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Advances in Space Research 72 (2023) 2917–2935

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

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Life cycle engineering of space systems: Preliminary findings

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Received 25 March 2022; received in revised form 8 December 2022; accepted 10 January 2023
Available online 18 January 2023

Abstract

The application of Life Cycle Engineering (LCE) within the concurrent engineering process presents a viable method for assessing environmental, social and economic impacts of space missions. Despite this, the novelty of the concept within space mission design has meant that the approach has not yet been widely implemented. This paper successfully demonstrates this technique for the first time and presents LCE results of three SmallSat missions designed at the University of Strathclyde using the concurrent engineering approach. The Strathclyde Space Systems Database (SSSD) was deployed to calculate the total life cycle impacts of each mission, including the identification of common design hotspots. A novel technique called Multi-Criteria Decision Analysis (MCDA) was also trialled, whereby several impact categories were converted into single scores as a test case to reduce the learning curve for engineers. Overall, the LCE results indicate that the manufacturing & production of the launcher dominate the majority of impact categories. Other common hotspots were found to relate to the use of germanium as a substrate as well as the launch event. As an additional observation, in terms of the behavioural aspects, it was clear that study participants were more open to the concept of LCE with each new concurrent engineering session, evidenced by increasing levels of interaction amongst study participants. These findings are intended to provide industrial stakeholders with a preliminary benchmark relating to the general sustainability footprint of SmallSats, whilst demonstrating the viability of integrating LCE within the concurrent engineering process of space missions.

Keywords: Life cycle engineering; Space systems; Concurrent engineering; SmallSats; Life cycle assessment; Ecodesign; Sustainable design

1. Introduction

Evolving market conditions and customer expectations has forced the need for organisations to continually adapt in order to deliver quality products and drive innovation. One particular driver for change is the concept of sustainable development, which is becoming an increasingly more important element of core business operations and a key consideration within the product development process. In this regard, a growing demand is steadily being placed upon organisations to disclose the impact of their products across all three sustainability dimensions: environment, society and economy. However, in most applications, current methods to lower adverse impacts only generate slightly modified or improved designs. This is because techniques are often applied late in the design process after many key decisions have already been made. As a result, this creates too many constraints to significantly alter the design and lessen burdens (Sheldrick and Rahimifard, 2013).

Within the space sector, concurrent engineering is commonly applied as a product development approach during Phase 0/A feasibility studies. It enables various design processes to be run simultaneously to decrease product development time and the need for multiple design reworks. This is often achieved by deploying multidisciplinary groups to work in a collaborative manner, facilitating the complete sharing of product data through instantaneous interactions of different disciplines (Winner et al., 1988).

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https://doi.org/10.1016/j.asr.2023.01.023
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Although concurrent engineering is not an essential practice within the space sector, it has become a well-established means for developing early space system design concepts. This is primarily due to its ability to reduce lead times, produce a higher quality of product and fulfil customer requirements (Jo et al., 1993; Hambali et al., 2009).

Given that an estimated 80% of a product's sustainability impacts are set by early design choices (European Commission, 2019; Saravi et al., 2008), applying Life Cycle Engineering (LCE) as part of the concurrent engineering process of space missions could present a possible solution and enable sustainable product design. In this regard, LCE is an approach which can be used to direct engineering activities towards sustainability, based on scientific and technological principles (Laurent et al., 2019). More specifically, it is an engineering technique for assessing environmental, social, economic and technical impacts of products, processes and services over their entire life cycle (Cooper and Vigon, 2001; Hutchins and Sutherland, 2008; Hauschild et al., 2017). Its goal is to find a balance between societal needs, economic growth and minimising environmental impacts in product engineering. This method is commonly applied in areas where sustainability concerns coincide with design and production engineering (Jeswiet et al., 2005; Henriques et al., 2008).

Evidently, this makes this approach particularly well-suited to concurrent engineering sessions of early space mission concepts as adverse impacts are easier to modify the earlier into the design process that they are identified. For this reason, the application of LCE within the concurrent engineering process has the potential to act as an important first step for the space sector on mitigating potential adverse life cycle sustainability impacts of space technologies. This is because the approach can be integrated into the decision-making process from an early stage to identify mission hotspots, thereby assisting the space industry to design next generation sustainable space systems in the frame of the 2030 Agenda for Sustainable Development.

Nonetheless, to date, there has been no active demonstrations to evidence the potential application of such an approach within the space sector. As such, due to the novelty of the approach, the purpose of this paper is to outline the methodology and preliminary findings from the initial application of LCE within the concurrent engineering process of space missions undertaken at the University of Strathclyde. The findings are relevant for three Phase 0/A SmallSat missions. For each mission concept, the life cycle impacts and design hotspots will be outlined as a basis for further discussion, including evolving participant behaviours and attitudes towards LCE. These results should provide industrial stakeholders with a greater insight into the potential sustainability footprint of SmallSat missions whilst highlighting the suitability of the approach within the concurrent engineering process of space missions.

2. Background

Since 2009, the European Space Agency (ESA) Clean Space Office have been pioneering the application of Environmental Life Cycle Assessment (ELCA) within the space sector to scientifically quantify and reduce geocentric environmental impacts of space missions. ELCA is a technique used to assess environmental impacts of products, processes or services over their entire life cycle. However, ELCA addresses only one of three sustainability dimensions although the 2030 Agenda for Sustainable Development, Guidelines for the Long-term Sustainability of Outer Space Activities and European Union Green Deal are increasing the motivation and necessity for addressing the full spectrum of sustainability aspects within future space missions and technologies. Despite this, combining environmental, social and economic considerations through a single life cycle study has thus far never been attempted within the space industry. Additionally, although concurrent engineering is not a standardised practice within the space sector, it is a well-established means for developing early space system design concepts. For example, ESA have currently conducted over 275 concurrent engineering studies since 1998 (European Space Agency, 2022). The integration of ELCA into this process has been lacking, with all attempts initiated by ESA having failed (Wilson, 2019). As such, this section will explore the fundamentals of both concurrent engineering and LCE, before outlining preliminary work on the integration of both concepts within the space sector.

2.1. Concurrent engineering

The life cycle of a space mission can be broken down into several mission phases, as outlined in Fig. 1. As a given design concept proceeds through the various stages of development, it will hit an increasing number of milestones. These milestones come in the form of reviews, which are used to determine the readiness level of a space mission at a given stage of the life cycle. They provide natural points where decision-makers can elect whether or not to progress the design concept to the next phase or milestone review based on the findings of an independent peer-reviewed assessment of design quality.

Concurrent engineering is defined by ESA as "a systematic approach to integrated product development that emphasises the response to customer expectations. It embodies team values of cooperation, trust and sharing in such a manner that decision making is by consensus, involving all perspectives in parallel, from the beginning of the product life-cycle" (Bandecchi et al., 1999). Concurrent engineering activities are primarily used to assess the technical and financial feasibility of future space missions and new spacecraft concepts. This makes the technique most applicable to Phase 0 and Phase A conceptual studies where design maturity is low and there is a need for focused product development. More specifically, Phase 0 mission

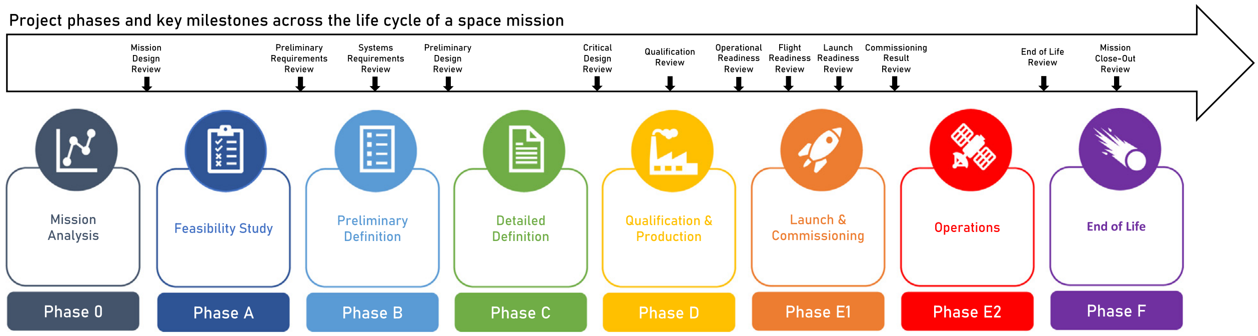

Fig. 1. Project phases and key milestones across the life cycle of a space mission.

analysis studies mainly focuses on identifying mission needs, science performance goals and safety & operations constraints whilst building initial technical requirement specifications. This phase is usually classed as completed after the Mission Definition Review has been accepted, meaning that the concept design can move on to Phase A for a mission feasibility study. At this point, the focus is on producing initial technical designs, a management plan, a system engineering plan and a product assurance plan. An assessment will also be made on project management data, risks and feasibility, including implementation, programmatic, cost, operations, organisation, production, maintenance, disposal, etc. The design phase will conclude with acceptance of the Preliminary Requirements Review, which will also include the final technical requirements specification. As such, the approach is capable of rapid design development as it overcomes traditional communication gaps by organising existing tools, design information and human resources in a more effective manner.

