Advanced Methods of Life Cycle Assessment for Space Systems

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This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: A.Wilson

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to preserve and cherish the pale blue
dot, the only home we've ever known

- Carl Sagan, Pale Blue Dot, 1994

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Abstract

Environmental Life Cycle Assessment is increasingly being applied within the space industry to scientifically quantify environmental impacts of space missions over their entire life cycle. This technique is particularly useful in early mission design phases since adverse life cycle impacts are more difficult to modify the later into the design process that they are identified. However, the use of Environmental Life Cycle Assessment does not fully align with the concept of sustainability envisioned within the 2030 Agenda for Sustainable Development which seeks to "balance the three dimensions of sustainable development: the economic, social and environmental". Despite this, combining all three sustainability dimensions within a single life cycle study has thus far never been attempted within the space industry.

To address this, a new space-specific Life Cycle Sustainability Assessment framework and database was developed to assist industry advance this methodology by integrating social and economic considerations into concurrent engineering activities. This approach combines Environmental Life Cycle Assessment, Social Life Cycle Assessment and Life Cycle Costing to enable engineers to create sustainable technologies and products for space that are cost-efficient, eco-efficient and socially responsible in the frame of the 2030 Agenda.

The application of the developed approach has been exemplified using case studies for the design of next generation sustainable space systems, allowing conclusions to be reached based on the interactions of each sustainability dimension during the mission design process. It is expected this approach will assist the space industry to streamline future decision-making and monitoring in a more systematic and coordinated fashion which accords with the vision of sustainability outlined in the 2030 Agenda.

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List of Symbols

1,4-DB	Paradichlorobenzene
Al	Aluminium
$\mathbf{Al_2O_3}$	Aluminium Oxide
CFC-11	Trichlorofluoromethane
$\mathbf{cm^3}$	Centimetre Cubed
$\mathbf{ClO}_x$	Chlorine Oxide Radicals
CO	Carbon Monoxide
$\mathbf{CO_2}$	Carbon Dioxide
$\mathbf{CO_2e}$	Carbon Dioxide Equivalent
eq.	Equivalent
$\mathbf{H_2}$	Hydrogen Gas
$\mathbf{H_2O}$	Water
HCl	Hydrogen Chloride Gas
$\mathbf{HO}_x$	Hydrogen Oxide Radicals
kg	Kilogram
km	Kilometre
kWh	Kilowatt-Hour
LNG	Liquefied Natural Gas
$\mathbf{LO}_x$	Liquid Oxygen
$\mathbf{m^3}$	Metre Cubed
MJ	Megajoule

N	Nitrogen
$\mathbf{N_2}$	Nitrogen Gas
$\mathbf{N_2O_4}$	Dinitrogen Tetroxide
$\mathbf{NH_3}$	Ammonia
$\mathbf{NH_4ClO_4}$	Ammonium Perchlorate
$\mathbf{NO}_x$	Nitrous Oxide Radicals
P	Phosphorus
$\mathbf{PM_{10}}$	Particulate Matter (under 10 micrometres in diameter)
Sb	Antimony
$\mathbf{SO_2}$	Sulphur Dioxide
t	Time
U-235	Uranium-235
UDMH	Unsymmetrical Dimethylhydrazine

List of Abbreviations

ABC	Activity-Based Costing
AI	Artificial Intelligence
API	Application Programming Interface
APOS	Allocation at Point Of Substitution
CBS	Cost Breakdown Structure
CCDS	Concurrent & Collaborative Design Studio
CDF	Concurrent Design Facility
CDP-4	Concurrent Design Platform 4
CER	Cost Estimation Relationship
CF	Characterisation Factor
CNES	Centre National d'Études Spatiales
ConCORDE	Concurrent Concepts, Opinions, Requirements & Design Editor
COPUOS	Committee On the Peaceful Uses of Outer Space
COTS	Commercial Off-The-Shelf
CSR	Corporate Social Responsibility
CSV	Comma-Separated Values
DDT&E	Design, Development, Testing & Evaluation
DoD	Department of Defense
E-LCA	Environmental Life Cycle Assessment
EA	Environmental Assessment
EC	European Commission
EEIO	Environmentally Extended Input-Output

EIS	Environmental Impact Statement
ELCD	European Life Cycle Database
ESA	European Space Agency
ESTEC	European Space Research & Technology Centre
EU	European Union
FU	Functional Unit
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GRI	Global Reporting Institute
HPGP	High Performance Green Propellant
IAEG-SDGs	Inter-Agency & Expert Group on SDG Indicators
IEC	International Electrotechnical Commission
ILCD	International Reference Life Cycle Data System
ISO	International Organization for Standardization
JRC	Joint Research Centre
JSON	JavaScript Object Notation
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCE	Life Cycle Engineering
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
LCT	Life Cycle Thinking
LEO	Low Earth Orbit
LEOP	Launch & Early Orbit Phase
LOFT	Large Observatory For x-ray Timing
MAVT	Multi-Attribute Value Theory

MCDA	Multi-Criteria Decision Analysis
MDGs	Millennium Development Goals
NASA	National Aeronautics & Space Administration
NF	Normalisation Factor
OCDT	Open Concurrent Design Tool
OECD	Organisation for Economic Co-operation and Development
P-BEAT	Process-Based Economic Analysis Tool
PBCM	Process-Based Cost Model
PEFCRs	Product Environmental Footprint Category Rules
PSILCA	Product Social Impact Life Cycle Assessment Database
RDL	Reference Data Library
RSPs	Re-Entry Smoke Particles
S-LCA	Social Life Cycle Assessment
SBSP	Space-Based Solar Power
SDGs	Sustainable Development Goals
SEIA	Socio-Economic Impact Assessment
SETAC	Society of Environmental Toxicology & Chemistry
SHDB	Social Hotspots Database
SMART	Strathclyde Mechanical & Aerospace Research Toolboxes
SPS	Solar Power Satellite
SSSD	Strathclyde Space Systems Database
TBL	Triple Bottom Line
TRL	Technology Readiness Level
UN	United Nations
UNEP	United Nations Environment Programme
VCAs	Value Chain Actors
WEF	World Economic Forum
WF	Weighting Factor
ZOLCA	Zipped OpenLCA

Chapter 1

Introduction

1.1 Background

Until recently, environmental impacts of space activities had often been omitted from key legislative and regulatory requirements, with the result that the environmental impacts of industry activities were traditionally overlooked or ignored. For example, when the Montreal Protocol on Substances that Deplete the Ozone Layer was introduced in 1987, it completely left out the space industry despite rocket propulsion being the only source of anthropogenic emissions to inject ozone destroying compounds directly into all layers of the atmosphere [1, 2]. A key difficulty arising from neglecting such impacts from mainstream legislative and regulatory requirements was that the industry lagged behind others in terms of its ability to determine and account for its environmental impacts. However, renewed commitments in recent years by national and international bodies towards environmental problems has allowed a range of mitigation measures and key sustainability issues to filter down and become embedded in a variety of sectors. In particular, the adoption of both the Paris Agreement by 195 Member States and the 2030 Agenda for Sustainable Development by 193 Member States of the United Nations (UN) in 2015 has created a much more coordinated global approach towards setting goals and in achieving environmental sustainability [3, 4]. This vision illustrates that to achieve sustainability all sections of society must be fully engaged, and the space industry is no exception.

Important within this context is Life Cycle Assessment (LCA) which is a pragmatic and useful environmental management technique which is beginning to be applied within the space industry. LCA is used to assess environmental impacts of products, processes or services over their entire life cycle from raw material extraction through processing & manufacturing, assembly, transportation, use and end of life. The method is internationally standardised by the International Organization for Standardization (ISO) through the ISO 14040:2006 and 14044:2006 environmental management standards on LCA which provide a globally accepted framework to which all LCA studies should adhere [5, 6]. Interest in the topic has dramatically increased over the last couple of decades, with McManus & Taylor showing that annual LCA related publications rose from around 10 to more than 1,700 between 1992 and 2013 [7]. Within the space sector, it is increasingly being recognised as an extremely important aspect of product development and improvement. Its application allows the industry to become fully transparent in their operations by scientifically quantifying the overall environmental impact of space activities which allows decision-makers to mitigate potential 'hotspots' before they occur.

The suitability of applying this tool within the space sector is reemphasised by the 'Guidelines for the long-term sustainability of outer space activities' which were released in 2017 by the UN Committee on the Peaceful Use of Outer Space (COPUOS), acting as the first ever international sustainability guidelines for space activities [8]. In particular, Guideline 27.3 suggests the utilisation of 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 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. This is because the traditional concept of sustainability encompasses not just the environment but also society and the economy [9]. Thus, to determine the true 'sustainability' impact of a product, all three aspects need to be considered. This notion is reiterated by Guideline 27.2 of the COPUOS guidelines 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" [8]. This clearly aligns more closely with the traditional three pillar view of sustainability and suggests that LCA of space systems should go beyond the traditional focus on the environment to include social and economic impacts as well. For this reason, the space sector may need to move to a more encompassing sustainability assessment which considers the full sustainability spectrum of the environment, society and economy.

In step with this, the explosion of LCA activity in recent years has led to a number of proposals for advancing its methodology, including a move from the current LCA concept to a more comprehensive type of sustainability assessment called Life Cycle Sustainability Assessment (LCSA) [10]. LCSA is a new environmental management tool used to measure the environmental, social and economic impacts of products, processes and services over their entire life cycle. It allows for product assessment based on the traditional 'three pillar' interpretation of sustainability by combining the traditional form of environmental LCA (also known as 'E-LCA') with Social Life Cycle Assessment (S-LCA) and Life Cycle Costing (LCC) [10]. Similar to E-LCA, S-LCA is an assessment type used to predict the social and sociological aspects of products, processes or services over their entire life cycle whilst LCC is an economic assessment used to determine the entire cost of a product, process or service over its entire life cycle including both one time and recurring costs [11, 12]. However, rather than a model itself, LCSA is a framework of models designed to provide more relevant results in the context of sustainability and allow integrated decision-making based on a life cycle perspective [13]. The framework, therefore, underlines the importance of evaluating the results of each sustainability dimension, including how they interact with one another rather than merely viewing each result as separate entities in themselves.

Although the possibility of encompassing more than just the environment in E-LCA of space missions has been briefly mentioned by some researchers [14–17], to date there has been no serious effort made or projects conducted on LCSA for space systems. However, in an evaluation of the E-LCA evolution, Guinée et al. predicted that LCSA will be the future of E-LCA [18]. 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.

Employing such a technique has numerous advantages, including the direct alignment with the 2030 Agenda. This was created based on the principles which were agreed upon under A/RES/66/288, as mentioned by Guideline 27.2 of the 'Guidelines for the long-term sustainability of outer space activities'. As such, the 2030 Agenda acts as a new coordinated global approach towards achieving sustainability which seeks to "balance the three dimensions of sustainable development: the economic, social and environmental" [4]. It sets out a plan of action over the next decade to 2030 to stimulate action in the five identified areas of critical importance (people, prosperity, planet, partnership and peace). Stemming from this, a proposal was put forward in November 2015 by product designers at the Forward Thinking conference in Oslo, Norway relating to how the 2030 Agenda could be used as a useful framework for design [19]. This led to the establishment of the Oslo Manifesto which is a voluntary initiative which tasks product engineers to embrace the goals contained within the 2030 Agenda as design standards for their products. Adopting such an approach within concurrent engineering allows environmental, social and economic concerns to be integrated into the decision-making process which closely aligns with the goals of LCSA when considered from a life cycle perspective [20]. This technique is known as design for sustainability (or sustainable design) which can help to facilitate streamlined decision-making and monitoring in a more systematic and coordinated fashion which accords with the renewed vision of sustainability outlined in the 2030 Agenda.

As such, product designers have a pivotal role with regards to the successful delivery of sustainable development. In this sense, as most impacts are set by early design choices [21, 22], integrating LCSA into the design process of space missions is vital since it will allow decision-makers to design space missions which are fully aligned with the global aspirations envisioned by the 2030 Agenda. By taking into account the full spectrum of life cycle impacts and sustainability issues associated with space systems when selecting and designing technologies, space missions can be optimised towards more sustainable solutions by mitigating adverse environmental, social or economic impacts as early into the design process as possible.

1.2 Historical Overview

E-LCA was first identified by the European Space Agency (ESA) Clean Space Initiative as the most appropriate method to measure the environmental impacts of space missions. Before E-LCA, typically environmental assessments (EAs) and environmental impact statements (EISs) were used as the main method to measure environmental impacts within the industry. These types of assessment were used for several decades, with the furthest traceable record of an EIS being that of the National Aeronautics & Space Administration (NASA) Space Shuttle Program which was first released for comment in March 1971 [23]. EAs are documents which are used to determine if a proposed action or activity will have a significant adverse impact on the environment [15]. If it is determined that such an impact may occur, then an EIS statement will be issued. EISs describe the proposed action or activity, listing any possible alternative measures which could be put into place to mitigate these adverse impacts and the expected environmental impacts of such changes [15]. However, these types of reports did not adopt a life cycle approach and tended to focus exclusively on localised impacts of the launch event only. These assessments also lacked methodological consistency meaning that they often displayed significant variances in scope from one mission to another. Despite this, most of these assessments were qualitative or narrative in nature meaning that many failed to scientifically quantify the overall impact to the environment. Due to this, ESA decided that E-LCA may provide a more accurate scientific quantification regarding the environmental impacts of their activities. Through its internationally standardised methodology, the tool can assist in cutting costs and facilitating technological development to establish a competitive advantage. Equally, it can also help organisations to maintain compliance with current and future legislation to avoid any potential supply chain disruption.

Since 2009, ESA has been pioneering its application within the space sector in order to assist industry in protecting the environment by minimising the impacts of space activities to Earth and space [24]. Prior to the work of ESA, only one space-specific study which adopted life cycle principles had ever taken place [25], but this analysis did not actually consider any environmental impacts. To address this, the topic was first employed in an internal concurrent design study called ECOSAT to consider the life cycle environmental impacts of satellite design, manufacturing, launch and operation of a space mission. The successful outcome of this study led to the ESA Directorate of Launchers calling for the environmental impacts of launch vehicles to be investigated [26]. As such, a study on a Vega, Soyuz and Ariane 5 launcher was carried out in 2011 [27, 28]. Attention then turned to full missions in 2012 and the impacts of four satellite missions (earth observation, telecommunications, meteorological and science) were investigated. Each of these missions used the results from the launchers study to provide an insight into the comparative impacts of the launch, space and ground segment [29].

Subsequently, ESA continued to work on refining the E-LCA methodology to make it more applicable for space systems. The reason for this is because typically E-LCA is used to assess products which are mass produced. In comparison, the space sector is a unique domain (i.e. it has low production rates, long development cycles and uses specialised materials and industrial processes). This means that if E-LCA is to be used for space systems, traditional methodological rules used for E-LCA would require adapting. To facilitate this, ESA produced the first set of E-LCA guidelines for space systems which were released in 2016 [30]. These guidelines adapt current ISO standards on E-LCA to be more space-specific. Furthermore, ESA also developed a new E-LCA database which saw the first dedicated datasets capable of calculating the environmental impacts of space missions [31]. Alongside this database, ESA created a new ecodesign tool called Space Opera in order to integrate environmental considerations into mission design [32]. Creating the database and ecodesign tool was a lengthy process due to the complexity and uniquely differing requirements of space systems. These tools are still classed as under development despite involving hundreds of experts from around the world [33]. Together with the space-specific E-LCA guidelines, these tools are critical components of the ESA E-LCA framework for space missions at ESA. This framework is discussed further in Chapter 2.

The ESA Clean Space Initiative continues to work on E-LCA and to the end of 2018 have had 46 studies on the topic since its inception in 2009, at a cost of over €20 million [34]. Despite ESA taking the leading role, many other organisations and institutions have been contributing to the E-LCA remit within the space sector in recent years. For example, Maury et al. investigated the possibility of considering space debris within the E-LCA framework of space missions by creating a new life cycle impact assessment method relating to orbital space use [16]. Moreover, the French Space Agency (CNES) and ArianeGroup have conducted independent studies on the Ariane 5 and Ariane 6 launch vehicles respectively [34, 35]. Life cycle studies have also been conducted at the University of Texas at Arlington on environmental impacts of launchers in the USA [36]. Newer studies have begun to emerge on topics such as asteroid mining [37].

Although no known space-related S-LCAs have ever taken place, socio-economic impact assessments (SEIAs) have begun to be applied more widely within the space sector. These are systematic methods of analysis which are commonly applied during EIAs to evaluate socio-economic and cultural impacts of a proposed development [38]. Space-related SEIAs can be traced back to 1975 where economic studies were required in the USA in order to justify the vast investments prescribed to the Apollo Programme. As well as identifying the absolute costs of the programme, one of the assessments conducted by NASA scientist Dr. Paul D. Lowman Jr also discussed the societal benefits stemming from this investment as they related to democracy between states, improvement of international relations, greater knowledge of the universe, technology development, spin-off applications and other intangible issues [39]. This was the first time that qualitative societal benefits had formally been used within a written economic assessment to justify investment in a space mission.

Despite its novel approach to economic analysis, assessments into social impacts of space missions remained scarce in nature and were not often included in economic analyses. It has only been in the last decade that studies into social impacts have started to become more prevalent. The main reasons for this are due to the transparency requirements and high pressure placed on justifying public budget spending, as well as a growing importance and awareness placed upon addressing a wider range of sustainability issues. However, SEIAs are not standardised and do not adopt a life cycle approach concerned with addressing adverse impacts. Due to this, a wide range of methodological approaches have been developed from the economic field as a suitable technique to assess the socio-economic impact of space activities. To date, these approaches have been applied within a range of different space-related SEIAs to measure the socio-economic impact of a variety of programmes, projects and sectors. These include studies related to improved weather and climate information [40, 41], the global space economy [42], NASA's space programme [43], the Canadian space sector [44], space activities in the European Union (EU) [45], Copernicus from an EU context [46, 47], the European launcher sector [48] and the formation of a dedicated national space agency for Australia [49]. Additionally, ESA have also begun to conduct ex-ante SEIAs of their different programmes. In the context of Clean Space, the purpose of the SEIA was to identify the socio-economic impacts related to the work of the Clean Space Initiative from its inception to 2017. It also sought to identify the impacts of potential European industry participation to a future global On-Orbit Servicing market and the realisation of the e.Deorbit mission as a technological enabler for a possible future European On-Orbit Servicing capability. This study concluded in early 2019, with results remaining confidential [50].

Within the context of aerospace, LCC has received more attention than both E-LCA and S-LCA since its inception. As a concept, LCC emanated from a US Department of Defense (DoD) study in the 1960's which assessed the long-term cost effects of weapon systems when making purchasing decisions due to rising concerns regarding the economic implications of awarding procurement contracts on the basis of acquisition price [51,52]. The resulting report took a life cycle approach for the first time, defining specific categories of cost and their possible magnitude. In particular, it showed that the operation and support phase could contribute as much as 75% of the total cost which demonstrates the importance of conducting this kind of analysis [53]. This led to the DoD issuing the first set of guidelines for LCC worldwide in the 1970's and making the application of the assessment a mandatory requirement for major defence acquisitions through 'Directive 5000.1: Acquisition of Major Defense Systems' [12].

Since then, LCC has become a fundamental tool in space system design. NASA has developed a number of cost estimating models based on parametric, analogous and grassroots methodologies [54]. However, the majority of these models use a parametric methodology to estimate design, development, testing and evaluation (DDT&E) costs of space hardware in early mission design phases, despite the LCC of a space mission being the sum of the costs for DDT&E, together with launch & emplacement and operations [55]. As such, NASA reports that none of these models alone are capable of sufficiently estimating the entire life cycle cost of a space mission [54]. For this reason, several different cost models and techniques often need to be used in conjunction for this purpose. In comparison to NASA, ESA applies a mixture of in-house build cost estimation relationship (CER) tools based on excel and commercially available cost estimation tools [56]. Since ESA has much less data on large manned space systems than NASA, they mainly use tools based on unmanned spacecraft data, adding cost multiplication factors to take into account the higher equipment and testing standards for human space flight. The benefit of the data used by ESA is that it is contemporary, incorporating the actual, current state of the technology and the market [56].

Combining environmental, social and economic principles into one overarching sustainability assessment is only just beginning to be considered within the space sector, albeit not from a life cycle perspective. Currently, the only form of assessment which provides information relating to impacts from each of the three sustainability dimensions within the space sector is corporate social responsibility (CSR) reports. ESA published their first CSR report in 2008 and have continued to publish bi-annually since [57]. According to the Global Reporting Initiative (GRI), a CSR report is "a report published by a company or organization about the economic, environmental and social impacts caused by its everyday activities" [58]. They are typically used to improve the transparency of organisational activities by enabling entities to externally communicate the impacts of their activities to their stakeholders and outline their sustainable development policies and practices. However, as CSR reports are designed to provide a high-level overview of sustainability within organisations, this means they are effectively incapable of providing detailed information relating to the intricate details involved at product-level. Additionally, it is important to note that unlike CSR reports or SEIAs, LCSA is mostly concerned with burdens of activities rather than their benefits. This is because CSR reports and SEIAs are typically used for communication, information or reporting purposes whilst LCSA is an analytical tool generally used to aid decision-making.

More recently, the World Economic Forum (WEF) Global Future Council on Space Technologies established a consortium of companies, universities and agencies to work on a new project which will develop a system to rate the sustainability of space systems and help drive the goals outlined in the 2030 Agenda. This work was proposed in May 2019 as part of the Council's objective to "explore critical challenges for the sector such as the need for new governance frameworks and new forms of public-private collaboration, as well as a greater understanding of the sector's socio-economic impact" [59]. Through a series of workshops, the consortium will make use of publicly available data to develop a metric system which will define how well an individual satellite or satellite constellation follows the UNOOSA sustainability guidelines to ensure the long-term sustainability of outer space activities. It is envisioned that this space sustainability rating will be similar to the Leadership in Energy and Environmental Design system that rates the energy efficiency of buildings. In this sense, it has been suggested that space missions that achieve a 'good' score on this rating system could benefit from a reduction of insurance premiums. However, it is still undetermined what this rating or scoring system will look like (e.g. a numeric score, stars or colours). Additionally, this work will not be finalised until mid-2021 at the earliest and it is uncertain at this point what stakeholder groups will be addressed, whether it will adopt a life cycle approach or if environmental criteria will be considered at all [60].

1.3 Contribution Statement

With the publication of the '2030 Agenda for Sustainable Development' [4] and the 'Guidelines for the long-term sustainability of outer space activities' [8], the identification and reduction of sustainability impacts are becoming an ever more prevalent and important issue for the space sector to address. Since up to 80% of sustainability impacts are set by early design choices [21, 22], it is important to measure and mitigate adverse sustainability impacts as early into the design process as possible in order to create space systems which can justify and evidence their sustainability.

Despite this, to date, no effort has been made to develop an assessment type which allows adverse impacts deriving from the traditional three pillar view of sustainability to be scientifically quantified and mitigated within space mission design. Additionally, the ESA E-LCA database and Space Opera ecodesign tool has not yet been released to external stakeholders [33], which severely restricts the ability of the space sector to scientifically account for life cycle impacts during early design phases.

In response to this problem, this study will investigate the strengths and weaknesses of the space-specific E-LCA framework developed by ESA and suggest methods to transition this methodology towards LCSA based on established life cycle techniques and adopted practice within the space industry. A life cycle thinking approach (LCT) will be applied in accordance with this new methodology to generate a new space-specific LCSA database which also functions as a sustainable design tool. This new tool will then be tested within concurrent engineering sessions to demonstrate the applicability of this new methodology within the space sector and its contribution towards achieving sustainable development.

As such, the expected outcome of this study is the proposal of a space-specific LCSA framework and the development of the first ever life cycle sustainability database for space-based applications. The LCSA framework will be created to direct the future implementation of LCSA within the space sector using best practice. Based on the LCSA framework, the new database aspires to support the implementation of sustainability assessment within the concurrent design process to identify and lower adverse sustainability impacts of space missions. These proposed contributions help to form the core aim and objectives outlined in Section 1.4 below.

1.4 Aim & Objectives

The aim of this study is to successfully transition the E-LCA methodology for space systems towards a more holistic approach of sustainability assessment which aligns with the global aspirations envisaged within the 2030 Agenda for Sustainable Development. Specifically, in order to achieve this, a new space-specific LCSA framework and life cycle database was created at the University of Strathclyde which can assist industry in the design of next generation sustainable space systems during concurrent engineering activities. This raises the following core project objectives which are addressed throughout this thesis in order to achieve the above aim:

1. Identify and critically review current practice relating to E-LCA within the space sector and sustainability assessment more widely, including gaps in knowledge, in order to develop a space-specific LCSA framework and methodology.

2. Create a fully functioning and robust life cycle database for space systems which facilitates a transition from the traditional form of environmental assessment to a more encompassing and fully integrated sustainability assessment with respect to the 2030 Agenda for Sustainable Development.

3. Investigate and apply methods which enables the new life cycle database to be used within the concurrent design process of space missions.

4. Demonstrate the appropriateness of the developed LCSA framework and methodology by applying the new life cycle database within the concurrent design process of space missions using practical case studies as test cases.

1.5 Thesis Outline

Chapter 1 begins by introducing key background information on E-LCA and LCSA including their importance to the space sector before providing historical context based on the status of their current application. It goes on to outline the proposed contribution this work will have on the space industry which has helped to inform the aim and objectives.

Chapter 2 explores and critically reviews the current methods developed by the industry for conducting E-LCA and ecodesign of space systems. It also examines the strengths and weaknesses of the only space-specific ecodesign tool in existence (Space Opera) based on its integration within a concurrent design study.

Chapter 3 proposes the development of a new space-specific LCSA framework based on the findings of the previous chapter and from a review of current methodologies for applying social and economic criteria within space missions and LCSA generally. Building on the findings from this process, the LCSA framework suggests methods of best practice relating to the aggregation of E-LCA, S-LCA and LCC methodologies within one single space-specific assessment.

Chapter 4 describes the process for creating the first ever space-specific LCSA database, developed in line with the new LCSA framework concept in the previous chapter. It uses several case studies to provide examples for the implementation of the various life cycle stages outlined within the framework.

Chapter 5 identifies and discusses methods applied to integrate the new LCSA database into the concurrent design process to facilitate sustainable design. Comparability and functionality analyses are also conducted using the Space Opera ecodesign tool as a baseline for final data quality and validation checks.

Chapter 6 demonstrates the use of the new space-specific LCSA framework and database to facilitate sustainable design through two case studies of actual space missions designed using the concurrent engineering approach. The outcome of this process provides proof of concept for the feasibility and usefulness of each of these outputs for application within the space sector.

Chapter 7 provides an estimation of the annual environmental, social and economic impact of the space sector based on the analyses run using the new space-specific LCSA database. Additionally, the overall contribution to the field produced by this project is evaluated whilst planned future work is also outlined.

Chapter 8 draws conclusions from the findings presented within this thesis and provides a list of study limitations. The conclusions and limitations are then used in conjunction with one another to frame a set of recommendations for advancing the future development of LCSA within the space sector beyond the near-term work proposed in the previous chapter.

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Chapter 2

Life Cycle Assessment of Space Systems

2.1 Chapter Overview

The recent adoption of E-LCA 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 measure and mitigate the overall environmental impacts of space programmes and activities. However, with a renewed focus on sustainability issues, the space sector may need to advance towards a more encompassing form of sustainability assessment which focuses on more than just environmental implications.

In pursuing this methodology, it becomes important to examine how E-LCA is currently applied within the space sector. For this reason, a literature review will be conducted to outline prior work relating to E-LCA of space systems before going on to critically review current methods which have been developed for its application. It will also practically test the space-specific ecodesign tool developed by ESA to integrate E-LCA into concurrent design studies in order to examine its strengths and weaknesses. It is hypothesised that this information will provide a sound synopsis of the state of E-LCA application within the industry which can then be used as a basis for integrating social and economic considerations into the methodology.

2.2 The Environment & the Space Sector

Earth is currently the only known planet which is capable of supporting complex life forms. This means that protecting our planetary ecosystem is critically important for ensuring the long-term survival of mankind. However, anthropogenic activities pose a significant threat to Earth's environment. According to current predictions, if urgent action is not taken within the next ten years, we risk causing massive irreversible changes to the planet's ecological balance which could lead to the sixth mass extinction event in Earth's history [61].

In an attempt to control these impacts, a wide range of high-level environmental agreements have been proposed in recent years such as the Paris Agreement [3] and Montreal Protocol on Substances that Deplete the Ozone Layer [62], both of which have become legally binding for countries that have formally ratified them. However, since the impact of the space sector has typically been omitted from such legislative and regulatory requirements, it is important to determine how the industry currently contributes to environmental sustainability and how E-LCA can fit into this framework of sustainable development.

2.2.1 Contribution of Space towards Environmental Protection

In 2018, the United Nations COPUOS produced the first ever sustainability guidelines for the space sector called the 'Guidelines for the long-term sustainability of outer space activities' (A/AC.105/2018/CRP.20) [8]. These guidelines describe space sustainability as "the ability to maintain the conduct of space activities indefinitely into the future in a manner that realizes the objectives of equitable access to the benefits of the exploration and use of outer space for peaceful purposes, in order to meet the needs of the present generations while preserving the outer space environment for future generations". The wording of this definition provides a very broad scope relating to the terms of reference, which leaves it open to interpretation. For this reason, in order to provide more context, the current contribution of the space sector towards environmental sustainability will be explored further.

Over the past few decades, space technologies and applications have played a significant role in reducing environmental impacts, promoting social well-being and fostering economic growth on Earth. From an environmental perspective, this is typically achieved through Earth observation missions, where data is collected and transmitted from spacecraft so that sustainability issues can be addressed terrestrially on Earth [63] [64]. Therefore, the development of new space missions can have a direct contribution to the success of different environmental agreements by providing a range of services such as the provision of additional knowledge, science-based analyses, environmental monitoring or early warnings. As a result, such missions can also be aligned with the goals contained in the 2030 Agenda which is typically the approach used by the space sector for declaring their contribution towards sustainable development [65]. However, in addition to these passive approaches, addressing environmental issues from space has also received considerable attention from a practical viewpoint in recent years. For example, several studies have been conducted on the applicability of space sunshades as a geoengineering option and space-based solar power (SBSP) as a form of alternative clean energy [66–68]. Both of these technologies are intended to act as a potential solution to climate change.

Besides Earth-based environmental impacts, space can also be seen as a natural resource itself. One of the biggest issues which threatens the long-term survivability of the space sector is space debris. Space debris is the accumulation of man-made objects in-orbit around Earth from over 60 years of space exploration [69]. It is a serious and dangerous problem as the growth of debris could render space inaccessible for the foreseeable future. Unless it is urgently addressed, this has the potential to effectively end industry operations [70]. The reason for this is described through the Kessler syndrome which is a mathematical singularity where the population of orbital space debris is high enough (even without any more launches) that collisions between objects could cause a cascading effect, generating more debris and significantly increasing the likelihood of further collisions [71]. Besides the growing awareness within the industry concerning the need to preserve this precious resource, there has also been several proposals put forward over the few last decades for exploiting and exploring outer space. Many of these involve a variety of activities with overlapping environmental themes such as terraforming [72], celestial mining [73, 74] and the continued search for Earth-like planets [75]. Some of the main reasons for these proposals are to increase our understanding of the universe, reduce demand on Earth's resources due to overpopulation and to ensure our species long-term survival by spreading out into the universe to become an interplanetary species.

Whilst the importance of the previously mentioned topics should not be understated, limiting the scope of space sustainability to refer exclusively to them is quite restrictive and absolves the space sector from responsibility for the direct impact of their operations. In this regard, it is equally important that space exploration does not neglect our current planetary home. Nevertheless, viewing space activities as a possible source of pollution to Earth is a topic which has seldomly been addressed [14]. Therefore, E-LCA is supremely applicable within this context in order to allow the space sector to start taking responsibility and cognisance of the environmental impacts of their activities.

Based on this, it is can be inferred that the role of the space industry towards environmental sustainability encompasses a wide range of sustainability issues, including;

1. Using space as a platform to directly or indirectly address global problems.
2. Viewing space as a natural resource for preservation, exploitation & exploration.
3. Addressing impacts of space activities to the terrestrial & space environment.

The latter point refers directly to the use of E-LCA to address the environmental impacts of space activities to Earth. In this regard, the COPUOS guidelines specifically suggest the use of E-LCA within Guideline 27.3 by stating that space actors "should promote the development of technologies that minimize the environmental impact of manufacturing and launching space assets" [8]. This means that identifying key environmental impacts in relation to the life cycle of a typical space mission is imperative. In this regard, a literature review will be conducted in Subsections 2.2.2 and 2.2.3 below in order to highlight relevant studies in this area.

2.2.2 Environmental Life Cycle Impacts of Space Missions

The primitive nature of life cycle impact modelling within the space sector means that its application within the industry is still in its infancy. As such, literature on the topic is sparse. In an analysis, Maury [76] found a total of 52 published documents covering E-LCA of space systems to 2019. However, 14 of these were immediately discounted due to their limited scope or because they did not address the environmental dimension at all. This latter point is particularly relevant in the case of many NASA studies which do not match the standardised E-LCA methodology outlined in ISO 14040:2006 and 14044:2006. ESA were associated with 74% of the remaining 38 documents, which as a whole were made up by 84% conference proceedings, 8% peer-reviewed journal papers and 8% technical reports or dissertations. Additionally, 27 of these documents can be classed as E-LCA studies whilst the remaining 11 are related to framework and good practices. However, it was found that the vast majority of these documents present limited information in order to maintain confidentiality. In this regard, they consistently cite the lack of maturity relating to E-LCA within the space sector in comparison to other industries as a major limitation.

As such, the 27 documents classed as E-LCA studies can be used to identify key environmental life cycle impact areas in a typical space mission. In order to do this, adopting a life cycle perspective is critical if the total environmental impacts of a space mission are to be properly considered. In this regard, an LCT approach can be applied. LCT is a term which conceptualises the process of considering and capturing a wide range of environmental, social and economic impacts of a product over its entire life cycle [77]. It is a philosophy which enables the user to consider cradle-to-grave implications of different activities without the need for the scientific method of E-LCA [78]. This qualitative approach can assist in the identification of potential areas of impact as a pre-scoping exercise before a full E-LCA is conducted. According to Pettersen et al. [79], the environmental impacts are typically dispersed across a wide variety of activities and processes which highlights the complexities involved with applying E-LCA to space systems. As such, the life cycle of a space mission can be broken down into mission phases [80]. These are outlined below.

- **Phase 0:** Mission analysis and identification
- **Phase A:** Feasibility
- **Phase B:** Preliminary definition
- **Phase C:** Detailed definition
- **Phase D:** Qualification and production
- **Phase E1:** Launch and commissioning
- **Phase E2:** Utilisation
- **Phase F:** Disposal

Each of these mission phases have been split into five different categories which and are representative of the traditional cradle-to-grave life cycle phases. This is outlined in Figure 2.1 below. In this regard, 'Design Activities' reflects Phase 0, A, B & C, 'Manufacturing & Assembly' reflects Phase C & D, 'Launch Campaign' reflects Phase E1, 'Use Phase' reflects Phase E2 and 'End of Life' reflects Phase F. Evidently, each category encapsulates a range of different activities which will all have some form of inherent environmental impact. This will be discussed below in order to outline typical environmental life cycle impact areas of space missions uncovered from literature.

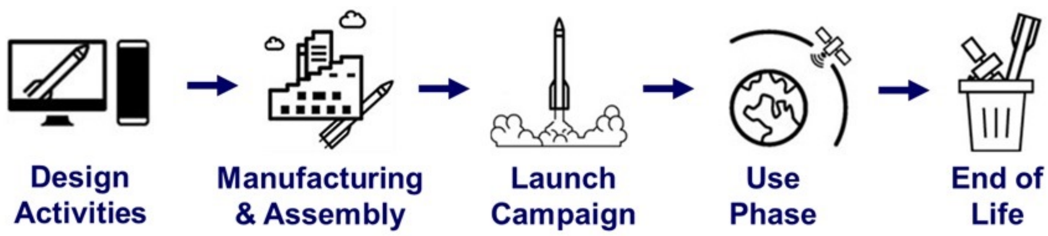


Figure 2.1: Applying Life Cycle Thinking to Space Missions (adapted from [81])

Design activities refer to office work which also includes concurrent design sessions in order create a spacecraft 'blueprint'. This involves many hours of office work which generates environmental impacts from electricity consumption, natural gas consumption, water consumption, and waste production. It also involves plane travel in order to transport engineers to and from design facilities so that they can assist with mission design efforts. Office work generally provides the greatest environmental impact during mission phases 0, A, B & C due to the exceptionally high number of work hours required to reach a final mission design (>50% for most impact categories) [82, 83].

Most studies relating to the manufacturing & assembly have been conducted within the frame of ESA contracts. According to Boonen et al., the manufacturing and assembly of space components differ from standard applications since they are not mass produced and need to go through highly specialised, advanced and energy intensive processes [84]. This also includes lengthy testing and qualification procedures to ensure compliance with space industry standards. This is because such components require particular properties which allow them to operate in extreme conditions and environments. In particular, most space-specific E-LCA studies focus on environmental impacts deriving from the manufacturing, production, assembly and testing of several materials. Examples of such studies include the use of composites, thermal protection and metal used in the production of a solid rocket motor case [85], germanium in photovoltaic systems [86, 87], steel passivation (surface treatment) processes [88], polymer composites for electromagnetic interference shielding [89], metal additive manufacturing [90] and carbon fibre reinforced polymers for structural elements [91, 92]. Additionally, the manufacturing and production of space propellants is also addressed in two studies by Pettersen et al. who provide around thirty datasets relating to current and potentially future chemical production as part of an ESA funded study [93, 94]. These datasets allow for comparisons to be made in order to identify more environmental friendly alternatives to replace commonly used and more environmentally impacting space propellants. As part of this study, three propulsion systems were compared: hydrazine, mixed oxides of nitrogen (MON)/monomethyl hydrazine (MMH), and chemical-electric propulsion hydrazine/xenon. Surprisingly, it was found that the chemical-electric propulsion system with xenon/hydrazine produced the highest environmental impact for almost all impact categories in comparison with the two other systems. This was primarily due to the electricity consumption required for the production of xenon which uses 1,400 kWh per kg when extracted in the cryogenic air separation process.

With regard to the launch campaign, in 2012 ESA conducted a study which focused on the European family of launchers (Ariane 5, Vega, Soyuz) [28]. The study assessed environmental impacts deriving from research & development, production & manufacturing of launcher stages (including AIT), production & manufacturing of propellants, the launch campaign deriving from operations at the launch site and the launch event. Results from this study are classed as highly confidential and have not been released publicly. However, Chanoine et al. provides relative results from these assessments, showing that around 50-70% of the carbon footprint of an entire space mission is due to electricity and heat consumption during the propellant production, stage production and launch integration [27]. Additionally, the launch event contributes almost 100% of the ozone depletion footprint. Gallice et al. also identified that the 'production & assembly' and 'propellant manufacturing' stages were the largest contributors across environmental impact categories for both the Ariane 5 and future Ariane 6 launchers [35]. These results come as no surprise given that a spacecraft will typically represent <1% of the complete mass of a space mission when considered with the launcher. This highlights that the launch segment is a major hotspot for a space mission. Additionally, Neumann sought to compare the same criteria for expendable and reusable launchers in the USA [36]. However, this study emphasised the difficulty in collecting reliable space-specific data for use within E-LCA. Durrieu & Nelson also indicate that besides the impact of the propellant system functioning, the immediate return-to-Earth of launcher stages after fuel exhaustion is another potential source of pollution since these are not systematically salvaged and seldom reused [14].

For the utilisation phase, ESA recently funded an ongoing study which aims to determine the environmental impacts of terrestrial-based activities [95]. This refers to the environmental impacts which occur due to the use of control centres, data processing centres, ground stations and facilities whilst the spacecraft is operational in order to fulfil the mission requirements. The study investigates the entire operational phase including transportation as well as infrastructure and building construction. Utility management and infrastructures was also addressed by Castiglioni et al. who discussed energy solutions, water and waste management at the European Astronaut Centre [96]. This study highlighted the large carbon footprint that can occur from the refrigerant gas leakage in specialised facilities, particularly due to air conditioning. Sydnor et al. also included the construction and demolition of NASA's high-energy ground test facilities within the scope of their study, highlighting that the majority of environmental impacts (around 50% of the carbon footprint) stems from electricity and natural gas consumption [97]. For this reason, the use of renewable energy options coupled with optimised facility management was proposed as an improvement measure in the frame of the 'GreenSat' project [83, 98]. Another impact area which may occur during this phase is the potential for debris strikes which pose a significant threat to space missions. However, the issue of space debris has been excluded from the scope of ESA E-LCA studies since their focus has been exclusively on the Earth ecosphere [30]. ESA generally considered this problem to be addressed by the 'ESSB-HB-U-002 - ESA Space Debris Mitigation Compliance Verification Guidelines' [30, 99]. To account for this, Maury mapped the flux of space debris to orbital resource use in low Earth orbit (LEO) for altitudes between 200 km and 2,000 km with inclinations of 0-180° [81]. This can be used to determine the average flux of space debris which crosses the target's path by multiplying the cross-sectional area of the spacecraft by the total number of orbits per dwelling time at the appropriate altitude and inclination.

It was found that end of life impacts is an area which has commonly been overlooked within these space-specific E-LCA studies. Spacecraft in geocentric orbit are typically re-entered into Earth's atmosphere or placed into a graveyard orbit which is 'out the way' [68]. The latter of these options is beneficial for fuel efficiency, but may eventually add to the problem of space debris due to orbital drag. In terms of re-entry, two instances will occur during a typical space mission. The first is the immediate return to Earth of the launcher stages and components after use during the launch event and the second is the eventual re-entry of the spacecraft after its on-orbit lifetime has ended [14]. In the first instance, the Solid Rocket Boosters, payload fairing and initial first stages of launchers are generally jettisoned at very low orbital speeds meaning that extreme heating does not take place [100]. Typically, these charred components will end up at the bottom of the ocean. The second instance is the re-entry of the spacecraft which undergoes intense pyrolysis. In just 20 seconds a space system would heat, melt and then vaporise before dispersing as dust [101]. This release is commonly referred to as re-entry smoke particles (RSPs). Currently RSP generation is not yet widely appreciated and the impact is currently considered insignificant. However with the prospect of future mega-constellations being proposed, it is becoming an area that requires much further study, as such constellations may produce a constant 'rain' of objects which may lead to RSP generation becoming a more significant concern due to its greater impact on climate or ozone [100]. Larson et al. found that NO_x emissions was one of the primary ozone depleting emission products of RSPs. When looking at the re-entry of 105 launch vehicles per year, they noted that NO_x emissions produced during re-entry heating exceeds meteoritic production by more than an order of magnitude and results in the loss of 0.5% of the globally averaged ozone column, with column losses in the polar regions exceeding 2% [102]. Other than this study, there has been very few attempts made to characterise the amount or composition of RSPs since the fraction of re-entering mass that forms RSPs is highly variable from object-to-object and depends on various factors such as materials, mass and entry velocity. However, further studies into re-entry impacts are under way [103, 104].

