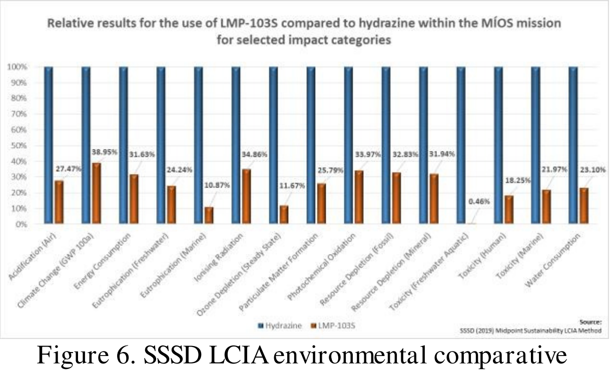
The data used in this study came directly from SSSD and Ecoinvent processe which are based on literature reviews and experimental data. The data input to these processes came directly from the concurrent design session and is stored within the OCDT.

The mission used 138.6 kg of hydrazine which was held within a propellant tank with a mass of 6.4 kg. However, due to the attributes of LMP-103S (such as having a 6% higher specific impulse than hydrazine and being 24% more dense [13]), it was found that 0.7144 kg of the monopropellant was required for every 1 kg of hydrazine. As such this meant that just 99.0 kg of LMP-103S was required for the mission meaning that the engine size could be reduced and the propellant tank scaled down to 4.6 kg.

4.2.3 Life Cycle Impact Assessment

The selected E-LCA impact categories and classification/characterisation source can be found in Table 2 in Section 4.1.3. Single score S-LCA and LCC were also used as impact categories within the E-LCA.

The results as shown in Figure 6 below identify that LMP-103S again has a significantly lower impact than hydrazine across every impact category and reiterates the conclusions from the Scenario 1 results.



Source:
SSSD (2019) Midpoint Sustainability LCIA Method

Figure 6. SSSD LCIA environmental comparative results within a concurrent design session

The S-LCA scored for Hydrazine was 20.76 and 15.23 for LMP-103S whilst the LCC scored 20,160.64 EUR 2000 for hydrazine and 71,565.56 EUR 2000 for LMP-103S. The reason for this variation in social score is primarily due to the risks involved with workers handling hydrazine which is highly toxic and the difference in production time for workers/value chain actors. Additionally, the price variation again comes from the fact that LMP-103S is not yet being mass produced, but the cost of having a smaller propellant tank does marginally reduce the cost gap.

4.2.4 Interpretation

This study shows that LMP-103S has a significantly lower environmental impact than hydrazine for use in the MÌOS mission. However, despite requiring a smaller quantity of monopropellant for use within the mission than hydrazine, the large upfront costs currently associated with LMP-103S means that it is perhaps unfeasible to consider for selection within the mission.

4.3. Analysis & Evaluation

Although LMP-103S continued to generate a lower result across each E-LCA impact category under this scenario, the difference between hydrazine and LMP-103S reduced for most categories. Overall, it was found that the results varied by up to 18.1% per impact category and averaged at a 4.3% decrease in difference between LMP-103S and hydrazine. Despite the decrease in propellant required, the primary reason for this result is due to the considerable influence of the production and manufacturing of spacecraft components such as the propellant tank. This highlights the influence of concurrent design on indirect results.

Additionally, the overall difference in results did increase for the impact categories of climate change, fossil resource depletion and mineral resource depletion. This adds complexity as to what impact categories to prioritise in mission design. In this regard, reducing the number of impact categories may be beneficial. However, as can be seen, the added impact categories of social and economic impact also gives added dimensions for decision-makers to select more sustainable products. In this case, the cost score acted as a deterrent to selecting LMP-103S in Scenario 2.

To continually improve the database, the SSSD will undergo strict validity testing with SPACE OPERA for environmental processes before being trialled in more mission designs in early 2019.

5. CONCLUSION

It is hoped that the SSSD will be released publically by mid-to-late 2019 where it will contribute to the global sustainability agenda by allowing the space industry to become more accountable and responsible for their operations. The tool will therefore assist decision-makers in choosing sustainable 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.

6. ACKNOWLEDGEMENTS

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7. ABBREVIATIONS AND ACRONYMS

E-LCA	Environmental Life Cycle Assessment
ESA	European Space Agency
FU	Functional Unit
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
OCDT	Open Concurrent Design Tool
S-LCA	Social Life Cycle Assessment
SETAC	Society of Environmental Toxicology & Chemistry
SSSD	Strathclyde Space Systems Database
UNEP	United Nations Environment Programme

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