To help facilitate this, the European Space Agency (ESA) launched an initiative to create a new client/server software package which would allow collaborative multidisciplinary work to be embedded from the embryonic stages of any given mission through concurrent engineering. The new design tool, named the Open Concurrent Design Tool (OCDT), is distributed under an ESA community open-source software licence. It was released publicly in 2014 and provides the building blocks for concurrent engineering using Open Standards Information Models and Reference Data Libraries (RDL) (European Space Agency, 2019b). The OCDT is just one of many data exchange tools that has been developed for concurrent engineering, but will form the basis for further discussion within this section since it is applied at the University of Strathclyde and is fully inter-operable with RHEA Group's Concurrent Design & Engineering Platform 4 - Community Edition (CDP4-CE), which is the other central design tool used at the University of Strathclyde.

The OCDT consists of a front-end web-services processor using a representational state transfer application programming interface and a back-end PostgreSQL database system for the persistent storage of OCDT shareable data (Koning et al., 2014). The tool implements the semantic data model defined in ECSS-E-TM-10-25 Annex A (2010) Technical Memorandum, titled "System Engineering-Engineering Design Model Data Exchange (CDF)", working as a Microsoft Excel plug-in for sharing mission design data and information. The OCDT facilitates the complete sharing of data between disciplines by pushing and pulling data to and from a central server through the Concurrent Concepts, Opinions, Requirements & Design Editor (ConCORDE) using a domain-specific adapter (typically an Excel workbook). Pushing data deposits the values of parameters contained within the Excel workbook that are attributable to the owned discipline to the OCDT server. Pulling data retrieves values from the OCDT server which are owned or subscribed to by the discipline to the Excel workbook. The server is able to support concurrent engineering teams of more than 20 users and synchronises engineering model content twice a minute or faster. Domain users can input relevant data to this server by applying a set of parameters from the selected RDL to the relevant engineering model. Each parameter type has its own measurement units/scales to which calculated values can be set. Domain users can also subscribe to parameters input to the server by other disciplines to use within their own calculations. The analysis and calculations for each discipline should occur externally to the OCDT in a separate domain specific tool since the OCDT is not a method of calculation. Results from these tools are typically transitioned to an Excel worksheet and then uploaded to the OCDT server. However, other client tools for engineering analysis and simulation may be able to connect with the OCDT directly through the web-service processor (Biesbroek and Vennekens, 2017).

Based on the above process, concurrent engineering studies (or sessions) can be applied based on an iterative design working environment where each subsystem expert shares and updates information until mission requirements are fulfilled. Each step of this process is called an iteration (Álvarez and Roibás-Millán, 2021). The whole process will require several iterations to take place, with each iteration involving a change to at least one engineering parameter towards the convergence of a design solution.

2.2. Life cycle engineering

As a term, LCE is closely related to ecodesign. Ecodesign is defined as a systematic approach that considers environmental aspects in design and development with the aim to reduce adverse environmental impacts throughout the life cycle of a product. The technique has two international standards governing its application, those being ISO 14006:2020 (2020) and ISO/TR 14062:2002 (2002). In this regard, ISO 14006:2020 (2020) provides guidance to organisations wishing to implement ecodesign as part of an environmental management system (EMS) and therefore isn't particularly relevant as part of the concurrent engineering process. In comparison, ISO/TR 14062:2002 (2002) describes the concepts and current practices relating to the integration of environmental aspects into product design and development, drawing upon the ISO 14040:2006 (2006) and ISO 14044:2006 (2006) standards on Environmental Life Cycle Assessment (ELCA). Although the ISO/TR 14062:2002 (2002) standard has now been officially withdrawn without a superseding document, it's principles are enshrined within the LCE concept. Additionally, whilst space systems are not listed as a product that must meet ecodesign requirements, it is advisable that the LCE process aligns with Directive 2009/125/EC of the European Parliament and of the Council which establishes a framework for setting ecodesign requirements for energy-related products. Based on these guidance documents, the LCE process can be visualised through the seven key steps outlined in Fig. 2, for which steps one to five are relevant to the concurrent engineering process.

The main goal of LCE is to scientifically quantify adverse environmental, social and economic impacts of products over their entire life cycle and minimise these as much as technically possible. Whilst all adverse impacts are of course relevant in principle, there is a need to prioritise and start reducing large impacts immediately. To achieve this, a hotspot analysis is typically used to assist in the identification of hotspots and to prioritise areas for improvement. A hotspot is usually defined as a life cycle stage, process or elementary flow which accounts for a significant proportion of the impact of the product system

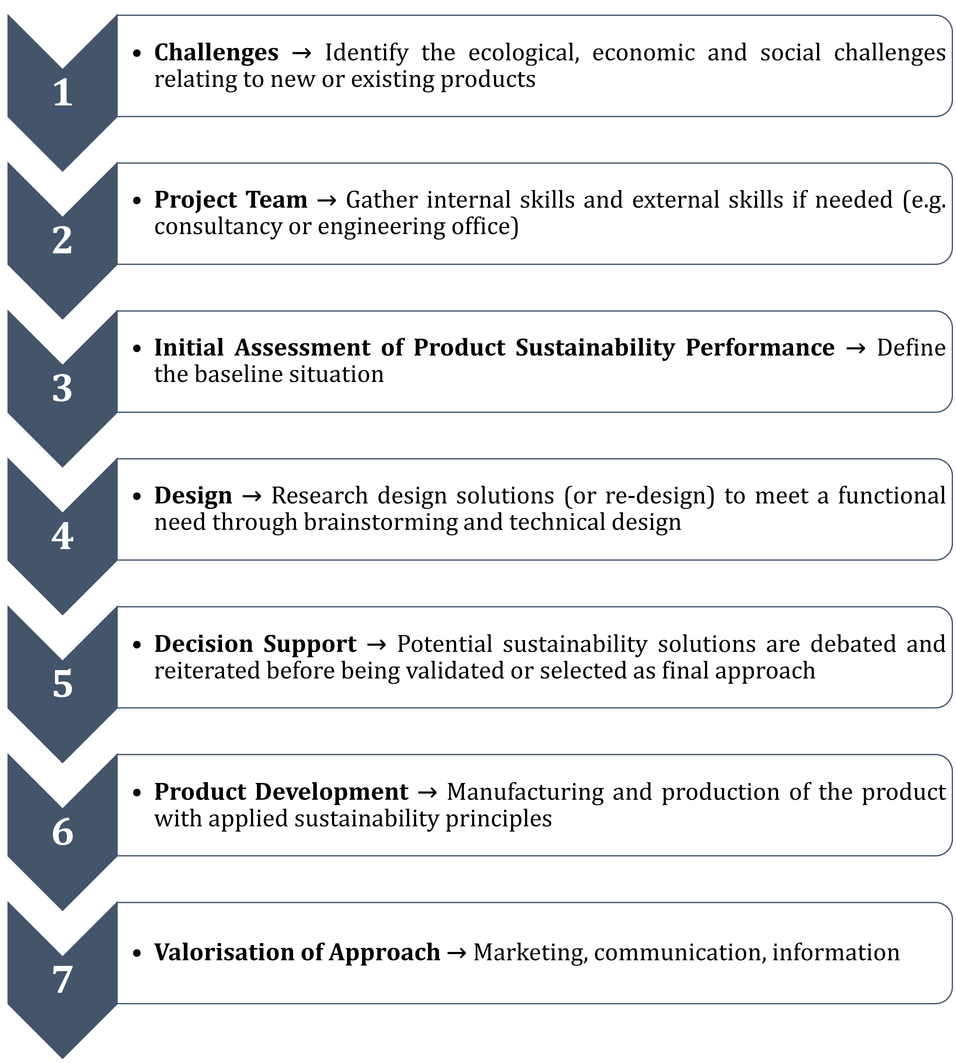

Fig. 2. The LCE Process of Products (adapted from ISO/TR 14062:2002 (2002), Directive 2009/125/EC (2009)).

under study. As such, the criteria and metrics used for ranking and prioritising hotspots is critical to understanding these hotspots. A spectrum of options exists to do this including aggregating results into different environmental themes, grouping processes into life cycle stages, looking at individual emissions and resource uses or creating a single metric. However, it is important to note that improvement measures should not only be implemented at the design phase. Whilst the most dramatic impacts and optimisation activities associated with systems engineering are obtained in the early stages, decisions that affect the environment, society and cost continue to be amenable to the systems approach even as the end of the system lifetime approaches.

In practice, LCE deliberations are typically handled by product developers or environmental specialists brought into collaborate with the product developers. Organisations who decide to apply ecodesign and/or LCE usually undergo a period of experimentation with the approach and other tools such as ELCA (Baumann and Tillman, 2004). Some of the main challenges which are encountered during this trial period relate to time pressures in producing results during design sessions and the difficulty in making trade-off decisions due to competing issues from different impact categories caused by their complex interrelationships. Finally, despite its implementation, the LCE approach does not always lead to product sustainability. As such, careful interpretation of results is necessary if they are to be used for any kind of communication purposes.

2.3. Sustainable space system design

Within the space sector, life cycle studies are only just beginning to emerge and evolve, with coordination efforts principally being led by ESA. Under the ESA Clean Space Initiative, a new framework has developed for ELCA consisting of a set of consolidated guidelines, an inventory database and ecodesign tool (Serrano, 2018). However, the ecodesign tool is currently non-functional and does not link with the inventory database (Wilson, 2019). Additionally, although the possibility of encompassing more than just the environment in ELCA of space missions has been briefly mentioned by some researchers (Durrieu and Nelson, 2013; Viikari, 2004; Maury et al., 2017), to date there has been no serious effort made or projects conducted on the integration of social or economic impacts of space systems into this framework.