2.2.3 Building a Framework

In order to coordinate these efforts and assist the European space industry to apply E-LCA, ESA have developed a new framework for space systems. The framework was developed based on knowledge acquired from various studies they have conducted and after consultation with various stakeholders. This is the first and only framework for space-specific E-LCA in existence, and consists of three components:

Figure 2.2: The Space E-LCA Framework developed by ESA [34]

The ESA E-LCA handbook (hereafter referred to as the ESA E-LCA guidelines) was developed to provide common methodological rules to be followed when performing space-specific E-LCAs. As such, its purpose is to assist E-LCA practitioners with the application of E-LCA within the space sector [30]. These guidelines are complimented by the ESA E-LCA database which is a new, dedicated database developed by ESA containing specific datasets for performing E-LCAs of space missions. The use of these datasets enables space-specific E-LCAs to be applied properly for the first time by accurately measuring the environmental impacts of space systems [84]. Space Opera is ESA's new ecodesign tool which integrates this processes into mission design scenarios of future space missions. The purpose of the tool is to assist decision-makers assess, compare and lower the environmental impacts of preliminary design choices made during the mission design process [32]. Each component of the framework is discussed in more detail within Sections 2.3 to 2.5 below.

As such, of the eleven documents identified by Maury [76] which relate to framework and good practices, six are directly attributable to the development of this framework by ESA [26, 31, 32, 105–107]. The remaining five consisted of one position paper [14], two conference papers which investigated the inclusion of technology readiness levels (TRL) within E-LCA [108, 109] and two other conference papers relating to advancing the current E-LCA methodology towards LCSA which were produced by the current author [110,111]. In addition to these documents, an additional study which considered environmental performance as a decision parameter in the concurrent design process of satellites was also uncovered [112].

Moreover, it is also important to note that this framework has been developed to consider Earth-bound and geocentric orbital impacts only. Despite this, in order to expand the methodology of space-based E-LCA in the future, Ko et al. suggests a further three development phases in accordance with the predicted growth of space exploration and travel [113]. These phases are summarised in Table 2.1. However, these phases will not be discussed within this thesis as their application is considered to be outside the scope of the current study.

Table 2.1: Four development phases of E-LCA application in space [113]

SPACE E-LCA DEVELOPMENT PHASE	ACTIVITY	GOAL	SYSTEM BOUNDARY	IMPACT CATEGORY
Earth-bound *(now)*	Satellites in orbit around Earth	Preservation of human life on Earth	Earth & the Exosphere	Current LCA impact categories & space debris
Solar System-bound *(50-100 years)*	Missions in the Solar System	Search for extra-terrestrial life & resource mining	Earth & other space objects	Extra-terrestrial life toxicity & space biodiversity
Transition phase *(100-1,000 years)*	Missions in other solar systems & terraforming	Colonisation of other planets & space objects	Earth & other planets	Terraforming indicators
Intergalactic *(1,000+ years)*	Interplanetary trade	Preservation of human life in the Universe	Planet X, Planet Y	Regionalised (current) impact categories

2.3 Guidelines for E-LCA of Space Systems

The ESA E-LCA guidelines provide the primary guiding principles which should be applied when conducting a space-specific E-LCA at either system level and/or equipment/component/material level. These guidelines are based on the ISO 14040:2006 and 14044:2006 environmental management standards on E-LCA which provide a globally accepted framework to which all E-LCA studies should adhere to [5,6]. This framework consists of four stages which can be visualised in Figure 2.3 below. The ESA E-LCA guidelines tailor the methodological rules contained within the ISO framework to be more appropriate to the space sector without risking non-compliance [30]. As such, they should be seen as an extension of the ISO framework rather than an alternative to it. The guidelines are also orientated as closely as possible with the Product Environmental Footprint Category Rules (PEFCRs) developed by the European Commission (EC). The PEFCRs were created in accordance with ISO 14040:2006 and 14044:2006 to provide specific guidance for calculating and reporting products' life cycle environmental impacts as part of the EC's work on harmonising E-LCA across European industries [114]. Although no PEFCRs currently exist for space systems, general compliance with the methodological approach contained within this framework allows the ESA E-LCA guidelines to align more closely with the strategic goals of the EC.

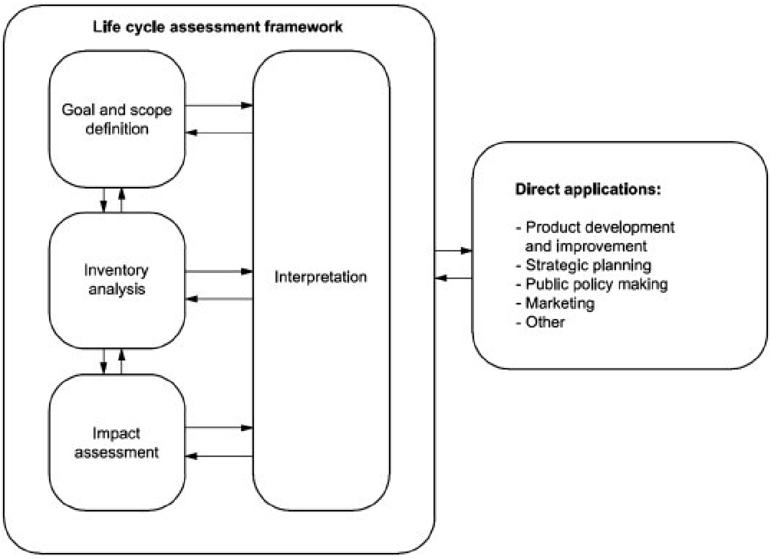


Figure 2.3: Environmental Life Cycle Assessment Framework [5, 6]

The following sections (2.3.1 to 2.3.4) provide an overview of the ISO 14040:2006 and 14044:2006 standards, including the ESA space system E-LCA guidelines and its key features as it relates to the E-LCA methodological framework outlined within Figure 2.3. Together, these principles provide common methodological rules which should be adhered to when conducting a space-specific E-LCA.

2.3.1 Goal & Scope Definition

The goal and scope definition is outlined at the beginning of the study before any data collection occurs. It sets the purpose of the assessment and establishes criteria relating to the product system under study to which all decisions within each stage of the LCA framework should relate [5, 6]. The two most important features within this stage are the functional unit (FU) and system boundaries of the study.

The FU is a quantified performance of a product system for use as a reference unit. As such, it defines what all inputs and outputs of the study should be related to [5, 6]. However due to varying requirements and specifications of different space missions, an applicable FU can be hard to define, particularly if results are to be used for comparison. As such, ESA suggest a common, simplified FU of 'one space mission in fulfilment of its requirements' which can be applied to multiple space systems [30].

The system boundary specifies which unit processes are included as part of the product system. Defining the system of study is particularly important for clarifying which unit processes are included as inputs and outputs within the study [5, 6]. Using an LCT approach similar to that displayed in Section 2.2.2, the lifetime cycle of a space mission can be viewed in terms of mission phases from Phase A to Phase F. Within each of these phases, the space mission can then be broken down into 4 segments; space segment, launch segment, ground segment and infrastructures. When combining each of these segments across each stage, a basic system boundary of a space mission is formed. This is outlined in Figure 2.4 below along with a detailed breakdown of the life cycle steps involved under each segment for each phase.

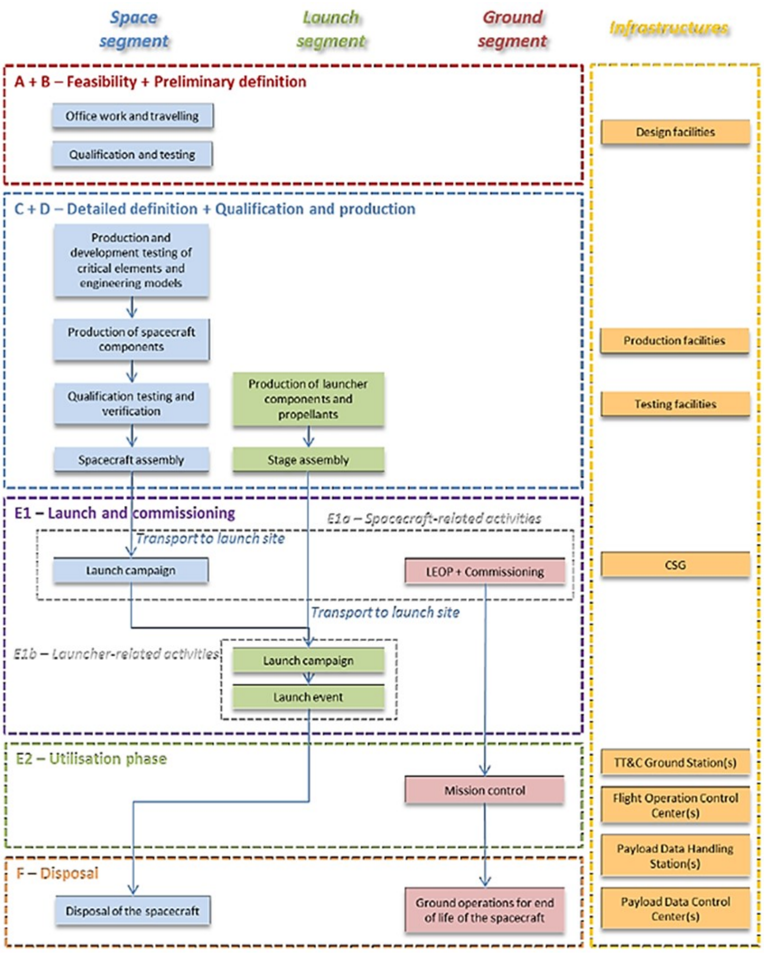


Figure 2.4: Space mission system boundary defined by the ESA E-LCA guidelines [30]

ESA recommends that this system boundary is followed as closely as possible when conducting an E-LCA of a space mission, although this may depend on the study requirements [30]. However, it is worth noting that the system boundary outlined within this figure should be tailored according to the goal and scope of the study. For example, a study on the Ariane 5 ECA launcher which had a FU of 'one launch of Ariane 5 ECA' included only the launch segment within the system boundary [27]. Therefore, this was considered to be more consistent with the objectives of the study.

2.3.2 Life Cycle Inventory Analysis

The life cycle inventory analysis (LCI) phase involves data collection and calculation procedures to quantify relevant inputs and outputs of the product system under study. This can often be an extremely time consuming and complex stage but importantly allows for the accounting of everything involved in the system of interest. According to ISO 14040:2006 and 14044:2006, the LCI stage involves three operational steps; data collection, data calculation and allocation [5, 6].

The data collection step involves gathering data for all unit processes which are defined within the system boundary [5, 6]. This data can be classified under the major headings outlined in Figure 2.5. The ESA E-LCA guidelines state that in reality this collected data will likely come from a mixture of both primary and secondary sources [30]. In this sense, primary data is information which has been obtained from direct sources such as on-site production and operating facilities whilst secondary data is information which has been obtained from indirect sources such as E-LCA databases or literature reviews.

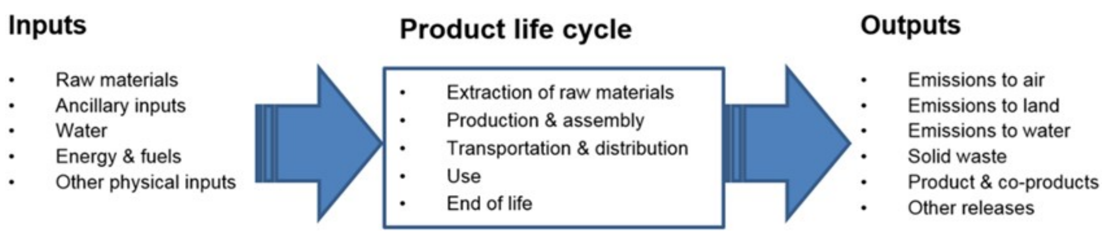


Figure 2.5: Major headings under which E-LCA data can be classified

The data calculation step generates the results of the LCI. As shown by ESA, collected data in this sense can also be used to generate new LCI datasets (in the form of unit processes) by scaling input and output flows to a quantitative reference which represents a singular unit of output [30]. This is discussed further in Section 2.4. The quantitative reference of all unit processes involved under the system of study should then be related to a reference flow meaning that all input and output data being referenced is relevant to the FU. In addition to the calculation procedure, a check on data validity should also be performed [5, 6].

The use of allocation is extremely significant in unit processes which involve co-products as it allows environmental burdens to be proportionally attributed to each product. Allocation is one of the most highly debated and controversial topics in E-LCA and for this reason it should be avoided wherever possible, but this is not always feasible. Where it cannot be avoided, system expansion should be applied, thus widening the system boundary to add additional functions so that allocation is no longer required [5, 6]. These techniques are discussed further in Subsection 2.4.1. However, it should be noted that in situations where system expansion is required, ESA propose the use of proxies instead since it was found that expanding the system can lead to an unbalanced assessment within space-specific E-LCA studies [30, 33].

2.3.3 Life Cycle Impact Assessment

The third stage is the life cycle impact assessment (LCIA) phase. Using the LCI results, this stage evaluates the significance of the potential environmental impacts of the product system under study [5, 6]. As such, this process involves associating inventory data with specific environmental impact categories and category indicators, thereby attempting to understand these impacts. The stage consists of three mandatory steps which are typically achieved through the application of robust LCIA methods. These classify and characterise unit flows for selected impact categories based on scientific methods [5, 6]. The recommended LCIA methods and their sources which are outlined by the ESA Space System E-LCA Guidelines are summarised in Table 2.2 below [30]. ESA based the selection of their adopted methods on recommendations provided by the International Reference Life Cycle Data System (ILCD) [33]. The ILCD was established in 2005 by the EC's Joint Research Centre (JRC) to harmonise European E-LCA methodology and provide a common basis for consistent, robust and quality assured life cycle data, methods and assessments [115].

Table 2.2: Summary of ESA's recommended environmental impact categories and their LCIA method (adapted from [30])

Impact Category	Unit	Source
Acidification	kg SO_2 eq.	CML 2002
Climate Change	kg CO_2 eq.	IPCC 2007
Eutrophication - Freshwater	kg P eq.	ReCiPe
Eutrophication - Marine	kg N eq.	ReCiPe
Ionising Radiation	kg U-235 eq.	ReCiPe
Ozone Depletion	kg CFC-11 eq.	WMO 1999
Photochemical Oxidation	kg NMVOC	ReCiPe
Resource Depletion - Fossil	MJ fossil	CML 2002
Resource Depletion - Mineral	kg Sb eq.	CML 2002
Toxicity - Freshwater Aquatic	PAF.m^3.day	USEtox
Toxicity - Human	cases	USEtox
Toxicity - Marine	kg 1,4 DB eq.	CML 2002
Water Consumption	m^3	ReCiPe
Al_2O_3 emissions	kg Al_2O_3	ESA 2016
Mass disposed in ocean	kg	ESA 2016
Mass disposed in space	kg	ESA 2016

The first mandatory step is the selection of impact categories, indicators and characterisation models which will be used within the study [5,6]. The selection of impact categories refers to what type of impact pathways will be assessed under the goal and scope of the study and on what geographical level. Environmental indicators are the result of the aggregation of converted LCI results into an environmental impact category. There are two levels which these can exist on; midpoint and endpoint. Midpoint indicators are a problem-oriented approach used to translate impacts into environmental themes such as climate change, ozone depletion, acidification, human toxicity, etc. Endpoints are a damage-oriented approach which translates environmental impacts into issues of concern such as human health, natural environment, and natural resources [116]. The midpoint method traditionally has been viewed as the scientifically correct way on which to generate E-LCA results in order to reduce subjective evaluation associated with endpoint indicators or single scores. As such, the LCIA methods recommended by the ESA Space System E-LCA Guidelines are based on this approach (see Table 2.2 above). Characterisation models provide factors for individual substances contained within each method so that their relative contribution to a given impact category can be quantified.

The second mandatory step in the LCIA stage is classification which is the assignment of LCI results to the relevant impact categories defined in the previous step [5,6]. This is done based on the effect that each substance has on the environment, determined at midpoint or endpoint level. An example of this process is provided in Figure 2.6.

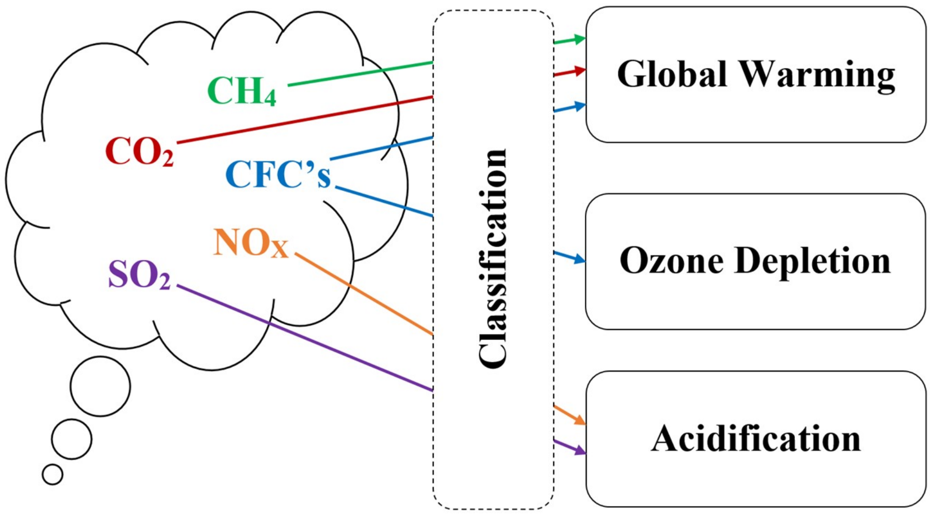


Figure 2.6: Classification of substances to impact categories in E-LCA

Thirdly is characterisation which involves calculating impact category results. This is achieved by converting LCI results into common units using characterisation factors (CFs) [5,6]. CFs are applied to each individual substance classified as part of a given impact category in order to determine their relative contribution to that impact category based on their fate, exposure and effect. The converted units are then aggregated within the same impact category to arrive at a numerical indicator result. Based on the IPAT equation, E-LCA impact category results achieved through characterisation are typically calculated by:

$$IR_c = \sum_s CF_{cs} \cdot m_s \tag{2.1}$$

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.

In addition to the three mandatory steps within the LCIA stage, there are also four optional steps which consist of normalisation, grouping, weighting and data quality analysis [5, 6]. Normalisation relates the LCIA results of each impact category to a certain reference value in order to make results more understandable. A commonly used method in this regard is to relate impacts to annual consumption rates (e.g. the amount of CO_2e released by a product system as a percentage of the amount released by an average European citizen in one year). Grouping is the sorting and ranking of impact categories to one or more groups/sets as predefined in the goal & scope. Weighting involves assigning a level of importance to impact categories which is typically used in conjunction with normalisation to generate a single score. Data quality analysis is performed in order to test the reliability of the LCIA results. However, normalisation, grouping and weighting are less scientific and can add high levels of subjectivity to the results. For this reason, careful consideration is required when applying these steps. ESA's approach with regard to these optional steps is discussed further in Section 2.5.

2.3.4 Interpretation

Lastly, the interpretation phase considers the findings from the LCI and LCIA together. It should deliver results that are consistent with the goal and scope whilst providing a set of conclusions, limitations and recommendations. Additionally this phase should also identify any significant issues from LCI and LCIA and provide completeness, sensitivity and consistency checks [5, 6]. According to the ESA Space System E-LCA Guidelines, this should also include the identification of environmental hotspots [30].

The guidelines also state that uncertainties of the LCIA should also be calculated using a Monte Carlo simulation (5000 iterations) and an assessment of data quality should be made.

Although they are not strictly 'elements' of the E-LCA Framework, reporting and critical review are still an integral component of E-LCA. Interpretation should be included within reporting which is a mandatory component of an LCA study according to ISO 14040:2006 and 14044:2006 [5,6]. This can be incorporated into mission design reports. In addition to this, a critical review is only required in the case of a comparison. This is not recommended between different space missions due to inherent variations in mission design and goals [30].

2.4 Applying E-LCA Databases to Space Systems

In order to perform an E-LCA of any product, the use of both foreground and background LCI data for the complete supply chain is vital [30]. Foreground LCI data consists of processes which the decision-maker has direct control over at source. This refers to specific data required to model the product system under study. Background LCI data consists of processes where the decision-maker has either an indirect influence or no control over. This refers to generic data such as the production of generic materials, energy, transportation and waste management. Due to the complexity and tedious nature of the LCI stage, collecting and organising data for the complete background system is practically impossible due to the amount of data required to perform the study [117]. For this reason, E-LCA databases are commonly used as a background inventories, providing a wide range of LCI datasets which allows decision-makers to concentrate purely on collecting data for their specific foreground system.

The use of background inventories are therefore vital in any E-LCA study. However, due to the novelty of E-LCA within the space sector, current databases are not tailored to cope with the specificities of this industry [30]. For this reason, it is important to understand how typical E-LCA databases work and the difficulties of applying them to space systems.

2.4.1 An Overview of Traditional Databases

Selecting an appropriate E-LCA database as a background inventory can be a difficult process. There are several considerations which need to be made before a decision is reached [118]. In particular, some of these considerations include determining the;

1. Relevancy of the database's LCI datasets to the product system.
2. Software required to host the database.
3. E-LCA method according to database type.
4. System model which the database adopts.

The first point refers to which database is most suitable to the product system under study and can therefore be applied as an appropriate background inventory. Several factors relating to the LCI datasets contained within the database need to be considered including the reliability, completeness, temporal correlation, geographical representativeness and technological correlation of data as it relates to the product system under study [118]. This also includes attention to the database methodology and the system model adopted. A plethora of commercial and non-commercial E-LCA databases exist in a variety of different formats. Ecoinvent is the largest and the most common background database used by the LCA community, hosting around 17,000 datasets in many areas such as energy supply, agriculture, transport, biofuels and biomaterials, bulk and speciality chemicals, construction materials, wood and waste treatment [117].

Additionally, the applied software must also be compatible with the selected background inventory [118]. Similar to E-LCA databases, a variety of commercial and non-commercial E-LCA platforms exist. Currently, openLCA is the only open-source and free software available for E-LCA. The software was created by GreenDelta and uses zipped openLCA (ZOLCA) files [119]. A variety of different E-LCA databases can be purchased and/or downloaded in this format, including the Ecoinvent database. File converters are typically used to convert databases into the required file format, but this can often be problematic due to various data migration issues such as source data complexity or data loss/corruption [120]. For this reason, it is generally considered that using a single file format is best which is why selecting appropriate host software is so important. Alternatively, if using a single file format is not possible, the amount of conversions should be limited as far as practically possible.

The method for performing an E-LCA is also extremely important. Currently two methods exist. The first is the application of process databases whilst the other applies environmentally extended input-output (EEIO) databases. Process E-LCA databases are the most commonly used and address environmental impacts associated with a product or system process. They rely on physical activity data to develop a product tree derived from assessing all the known energy and environmental inputs of a particular process and calculating the direct emissions associated with the outputs of the process [121]. Inputs (materials and energy resources) and the outputs (emissions and wastes to the environment) are typically itemised within datasets and scaled to a reference value (see Figure 2.5). This straightforward concept provides a high level of specificity and focus but the collection of data may be time, cost, and labour intensive. In comparison, EEIO E-LCA databases are not commonly applied and would only be used if environmental data is significantly lacking to a point whereby the missing piece of information cannot be scoped out of the study without severely impacting its result. The concept was theorised and developed by economist Wassily Leontief in the 1970s based on his earlier input-output work from the 1930s for which he received the Nobel Prize in Economics. It estimates the materials and energy resources required for, and the environmental emissions resulting from, activities in the economy [122]. To do this, EEIO databases use aggregate sector-level data to quantify the amount of environmental impact that can be directly attributed to each sector of the economy and how much each sector purchases from other sectors in producing its output [123]. This is not a wholly precise method of analysis but gives as accurate an estimation as possible without the use of specific product related data. However, broad sector averages are limited to specific geographical regions and may not represent nuances of unique processes and products, especially for nonhomogeneous sectors [124]. In particular, the linear attribution assumption between monetary and environmental flows provides only indicative results (i.e. EEIO models cannot distinguish between products of different monetary value within a single sector) [125]. Figure 2.7 below provides a comparison between these two methods by distinguishing the differences in information required for each during product design.

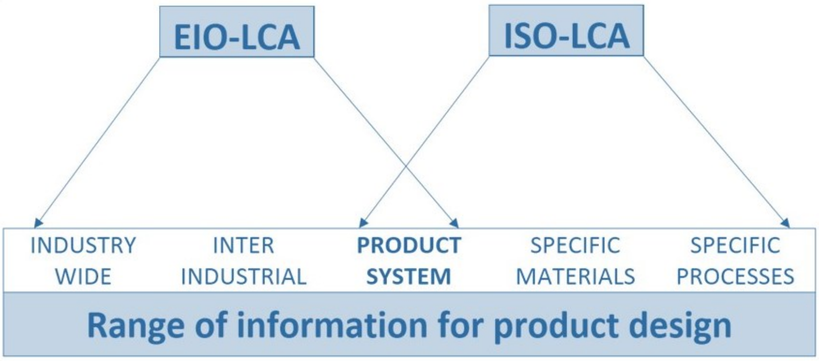


Figure 2.7: Information required for different E-LCA Databases

However, EEIO databases are often used in conjunction with process databases to create a hybrid E-LCA [122]. Hybrid E-LCA uses a combination of the previous two methods to form an integrated background inventory. Combining the two gives the best of both worlds: the accuracy and transparency of a process database and the completeness of an EEIO database [126]. Under the circumstances of incomplete environmental data, this can provide the most accurate estimation of the impacts caused by the product in question.

When selecting the system model to adopt, another key consideration is allocation procedures and system expansion [5, 6]. These are techniques used to partition the inputs and outputs between products and co-products. The reason for this is because many processes produce more than one product. Allocation is therefore a division of environmental impacts between the product and co-products according to a set of pre-defined criteria. In comparison, system expansion considers co-products as alternatives to other products on the global market. Allocation procedures and/or system expansion are typically applied using system models to describe how processes are used and link together. The two most common methods to achieve this is through consequential modelling and attributional modelling [127]. In E-LCA databases, consequential modelling avoids allocation by using system expansion to deal with co-products. It links all activities in a product system based on how activities are affected by a change in demand for the FU. This adds a future-orientated perspective to the study and identifies the environmental consequences of a decision or proposed change (including effects inside and outside) to the system under study [128]. However, consequential models are typically based on economic models which rarely provide any level of accuracy or precision. In comparison to this approach, although avoiding allocation by using system expansion to handle co-products is possible with attributional modelling, co-product allocation is commonly used [128]. The attributional modelling approach attributes inputs and outputs to the FU of a product system by linking and/or partitioning unit processes of the system according to a normative rule. Under the specified normative rule, the allocated share of activities that have contributed to the life cycle impact of the product is provided. Thus, the purpose of this technique is to trace a specific aspect of the product back to its contributing unit process. The normative rule applied can be based on physical or economic characteristics (i.e. mass, volume, energy content or price of products/co-products) and/or by using other techniques including allocation at point of substitution (APOS) or the cut-off approach. The APOS approach uses expansion of product systems to avoid allocating within treatment systems. To do this, by-products substitute reference products as inputs to activities without further treatment. As such, all activities that have a material for treatment as an input will be handled in the same way. Cut-off follows the same methodology as the APOS approach but does not take into account any environmental benefit related to the recycling of a material. As such, recyclable materials are available burden-free to recycling processes whilst secondary materials bear only the impacts of the recycling processes [129].

Additionally, each of these system models can be applied as either system processes or unit processes [5, 6]. Although the LCIA results will not significantly differ between the two methods, there are some important differences. System processes are fully aggregated datasets whereas unit processes are very small, specific datasets for which input and output data are quantified (see Figure 2.8 below). As such, unit processes will often require linking with many different upstream processes. This creates a large but transparent product tree with traceable contributions from these upstream processes. Unit processes will also typically contain uncertainty information which allows a statistical analysis (Monte Carlo simulations) to be run but calculation times can be considerable. In comparison, the simplified product tree produced by system processes allow calculations to be run very quickly. However, importantly, this method typically does not include uncertainty information [130].

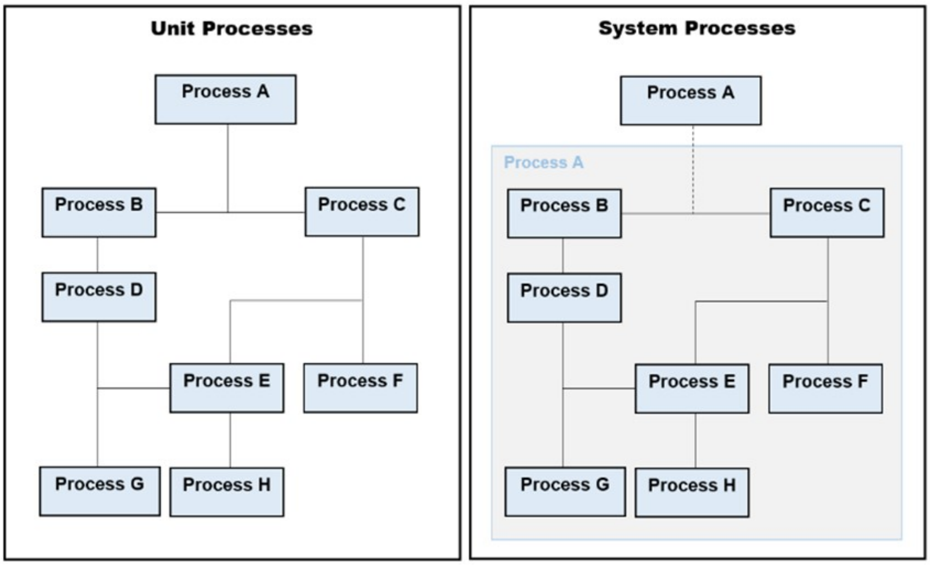


Figure 2.8: Unit versus System Processes in E-LCA

2.4.2 Applying Traditional Databases to Space Systems

Since space is a unique domain, applying E-LCA to the space sector is not a straightforward process. Traditional E-LCA databases currently do not have the capability to accurately model the life cycle of a space mission. This is because the space industry experiences low production rates, long development cycles, and uses specialised materials and industrial processes [30]. In comparison, traditional E-LCA databases typically consists of common, mass-produced products and processes. This is not particularly well-suited to the space industry which often uses specialised, custom-made components with a low product output. These components also have to satisfy stringent safety and quality requirements which means that they are subjected to significantly more research and testing than other projects.

Additionally, current conventional LCI process databases generally lack data pertaining to the extraction, production and manufacturing of a variety of metals and elements which are increasingly being applied in today's technologies [131]. This exclusion also covers several resources which are frequently used in the production of space systems (i.e. in the case of the Ecoinvent database [132]; beryllium which is required for mirrors, zirconium for ablative shielding, germanium for solar modules, etc.). This is highly problematic as potentially meaningful impacts could be overlooked if such inputs are omitted from an environmental analysis.

Similarly, the space sector also exhibits unique environmental impacts (e.g. direct emissions into the high atmosphere from the launch event and marine effects from the disposal of spent launcher stages to the ocean). These types of impacts are not captured by conventional E-LCA databases due to their exclusive sector specific nature meaning that E-LCA in its current form is not particularly suited to the space industry [30].

In this regard, a consortium established by the ESA Clean Space Initiative to investigate the applicability of space-specific E-LCA found that process databases considerably underestimated the impact of satellite missions [133]. Due to this (and the aforementioned issues), it is clear that current conventional process E-LCA databases cannot be used as a single data source within space-specific E-LCA. To overcome this, the consortium proposed a hybrid E-LCA approach [134]. However, it was found that using EEIO databases was a highly inaccurate method to account for these gaps as it significantly overestimates the total environmental impacts [30]. This is because the space industry does not fulfil the requirements of a completely free market due to state financing schemes and limited players. Additionally, monetary flows are different than in other sectors since space components generally have an extremely high cost per weight and a large proportion of the cost of custom-made materials goes into research and development activities as opposed to manufacturing (which is a common underlying assumption within traditional E-LCA databases). As such, ESA do not recommend applying EEIO databases to space-specific E-LCAs or using a hybrid approach since these only fill data gaps in inaccurate ways [30].

In addition to these findings, with regards to system expansion/allocation procedures, consequential modelling should not be applied since these are typically based on economic models which are not well suited to the space industry for reasons stated above. As such, it can be considered that the attributional modelling approach and the use of proxies (to avoid system expansion) are a better suit for space missions. Either system or unit processes can be used to represent this modelling approach depending on the desired application [30].

It is clear that in order to properly apply E-LCA, space projects require the use of dedicated process databases and methodological rules. Since no space-specific database or PEFCRs existed, ESA decided to create a new space-specific E-LCA framework in order for them to continue their work on E-LCA of space systems [34]. A key component of this framework was the development of a new process database which was considered vital in the application of space-specific E-LCA. This is discussed in more detail in the following subsection.

2.4.3 The First Space-Specific E-LCA Database

Due to the novelty of E-LCA within the space sector, coupled with the problems of applying traditional E-LCA databases to space systems, this presented a challenging and complex problem to overcome. To address this, the ESA Clean Space Initiative decided to create a new dedicated process E-LCA database for space systems to assist the European space sector to conduct space-specific E-LCA studies. As such, the database would provide a robust set of consolidated and centralised LCI datasets specific to space activities which can be used to conduct an E-LCA of space systems [34].

Creating space-specific LCI datasets was a lengthy process due to the complexity and uniquely differing requirements of space systems. As such, the task involved input from hundreds of experts from around the world [33]. Data collected from previous dedicated E-LCA studies conducted by ESA on the launch and space segment was used to initially create the ESA E-LCA database (see Subsection 2.2.2). This database was designed by the 'Eco-design Alliance for Advanced Technologies' and managed by the consultancy Asplan Viak with industrial support from ArianeGroup [76]. The generated environmental LCI datasets mainly related to material and manufacturing processes which were connected to Ecoinvent as a generic background database. These datasets were added because, in its current form, Ecoinvent did not have all the necessary processes required to account for space systems. By October 2015, 233 LCI datasets had been generated which were added to the E-LCA database [79]. In 2017, more LCI datasets were added relating to the manufacturing and production of propellants [94], with the database continuing to grow since.

The ESA E-LCA Database currently runs in SimaPro as a comma-separated values (CSV) file using Ecoinvent version 2.2 and 3.3 APOS as its background inventory. Ecoinvent version 2.2 is based on the unit system model and version 3.3 is based on the APOS system model. Appropriate proxies have also been included in order to avoid system expansion. The database has just undergone a harmonisation project to standardise all LCI datasets and update Ecoinvent to version 3.5 [135]. ESA have and will continue to expand this database over time to update the methodology and add more space systems as data become available. As can be seen in Figure 2.9 below, the database currently hosts over 1,000 unique space specific datasets.

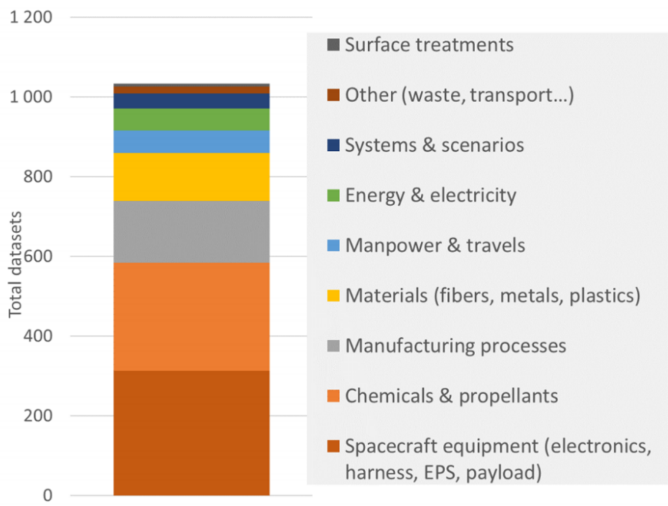


Figure 2.9: Datasets currently included within the ESA E-LCA Database [135]

The database and its compiled LCI datasets are to be made available for future use by European stakeholders. Despite this, although ESA plans to eventually release the database more widely in the near future, it is currently only available under contract with no near-term release foreseen [136].

2.5 Ecodesign of Space Systems

The purpose of applying E-LCA within the space sector is to scientifically quantify the environmental effects of space missions over their entire life cycle with a view of reducing their overall impact. However, in order for the technique to have any meaningful influence it must be able to be used as a decision-making tool. In this regard, integrating the approach into the space mission design process is an interesting option since the majority of a space mission's environmental impact is set by early design choices. Space missions are increasingly being designed using the concurrent engineering approach which is a systematic method of designing and developing products in a simultaneously manner to enable decision-making by consensus. Considering environmental impacts within this process is known as ecodesign, which developed independently of E-LCA (although E-LCA has now become an important element within ecodesign). Both techniques share a common goal which is to design products with consideration to the environment in order to minimise direct and indirect effects as far as conceivably possible. For this reason, if ecodesign is to be applied within the concurrent design process of space missions, then it is important to define how this can be achieved.

However, it should be noted that concurrent engineering is not a standardised practice within the space sector. Additionally, according to the ESA E-LCA guidelines [30], the application of E-LCA can be split into two levels of application which follow the space system breakdown defined by ECSS-S-ST-00-01C [137]. These two levels relate to system level design and equipment, component & material level design. Whilst several redesign activities are currently being pursed by ESA at equipment, component & material level, when applied through concurrent engineering, ecodesign is mostly applicable at system level [33]. Targeting specifically this level of application through concurrent design activities therefore places emphasis on system and mission level assessments.

For this reason, due to the aim and objectives outlined within Section 1.4, the focus of this thesis specifically relates to system and mission level assessments through the application of ecodesign using the concurrent engineering approach.

2.5.1 The Concurrent Engineering Approach

Dating back to the 1980s, concurrent engineering is a relatively new approach of product development where various design and manufacturing processes are run in a simultaneous manner in order to decrease product development time and the need for multiple design reworks [138, 139]. It is a system engineering technique for design which is often achieved by employing multidisciplinary groups to design products in a collaborative and timely manner, leading to improved productivity and reduced costs [140]. As such, a concurrent design session allows the complete sharing of product data through simultaneous interactions of different disciplines. This teamwork allows consensus decisions to occur through active participation of all players (including the customer). According to Biesbroek & Vennekens [141], to facilitate this approach to product design, five basic elements are required which include:

- A design facility.
- A multi-disciplinary team.
- A process.
- Domain-specific software/hardware.
- A design tool.

Evidently a facility is required to host concurrent design sessions. The room which this occurs in will normally host a number of computers which are required to facilitate the concurrent design session. This room is commonly referred to as a concurrent design facility (CDF). A multi-disciplinary team will then need to be assembled in order to facilitate the product design requirements during the concurrent design process itself. Each participant will be an expert in a particular area of design and collectively represent a variety of different design disciplines. The process usually occurs over a number of days, weeks or months (depending on the stage of product development) with breaks between sessions to allow for design consolidation. Domain specific software and hardware also needs to be installed for each team member in order for them to conduct calculations and analysis for their discipline during design sessions. Finally, a design tool is also required. This tool will essentially act as a central server and facilitate the complete sharing of information and data amongst participants as can be seen in Figure 2.10.

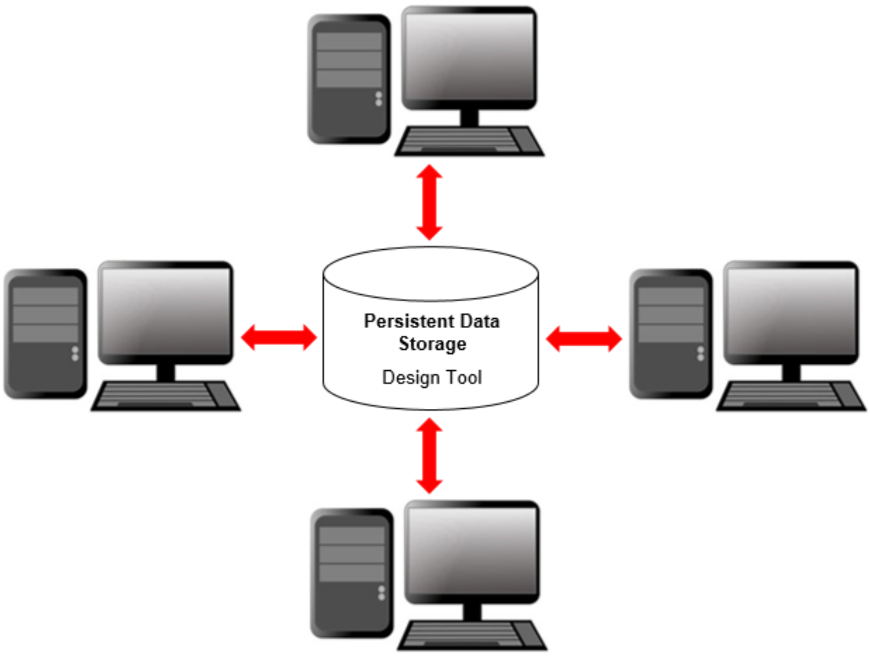


Figure 2.10: The Concurrent Design Process

In the last couple of decades this approach has begun to be adopted by the space sector during preliminary system designs of space missions [142]. As such, various space organisations have initiated work on the topic by developing their own mission design facilities and design tools. NASA/JPL established their own facility dedicated to conceptual mission design called the Project Design Center (PDC) in 1995. This was the first CDF in the aerospace industry and by 2015 had carried out well over 1,000 studies [143]. In 1997, NASA established a mission design facility at the Goddard Space Flight Centre called the Integrated Mission Design Centre (IMDC) which by 2003 had been used to perform more than 150 mission concept studies [144]. To assist with these CDF sessions, NASA created their own design tool called the Global Integrated Design Environment (GLIDE) which was used for these studies [145].

From a European perspective, several CDFs have been established in recent years. Of these, the largest and most used facility for future space missions and industrial reviews belongs to ESA and is located in Noordwijk, Netherlands within the European Space Research and Technology Centre (ESTEC). The ESA CDF was established in November 1998 with a total of 233 studies having been conducted to the end of 2018 (see Figure 2.11) [146,147]. Initially, ESA developed a design tool called the Integrated Design Model which was used as their main data sharing platform during concurrent engineering studies within their CDF [148]. However, although the tool was capable of delivering satisfactory outcomes for standard space missions, its flexibility for non-standard missions was severely lacking [149]. For this reason, ESA launched an initiative to create a new client/server software package which would allow collaborative multi-disciplinary work to be embedded from the embryonic stages of any given mission through concurrent design.