Therefore, based on the work of ESA, a recent project conducted at the University of Strathclyde sought to expand the ESA LCA framework by including social and economic impacts and then integrate this fully into the concurrent engineering process through LCE for the first time based on the basic concept outlined in Fig. 3. To achieve this, a new process-based tool called the Strathcyde Space Systems Database was developed in order to quantitatively determine the life cycle sustainability impacts as part of the space mission design process and use this information to lower adverse environmental, social and economic impacts (Wilson, 2019). The developed approach was principally based on Life Cycle Sustainability Assessment (LCSA), which rather than a model itself, is a framework of models designed to provide more relevant and transparent results in the context of sustainability. It allows for integrated decision-making based on a life cycle perspective (Guinée, 2016) by combining ELCA, Social Life Cycle Assessment (SLCA) and Life Cycle Costing (LCC). However, since around 80% of a product’s sustainability impacts are set by early design choices, it was decided that the SSSD would double as both an LCSA database and LCE tool which could be used within concurrent engineering studies (Wilson and Vasile, 2017).

The SSSD was formed in openLCA using a process-based, attributional methodology which relies on physical activity data to develop a product tree derived from assessing all the known inputs of a particular process and calculating the direct impacts associated with the outputs of that process. Validated at ESA through a collaborative project in late 2018 (Wilson, 2018), the SSSD consists of >250 unique space-specific life cycle sustainability datasets, based on Ecoinvent and ELCD background inventories, which each contain environmental, costing and social data. The SSSD also includes several impact categories at midpoint-level. This is a problem-oriented approach which quantifies and translates the life cycle impacts into themes such as climate change, ozone depletion, acidification, social performance, costs, etc. Additionally, the SSSD aligns closely with a variety of widely accepted international standards and norms, including (but not limited to) the ISO 14040:2006 (2006), ISO 14044:2006 (2006) and ISO/TR 14062:2002 (2002) standards, as well as Valdivia et al. (2011), the ESA ELCA framework and the LCE approach developed at the University of Strathclyde.

Beyond this, in order to simplify the decision-making process with a view of identifying the most prominent design hotspots, interpreting trade-offs between multiple impact categories is vital within each concurrent engineering study. This is because the sheer number of impact categories within each of these assessment types creates an obvious risk of cherry-picking, burden-shifting effects and sub-optimised decision-making. Common methods proposed to address this is through a single score generated using Multi-Criteria Decision Analysis (MCDA). This is not currently implemented as a default option within the SSSD since it is not proposed to be used for LCSA, but can be applied as an additional step within LCE. Whilst its application adds subjectivity to the analysis, it simplifies the decision-making process, thereby reducing the learning curve for engineers. An overview of the SSSD and its use in space system studies, including this additional step, is outlined in Fig. 4.

This paper will demonstrate the use of this new space LCE tool and methodology within the concurrent engineering process. To facilitate concurrent engineering, the University of Strathclyde has its own Concurrent Design

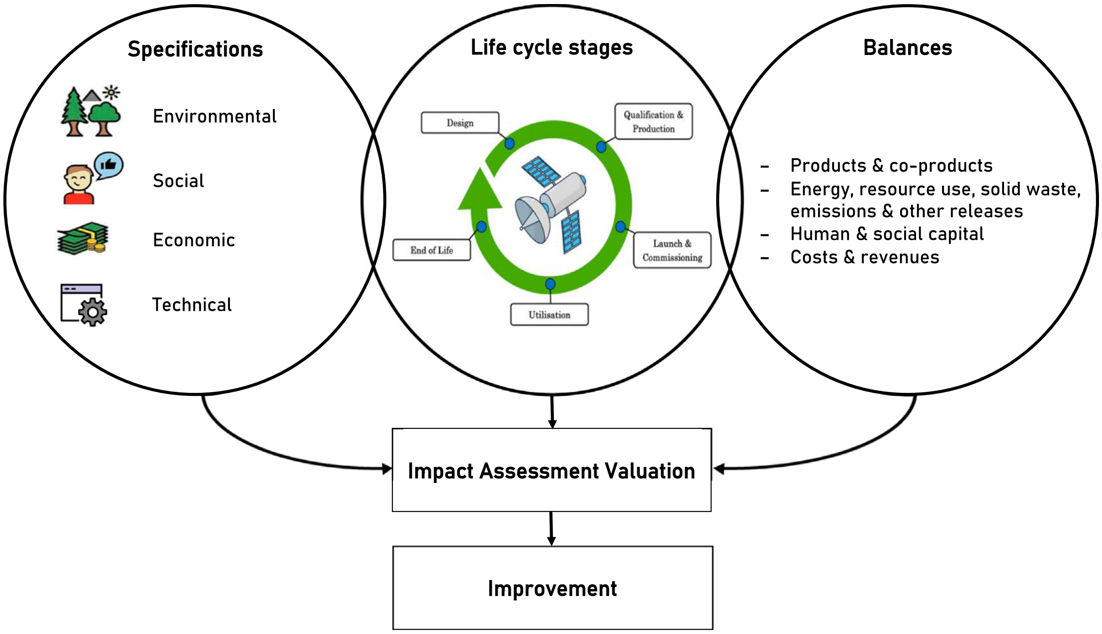

Fig. 3. Basic LCE concept for space missions (adapted from Saur et al. (1996)).

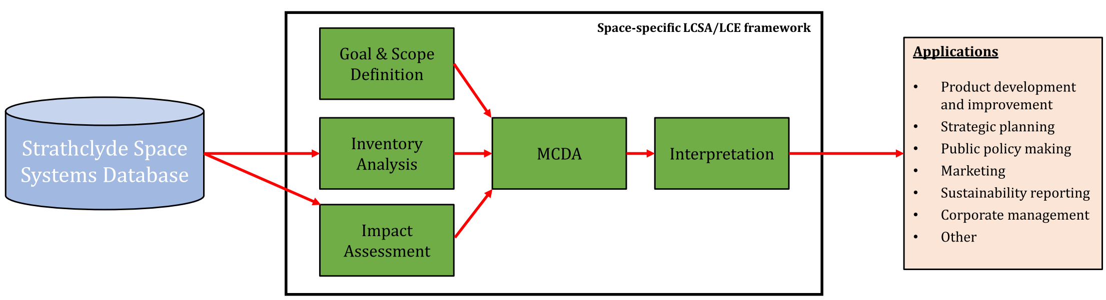

Fig. 4. Application of the SSSD in LCSA and/or LCE studies of space systems (Wilson, 2019).

Facility called the Concurrent & Collaborative Design Studio (CCDS). This facility was opened in October 2015 and is located within the Technology & Innovation Centre in Glasgow. It is used for all concurrent engineering activities within the university and consists of 18 workstations, each of which are equipped with Linux and Windows operating systems. The CCDS uses both the ESA OCDT and RHEA Group's CDP4-CE as central design tools hosted on an Ubuntu virtual server. The CCDS also implements a suite of computational toolboxes, databases and software, including a Space Systems Toolbox, an Optimisation Toolbox, and an Uncertainty Quantification Toolbox, all part of the larger collection known as the Strathclyde Mechanical and Aerospace Engineering Toolbox (SMART). SMART is an internal project developed and maintained by the Aerospace Centre of Excellence at the University of Strathclyde which supports all concurrent engineering activities at the university. The suite allows designers to perform robust design optimisation, to design for reliability and to build resilience into complex systems. The SSSD is contained within the Strathclyde Design and Optimisation Toolbox of SMART. This toolbox is also linked with the Space Systems Toolbox where together, their purpose is to support design automation of complex space systems using one or multiple performance criteria.

3. Methodological approach

The motivation for applying LCE to concurrent engineering process of early space mission design concepts is to aid decision-making and assist industry to design next generation sustainable space systems in the frame of the 2030 Agenda for Sustainable Development. This section outlines a novel methodological approach for this process which is achieved by interfacing the SSSD with the OCDT, thereby expediting the transfer of LCE results to discipline experts directly via the engineering model. This approach will then be applied to three Phase 0/A concurrent engineering studies on SmallSats, with the results providing a general indication into the sustainability footprint of space missions for the first time. As such, the section will go on to introduce these space mission design concepts including inventory modelling considerations. Methods for quantifying impacts and suggesting improvements measures will then be outlined. Finally, limitations of this work are presented to provide additional clarity on the potential weaknesses of these studies.

3.1. Integrating LCE within concurrent engineering

The application of LCE in the space sector can generally be broken down to two levels of application, which the space system breakdown defined by ECSS-S-ST-00-01C (2012). The first level follows a functional view and addresses system level activities. The second level represents equipment, components, materials or processes. When applied in the concurrent engineering process, LCE is mostly applicable at system level since the technique allows expert users to identify design hotspots of the entire mission and recommend solutions to these.

However, without manual manipulation, the OCDT is unable to host LCE data, rendering the process impossible. This is because the OCDT RDL follows the ECSS-E-TM-10-25 Annex A (2010) standard which defines the parameter types that it can host. Unsurprisingly, this standard does not include LCE parameter types within its metric system which is problematic for sustainable design. To rectify this, a range of technical and procedural steps had to be put in place including design model manipulation to cater for LCE data as well as the creation of a data exchange interface between the SSSD and OCDT. These elements were addressed locally by creating relevant parameters for all the midpoint and MCDA impact categories contained within the SSSD. After this step was completed, it was possible to establish a connection between the OCDT and the SSSD through an Excel-based data exchange interface. An overview of this process is outlined in Fig. 5.

As can be seen, during a concurrent engineering study, various activities are conducted by each discipline expert using domain specific tools to conduct calculations and analyses. The SSSD then imports the sum of all mission specific data deposited to the engineering model during the concurrent engineering process through the WebService Processor. Data from the baseline and/or back-up design is then be assigned to the relevant life cycle inventory (LCI) datasets associated within each parameter during the import procedure through field mapping. At present, this is done manually using Excel, but this is planned to be an automatic operation in the future. The data contained within the engineering model can be considered as dynamic since it is generally concerned with aspects which are influenced by decisions made within the concurrent engineering session only. Despite this, there is also a need to consider other elements of the space mission's life cycle that are not influenced by decisions made within the concurrent engineering session. This data is called static and would also be included within the LCI of the SSSD. Such elements would be selected by the LCE user based on expert knowledge or default values contained within the SSSD. The collective sum of LCI results across both the dynamic and static elements (along with other methodological choices and generic data implemented by the expert user) are then run through a calculation engine to produce life cycle impact assessment (LCIA) results. These results can then be deposited to the OCDT via the WebService Processor. Whilst a direct connection would be preferred in order to simplify the process, at present, a domain-specific adaptor is used instead. In this sense, the results are directly exported from the SSSD in Excel format, converted into a single score via MCDA, and then both are uploaded to OCDT. Once deposited to the integrated design tool, the other disciplines can then use these sustainability results to refine the spacecraft design further and reduce the overall environmental, social and economic impacts of the mission. This process then repeats until a final design is reached. However, verbal communication will also be required by the LCE expert to inform all relevant disciplines of specific design hotspots relating to their subsystems, since the results deposited to the persistent storage database will be at system level rather than equipment, component, material or process level.

Overall, the process described ensures that the LCE tool is simple, efficient and user friendly. This is because the approach facilitates the complete sharing of data and minimises the amount of work required by the expert user, whilst allowing all disciplines to visualise the system level sustainability footprint arising from the space mission design. This allows the LCE discipline expert to spend more time communicating the main drivers and hotspots (i.e. what specifically is causing them to be hotspots and what can be done to lessen this impact) to the disciplines responsible, thereby increasing the level of specificity and usefulness of the LCE tool.

3.2. Selected missions

Three Phase 0/A SmallSat studies are presented as part of this paper. These mission concepts were called the Moon Ice Observation Satellite (MÌOS), Nanospacecraft Exploration of Asteroids by Collision and flyby Reconnaissance (NEACORE) and STRATHcube. Each were designed within the CCDS at the University of Strathclyde between 2017 and 2020, where LCE was specifically applied as a design discipline. In particular, MÌOS is a small satellite mission with a mass of <300 kg. It aims to collect data on the lunar micrometeorite and radiation environment as well as detect the presence of water and ice content on the lunar South Pole in view of a future Moon base. Its expected mission duration is 913 days. NEACORE is a low-cost interplanetary mission involving up to six 12U CubeSats. The mission aims to estimate the relative position, velocity and 2D shape of near-Earth objects. The mission duration is expected to last 1,705 days, with a low thrust propulsion system. STRATHcube is a 3U CubeSat developed in support of an internal student-led project. The mission was originally designed with three objectives: space debris detection, re-entry analysis and to demonstrate wireless power transmission. It is intended that the lifetime of the CubeSat would be 576 days. An overview of each mission concept is provided in Fig. 6.

However, it should be noted that subsequent concurrent engineering sessions has since led to the advancement of each concept in comparison to the conceptual designs presented in this paper. Additionally, the application of LCE within the MÌOS study informed discipline experts of the sustainability impacts of the concept, allowing them to act on these retrospectively ahead of further iterations or design sessions. In this regard, impact reduction measures were not specifically implemented during this concurrent engineering study as it was mainly used to provide a first test case for the SSSD. In comparison, improvement mea-

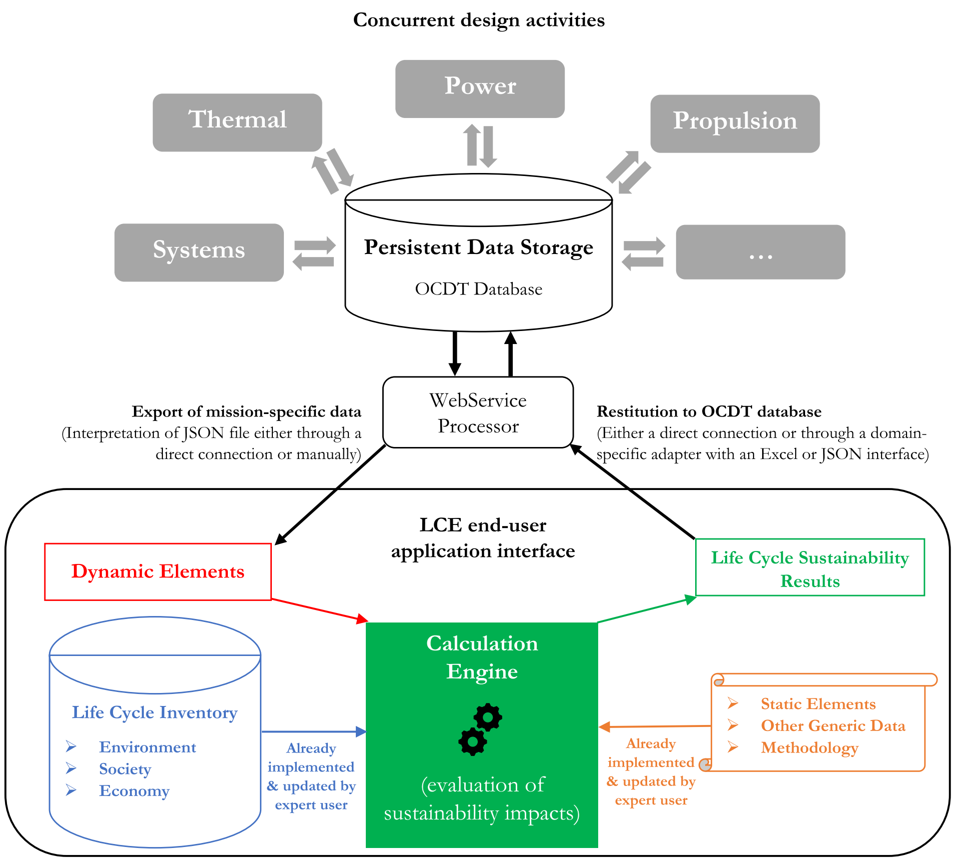

Fig. 5. SSSD functionality within the concurrent engineering process.

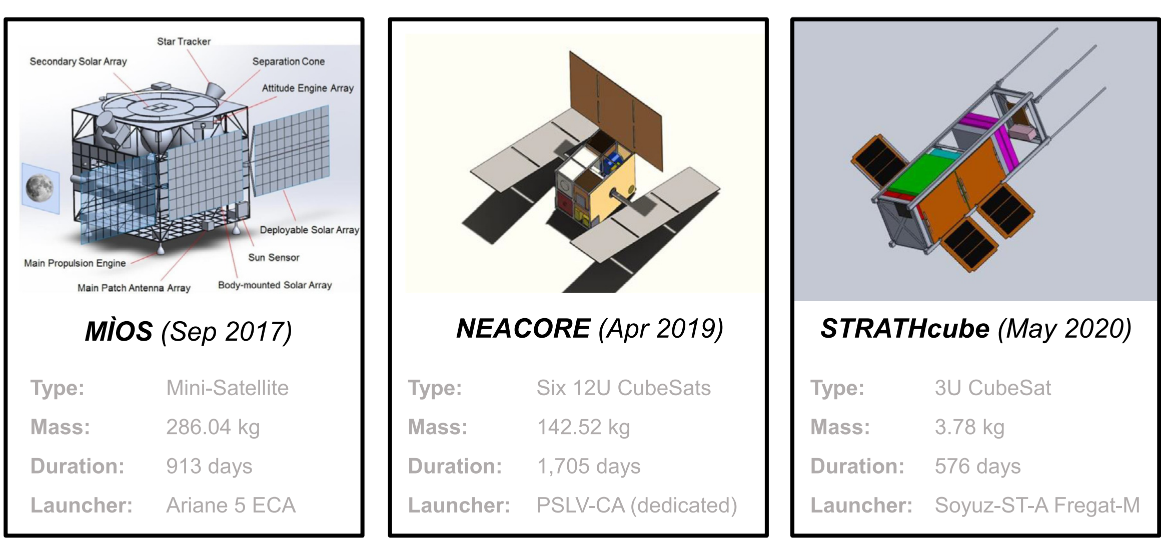

Fig. 6. Selected SmallSat CCDS mission concepts.

sures were attempted in real-time during both the NEACORE and STRATHcube concurrent engineering studies.