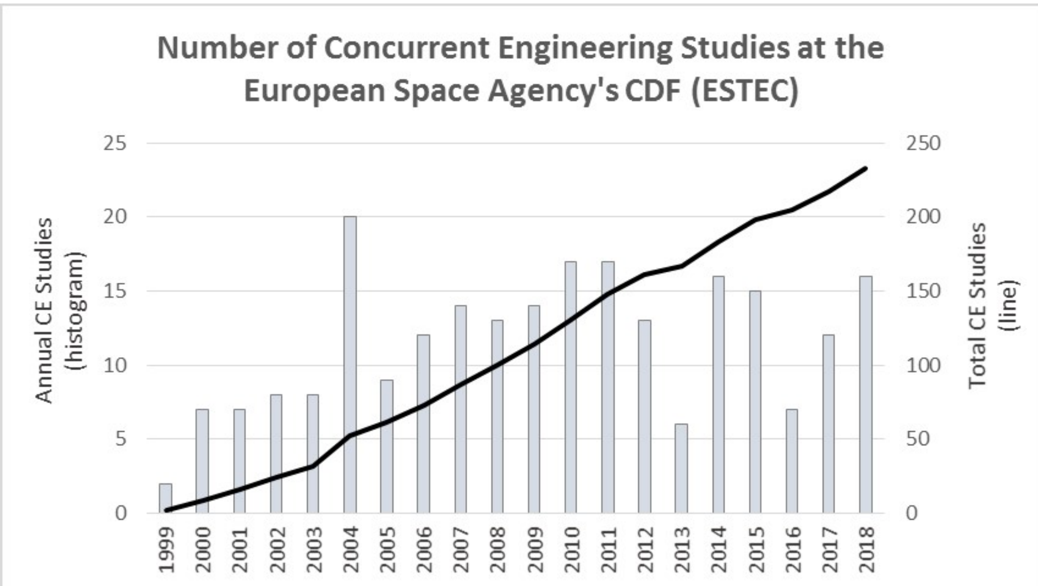


Figure 2.11: Number of Concurrent Engineering Studies at ESA's CDF (adapted from [147])

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) [150]. 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 [151]. The tool implements the semantic data model defined in ECSS-E-TM-10-25 Technical Memorandum, titled "System Engineering – Engineering Design Model Data Exchange (CDF)" [152], working as a Microsoft Excel plug-in for sharing mission design data and information. This process is indicated within Figure 2.12 below and 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 [153].

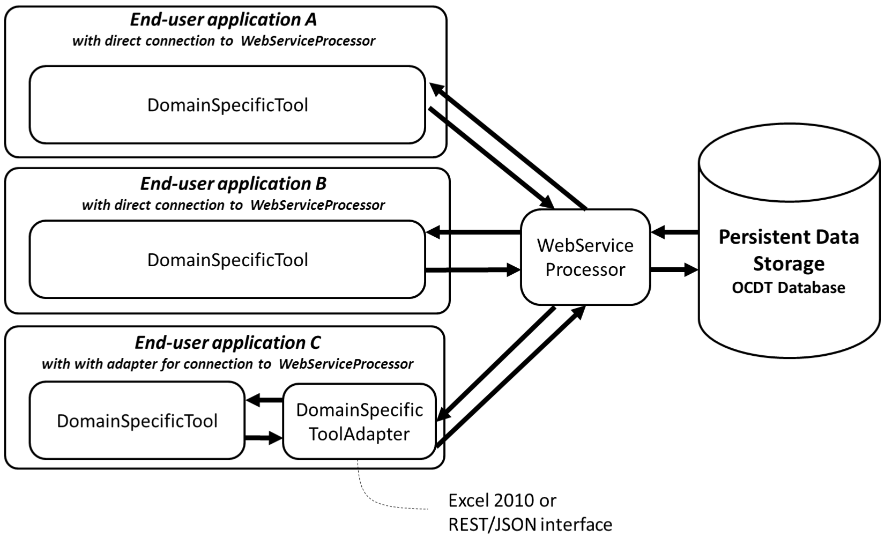


Figure 2.12: Connecting Domain Specific Tools to the OCDT [154]

2.5.2 The Ecodesign Approach

Environmental impacts of products and services have grown to become a key element of the decision-making processes across various industries. As such, it is important that these implications are considered during design and development before decisions are made. Within the space sector, this can be facilitated through the integration of E-LCA into the mission design process via an approach called ecodesign [155]. Ecodesign is an environmental management technique which aims to improve the environmental performance of products and services by assessing their environmental impact at the design stage, without reducing their quality or performance [156]. The technique is internationally standardised through ISO 14062:2002 [157] which is closely related to E-LCA but describes the concepts and current practices relating to the integration of environmental aspects into product design and development. The key difference is that E-LCA is an analytical tool whilst ecodesign is a procedural tool. Analytical tools are primarily defined by principles of quantitative modelling whilst procedural tools are defined by the structure of work and used for integrating environmental concerns into various activities [156]. This can be achieved through ecodesign which is defined as the integration of environmental aspects into product design and development, based on E-LCA principles.

Ecodesign is closely linked to Life Cycle Engineering (LCE) which is similar to the concept of LCT. LCE is an engineering technique used to assess the environmental, social, economic and technical impacts of products, processes and services over their entire life cycle [158–160]. Its goal is to find a balance between societal needs, economic growth and minimising environmental impacts in product engineering. This method is commonly used in areas where environmental concerns coincide with design and production engineering [161, 162]. Evidently, this makes this approach particularly well-suited to concurrent engineering sessions where ecodesign is deployed.

Figure 2.13: The Ecodesign Process of Products (adapted from [157])

Based on the ISO 14062:2002 standard [157], the ecodesign process can be visualised through the seven key steps outlined in Figure 2.13 above. This approach is based on three main ecodesign approaches; focussed, global and functional. Focussed ecodesign is a very specific analysis which is typically concerned with only one (or very few) life cycle stages and/or environmental criterion. Global ecodesign considers several life cycle stages and environmental criteria with work flow tending to focus on the technological concept and product use. Functional ecodesign also involves several life cycle stages and environmental criteria, but the innovation exceeds the product framework to also focus on the product's main function (i.e. the FU). In other words, the design team thinks in terms of service provided. The adopted approach will depend on the technical requirements of the product system under study [136].

In practice, ecodesign deliberations are typically handled by product developers or environmental specialists brought in to 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 E-LCA [156]. 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. It is also important to note that using the ecodesign approach does not always lead to product sustainability. Careful interpretation of results is necessary if they are to be used for any kind of communication purposes. Currently ecodesign tools within the space sector have been developed and are being experimented with for the purposes of LCE when analysing environmental and technical impacts of space systems during mission design sessions.

2.5.3 Applying Ecodesign to the Space Mission Design Process

In most applications, current methods to lower environmental impacts of products 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. This typically means that too many constraints are already in place to significantly alter the design and lower adverse impacts [163]. However, as one of the primary purposes of ecodesign is to inform decision-makers of life cycle environmental impacts of products during early design stages, the technique should be capable of functioning within a concurrent design session. This process is vital if environmental impacts of space missions are to be lowered since adverse impacts are easier to modify the earlier into the design process that they are identified (see Figure 2.14).

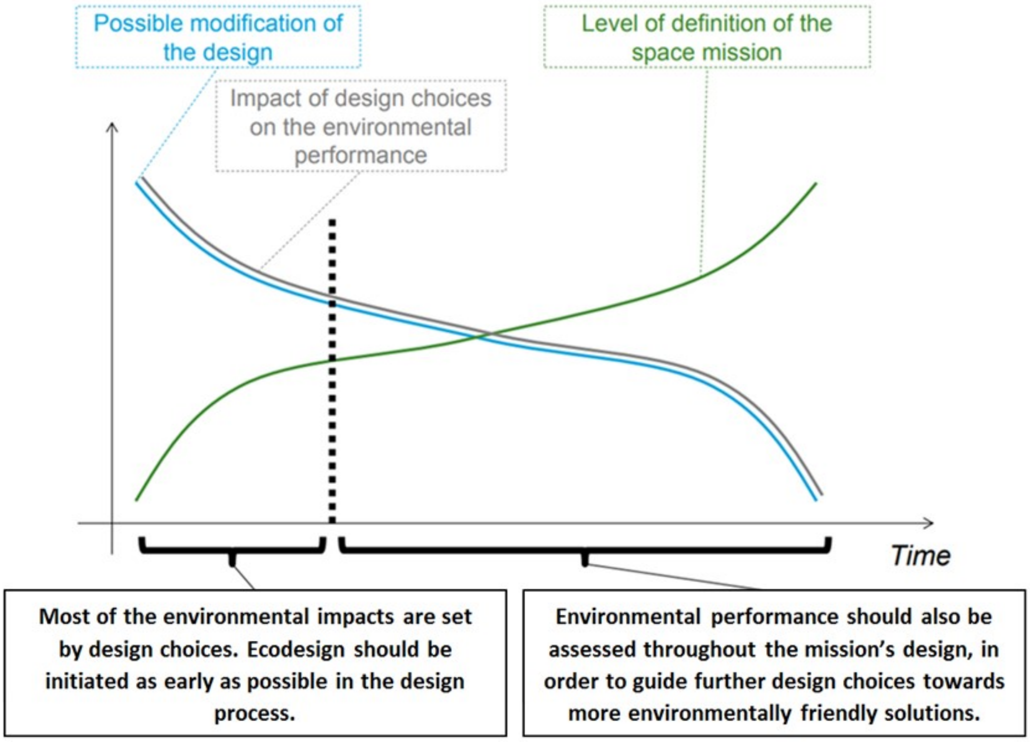


Figure 2.14: Ecodesign Process for Space Missions [105]

In this regard, as part of the new ESA space E-LCA framework, ESA issued a contract to BIO by Deloitte to create a new space-specific ecodesign tool which will allow users to carry out E-LCAs of space missions during early design stages. ESA plan to make the new tool (called Space Opera) fully operational for systematic use within all future CDF studies at ESTEC, but it has not yet been made available to European stakeholders [136]. The tool is an adapted version of an existing E-LCA tool called Opera which BIO by Deloitte also developed. The new tool takes into account the specificities of the space sector whilst interfacing with the OCDT to facilitate and enable the complete sharing during the concurrent design process [164]. Space Opera's LCI was primarily developed based on generic data from two pilot E-LCAs performed during this project (MetOp-A and Astra 1N [165]), using Ecoinvent versions 2.2 and 3.2 as its background inventories. Although it has not yet been achieved, ESA intends to eventually link Space Opera to the LCI datasets contained within the ESA E-LCA Database to provide a bigger and more robust inventory [33]. Additionally, the applied LCIA methods are identical to the ones adopted within the ESA E-LCA Database, as recommended within the ESA Space System E-LCA Guidelines. However, the LCIA results of Space Opera only provide characterised values instead of elementary flows which severely limits its specificity. The functionality of the tool was initially tested during its development in a study called the Large Observatory For x-ray Timing (LOFT) but during its first implementation on real studies, it was clear that there were some significant bugs that need to be addressed to allow smooth operation. These issues are discussed further in Section 2.6.

Integrating ecodesign into the concurrent design process for space systems was first investigated by Chanoine et al. [105] as part of this contract. This study suggested that the ecodesign discipline should work in a similar manner to how other disciplines interface with the OCDT during concurrent design (as shown in Subsection 2.5.1). Other disciplines deposit domain specific data within the OCDT which can be used by Space Opera to generate environmental results at system or equipment level. The Space Opera interface automatically updates the list of OCDT studies available to it through a web-service processor by sending a request directly to the OCDT database. The OCDT database will then send back a list of available studies including the number of iterations and options of each. Once the user selects which engineering model to import (i.e. the option within an iteration within a study), the web-service processor will send a request to the OCDT database which will send back a JavaScript Object Notation (JSON) file containing all the parameters related to the selection. The ecodesign tool should automatically interpret the file meaning that Space Opera will automatically assign the relevant LCI datasets and values to the information provided by the engineering model.

Once input values are assigned to the static elements of the E-LCA model, the user can perform a manual check of the imported data before running the environmental impact calculation. Once the calculation is completed, the user can then export the results back into the OCDT database via the web-service processor so that other domain users can view the results and alter design parameters appropriately [154, 164]. This process can be visualised within Figure 2.15 below.

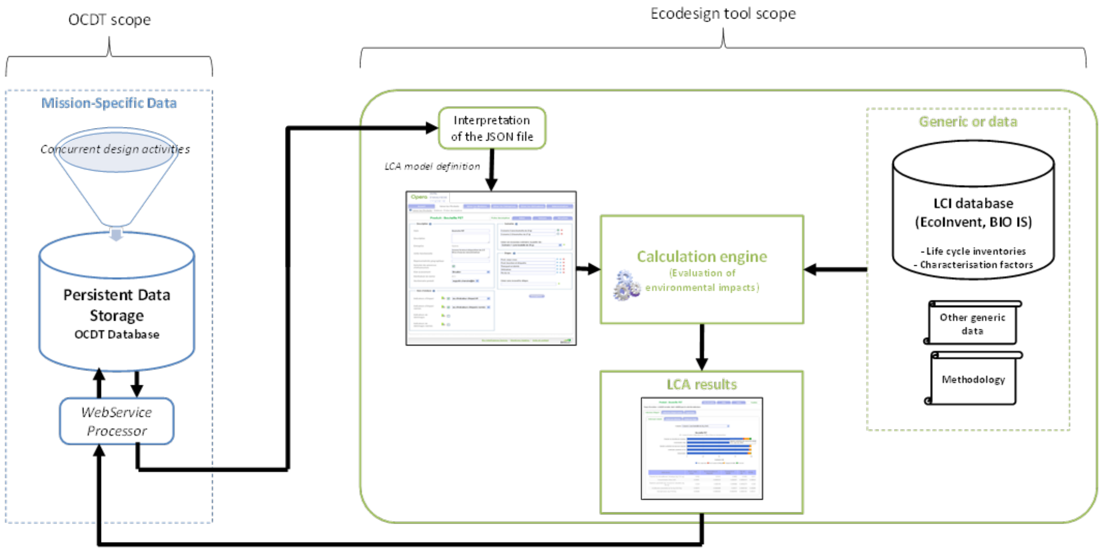


Figure 2.15: Architecture overview of Space Opera and its connection to the OCDT [154]

Despite this, there is currently no clear-cut or accepted agreement on what constitutes as ecodesign of space systems or which ecodesign approach should be adopted. This is because the OCDT typically contains data which relates to the design of the space segment only. When pulling this data from the OCDT, this means that all elements which can be influenced within the design session relate to the space segment (i.e. dynamic elements) whilst all other elements of the space mission's life cycle (i.e. static elements) require to be manually input by the ecodesign domain user based on expert knowledge [32]. An overview of dynamic and static elements as they relate to the concurrent design process of a space mission can be seen in Figure 2.16. This clearly raises a number of issues relating to which is the most appropriate or best-suited ecodesign approach to apply under such circumstances. The inter-relationship between static and dynamic elements thus far has never been investigated which is particularly problematic since static elements may indirectly (or in some cases even directly) affect or be affected by design choices and may be where the greatest hotspots lie. Since each ecodesign approach could provide very different results, it can be considered good practice to clearly communicate the adopted approach and all methodological assumptions (particularly relating to static elements) in any reporting of results.

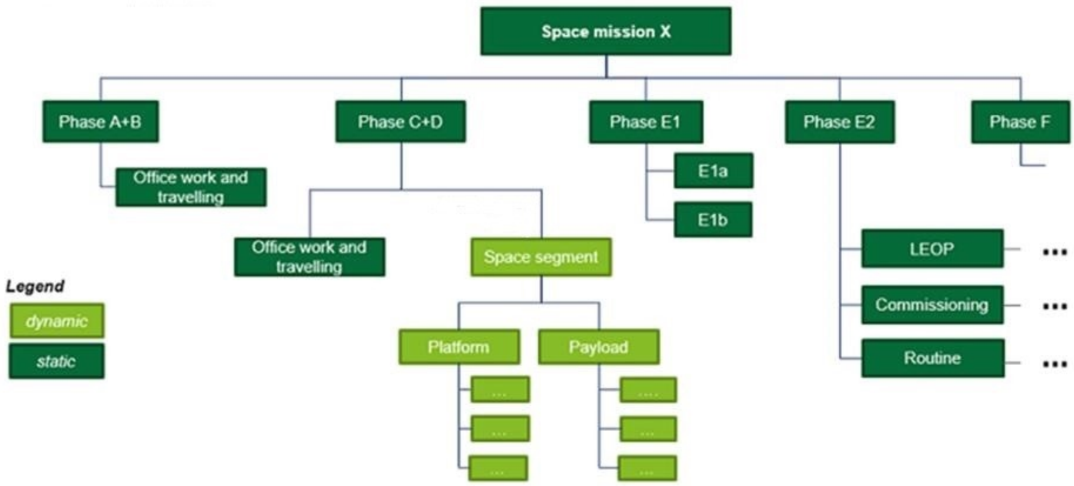


Figure 2.16: Product Tree of a Space Mission defined within Space Opera [32]

Although ecodesign does not directly contribute to the physical design of space systems within a concurrent design session, it can influence decisions made during this process by identifying environmental hotspots in order to assist decision-makers to lower the net impact with regards to the FU. Within an ecodesign study, an environmental hotspot can be determined if the LCIA results of a given impact category produces a significant impact compared to a benchmark and/or other impact categories [156]. As such, hotspots are generally identified by comparing absolute values of each impact category to a given normalisation factor (NF). In the case of the ESA, environmental hotspots of space missions were investigated using impact per EU citizen as a normalisation factor [33]. Based on this, average LCIA results across a variety of different space missions were analysed leading to the identification of five impact categories as key environmental hotspots for space missions. These impact categories include climate change, freshwater aquatic ecotoxicity, human toxicity, mineral resource depletion and ozone depletion [33]. Adopting this approach for hotspot identification is useful if decision-makers wish to identify key environmental themes for impact reduction.

In this regard, another hotspot identification method can be applied for impact reduction whereby hotspots are identified within impact categories themselves. In comparison to the previous approach, identifying hotspots or areas of significant impact within an impact category is typically achieved by looking at the breakdown of characterised results as a percentage across the entire product tree [156]. Adopting this approach for hotspot identification assists decision-makers to identify which processes contribute the most to the LCIA result of a given impact category. This is the most commonly applied method of hotspot identification and can be used to facilitate the implementation of ecodesign options for impact reduction of key contributing processes. ESA considers this method to be particularly useful for maintaining confidentiality of activity data when communicating LCIA results, particularly when comparing different technologies [30, 33].

2.6 Practical Application: HATHI Case Study

ESA have now reached a point where they are beginning to test E-LCA integration within the concurrent design process in order to enable ecodesign. To do this Space Opera will be used on a number of CDF studies in the near future in order to test its functionality. To date only one study of this nature has taken place, occurring 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, run as part of the ESA Academy's third Concurrent Engineering Workshop. The ESA Clean Space Initiative saw this mission as ample opportunity to test the current state of ecodesign at ESA and agreed with the ESA Academy that the inclusion of this discipline should be included as part of the HATHI study. The task was proposed and executed by the author of this thesis.

2.6.1 Study Overview

The ESA Concurrent Engineering Workshop took place in Redu (Belgium) at the ESA Academy Training and Learning Centre within the European space Security and Education Centre (ESEC). The HATHI mission was the first space-specific CDF study to include the ecodesign discipline and focussed on elephant counting and tracking via satellite since the use of GPS collars are dangerous to the elephants and poachers have been known to hack the data. With the World Wildlife Fund predicting that African elephants could be extinct within the next 15 years [166], the purpose of this study was to help protect African elephants from ivory trafficking by identifying grazing locations, conserving farmland and preventing poaching by matching satellite images of possible paths poachers could use with the elephant movement data in the identified areas indicated in Figure 2.17 below.

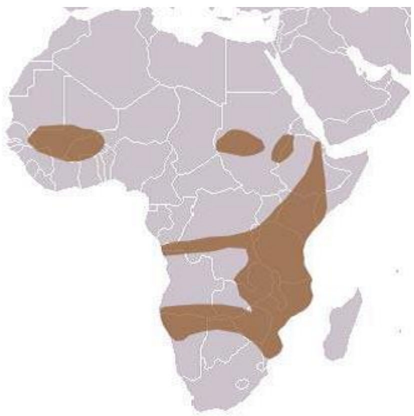


Figure 2.17: Target areas of observation for the HATHI study

In order to achieve these mission goals, a full set of mission requirements were set by the ESA Academy which can also be found in Table 2.3 below. The first iteration began by considering a slewing option where it quickly became apparent that the coverage and resolution requirement would force the need for two identical satellites in a dawn-dusk sun-synchronous orbit with a different longitude of ascending node to allow for rapid revisiting times of the target areas. This system design was then refined further during the second iteration which considered moving towards a scanning option instead of slewing the satellite through the use of Gregorian design telescopes with a "whisk broom" method via a moving mirror. The third iteration then consolidated this concept and finalised the design which was presented to ESA at the end of the study.

Table 2.3: Mission requirements for the HATHI study

Req / goal	Level	Number	Text
R	MIS	10	The mission shall track African elephants from space with a spatial resolution of 0.5 m
R	MIS	20	Observations shall take place during local day
R	MIS	30	Day pictures of elephants should be visible and in colour
R	MIS	40	The pictures shall be sent to the Elephant Control Centre within 15 min
R	MIS	50	The mission lifetime shall be at least 10 years (5 years nominal + 5 years extension)
R	MIS	60	The mission shall cover the brown areas as indicated in Figure 2.17
R	MIS	70	The revisit time shall be 1 day
R	MIS	80	All elements in the space segment shall de-orbit within 25 years after end of the mission
R	MIS	90	All space segment elements shall have a casualty risk less than 10^-4 upon reentry

Overall, the final Phase 0 baseline design of the HATHI mission had a total wet mass of 1802.71 kg and the components were configured according to Figure 2.18 below. From a very early stage it became clear that the mission was more complex than ESA had initially expected. Despite this, coupled with the short and intense nature of this workshop (which is comparatively shorter than a typical Phase 0 design study), a highly complex design was achieved. It was concluded by the ESA experts that the design was indeed feasible and with a few more iterations could be refined further which was suggested as a basis for future work at ESA.

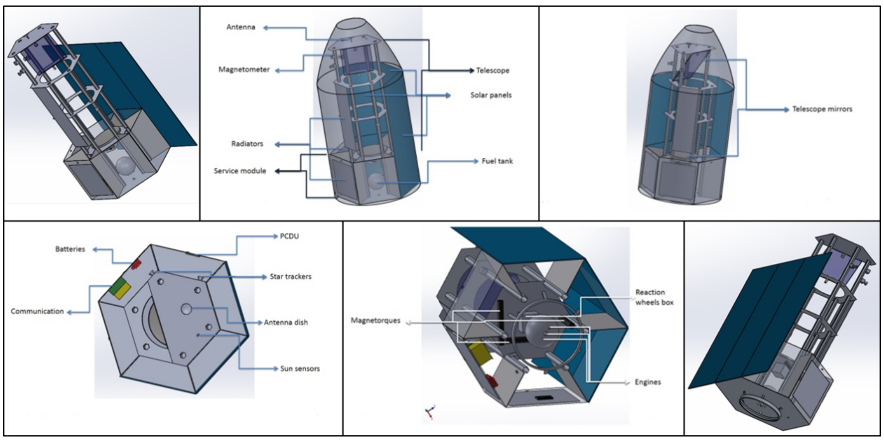


Figure 2.18: Final Phase 0 Baseline Design of the HATHI Mission

2.6.2 Ecodesign of the HATHI Mission

The subsystem requirement of the ecodesign discipline was simply to define the environmental life cycle impact of the satellite. The FU and system boundaries are indicated in Figure 2.19 below along with the LCI data inputs which are required by Space Opera.

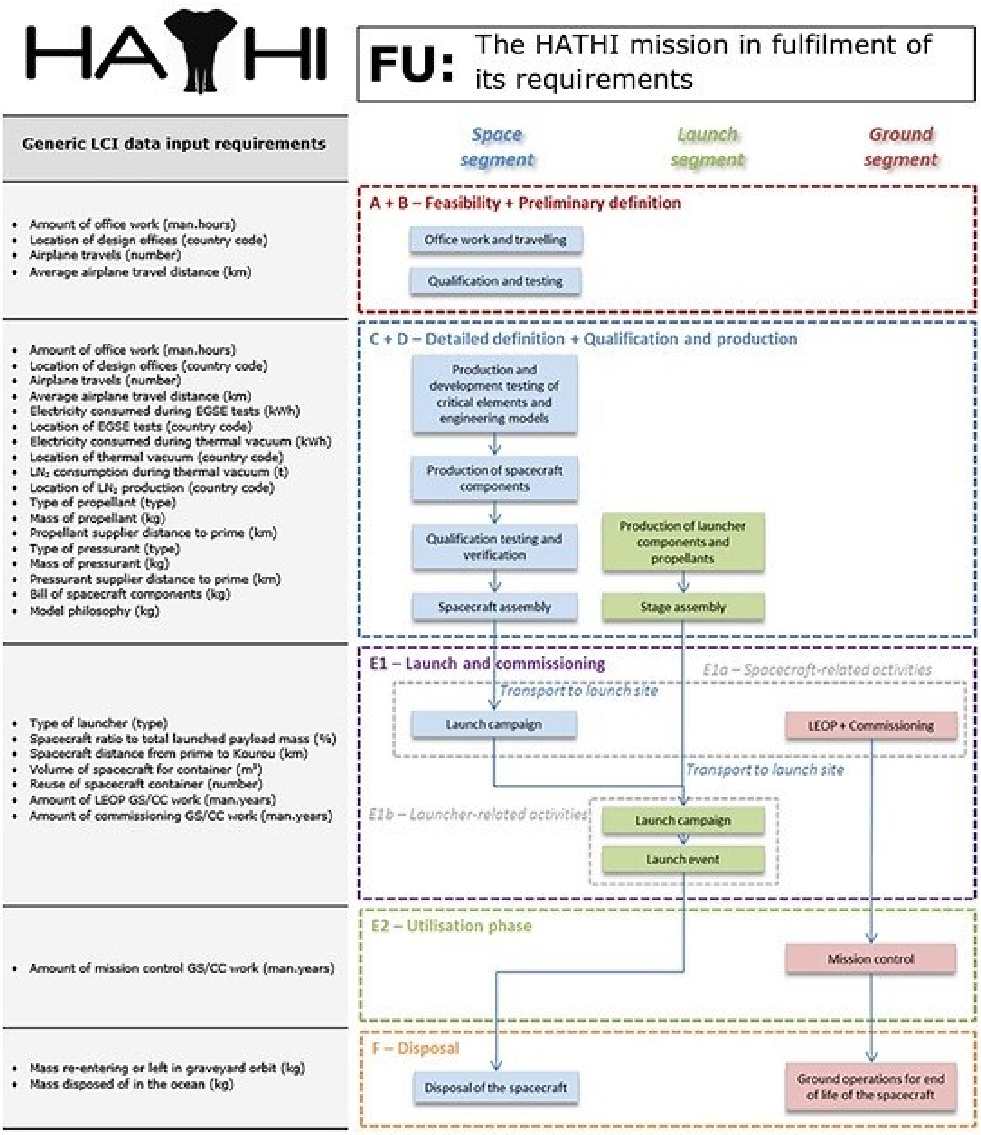


Figure 2.19: HATHI mission functional unit & system boundary with generic LCI data input requirements (adapted from [30])

As can be seen from this figure, Space Opera requires the use of both static and dynamic elements as inputs for the LCI as indicated in Figure 2.16. As such, input for the static elements were principally based on primary data provided by an ESA Clean Space Initiative expert obtained from a previous ESA E-LCA study of a large Earth observation mission. Despite this, it was found that some static elements were unavoidably influenced by mission design. This included the type of launcher used (if not stated in mission requirements), the ratio of spacecraft mass in terms of total launched payload mass in case of dual launch, the volume of spacecraft for spacecraft container, and re-entry characteristics. Data for such aspects were obtained from information contained within the OCDT engineering model and through communication with the relevant subsystem teams. Input for dynamic elements were based on the characteristic values of the components and equipment used by each subsystem within each iteration of the HATHI mission design. The import of the OCDT engineering model to Space Opera should allow these characteristic values (input as parameters) to be automatically assigned to the relevant Space Opera inventory dataset. In theory, this allows the ecodesign part of the E-LCA process to be calculated with minimal user input.

As agreed with the ESA Clean Space Initiative and ESA Academy, absolute results of this study shall remain confidential. For this reason, Figure 2.20 below provides the baseline results of the final design as percentage contribution to each midpoint impact category by phase. The LCIA results are based on the recommended impact categories stated within the ESA E-LCA guidelines. The results show that routine during Phase E2 generally has the highest environmental impact over the life cycle of the mission. This can be primarily attributed to computer use and facility related emissions (i.e. electricity and natural gas) over the 10 year mission lifetime of the satellite. Phase E1 also notably has a particularly high influence on results. This is primarily due to the manufacturing and production of Vega coupled with the assumption that the HATHI spacecraft was the only payload on-board the launcher. This meant that a reduction in impact could not be applied (i.e. the total impact is related to the ratio of spacecraft mass in terms of total launched payload mass). Surprisingly, Phase C+D has a relatively benign impact despite hosting the production and manufacturing processes for the HATHI mission. This was expected to produce a particularly high impact, which indicates that something is incorrect with these results.

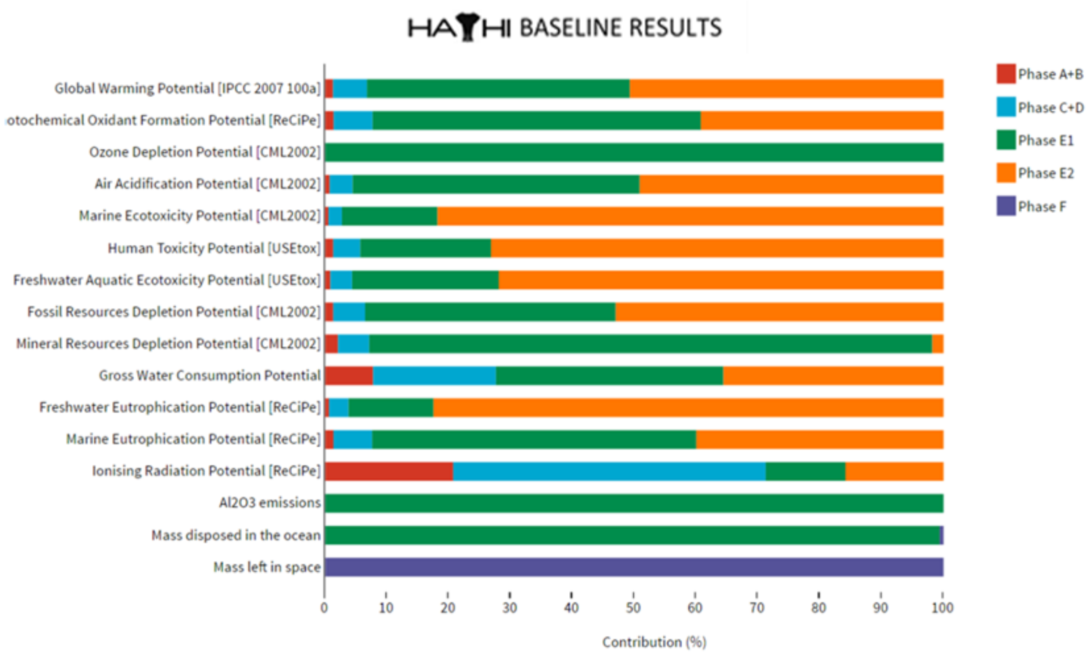


Figure 2.20: Relative HATHI mission baseline Environmental Life Cycle Assessment Results

When comparing the HATHI results to other space-specific E-LCA studies conducted by ESA, it was found that the results notably differ in comparison to those of the Astra 1N, MetOp-A and Sentinel-3B missions [98,165]. In particular, the percentage contribution of Phase C+D was significantly lower across each impact category in the HATHI study, averaging at a difference of approximately 15-20% per impact category in comparison to the total contribution. Although this can be partly attributable to the level of impact greatly varying between different missions, the main reason for this difference at Phase C+D was due to numerous technical problems which were encountered during the ecodesign process. This meant that the dynamic part of the E-LCA process could not be completed and in turn, the subsystem requirement of defining the environmental impact of the entire life cycle of the satellite could not be fulfilled.

In terms of interpretation, although a review is not an essential component of ecodesign, the results were reported to all study participants, team leaders and ESA Clean Space experts. A problem report was also sent to the ESA Clean Space Initiative regarding the issues faced during the HATHI study. These are discussed further in Subsection 2.6.3 below.

2.6.3 Critical Review of Ecodesign

The novelty of space-specific ecodesign has meant that there has been very little evidence to base how well E-LCA can be integrated within a concurrent design session. However, from the issues encountered during the concurrent design session of the HATHI mission, it was clear that the integration of Space Opera into mission design needs to be refined. The identified issues which were found have been broadly grouped into the following categories:

1. Technical issues
2. Behavioural issues
3. Methodological issues

Technical issues refer to specific problems which affected the desired functionality of the Space Opera ecodesign tool. The technical issues encountered for Phase C+D of the HATHI study were primarily caused by several bugs which had not yet been identified within the tool. In particular, a deserialisation error meant that the HATHI engineering model was not properly imported from the OCDT, leading to the vast majority of spacecraft components being flagged as red within the Space Opera product tree. These red flags meant that although the parameter value was expected and mapped to a Parameter Type, it had not been identified by JSON. JSON is a minimal, readable format for structuring data and is primarily used to transmit data between a server and web application as an alternative to XML [164]. Ordinarily, this would mean that data is missing from the OCDT engineering model despite the fact that it is deemed crucial for the E-LCA model. However, in the case of HATHI, it was clear that this was being caused by a bug within the software. To overcome this, relevant modules were manually added to the product tree. However, when adding a new module, the inventory formula field (indicated in Figure 2.21 below) was left blank for all spacecraft components. Values were then manually added by calling the ID of other modules and processes. In the case of Figure 2.21 the ID would be $17805 since the syntax is similar to Excel (i.e. + -* / 'IF' operators). However, when calculating the LCIA results, it was evident that these parameters were not being called or influencing the results since the inventory formula fields of all manually added modules would revert to being blank again. This meant that the dynamic section of the E-LCA could not be calculated and a major part of the mission's impacts were omitted from the results.

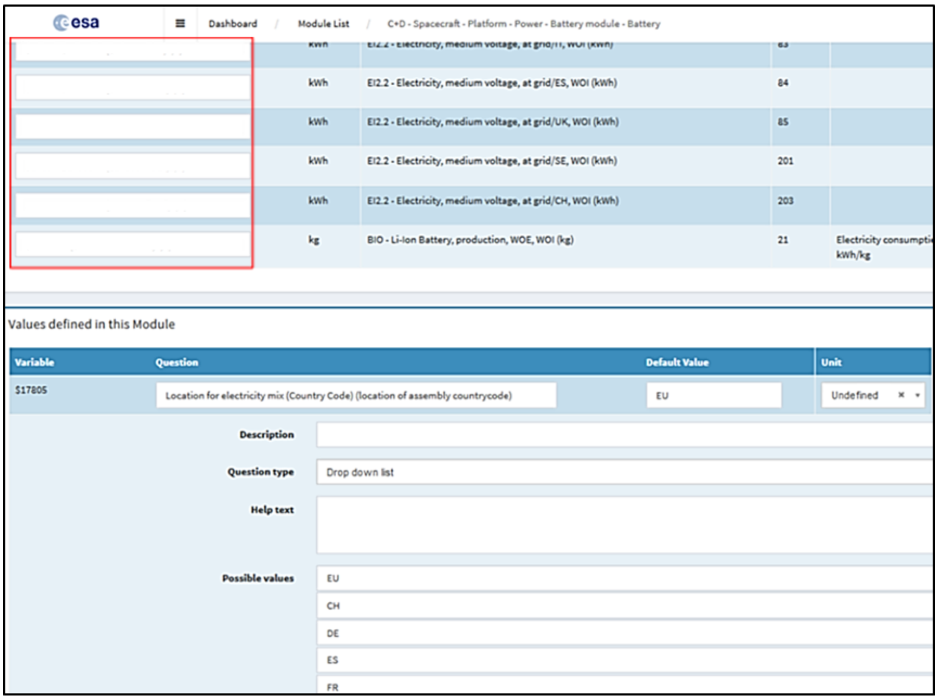


Figure 2.21: Blank formula fields encountered during the HATHI study

Additionally, another major problem encountered was the fact that the results themselves lacked specificity in their breakdown. Results could only be broken down to total impact per phase meaning that the influence of individual processes or materials could not be investigated. Detailed results can be downloaded via excel or sent to users e-mail address as an excel file. The visualisation of these detailed results is crucial to the ecodesign process since it will allow users to focus directly on the impacts of specific subsystem equipment and components. However, due to bugs, the tool also would not export the LCIA results via either method meaning that the environmental impacts of specific components could not have been analysed.

Methodological issues refer to problems which affected the manner in which E-LCA can be implemented. In this regard, the exact processes and species which constituted to the results at phase level could not be determined since the Space Opera LCI cannot be viewed within the tool due to its design and also because the LCIA deploys characterised results instead of elementary flows. This was problematic as the Space Opera LCI is currently not connected to the ESA E-LCA Database meaning that users are unaware what inputs and outputs are involved in many of the deployed LCI datasets. It was also found that the uncertainty analysis was non-functional since its values did not change depending on what LCI datasets was used and that data quality analysis was not included within the tool.

Moreover, the ability to select the most relevant LCI datasets was also severely restricted by Space Operas design. For example, the rigid nature of the product tree for static elements means that only chemical propulsion can be selected opposed to electrical and the use of dropdown menus means that only mono-propellants can be selected opposed to bi-propellants. Additionally, no LCI datasets currently exist for in-space operations and re-entry which are major omissions from the life cycle of a space mission.

Despite this, the generated LCIA results should be fed back into the OCDT to highlight the environmental impacts of the static elements (as shown in Figure 2.16). However, restitution of LCIA results to the OCDT was not possible since ESA's OCDT RDL currently does not have specific E-LCA parameter types mapped to it. Before LCIA results can be fed back into the OCDT, relevant E-LCA parameter types would need to be created in addition to an E-LCA workbook which organises LCIA results in a format that allows it to be pushed to the OCDT server.

One final methodological issue related to the use of mass margins. ESA deploys a mass margin philosophy within CDF studies and industrial activities to ensure that space missions and activities are designed with an appropriate level uncertainty/error included [167]. At system level, this margin is usually applied on top of the total mass of all subsystems. For this reason, the automatic OCDT import will not take into account this additional step meaning that a large proportion of the spacecraft mass could be overlooked. Additionally, the influence of the dynamic elements imported from the OCDT to the static elements have so far not been investigated. Despite this, it is clear that the ecodesign process will have some degree of influence on these elements (e.g. a system design which has rapid revisit times may require more man-hours during routine).

On a behavioural level, the importance of E-LCA was not considered to be a very influential design driver during mission options and trade-offs since it was given one of the lowest weighting factors (WFs) amongst all of the trade-off parameters (see Table 2.4). This table shows that a single satellite design was considered as the best option, which also coincides with the option favoured by the ecodesign discipline. However, as discussed in Subsection 2.6.1, it was discovered during the first iteration that the coverage and resolution mission requirements forced the need for multiple satellites. Due to time restrictions involved with designing a secondary satellite, the multiple same satellite option was chosen instead. With particular reference to E-LCA, the low weighting given to ecodesign by study participants can perhaps be explained by the novelty of the discipline within CDF sessions. Despite this, it is expected that the relative importance of E-LCA will increase in the future, particularly during the design of space missions with direct environmental applications like HATHI.

Table 2.4: HATHI mission options & trade-offs

Trade-Off Parameter	Weighting Factor	Importance of Mission Options		
		Single Satellite	Multiple Same Satellites	Multiple Complimentary Satellites
Cost	0.30	5	2	1
Coverage / Revisit Time	0.30	1	3	5
Instrument Design	0.15	4	5	5
System Reliability	0.11	1	3	3
Ecodesign	0.07	5	3	2
Launcher(s) / Schedule	0.07	5	3	2
		3.2	**2.9**	**3.1**

In terms of the HATHI study, after discussion with ESA Clean Space experts and the developers of the tool, it was found that these problems could not be resolved. Additionally, since this was the first time that Space Opera had been used outside of ESTEC, it led to the emergence of other technical issues relating to the central server. In particular, the use of the tool in Redu caused the ESTEC CDF server to shut down. These negative functionality findings are corroborated by another study which took place in March 2017 at ESTEC. This was a post-CDF E-LCA study of the Laser Interferometer Space Antenna (LISA) conducted by an ESA ecodesign expert [33]. During this study, a decentralisation error occurred meaning that the LISA engineering model could not be imported from the OCDT. When trying to import the engineering model, after several hours of loading, the server connection would time out giving a '500 Internal Server Error' message. This meant that the post E-LCA LISA study was forced to be abandoned.

Whilst Space Opera is the first tool of its kind worldwide, from the issues encountered by these two studies, it is clear that Space Opera is currently not yet at a point where it can be successfully integrated into the concurrent design process. To address the problems identified by both the LISA and HATHI studies, ESA conducted internal work to identify all bugs plaguing the tool based on the problem reports submitted from both of these studies. ESA now intend to issue a small contract to the Space Opera developers in order to debug the tool so that it is fully operational for systematic use within future CDF studies. To date, it is understood that this contract has not yet been issued due to various financial and management logistics [33].

2.7 Chapter Summary

This chapter has outlined prior work relating to E-LCA of space systems and critically reviewed the space-specific E-LCA framework developed by ESA. The ESA Space Opera ecodesign tool was also practically tested to examine its strengths, weaknesses and functionality within space mission design sessions.

The findings from this process has highlighted potential data sources for space-specific E-LCA studies, but also the limited amount of work which has been conducted on the topic, particularly outside of ESA. As such, the importance of the new E-LCA framework built by ESA to guide the development of space-specific E-LCA is evident given the unique nature of the space sector and the restricted applicability of traditional forms of E-LCA. In particular, the ESA E-LCA guidelines are crucial in guiding the application of this assessment type within the space sector. However, the non-release of the ESA E-LCA database and Space Opera ecodesign tool continues to hinder the application of the topic within the space community. Bugs found within Space Opera also cast doubts over its applicability within concurrent design sessions. These factors will need to be taken into account if social and economic considerations are to be integrated into the methodology for application within space mission design.

Chapter 3

Towards Life Cycle Sustainability Assessment

3.1 Chapter Overview

The ability to measure and mitigate life cycle environmental impacts of space missions is an extremely important issue which highlights the space sector's willingness to contribute towards the global sustainability agenda in all aspects of their operations. Whilst E-LCA is extremely useful in this regard, on its own it is not enough to accurately gauge how sustainable a space mission is. This is because the traditional concept of sustainability encompasses not just the environment but also society and the economy, as reiterated within the 2030 Agenda. As such, it may be necessary to move E-LCA of space systems towards a new assessment type which covers the full sustainability spectrum rather than just the environment.

The E-LCA framework developed by ESA represents a solid foundation on which this transition can be made. Based on this, a new space-specific LCSA framework will be proposed within this chapter, formed from a literature review on current LCSA methodologies and practice relating to the application of social and economic criteria within space missions. This framework will suggest methods of best practice relating to the aggregation of E-LCA, S-LCA and LCC methodologies within one single space-specific assessment, in line with the 2030 Agenda.

3.2 Sustainability & the Space Sector

If methods to move the current space-specific E-LCA methodology towards a more holistic approach of sustainability assessment are to be pursued, it is important to specify the definition of the terms 'sustainability' and 'sustainable development' and illustrate how they relate to life cycle modelling. Additionally, it is also critical to identify whether any of the remaining sustainability dimensions are currently applied within the concurrent design process of space missions (in whole or in part) so as not to 'reinvent the wheel'. Collectively, this information will provide a sound basis on which to develop the space-specific LCSA framework and methodology in relation to generally accepted principles and gaps in knowledge.