3.3. Inventory data & modelling

According to the various international standards and guidance which the SSSD aligns with, the first element to be defined in a life cycle study is the goal and scope definition, as directed by the (ESA Lca Working Group, 2016) as well as the ISO 14040:2006 (2006) andISO 14044:2006 (2006) standards. In each concurrent engineering session, the goal of the LCE discipline was to measure the life cycle sustainability impacts of each space mission design concept, identify prominent hotspots and lower these are far as practically possible.

In terms of the scope, since the results of each space mission design concept are comparatively presented within this paper, the functional unit (FU) and system boundary become extremely important. An FU is a quantified performance of a product system for use as a reference unit for which all inputs and outputs of the study should relate. A system boundary specifies which unit processes are included as part of the product system. To ensure comparability of results, the same FU and system boundary have been followed by each study, based on the recommendation contained within the ESA LCA guidelines (ESA Lca Working Group, 2016). In this regard, the FU used was defined as '≪name of space mission design concept≫in fulfilment of its requirements' whilst the system boundary is outlined in Fig. 7.

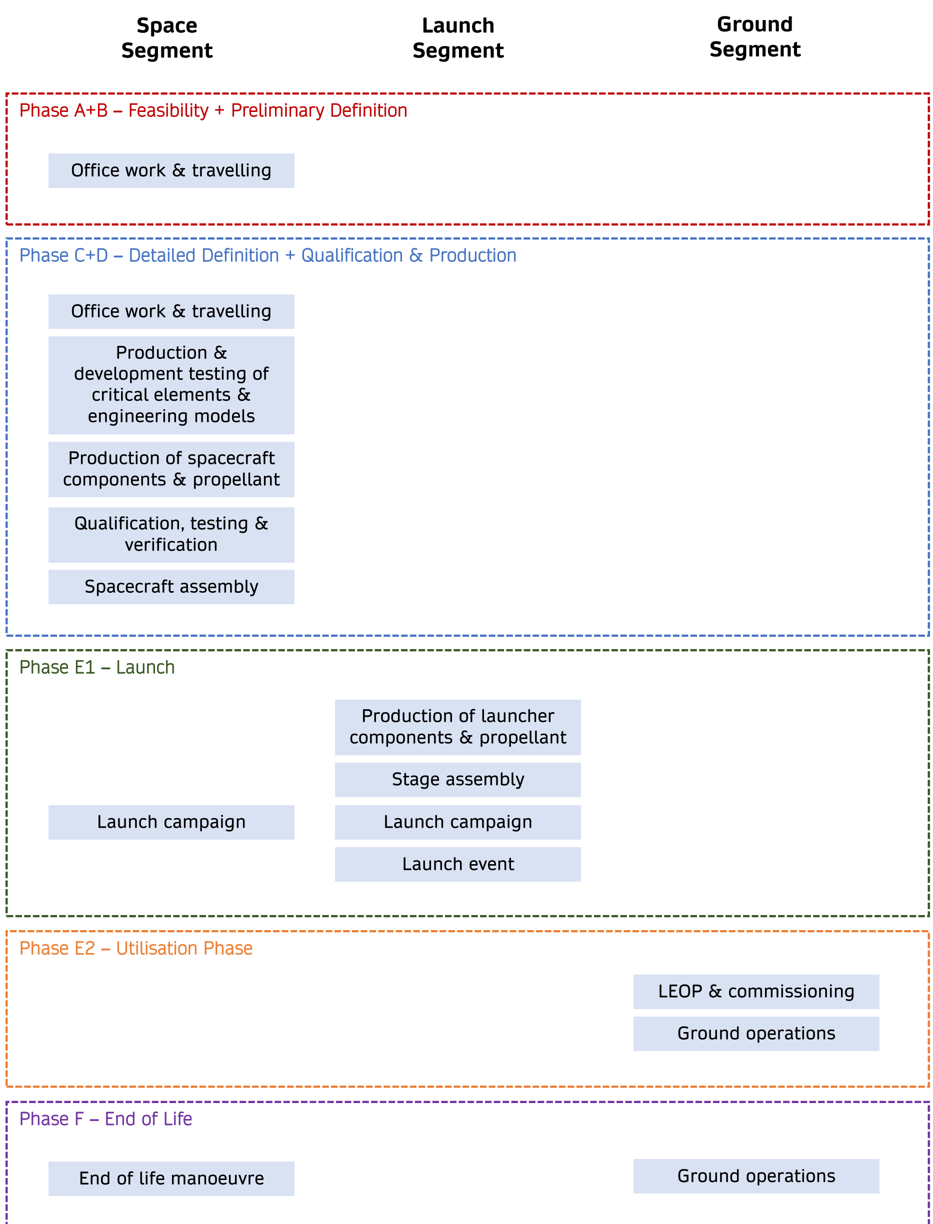

Fig. 7. System boundary applied for each mission design concept (adapted from ESA Lca Working Group (2016)).

The SSSD was used to generated LCE results for each of these missions (see Section 4). The inventory was formed using a combination of dynamic data and static data. Dynamic data was based on the design data deposited to each engineering model, whilst the static data was based on data calculation and/or extrapolation techniques, expert knowledge and default values contained within the SSSD. In particular, the dynamic data was pulled exclusively from the spacecraft engineering model whilst the static data related to all other elements of the system boundary outlined in Fig. 7. An overview of the inventory data used as part of each model is provided within the accompanying datasheet to this paper. The engineering model of each space mission design concept includes mass margins at both subsystem and system level, and hence are reflected in the results. Additionally, the allocation of launch segment impacts reflected the launch option chosen for each mission. This was based on the mass of each mission concept as a percentage of the total payload mass onboard the launcher. In this regard, it was envisaged that MÌOS will be launched as rideshare on an Ariane 5, and hence was allocated 25% of the impact. In comparison, NEACORE would be launched via a dedicated PSLV-CA and so attributed 100% of the impact whilst STRATHcube would be launched as a piggy-back payload onboard a Soyuz-ST-A Fregat-M, and hence attributed only 0.16% of the impact.

The impact categories which were applied follow the recommendations contained in the ESA LCA guidelines (ESA Lca Working Group, 2016), with the addition of Social Impact and Whole Life Cost impact categories, as implemented by the SSSD (Wilson, 2019). However, since the purpose of this paper is to outline preliminary findings from the initial application of LCE within the concurrent engineering process of space missions, a description of the underlying methodological choices of the SSSD will not be outlined here. Instead, the focus will remain on the process, including the identification and reduction of adverse impacts.

3.4. Impact assessment valuation & improvement

In their initial attempts to apply ecodesign within concurrent engineering studies, 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. Therefore, when interpreting trade-offs between multiple impact categories, a systematic and structured decision-analysis technique is required to assist decision-makers to evaluate and improve the sustainability performance of each space mission design concept. This technique must be able to condense these impact categories in order to reduce the learning curve for engineers due to the increased volumes of information during concurrent engineering sessions. One technique which could be used to address this is MCDA. MCDA 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 (Hannouf and Assefa, 2018). It is increasingly being applied to product design studies to address multidimensional results and is recognised by many researchers as a critical component of LCE.

As documented by Velasquez and Hester (2013), various methodological approaches exist for MCDA, but of particular relevance to LCE is the multi-attribute value theory (MAVT) approach (Atilgan and Azapagic, 2016). 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 (Angelis and Kanavos, 2017). 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:

$$v(a) = \sum_{i=1}^{I} w_i \, v_i(a) \quad (1)$$

where $v(a)$ is the overall performance of product a, w_i is the weighting factor for impact category $i, v_i(a)$ 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, reaching a value for $v(a)$ thus relies on the use of both normalisation and weighting procedures. Normalisation is the magnitude of impact relative to a benchmark of other reference information whilst weighting expresses the relationship between normalised impacts and politically determined goals or targets. Therefore, the first step is to determine $v_i(a)$ which can be calculated by dividing midpoint LCIA results by a normalisation factor. Midpoint LCIA results can be determined using life cycle tools such as the SSSD to express product-specific impacts from the LCI in the form of impact categories. The normalisation factors used in this paper refer to the normalisation approach recommended for the Product Environmental Footprint method (Benini et al., 2014) which is related to the EU-27 domestic inventory in 2010 per EU citizen. Secondly, a numerical value to represent w_i was taken from JRC recommended weighting set (Sala et al., 2018) and reformulated to 100% based on the impact categories used.

The only exceptions to the above are for the newly formed Social Impact and Whole Life Cost impact categories within the SSSD. In this regard, a new normalisation method for Social Impact based on the percentage of global companies which have set quantitative targets linked to their societal impact for at least one KPI in 2016 (28%) (PwC, 2017). Therefore, a social score of 72.00 was used to represent the average social score of an organisation since this refers to the percentage of global companies where quantitative sustainability targets have not been set. This was then multiplied by the total number of active EU-28 entities to generate a total social score for all EU entities in one hour (Eurostat, 2008) due to similarities with the SSSD which uses work-hours as an activity variable (Wilson, 2019). 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 (Eurostat, 2021) to produce the average share of total annual European organisational social score per EU citizen (3.34E + 04). The adopted normalisation procedure for Whole Life Cost was calculated more simply by multiplying the GDP per capita by the average tax rate of EU-28 nations in 2015 to the value of the euro in the year 2000 (€8550) (European Commission, 2015). The individual weighting factors for both were given a value of 100% to be equal to the sum of all environmental impact categories.