3.2.1 Linking Sustainability & Life Cycle Modelling

Although sustainability is often seen as essentially about the environment, the Organisation for Economic Co-operation and Development (OECD) argue that the concept is in fact about using economic development to foster a fairer society whilst respecting ecosystems and natural resources [168]. The most widely cited definition of sustainable development is contained within a report called 'Our Common Future' which was released by the World Commission on Environment and Development in 1987. Within this report, the term is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [169]. This definition has become interrelated with triple bottom line (TBL) sustainability, a term coined by Elkington in 1997 to expand this framework to reflect profit, people and the planet [170]. This concept is also known as the three pillar approach to sustainability whereby sustainability can be achieved by balancing environmental, social and economic factors. The prevalence of this concept has grown to a point where it has now become a ubiquitous and fundamental principle of sustainability which is now reflected within the 2030 Agenda [4].

Sustainability principles have also begun to filter into life cycle studies at product-level. Bettencourt & Kaur found that between 1974 and 2010, over 20,000 scientific papers contained the words "sustainability" and/or "sustainable development" in their abstract, title or keywords [171]. Of these papers, Zamagni identified that around 3% contained the words "sustainability" and "LCA" [172]. She went on to state that the occurrence of these key words increased in recent years, with publications in 2010 three times higher than in 2007. The increasing number of papers in this regard highlights the relevance of integrating sustainable development considerations into the life cycle approach. In this regard, sustainable consumption and production is increasingly becoming a priority for business and for policy-making, with many organisations already signing up to voluntary initiatives (such as the Oslo Manifesto) or adopting life cycle approaches to demonstrate their commitment to enabling cleaner and more responsible patterns for product design.

In this regard, the best way to integrate these multi-dimensional considerations into the life cycle framework is to combine the three intersecting pillars of sustainable development. The life cycle approach which most accords with this concept is LCSA. This is because LCSA focuses on combining E-LCA, S-LCA and LCC within a single LCSA assessment according to the methodology outlined in Section 3.3. An overview of this concept as it relates to TBL sustainability is presented by Figure 3.1 below.

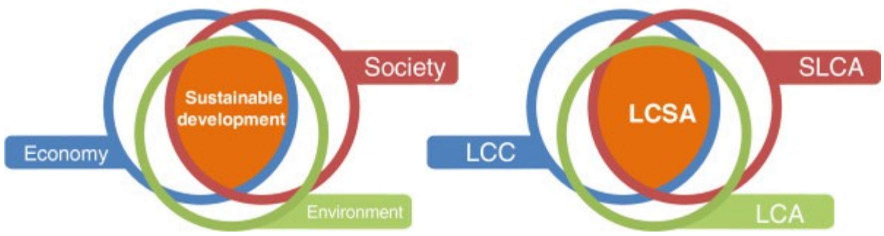


Figure 3.1: Triple Bottom Line Sustainability as it relates to LCSA [173]

3.2.2 Sustainability Dimensions Applied within Space Mission Design

Whilst environmental elements are currently at the forefront of the space-specific E-LCA methodology, life cycle impact modelling of space missions must also include social and economic dimensions if they are to be considered from a TBL sustainability perspective that aligns with the 2030 Agenda. As such, it is worth defining the significance of these other sustainability dimensions within the space mission design process.

At present, social aspects are not currently included as a design discipline within the concurrent design process of space missions [33]. In fact, S-LCA within the space sector has never been attempted. Therefore, without the inclusion of S-LCA, most design choices are currently based purely on environmental, costing and technical criteria. This could be classed as sub-optimised decision-making. Nevertheless, a wide range of stakeholders are typically involved in the supply chain of a space mission over its entire life cycle [174]. In this regard, S-LCA can be used to address a wide range of social concerns which may occur relating to these stakeholder groups, such as employment, politics, equal rights, peace & security and health & well-being. The provision of this information may allow decision-makers to make ethical choices regarding product design criteria based on the identification of social 'hotspots' to improve social conditions throughout the life cycle of the product. Addressing such adverse issues is extremely important to increase efficiency, avoid potential supply chain disruption and improve profitability [175]. With the global space economy expanding to a size of $360 billion in 2018 (of which 77% accounts exclusively for the satellite industry) [176], it is important to measure the effect that this growing economic activity may have on the sector's various stakeholders for the first time in order to ensure continued economic growth, the improved performance of organisations and ultimately the well-being of stakeholders. The growth in the number of SEIAs produced in recent years highlights the growing awareness of the importance social impacts carry across the industry at a broad level. As such, the integration of S-LCA with the space-specific E-LCA methodology seems highly advisable to measure potential adverse social impacts which may affect the various different stakeholders involved in the supply chain, particularly in relation to the dominant social issues outlined within the 2030 Agenda.

Within the space industry, high demands are often placed on performance and affordability. As such, cost estimations of space missions cannot be properly validated based purely on purchase prices. In order to build a full picture concerning total cost incurred, the whole life cycle cost must be taken into account within early design phases where around 80% of the cost is set [22]. For this reason, cost engineering is typically included as an extremely important discipline within concurrent design sessions. As part of this, cost models are highly prevalent within the space sector and are typically used to justify project funding [55, 177]. In this context, the importance of LCC is reemphasised within Article 67(2) of Directive 2014/24/EU of the European Parliament and of the Council which states that "the most economically advantageous tender from the point of view of the contracting authority shall be identified on the basis of the price or cost, using a cost-effectiveness approach, such as life-cycle costing" [178]. This requirement on contract award criteria clearly indicates the increasing relevance and influence of this approach within Europe as a leading cost estimation method. As such, the necessity of its integration with the space-specific E-LCA methodology would seem clear-cut, particularly if this eliminates the need for additional analyses.

Combining both of these approaches with E-LCA to form a single LCSA within the space sector has thus far never been attempted. However, such an approach could enable decision-makers to organise and structure complex environmental, social and economic information/data by providing a more comprehensive overview of trade-offs which may occur between the three sustainability pillars and life cycle stages. Within the space sector, employing such an approach would enable product-based assessments which consider life cycle sustainability impacts to be made on a range of space applications for the first time. As such, this can be used to aid decision-makers to optimise next generation space systems in the frame of the 2030 Agenda.

3.3 Methodologies for LCSA

LCSA is a new analytic environmental management tool used to measure the environmental, social and economic impact of products, processes and services over their entire life cycle. The technique was conceptualised in 2008 and culminated efforts of linking environmental, societal and economic principles as they relate to product life cycle. Based on LCT principles, it combines three life cycle perspective assessment types (E-LCA, S-LCA and LCC) to form a single assessment which can address each of the sustainability dimensions. This approach is shown through conceptual formula given below:

$$LCSA = E\text{-}LCA + S\text{-}LCA + LCC \quad (3.1)$$

When proposing the LCSA framework, Klöpffer suggested two options on which LCSA results can be analysed. The first method is to view each of the three assessments as standalone sustainability aspects in themselves. The second method involves using S-LCA and LCC results as separate impact categories within E-LCA. He concluded by suggesting that the first option may be the most appealing due to the transparency of the method, its ability to include comparative assessments and because it best conforms with the ISO 14040:2006 and 14044:2006 standards in their present form [10].

Although the technique itself is not currently standardised, it is primarily governed by guidelines produced by the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) called 'Towards Life Cycle Sustainability Assessment' [179]. These guidelines state that the ISO 14040:2006 and 14044:2006 E-LCA framework should also be applied when conducting an LCSA.

As such, the following sections 3.3.1 to 3.3.5 will discuss the LCSA framework outlined within these guidelines and other appropriate literature as it relates to the ISO 14040:2006 and 14044:2006 framework.

3.3.1 Goal & Scope Definition

The UNEP/SETAC LCSA guidelines strongly recommends the use of a common goal and scope definition when conducting an LCSA which takes into account the different requirements of the three assessments types, including the FU and system boundary [179]. In particular, they state that careful attention should be paid to the system boundary since each life cycle technique may have slightly different boundaries based on their relevancy to the overall assessment. For example, LCC may be considered for the use of a cost breakdown structure (CBS) which adopts a life cycle actor perspective (e.g. supplier, manufacturing, user or consumer) to facilitate consistent data collection along the full life cycle. However, identical system boundaries should be applied to each of the three approaches whenever possible. Additionally, other small methodological differences can be considered within the goal & scope in order to determine how they might affect the study. In particular, S-LCA requires the selection of an activity variable to measure the share of a given activity as it relates to each unit process. Furthermore, the scale of the relationship between the activity and unit process can massively impact the results and is therefore an important consideration within the goal & scope definition of an LCSA [180].

3.3.2 Environmental Life Cycle Assessment

E-LCA should be performed in accordance with the framework outlined in the ISO 14040:2006 and 14044:2006 standards. However, ESA also developed a set of E-LCA guidelines which tailor the methodological rules contained within this framework to be more appropriate to the space sector without risking non-compliance. This process was described within Section 2.3 and can be used as a basis for integrating social and economic criteria.

3.3.3 Social Life Cycle Assessment

S-LCA is a method which can be used to assess the social and sociological aspects of products, processes or services over their entire life cycle [11]. Although the technique is also not standardised, S-LCA guidelines produced by UNEP/SETAC direct its application [181]. These guidelines were released in 2009 and state that S-LCA should follow the same life cycle steps as the E-LCA framework outlined by ISO 14040:2006 and 14044:2006. However, certain aspects differ, particularly during the LCI and LCIA stages.

According to the S-LCA guidelines, the LCI involves the collection and calculation of social data [181]. In this regard, data is gathered for a range of stakeholder categories and subcategories instead of impact categories via the process indicated in Figure 3.2. Stakeholder categories are relevant social groups with a shared interest or relationship to the investigated product system. Stakeholder subcategories are socially significant themes or attributes relevant to each stakeholder category. As such, they provide the basis of the assessment. The categories and subcategories listed within the UNEP/SETAC S-LCA guidelines are detailed in Figure 3.2 and were developed based on international agreements (conventions, treaties etc.), most notably the Millennium Development Goals (MDGs) [182]. LCI data is then gathered for a range of indicators which are individually applicable to each stakeholder subcategory. To assist with the selection of appropriate indicators, UNEP/SETAC released 'The Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA)' in 2013 which provides a list of 189 inventory indicators [183]. These indicators are split into generic analyses (i.e. country/sector -level) and specific analyses (i.e. organisational or product -level) and were developed based on international instruments, CSR initiatives, model legal framework and social impacts assessment literature. LCI data can then be generated for a selection of these indicators either quantitatively or qualitatively (based on the nature of social criteria). The influence of each of these indicators (including their LCI results) as they relate to each unit process should be defined by the activity variable in the goal & scope definition [181].

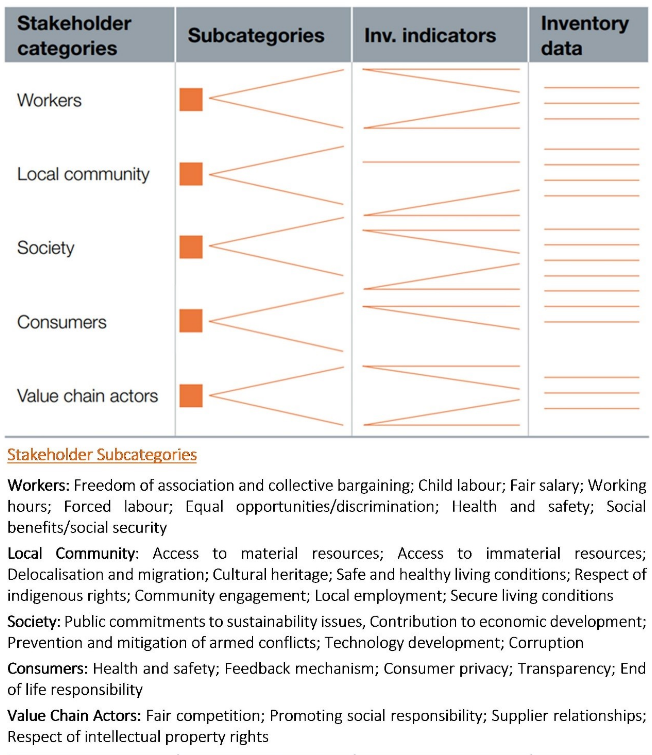


Figure 3.2: LCIA process for S-LCA from stakeholder categories to units of measurement (adapted from [181])

Generally, in practice, stakeholder categories and subcategories are used as impact categories within S-LCA. However, the UNEP/SETAC S-LCA Guidelines do not propose LCIA methods or interpretation approaches but suggest that if used, they should be well defined and transparent [181]. This is due to the mix of quantitative and qualitative data involved during the LCI phase which makes characterisation very difficult. As such, the UNEP/SETAC S-LCA guidelines propose that a scoring system could be used to assess the 'meaning' of the LCI based on performance reference points [181]. However, no information is provided on appropriate units of measurement for the evaluation of social criteria with regards to such a scoring system.

3.3.4 Life Cycle Costing

LCC is a method of economic analysis which can be used to assess all costs relating to products, processes or services over their entire life cycle [12]. It is standardised for electrical, electronic and related technologies through the International Electrotechnical Commission (IEC) 60300-3-3:2017 standard [184]. However, many industries have applied their own standards for LCC such as the building and asset management industry through ISO 15686-5:2017 [185]. However, in terms of LCSA, Swarr et al. consolidates the LCC approach, stating that the methodology should be consistent with the E-LCA framework [186]. In this sense, the SETAC Working Group on LCC states that there are two main approaches which exist that can be applied to perform LCC [187, 188]. The first is conventional LCC which is based purely on economic evaluations that consider various costs associated with the life cycle of a product from one or more actors. The second is environmental LCC which summarises the above mentioned costs but also takes into account external environmental costs (i.e. cost value per unit of pollutant). Conventional LCC is the most commonly applied approach but external costs are often neglected. In comparison, environmental LCC is seen as a complementary analysis to E-LCA but costs are much more difficult to measure since most pollutants will have different damaging effects between impact categories [189]. Additionally, cost values per unit of pollutant can severely and unpredictably fluctuate making it difficult to calculate external cost factors [190].

According to Swarr et al. and the IEC 60300-3-3:2017 standard [184, 186], the LCI phase involves the collection and calculation of monetary data. Typically dedicated cost estimating models will be used for this purpose, particularly in the case of conventional LCC. The data used will normally come from a diverse range of sources, which means that achieving consistency can be challenging, particularly as costing data can be extremely volatile [186]. Also, appropriate aggregation of costing data is extremely important in cases where co-products are produced. This is because some expenses, particularly overheads, cannot always be directly related to a product [191]. Additionally, since costs might occur for different actors, it is also important to differentiate and select which costs and cost bearers are included within the assessment [192]. For this reason, caution must be exercised when calculating the LCI or using cost models. According to Ciroth, another important consideration during this phase involves the selection of an appropriate discount rate [193]. Discount rates are used to convert future costs associated with a product system into a present value, thus accounting for future inflation rates. Cost data might also be gathered in different currencies over different time periods [186]. LCI data will therefore need to refer to a common currency at present value using appropriate exchange and discount rates.

The LCIA phase is not strictly required within LCC since the LCI data is comprised of a single unit of measurement, namely currency. This means that characterisation or weighting does not need to be applied assuming that all monetary values have already been converted to a common currency at net present value [179]. However, costs can be aggregated into economic cost categories, life cycle stages, activity types (based on CBS) or cost elements [184]. Economic cost categories relate to general costs such as market, budget or labour costs. Life cycle stage categories relate to segments of the supply chain where a given cost occurs. Activity type categories provide a more detailed specification of life cycle stages, including processes involved. Cost elements detail cost items within activities and stages. However, as indicated in Figure 3.3 below, this latter approach is typically a component of other aggregation methods rather than being used exclusively to present LCIA results.

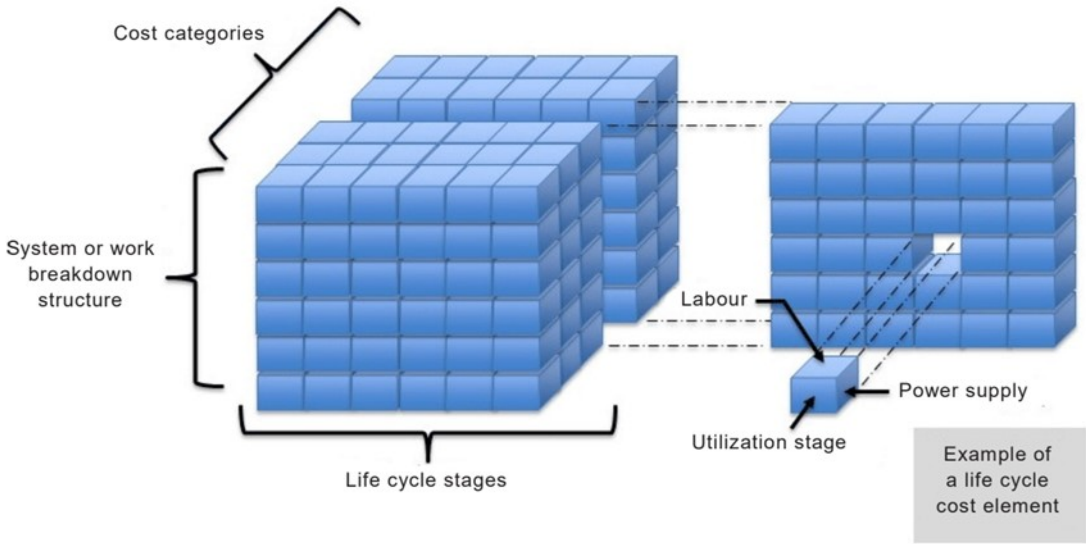


Figure 3.3: Cost breakdown structure concept [184]

3.3.5 Interpretation

Since the purpose of LCSA is to provide a single sustainability assessment of a product system, it is recommended that the results are interpreted in a combined fashion based on the goal and scope definition [179]. This evaluation should align with the two options proposed by Klöpffer for analysing LCSA results [10]. This evaluation should clarify the trade-offs between each sustainability aspect and identify potential sustainability 'hotspots' [30]. Therefore, results should be presented in a clear manner in order to support the decision-making process. Additionally, the interpretation should also provide recommendations, limitations and conclusions, including information regarding data quality [5, 6].

A critical review should also be conducted if the LCSA will be used for public assertions or comparisons [5, 6]. In this case, independent qualified reviewers with appropriate expertise for E-LCA and LCC should conduct the review. In terms of S-LCA, elaborated opinions and feedback on the social data should be obtained from third party (stakeholder) sources.

3.4 Methods for Modelling Sustainability Dimensions

If LCSA is to be applied for space-specific applications, it is important to understand how environmental, social and economic impacts of space systems are currently calculated, including the inter-relationships of these sustainability dimensions. Determining the methodologies which are currently used to assess each aspect of sustainability could help to establish opportunities for tailoring or adapting these techniques to a life cycle perspective. As such, the main modelling approaches which are currently used within the space industry to measure environmental, social, economic and sustainability impacts as they relate to TBL sustainability are provided in the following subsections. Of the main modelling approaches discussed, due to the volume of different methods which can be applied, only the most relevant for each technique with regards to their applicability to LCSA and concurrent design sessions of space missions are explored.

3.4.1 Environmental Life Cycle Assessment Modelling

The space-specific E-LCA framework outlined by ESA provides a common methodological approach and set of rules which should be followed when performing space related E-LCAs. As part of this framework, the creation of a new space-specific E-LCA database and CDF ecodesign tool has allowed environmental impacts of space systems to be scientifically modelled for the first time. In turn, this has assisted decision-makers to decrease environmental impacts of future space missions through specific design choices whilst also facilitating the replacement of existing technologies with new and greener alternatives. However, since methods for modelling environmental impacts of space missions has already been demonstrated in Chapter 2, the remainder of this section will concentrate exclusively on how social, economic and sustainability impact modelling is currently applied within the space sector.

3.4.2 Social Aspect Modelling

Assessing social impacts of space missions is becoming more critical if the space sector is to actively contribute to the realisation of the 2030 Agenda. However, as identified in Subsection 3.2.2, social aspects are currently not considered within the concurrent design process of space missions. Expanding this approach, SEIAs are typically used in practice to determine wider social and economic benefits of a programme or mission, including spin-offs [174]. However, this is not a standardised method of assessment meaning that the applied scope and methodologies tend to vary considerably between studies [194]. Despite this, there are some commonalities. These relate to the general required taxonomy for SEIAs which consists of a definition of impacts, multipliers and indicators [46].

With regards to defining impacts, SEIAs principally adopt a qualitative approach for listing social impacts or quantify these impacts economically. When adopting a quantitative economic method, one of the most commonly applied approaches is to calculate impacts based on output per gross domestic product (GDP) [195]. The GDP impact approach is used to identify the range of the economic activities resulting from a public investment. This is typically achieved by measuring the direct, indirect or induced GDP impacts [196]. Direct GDP impact refers to the economic activity deriving from upstream capital spending of an industry so that it may carry out its intended activities. Indirect GDP impact is similar to direct GDP impact but looks further down the value chain to the economic activity which is supported by the expenditures of suppliers in goods and services to support industry orders. Induced GDP impact refers to economic activity supported by those directly or indirectly employed in a given industry spending their incomes on goods and services in the wider economy [195].

A multiplier is a factor that quantifies a change in a given dependent variable (usually revenues or GDP) compared to the injection of capital [46]. For example, when considering GDP impact, the GDP multiplier concept relates initial capital investment to the final resulting GDP effect. As such, GDP multipliers determine the expected immediate impact (in time) of spending into a sector, accounting for the additional gross value added created in the economy in the very short term. This concept is based on input-output methodologies (which is not well suited to the space sector for E-LCA). There are two main types of GDP multipliers which exist based on the GDP impact approach [45]. These are outlined below:

$$Type\ I = \frac{Direct\ Impact + Indirect\ Impact}{Investment} \tag{3.2}$$

$$Type\ II = \frac{Direct\ Impact + Indirect\ Impact + Induced\ Impact}{Investment} \tag{3.3}$$

Indicators are parameters or benchmarks which are used to monitor the performance of a given economic or industrial sector. They are applied to assess multiplying effects, particularly related to GDP impact [38]. A list of suggested indicators for systematic assessment of impacts of space activities was provided as an output of an evaluation on socio-economic impacts of space activities in the EU [197]. This list is outlined in Table 3.1 below which also provided indicators for qualitative social impacts.

Table 3.1: Indicators for systematic assessment of impacts of space activities [197]

Indicator Type	Example Indicators
Indicators of economic activities	Industry revenues, Gross Value Added, Profitability, Exports, Market Share, Productivity
Employment indicators	Employment, Employment of highly skilled personnel
Institutional funding	Budget as % of GDP
Catalytic indicators	Downstream industry sales (EO data sales, GNSS devices and services sales)
Knowledge and IP creation indicators	Number of patents, Number of publications, Number of academic programmes
Technology transfer indicators	Number of spin-off companies, Number of spin-off products
Non-quantifiable externalities indicators	Attractiveness of careers in space
Domain specific technology adoption indicators	Number of EO Earth user stations, Number of GNSS equipped vehicles, Number of flight procedures based on SBAS, Number of communication satellites in orbit, space launch activity

Clearly this economic SEIA method is not directly applicable to S-LCA since it relates socio-economic benefits to socio-economic costs, opposed to directly quantifying holistic social impacts. However, this method is used within SEIA because social impacts can be very difficult to measure in quantitative terms [198]. In order to address this, many SEIAs will contain a separate social impact assessment for all qualitative social impacts [199–201]. Methodologies significantly vary for this part of SEIA, but impacts are typically identified and measured using surveys, focus groups or interviews [47]. Although no multiplier is required for qualitative social impacts, indicators may be applied where appropriate to give these social results meaning. These impacts are generally communicated as standalone results in reports, separate from economic SEIA method results.

Despite this, the methodologies adopted by some space-related SEIA studies are beginning to align more closely with an LCT approach. In particular, a new data classification framework was developed in a study to evaluate the socio-economic impacts of space activities in the EU [197]. This framework was built from a generally accepted taxonomy for socio-economic impact based on macroeconomic theory. The taxonomy was developed by reviewing the underlying assumptions and methodologies used within different space-related SEIAs. Data presented among these studies was then reclassified in accordance with the proposed common taxonomy and used within the study. However, in a second study on the same topic, a value chain approach was adopted which did not use this standard taxonomy. The reason for this change was due to difficulties concerning data acquisition and its applicability to the new data classification framework. As such, a new value chain approach to socio-economic impact classification was applied to "build on the set of available data to provide a coherent, complete and easily monitorable overview of how space activities impact the EU economy and society" [45].

Building on this approach, the ex-ante SEIA of Clean Space adopts a similar value chain perspective, but goes one step further by providing an example of potential metrics/indicators for key social drivers [174]. Although the basis to this assessment is still fundamentally an economic analysis, the key social drivers and indicators used are similar to the stakeholder subcategory indicators required within S-LCA. The key social drivers used as part of this study remain strictly confidential, however using a framework of indicators within S-LCA may allow life cycle social impacts to be benchmarked in order to gauge social performance.

3.4.3 Cost Estimation Modelling

In terms of economic impacts, space mission expenditure is typically calculated using cost estimation models. These models are commonly used within space mission design sessions to estimate the overall cost of a mission or programme, with their output generally considered to be one of the most important design drivers. According to NASA, the type of cost estimation method used will primarily depend on the adequacy of the mission definition, level of detail required, availability of data and time constraints [54]. In this regard, three main types of cost estimating methodologies exist; parametric, analogous and grassroots. Parametric methodologies are statistical extrapolations of historic costs which are used at an aggregated level to make cost estimations. The technique is often used during conceptual studies in early mission design stages where there is limited mission definition [202]. The analogous methodology is a top-down approach which uses cost estimations from similar existing projects or studies to predict costs, adjusting for the complexity, technical or physical differences of the new system. This technique is typically applied once a mission design is more adequately defined but there is still insufficient actual cost data to use as a basis for a detailed approach. The grassroots methodology is a bottom-up estimate of every activity in the project's work breakdown structure including overheads. It is applied when there is adequate project maturity which allows far more detailed cost data to be accumulated despite being a lot slower and more labour intensive [203].

Despite the differences in these methodological approaches, NASA states that none of these techniques are individually sufficient to accurately estimate the life cycle cost of a space mission [54]. In practice, it is typically found that using a combination of these models through a hybrid approach provides the best cost estimates. Several estimating tools and models are available and used at NASA which often rely on a mix of methodological approaches. These are outlined in Table 3.2 below.

Table 3.2: NASA Cost Models and Tools [54]

Tool Type		ONCE Portal[14]	Estimating Methodology Applicability: Parametric	Analogy	Build Up
NASA-Sponsored Models and Tools					
Project Cost Estimating Capability (PCEC)			✓		
NASA Air Force Cost Model (NAFCOM)	*(Transitioning users to PCEC)*		✓		
NASA Instrument Cost Model (NICM)		x	✓	✓	
Technology Cost and Schedule Estimation (TCASE) Tool		x		✓	
Schedule Management and Relationship Tool (SMART)		*soon*	✓	✓	
Phasing Model		x	✓		
Schedule Estimating Relationship Risk Analysis (SERRA)			✓	✓	✓
Quantitative Techniques Incorporating Phasing and Schedule (QTIPS)			✓	✓	✓
QuickCost			✓		
One NASA Cost Engineering (ONCE) Database		x	✓	✓	✓
REDSTAR Database			✓	✓	✓
Models and Tools with NASA-Provided Licenses					
Polaris[4] *(JCL Analysis)*	x		✓	✓	✓
Argo (Monte Carlo simulation)		x	✓	✓	✓
Automated Cost Estimating Integrated Tools (ACEIT)		x	✓	✓	✓
CO$TAT (statistical analysis package)		x	✓	✓	✓
Joint Analysis of Cost and Schedule (JACS)	*(JCL Analysis)*	x	✓	✓	✓
SEER for Hardware, Electronics, & Systems (SEER-H)		*soon*	✓		
SEER for Software (SEER-SEM)		*soon*	✓		
PRICE® TruePlanning™			✓		
PRICE® Estimation Suite (PES)			✓		

According to Keller et al., the NASA/Air Force Cost Model (NAFCOM), the Parametric Review of Information for Costing & Evaluation Hardware model (PRICE-H) and the System Evaluation & Estimation of Resources Hardware model (SEER-H) are the only models sufficient enough in size and scope to model space projects [204].

Although the design of space missions relies on many technical considerations, managers and engineers are generally aware that their choices have large implications for the cost, schedule and risk of their mission [205]. Since about 80% of costs are set by choices made during early design stages [22], it means that introducing cost estimating modelling to conceptual design studies within the concurrent design process is an appealing option for engineers and decision-makers to control mission costs. Conceptual design studies which consider several options would dictate an estimating model requiring no actual cost data and limited mission definition on the systems being estimated. In this regard, a parametric methodology would be the most appropriate and is currently the most common cost estimation type applied within the space sector [206].

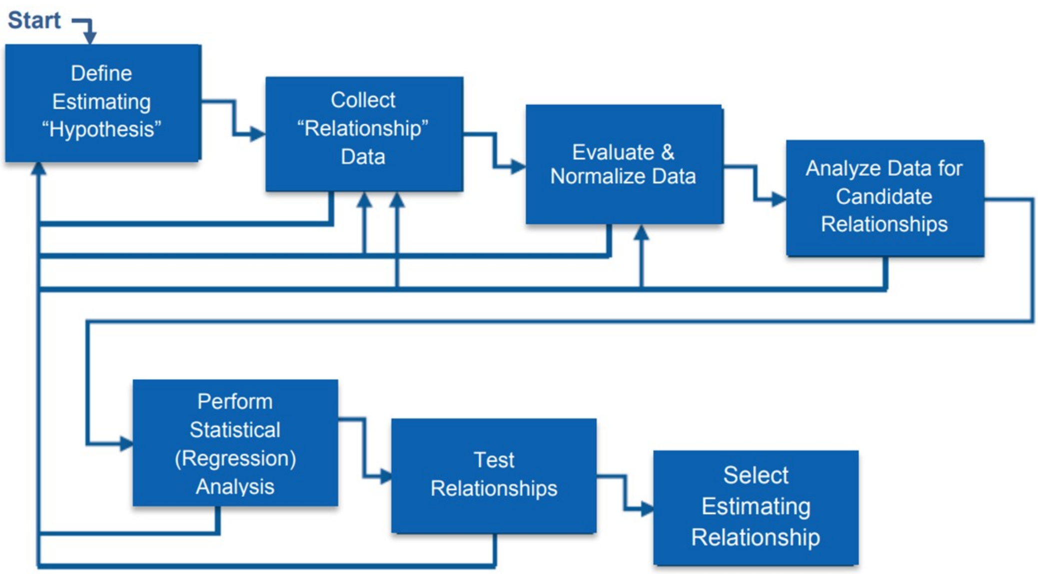


Figure 3.4: Parametric Cost Modelling Process as defined by NASA [54]

NASA identified seven methodological steps for parametric cost estimating within their Cost Estimation Handbook to streamline its application [54]. These are outlined in Figure 3.4 above. As part of this process, the methodology requires a series of regression analyses to be performed in order to determine the input drivers of the mission's total cost. These drivers are controllable system design characteristics which have a casual effect on system cost. As such, parametric models are generally classified by their base metric. The most common of these are weight-based models which apply a curve to describe relationships between mass and cost, and can be modified by a series of multipliers that range from team experience to material selection.

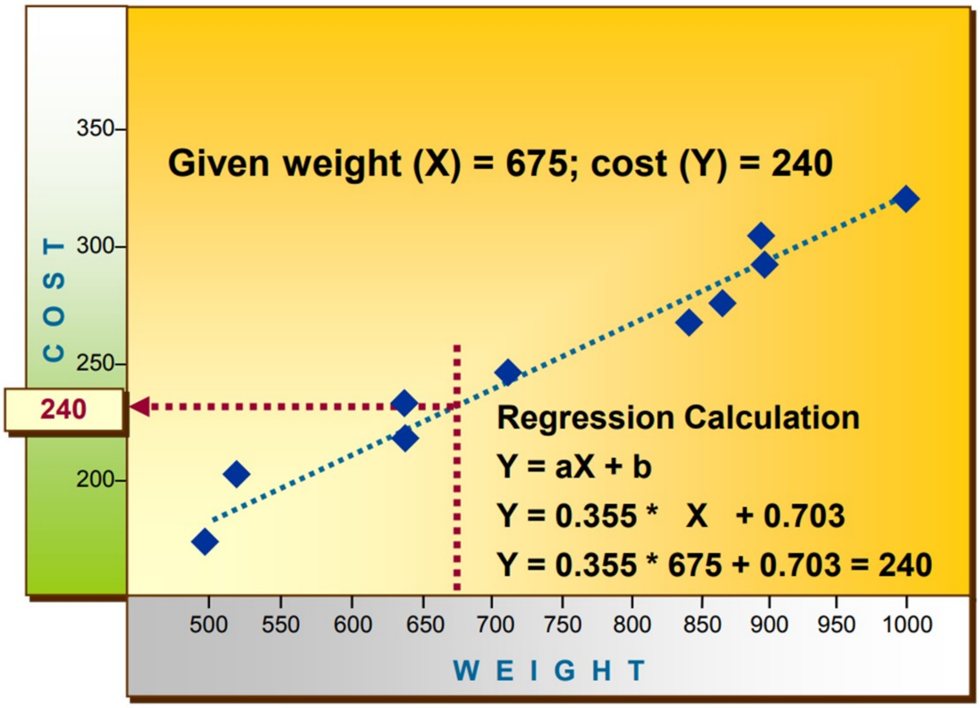


Figure 3.5: Example Cost Estimation Relationship of a Space System Component [54]

As such, a cost engineer will firstly gather and normalise cost data based on a predefined base metric defined by the estimating hypothesis. This normalisation may involve converting the data to a single predefined currency at net present value by taking inflation rates into account. The normalised data can then be plotted onto a scattergraph against its base metric (as can be seen in Figure 3.5 above). At this point, a regression analysis should be performed. Once this has been done, a CER can be produced by calculating the relationship between the dependent (Y) and independent (X) variables. This relationship can be expressed using the following equation:

$$Y = AX + B \tag{3.4}$$

Where x, y are coordinates of any point on the line of regression with y representing costs and x representing a unit of measurement to which costs are being compared (typically mass in the case of space system components), a is the slope of the line of regression, and b is the y-intercept.

However, this equation cannot be applied in all cases and should only be used when data is observably linear. Despite this, most nonlinear data can also be found to be intrinsically linear in some way [54]. For this reason, a suitable transformation of the dependent and/or independent variables could lead to a linear relationship being uncovered. An example of such a transformation includes re-plotting the data on a log-log chart. If the data appears to 'straighten out' on the log-log chart, then a power function in the following form may be appropriate:

$$Y = AX^B \tag{3.5}$$

Assuming that the most accurate model for such data is a power function, then taking the natural log of both sides of the power function yields:

$$\ln Y = \ln A + B \ln X \tag{3.6}$$

This is the equation for a straight line in fit space, where the transformed variables 'exist' with slope B and intercept ln A. In the event that relationships are still not suspected to exist for either linear, power, exponential or logarithmic curves, an approximate average can be provided based on the total mass and total cost of all normalised data points. Although this method is expected to be less accurate, it does provide a conservative approach to avoid a null value by producing a generic cost estimation.

Whilst parametric models are good at predicting within the bounds of similar projects, they are restricted with the introduction of new technologies due to their limited predictive capability [207]. This is because parametric models use historical data meaning that they are statistically limited in their ability to extrapolate beyond past programmes [204]. Past performance does not guarantee future results. As such, it can be argued that these models do not provide the level of insight necessary for decision-making and that these models should instead be used as a tool to control programme costs rather than attempt to predict them. For this reason, all CERs should be tested and verified by the cost engineer before being selected for use within the cost model or applied within the cost study [204]. This ensures that each CER accurately reflects the cost of the system it is trying model as far as practically possible.

3.4.4 Sustainability Impact Modelling

Sustainability impact modelling explores the inter-related consequences of environmental, social and economic impacts deriving from a development, product, programme or service. However, due to the novelty of introducing TBL sustainability into product-based assessment within the space industry, no cases of sustainability impact modelling for space missions could be found, besides the space sustainability rating proposed by WEF [59]. This is because environmental and economic impacts of space missions are currently treated as separate components within the sector, whilst social impacts are not considered at all [33]. Indeed, the only time where the three components of TBL sustainability are addressed collectively is within annual CSR reports of space actors.

CSR reports are documents which are periodically published by organisations to publicise their corporate social actions and results whilst improving transparency in business activities. As such, CSR reports provide a synthesised overview of TBL sustainability impacts attributable to the organisation. These impacts are based on accurate and insightful data which can be used to help improve organisational practice. CSR reports also importantly allow organisations to communicate their sustainability goals and targets to stakeholders, including any improvements which have been made since the previous CSR report. Typically such reports have a strong focus on social issues, but also include environmental impacts and occasionally economic aspects such as budget breakdown and spending [58]. Although no play-off between sustainability dimensions occurs, CSR reports could provide a good source for organisation-specific LCSA data, particularly relating to social impacts.

Since the adoption of the 2030 Agenda, many organisations are beginning to align their CSR key performance indicators (KPIs) with the Sustainable Development Goals (SDGs) and their associated targets. In terms of the space sector, ESA provide a range of KPIs within their annual CSR report which also address each aspect of sustainability [57]. Although these KPIs do not specifically consider the SDGs, ESA have already aligned their programmes with the SDGs and specify which of their programmes will help to achieve each SDG [65]. In this regard, from a LCT perspective, UNOOSA are also considering launching a study that will investigate the possibility of integrating the SDGs into E-LCA of space missions using a single score approach which takes other agendas such as the Paris Agreement into account [208, 209]. To do this, UNOOSA propose aligning the indicators and targets of selected SDGs to the existing space-specific E-LCA framework, using the SDGs as endpoints which are also capable of generating a single score. Additionally, the ESA Clean Space Initiative recently stated that considering life cycle social and economic aspects of space missions may be a natural transition in the future [33]. If this approach is to be adopted, then integrating the SDGs into other elements of the LCSA framework such as S-LCA or LCC may provide a more streamlined approach towards sustainability.

3.5 The Sustainable Design Process for Space Missions

Sustainable design is a procedural tool which builds on the ecodesign process outlined in Figure 2.13 by additionally taking social and economic impacts into account to generate solutions that consider the entire life cycle of a product [210]. The method allows key factors for sustainability to be considered within the product design process and enables decision-makers to modify their designs based on a number of predefined objectives [211].

As such, the sustainable design process closely aligns itself with the LCE concept which aims to find a balance between societal needs, economic growth and minimising environmental impacts in product engineering. Therefore, sustainable design is closely related to and often applied using principles of LCSA in order to facilitate LCE. For this reason, creating a framework for space-specific LCSA which is robust enough to be used as part of the sustainable design process is necessary if space missions are to be designed in a manner which considers the full spectrum of TBL sustainability dimensions. In this regard the framework will outline and propose a new methodology which allows LCSA to be implemented within the concurrent design process of space missions based on best practice.

3.5.1 Methodological Challenges Related to LCSA

According to the UNEP/SETAC guidelines [179], LCSA should methodologically conform to ISO 14040:2006 and 14044:2006 standards. This suggests that E-LCA in its current form is already applicable for use within LCSA. However, this has implications for the other LCSA components, meaning that S-LCA and LCC data may require careful manipulation to conform with the functionality of existing E-LCA LCI datasets. For this reason, if space-specific LCSA is to be applied, it is important to properly investigate and address potential methodological challenges relating to the LCSA methodology.

Notwithstanding, despite the robustness of certain aspects of LCSA, several methodological challenges still exist. In this regard, the three most commonly cited relate to the low maturity of the S-LCA approach (particularly relating to the lack of quantitative social indicators) [10, 13, 180, 212–219], how to interpret the interrelationships between the three sustainability dimensions when used in the decision-making process [13, 180, 212, 218–222] and the lack of practical demonstrations showcasing best practice for LCSA [13, 213, 217, 219, 223, 224]. As such, it is important to explore these issues and the complications that they present.

In relation to the first point, the main limitation of the S-LCA approach involves maintaining consistency with other quantitative life cycle studies due to the LCI typically containing a mix of quantitative and qualitative data [175]. This has numerous methodological ramifications ranging from selecting appropriate social indicators to creating an appropriate scoring system for social impacts [225]. In particular, there is a lack of international consensus relating to the selection of social indicators meaning that the indicators which are applied can significantly vary between studies. This is because it can be very hard to quantify the nature of impact areas since these will typically change with the behaviour of the company. The FU is also less clear for performance reference point methods. This is because these attribute social impacts through proxies (e.g. working hours or monetary values or a combination of both) [225]. The casual link between these proxies or activity variables and social impacts are often tenuous. A linear relationship between magnitude of the social impact and the proxy is assumed and this has to be taken with caution, particularly for social impacts which are largely qualitative in nature. Unlike E-LCA where impacts are mostly negative, social impacts may also be distinctly positive depending on their nature. This is problematic since life cycle modelling mainly assumes a burden-based approach. Methodologically it may be difficult to account for positive social impacts due to the evaluation scheme which can be subjective in context.

If the LCSA framework is to be used within the decision-making process then careful interpretation of results are required, including how each sustainability dimension interacts within one another [179]. However, reaching a conclusion based on the combined results of each of the three individual assessments is a complex procedure. This is because the three assessments of LCSA are not directly comparable to one another due to their nature, objectives and existent trade-offs [219]. This presents a problem if LCSA results are to be used for product improvement purposes. As previously stated, LCSA results can be analysed based on two options; viewing the LCIA results of each assessment as standalone results or using S-LCA and LCC as impact categories within E-LCA [10]. Regardless of which option is selected, it is clear that both of these approaches require the use of subjective evaluations. This is confirmed within the UNEP/SETAC LCSA guidelines where colour-coded diagrams representing the sustainability performance of each sustainability aspect assessment are given as an example of a potential method to convey LCSA results [179]. This example is provided within Figure 3.6 below which showcases LCSA results of marble slabs based on a concept developed by Traverso et al. [220]. The concept groups impact categories into a number of topics which are used along with LCSA inventory data to rank each sustainability aspect in terms of ideal performance (dark green) to worst performance (dark red). Therefore, it can be consider that some form of quantitative evaluation is required to reach such conclusion. This is a particularly important element of the LCSA process since it provides a method on which to score the three dimensions of sustainability. For this reason, numerous LCSA studies have formally investigated approaches for interpreting trade-offs between competing sustainability dimensions.

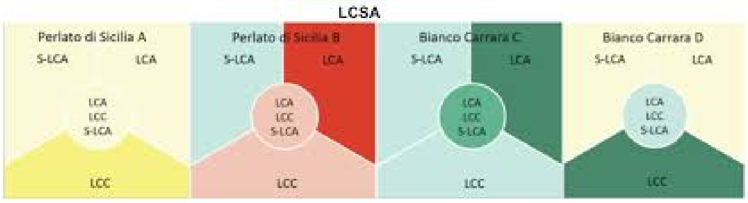


Figure 3.6: Colour-Coded Diagram presenting LCSA results of the marble slabs [179]

With regards to the lack of practical demonstrations showcasing best practice, this has led to a number of different methodological approaches being used for LCSA application. For this reason, it could be considered that the development of a standardised LCSA framework is required in order to direct the application of this assessment type in the future. In this context, Hannouf & Assefa propose a new systematic and structured LCSA framework for decision-analysis which can be used to appraises potential sustainable design solutions based on LCSA results and evaluate their trade-offs [219]. However, this framework does not recommend a methodological approach for each sustainability element of the framework since this may be study or industry specific. This could hinder its application in the future due to the methodological challenges already outlined within this subsection.

3.5.2 Tailoring Space-Specific Impact Modelling to LCSA

Having identified potential issues with the LCSA methodology, the applicability of modifying current sustainability modelling techniques for space applications towards LCSA can now be considered. Since E-LCA provides the foundations of the LCSA methodology, it has considered that the space-specific E-LCA approach developed by ESA does not require any form of adapting to make it appropriate to a space-specific LCSA study. Instead, only current social aspect and cost estimating modelling techniques for space systems will be investigated for modification towards the LCSA methodology. Combining and balancing these three aspects is discussed further in Subsection 3.5.3.

In comparison to S-LCA, SEIAs are a very contrasting modelling technique. In particular, the way in which SEIA information and data is calculated makes it highly unsuitable to S-LCA. This is due to the quantitative, qualitative and semi-qualitative nature of social impacts deriving from the methodology applied in SEIAs as well as their specificity to their mission which is often calculated based on an economic input-output analysis. S-LCA measures social impacts very differently, typically using predefined indicators and criteria as a measure of performance. The problem with both approaches is that a common and agreed methodology does not exist. In terms of S-LCA, this particularly refers to both the selection of impact indicators and scoring mechanisms to measure the relevance of social data during the LCIA phase [226].

Although a list of indicators are provided within the UNEP/SETAC S-LCA methodological sheets [183], these are generally considered outdated since they are mainly based on the MDGs. In particular, Martínez-Blanco et al. categorised the 189 indicators contained within the current UNEP/SETAC methodological sheets into different levels based on their data sources and their suitability to assess performance [227]. The results from this process are provided in Figure 3.7 below.

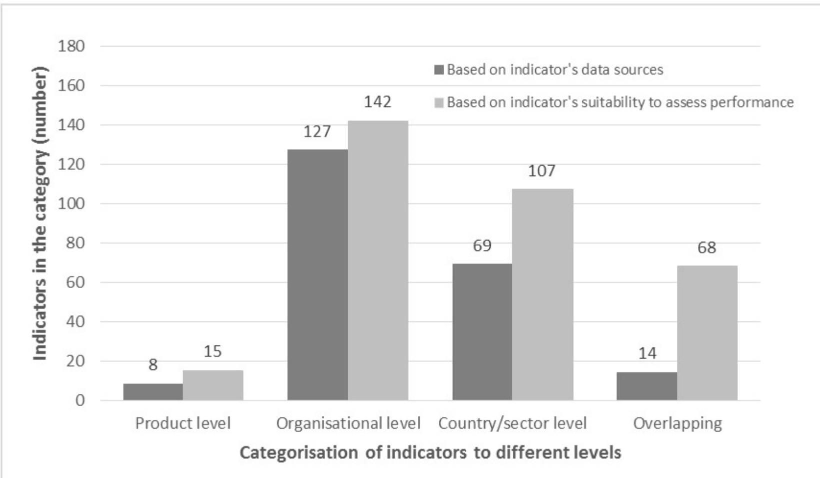


Figure 3.7: Categorisation of the UNEP/SETAC social indicators [227]

This clearly shows that these indicators are better suited at performing an assessment at organisational-level, suggesting that S-LCA in its current form does not readily fit into the traditional product-based form of assessment like E-LCA or LCC. For this reason, they propose that S-LCA adopts a new organisational perspective in order to enhance the scope of the assessment and make it more applicable for use [227]. Although the SETAC/UNEP S-LCA guidelines are currently going through a revision process to provide a more robust methodology (with a planned release date of late 2019) [228], this organisational perspective is perhaps more applicable for use within S-LCA at present at least until the updated guidelines are published.

The proposed organisational approach to S-LCA aims to adapt traditional product S-LCA to an organisational perspective to improve the social performance of an organisation, its value chain and all stakeholders. As such, the main difference lies in the unit of analysis [227]. Whilst function is the main basis for units of analysis in product S-LCA, the unit of analysis used for organisational S-LCA is the organisation, its value chain and stakeholders according to the ISO/TS 14072:2014 standard on the requirements and guidelines for organisational life cycle assessment [229]. As such, the approach requires a reporting organisation to be defined as the reference unit which represents the quantification of the product portfolio.

However, current S-LCA databases do not align with the organisational approach suggested within the space-specific LCSA guidelines. Two of the most commonly used S-LCA databases are the Social Hotspots Database (SHDB) and Product Social Impact Life Cycle Assessment database (PSILCA) [230]. SHDB is an input-output LCI database whilst PSILCA is also based on an input-output model which contains 53 indicators across 1,500 sectors in 189 countries [231,232]. Additionally, the Soca database is the first attempt to combine environmental, social and economic aspects in one single database. It is an add-on for Ecoinvent which has added some primitive cost assumptions for certain processes and combined PSILCA indicators to each activity and process contained within the Ecoinvent v3.3 database for all system models [233]. However, as these databases adopt an IO approach, this makes them even more unsuitable to the specificities of the space sector.

If this organisational S-LCA approach is to be adopted instead of traditional IO or SEIA economic analyses for social impact quantification, then a variety of appropriate social indicators and unit of measurements with an applicable measurement unit need to be developed. As such, S-LCA indicators can either be developed generally for applicability with any space mission or created more specifically by establishing several sets of indicators which are dedicated to different mission types. Whilst it can be argued that the second option is most appealing, the first option is perhaps more applicable when adding social aspects to LCI datasets since many space system components are used in a variety of space mission types. This means that all information can be contained within a single LCI dataset without the need for user manipulation before it is applied due to flow duplication based on mission type.

However, linking indicators with product E-LCA and LCC data in a single LCI dataset could be problematic due to the different methodological approaches used and also since social impact changes with the behaviour of the organisation [234]. For this reason, a mechanism which links the organisational and product unit of analysis within a singular dataset is required. This could perhaps be achieved using an appropriate activity variable (e.g. working hours or monetary values or a combination of both). However, the casual link between activity variables and social impacts are often tenuous [175]. For this reason, a given linear relationship between magnitude of the social impact and the activity variable has to be taken with caution, particularly for social impacts which are largely qualitative in nature.

Each of these indicators then need an evaluation scheme on which gathered social data can be compared using the selected unit of measurement. Suggested evaluation schemes range from the use of performance reference points to proper characterisation through social impact pathways [235]. However, comprehensive, applicable, and tested impact assessment models are not yet available for S-LCA. Goedkoop et al. introduces a LCIA scoring mechanism for performance indicators which is based on a point-based reference scale [225]. An example of this is provided in Figure 3.8 below. However, this methodology provides no evaluation scheme on which to measure social performance. One interesting technique which could be used for this purpose is the re-interpretation of SDG indicators within S-LCA to enable the businesses to actively contribute to the 2030 Agenda [236]. As such, this allows the SDGs to be linked to business practice and frame decisions regarding product strategy and development.

+2	Ideal performance; a positive output achieved and reported
+1	Progress beyond compliance is made and monitored
0	Compliance with local laws and/or aligned with international standards
-1	Non-compliant situation, but actions to improve have been taken
-2	No data, or Non-compliant situation; no action taken

Figure 3.8: Example scoring mechanism for S-LCA performance indicators [225]

Since S-LCA is a relatively new field of research with limited consensus on indicator selection, using the goals, indicators and targets contained within the 2030 Agenda is an interesting approach which would allow product assessment to align more closely with the most dominant political framework for sustainability currently in existence. The 2030 Agenda expands on the MDGs which were agreed by governments in 2000 and expired at the end of 2015 [4]. It outlines 17 SDGs and 169 associated targets. These are supported by 232 indicators developed by the Inter-agency and Expert Group on SDG Indicators (IAEG-SDGs) and were developed for monitoring the goals and targets [237]. Each of the 193 UN Member States who adopted the Agenda are expected to use these goals, targets and indicators in order to frame their agendas and political policies to 2030. Despite this, the SDGs are still not widely implemented into business practice, and the sheer number of targets and indicators implies an obvious risk of cherry-picking and sub-optimised decision-making [238]. For this reason, the possibility of directly integrating the SDGs into the LCSA methodology is currently being explored by numerous organisations and researchers [239]. Adopting such an approach may be a credible and compelling potential method of streamlining decision-making and monitoring in a more systematic and coordinated fashion which accords with this renewed vision of sustainability. However, since the SDGs are predominantly targeted towards a national and international audience, this means that the goals, targets or indicators do not particularly fit as a metric for product assessment [225]. To close this gap, it is necessary to identify which of these could be adapted for use at product-level and be formulated into LCSA indicators or evaluation criteria which relate to specific SDGs and targets.

In terms of LCC, parametric cost estimation models are commonly applied within LCC studies. As such, most cost estimation models for space systems are used exclusively or in conjunction with other costing models for LCC studies in practice [55]. However, thus far, no space-specific costing data or CERs have been integrated with environmental and social data within a single LCI dataset. Adding CERs for each identified life cycle cost element in a process may be a challenging task since E-LCA LCI datasets mainly predict or rely upon linear relationships. However, LCC is rarely linear which adds complexity if LCI data for each type of assessment are to be combined within the same dataset. This is particularly relevant when considering the law of scale (i.e. although mass production of products will increase costs, the cost per unit will decrease). This cannot always be fully expressed in CERs. Additionally, when a parametric model is applied to values outwith its data range, the resulting estimate becomes questionable [204].

In this regard, an interesting cost estimating methodology which could be applied is activity-based costing (ABC). ABC is an approach whereby costs of organisational activities are identified and assigned to products, processes, services and activities according to the actual consumption of each. According to Curran et al., the implementation of this technique is based on activity pools which are a collective set of activities [240]. Each activity pool is then allocated to a specific cost driver as a base (i.e. the amount of an activity used). All overhead costs are then determined and calculated per cost driver. As such, the method assigns more indirect costs elements into direct costs compared to conventional costing approaches and evidently aligns closely with the E-LCA modelling approach. Besides this, one of the main advantages of using this method is that the number of cost pools used to assemble overhead costs can be expanded. As such, new bases on which to assign costs are produced (i.e. FUs as cost drivers) which allows the nature of several indirect costs to be altered in a way which makes them more traceable to certain activities. Although this is a far more labour intensive approach, the method can often lead to a significantly more thorough and informative costing analysis [204].

An example of ABC application in space-related cost estimation models include the Process-Based Economic Analysis Tool (P-BEAT) by Boeing and NASA as well as the Process-Based Cost Model (PBCM) by the Science Applications International Corporation. These models adopt a similar approach to the ABC methodology but ultimately are still founded on parametric equations. Neither were adopted for use at NASA due to the amount of detail processing required to produce timely estimates [204]. Nevertheless, it is clear that this approach is the most closely aligned to the LCC methodology outlined in Subsection 3.3.4. Incorporating such a method within space-specific LCSA using specialised life cycle modelling software which has been explicitly developed to handle life cycle activity-related data of products therefore represents an interesting and compelling approach [241]. This is because the method allows other overhead elements which are not typically included within space systems cost engineering models (e.g. cost of heating and/or electricity consumption during design work) to be considered. As such, a more complete cost model can be developed which better aligns with the current LCC methodology whilst covering the sum of DDT&E, launch & emplacement and operations costs and beyond.

3.5.3 Applying Multi-Criteria Decision Analysis

When interpreting trade-offs between sustainability dimensions, a systematic and structured decision-analysis technique is required to assist decision-makers to evaluate and improve the sustainability performance of a product. A commonly used and fascinating technique in this regard is multi-criteria decision analysis (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 [219]. It is increasingly being applied to LCSA studies to address the multidimensional results of LCSA and is recognised by many researchers as a critical component of LCSA.

As documented by Velasquez & Hester [242], various methodological approaches exist for MCDA, but of particular relevance to LCSA is the multi-attribute value theory (MAVT) approach [243]. 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 [244]. 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:

$$v(a) = \sum_{i=1}^{I} w_i \; v_i(a) \tag{3.7}$$

Where $v(a)$ is the overall sustainability score 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.

With reference to the ISO E-LCA framework [5, 6], this technique may require normalisation and weighing procedures to derive the score reflecting performance of each sustainability aspect. This is because MCDA typically uses weighted sums of normalised outputs obtained by direct elicitation procedures to generate sustainability results [245]. As such, this approach typically uses NFs and WFs in order to come to a single score for sustainability which identifies the relative importance of addressing each sustainability dimension [246].

NFs are reference values which can be used to compare the total impact of each impact category and convert LCIA results into common units across all impact categories [247]. From a European perspective, the most widely used normalisation methods and data for environmental footprints were developed by the EC JRC [248]. These factors typically relate to domestic inventories (national, regional or global), domestic inventories per citizen and planetary boundaries [249–251]. As such, dividing the LCIA results by the selected NF provides a score reflecting performance for each impact category (i.e. impact per reference situation). A list of the most common normalisation approaches and values developed by the EC JRC for E-LCA are outlined in Table 3.3 below. However, it is important to note that not all NFs cover all impact categories or their chosen methodologies. Additionally, applying NFs can be problematic for S-LCA and LCC since no globally accepted normalisation method currently exists for S-LCA due to the low maturity of the approach whilst normalisation is not typically applied within LCC. As such, no applicable NF could be found for S-LCA or LCC. This means that unique NFs for the S-LCA and LCC methodologies applied within the LCSA study may have to be created if this technique is to be pursued.

Table 3.3: Normalisation Methods & Values proposed by the JRC for E-LCA (adapted from [249–251])

Impact Category	Unit	Total Worldwide Emissions (2010)	Worldwide Emissions per Citizen (2010)	Total EU-27 Emissions (2010)	EU-27 Emissions per Citizen (2010)	Estimated Planetary Boundaries	Overall Robustness
Air Acidification	kg SO_2 eq.	1.23E+10	1.78E+00	7.55E+08	1.51E+00	3.20E+10	High
Climate Change	kg CO_2 eq.	5.79E+13	8.40E+03	4.06E+12	9.22E+03	6.79E+12	Very High
Eutrophication (Freshwater)	kg P eq.	5.06E+09	7.34E-01	7.41E+08	1.48E+00	5.79E+09	Medium to Low
Eutrophication (Marine)	kg N eq.	1.95E+11	2.83E+01	8.44E+09	1.69E+01	2.00E+11	Medium to Low
Ionising Radiation	kg U^{235} eq.	2.91E+13	4.22E+03	5.64E+11	1.13E+03	N/A	Medium
Ozone Depletion	kg CFC-11 eq.	1.61E+08	2.34E-02	1.08E+07	2.16E-02	5.38E+08	Medium
Photochemical Oxidation	kg NMVOC	2.80E+11	4.06E+01	1.58E+10	3.17E+01	2.62E+10	Medium
Resource Depletion (Fossil)	MJ fossil	4.50E+14	6.53E+04	N/A	N/A	N/A	Medium
Resource Depletion (Minerals)	kg Sb eq.	4.39E+08	6.36E+04	5.03E+07	1.01E-01	N/A	Medium
Toxicity (Freshwater Aquatic)	PAF.m^3.day	8.15E+13	1.18E+04	4.36E+12	8.74E+03	1.31E+14	Low
Toxicity (Human)	cases	3.54E+06	5.14E-04	2.84E+05	5.70E-04	N/A	Low
Water Consumption	m^3	7.91E+13	1.15E+04	4.06E+10	8.14E+01	6.85E+11	Medium to Low

Once the normalisation step has been applied to LCIA results, WFs can then be used. Similar to the normalisation approach, the JRC also provides a range of meta-weighting factors for E-LCA impact categories based on their relative importance (i.e. the severity of the threat) from a European perspective [252]. Meta-weighting is typically used to provide the magnitude of the problem with respect to other impact categories by multiplying these factors with the normalised LCIA results [253]. The JRC factors developed are outlined in Table 3.4 below which are based on a mixture of evidence-based and expert judgement. As such, it can be argued that this technique can add severe subjectivity to results. Additionally, WFs may not be applicable for S-LCA or LCC since both assessments types may already use common units of measurement due to their nature (e.g. social scores and currency at net present value). This means that the results of these two assessments can be communicated directly as a single score based on normalised values without the need for weighting. However, if this approach is to be applied, it is important that normalisation is still applied in a consistent manner to E-LCA so that the three assessment types are comparable.

Table 3.4: Weighting Method & Values proposed by the JRC for E-LCA [252]

	Aggregated weighting set	**Robustness factors**	**Intermediate Coefficients**	**Final weighting factors (incl. robustness)**
	(A)	(B)	C=A*B	C scaled to 100
Climate change	12.90	0.87	11.18	**21.06**
Ozone depletion	5.58	0.60	3.35	**6.31**
Human toxicity, cancer effects	6.80	0.17	1.13	**2.13**
Human toxicity, non-cancer effects	5.88	0.17	0.98	**1.84**
Particulate matter	5.49	0.87	4.76	**8.96**
Ionizing radiation, human health	5.70	0.47	2.66	**5.01**
Photochemical ozone formation, human health	4.76	0.53	2.54	**4.78**
Acidification	4.94	0.67	3.29	**6.20**
Eutrophication, terrestrial	2.95	0.67	1.97	**3.71**
Eutrophication, freshwater	3.19	0.47	1.49	**2.80**
Eutrophication, marine	2.94	0.53	1.57	**2.96**
Ecotoxicity freshwater	6.12	0.17	1.02	**1.92**
Land use	9.04	0.47	4.22	**7.94**
Water use	9.69	0.47	4.52	**8.51**
Resource use, minerals and metals	6.68	0.60	4.01	**7.55**
Resource use, fossils	7.37	0.60	4.42	**8.32**

When used together, the normalised and weighted results can then be applied as the score reflecting performance of each sustainability aspect within Equation 3.7. These can then be multiplied by another WF which reflects the weighting (or level of importance) of that sustainability dimension. Sustainability aspects can either be defined on an equally weighted basis or weighted based on the level of attention provided to the sustainability aspect through pre-defined or study-specific criteria. Typically, to avoid bias, the assigned WFs for each sustainability aspect within LCSA tend to assume equal importance [243]. The sum of the three MCDA results provides a single sustainability score where the relative importance of E-LCA, S-LCA and LCC results can be gauged in comparison to one another. Since it is extremely rare that a sustainable design decision will directly lower the results of each impact category or sustainability aspect, this is an extremely useful approach which helps to solve the inter-relationship problem between sustainability aspects as a whole based on their relative or absolute importance.

3.5.4 Proposed Method for Sustainable Design of Space Missions

Based on the findings of this chapter, it can be argued that the current E-LCA framework and LCSA guidelines do not go far enough when applying principles of sustainable design. For this reason, an adaptation of the ISO E-LCA framework is required to tailor this technique to LCSA in the context of space mission design. A new framework which considers MCDA as an additional step within the decision-making process is therefore proposed within this thesis as the basis for conducting LCSA. This is outlined in Figure 3.9 below and was developed based on the contents of the UNEP/SETAC LCSA guidelines and ISO 14040:2006/14044:2006 framework [5,6,179]. As such, the new framework should be seen as an extension of these guiding principles rather than an alternative to them.

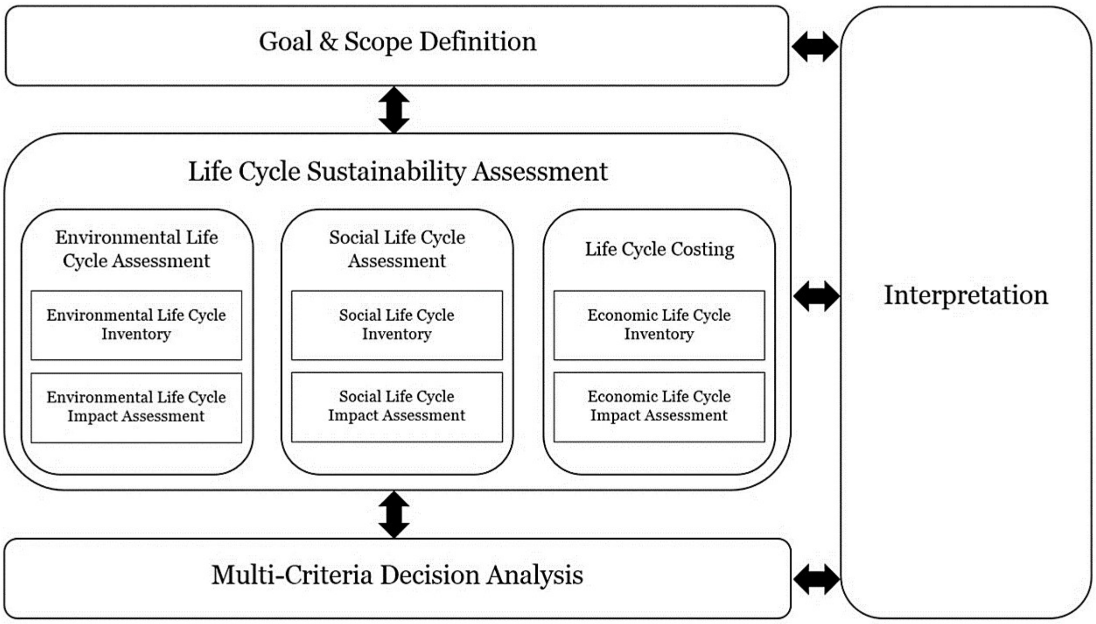


Figure 3.9: Proposed LCSA Framework for Sustainable Design of Space Missions

Consistent with the UNEP/SETAC LCSA guidelines [179], the framework includes the use of a shared goal and scope which considers the specificities of each assessment. This includes the adoption of same FU and system boundary which should be determined based on the perspective of the producer to support management and planning.

The LCI analysis and LCIA of each assessment type should be based on the most relevant methodology in the context of LCSA when it is applied to early space mission design phases. In particular, E-LCA should be seen as the baseline on which S-LCA and LCC criteria can be applied [179]. As such, E-LCA shall be conducted in a manner which is consistent with the approach specified by the ESA E-LCA guidelines.

The S-LCA LCI should be formed using a burden-based approach in order to be more comparable with E-LCA and LCC, hence replicating their general methodologies. Although it can be contemplated that space missions may create a distinctly positive social impact (e.g. through environmental monitoring, catastrophe prevention, etc.), it can generally be considered that SEIAs are a more appropriate assessment type to capture such impacts, meaning that positive social aspects are therefore outside the scope of S-LCA from a sustainable design perspective. Instead, defining social impacts by levels of risk may be a more appropriate method which also allows each social aspects to be compared. Additionally, an organisational-based approach should be adopted since the data sources listed for the social indicators suggested within the UNEP/SETAC 'Methodological Sheets for Subcategories in Social Life Cycle Assessment' are mainly pitched at organisational-level [227]. This makes adapting or creating a range of new indicators for a product-level approach extremely difficult. However, due to the unique nature of space systems and the fact that they are not commonly created within a mass production cycle, this disfavours a product-level approach in any case. As such, adopting the organisational method enhances the scope of the assessment and makes it more applicable for use. As part of this, a range of newly developed custom-made social indicators should be applied which are tailored to the specificities of the space sector and its supply chain. To further align with the 2030 Agenda, a viable technique which is proposed for this in the absence of standardised methods is to base indicator formulation on the SDGs. An appropriate scoring method should also be identified, including an applicable evaluation scheme with relevant benchmarks on which to measure LCI results. The stakeholder categories and subcategories suggested within the UNEP/SETAC S-LCA guidelines [181] are recommended as LCIA impact categories. Additionally, it would be advantageous for the applied scoring mechanism to use a single common unitary value in order to aggregate results as an impact category within E-LCA, thereby facilitating both options on which to evaluate LCSA results as proposed by Klöpffer [10].

Due to its applicability during conceptual studies, a parametric methodology is proposed for LCC using an ABC cost estimating approach which is more in line with the life cycle methodology [12]. This should take into account appropriate exchange and discount rates to convert costs into net present value for a given currency. Although the LCIA phase is not strictly required within LCC, it has been considered as a mandatory requirement within this framework to make the results comparable to those of E-LCA and S-LCA. As such, all monetary values should be aggregated into economic cost categories, life cycle stages, activity types or cost elements. Since this methodology uses a single unitary value, it is also recommended that a single score is generated and integrated as an impact category within E-LCA for the same reasons as stated for S-LCA. Moreover, the conventional LCC should be followed opposed to the environmental LCC. This is due to the severity and unpredictability of fluctuations associated with external environmental costs which makes environmental LCC extremely difficult to calculate. In comparison, conventional LCC allows economic flows easier to map in relation to products, processes and services whilst being more relevant for costing a space mission. In this regard, the main difference between the LCC approach proposed by this framework and cost analyses which typically occur during concurrent design sessions of space missions is the complete number of cost pools used to assemble overhead costs which leads to a more detailed assessment being conducted. This approach can also be seen to be more resource efficient since it requires just one discipline expert to cover three assessments and eliminates the need for a separate cost expert.

The importance of MCDA to the LCSA methodology should not be understated since its ability to address the multidimensional results of LCSA is vital to the decision-making process. As part of this, normalisation and weighting methods are required in order to generate a score reflecting performance, despite the subjectivity this approach introduces to results. Although these are listed as optional elements within the ISO 14040:2006 and 14044:2006 standards, they have already been adopted by ESA to calculate single score results for E-LCA of space missions, thereby reducing the number of impact categories and simplifying the decision-making process. This is currently one of the only and most applicable methods for generating a single score in life cycle studies. As such, the method can be used to generate a score reflecting performance for each sustainability aspect and hence facilitate MCDA. Therefore, to align with the approach adopted within the ESA E-LCA guidelines [30], the recommended method for this is to apply normalisation and weighting values based on the methods provided by JRC for E-LCA. New NFs will need to be sought for S-LCA and LCC which most accords with the adopted approach for E-LCA. However, since both S-LCA and LCC are calculated as a single score, WFs are not necessary. The score reflecting performance can then be used within Equation 3.7 in conjunction with a WF for each sustainability aspect to enable MAVT. A new method for applying this weighting is also proposed within the LCSA framework. In this regard, the WFs are based on the percentage of SDGs which are aimed at tackling each sustainability dimension. This allows the three dimensions of sustainability to be appropriately balanced according to the level of concern given to each with respect to the contents of 2030 Agenda. For this reason, MCDA has been considered as a mandatory component of the LCSA framework proposed within this thesis for sustainable design of space missions.

In terms of interpretation, the ESA E-LCA guidelines state that environmental hotspots should be identified during this phase. As such, this can be considered to be a critical element of decision-analysis and interlinked with MCDA. Building upon the LCSA decision-analysis framework proposed by Hannouf & Assefa [219], it has been considered that the interpretation phase within this framework should consist of the following steps which should be repeated after each analysis:

1. Hotspot identification.
2. Objective identification.
3. Solution generation.
4. Solution evaluation.
5. Trade-off analysis.
6. Implementation/recommendations.

In particular, the hotspots can be identified based on absolute or relative values from the LCIA impact categories and/or MCDA results. A set of objectives are then proposed to address the hotspots defined in the previous step. After this, a range of possible solutions should be sought in line with these objectives. All identified solutions can then be analysed in order to determine their effectiveness. The trade-offs are evaluated collectively for all solutions to determine which delivers the most optimal sustainability performance in relation to the sustainability dimensions and technical requirements. The selected solution can then be recommended or implemented within the system design model.

The interpretation phase should also seek to provide a set conclusions, limitations and recommendations whilst addressing uncertainties and data quality where possible. Although critical reviews are required for E-LCA in the case of a comparison, according to ISO 14062:2002 they are not an essential component of ecodesign [157]. If this standard is to be followed, this also means that a critical review is not strictly required for sustainable design, but is perhaps advisable. This could be conducted by independent experts between space mission design sessions.

Besides the necessity of the methodological guidance outlined above, it is equally as important that the versatility of this framework (hereafter referred to as the 'space-specific LCSA framework') is also understood with regards to its application. For this reason, the commonalities and differences of E-LCA, S-LCA and LCC have been synthesised in terms of the main drivers, methodologies applied and the necessary data required in order to better understand the benefits and limitations of addressing them within the same space-specific framework. The outcome of this exercise is provided in Table 3.5 below. In particular, this table highlights the fact that each assessment has distinctly different drivers. Although E-LCA is mainly driven by environmental impact mediums, S-LCA is primarily based on principles of social responsibility outlined within ISO 26000:2010 [254], whilst LCC is commonly steered by predefined financial factors typically based on mission requirements and/or a CBS [184]. As such, this makes the strategy and methodological choices which are determined during the goal and scope definition an extremely important element of the LCSA process.

Table 3.5: Overview of the main drivers, methodologies & necessary data required for each assessment within the space-specific LCSA framework

	E-LCA	S-LCA	LCC
Drivers	❖ Human Health ❖ Ecosystems ❖ Resource Depletion	❖ Accountability ❖ Transparency ❖ Ethical Behaviour ❖ Stakeholder Interests ❖ Rule of Law ❖ International Norms of Behaviour ❖ Human Rights	❖ Market Costs ❖ Budget Costs ❖ Labour Costs ❖ Income Streams
Strategy / Methods	❖ Set FU & Reference Flows ❖ Create System Boundary ❖ Establish LCI	❖ Choose Perspective (product, org. or nat.) ❖ Select Process Activity Variables ❖ Identify or Create Applicable Social Flows ❖ Establish LCI according to Activity Variable	❖ Choose Cost Bearers ❖ Create Cost Pools / Elements / Flows ❖ Select Discount & Exchange Rate ❖ Calculate & Assign Costs to Flows
Required LCI Data	❖ Products & Co-Products ❖ Raw Materials ❖ Water Consumption ❖ Energy & Fuel Consumption ❖ Emissions to Air, Land & Water ❖ Waste ❖ …	❖ Social Issues Relevant to Identified Social Flows (at product, org. or nat. level from a variety of sources including interviews, surveys, questionnaires, focus groups, literature reviews, international norms / standards, national / international policies / laws / legislation, etc…	❖ Costs (recurring & non-recurring) ❖ Revenues (recurring & non-recurring)
Required Inputs During Mission Design Process	❖ Mass ❖ Time ❖ Energy ❖ Length ❖ Volume ❖ Number of Items ❖ …	❖ Organisation (name / type) ❖ Country of Operation ❖ Product / Process Association (details) ❖ Time of Involvement in Process (if known)	❖ Real Costing Data (not essential but beneficial where it can be obtained, particularly for cost of operations)
Impact Areas / Outputs	❖ Midpoints ❖ Endpoints	❖ Stakeholder Categories ❖ Stakeholder Subcategories ❖ Sustainable Development Goals	❖ Economic Cost Categories ❖ Life Cycle Stages ❖ Activity Types (based on CBS) ❖ Cost Elements

In this regard, the space-specific LCSA framework aims to follow a common goal and scope in order to reduce the effort required in impact modelling. Since current practice dictates that E-LCA is used as the baseline methodology on which S-LCA and LCC should be applied [179], there is a need to tailor these assessments to E-LCA. In terms of S-LCA, selecting activity variables which best accords with reference flows of processes can be extremely challenging if an organisational perspective is adopted. However, this is necessary to relate organisational social impacts to processes. This becomes even more challenging if new social indicators need to be created since a scoring mechanism will also be required based for both quantitative and qualitative inventory data. Therefore, linking social inventory data to activity variables and then relating activity variables to quantitative references is extremely important for inventory relevancy but may limit what could be considered appropriate to reflect this relationship. In terms of LCC, the creation of costing flows are a lot more simple since they adopt a product-based perspective like E-LCA. However, it is important to define the cost bearer which should generally be viewed from the perspective of the organisation responsible for designing the space mission as a baseline.

Additionally, although it was not captured within the table, LCI data acquisition for compilation within a database may also be extremely challenging for all three assessment types meaning that stakeholder buy-in is particularly important for compiling an accurate and relevant LCI. Despite the varied and diverse LCI data requirements, a well developed sustainable design tool should look to minimise the amount of additional data which engineers are required to provide in space mission design sessions. Therefore, should dedicated environmental, social and economic datasets be developed in accordance with the proposed space-specific LCSA methodology, then integrating these within the same dataset should sufficiently achieve this since all of the LCI data refers to a common quantitative reference. This is highlighted within the penultimate row of Table 3.5 which shows the modest amount of data that engineers should provide in order to facilitate sustainable design during concurrent engineering activities, if the space-specific LCSA framework is followed.

The outputs of each assessment are based on the LCIA methods outlined within the space-specific LCSA framework, which are further elaborated on in Chapter 4. Although life cycle hotspots will mostly depend on the goal and scope definition, it is generally found that within E-LCA, the spacecraft, launcher and propellant production & manufacturing produces the greatest impact across most impact categories. In comparison, it is hypothesised that S-LCA will mostly be affected by activities with high levels of organisational involvement (typically during spacecraft and launcher production & manufacturing) whilst LCC will mostly comprise of costs from labour, launcher acquisition and satellite operations.

It should also be noted that the impacts of each assessment are considered to be self-contained before MCDA is applied (i.e. no direct interactions between assessment types). Whilst reasons for this have already been discussed within this subsection for the relationship between E-LCA and LCC, Subsection 4.4.1 provides further details with regards to S-LCA. Ultimately, despite the limitations mentioned, addressing each assessment type within the same framework also offers numerous benefits. Assuming that the space-specific LCSA framework is followed and that buy-in can be achieved for LCI data collection, then aggregating these three assessments allows for complex environmental, social and economic and social data to be organised in a structured and common form to generate a more comprehensive overview of life cycle sustainability impacts of space missions.

Finally, the purpose of the space-specific LCSA framework is to assist industry to integrate LCSA into the concurrent design processes of space missions during early design phases. It is not the intention of the framework to dictate which methodologies should be applied to each sustainability aspect in a space-specific LCSA study, but instead provide robust and systematic methodological guidance based on best practice. This was identified from literature reviews with reference to the LCSA methodology and current practice within the space industry. The framework also aligns with the 2030 Agenda through MCDA since this balances the three sustainability dimensions. This alignment is also supported by the use of the SDGs to frame social indicator formulation. The implementation of this framework within the concurrent design process was also supported through the creation of a new space-specific LCSA database which is outlined in Chapter 4. This provides more information regarding the intricate details of this methodological guidance which can be followed when applying sustainable design to space-based applications. As such, the new database should be seen as an extension of this framework.

3.6 Chapter Summary

A new space-specific LCSA framework was developed within this chapter based on a literature review of current LCSA methodologies and practice relating to the application of social and economic criteria within space missions. The new framework aligns with the ESA E-LCA guidelines and suggests methods of best practice relating to the aggregation of E-LCA, S-LCA and LCC methodologies within one single space-specific assessment, in line with the 2030 Agenda.

The findings from this process showed that current methods to integrate social considerations into space mission design are not directly applicable to life cycle modelling. Additionally, there were severe limitations relating to the applicability of the current

S-LCA methodology for space application use. As such, an entirely new methodology has been proposed. Cost modelling within the space sector was found to be much more aligned with the required LCC methodology. As such, little adaption is needed to make this methodology applicable for LCSA. The utilisation of MCDA also allowed these sustainability dimensions to be 'balanced' in line with the 2030 Agenda in order to handle the importance and relevance of these multiple perspectives. Importantly, this will allow decision-makers to reach conclusions based on these multi-dimensional results.

Chapter 4

The Strathclyde Space Systems Database

4.1 Chapter Overview

The space-specific LCSA framework established within Chapter 3 provides a sound basis for directing the future implementation of LCSA within the space sector. However, without the use of a dedicated database to direct its implementation, the use of this framework would be significantly hindered. For this reason, the development of a new LCSA database for space systems is vital in order to demonstrate the applicability of this new methodology within the space sector.

As such, this chapter describes the process for creating the first ever space-specific LCSA database, which allows the new LCSA framework conceived in the previous chapter to be implemented. This is primarily based on the development of new E-LCA LCI datasets and LCIA methods which integrated social and economic criteria based on the proposed approach explained within the space-specific LCSA framework. It uses several case studies to provide examples relating to the implementation of the various life cycle stages drafted within the framework and provides an overview of database logistics.

4.2 A Life Cycle Sustainability Tool for Space Missions

The space-specific E-LCA framework developed by ESA (outlined in Figure 2.2) demonstrates that three components are required if LCSA is to be applied within the space sector. The first element is the creation of common methodological rules which govern its application. The second relates to the provision of specific datasets for performing the assessment. The third is based on methods which enables this assessment to be used within concurrent design sessions of space missions. It can be considered that the first element has been addressed within Subsection 3.5.4 with the creation of a new space-specific framework for LCSA. For this reason, in order to continuing building the LCSA framework of space systems, it is necessary that the second element is addressed in order to integrate social and economic concerns within E-LCA and assist with the delivery of this methodology within the space sector. The third element is considered within Chapter 5.

4.2.1 Overview & Justification

The number and importance of space-specific E-LCA studies have begun to grow in recent years, even outwith the confines of the ESA Clean Space Initiative and their contracts. However, the majority of these studies note that a lack of publicly available process E-LCA datasets for space systems severely restricts the completeness of their studies. In the case of Harris & Landis [17] who conducted an E-LCA for the Falcon 9 and Falcon Heavy launchers, this issue forced the need for a hybrid methodological approach which is a highly inaccurate method for conducting space-specific E-LCAs according to the ESA E-LCA guidelines [30]. The reason for this is because the ESA E-LCA Database is currently only available under contract to European stakeholders and Space Opera is also only available to ESA personnel [136]. Although ESA plans to disseminate these tools publicly in the near future, this clear gap of publicly available process LCI data for space may be restricting the wide-spread application of E-LCA within the space sector.

Speaking at the special UNISPACE+50 High-level Segment of the 61st session of

UN COPUOS in June 2018, Director of the UNOOSA Simonetta Di Pippo stated that "space tools are highly relevant for the attainment of all 17 Sustainable Development Goals and their respective targets, either directly, as enablers and drivers for sustainable development, or indirectly, as an integral part of the indicators for monitoring the progress towards the implementation of the 2030 Agenda for Sustainable Development" [255]. Despite this, the current E-LCA framework developed by ESA does not fully align with this vision since it only considers environmental impacts and no life cycle database dedicated to LCSA of space systems has ever been developed. In this sense, advancing the current space-specific E-LCA methodology towards a more encompassing sustainability assessment which balances the three dimensions of sustainability in the frame of the 2030 Agenda means that the space sector can actively contribute to the global sustainability agenda by becoming more accountable and responsible for their operations.

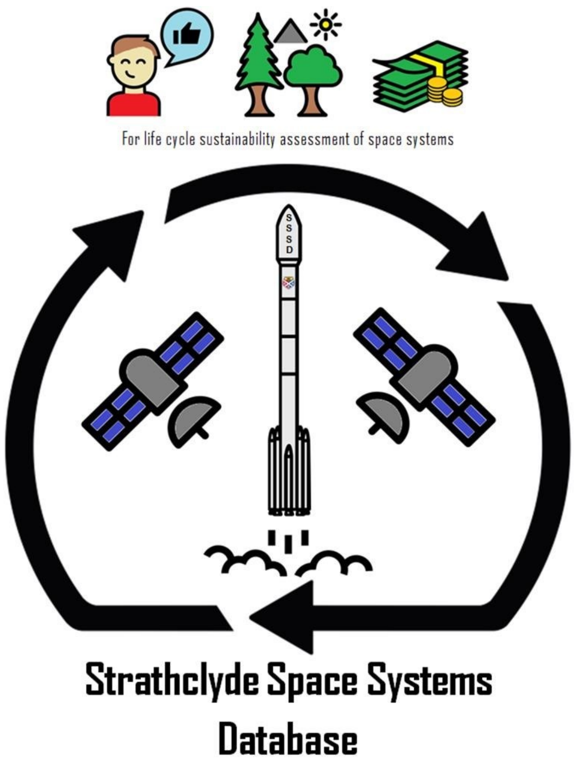


Figure 4.1: Strathclyde Space Systems Database Logo & Banner

This creates a real barrier to the successful delivery of the space-specific LCSA framework outlined in Subsection 3.5.4 as a method to support the space mission design process. To address these issues, it is the purpose of this work to create the world's first space-specific process LCSA database and sustainable design tool to provide the space industry sector with a robust, fully functioning and validated means to determine the life cycle sustainability impacts of a variety of space systems. This is facilitated through a new LCSA tool which was developed at the University of Strathclyde called the Strathclyde Space Systems Database (SSSD), the logo of which can be seen in Figure 4.1 above. The SSSDs intended goal is not to compete with or duplicate similar tools such as those developed by ESA, but to eventually bridge the gap between the lack of process-based life cycle databases for space systems and the public dissemination of the ESA tools, if an agreement can be reached with Ecoinvent for database disclosure. As such, an eventual integration of this methodology within the ESA E-LCA database and Space Opera ecodesign tool is envisioned to consolidate European LCI datasets specific to space activities in a single centralised location.

The main aim of the SSSD is to advance current methodologies for E-LCA within the space sector by moving towards a more holistic approach of sustainability assessment for space systems which aligns with the global aspirations envisaged within the 2030 Agenda. To achieve this, the tool provides a mechanism for decision-makers to design sustainable space technologies and products based on multiple sustainability parameters/criteria.

4.2.2 Methodological Approach

The SSSD was developed based on the LCSA framework and methodology outlined in Subsection 3.5.4, using several guiding documents for in-depth technical advice including the UNEP/SETAC 'Global Guidance Principles for Life Cycle Assessment Databases' which were created to promote consistent practices for data collection, dataset development and all aspects of database management [128]. An overview of the main guiding principles used to develop the SSSD are indicated in Table 4.1 below. This framework of documents was used in the development of the SSSD in order to allow the tool to align closely with widely accepted international standards and norms. These principles were implemented through the proposed space-specific LCSA framework outlined in Figure 3.9 as a coordinated, overarching approach for integrating each sustainability dimension within a single assessment.

Table 4.1: Guiding Documents for SSSD Development & Implementation

Assessment Type	Guiding Documents
E-LCA	• ISO 14040:2006 • ISO 14044:2006 • ESA LCA Space System Guidelines • Product Environmental Footprint Category Rules Guidance
S-LCA	• UNEP/SETAC S-LCA Guidelines • ISO 26000:2010 • A/RES/70/1 • A/RES/71/313 • Goedkoop et al (2018) • Global Reporting Initiative • UN Global Compact Framework • World Resources Institute
LCC	• IEC 60300-3-3:2017 • NASA Cost Estimating Handbook
LCSA	• UNEP/SETAC LCSA Guidelines • UNEP/SETAC Guidelines for LCA Databases

The SSSD was created as a new LCSA tool for space activities, using openLCA as the host software. OpenLCA is a life cycle modelling software developed exclusively by GreenDelta. It was selected for use since it is currently the only open-source and free platform available for this purpose [119]. This is particularly useful if the SSSD is to be developed as a free, open-source tool. As such, the SSSD has been built as a ZOLCA file within this software as default. However, openLCA also supports exports in EcoSpold, Excel, ILCD and CSV format, meaning that it is possible for datasets to be exported for use within other software. Despite this, at the moment, the SSSD is only available within openLCA.

The SSSD is 1.77 GB in size (binary) and currently contains 410 new space-specific processes in total. As indicated in Figure 4.2 below, it has been built on a tier basis where each tier feeds into the one above and represents a different level of depth on which an analysis can be made. This tier-style approach is used to represent the product tree of a space mission as defined in Figure 2.16.