Finally, Eq. 1 can also be applied for a second time to produce a single sustainability score. In this regard, $v_i(a)$ simply represents the $v(a)$ from the first use of the equation. However, the weighting factor used in the equation represents the relative importance of each sustainability dimension. In this case, the most dominant political framework for sustainability currently in existence can be used to reflect this (i.e. the number of indicators dedicated to each dimension within the 2030 Agenda for Sustainable Development as specified by Diaz-Sarachaga et al. (2018)). This give a split of 18% to the environmental dimension, 53% to the social dimension and 29% to the economic dimension.

As such, using this approach for the hotspot analysis, allows the criticality of impact category and/or sustainability dimension to be determined in terms of their relative contribution to a single score. The most contributing impact categories can then be investigated further within the SSSD to determine the main source of the hotspot. Improvement measures can then be suggested or implemented based on the most contributing processes within each concurrent engineering model to improve the overall $v(a)$. The MCDA can then be run again based on the redesigned engineering model to determine the net result of these measures has led to an improved score.

3.5. Limitations

Since the results reported in this paper are intended to be used publicly as preliminary benchmarks, it is important to define the limitations of the study.

Firstly, due to confidentiality agreements currently in place, the LCI data of each space mission design concept cannot be fully disclosed at this time, with particular emphasis on the engineering models. This was a notable exclusion within the accompanying datasheet of this paper. However, it is expected that these models, including their complete inventories, will become publicly available in the future.

Secondly, the methodology used in the SSSD had a high influence on the LCE results generated. In this regard, the SSSD did not always contain a full list of LCI datasets required for each engineering model due to their uniqueness (e.g. LIDAR within the NEACORE mission design concept) which meant that a best fits had to often be chosen instead. Very importantly, the applied approach which was implemented within the SSSD for the Social Impact and Whole Life Cost impact categories are extremely novel and still being developed. This means their robustness is still considered to be very low. In this regard, Social Impacts only consider workers and value chain actors, which excludes consumers, local community and society stakeholder categories (Wilson, 2019). However, it is therefore the aim to try to update the SSSD in the future so that it becomes even more accurate.

Thirdly, the selection of LCIA methods are also a highly influential decision. Although those selected follow the recommendations of the ESA LCA guidelines (ESA Lca Working Group, 2016), they do not perfectly align with the PEF guide recommendations (Zampori and Pant, 2019). In particular, for the Mineral Resource Depletion impact category, the horizon recommended by the PEF guide is ‘elements, ultimate, ultimate reserves’ whilst the SSSD uses ‘elements, reserve base’ as its baseline. The difference between these horizons is that ultimate reserves refer to resources in Earth’s crust whilst reserve base refers to resources that have reasonable potential to become economically and technologically available (Van Oers and Guinée, 2016). This is an important aspect since the selection of horizon can have a considerable impact on LCIA results. For example, germanium is typically used as a substrate in triple-junction spacecraft solar arrays (Kurstjens et al., 2018; Zimdars and Izagirre, 2017). When considering its use within the ultimate reserves horizon, germanium is indifferent with respect to other resources (e.g. 1 kg = 6.5 2E-07 kg Sb eq.). However, if using reserve base, germanium becomes one of the most impacting resources (e.g. 1 kg = 1.95E + 04 kg Sb eq.) (Leiden University, 2016). This is an extremely contentious issue since, in this respect, horizon selection can ultimately lead to vast variances in the identification of environmental hotspots, thereby leading to different impact mitigation priorities. Additionally, the environmental impact categories used within these analyses do not include several crucial flows due to uncertainty. These include (but are not limited to) black carbon and aluminium oxide emissions.

In terms of MCDA, although extremely useful in the impact assessment valuation and improvement process, the use of normalisation and weighting factors adds subjectivity to the analysis and is less scientific. Additionally, as previously mentioned, the novelty of social and economic impacts as part of this analysis meant that new normalisation and weighting factors had to be applied if these sustainability dimensions were to be considered as part of the MCDA approach. As such, the factors used for normalisation and weighting procedures for these aspects are considered to have very low robustness due to statistical quality assured sources and extrapolation strategies applied to define these factors.

Additionally, it is important to consider the time periods between each concurrent engineering session. In that regard, over 32 months elapsed between the first and third studies. As such, the SSSD was at very different stages of development at the point of each concurrent engineering study, having been consistently updated. Therefore, the reported results may be misleading since the SSSD grew in sophistication between analyses. It is expected that this will be particularly relevant between the MÌOS and NEACORE studies.

Lastly, it should be noted that all of the reported LCE results within this paper have not yet been validated by a third-party, nor has an uncertainty analysis been run. This is mainly due to the iterative nature of LCE, meaning that these engineering models are not considered to be finished. Instead, the generated results within each concurrent engineering session were used to guide decision towards more sustainable options. As such, without a formal review, it can be considered that the public disclosure of these results within this paper goes against ISO 14044:2006 (2006) guidance. However, it is intended that a full LCSA will take place following the critical design review at the end of Phase C, which will incorporate both of these issues when a more complete design is reached.

4. Results & discussion

The described methodology was then integrated and applied within the concurrent engineering process of the MÌOS, NEACORE and STRATHcube Phase 0/A design studies. This section, therefore, presents the results of each study using the LCE approach at both midpoint level and through a single score based on MCDA. The methodology, process and results then form a basis for discussion in order to interpret their significance and the viability of the LCE approach within the concurrent engineering process of early space mission design concepts.

4.1. Midpoint results

The absolute results of the three missions contained within Table 1 indicate that each space mission design concept has generally improved, with better results than the last. In that regard, since the STRATHcube mission performs better than MÌOS and NEACORE across all twelve impact categories, it could be said that the STRATHcube mission is the most sustainable SmallSat space mission ever designed at the university. However, as can be seen in Fig. 8, these results look very different when considering the impact per kg of spacecraft mass. However, it should be noted that the reported results for STRATHcube includes three full-scale engineering models for development and testing, whereas the MÌOS and NEACORE concepts do not. Therefore, when distributing the impact per kg over this total mass, STRATHcube actually performs better on every impact category except for Eutrophication (Freshwater) where MÌOS performs slightly better. However, it is important to note that this impact category has the highest uncertainty attached to it in the SSSD, as evidenced through the ESA Life Cycle Inventory (LCI) Validation Project (Wilson, 2018). As such, these findings place an added importance on how life cycle results should be reported and/or communicated.

Overall, it should be noted that the production & manufacturing of the launcher would generally dominate the majority of impact categories had a "share of emissions" not been used in the model set-up. As a result, the most dominating life cycle phase of each mission is different. In that regard, the NEACORE impacts were driven by choice to use a dedicated launcher rather than a rideshare like MÌOS or piggy-back like STRATHcube, as reflected by the domination of Phase E1 within most impact categories. The impact for these was mainly driven by the production & manufacturing of the launcher plus its propellants as well as the launch event for Ozone Depletion. For the STRATHcube concept, Phase C + D was the largest contributor across most impact categories (except ozone depletion which is only associated with launch). This was mainly associated with the production & manufacturing of the spacecraft, including design activities and testing. Final archival of data during Phase F was also found to be somewhat meaningful across various impact categories. Within the MÌOS concept, the impacts were fairly evenly split across the space segment and launch seg-

Table 1
Absolute LCE results of the MÌOS, NEACORE and STRATHcube missions at midpoint level.

Impact Category	Unit	LCIA Method*	LCIA Results		
			MÌOS	NEACORE	STRATHcube
Air Acidification	kg SO_2 eq.	CML (2002)	6.18E+04	7.17E+04	1.70E+03
Climate Change	kg CO_2 eq.	IPCC (2013)	1.12E+07	8.78E+06	4.79E+05
Eutrophication (Freshwater)	kg P eq.	ReCiPe Midpoint (H)	6.72E+03	5.64E+03	3.61E+02
Eutrophication (Marine)	kg N eq.	ReCiPe Midpoint (H)	1.09E+04	8.33E+03	3.91E+02
Mineral Resource Depletion	kg sb eq.	CML (2002)	2.58E+05	1.75E+05	1.08E+04
Ozone Depletion	kg CFC-11 eq.	WMO (1999)	2.17E+04	3.56E+04	6.26E+00
Photochemical Oxidation	kg NMVOC	ReCiPe Midpoint (H)	3.08E+04	2.96E+04	9.68E+02
Social Impact	social score	Wilson (2019)	7.70E+08	1.33E+08	2.67E+06
Toxicity (Freshwater Aquatic)	PAF.m^3.day	USEtox	6.93E+07	4.37E+07	3.10E+06
Toxicity (Human)	cases	USEtox	1.88E+03	1.27E+03	7.88E+01
Water Depletion	m^3	ReCiPe Midpoint (H)	5.80E+07	6.73E+07	2.70E+06
Whole Life Cost	EUR 2000	Wilson (2019)	1.19E+08	2.97E+07	2.42E+06

☆As adapted according to ESA Lca Working Group (2016) & Wilson (2019).

Fig. 8. Impact per kg LCE results at midpoint level.

ment with pertains to Phase C + D and Phase E1. In contrast, the utilisation phase was found to rarely be the largest contributor of any impact category due to the short lifetimes of the SmallSats.

4.2. MCDA results

The MCDA results are provided in Table 2, Figs. 9 and 10. In particular, Table 2 provides an overview of the applied normalisation and weighting factors, outlining the relative contribution of each impact category to each sustainability dimension. Fig. 9 relates to the performance evolution of the environment, social and economic single scores based on design progression. These have been included for information purposes only since the engineering models were not finalised until iteration three for MÌOS and NECORE and iteration four for STRATHcube. In this regard, each mission concept (including their masses) were constantly evolving, whilst sustainable design measures were continuously being implemented to address the most prominent hotpots based on the results of previous iterations. For example, due to the fluctuations of the STRATHcube spacecraft within each iteration, the overall sustainability score per kg relative to iteration one was 22% higher for iteration two, 29% higher for iteration three and 25% higher for iteration four. Comparatively, Fig. 10 provides an overview of the relative contribution of each sustainability dimension to the final single sustainability score based on new MCDA criteria and the old MCDA criteria that was used at the time of each study. The old MCDA criteria (described in Section 3.4) was used within each concurrent engineering study whilst the new MCDA criteria simply exchanges the normalisation factor used in the old MCDA criteria (annual taxation per EU citizen) to annual cost of space activities per EU citizen (€7.17 relative to the value of the Euro in the year 2000) (European Space Agency, 2019a).

Using the new MCDA criteria, the results suggest that costs somewhat unsurprisingly produce the highest share of the sustainability score out of all the sustainability

Table 2
Relative contribution of impact categories towards each sustainability dimension.

Sustainability Dimension	Impact Category	Normalisation Factor	Weighting Factor	Relative Contribution (%)		
				MIOS	NEACORE	STRATHcube
Environment	Air Acidification	1.51E+00	9.38E−02	0.55	0.73	0.41
	Climate Change	9.22E+03	3.19E−01	0.06	0.05	0.06
	Eutrophication (Freshwater)	1.48E+00	4.24E−02	0.03	0.03	0.04
	Eutrophication (Marine)	1.69E+01	4.48E−02	0.00	0.00	0.00
	Mineral Resource Depletion	1.01E−01	1.14E−01	41.92	32.44	47.83
	Ozone Depletion	2.16E−02	9.56E−02	13.79	25.81	0.11
	Photochemical Oxidation	3.17E+01	7.24E−02	0.01	0.01	0.01
	Toxicity (Freshwater Aquatic)	8.74E+03	2.90E−02	0.03	0.02	0.04
	Toxicity (Human)	5.33E−04	6.01E−02	30.43	23.46	34.77
	Water Depletion	8.14E+01	1.29E−01	13.18	17.44	16.72
Society	Social Impact	3.34E+04	1.00E+00	100.00	100.00	100.00
Economy	Whole Life Cost	8.55E+03	1.00E+00	100.00	100.00	100.00

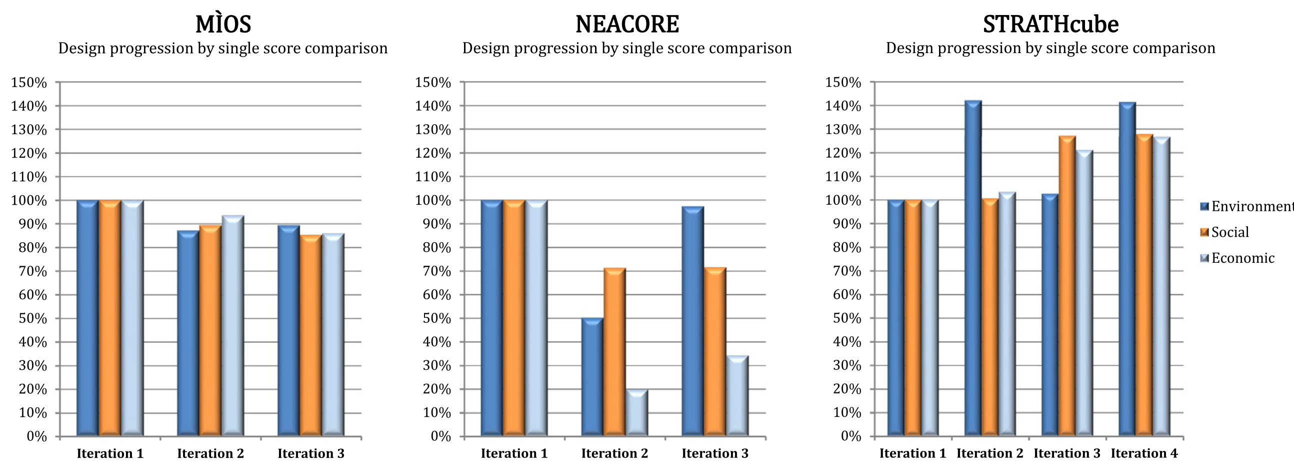

Fig. 9. MCDA results showing design progression by single score comparison.

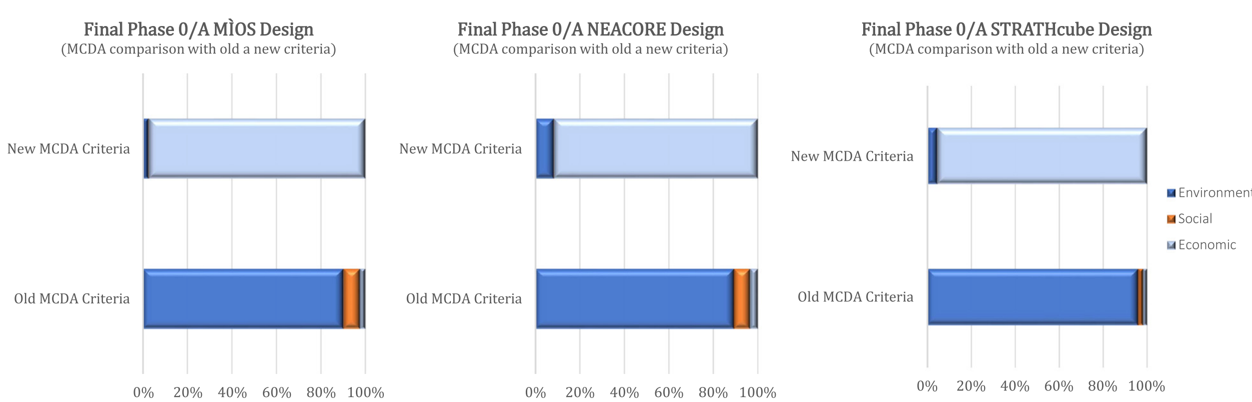

Fig. 10. Comparison of MCDA results with old and new MCDA criteria.

dimensions, representing 97.22% of the single score for the MÌOS mission, 91.47% for the NEACORE mission and 95.47% for the STRATHcube mission respectively. However, it is important to note that all the normalisation and weighting factors applied adds sensitivity. Before the new normalisation factor was applied for the whole life cost impact category, the environment consistently came out as the most impacting sustainability dimension. As such, MCDA must be applied with caution.

However, based on the old MCDA criteria, the results suggest that the environmental impact categories produce the highest share of the sustainability score out of all the sustainability dimensions, indicating that this sustainability dimension should be targeted for impact reduction efforts.

Across all three missions, the four most contributing impact categories were Mineral Resource Depletion, Ozone Depletion, Toxicity (Human), and Water Depletion, generating >99% of the total environmental score. In terms of both the Mineral Resource Depletion and Toxicity (Human) impact categories, the greatest common hotspot which was identified within these missions relates to the use of germanium as a substrate within solar arrays. In terms of human toxicity, this was notably due to the release of arsenic, mercury and dioxins to air from the production & manufacturing process. For mineral resource depletion, this impact was primarily due to germanium being listed as a critical raw material since the resource has limited potential of becoming widely economically and technologically available in the near-term future. Additionally, it can be noted that the release of ClO_x, NO_x, HO_x and HCl during the launch event has a considerable impact on ozone depletion. For water depletion, the majority of this impact comes from turbine use in the consumption of electricity for design work, the launch campaign, ground stations and final archival of data, as well as mechanical examinations, assembly, integration testing and inspections. This result is mostly due to the large volumes of distilled water which is used to spin the turbines to produce electricity and the amount of water used in cooling loops for the steam exiting the turbine.

Based on these hotspots, efforts were made to reduce these adverse impacts within the NEACORE and STRATHcube engineering models from iteration to iteration. In both cases, a reduction in the mass of the solar panels were targeted since they could not be phased out completely. In terms of NEACORE, the solar array was reduced by 32.78% leading to vast single score environmental savings. However, an increase in environmental results between iteration two and three was due to a change in launchers for commercial reasons (from a Soyuz 2-1b piggy-back assuming a 20% share in environmental, social and economic impact to a dedicated PSLV-CA launcher). Despite this change, the savings from the solar array limited the overall environmental score from increasing beyond the score of iteration one. In terms of STRATHcube, a 33.44% decrease in the solar panels was achieved between iteration two and three. However, additional design constraints placed on power by the thermal subsystem meant that the solar panels had to be up-sized again in iteration four. Comparatively, the other two impact categoties could not be fully addressed within this concurrent engineering session since ozone depletion contributed only 0.11% of the environmental score due to the small share of impacts from the launcher whilst the main impacts associated with water depletion impact category was not really affected greatly by the engineering model or user choices. Instead, it was recommended at the end of the concurrent engineering session that operations to optimise work-load and the amount of testing required at each stage should be investigated, including switching to greener electricity suppliers where possible.