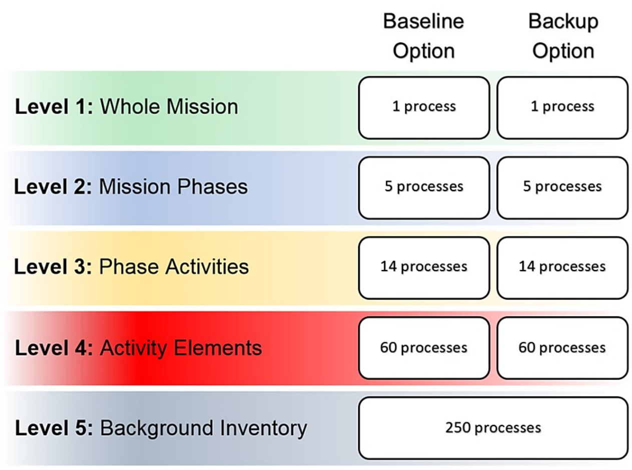


Figure 4.2: SSSD Architectural Overview

As can be seen from the above figure, the SSSD consists of processes for both a baseline and backup option which are identical to one another, allowing for comparison between different design alternatives under a single study. The bottom tier is the custom-made background inventory consisting of 250 processes. This background inventory is supported by LCI datasets from the European Life Cycle Database (ELCD) version 3.2 and Ecoinvent versions 2.2 and 3.3. Similar to the ESA E-LCA database, each of these inventories are based on the APOS system process model approach with relevant proxies implemented where appropriate. As such, the SSSD has a strong European focus although datasets have been built to be easily adaptable to other geographical perspectives. Appropriate LCI datasets were extracted from these databases using data mining techniques to support the development and creation of custom-made LCI datasets. These custom-made datasets were based on both primary and secondary data, the details of which are individually provided per LCI dataset within the SSSD version 1.0.0. Each of the 410 LCI datasets have environmental and costing data included, with an option to also add social criteria as well. Whilst the SSSD does not currently have inventory data relating to social aspects, this was compiled at national-level for the analyses and studies documented throughout this thesis, where appropriate. LCIA methods have also been included within the SSSD so that LCIA results can be generated within the tool itself.

The exact procedure and methodology adopted (in line with the space-specific LCSA framework and 2030 Agenda) is explained in the following chapter sections. This relates exclusively to the SSSD's development and function as an E-LCA database. The following chapter refers to its integration as a sustainable design tool for space-specific concurrent engineering studies.

4.3 Environmental LCI Datasets & LCIA Methods

The space-specific LCSA framework outlined in Subsection 3.5.4 has been developed to align with the global aspirations envisaged within the 2030 Agenda. For this reason, the SSSD has been designed following this framework. Its goal is to provide industry with a range of environmental, social and economic LCI datasets and LCIA methods to assist with the delivery of this framework. The envisioned role and contribution of the SSSD towards this goal is outlined in Figure 4.3 below.

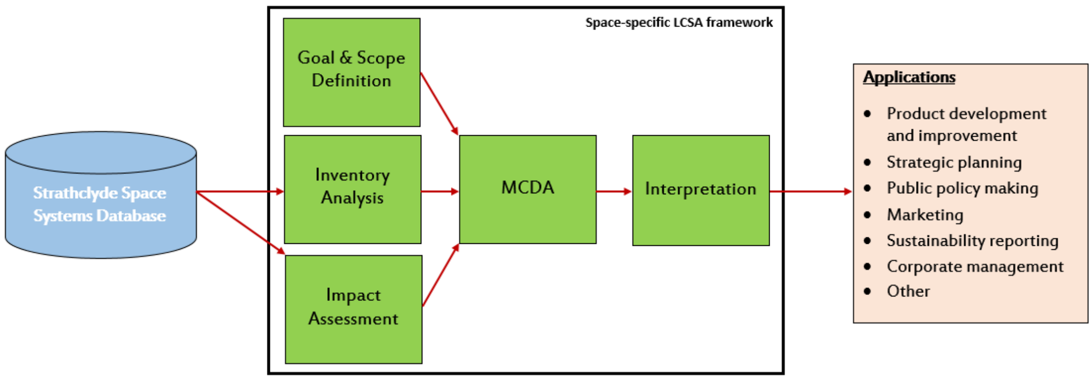


Figure 4.3: Application of the Space-Specific LCSA Framework using the SSSD

According to the UNEP/SETAC LCSA guidelines, LCSA should principally be applied using the E-LCA methodology [179]. Therefore, the SSSD is primarily based on principles of E-LCA whilst S-LCA and LCC are constructed around this. As such, all newly developed space-specific LCI datasets and LCIA methods are built to conform to the ISO 14040:2006 and 14044:2006 standards as defined within the ESA E-LCA space systems guidelines, whilst also adopting ESA's recommended system boundary [30]. The following subsections therefore outline the methodology and functionality of the SSSD LCI datasets and LCIA methods before social or economic criteria are added to them.

4.3.1 LCI Calculation

Each LCI dataset created within the SSSD was built within openLCA based on a new flow as the quantitative reference. Ecoinvent and ELCD flows were used to create new SSSD background inventory datasets. These processes were developed by tailoring Ecoinvent and ELCD flows or by using them directly with collected data in order to generate more space-specific datasets. Since a total of 250 LCI datasets were generated as part of the SSSD's background inventory, it would be impractical to provide detailed methodological and procedural information for each one. As such, the datasets contained within the background inventory have been broken down into nine category types in Figure 4.4 below to facilitate a high-level overview of dataset generation. Further methodological and procedural information relating to each specific dataset is provided within the SSSD as detailed in Subsection 4.6.2.

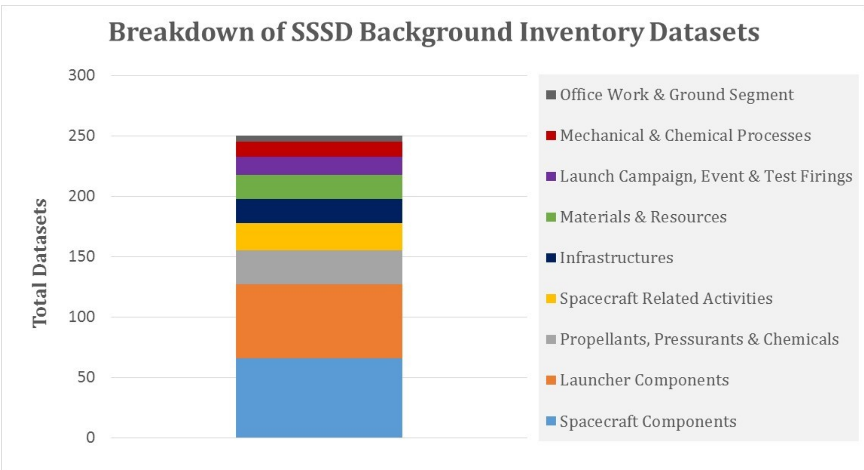


Figure 4.4: Breakdown of SSSD Background Inventory Datasets

Collectively, these LCI datasets allow the entire system boundary outlined by the ESA E-LCA guidelines to be fulfilled since these datasets were developed to reflect a specific activity included within them. In addition to this, some of new datasets also sought to address gaps in this system boundary and the lack of data noted within current conventional LCI databases. For this reason, some of the developed datasets within the SSSD relate to areas not covered by this system boundary. Examples of such datasets include the management of propellants & pressurants, mechanical examination, inspection & testing, platform erosion, platform repositioning, end of life ground operations, re-entry, spacecraft recovery/disposal at end of life (if applicable), additional manufacturing processes including additive manufacturing and new materials including carbon fibre reinforced polymer, tungsten & germanium. Each dataset contained within the SSSD background inventory is custom-built based on Ecoinvent and ELCD process, with the use of custom-built SSSD flows on occasion. All of these LCI datasets were built in accordance with the UNEP/SETAC 'Global Guidance Principles for Life Cycle Assessment Databases' [128]. As listed below, this document outlines five key steps which should be taken when generating a unit process dataset. These are:

- **Step 1:** Prepare an inventory list of inputs & outputs.
- **Step 2:** Define mathematical relationships.
- **Step 3:** Collect the raw data needed.
- **Step 4:** Perform calculations.
- **Step 5:** Provide other supportive information.

Therefore, each of these steps will be discussed generally before being related to the identified types of LCI datasets contained within the SSSD background inventory, highlighted during the categorisation procedure, as outlined in Figure 4.4. A specific example of LCI dataset formation and resulting LCIA results is provided in Subsection 4.3.5.

Step one is to prepare an inventory list of inputs and outputs which is required before data is collected. This can be considered as a form of classification where all of the input and output requirements of the LCI dataset under study are assigned to what is being measured. This refers to the reference flow which is usually a product, service or process. Some of the typical inputs attributed to a given reference flow are services, raw materials, ancillary inputs, water, energy & fuels and other physical inputs. Common outputs are the product itself, any co-products, emissions (to air, land and water), wastes and other releases. The inventory list for SSSD LCI datasets was mapped based on expert knowledge and information gathered during the data collection process. Additionally, ELCD and Ecoinvent processes were also applied within each LCI dataset as inputs which also provided additional downstream outputs for all input flows, such as emissions, wastes, co-products and other releases.

The second step seeks to define mathematical relationships of the data which refers to how the defined inventory items will relate to the process reference flow. To clarify, this means that the mathematical relationship for each inventory item is based on the total amount consumed or produced by the reference flow. This is typically achieved by scaling all inputs and outputs to reflect the value of the reference flow. Within the SSSD, this scaling is typically achieved for the inventory list of inputs using stoichiometric, mass, element or energy balance calculations. With regard to the inventory list of outputs, theoretical calculations were typically used during the calculation step in addition to ELCD and Ecoinvent background inventories. Such mathematical relationships within the SSSD were defined based upon the required baseline unit of the reference flow.

Step three is raw data collection which refers to data gathered for the inventory list of inputs and outputs. In that respect, for SSSD LCI datasets, this data has been gathered using three main methods:

1. **Primary data collection:** Interviews & on-site data collection/measurement.
2. **Secondary data collection:** Interviews, E-LCA databases & literature reviews.
3. **Data generation:** Quantitative calculations & qualified estimates.

Interviews primarily came from ESA E-LCA experts and other industry professionals as indicated within each specific LCI dataset of the SSSD. On-site data collection/measurement came from data gathered at the University of Strathclyde's Faculty of Engineering laboratories, particularly for testing LCI datasets. Extensive literature reviews were mainly used to define the values of the input inventory list. This was applied using a set of defined mathematical relationships using ELCD and Ecoinvent processes as input since SSSD datasets were built based on these background inventories. These processes provided the majority of data, particularly relating to emissions, wastes and co-products in the form of downstream processes. These direct data gathering techniques were often used in conjunction with methods of extrapolation which were applied through quantitative calculations based on existing trends. Where extrapolation could not be applied, quantified estimations were made so as not to scope out potential major areas of impact. Although these are rare within the SSSD, any estimations are clearly stated in order to maintain consistency, transparency and reliability. Where raw data could not be gathered, calculated or estimated for certain elements of the inventory list, placeholder flows were applied instead to represent this inventory item. All placeholder flows will be updated once more applicable inventory data becomes available. In this regard, it can be considered that direct measurements is the preferred option, followed by secondary data, quantitative calculations and then qualified estimates.

The fourth step is to perform calculations. This is done by feeding the raw data into the mathematical relationships to produce the unit process dataset as described in Equation 4.1 below:

$$f(raw\,data) \rightarrow unit\,process\,dataset \tag{4.1}$$

The result of this process is that the gathered data should now provide values for the inventory list of inputs and outputs which relate to the quantitative reference of the unit process dataset as defined by the mathematical relationship. However, since gathered data is rarely in the form required by the LCI dataset [128], careful manipulation of the data is required to scale this to the reference flow. For consistency, each LCI dataset within the SSSD was developed based on a single unit (e.g. mass = 1 kg, energy = 1 kWh, length = 1 m). This adds an element of simplicity and facilitates their potential scalability within upstream processes.

The fifth and final step is to provide supportive information in addition to the LCI dataset. This refers to data validation, reviews and updates which could be useful for dataset users. The datasets contained within the SSSD have gone through a validation and review process as part of a collaborative project between the University of Strathclyde and the ESA Clean Space Initiative. More information and results from this process is detailed in Subsection 4.3.4. Additionally, more information on other supporting documentation is provided within Subsection 4.6.2.

Table 4.2 below provides a high-level overview of five steps for LCI dataset generation outlined by UNEP/SETAC with regards to the identified types of LCI datasets contained within the SSSD background inventory. More detailed information with regards to specific LCI datasets (including data sources, modelling/validation information, data quality and other administrative information) can be found within the SSSD dataset itself.

Table 4.2: SSSD categorised dataset compliance with UNEP/SETAC Guidelines

Categorised Dataset	Step 1 Prepare an inventory list of inputs & outputs	Step 2 Define mathematical relationships	Step 3 Collect the raw data needed	Step 4 Perform calculations	Step 5 Provide other supportive information
Office Work & Ground Segment	***Inputs:*** Raw Materials, Energy & fuels, Water, Services ***Outputs:*** Emissions, Waste, Other	Mass, Energy, Element, Temporal, Theoretical, Inventories	On-site data collection/ measurement, Interviews, Databases, Literature reviews, QC	1 man-hour, 1 hour use	See Subsections 4.2.4 & 4.6.2
Mechanical & Chemical Processes	***Inputs:*** Raw Materials, Energy & fuels, Water, Services, Other ***Outputs:*** Emissions, Waste, Other	Stoichiometric, Mass, Energy, Element, Area, Volume, Theoretical, Inventories	On-site data collection/ measurement, Databases, Literature reviews	1 kg, 1 m², 1m³, 1 hour use, litres	See Subsections 4.2.4 & 4.6.2
Launch Campaign, Event & Test Firings	***Inputs:*** Raw Materials, Energy & fuels, Water, Services, Other ***Outputs:*** Emissions, Waste, Other	Mass, Energy, Element, Theoretical, Inventories	Interviews, Databases, Literature reviews, QC, QE	1 kg, 1 unit,	See Subsections 4.2.4 & 4.6.2
Materials & Resources	***Inputs:*** Raw Materials, Ancillary inputs, Energy & fuels, Water, Services, Other ***Outputs:*** Product, Co-products, Emissions, Waste, Other	Mass, Energy, Element, Area, Theoretical, Inventories	Interviews, Databases, Literature reviews, QC	1 kg, 1 m², 1 unit	See Subsections 4.2.4 & 4.6.2
Infrastructures	***Inputs:*** Raw Materials, Ancillary inputs, Energy & fuels, Water, Services, Other ***Outputs:*** Product, Co-products, Emissions, Waste, Other	Mass, Element, Area, Inventories	Databases, Literature reviews	1 m², 1 unit	See Subsections 4.2.4 & 4.6.2
Spacecraft Related Activities	***Inputs:*** Raw Materials, Ancillary inputs, Energy & fuels, Water, Services, Other ***Outputs:*** Product, Co-products, Emissions, Waste, Other	Stoichiometric, Mass, Energy, Element, Theoretical, Inventories	Databases, Literature reviews, QC	1 kg, 1 kg*a, 1 unit	See Subsections 4.2.4 & 4.6.2
Propellants, Pressurants & Chemicals	***Inputs:*** Raw Materials, Ancillary inputs, Energy & fuels, Water, Services, Other ***Outputs:*** Product, Co-products, Emissions, Waste, Other	Stoichiometric, Mass, Energy, Theoretical, Inventories	Interviews, Databases, Literature reviews, QC	1 kg	See Subsections 4.2.4 & 4.6.2
Launcher Components	***Inputs:*** Raw Materials, Ancillary inputs, Energy & fuels, Water, Services, Other ***Outputs:*** Product, Co-products, Emissions, Waste, Other	Mass, Energy, Element, Theoretical, Inventories	Interviews, Databases, Literature reviews, QC, QE	1 kg, 1 unit	See Subsections 4.2.4 & 4.6.2
Spacecraft Components	***Inputs:*** Raw Materials, Ancillary inputs, Energy & fuels, Water, Services, Other ***Outputs:*** Product, Co-products, Emissions, Waste, Other	Mass, Energy, Length, Theoretical, Inventories	Interviews, Databases, Literature reviews, QC, QE	1 kg, 1 m	See Subsections 4.2.4 & 4.6.2

4.3.2 Dataset Aggregation

Aggregation is a process for combining multiple unit process datasets into a single aggregated process dataset [5, 6]. Since the purpose of the SSSD is to provide LCIA results for entire space missions, it is important to aggregate datasets to allow this to occur. As specified within Figure 4.2, the SSSD has been created using a tier-style approach where SSSD background inventory datasets feed into upstream processes for both the baseline option and backup option. The tier-style approach has been developed to reflect the system boundaries suggested by the ESA E-LCA guidelines [30]. This means that the tier on which an analysis is run (or broken down to) will provide a different level of depth to the analysis.

This tier system was achieved using a vertical-horizontal aggregation approach. Vertical aggregation considers several sequential production steps by aggregating the process chain into a single dataset. The sum of these individual upstream and downstream process contributions (including their data providers) are then scaled within the new dataset according to the relative activity levels of the processes involved in the aggregation. Horizontal aggregation is applied through the creation of multiple unit process datasets in which each provides the same reference flow. This allows a range of variances or scenarios to be considered for similar industrial processes due to the presence of small discrepancies between them (e.g. geographical representativeness, temporal correlation, technological differences) [256].

Guidance is provided on the application of both the vertical and horizontal aggregation approaches within the UNEP/SETAC 'Global Guidance Principles for Life Cycle Assessment Databases' [128]. This document sets out a list of eight steps which are necessary for each aggregation approach to enable the aggregation of unit process datasets into a single aggregated process dataset. These steps are outlined below and will be discussed further for each aggregation approach as they related to the SSSD:

- **Step 1:** Define the goal of the aggregation process.
- **Step 2:** Identify the reference flow for each aggregated LCI dataset.
- **Step 3:** Define the system boundary of the aggregated LCI dataset.
- **Step 4:** Make explicit how the unit process datasets are linked.

- **Step 5:** Ensure consistency and completeness of all datasets being used.
- **Step 6:** Scale each unit process to the selected reference flow.
- **Step 7:** Sum the inputs and outputs of all scaled unit process datasets.
- **Step 8:** Document the aggregation process.

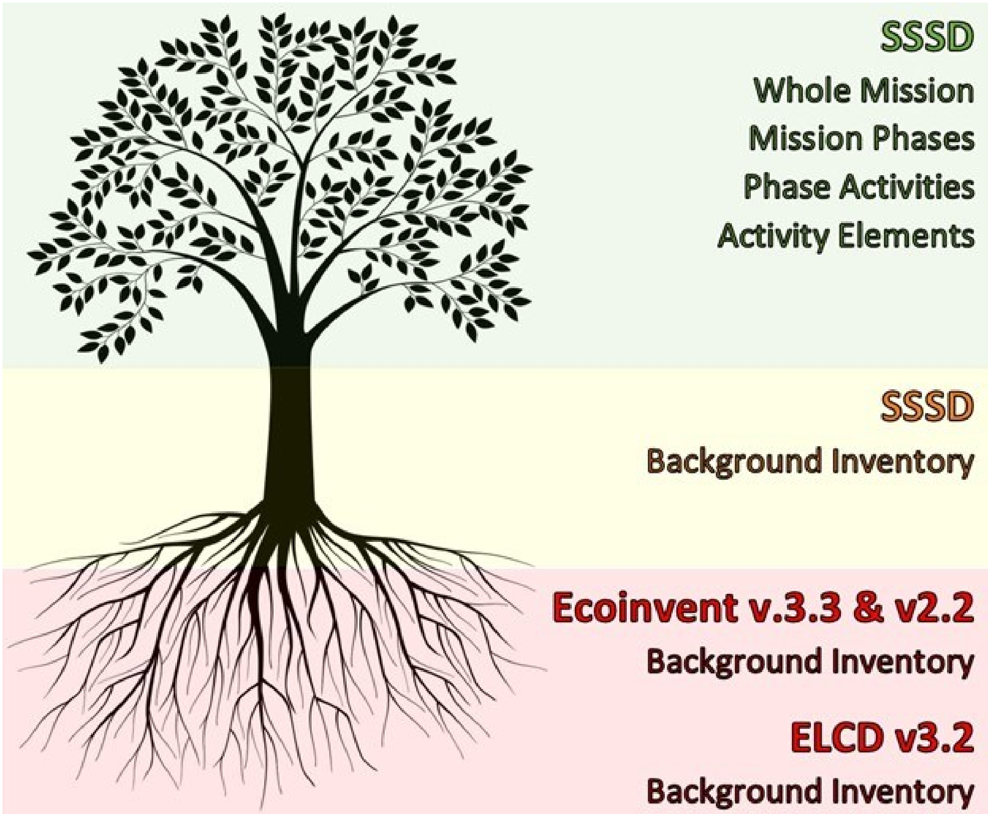


Figure 4.5: SSSD relationship with the Ecoinvent & ELCD background databases

The goal of the vertical aggregation process was to satisfy the system boundary outlined within the ESA E-LCA guidelines by aggregating LCI datasets with different levels of specificity in order to create a tier-based system for two mission design options. In this regard, using a pyramidal approach, each tier groups the number of LCI datasets contained in the tier below according to the number of processes at that level (see Figure 4.2). The reference flow for each aggregated dataset relates to what was being measured (i.e. the system boundary). A physical or service-based linking approach was generally applied where appropriate for Level 4 & 5 output reference flows but these became Boolean data types for the output of Level 2 & 3 process. This is because these processes represent entire phases or phase activities which will not be represented by physical or service-based impacts. The Level 1 reference flow reverts back to physical linking based on the total spacecraft mass. Each LCI dataset used within single vertical aggregated LCI datasets were therefore scaled appropriately to the reference flow in order to be representative, consistent and complete when used in upstream processes. This also takes data providers into consideration based on the horizontal aggregation approach. As such, the reference flow of each aggregated LCI dataset was classified and linked to the appropriate upstream process based on the required value (or sum) to create a product tree. This is process dependent and is documented within each of the SSSD LCI datasets. This tier-based system is based on ELCD v3.2 and Ecoinvent v3.3 & v2.2 background inventories which also used a vertical aggregation approach in order to establish relevant LCI datasets which could feed into the SSSD background inventory. This inventory is then used in the tier-based system as indicated in Figure 4.2. An overview of this relationship is described in Figure 4.5 above.

For the horizontal aggregation approach, the goal was to provide a range of scenarios for similar industrial process in order to provide a range of more appropriate alternative providers for LCI processes. Similar to the vertical aggregation approach, the reference flow for each aggregated dataset relates to what was being measured (i.e. the system boundary). As such, although the reference flow for these LCI datasets are the same (including the scaling of each unit process), slight alterations exist with regard to the LCI input values. Additionally, the linking approach is identical to the one specified for the vertical aggregation approach and makes use of physical, service and Boolean methods. This means that when one of these reference flows are used in a given process, a range of alternative scenarios can be considered to create a more representative, consistent and complete LCI. This is documented within each of the LCI datasets where this aggregation approach is applied. An example of this is the use of Ecoinvent processes within man-hours, where the default provider for electricity consumption is automatically set to a European average. Based on this approach, the default provider can be changed according to the requirements of the study to a more appropriate or specific geographical region. This limits the need for multiple LCI datasets relating to man-hours. However, this aggregation approach is also the reason why the number of spacecraft related activity processes are so high within the SSSD background inventory. In particular, re-entry processes were developed to calculate RSP generation depending on the percentage of spacecraft mass loss during burn-up. As such, a range of scenarios were developed for the percentage of mass loss experienced.

4.3.3 Adopted LCIA Methods

The SSSD has created its own LCIA method using a mix of environmental models presented within Ecoinvent version 3.3 and openLCA version 1.5.5 LCIA methods. Each of these environmental models include a range of fully classified and characterised environmental flows based on the formula indicated in Equation 2.1. The developed approach is based on the environmental models proposed by ESA [30] which align closely with the ILCD recommended impact categories [115]. The impact categories recommended by the ILCD are based on an analysis consisting of a wide range of existing methods which are typically integrated into LCIA methodologies. These models were assessed using expert judgement based upon a predefined evaluation criteria. This criteria investigated various quality elements including the completeness of scope, environmental relevance and scientific robustness of each model. This allowed a score to be produced for each criteria point which was used to compare environmental models and form a range of recommended LCIA methods. The recommended ILCD LCIA methods were then classified into three levels based on their quality as outlined below:

- **Level I:** Recommended and satisfactory.
- **Level II:** Recommended but in need of some improvements.
- **Level III:** Recommended but to be applied with caution.
- **Interim:** Best analysed method but too immature to be recommended.

In order for the SSSD to maintain compliance with the ILCD Handbook and ESA E-LCA guidelines, only the ESA or ILCD recommended and interim classified environmental models are included within the SSSD at midpoint level. As such, 25 impact categories have been included within the SSSD, of which 21 have been fully implemented. Of these 21 impact categories, 4 are custom-made which also includes S-LCA and LCC as single scores. All of these environmental models are outlined in Table 4.3 below which, when considered together, forms the SSSD's LCSA midpoint LCIA method. The E-LCA midpoint LCIA method is identical except it does not consider S-LCA or LCC as single score impact categories. The implemented models are considered to be covering a wide range of environmental themes relating to all the main impact areas of space activities. Additionally, endpoint impact categories have also been included within the SSSD using the ILCD LCIA method to ensure compliance. These have been included to describe the impact on critical areas of protection relating to ecosystems, human health and natural resources. The applied approach can be visualised in Table 4.4 below. However, at present, custom-made SSSD flows have not been classified or characterised into these endpoint impact categories. For this reason, LCIA midpoints remain the primary focus of the SSSD.

Table 4.3: SSSD LCSA Midpoint LCIA Method

Impact Category	Source	Unit	ILCD Classification	Suggested by ESA	Applied in the SSSD
Acidification – Air Acidification Potential	CML (2002)	kg SO_2 eq.	None	Yes	✓
Aluminium Oxide – Al2O3 Emissions in Air	ESA (2016)	kg Al_2O_3	-	Yes	✓
Climate Change – Global Warming Potential 100a	IPCC (2013)	kg CO_2 eq.	I	Yes	✓
Critical Raw Materials – CRM Depletion Potential	SSSD (2019)	kg mass	-	-	✓
Disposal – Mass Disposed in Ocean	ESA (2016)	kg mass	-	Yes	✓
Economic Impact – Single Score	SSSD (2019)	EUR 2000	-	-	✓
Energy Consumption – Total Cumulative Energy Demand	Cumulative Energy Demand	MJ	-	Yes	✓
Eutrophication – Freshwater Eutrophication Potential	ReCiPe Midpoint (H)	kg P eq.	II	Yes	✓
Eutrophication – Marine Eutrophication Potential	ReCiPe Midpoint (H)	kg N eq.	II	Yes	✓
Ionising Radiation – Ionising Radiation Potential	ReCiPe Midpoint (H)	kg U235 eq.	II	Yes	✓
Noise Pollution – Noise Creation Potential	SSSD (2019)	Leq dBA	-	-	✗
Orbital Risk – Space Debris Risk	Colombo et al. (2017)	Index Score	-	-	✗
Orbital Space Use – Orbital Resource Depletion Potential	Maury (2019)	objects.m^3.year	-	-	✗
Ozone Depletion – Ozone Depletion Potential	WMO (1999)	kg CFC-11 eq.	I	Yes	✓
Particulate Matter – Particulate Matter Formation Potential	ReCiPe Midpoint (H)	kg PM_{10} eq.	None	Yes	✓
Photochemical Oxidation – Photochemical Oxidation Potential	ReCiPe Midpoint (H)	kg NMVOC eq.	II	Yes	✓
Re-entry Smoke Particles – RSP Creation Potential	SSSD (2019)	kg RSP eq.	-	-	✓
REACH Substances – Restricted & SVHC Use Potential	SSSD (2019)	kg mass	-	-	✗
Resource Depletion – Fossil Resource Depletion Potential	CML (2002)	MJ fossil	II	Yes	✓
Resource Depletion – Mineral Resource Depletion Potential	CML (2002)	kg Sb eq.	II	Yes	✓
Social Impact – Single Score	SSSD (2019)	Social Score	-	-	✓
Toxicity – Freshwater Aquatic Ecotoxicity	USEtox	PAF.m^3.day	II/III	Yes	✓
Toxicity – Human Toxicity	USEtox	cases	II/III	Yes	✓
Toxicity – Marine Ecotoxicity	CML (2002)	kg 1,4-DB eq.	Interim	Yes	✓
Water Consumption – Water Depletion Potential	ReCiPe Midpoint (H)	m^3	None	No	✓

Table 4.4: SSSD E-LCA Endpoint LCIA Method

Impact Category	Source	Unit	ILCD Classification	Suggested by ESA	Applied in the SSSD
Ecosystems	ILCD (2011)	species*year	N/A	-	✓
Human Health	ILCD (2011)	DALYs	N/A	-	✓
Resources	ILCD (2011)	$	N/A	-	✓

According to the ILCD Handbook [115], the inclusion of any additional or non-classified environmental models within LCIA methods must be explicitly justified to claim compliance with the ILCD. From the above table, the identified variances between the models implemented by the SSSD and those which were recommended by ESA and the ILCD were categorised into the three different groups which are listed below:

- **11/25** comply with both ESA & ILCD recommendations.
- **9/25** comply with neither ESA or ILCD recommendations.
- **5/25** comply with ESA recommendations only.

As such, the environmental models applied within the SSSD at midpoint level will be discussed with respect to the ILCD recommended and interim classified models in order to determine their overall justification for use within the SSSD and space-specific E-LCA.

Of the eleven models which comply with both ESA and ILCD recommendations, three main issues were identified. The first concerns the environmental model applied within the SSSD for climate change. This has been updated to the newest version of the proposed method compared to the version recommend both by ESA and the ILCD (i.e. IPCC 2007 to IPCC 2013). The second issue concerns the source used for the ozone depletion model which is based on the Montreal Protocol. This excludes key ozone depleting substances that are more significant today compared to when this model was released. In particular, ClO_x, NO_x, HO_x and HCl emissions from the launch event of rockets all have the potential to cause ozone depletion [1], but will not be considered using this model [62]. As such new flows will need to be added to this model to account for such impacts (see Subsection 4.3.5). Finally, it is worth noting that the ILCD recommends a different horizon as the baseline for the mineral resource depletion model compared to the source [115]. CML (2002) proposes three different horizons for this impact category [257]. The horizon recommended by the ILCD is 'elements, reserve base' whilst CML (2002) uses 'elements, ultimate, ultimate reserves' 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 [258]. As such, the selection of horizons can have a considerable impact on LCIA results. For example, germanium is typically used as a substrate in triple-junction spacecraft solar arrays [86, 87]. When considering its use within the ultimate reserves horizon, germanium is indifferent with respect to other resources (e.g. 1 kg = 6.52E-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.) [257]. This is an extremely contentious issue since, in this respect, horizon selection can ultimately lead to vast variances in the identification of environmental hotspots. There is no international agreement between E-LCA practitioners on which horizon is more appropriate to use and as such careful communication of LCIA results should be exercised for this impact category. Ultimately, the reserve base horizon was selected for use within the SSSD to align with the ILCD and ESA recommendations.

Six of the nine environmental models which do not comply with either the ESA or ILCD recommendations are newly developed space-specific impact categories created purposely for the SSSD. Two of these models reflect single score results for S-LCA and LCC. The methodology for these impact categories is described in more detail in Section 4.4. Two more are currently under development and not yet implemented. One of these measures noise pollution using equivalent continuous level in decibels. This is being developed to provide constant noise level resulting from the same total sound energy being produced over a given period of time. The second impact category is similar to the work of Chanoine et al. [259] and relates to the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulations. This new flow indicator will be used to identify the total mass of chemicals being used in the product system that are contained on the restriction list (Annex XVII) or is named on the Substances of very high concern (SVHC) candidate list (Annex XIV). Currently, the complete restricted substance list covers 70 substances with 201 on the SVHC list [260].

The purpose of implementing this impact category is to comply with current and future legislation whilst also assisting decision-makers to identify and phase out potentially harmful substances early in the supply chain which have a likelihood to cause potential disruption in the future. The final two of the six impact categories have both been fully implemented within the SSSD as placeholder flow indicators which cover critical raw material (CRM) depletion potential and RSP creation potential. With regards to CRM depletion potential, the adopted approach is also similar to another study conducted by Chanoine et al. [261]. In this regard, the EC lists 27 CRMs materials which are of high importance to the EU economy but have a high risk associated with their supply [262]. As such, 25 out of 27 CRMs listed have been mapped in the SSSD (all rare earth metals except promethium) since hafnium and natural rubber are not present with Ecoinvent or ELCD flows. In a similar manner to the proposed REACH impact category, this allows decision-makers to identify materials where potential supply chain disruption could occur. With regards to RSP creation potential, this estimates the mass of a spacecraft that will become RSPs based on the research documented in Subsection 2.2.2. However, RSPs generally are very challenging to characterise as the process from solid to ionised vapour through condensation to smoke is not well understood for natural or human produced objects. The fraction of re-entering mass that forms RSPs is highly variable from object-to-object and depends on various factors such as materials, mass and entry velocity. There is no tool currently capable of measuring RSP generation as the assimilation of data relating to the history of the number, mass, and composition of re-entering objects has not been created. Additionally, the fate of smoke (meteoritic or spacecraft) particles once they are generated in the mesosphere is not fully understood [100]. In this regard Massachusetts Institute of Technology Associate Professor Dan Cziczo's work on measuring particles in the stratosphere and identifying their source is extremely important [263]. It was noted that his team identified a 'menagerie of metal compounds' which points to the possibility of an anthropogenic impact on cloud formation. On these findings, Dr Ross commented that he would suspect some of what Professor Cziczo is seeing "are RSPs as it is not clear if typical troposphere/stratosphere exchange can explain the abundance of 'strange metal particles' coming into the stratosphere from below" [100]. He went on to explain his theory is merely conjecture until the experiments and measurements have been done. Despite this, it is not clear if these particles are coming into the lower stratosphere from above or if RSPs have unusual cloud condensation behaviour. Due to this there has been no serious attempt made to characterise, based on known space debris entries, the amount or composition of RSPs. Since this phenomenon is clearly expected to alter the chemical and ionic composition of the upper atmosphere to some degree, this process was considered to be an important element of a space mission's life cycle. As such, a new flow indicator was developed at a basic level which can be used to indicate the total amount of spacecraft mass which burns-up during re-entry and converts to RSPs. Therefore, this will require input from an external re-entry simulation tool.

Two of the other three environmental models mentioned above are newly developed space-specific impact categories based on external research. These relate to risks from space debris and orbital resource depletion as discussed in Subsection 2.2.2. These impact categories will be implemented within the SSSD in the future if appropriate permissions can be obtained. The final environmental model that does not comply with either the ESA or ILCD recommendations is water consumption. Water consumption is one of the most contentious impact categories within E-LCA and as such ESA and the ILCD proposed entirely different methodologies. However, within the E-LCA community, there is a growing acknowledgement that the AWARE model should be used to assess water consumption [264]. Since this environmental model was not available in the Ecoinvent version 3.3 or openLCA version 1.5.5 LCIA methods, the ReCiPe Midpoint (H) model was chosen as the most comparable method instead. Additionally, this method was considered to be more detailed than either model recommended by ESA or the ILCD.

With regards to the five impact categories that comply only with ESA recommendations, two of them are custom-made space-specific flow indicators developed by ESA which are used to indicate Al_2O_3 emissions from the launch event and the mass disposed in the ocean from launcher stages and spacecraft parts surviving re-entry. Since research into both these processes is still ongoing, there is not enough data to accurately quantify their full environmental impacts. Nevertheless, each issue is a key component of a space mission's environmental impact and considered too important to scope out due to lack of data. As such, the LCIA results of each impact category are simply calculated using mass. Additionally, the ESA E-LCA guidelines also suggests applying primary energy consumption potential as an impact category [30]. No environmental models are considered by the ILCD for this environmental theme. However, since the space sector uses many specific and highly energy intensive manufacturing processes in order to produce high precision components, this was considered to be an important environmental model to include within the SSSD. The final two environmental models suggested within the ESA E-LCA guidelines (acidification and particulate matter formation) are not those suggested by the ILCD handbook. No indication is provided within the ESA E-LCA guidelines handbook as to the reasons behind this. However, the suggested ILCD models [115] were not contained within either the Ecoinvent version 3.3 or openLCA version 1.5.5 LCIA methods. For this reason, the recommendations contained within the ESA E-LCA guidelines were followed for implementation in the SSSD.

Each of the impact categories documented in Table 4.3 were manually added to the newly created SSSD LCIA method. These environmental models were updated to include the range of new custom-made SSSD elementary, product and waste flows were implemented within SSSD processes. New CFs were based on literature reviews or CFs listed in the most appropriate environmental models (e.g. 1.95E+04 kg Sb eq. for germanium using the CML (2002) reserve base approach [257]).

Additionally, characterisation was attempted for the release of exhaust products caused by platform repositioning and platform erosion, despite the fact that the LCIA results from such processes are expected to be highly insignificant with regards to the entire life cycle of a space mission. This is because the overall environmental relevance of an emission greatly varies with altitude compared to the release of the same emission at sea level. As such, the reason that platform repositioning and platform erosion processes are included as part of the SSSD is to provide datasets for the complete system, regardless of environmental significance levels, thus accounting for potential tailoring of the goal and scope definition and inherently higher levels of social and/or economic impact. With regards to platform repositioning, atmospheric drag causes orbital decay which requires satellites to be occasionally repositioned [265]. This repositioning is usually performed with nozzle-based systems, with hydrazine typically being the most favoured mono-propellant. The highly exothermic catalytic decomposition of hydrazine produces jets of hot gas for thrust [14]. The emitted gas is composed of hydrogen (H_2), nitrogen (N_2) and ammonia (NH_3) and once released into the LEO domain, these substances all have the potential to mix back into the upper layers of the atmosphere [266]. Specifically around the vicinity of the release, it is possible that the expelled hydrazine gas may also react with atomic oxygen present in LEO to produce nitrosamines. Assuming that these nitrosamines (which are known to be carcinogens) are diffused directly into the upper atmosphere, they could remain present there for some time before being consumed by hydroxide (OH) radical reactions [267,268]. In terms of platform erosion, the presence of a diffused atmosphere in LEO slowly erodes satellite platforms. The predominant component in the LEO atmosphere is atomic oxygen which is responsible for the degradation of thermal, mechanical and optical properties of exposed materials [14]. It interacts with hydrocarbon polymers (e.g. Kapton, Teflon, Mylar, etc.) that are used to thermally insulate and protect parts of the satellite. McCarthy et al. and Banks et al. developed a model to assess the oxygen erosion yield according to molecular characteristics of several polymers [269, 270]. The experimental data they used shows that erosion yields (expressed as the volume lost per incident atomic oxygen atom in cm3/atom) vary from a factor of about 90 between the most and least resistant polymers. It also demonstrates that a significant portion of the simulation materials used to protect the satellites can be released into the LEO domain in the form of volatile oxidation products. A typical solution to characterise these impacts would be to apply the Ideal Gas Law which is commonly used to find the pressure, volume, temperature or amount of a given gas. This is particularly relevant for releases in lower parts of the atmosphere as it provides a good approximation for the behaviour of several gases under many conditions. However, the ordinary gas law can only be applied to an atmospheric gas if the molecules make enough collisions to establish equilibrium with their surroundings [271]. Most particles entering the thermosphere from gravity-controlled orbits will not make collisions due to the relatively small number of molecules and atoms present at these altitudes. As such, this means that these emissions will either escape Earth's gravitational field via the exosphere if their kinetic energy is larger than their potential energy at the height of escape or they will return back to lower levels of the atmosphere below. For this reason, significantly different CFs will be required for high-altitude releases in areas with sparsely populated atoms and molecules. A good first assumption for the characterisation of these high-altitude releases could be to surmise that standard CFs are inversely proportional to atmospheric density, as outlined in the equation below:

$$IRHAR_c = \sum_{s} (\frac{CF_{cs_o} \cdot m_{s_a}}{AD_o}) \cdot AD_a \tag{4.2}$$

Where $IRHAR_c$ is the indicator result for high-altitude releases for impact category c, CF_{cs_o} is the characterisation factor that connects intervention s released at sea level o with impact category c, m_{s_a} is the size of intervention s released at altitude a, AD_o is the atmospheric density at sea level o, and AD_a is the atmospheric density at altitude a.

4.3.4 Data Quality & Validation

Unreliable or invalid data means that any generated results stemming from a given E-LCA would be unable to answer the research question of the study, rendering the output meaningless. On this subject, the need for reliable and valid data is well documented. In particular, the UNEP/SETAC guidelines for LCA databases state that data quality & validation checks should be conducted when developing aggregated process datasets [128]. Data quality in E-LCA typically concentrates on aspects such as the reliability, completeness, temporal representativeness, geographical representativeness and technological representativeness [272]. In comparison, data validation is not directly related to quality aspects but instead focuses on the quality dimensions related to the structure of the data (i.e. accuracy, comparability, coherence) [273]. As such, before the SSSD can be used for sustainability assessments, it is vital that the tool contains environmental data (for which the social and economic aspects have been added) that is comparable and materially correct.

Although accuracy is invariably sought when measuring impacts, it is impossible to scientifically measure something without some degree of inherent errors and uncertainties. These are usually related to measurement error-determination of the relevant data since 'true' values (especially for background data) are often unknown, as well as a lack of scientific knowledge and the use of non-ideal datasets which force the need for temporal or spatial approximations [128]. This makes it impossible to make an exact measurement from any kind of systematic scientific calculation procedure in E-LCA. This means that all LCI datasets will contain some level of uncertainty which cannot always be measured directly from available information. As such, data quality matrices are often used to measure uncertainty. Statistical methods are used to quantify uncertainty since measurements have a distribution that can be defined through standard deviation [274].

Table 4.5: Applied Ecoinvent Data Quality System indicators, scores & uncertainties [275]

	1	2	3	4	5
Reliability	Verified data based on measurements **Uncertainty: 1.00**	Verified data partly based on assumptions or non-verified data based on measurements **Uncertainty: 1.05**	Non-verified data partly based on qualified estimates **Uncertainty: 1.10**	Qualified estimate (e.g. by industrial expert) **Uncertainty: 1.20**	Non-qualified estimates **Uncertainty: 1.50**
Completeness	Representative data from all sites relevant for the market considered, over and adequate period to even out normal fluctuations **Uncertainty: 1.00**	Representative data from > 50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations **Uncertainty: 1.02**	Representative data from only some sites (<< 50%) relevant for the market considered or > 50% of sites but from shorter periods **Uncertainty: 1.05**	Representative data from only one site relevant for the market considered or some sites but from shorter periods **Uncertainty: 1.10**	Representativeness unknown or data from a small number of sites and from shorter periods **Uncertainty: 1.20**
Temporal Correlation	Less than 3 years of difference to the time period of the data set **Uncertainty: 1.00**	Less than 6 years of difference to the time period of the data set **Uncertainty: 1.03**	Less than 10 years of difference to the time period of the data set **Uncertainty: 1.10**	Less than 15 years of difference to the time period of the data set **Uncertainty: 1.20**	Age of data unknown or more than 15 years of difference to the time period of the data set **Uncertainty: 1.50**
Geographical Correlation	Data from area under study **Uncertainty: 1.00**	Average data from larger area in which the area under study is included **Uncertainty: 1.01**	Data from area with similar production conditions **Uncertainty: 1.02**	Data from area with slightly similar production conditions **Uncertainty: 1.05**	Data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia) **Uncertainty: 1.10**
Further Technological Correlation	Data from enterprises, processes and materials under study **Uncertainty: 1.00**	Data from processes and materials under study (i.e. identical technology) but from different enterprises **Uncertainty: 1.05**	Data from processes and materials under study but from different technology **Uncertainty: 1.20**	Data on related processes or materials **Uncertainty: 1.50**	Data on related processes on laboratory scale or from different technology **Uncertainty: 2.00**

OpenLCA currently supports two uncertainty analysis methods; the Pedigree approach and Monte Carlo simulations [119]. The pedigree approach relies on a data quality matrix composed of five data quality indicators. These indicators are based on a qualitative assessment of data quality which can be added to LCI datasets at process or flow level. In the case of the SSSD, since Ecoinvent has been used as the background database, the Ecoinvent data quality system has been applied [275]. This data quality matrix, including its indicators and evaluation criteria can be found in Table 4.5 above. This also includes the different uncertainty values which are attached to each indicator according the score generated by its criteria.