The reason that the improvement measures applied to the MÌOS concept have not been discussed above is because they were implemented after the concurrent engineering session took place, so are not reflected in Fig. 9. However, to provide further insight, the executed LCE measures related to the downsizing of the solar array (21.71% achieved) and the replacement of the hydrazine propellant with LMP-103S. This latter option was implemented as an experiment since the use of LMP-103S 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. 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. However, the combination of these two measures led to waterfall mass savings of 5.05% and a reduction in MCDA score by 15.66%. It is hypothesised that this is almost entirely due to the reduction of the solar array mass and that the replacement of hydrazine with LMP-103S actually suppressed the improvements measures. However, proving this would be extremely challenging since tracing the full indirect impacts to a single LCE 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 LCE option primarily drove this change since both created reductions in system mass. Therefore, the results suggest how imperative it is that system level technical considerations are also taken into account. 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.

4.3. Discussion

Using practical examples, this paper has successfully provided proof of concept of integrating LCE into the concurrent engineering process of space missions, thereby addressing one of the most commonly cited problems pertaining to a lack of practical demonstrations showcasing best practice for LCE. The case studies have demonstrated both the functionality and capability of the SSSD to calculate LCE results of space missions. Despite this, the generated results should not be seen as a ‘gold standard’ if they are to be used for comparison or benchmarking purposes since they have not yet been validated. User decisions and methodological choices were also highly influential throughout each study. For example the selection of reserve base as the horizon within the Mineral Resource Depletion impact category ultimately led to germanium being identified as a hotspot, whereas it would not have been if ultimate reserves had been used. Moreover, it should also be noted that the reported impacts are relevant for different mission concepts with different input criteria whilst the growing sophistication of SSSD between concurrent engineering sessions could potentially be partly responsible for the higher impact per kg between studies. Another consideration could be that this metric (impact per kg) is not symbolic of the sustainability footprint of space missions since non-linear adverse impacts are footprint distributed over more mass. For example, certain aspects such as mechanical inspections and tests won't scale linearly with mass. Accordingly, more definitive benchmarks need to be defined for space systems. Nonetheless, in the absence of more robust data, the output of this work provides an important preliminary measure of the life cycle sustainability impact of SmallSats.

In terms of the process for reducing impacts, the LCE approach has great potential for improving system performance through the identification and mitigation of sustainability hotspots when applied within concurrent engineering sessions (by lowering ecological burdens, avoiding potential supply chain disruption and reducing costs). It is also important for demonstrating 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. Consequently, these results can then be fed into the decision-making process at a strategic level (e.g. the procurement process) or at equipment, component & material level (e.g. redesign activities) to drive internal change, thereby creating a truly sustainable space sector. More specifically, the results from the hotspot analysis provides concrete starting point for discussions with relevant stakeholders along the supply chain or to develop an entirely new business model (although this was considered to be beyond the scope of this study). Instead, the focus was on how to implement improvement options in real-time within the concurrent engineering session itself.

As such, only two options were open for the reduction of hotspots. The first was to replace poorly performing processes with alternatives whilst the second was to minimise the use or quantity of poorly performing processes. Only in cases where neither of these options could be achieved without significantly compromising technical aspects were they ignored. Under this scenario, addressing hotspots can then be investigated on a supply chain level outside the concurrent engineering session. However, as demonstrated within this paper, beginning the process of addressing the most prominent hotspots within concurrent engineering sessions provides an important foundation for implementing further improvement options with a view of reaching an optimum sustainable design. In this regard, the use of MCDA as part of the hotspot analysis was extremely useful and significantly helped to simplify the decision-making process. Despite this, the approach is less scientific than midpoint results and can add high levels of subjectivity, as demonstrated by the change of whole life cost normalisation factor. In this regard, the focus of this paper has been on the environment since it consistently came up as most impact sustainability dimension. However, with the new MCDA criteria, it is possible that this may switch to costs in the future. For that reason, it could be advantageous to establish a consortium of interested stakeholders to establish consensus on the best method for performing MCDA on space products. Until then, it is recommended that the single scores generated for the environment, society and economy sustainability dimensions are used instead of a single sustainability score. This would enable the mitigation of impacts across three dimensions, rather than targeting only the most dominant one, as in this paper. Additionally, these should then only be used as an indication of the most prominent impacts and should not be used alone to make sustainable design decisions.

Moreover, the use of MCDA also presents a clear trade-off between accuracy/comprehensiveness of the sustainability assessment and the facilitation of decision-making. In this regard, whilst the use of MCDA reduces the learning curve of engineers and prevents experts from addressing only the impact categories which they are familiar with, it does not provide engineers with adequate information to identify and address hotspots themselves. For this reason, it is important that the underlying design hotspots are still communicated verbally to subsystem experts within the concurrent engineering process by the sustainability specialist. However, whether LCE discipline is handled as a subsystem itself or addressed in a similar manner to power and mass budgets has still to be determined. In the case of this paper, it was considered to be a separate domain discipline, but in practice more closely resembled a system engineer completing a mission budget. Either way, there will be a need for someone with sufficient knowledge and oversight of the sustainability results to be present in the room to calculate life cycle impacts and continuously communicating these with engineers throughout the process to ensure meaningful change is made at system level.

Moreover, although LCE has been demonstrated as a viable technique for measuring and reducing adverse impacts, another emerging topic which is beginning to be discussed within the sector is carbon offsetting and whether it can or should be applied to space missions to make them carbon neutral. This concept is considered to be outside the scope of this work, since LCE is mainly applicable within early conceptual studies before the design (and associated impacts) are 'set'. At this stage, emphasis should be on reducing impacts as far as practically possible. Implementing such an approach at this stage may also put more focus or an emphasis on address climate change impacts only, hence shifting focus from other potentially meaningful impacts. As such, it is recommended that a set of definitive rules should be developed before this topic is considered as a viable strategy.

An additional observation was the evolving behavioural trends. In this regard, there was a clear growing enthusiasm amongst study participants with regard to the LCE discipline in each new concurrent engineering session. In particular, the MÌOS study was used as a test case for the operability of the SSSD. As such, whilst the LCE results were used to inform of life cycle impacts, they not used as a design driver by discipline experts, with sustainable design approaches investigated retrospectively. During the NEACORE study, there was clear evidence of discipline experts proactively seeking solutions for improving the overall sustainability score. For example, one discipline expert questioned whether switching the AOCS propellant from argon to AF-M315E (which is classed as a high-performance green propellant) would make a difference with respect to environmental performance. This was a welcomed change from the normal reactive approach based on the implementation of corrective measures for identified hotspots. In comparison, the STRATHcube study had LCE as a mission driver from the outset which led to higher levels of participant interaction in relation to finding solutions to design hotspots. This is evidenced by an improved sustainability score per mass when considering the additional contribution of its three engineering models. Although it was unclear whether this motivation and associated change in participant behaviour was driven by the growing reputation of the ELCA/LCE within the industry, familiarity with the process or society's perception with regards to sustainability issues, this clearly highlights the growing awareness concerning the importance of addressing sustainability issues amongst engineers.

Finally, despite these challenges, the adoption of LCE is not difficult to envisage. Ecodesign 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 and Neumann, 2022). Such a scenario would provide an ideal opportunity for LCE to also be integrated as a complimentary tool to ecodesign (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 European space sector.

5. Conclusion

The integration of LCE within the space mission design process provides 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. This study has validated the operational and technical feasibility of the approach within concurrent engineering. It has demonstrated how space missions can be optimised towards more sustainable solutions by mitigating adverse environmental, social and economic impacts as early into the design process as possible. The paper provided insight into the life cycle sustainability impacts of three SmallSat missions based on a LCE approach. These findings can be used as an indicative gauge into the general sustainability of SmallSats for the first time. Following on from the example set by this study, it is hoped that LCE approach can begin to be streamlined within the space industry, thereby allowing the sector to become accountable and responsible for their operations in the frame of the 2030 Agenda for Sustainable Development. To help facilitate this, four high-level recommendations are outlined below:

- Careful communication of all publicly declared LCSA/LCE results is required to avoid greenwash and ensure transparency, particularly in cases where MCDA is applied due to the subjectivity introduced by normalisation and weighting procedures.
- A consensus on best practice for MCDA of space products should be established through a consortium of interested stakeholders to ensure methods for generating single scores are as robust and sophisticated as possible.
- A streamlined approach for communicating design hotspots to subsystem experts during a concurrent design study should be investigated further, including consideration as to whether LCE should be a domain discipline itself or considered as a mission budget.
- When considering sustainable design solutions as part of a trade-off analysis, a final check must be performed to ensure that an optimised performance is achieved at system level.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This paper was originally presented at the Stardust-R Global Virtual Workshop II from 13–17 September 2021. This work was supported by the Engineering & Physical Sciences Research Council (Grant No. 1886740) and SPACE Canada (Grant No. 20150722095511).

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.asr.2023.01.023.

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