A Monte Carlo simulation can be run when the pedigree approach is applied at flow level. This means that data quality is assessed for each individual flow within a process [119]. Monte Carlo simulations are used to model the probability of different outcomes in a process that cannot easily be predicted due to the intervention of random variables. It is a technique used to understand the impact of risk and uncertainty in prediction and forecasting models [276]. As such, the uncertainty factors from the data quality system selection are aggregated to the standard deviation in a formula that is valid for log-normal distribution data only. Once the Monte Carlo simulation is run, a coefficient of uncertainty can be generated. This coefficient is obtained by dividing the standard deviation generated by the Monte Carlo simulation by the mean. In the case of the SSSD, it was decided that convergence of the Monte Carlo simulation is achieved if the coefficient of uncertainty results in a value that is less than 20% of the mean.

Currently, the Pedigree approach has been adopted exclusively within the SSSD at process level. This constraint is due to the use of Ecoinvent as a background inventory for which the majority of SSSD processes rely upon. Since a system process method was adopted, this means that the Ecoinvent flows do not have any data quality information attached. Due to project time constraints, gathering uncertainty information for each individual flow which would be required to run a Monte Carlo analysis is an unviable objective. As such, the adopted approach is mainly used for documentation purposes. However, there are plans for future versions of the SSSD to use Pedigree values in order to determine all uncertainty parameters for flows and run a Monte Carlo simulation.

In addition to data quality, it is also critical that the LCI of any given life cycle database contains information and data which can be considered valid. According to the main international standards on E-LCA (ISO 14040:2006 & 14044:2006), the LCI stage of E-LCA involves 3 main elements:

- Data collection
- Data calculation
- Allocation of flows and releases

In particular, ISO 14044:2006 [6] specifies that data calculation procedures should undergo a strict validation process "to confirm and provide evidence that the data quality requirements for the intended application have been fulfilled". Potential methods suggested for such validation procedures involve establishing mass & energy balances and/or comparative analyses of release factors. The standard expands on this by stating that any "obvious anomalies in the data resulting from such validation procedures require alternative data that comply with the data selection as established according to the types and sources of data".

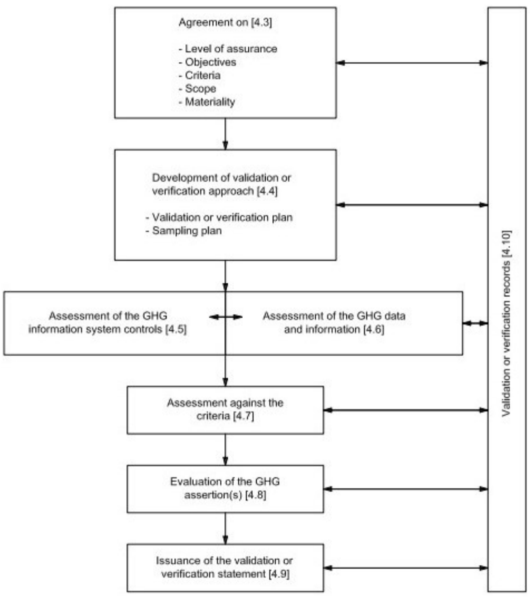


Figure 4.6: Validation & verification process outlined in ISO 14064-3:2012 [277]

In this regard, these types of study are one of the mostly commonly applied methods for E-LCA validation procedures which affirms that they are an acceptable method of data validation. The ISO 14064-3:2012 standard on validation of greenhouse gas (GHG) assertions [277] provides a validation and verification framework which could also be used for such E-LCA validation procedures (see Figure 4.6 above). The standard describes data validation in terms of GHGs as the "systematic, independent and documented process for the evaluation of a GHG assertion in a GHG project plan against agreed validation criteria". Its framework is for an inventory analysis of GHG assertions which is often adapted to other environmental inventories. It seeks to evaluate the validity of LCI dataset input values based on expert judgement and information contained within the data quality matrices. Ultimately this should lead to the issuing of a validity statement for individual LCI datasets. As such, the framework described in Figure 4.6 above was applied as the methodology during this validation exercise.

With this requirement in mind, validating the LCI datasets contained within the SSSD is vital if decision-makers are to use the tool for any kind of justification purposes. Since the ESA E-LCA database is the only space-specific life cycle database which exists other than the SSSD, a comparative assessment is the obvious choice for conducting this procedure. This is particularly useful since the LCIs of both databases have been developed independently of one another. Therefore, a collaborative project between the University of Strathclyde and the ESA Clean Space Initiative was initiated to validate LCIs of the ESA E-LCA database and the SSSD. This project was executed by the author of this thesis through a comparative, cross-examination analysis which took place over 13 weeks from 17 September 2018 to 14 December 2018 at ESTEC in Noordwijk, Netherlands.

The applied methodology is based on the framework outlined within the ISO 14064-3:2012 standard [277]. This provides an appropriate and internationally standardised approach to environmental inventory validation to guide the inventory validation process. Additionally, principles were also considered to be fundamental to the study if it is to be seen as credible. In this regard, ISO 14064-3:2012 outlines 4 key principles which could be used as the backbone to guide the validation process of this project.

The suggested principles in this standard were derived from the ISO 19011:2011 standard on auditing management systems [278] and adapted to reflect the context of the ISO 14064-3:2012 standard (see Table 4.6 below).

Table 4.6: Applied study principles

Independence:	Remain independent of the activity being validated, and free from bias and conflict of interest. Maintain objectivity throughout the validation process to ensure that the findings and conclusions will be based on objective evidence generated during the validation process.
Ethical conduct:	Demonstrate ethical conduct through trusty, integrity, confidentiality and discretion throughout the validation process.
Fair presentation:	Reflect truthfully and accurately validation activities, findings, conclusions and reports. Report significant obstacles encountered during the validation process, as well as unresolved, diverging opinions among validators, the responsible party and the client.
Due professional care:	Exercise due professional care and judgement in accordance with the importance of the task performed and the confidence placed by clients and intended users. Have the necessary skills and competences to undertake the validation.

The objective of the study was to assess the validity of data contained within the ESA E-LCA database and SSSD in order to produce validation statements for each LCI dataset under study. The assessed criteria related to all datasets covered by the system boundary outlined in the ESA E-LCA guidelines for which datasets were available and comparable. In this regard, particular consideration was applied when assessing LCI datasets with non-identical quantitative references or dissimilar production & manufacturing techniques.

In line with the ISO 14064-3:2012 methodology, Grucza & Goldberg suggests that any applied methodology for comparative inventory analyses should seek to evaluate statistical differences between inventory data based on data quality and sources [279]. As such, a comparative inventory analysis was adopted as the most appropriate validation approach to statistically evaluate the LCIs of the SSSD and ESA E-LCA database. This was achieved qualitatively based on expert judgement through dataset information relating to accuracy, comparability and coherence of data, including consideration of data sources and information contained within the data quality matrices. The SSSD inventory is contained within openLCA as its own database whilst the ESA E-LCA Database is contained within SimaPro as its own database called SpaceLCI2017.csv. A variety of Excel files (used for the Space Opera inventory) was also used to support the

LCI investigation of the ESA E-LCA database. The assertions made in the inventories of these tools were then evaluated based on criteria listed in the ISO 14064-3:2012 standard relating to the assessment of inventory data against validation criteria (i.e. by comparing the LCIs of the SSSD and ESA E-LCA database) and by evaluating the overall inventory assertion.

Overall, 75 SSSD LCI datasets were compared which represents 30% of the SSSD background inventory. This involved comparing the SSSD to a mixture of Space Opera and ESA E-LCA database LCI datasets. The main outcomes of the inventory validation was that sixty LCI datasets were considered valid. Eight could not be validated due to differences in production & manufacturing techniques whilst seven were considered to provide limited level of confidence meaning that additional updates or information may be required before they can be fully validated (six of these only apply to the SSSD). Specifically, the analysed LCI datasets can be broken down according to mission segment (i.e. man-hours + travel, ground segment, launch segment and space segment).

In terms of man-hours + travel inventory data examination, the LCI values input for electricity consumption within the ESA E-LCA database was slightly higher than the SSSD for one-man hour in France and significantly less for one man-hour in Italy. The reason for this difference is directly attributable to the fact that the data inside ESA E-LCA database for man-hours comes from the ESA Corporate Responsibility & Sustainability 2015-16 Report [57] and the ESA Facilities Environmental Performance 2007-14 Report [280] whilst the data contained within the SSSD for man-hours is based on European average benchmarks for typical office work. The reason that the ESA E-LCA database is based on the figures contained within these reports is because applicable data is not yet available since the work for E-LCA of the ground segment was not due to be completed until June 2019 [95]. Additionally, unlike the ESA E-LCA database which currently only considers electricity consumption for man-hours, the SSSD also considers other inputs such as natural gas consumption, water consumption and waste production. These factors were not considered as part of the validation procedures. Travel was calculated using the exact same LCI dataset input values and flows.

The ESA E-LCA database LCI for ground segment was based on annual data taken directly from ESRIN and ESOC derived from the ESA Facilities Environmental Performance 2007-15 Report [280] which divides these values by the number of employees. Work specifically on the ground segment at ESA has already begun for E-LCA but was not completed during the ESA LCI Validation Project time frame. Similar to man-hours, the SSSD based its figures on European average benchmarks for typical office work. Overall, the LCI dataset input values for ground stations found that electricity consumption for the SSSD was significantly less than the ESA E-LCA database whilst gas consumption is significantly more. Additionally, the SSSD does not consider paper use, waste treatment or water consumption. For control centres, inputs for electricity consumption, gas consumption and wastewater are comparable whilst the ESA E-LCA database predicts significantly less waste. Additionally, for certain LCI processes, the ESA E-LCA database and the SSSD use their own custom-made processes. Overall, it was considered that LCI datasets for control centres were extremely comparable whilst LCI dataset input values for ground stations were not.

Since the launch segment is highly confidential and not to be communicated to persons outwith ESA, only certain parts of the launch segment LCI could be investigated. These parts include the launch campaign, spacecraft container for 1 m^3 of spacecraft and spacecraft transported to Kourou. In terms of the launch campaign inventory the processes included are very similar, with impacts generally predicted of the same magnitude. For helium, nitrogen, and electricity consumption the ESA E-LCA database had larger inventory inputs (50.32%, 50.38%, 98.37%). For tap water the SSSD has a larger inventory input (41.60%). Unlike the SSSD, the ESA E-LCA database does not included processes for diesel, heavy fuel oil, machine operations, petrol and waste water treatment. Unlike the ESA E-LCA database, the SSSD does not include the process of 'Helium – Boat Travel' or the added process emissions of 'SO_x in air', 'Hydrazine in river', 'COD in river', 'BOD in river', and 'Suspended matter in river'. In terms of the spacecraft container, the two LCI datasets are not comparable as the ESA E-LCA database considers a steel container whilst the SSSD considers an aluminium one. However the mass is comparable when considering the density of aluminium per unit of volume compared to steel. The only significant difference is in the electricity consumption. Travel was calculated using the exact same LCI dataset input values and flows. Similar to ground segment processes, the ESA E-LCA database and the SSSD use their own custom-made processes in each LCI dataset except travel (where the same process is used in both cases).

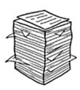
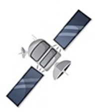
For the space segment, both the ESA E-LCA database and the SSSD use their own custom made LCI datasets for propellants and pressurants. Since the ESA E-LCA Database is not yet harmonised, it was tricky to find the correct inventories for certain processes such as MON-3, N_2 and helium production & manufacturing. For all LCI datasets (except MON-3 and helium), the ESA E-LCA database was far more detailed. Except for the LCI datasets on MMH and N_2 (which have vastly different input processes), the LCI datasets can be described as loosely resembling one another. In terms of AIT, the electricity consumed during both EGSE tests and thermal vacuum uses the same LCI processes and input values. However, the liquid nitrogen used by the ESA E-LCA database is based on a custom-made LCI process whilst the SSSD uses only the standard Ecoinvent LCI process for liquid nitrogen. Nevertheless, despite both having the same input values, the SSSD and ESA E-LCA database N_2 LCI datasets display vastly different input processes. In terms of spacecraft components, 75% of these were based on data provided through the ESA Space System LCA Guidelines so were already highly accurate. The other 25% included a 1 kg propellant tank, a 1 kg sun sensor and a 1 kg thruster (1N). For the first two, the LCI datasets displayed similar input values for shared LCI processes, with slight LCI process variation. The dataset on thrusters could not be compared due to the selection of different materials requiring different LCI processes. Overall it was found that spacecraft components not guided by the ESA Space System LCA Guidelines generally displayed similar inventory inputs for comparable LCI activities and processes [30] (but these were often more detailed in the ESA E-LCA Database).

On evaluation of these findings, numerous reasons for the differences in LCI datasets were identified. From these, it was determined that the observed differences were primarily due to the following:

- **Differences in LCI processes used:**
  - Differences in database versions.
  - Differences in dataset requirements.
  - Use of custom-made LCI processes.
- **Differences in input vales used for LCI processes:**
  - Site specific values versus averaged or benchmarked values.
  - Differences in measured values, calculated values and/or assumptions.

The differences in input values for LCI processes were considered on a case-by-case basis to determine overall validity based on expert judgement through comparability, data sources and data quality. Based on this inventory examination, the study validator has produced a set of validation statements which can be seen in Table 4.7 below.

Table 4.7: Blanket SSSD validation outcomes & statements

Mission Segment	Inventory Validation Outcome	Validation Statement
Man-Hours + Travel 	In terms of inventory inputs, since both tools use either benchmarked or measured input values which (in the most part) closely resemble one another then both inventories can be considered valid. However it may be more advisable in the case of ecodesign for the ESA data to also use benchmarked values since the energy consumption used by the ESA E-LCA database is based on observed annual consumption of ESA facilities despite the introduction of new space missions having the distinct possibility to alter these facility-wide values.	Considering the data similarity and/or input sources, all LCI dataset input values have be determined to be valid. All LCI datasets within the SSSD and the ESA E-LCA database can be considered to be materially correct and a fair representation of the data and information, prepared in accordance with relevant International Standards and guidelines.
Ground Segment 	Data on ground segment was difficult to compile. As such, this forced each dataset to be based on literature. The SSSD also used the ESA the ESA Facilities Environmental Performance 2007-15 Report as input for the type of processes to include, but ultimately used benchmarked values. The ESA E-LCA database used site-specific values. For Control Centres, these values were comparable. However, there were major differences in LCI process input values for Ground Stations. It is advisable to update these values on completion of the ESA Ground Segment LCA study in June 2019.	Considering the data similarity, the LCI Control Centre datasets within the SSSD and the ESA E-LCA database can be considered to be materially correct and a fair representation of the data and information, prepared in accordance with relevant International Standards and guidelines. However, due to the major differences in data (which were obtained for literature in the case of both tools), the LCI Ground Station datasets within the SSSD and the ESA E-LCA database express a limited level of assurance and may require further investigation before they can be considered valid.
Launch Segment 	Since the inventory inputs for the launch campaign and travel for the ESA E-LCA database came from source and are so similar to the SSSD, then inventories of these parts can be considered valid. Although the inventories of launcher production + AIT and propellant production could not be investigated for validation purposes, the LCIA results suggest that the data is comparable.	For the launch campaign, although the SSSD considers more processes, the data which is compared is highly comparable with minimal differences in LCI dataset inputs. The LCI dataset for transportation is also identical. For this reason, both datasets can be considered to be materially correct and a fair representation of the data and information, prepared in accordance with relevant International Standards and guidelines. For the spacecraft container, a validation statement could not be issued as the LCI datasets models a completely different type of spacecraft container.
Space Segment 	The space segment had by far the most LCI datasets and processes to consider. There were several upstream/downstream processes involved which were issued with a simplified validity statement but were not considered as part of this analysis. For the LCI datasets considered, the electricity consumption LCI datasets for AIT were considered valid. However the N2 consumption during AIT as well as the propellants and pressurants lacked detail on the SSSD side in comparison with the ESA LCA database which meant that these datasets were limited and could not be validated. The spacecraft components LCI datasets were very similar even for the 25% not from the ESA Space System Guidelines and were based on sound sources. For this reason, all spacecraft components (except for thrusters which could not be validated since the LCI datasets were incomparable) can be considered to be valid.	For electricity consumption LCI datasets during AIT, and all spacecraft components (excluding thrusters), the LCI processes closely resemble one another and are based on sound sources. For this reason, these datasets can be considered to be materially correct and a fair representation of the data and information, prepared in accordance with relevant International Standards and guidelines. For the LCI dataset on thrusters, a validation statement could not be issued as the dataset models a completely different type of thruster. For the all propellants and pressurants (including N2 consumption during AIT), due to the sources of data (for the SSSD) and difference in LCI processes, a validation statement could not be issued and (in terms of the SSSD), the data expresses a limited level of assurance and may require further investigation before they can be considered valid.

Overall, several limitations were identified. Perhaps the biggest related to confidentiality issues which meant that access to launcher LCIs was not permitted. Therefore, a validation statement could not be issued for any of these datasets. However, the similarities of LCIA results during the comparisons suggest that the LCI dataset used and their input values are comparable (see Subsection 5.4.1). Software issues and bugs also contained within the ESA E-LCA database and Space Opera also severely limited the amount of LCI datasets that could be included within the scope of this study. In particular, the usability of the ESA E-LCA Database was severely restricted since a single user license of SimaPro is used on a multi-user platform. This meant that the database did not function properly and certain processes would not open. In addition to this, the ESA E-LCA Database was highly disorganised. This meant finding certain LCI datasets was a difficult but unavoidable feature. The database is currently going through a harmonisation project to 'tidy it up' [135]. To ensure that the study was not hindered by this, multiple excel files were used which contain ESA E-LCA database and Space Opera LCI datasets. However, this made finding the correct LCI a difficult and time consuming process, particularly due to cross-checking to ensure that the correct LCI dataset was used. Also, it was found that some of the datasets used were either based on outdated data (i.e. Ecoinvent processes) or are in the process of being updated (i.e. ESA currently conducting a study into Ground Segment LCA). Despite this, the project was completed as intended, on time, to a high standard. As an outcome, excluding the launch segment, the LCIs were assessed and compared for all datasets under study and a validation statement was issued for all of these within both Space Opera and the SSSD.

The final presentation of this project was submitted to the ESA Clean Space and CDF teams on 10th December 2018 for critical review. This is a vital part of LCI validation procedures since it ensures that study outcomes are appropriate, transparently documented, scientifically valid and consistent with ISO standards through a comprehensive peer-review process. For this reason, on 12 December 2018, four members of the ESA Clean Space team formed an internal review panel for the ESA LCI Validation Project to critically evaluate the work conducted. The project outcomes were also analysed by the entire CDF team at ESA on 14 December 2018 as a secondary review panel. The final project report was subsequently approved at the end of these meetings after valuable discussions. In both reviews, the results outlined within the report were considered to be fully transparent and credible. Nonetheless, it is recommended that an independent review panel is formed (in addition to this internal one) in order to verify the results of this project. This is because the validator and internal review panels were not independent in the strictest sense, meaning that unconscious bias or a lack of impartiality may have been present. Therefore, an external review panel should be formed using third party experts with sufficient expertise in space-specific E-LCA but no direct connection to either ESA or the University of Strathclyde in order to confirm the validity of the project outputs. In the meantime, corrections and further updates will now be made for SSSD LCI datasets and processes which either displayed a limited level of assurance or could not be validated. It is suggested that ESA do the same for the ESA E-LCA Database.

The inventory information of the LCI datasets which were compared cannot be directly shared within this thesis as was agreed under contract with ESA since the ESA E-LCA database LCI datasets are currently classed as strictly confidential. A full list of all compared datasets (including their inventory data) can be found within Appendix 9.8 of the 'ESA Life Cycle Inventory (LCI) Validation Report' [281]. This document is the final project report of the ESA LCI Validation Project and contains all validation records and methodologies. It has been securely deposited on the ESA Clean Space Sharepoint and within the University of Strathclyde Sharepoint (Pure) under the highest restriction level. This means that it is accessible to authorised persons only, as agreed with ESA. All communicated results in any published or unpublished work relating to the ESA LCI Validation Project require prior written consent from ESA. Permission was therefore granted by ESA to use certain results from this project as part of this thesis. Due to these restrictions, all validation statements input to the SSSD are generic so as not to breach any confidentiality agreements. A letter provided by the Head of the Clean Space Office at ESA which grants permission to the current author to disclose the results generated during his time working with the Clean Space Initiative (between 17 September 2018 and 14 December 2018 at ESTEC in Noordwijk, Netherlands) in their current form as presented within this thesis is provided in Appendix C.

4.3.5 Results & Discussion

Since the SSSD contains over 250 newly formed environmental LCI datasets within the background inventory alone, it would be impossible to describe the methodology behind each one within this thesis. As previously mentioned, all methodological descriptions are contained within the 'Modelling and validation' tab within each process of the SSSD. However, as an example, the development of launch event processes were selected as a case study within this subsection. These processes were selected since, according to Ross et al. [1], "rocket emissions are complex, variable and not well understood" despite having the potential to be one of the most polluting parts of a space mission. For this reason, the formulation of new launch event processes are critical for space E-LCA. As such, eleven new launch event LCI datasets were created within the SSSD, seven of which describe the emissions from the launch event by specific launchers whilst the other four relate to launch events by propellant type. In addition, data quality information was also evaluated for these processes based on the Ecoinvent data quality matrix outlined within Subsection 4.3.4.

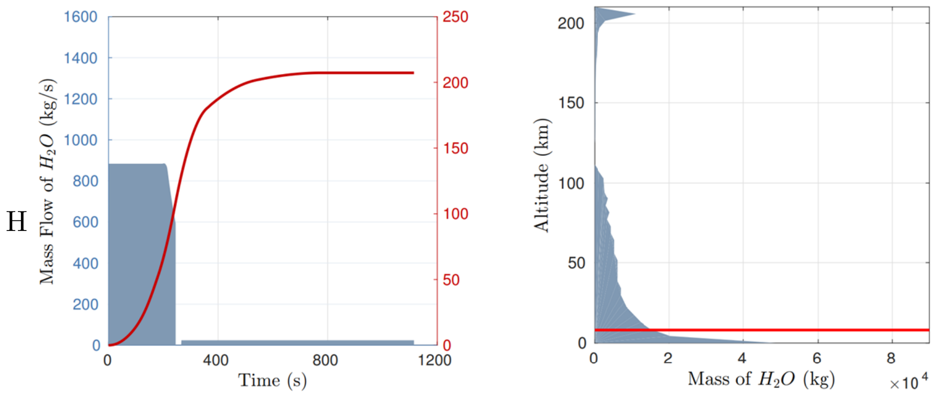
Firstly, the goal of each launch event process was to model the typical environmental impacts produced by rocket emissions. As such, the FU of the datasets relating to launch event by specific launchers was set to 'one launch at maximum propellant capacity' whilst the quantitative reference was defined as 'one launch', assuming that 100% of the launcher propellant is burned during the launch event. In comparison, the FU of the launch event by propellant type datasets was set to 'one kilogram of propellant burned'. Therefore, the quantitative unit was defined as 'one kilogram'. The system boundary for all of the launch event processes covers all emissions to air produced by the propulsion system functioning, taking into account the influence of afterburning and mesoscale processing.

The initial estimation for the LCI of each process is based on research by Ross et al. [1] who approximate emission levels for the four main propellant types as a mass fraction (see Table 4.8 below). The total mass fraction exceeds unity in this table because of the assumption that air mixed into the plume oxidises CO and H_2. However, the impacts from this process as a whole are poorly understood with very little freely available data. As such, the predicted impact of this process is unknown but expected to be relatively small in comparison to other industries such as from aircraft which only account for between 2-3% of total anthropogenic CO_2 emissions from all activities [282].

Table 4.8: Approximate emissions for the four main propellant types as a mass fraction for each component [1]

Propellant Type		N_2	$CO_2 + CO$	$H_2O + H_2$	ClO_X, HO_X, NO_X	HCl	Al_2O_3
Solid	(NH_4ClO_4/Al)	0.08	0.27	0.48	0.10	0.15	0.33
Cryogenic	(LO_X/H_2O)	-	-	1.24	0.02	-	-
Kerosene	(LO_X/RP-1)	-	0.88	0.30	0.02	-	0.05
Hypergolic	(N_2O_4/UDMH)	0.29	0.63	0.25	0.02	-	Trace

These species of exhaust products for each propellant type and their quantities were coupled with data held by other researchers within the Aerospace Centre of Excellence at the University of Strathclyde. Ideally the figures obtained from the literature review would not be used to predict emissions of a given rocket engine type, particularly as they provide specific propellant formulations to reflect generic propellant types. However, due to a lack of reliable data, this data was adopted for use within the SSSD. For this reason, using in-house data and software, it was important that the accuracy of the stated mass fractions were tested. This was done by comparing these values using simulations run through the International Standard Atmosphere (ISA) atmospheric model and University of Strathclyde in-house spaceplane Integrated Design Environment software [283–285]. These simulations were conducted by Garner et al. who estimated the quantity of each exhaust product species emitted into each layer of the atmosphere for a given launch vehicle based on their propellant type and launch trajectory [286]. An example of this modelling technique is provided below for an exhaust product species (H_2O) of the Delta IV launcher. The areas highlighted in blue represent the total emissions of the launcher. The graph on the left shows mass flow rate of H_2O emissions with time, whilst the red line indicates the trajectory (altitude with time). The graph on the right shows mass of H_2O emissions with altitude. The data for this has been binned and plotted into altitude bins of 4km.



(a) Mass flow rate with time **(b)** Mass with altitude

Figure 4.7: Simulated H_2O emissions from the launch event of a Delta IV [286]

Overall, for launcher types where data was available, it was found that these simulations largely conformed with the mass fractions calculated by Ross et al. These simulations also calculated results for individual exhaust species meaning that they could be used to provide an updated approximation relating to the breakdown of the grouped exhaust products as a mass fraction which were initially provided in Table 4.8. This breakdown in provided within Table 4.9 below.

Table 4.9: Approximate breakdown of grouped products with respect to mass fractions

Propellant Type		N_2	CO_2	CO	H_2O	H_2	ClO_x	HO_x	NO_x	HCl	Al_2O_3
Solid	(NH_4ClO_4/Al)	0.080	0.108	0.162	0.384	0.096	0.080	0.015	0.005	0.150	0.330
Cryogenic	(LO_x/H_2O)	-	-	-	0.992	0.248	0.016	0.003	0.001	-	-
Kerosene	(LO_x/RP-1)	-	0.352	0.528	0.240	0.060	0.016	0.003	0.001	-	0.050
Hypergolic	(N_2O_4/UDMH)	0.290	0.252	0.378	0.200	0.050	0.016	0.003	0.001	-	0.001

As such, the data contained within this table can be used as the LCI for the launch events by propellant type processes. In this regard, the table identifies the total amount of exhaust species emitted per kg of fuel burned for each propellant type. However, for the LCI of the launch event by specific launchers processes, an additional step is required. As such, a literature review was conducted to find the maximum propellant capacity of a variety of launchers, including the type of propellant used at each stage. The values contained within Table 4.9 were then multiplied by the propellant mass of each launcher to quantify the total amount of exhaust product released. These values can be found below and are used as the LCI of these processes.

Table 4.10: Approximate launch event emissions of different launchers

(a) Ariane 5

Consumed Propellant			N_2	CO_2	CO	H_2O	H_2	ClO_x	HO_x	NO_x	HCl	Al_2O_3
Type		Mass										
Solid	(NH_4ClO_4/Al)	480,000 kg	38,400	51,840	77,760	184,320	46,000	38,400	7,200	2,400	72,000	158,400
Cryogenic	(LO_x/H_2O)	184,900 kg	-	-	-	183,420	45,860	2,960	550	180	-	-
Kerosene	(LO_x/RP-1)	-	-	-	-	-	-	-	-	-	-	-
Hypergolic	(N_2O_4/UDMH)	10,000 kg	2,900	2,520	3,780	2,000	500	160	30	10	-	10
	Total:	**674,900 kg**	**41,300**	**54,360**	**81,540**	**369,740**	**92,360**	**41,520**	**7,780**	**2,590**	**72,000**	**158,410**

(b) Atlas V

Consumed Propellant			N_2	CO_2	CO	H_2O	H_2	ClO_x	HO_x	NO_x	HCl	Al_2O_3
Type		Mass										
Solid	(NH_4ClO_4/Al)	85,260 kg	6,821	9,208	13,812	32,740	8,185	6,821	1,279	426	12,789	28,136
Cryogenic	(LO_x/H_2O)	20,830 kg	-	-	-	20,663	5,166	333	62	21	-	-
Kerosene	(LO_x/RP-1)	284,089 kg	-	99,999	149,999	68,181	17,045	4,545	852	284	-	14,204
Hypergolic	(N_2O_4/UDMH)	-	-	-	-	-	-	-	-	-	-	-
	Total:	**390,179 kg**	**6,821**	**109,207**	**163,811**	**121,584**	**30,396**	**11,699**	**2,193**	**731**	**12,789**	**42,340**

(c) Delta IV

Consumed Propellant			N_2	CO_2	CO	H_2O	H_2	ClO_x	HO_x	NO_x	HCl	Al_2O_3
Type		Mass										
Solid	(NH_4ClO_4/Al)	61,800 kg	4,944	6,674	10,012	23,731	5,933	4,944	927	309	9,270	20,394
Cryogenic	(LO_x/H_2O)	227,620 kg	-	-	-	225,799	56,450	3,642	683	228	-	-
Kerosene	(LO_x/RP-1)	-	-	-	-	-	-	-	-	-	-	-
Hypergolic	(N_2O_4/UDMH)	-	-	-	-	-	-	-	-	-	-	-
	Total:	**289,420 kg**	**4,944**	**6,674**	**10,012**	**249,530**	**62,383**	**8,586**	**1,610**	**537**	**9,270**	**20,394**

(d) Falcon 9

Consumed Propellant			N_2	CO_2	CO	H_2O	H_2	ClO_x	HO_x	NO_x	HCl	Al_2O_3
Type		Mass										
Solid	(NH_4ClO_4/Al)	-	-	-	-	-	-	-	-	-	-	-
Cryogenic	(LO_x/H_2O)	-	-	-	-	-	-	-	-	-	-	-
Kerosene	(LO_x/RP-1)	488,370 kg	-	171,906	257,859	117,209	29,302	7,814	1,465	488	-	24,419
Hypergolic	(N_2O_4/UDMH)	-	-	-	-	-	-	-	-	-	-	-
	Total:	**488,370 kg**	**-**	**171,906**	**257,859**	**117,209**	**29,302**	**7,814**	**1,465**	**488**	**-**	**24,419**

(e) Falcon Heavy

Consumed Propellant			N_2	CO_2	CO	H_2O	H_2	ClO_x	HO_x	NO_x	HCl	Al_2O_3
Type		Mass										
Solid	(NH_4ClO_4/Al)	-	-	-	-	-	-	-	-	-	-	-
Cryogenic	(LO_x/H_2O)	-	-	-	-	-	-	-	-	-	-	-
Kerosene	(LO_x/RP-1)	1,397,000 kg	-	491,744	737,616	335,280	83,820	22,352	4,191	1,397	-	69,850
Hypergolic	(N_2O_4/UDMH)	-	-	-	-	-	-	-	-	-	-	-
	Total:	**1,397,000 kg**	**-**	**491,744**	**737,616**	**335,280**	**83,820**	**22,352**	**4,191**	**1,397**	**-**	**69,850**

(f) Soyuz-FG

Consumed Propellant			N_2	CO_2	CO	H_2O	H_2	ClO_x	HO_x	NO_x	HCl	Al_2O_3
Type		Mass										
Solid	(NH_4ClO_4/Al)	-	-	-	-	-	-	-	-	-	-	-
Cryogenic	(LO_x/H_2O)	-	-	-	-	-	-	-	-	-	-	-
Kerosene	(LO_x/RP-1)	218,150 kg	-	76,789	115,183	52,356	13,089	3,490	654	218	-	10,908
Hypergolic	(N_2O_4/UDMH)	7,360 kg	2,134	1,855	2,782	1,472	368	118	22	7	-	7
	Total:	**225,510 kg**	**2,134**	**78,644**	**117,965**	**53,828**	**13,457**	**3,608**	**676**	**225**	**-**	**10,915**

(g) Vega

Consumed Propellant			N_2	CO_2	CO	H_2O	H_2	ClO_x	HO_x	NO_x	HCl	Al_2O_3
Type		Mass										
Solid	(NH_4ClO_4/Al)	124,865 kg	9,989	13,485	20,228	47,948	11,987	9,989	1,873	624	18,730	41,205
Cryogenic	(LO_x/H_2O)	-	-	-	-	-	-	-	-	-	-	-
Kerosene	(LO_x/RP-1)	-	-	-	-	-	-	-	-	-	-	-
Hypergolic	(N_2O_4/UDMH)	550 kg	160	139	208	110	28	9	2	1	-	1
	Total:	**125,415 kg**	**10,149**	**13,624**	**20,436**	**48,058**	**12,015**	**9,998**	**1,875**	**625**	**18,730**	**41,206**

The next step is to apply LCIA methods. Since combustion emissions from rocket engines are released directly into the atmosphere, it was decided that only air pollution impact categories would be considered for these processes. This means that classification and characterisation of exhaust products occurred for the impact categories of Al_2O_3 emissions, air acidification, climate change, ozone depletion, particulate matter formation and photochemical oxidation. However, it should be noted that although exhaust product species have been mapped at altitude for each launcher within the previously mentioned experimental simulations, the impact of these pollutants could not be determined within each altitude bin. This is because CFs for emissions released at altitude do not yet exist due to the novelty of space-related E-LCA. Therefore, further study is required to determine more appropriate CFs by analysing the mixing of launcher exhaust products into the upper atmosphere and propagating their dispersion and influence over a number of years or decades. As such, the classification and characterisation of each exhaust species is based on the conventional LCIA methods which are adopted as part of the SSSD. Table 4.11 identifies the relevancy of each exhaust products to E-LCA air pollution impact categories and provides a CF to convert each exhaust product into reference unit equivalences.

Table 4.11: Classification & characterisation of exhaust products

Exhaust Product	N_2	CO_2	CO	H_2O	H_2	ClO_x	HO_x	NO_x	HCl	Al_2O_3
Al_2O_3 equivalence	-	-	-	-	-	-	-	-	-	1.00
SO_2 equivalence	-	-	-	-	-	-	-	0.70	0.88	-
CO_2 equivalence	-	1.00	1.57	-	-	-	-	-	-	-
CFC-11 equivalence	-	-	-	-	-	0.70				-
PM_{10} equivalence	-	-	-	-	-	-	-	0.22	-	1.00
NMVOC equivalence	-	-	0.0456	-	-	-	-	1.00	-	-

The reason that CFC-11 equivalences are highlighted in blue is because although ClO_x, NO_x and HO_x all have the potential to cause ozone depletion, they are not classified for ozone depletion within traditional LCIA methods. This is particularly troublesome since in 2009, Ravishankara et al. found that NO_x radicals from human activity can cause twice as much ozone depletion than the next leading ozone-depleting gas [287]. These findings are confirmed by the World Meteorological Organization who state that NO_x emissions are growing relatively steadily at present and are likely to remain a major contributor to ozone depletion throughout the 21st century [288]. The reason for this omission is because these radicals are not regulated by the Montreal Protocol [62] which the applied LCIA methods refer to. Additionally, HCl is not classified for ozone depletion either since it is considered to be harmless to ozone in this form. However, chemical reactions on the surface of ice crystals can convert chlorine-containing compounds such as HCl into more reactive forms, priming severe ozone destruction [289]. Since no CF is available for these exhaust products, the factor used in this table is an approximation provided by Dr Martin N. Ross of the Aerospace Corporation [100]. The approximation was semi-quantitatively calculated based on the results of his work on ozone loss from launch vehicles, since Equation 4.2 was not deemed appropriate for use in this case due to the unique nature of the process (i.e. injection of ozone depleting particles directly into the stratosphere.

It should also be noted that CO value for CO_2 equivalence is also based on IPCC 2001 and CML 2001 LCIA methods since the IPCC 2007 and 2013 methods do not include CO within GWP_{100}. The CF of 1.57 equates to the molar mass conversion of CO to CO_2 (i.e. $44/28 = 1.5714285471$). However, the PEFCR guidelines state that "the GWPs for near term GHGs are not recommended for use due to their complexity and high uncertainty. Near term GHGs refer to substances that are not well-mixed once emitted to the atmosphere because of their very rapid decay (black carbon, organic carbon, nitrogen oxides, sulphur oxides, volatile organic compounds, and carbon monoxide)" [114]. However, CO has been included within the SSSD's GWP_{100} LCIA method for launch event impacts since it is a major area of pollution which cannot be scoped out and it is theorised that the emitted CO will eventually oxidise further to create more CO_2.

Table 4.12: LCIA results per 1 kg of fuel burned

Propellant type		Unit	Al_2O_3 emissions [kg Al_2O_3]	Air Acidification [kg SO_2 eq]	Climate Change [kg CO_2 eq]	Ozone Depletion [kg CFC-11 eq]
Solid	(NH_4ClO_4/Al)	1 kg	0.33000	0.27498	0.36257	0.27956
Cryogenic	(LO_X/H_2O)	1 kg	-	0.00164	-	0.05527
Kerosene	(LO_X/RP-1)	1 kg	0.05000	0.00164	1.18171	0.05527
Hypergolic	(N_2O_4/UDMH)	1 kg	0.00100	0.00164	0.84600	0.05527

To generate LCIA results for the four launch event by propellant type processes, these CFs are then multiplied by the LCI results contained in Table 4.9 for each propellant type to provide the impact per 1 kg of fuel burned of each exhaust product. The sum of these values across all E-LCA air pollution impact categories provides the total impact of each E-LCA impact category in equivalences per 1 kg of fuel burned. These values can be seen in Table 4.12 above.

To generate LCIA results for the seven launch event by specific launcher processes, the CFs can be multiplied to all values contained in Table 4.10 for all propellant types used by each launcher. The sum of these values across all E-LCA air pollution impact categories provides the total impact of each E-LCA impact category in equivalences for one launch event. These values can be seen below alongside a comparison which provides the relative LCIA results of each launcher.

Table 4.13: LCIA results per launch event of specific launchers

Impact Category	Unit	Ariane 5	Atlas V	Delta IV	Falcon 9	Falcon Heavy	Soyuz-FG	Vega
Al_2O_3 emissions	kg Al_2O_3	158,410	42,340	20,394	24,419	69,850	10,915	41,206
Air Acidification	kg SO_2 eq	65,176	11,766	8,533	342	978	158	16,920
Climate Change (GWP_{100})	kg CO_2 eq	182,494	366,624	22,407	577,112	1,650,849	264,017	45,738
Ozone Depletion (Steady State)	kg CFC-11 eq	86,729	19,189	14,002	6,837	19,558	3,157	21,859
Particulate Matter Formation	kg PM_{10} eq	158,981	42,501	20,512	24,526	70,157	10,964	41,343
Photochemical Oxidation	kg NMVOC	6,315	8,182	993	12,214	34,939	5,590	1,557

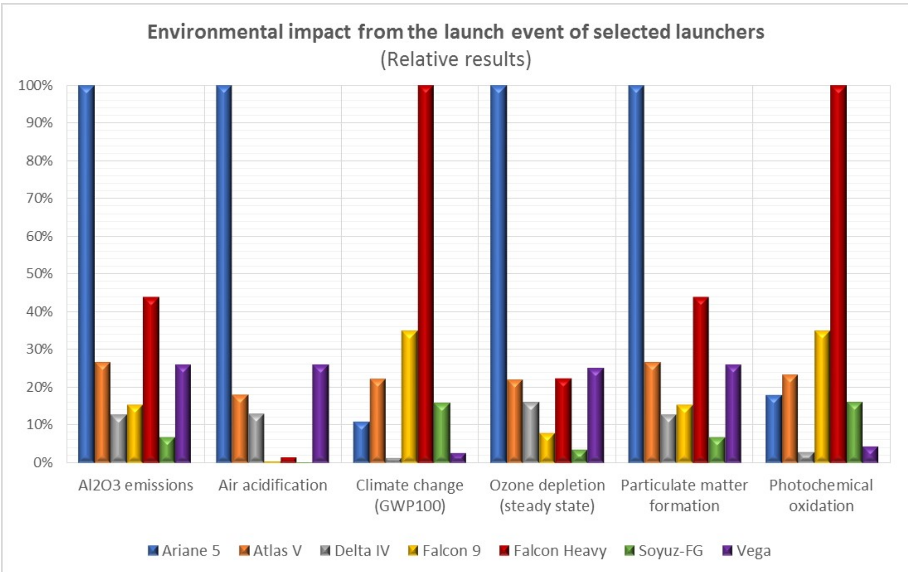


Figure 4.8: LCIA results comparison of specific launchers

In addition to the release of exhaust products, a second source of pollution which occurs during the launch event is the immediate return to Earth of launcher stages after fuel exhaustion. Typically after ejection, the launcher accelerators, payload fairing and initial first stages of launchers fall into the ocean. These are not systematically salvaged and are seldom reused [14], so end up lying on the seabed for decades. The environmental impacts of this process could not be determined since research into this phenomenon is still in its embryonic stages [290]. To overcome this issue, ESA created a new impact category to quantify the total mass which ends up at the bottom on the ocean [30]. As such, the LCI for each launcher was developed to reflect this and was simply calculated based on the sum of each launcher stage which ends in the ocean. The results of this can be seen in Table 4.14 below. The reason that the Falcon 9 and Falcon Heavy exhibits a null value is based on an assumption that each stage of these launchers are completely reused. This can be altered within the SSSD if reusable stages are not used for these launchers during a particular mission.

Table 4.14: Mass disposed in the ocean by launcher

Impact Category	Unit	Ariane 5	Atlas V	Delta IV	Falcon 9	Falcon Heavy	Soyuz-FG	Vega
Mass Disposed in Ocean	kg mass	96,595	91,205	88,230	0	0	34,250	13,258

Additionally, since the solid rocket boosters, payload fairing and initial first stages of launchers are generally jettisoned at very low orbital speeds, this means that they will not burn-up on re-entry as extreme heating does not take place. However, the friction caused by these components falling through the atmosphere will cause the objects to char [100]. Since the mass loss caused by this reaction is not considered to be significant, RSP generation was excluded from launch event processes.

The criteria contained within this dataset could not be validated during the ESA LCI Validation Project due to confidentiality issues concerning ESA data. However, as part of this project it was found that the average variance in LCIA results between Space Opera and the SSSD across all impact categories for the entire launch segment was only 10.33% (see Section 5.4). This suggests that the inventory data between Space Opera and the SSSD are closely aligned. More information regarding this analysis can be found in the 'ESA LCI Validation Project Report' [281].

In terms of data quality, a pedigree data quality matrix was added to each process (see Figure 4.9 below). In particular, reliability and completeness both scored a '3' because data is based on a mixture of simulations and qualified estimates for very specific propellant formulations, all of which could not be validated during the ESA LCI Validation Project. In turn, this leads to a value of 1.12534 being produced for the geometric standard deviation of each launch event process under a logarithmic normal uncertainty distribution. When applying these values to individual process flows, a Monte Carlo analysis can be generated. An example of such an analysis is provided in Figure 4.10 below. The specific analysis outlined consisted of 1,000 iterations for climate change LCIA results relating to 1 kg of solid propellant burned during a launch event (i.e. 0.36257 kg CO_2e). From this simulation, the coefficient of uncertainty suggests that the results fall within acceptable boundaries, since the standard deviation falls well under 20% of the mean. This indicates sufficient convergence of the Monte Carlo simulation. However, it is important to note that this uncertainty information has not yet been added to launch event flows. Instead, this data quality information is still exclusively at process level.

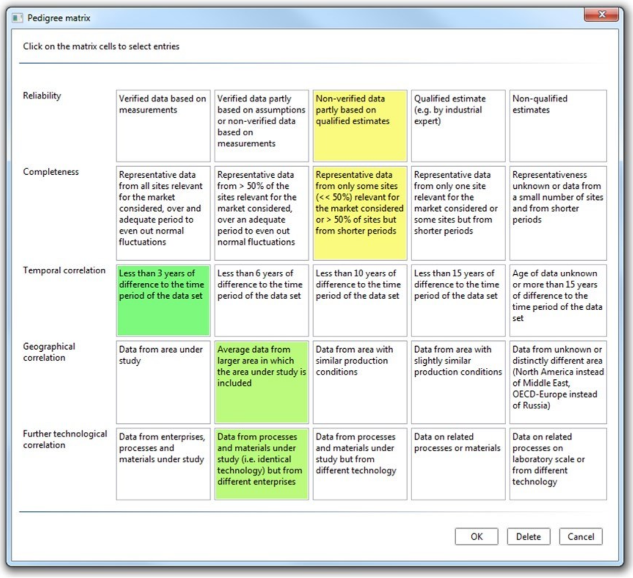


Figure 4.9: Data quality matrix for launch event processes

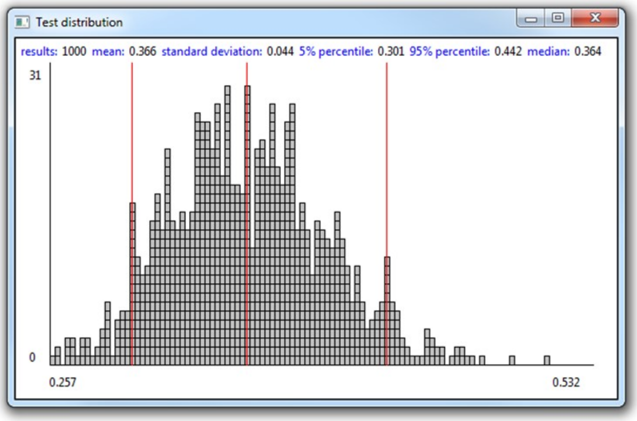


Figure 4.10: Example Monte Carlo results for climate change impacts relating to the burning of 1 kg of solid propellant during a launch event

Additionally, several limitations to this approach were identified. Firstly, as previously mentioned, specific propellant formulations have been used to represent the impacts of entire propellant types. This is a broad generalisation that may not be representative to all launchers, particularly those using a different propellant formulation to the one represented by the given propellant type. For example, switching from LOx/H_2O to LOx/LNG within cryogenic would create a much larger climate change impact since the GWP_{100} of methane is 28 kg CO_2e based on the IPCC [291]. Nevertheless, this approach has been used as a 'best fit' until more reliable data becomes available. Additionally, each approximation applied during the LCI and LCIA calculation phases have the potential to alter results. These approximations relate to the breakdown of grouped products (from literature, scientific data and simulation), the amount of propellant consumed by each launcher (based on literature) and the CFs applied for ozone depletion impacts (guesstimate by an industry expert). However, perhaps the biggest drawback of this method is that characterisation of exhaust products at different altitudes has not taken place yet. This leads to major levels of uncertainty regarding LCIA results for which an uncertainty analysis was not run. Finally, it should also be noted that this only represents one part of the launch segment according to the system boundary adopted within the SSSD. For this reason, no launcher should be discounted for use in a space mission purely based on the environmental performance of its launch event.

The adoption of this approach was driven by a lack of publicly available data. However, in comparison to this approach, ESA used climate modelling within their studies on the launch segment to quantify permanent global impacts (rather than localised impacts) caused by exhaust plumes emitted directly into high layers of the atmosphere. Key findings from this exercise showed that the concentration of exhaust plume columns play a significant role in the observed impact. Generally, it was found that columns of 1 kilometre or less in diameter caused a local ozone hole which dispersed after a few minutes [33]. However, further research into this is currently ongoing. Despite this, the adopted approach represents a novel and embryonic technique to quantify launch event impacts. It provides an E-LCA trade-off between different launchers and propellant types, providing publicly available data on this process for the first time. In particular, this analysis highlighted that launchers which use large amounts of solid propellant generally perform worse environmentally since this propellant type generates the poorest LCIA results for Al_2O_3 emissions, air acidification, ozone depletion and particulate matter formation per kg of fuel burned. In comparison, kerosene generated the poorest LCIA results for climate change and photochemical oxidation whilst cryogenic performed the best across all impact categories out of the four propellant types.

4.4 Amalgamation of Social & Costing Criteria

Since it is envisaged that LCSA could be the future of E-LCA [18], enabling such an assessment can be considered to be the logical next step for E-LCA of space systems. As such, TBL sustainability is enshrined within the space-specific LCSA framework in order to balance the three dimensions of sustainable development as required by the 2030 Agenda. Since the SSSD has been constructed as a mechanism to deliver this framework, combining the developed E-LCA LCI datasets with social and economic criteria is a key factor in achieving this.

According to the UNEP/STEAC 'Global Guidance Principles for Life Cycle Assessment Databases' [128], these additional analyses are commonly applied using completely separate LCI datasets. However, these guidelines go on to mention that within life cycle database development, social and economic criteria is often unified directly with E-LCA LCI datasets (see Figure 4.11 below). This LCI-based methodology is particularly useful in the production of specific goods or products and significantly lessens the volume of work and time required by the LCSA practitioner to complete an analysis or study. As such, an LCI-based methodology was adopted for integrating S-LCA and LCC data into the SSSD. These methodologies present a novel first attempt at combining such criteria within a space-specific life cycle study whilst fulfilling the requirements of the newly developed space-specific LCSA framework with respect to the 2030 Agenda. Additionally, the SSSD has also been designed to facilitate both methods on which to analyse LCSA results as proposed by Klöpffer [10]. The following subsections will outline how this was used in the development of social and economic LCI datasets and LCIA methods, before going onto provide an example regarding the application of these elements in the case of a spacecraft battery module.

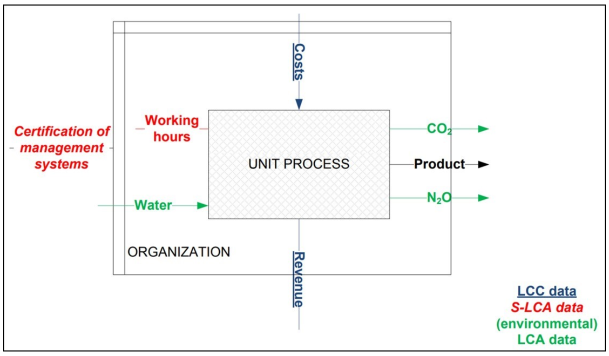


Figure 4.11: Example of LCSA inventory data for unit processes [179]

4.4.1 Development & Merging of Social LCI Data

The S-LCA segment follows a process-based organisational life cycle assessment model. This enhances the scope of the assessment by making it more applicable for use [227]. The model has been designed to handle the importance of national socio-economic conditions in which organisations operate, the direct accountability of organisational conduct and the social implications based on organisational relationships with relevant stakeholders. Therefore, identified social aspects at national-level are converted to be applicable at an organisational-level. Additionally, since social impacts are modelled from the viewpoint of organisations, they can be added to product-based LCI datasets where a relevant organisation is a contributor to a given process according to the activity variable. This means that whilst the social impact assessment is mostly applicable at organisation-level, it can also be used at product-level which adds value to the assessment and makes it more applicable for use in LCSA. Based on this, a range of social indicators needed to be developed which could be used to reflect the direct involvement of organisations in a given LCI dataset or activity [292]. These social indicators had to be quantifiable and measurable in order to address potential implications for all stakeholders as a result of the organisations' activities.

With regards to creating new social indicators, it is problematic if the SDGs are to be integrated into S-LCA according to the space-specific LCSA framework since these are primarily aimed at an international audience for country-level application [226]. This means that diluting these to product or industry-level is very complicated. However, attempts to do this can be observed by other researchers. Examples include the work of Maier et al. where the SDGs were assigned to impact category groups and LCIA impact categories [293], Goedkoop et al. where SDG indicators were linked to stakeholders based on E-LCA and the Product Social Metrics Handbook [225] and Wulf et al. where LCSA indicators were assigned to the SDGs within a micro level study on electrolytic hydrogen production [294]. Following a similar approach to the method conducted within these studies, the targets and indicators of the 2030 Agenda [4] were analysed for relevancy to both LCSA and the supply chain of space-specific products (as defined within the system boundary of the ESA E-LCA guidelines [30]). The findings from this method highlighted that just 60% of the 169 targets were classed as relevant for further analysis which rose to 73% when including indicators that were considered influential but not necessarily relevant. Similarly, 62% of the 232 indicators used to measure the targets were classed as relevant which rose to 69% when including indicators that were influential. As such, these formed the basis for social indicator and evaluation scheme formulation by tailoring them in a manner which accords with the space sector and its supply chain whilst also aligning closely to the SDGs.

In this respect, a total of 105 social indicators were created within the SSSD at organisational-level, 56% of which can also be used at country-level if desired. Each indicator falls under the relevant stakeholder categories and subcategories as defined within the UNEP/SETAC S-LCA guidelines [181] (see Figure 3.2). The selection of indicators used within the SSSD were based on an adapted mixture of sources. These included the 189 recommended generic and specific UNEP/SETAC inventory indicators [183], the 73% of SDG targets contained within the 2030 Agenda [4] which were classified as influential during the relevancy assessment and the 62% of SDG indicators of the global indicator framework for the SDGs and targets provided within A/RES/71/313 [237] which were also classified as influential during the relevancy assessment. Specifically, the UNEP/SETAC indicators and SDG targets which were analysed and determined to be the most relevant for a space-specific S-LCA were selected for further investigation. These were then sorted into 23 broad thematic areas which were then classified into the most applicable stakeholder subcategory. These were then cross-examined with the 'core subjects and issues of social responsibility' documented within ISO 26000:2010 [254] to find any linkages or gaps relating to the coverage of indicators within the required stakeholder subcategories based on this organisational approach and to also identify the most appropriate measurement scale for each indicator. Each of the developed indicators are provided within Appendix A. This also includes their measurement scales, evaluation schemes, indicator data sources and the SDGs that they affect.

With regards to the SDGs, each indicator relates to a minimum of 1 SDG and a maximum of 10 SDGs. This means that the SDGs can be considered to be interrelated (i.e. an impact on one will have an impact on another). In this sense, since more than one SDG is often linked with a single indicator, if the scope of the analysis is to lower adverse social impacts of a specific SDG, then targeting social indicators associated with that SDG will have an impact on all other SDGs that are linked with those indicators. Additionally, it should be noted that environmental and economic SDGs have not been applied in relation to E-LCA impacts or to LCC as a cost function. This is because of the mixture of qualitative and quantitative information required as part of social LCI procedures which makes the data not applicable for use with other assessment types. Besides this, since E-LCA and LCC adopt a product-specific approach exclusively, integrating the SDGs to these methodologies in the form in which they are contained within social indicators may risk deviation from the outlined system boundary. This is because the social impact take an organisation perspective which is assumed to have more far-reaching and widespread implications than purely product-level. However, whilst it was found that all of the SDGs are applicable to the space sector when using a process-based organisational S-LCA model to varying degrees, some were far more relevant than others. As part of this approach, Appendix A2 outlines the number of social indicators associated with each SDG across all 105 indicators.

From this it was found that the five most relevant SDGs were Goal 16 (Peace, Justice & Strong Institutions), Goal 10 (Reduced Inequalities), Goal 8 (Decent Work & Economic Growth), Goal 11 (Sustainable Cities & Communities) and Goal 17 (Partnerships for the Goals). These SDGs were used in sixty-nine, fifty-one, forty-eight, thirty-two and thirty-two out of 105 social indicators respectively. Whilst Goal 16 was found to be driven by every stakeholder categories, Goal 8 and Goal 10 were driven mainly by the local community and worker stakeholder categories (which contain the most social indicators). In addition, Goal 11 was driven almost exclusively by the local community stakeholder category whilst Goal 17 was spread evenly amongst all stakeholder categories (except workers where it was not affected). There are numerous reasons that these indicators were more relevant in terms of space-specific S-LCA than others. Firstly, as organisation's are mainly driven by profit, it comes as no surprise that Goal 8 is featured within the top 5. However, since the driving force of social responsibility within organisations is to create a fairer and more just society, Goals 10 and 16 are also featured heavily. Goal 16 is also particularly relevant given the space sector's association with weapons. Furthermore, creating a fairer and more just society, is not only concerned with creating job opportunities (including spin-off jobs) but also about retaining a happy and healthy workforce, including supplier relations whilst attracting interesting in communities and society in general. Therefore, the inclusion of

Goals 11 and 17 within the five most affected SDGs can also be seen to be a prominent feature of a process-based organisational S-LCA.

In comparison, the five least relevant SDGs were Goal 2 (Zero Hunger), Goal 4 (Quality Education), Goal 1 (No Poverty), Goal 7 (Affordable & Clean Energy) along with both Goal 5 (Gender Equality) and Goal 6 (Clean Water & Sanitation) equally. These SDGs were used in six, six. eight, nine, twelve and twelve out of 105 social indicators respectively. There are a number of factors which could influence this. The most driving factors perhaps relate to the fact that most of these issues are not a direct focus of the space industry (besides services offered through space missions themselves). Moreover, a single dedicated social indicator and/or stakeholder subcategory has also been created for the likes of Goals 4 and 5 due to their relative importance. As such, their use within other social indicators have been limited or reduced. Although it has not yet been implemented within the SSSD, the inclusion of a weighting approach where each SDG is weighted evenly regardless of the number of social indicators attributed to each one could provide fairer results.

Each of the newly developed social indicators have been added to the SSSD using the openLCA social flow feature based on the above criteria. An example highlighting the formation of such a social indicator is provided within Table 4.15 below. In particular, this describes the formation of an indicator called 'Percentage of annual spending on educational opportunities' under the society stakeholder category and contribution to economic development subcategory. The unit of measurement is based on the percentage of annual budget that the organisation dedicates to educational opportunities, which was formed based on process mentioned above. Values obtained from a literature review outlined in the source description were used to form the evaluation scheme, measured in uniformed intervals. Evaluation schemes and their use within the SSSD are described further in Subsection 4.4.3. Additionally, the inclusion of information on which SDGs are affected by each social indicator is particularly beneficial for decision-makers. In this regard, the approach allows the most impacting social indicators identified within the LCIA results to be traced along the product tree to identify which SDGs are the most adversely affected during the life cycle of a space mission.

Table 4.15: SSSD Social Indicator Formulation Example

Indicator Information	Source Description	Effected SDGs & Targets
Stakeholder Category Society ⬇ **Stakeholder Subcategory** Contribution to economic development ⬇ **Subcategory Indicator** Percentage of annual spending on educational opportunities ⬇ **Unit of Measurement** % of annual budget dedicated to education ⬇ **Evaluation Scheme** **No risk:** ≥0.5300% **V. low risk:** 0.3975% - 0.5300% **Low risk:** 0.2650% - 0.3975% **Med risk:** 0.1325% - 0.2650% **High risk:** 0.0000% - 0.1325% **V. high risk:** 0.0000%	In 2014, NASA had a budget of $94.2 million to spend on education. In the same year, NASA's total budget was $17,646.5 million. This represents a 0.53% expenditure of the total annual budget on education. ESA spending as a percentage of annual budget is also reportedly similar. As one of the world's largest and most forward-looking space agencies, this figure has been used to represent a sound amount to spend on education. For this reason it was decided that if 0.53% or more of an organisation's total annual budget was spent on education, that this should represent 'No risk'. On the other hand, it was decided that organisations which spend 0% of their annual budget on education represents 'Very high risk'. Uniformed intervals were then used for each risk level between these two values for this evaluation scheme. NASA (2014). "NASA Budget Education". FY 2014 Budget. https://www.nasa.gov/pdf/742595main_FY14_NASA_Budget_Education.pdf NASA (2015). "FY 2015 President's Budget Request Summary". https://www.nasa.gov/sites/default/files/files/508_2015_Budget_Estimates.pdf	4 QUALITY EDUCATION **4.4** By 2030, substantially increase the number of youth and adults who have relevant skills, including technical and vocational skills, for employment, decent jobs and entrepreneurship. 8 DECENT WORK AND ECONOMIC GROWTH **8.6** By 2020, substantially reduce the proportion of youth not in employment, education or training.

Each indicator can then be added into the 'social aspects' tab of each LCI dataset to provide raw values. These raw values are produced in accordance with the measurement scale of each social indicator which can then be benchmarked against predefined performance criteria contained within each dataset's evaluation scheme to produce a social score. This is explained in more detail in Subsection 4.4.3. Additionally, 840 social flows have been created based on the eight risk levels of the 105 social indicators which can be added as inputs and outputs to each LCI dataset. In this regard, these social flows can be added to LCI datasets to reflect the applied quantitative reference using the methods described in Subsection 4.4.3. This can be done based on two approaches. The first applies S-LCA social indicator flows to all SSSD E-LCA LCI datasets based on averaged data which represents a wide-range of organisations. The second is to create new S-LCA LCI datasets where social indicator flows are added in order to represent specific organisations. These new S-LCA LCI datasets can then be added to SSSD E-LCA LCI datasets to reflect a variety of different organisations involved in specific processes across the entire product tree. In this regard, the social aspects tab would reflect averaged organisational data for the specific organisations involved in the given process. Whilst selecting either option can be considered as a valid approach, there are positives and negatives of each. In this regard, the first option may over simplify this process through generalisation of social impacts since such impacts vary drastically from organisation to organisation. However, this is a far less laborious method and is a good alternative if social data for a specific organisation cannot be obtained. In comparison, the second method is far more specific and can accurately pinpoint social hotspots of specific organisations or entities involved in the supply chain. However, this is a far more time consuming method to develop and may require consistent and regular monitoring/updating of these LCI datasets. Overall, it was concluded that this second method is the preferred option since the developed S-LCA approach for the SSSD follows an organisational life cycle model. This approach allows organisations to gather social information specifically related to their own organisations and stakeholders. Once input into the database, this will allow these S-LCA LCI datasets to be integrated with the E-LCA LCI datasets for use during a mission design session.

However, due to the primitive nature of research in this field, there was a clear lack of organisational willingness to provide S-LCA data in case they are seen as 'the black sheep' of the industry based on LCIA results since this is a burden-based analysis. As a result, the SSSD currently does not contain a social inventory because of a lack of data. This means that the first approach outlined above could not be completed. However, since the second approach is the preferred option, this means that this lack of organisational S-LCA might not be seen as a major omission. In this regard, it is highly recommended that the findings of the LCI data collection process are fed into the procurement process, with any entity which is found to be using severe, unjust or malicious practices (e.g. forced labour by means of torture) should be automatically blacklisted by the organisation. Although organisations may not be directly accountable for poor practises which occur further along the supply chain, they still have a duty to conduct themselves in a responsible manner and cut ties with socially negligent practices.

4.4.2 Development & Merging of Costing LCI Data

In terms of the LCC component, the adopted methodology follows the NASA Cost Estimating Handbook guidelines [54]. As such, a new parametric-analogous hybrid cost model was developed which adopts an ABC estimating approach. This ABC approach treats each activity of a space mission defined by the system boundary within the ESA E-LCA guidelines [30] as cost pools. In this regard, the model covers the entirety of DDT&E, launch & emplacement, operations and end of life. However, since SSSD LCI datasets have been built to reflect general spacecraft components or space mission activities, using specific data or equipment from a particular manufacturer, organisation, practice or model is not applicable. Without the availability of specific data, the best approach for predicting future costs is based on historical trends of past costs (i.e. a parametric methodology) [204]. The analogous part is applied by adjusting these parametric costs for complexity, technological and physical differences. Based on the principles developed by Saint-Amand & Ouziel and Ouziel & Saint-Amand [108, 109], this has been applied to represent different technology readiness levels (TRLs) since these are an extremely important design consideration within concurrent engineering. Linick maps development costs of different technological components at each TRL as a percentage of total cost at TRL 9 [295]. Using this data, a complexity factor was developed for each TRL in order to translate the costs of a technology at a given TRL to the costs of a TRL 9 technology (i.e. flight proven). This is done by multiplying the current cost at a given TRL by the appropriate complexity factor identified in Table 4.16 below. These complexity factors have been input to the SSSD as parameters and can be used in conjunction with CERs at the discretion of the LCSA expert.

Table 4.16: TRL Complexity Factors for Analogous Application (adapted from [295])

Phase	TRL	Development Cost	Complexity Factor
Research	1	0.9%	111.1
	2	1.7%	58.8
	3	5.9%	16.9
Development	4	13.6%	7.4
	5	24.6%	4.1
	6	39.1%	2.6
Deployment	7	57.0%	1.8
	8	78.3%	1.3
	9	100.0%	1.0

Since the ABC approach has been explicitly developed to handle life cycle activity-related data of products, this approach directly aligns with the goal of LCSA. As suggested by Duyan & Ciroth [296], there are two methods in which this LCC approach can be performed within openLCA. The first is by treating costs like emissions (i.e. adding cost flows). This method takes a life cycle approach and is identical to how the environmental impacts were created within the SSSD. The second method is by using the built-in openLCA cost feature which adds costs to process flows. Using this feature, costs can be specified for each flow/process and summed up in product systems under the fix and variable cost categories. The first approach was selected since it allows advanced cost calculations such as discounting and inflation to be performed to provide LCIA results and is relatively straightforward to use. On this basis, since money flows vary greatly depending on what perspective they are calculated from (i.e. customer, organisation, etc.), it is important to define on what perspectives these should be calculated. In this respect, Asiedu & Gu argue that costs should be restricted to those which can be controlled [53]. In line with the goal & scope of the space-specific LCSA framework, this has been based on the perspective of the producer within the SSSD.

Overall, 68 costing flows and 13 revenue flows were created over each mission segment meaning that 324 economic flows were created in total. These costing flows were developed as the cost drivers of all environmental and social criteria contained within the LCI inventory list. However, these were input to each SSSD LCI dataset as input and output flows. These potential cost drivers were identified based on information contained within ISO 15686-5:2017 [185], IEC 60300-3-3:2017 [184] and literature reviews. Each flow has been developed to use appropriate exchange, inflation and discount rates of 35 different international currencies to automatically calculate the value of a selected currency in a given year to the value of the euro in the year 2000. These currencies and their associated data were manually added to the SSSD as a unit group and flow property, using 1 Euro in 2000 as the reference unit. The value for the Euro with regards to inflation was calculated to 2019 using annual inflation rates from the EC and the European Central Bank's Harmonized Index of Consumer Prices [297], which is computed based on the reported consumer price indices in member countries of the

EU. Average annual currency exchange rates were then calculated based on the value of the Euro per singular currency unit from OFX's Historical Exchange Rate tool [298]. This calculated value was then multiplied by the annual Euro inflation rate for each year to 2019 in order to relate the annual value of each currency to the value of 1 Euro in the year 2000. In addition to this, trends in historic inflation and currency exchange rates were also mapped for each currency. This created an average annual discount rate for each currency in order to account for future inflation rates up to 2050. This method therefore accurately takes into account exchange, inflation and discount rates of all 35 international currencies in relation to the SSSD's reference unit. As such, the SSSD will automatically calculate this information for a selected currency in the given year and relate this to the value of the euro in the year 2000 within the LCIA results. An example of this is provided below for United State Dollars (USD), where it can be seen that 1 USD spent in the year 2050 equates to 0.3647 EUR spent in the year 2000. Equivalent data is provided for a further 34 international currencies within the SSSD.

Table 4.17: Example of United States Dollar conversion to the value of the Euro in the year 2000 (adapted from [297, 298])

Fiscal Year	Discount Factor of Euro to base year 2000	Exchange rate from USD to EUR	USD → EUR to base year 2000	Fiscal Year	Discount Factor of Euro to base year 2000	Exchange rate from USD to EUR	USD → EUR to base year 2000
2000	1.0000	1.0859	1.0859	2026	0.6422	0.8414	0.5403
2001	0.9764	1.1171	1.0907	2027	0.6317	0.8414	0.5315
2002	0.9558	1.0644	1.0173	2028	0.6215	0.8414	0.5229
2003	0.9350	0.8834	0.8260	2029	0.6114	0.8414	0.5144
2004	0.9150	0.8047	0.7363	2030	0.6014	0.8414	0.5060
2005	0.8954	0.8039	0.7198	2031	0.5917	0.8414	0.4978
2006	0.8760	0.7967	0.6979	2032	0.5821	0.8414	0.4898
2007	0.8575	0.7308	0.6267	2033	0.5726	0.8414	0.4818
2008	0.8291	0.6831	0.5668	2034	0.5633	0.8414	0.4739
2009	0.8271	0.7190	0.5947	2035	0.5542	0.8414	0.4663
2010	0.8140	0.7549	0.6145	2036	0.5452	0.8414	0.4587
2011	0.7924	0.7188	0.5696	2037	0.5363	0.8414	0.4512
2012	0.7731	0.7783	0.6017	2038	0.5276	0.8414	0.4439
2013	0.7628	0.7530	0.5744	2039	0.5190	0.8414	0.4367
2014	0.7595	0.7536	0.5724	2049	0.5106	0.8414	0.4296
2015	0.7593	0.9017	0.6847	2041	0.5023	0.8414	0.4226
2016	0.7582	0.9042	0.6856	2042	0.4942	0.8414	0.4158
2017	0.7441	0.8868	0.6599	2043	0.4861	0.8414	0.4090
2018	0.7320	0.8475	0.6204	2044	0.4782	0.8414	0.4023
2019	0.7201	0.8905	0.6412	2045	0.4704	0.8414	0.3958
2020	0.7084	0.8414	0.5960	2046	0.4628	0.8414	0.3894
2021	0.6969	0.8414	0.5863	2047	0.4553	0.8414	0.3831
2022	0.6856	0.8414	0.5768	2048	0.4479	0.8414	0.3768
2023	0.6745	0.8414	0.5675	2049	0.4407	0.8414	0.3708
2024	0.6635	0.8414	0.5582	2050	0.4335	0.8414	0.3647
2025	0.6528	0.8414	0.5492				

This means that creating discount factors prior to 2000 are not required. Only inflation factors have been used since no costing information has been included for dates prior to the base year 2000. This maintains inventory consistency by ensuring that outdated costing information is not used. Residual value was not taken into account as part of the LCC since this was considered to be null at end of life. The reason for this was due to typical end of life operations within the industry. In this regard, spacecraft are normally left in space at the end of life or re-enter Earth's atmosphere where they burn up, with any part that survives being deposited to the bottom of the ocean. Systematic salvaging is not currently conducted for either option [14].

Based on the activities defined by the ESA E-LCA guidelines [30], these flows were added to LCI datasets to reflect monetary values of cost drivers. These monetary values were mainly calculated using CERs which were based on data primarily obtained from a mixture of literature reviews, commercial off-the-shelf (COTS) product market data and expert input which best reflects the activity and cost driver for which the data is being gathered. A minimum of three data sources were used in the creation of each CER, which have been calculated to represent the value of the reference unit pertaining to the given LCI dataset. As such, this means that if the dataset in question is used within other unit or system processes, the CER is automatically scaled with the reference unit. Where only one data source could be acquired, this value was directly adopted and scaled to quantitative reference unit. In the case of two data sources being acquired, these values were averaged and scaled to quantitative reference unit. All data sources used for the development of monetary values are defined within the general description of each SSSD LCI dataset.

Where CERs were used within an LCI dataset, a regression analysis was performed using values within a single currency (some conversions may have to be applied as exemplified in Table 4.17). However, this currency can be any of the 35 currencies included within the SSSD. Each regression analysis was performed, tested and verified using RegressIt v3.4.1 [299] which is a free Microsoft Excel add-in capable of performing multivariate descriptive data analysis and regression analysis. The resulting CERs were directly input to SSSD datasets as parameters within openLCA according to Equation

3.4 and then linked to costing output flows as formula to reflect the E-LCA reference unit. An example of such an analysis can be found in Subsection 4.4.6 which provides the linear regression model generated by the RegressIt software for a spacecraft battery module before going on to present the application of this CER within the SSSD. Each estimation assumes a positive correlation (i.e. as the unit of measurement increases so does the cost) since it is highly unlikely that a generated CER will exhibit a negative correlation. No negative correlations exist within the SSSD. Additionally, the analogous elements can also be added to this by multiplying the CER with the complexity factor provided within Table 4.16.

4.4.3 Applied Social LCIA Methods

Evaluation schemes have been created for each social indicator and are contained within their general descriptions. These evaluation schemes can be used to measure the LCI results of social indicators against a set of predefined performance criteria (benchmarked values from literature) based on their general performance. Adopting a similar method to the sustainability rating system of space missions proposed by WEF [59, 60], the predefined performance criteria of each evaluation scheme has been sorted into bands according to 'good' and 'bad' practice. In this regard, each evaluation scheme uses the benchmarked values to map a route to the attainment of specific SDG targets and indicators through these bands. In line the methodology outlined by Mancini et al. [300], each band has been attributed a risk factor with an associated scoring mechanism, as outlined in Table 4.18 below. Defining a numerical score to these risk bands aligns the SSSD methodology with the risk matrix approach suggested by Goedkoop et al. in the 'Handbook for Product Social Impact Assessment' [225] outlined in Subsection 3.5.2 and can be used for characterisation of LCI results based on numerous levels, as defined by Wu et al. [301]. Therefore, LCI data can be generated for each social indicator using the appropriate measurement scale defined by the specific indicator under study. The evaluation scheme of this indicator then makes this value comparable to the benchmarked values contained within one of these evaluation scheme bands to produce a social score of between 0 and 100.

Table 4.18: Risk bands for evaluation schemes

Band	No Risk	Very Low Risk	Low Risk	Medium Risk	High Risk	Very High Risk	Not Applicable	No Data
Score	0	20	40	60	80	100	0	50

The evaluation scheme of each social indicator and its performance criteria were primarily formulated to reflect and measure the indicators outlined by the IAEG-SDGs in the 'Global indicator framework for the Sustainable Development Goals and targets of the 2030 Agenda for Sustainable Development' [237]. Where applicable, the measurement scale of each evaluation scheme have also been created to comply with the Reporting Requirements of the GRI Social and Economic Standards [302]. The GRI is an independent international non-profit organisation which provides the first set of global standards for sustainability reporting. These standards are commonly used by businesses, governments and other organisations to help them to understand and communicate on their sustainability impacts. The social and economic standard represent global best practice for reporting on a range of economic and social impacts. For this reason, the information contained within the Reporting Requirements of these standards were considered to provide an appropriate, relevant and reliable method for creating measurement scales for these stakeholder subcategory indicators and evaluation schemes within the SSSD. However, in addition to the GRI Standards, many of these measurement scales also aligned with the UN Global Compact Framework and World Resources Institute data which both provide useful information when GRI standards are lacking [303,304]. This information provides a basis for the type of indicators, measurement scales and evaluation schemes which should be used for each stakeholder subcategory in order to determine the overall social impact score for that subcategory. The performance criteria used within each evaluation scheme was based on benchmarks taken from relevant literature. An example of this is provided within Table 4.15.

The evaluation schemes outlined within the SSSD are merely suggestions and are not intended to accurately represent a variety of different geographical regions, organisations or stages along the supply chain. In this regard, although international criteria were used wherever possible, the suggested evaluation schemes within SSSD social indicators primarily concentrate on European and UK based criteria. The development of regional evaluation schemes for each social indicator within the SSSD may be pursued for global coverage in the future. Additionally, not all entities along the supply chain will necessarily have a space-related focus which means the suggested evaluation scheme may not be the best method for benchmarking their performance. These kinds of variants need to be taken in consideration in order to determine whether the suggested evaluation scheme is the most representative for the organisation for which LCI data has been added.

Three LCIA methods were created for S-LCA. The first two related to the stakeholder categories and subcategories for which indicators were developed (see Appendix A). The former of these two LCIA methods has been set as the baseline social LCIA method within the SSSD since it best accords with the approach outlined within the UNEP/SETAC S-LCA guidelines [181]. Activity variables were set for all social indicators under this LCIA method to describe the relevance of impacts caused by each social indicator in a life cycle. Within the SSSD, this identifies the contribution of each social indicator to the process overall as a percentage in terms of the assigned risk factor. The SSSD assumes that all stakeholder categories are weighted equally, all stakeholder subcategories under each stakeholder category are weighted equally and that all social indicators under each stakeholder subcategory are weighted equally. An example of this can be seen in Figure 4.12 below.

Stakeholder categories	'Society' Stakeholder subcategories	'Technology development' social indicators & activity variable	
Consumers	Contribution to economic development	R&D spending	1.33%
Local community	Corruption		
Society	Prevention & mitigation of armed conflicts	Technology readiness level & innovation	1.33%
Value chain actors	Public commitments to sustainability issues		
Workers	Technology development	Technology transfer	1.33%

Stakeholder Categories:	*20% contribution*	*(100% / 5 categories)*
'Society' stakeholder subcategories:	*4% contribution*	*(20% / 5 subcategories)*
'Technology development' social indicators:	*1.33% contribution*	*(4% / 3 social indicators)*

Figure 4.12: SSSD activity variable example in S-LCA

These activity variables were used to convey results of two approaches which have been developed (time dependant and rating related). The time dependant approach requires LCI data to reflect the total number of hours contributed by each organisation under study for a given process. Using the appropriate risk factor and activity variable, the following equation has been formulated to represent impact category results of this approach:

$$IR_c = \sum_s \frac{RF_{em_s}}{I_{xs} \cdot SS_{cs}} \cdot t_{pcs} \tag{4.3}$$

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, SS_{cs} is the total number of stakeholder subcategories contained within stakeholder category c containing intervention s, and t_{pcs} is the amount of time taken by each organisation (in hours) to complete process p which connects intervention s with impact category c.

The rating related approach uses the same methodology, but under this scenario, LCI data is input as a single unit. As such, Equation 4.3 can be used again to reflect this, but rather than multiply results by the time taken by each organisation to complete each process, it divides everything by the total number of processes where each intervention was used. This provides a score which reflects the average sustainability score of all entities involved at any stage during the life cycle of the space mission under study. Similar to the WEF sustainability rating system [59, 60], a score of between 0 and 100 will be generated to reflect the social performance of the space mission. This has been used as a backup option to the time dependent approach, with LCIA results able to be compared to the social matrix. This is outlined below in Figure 4.13 below in accordance with the SSSD risk bands as a scale on which LCIA results can be measured against.

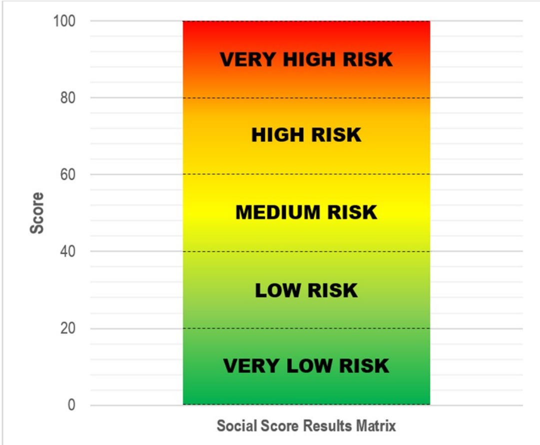


Figure 4.13: SSSD Social Score Results Matrix

The third LCIA method is a points-based system dependant on the affected SDGs. This provides LCIA results for the identified SDGs which are covered by each social indicator. It can be used to provide additional context to S-LCA results in line with the 2030 Agenda [4] by framing the greatest areas of adverse impact with respect to the SDGs and targets generated by the mission. As such, to apply this LCIA method, LCI data should also be kept to a single unit. Although risk factors are still used, unlike the previous method no activity variables are applied meaning that this is an unweighted approach. As such, this provides absolute results relating to which SDGs are most adversely affected during the life cycle of a space mission. Relating these impacts to areas of concern according to the 2030 Agenda could be seen to be more robust than the previous two methods and an eventual transition to this LCIA method as the new S-LCA baseline within the SSSD is envisioned in the future. This could also be considered as being more in line with the WEF space sustainability rating system. The approach is also less time consuming since it eliminates the need for LCSA practitioners to manually check which SDGS have been adversely affected based on the specific social impacts identified using the first LCIA method.

However, the impact category results from the current baseline LCIA method (generated using Equation 4.3) are currently used to reach a single score for the entire product system. This is achieved using the following equation:

$$SR_{SLCA} = \frac{IR_c + IR_{n...}}{IR_n} \tag{4.4}$$

Where SR_{SLCA} is the single score result for the whole S-LCA, IR_c is the indicator result for stakeholder category c, $IR_{n...}$ are the indicator results for all of the remaining stakeholder categories, and IR_n is the total number of stakeholder categories for which there are indicator results (typically five). This single score method can be applied as a single impact category within E-LCA as indicated in Table 4.3.

4.4.4 Applied Costing LCIA Methods

Due to the nature of the assessment type, LCC LCIA results are much more simple to calculate. In order to measure the economic impact, two custom-made LCIA methods were generated. The first LCIA method splits the 324 custom-made monetary flows which were developed as part of the LCI into costs, revenues and net balance for each segment of a space mission in accordance with the ESA E-LCA guidelines. The second LCIA method splits these cost and revenue flows across a variety of impact categories based on the main impact areas outlined within ISO 15686-5:2017 [185], IEC 60300-3-3:2017 [184] and literature reviews in order to reflect net balance. As such, the monetary flows were classified into the newly formed impact categories (developed as part of each LCIA method) based on their life cycle stage and/or applicability. The impact categories defined under each of these two LCIA methods can be seen below.

Table 4.19: SSSD LCC LCIA Methods

Cost Segments	Cost Divisions
Ground segment - Costs	End of life
Ground segment - Income	Energy & fuel
Ground segment - Net balance	Facilities management
Infrastructures - Costs	Income & profits
Infrastructures - Income	Initial investment
Infrastructures - Net balance	Integration & testing
Launch segment - Costs	Labour
Launch segment - Income	Launch
Launch segment - Net balance	Operations & maintenance
Space segment - Costs	Overheads & miscellaneous
Space segment - Income	Production & manufacturing
Space segment - Net balance	Transportation & travel

Since exchange, inflation and discount rates have been added to each costing flow as a unit group and flow property, these LCIA methods are also able to automatically relate LCI results of 35 international currencies to the value of the Euro in the year 2000 as a form of characterisation. This allows the LCIA results to be displayed as a single unitary value. The only additional form of characterisation which is applied is to assign all cost flows a negative value and all revenues flows a positive value. This allows the net balance to be identified which is represented by the following equation:

$$IR_c = \sum_s (TR_{cs} - TC_{cs}) \cdot (CR_{ays_b}[1 - CP_{bys_z}]) \tag{4.5}$$

Where IR_c is the indicator result for cost category c, TR_{cs} is the total revenues that connects intervention s to cost category c, TC_{cs} is the total costs (not as negative values) 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.

This equation has been applied to all cost division LCIA impact categories and particular cost segment LCIA impact categories as defined within Table 4.19. In a similar manner to S-LCA, a single score can be formed for the entire product system based on this method, where the sum of all of the applied cost categories produces a single LCIA result. This is achieved using the following equation:

$$SR_{LCC} = IR_c + IR_{n...} \tag{4.6}$$

Where SR_{LCC} is the single score result for the whole LCC, IR_c is the indicator result for cost category c, and $IR_{n...}$ are the indicator results for all of the remaining cost categories. This single score method can be applied as a single impact category within E-LCA as indicated in Table 4.3.

4.4.5 Data Quality & Validation

Since no LCI data is currently included for S-LCA, data quality information could not be added for this. However, LCC data quality has been integrated with E-LCA data quality information at process level using the Pedigree approach as defined within Subsection 4.4.4. Similarly, the adopted approach is mainly used for documentation purposes and an eventual transition to include Pedigree values at flow level will be pursued in order to properly determine all uncertainty parameters of inputs and outputs and run a Monte Carlo simulation.

Additionally, the SSSD S-LCA and LCC methodologies and LCIs could not be validated during the ESA LCI Validation Project since neither the ESA E-LCA database or Space Opera contains social or cost data [281]. It is proposed that cost data should be inspected by cost engineers at ESA in the near future. Additionally, since the SSSD currently does not hold social data, no validation procedures are required for S-LCA at this point. However, when social data is added, an appropriate validation procedure will be identified. After this, an independent review panel will be sought to review the findings from both of these elements.

4.4.6 Results & Discussion

An LCI dataset relating to the production & manufacturing of a 1 kg spacecraft battery module in France was selected as a case study to demonstrate the application of the S-LCA and LCC methodologies. This dedicated dataset refers to a LEO battery with li-ion cells at TRL 9. The system boundary involves material inputs for the li-ion cells, aluminium casing and electronic unit. It also includes the manufacturing processes of sheet rolling aluminium, anodising of aluminium, cleansing with solvent and electricity consumption. The output is a 1 kg spacecraft battery module. E-LCA input data is not considered as part of this case study. However, E-LCA LCIA results can be seen in Table 4.26 in Subsection 4.5.4.

Firstly, since no social LCI data is contained within the SSSD, several assumptions had to be made. Firstly, according to the organisation S-LCA approach outlined within Subsection 4.4.3, if the time dependant approach is to be used then LCI data must reflect the total number of hours contributed by each organisation under study for a given process. In this scenario is was considered that it would take a single organisation 160 hours to manufacture and produce the spacecraft battery. Secondly, in order to create an LCI specifically for this process, it was considered that country-level data would need to be used within the 56% of indicators applicable at this level since organisation information which can be used for these indicators is not freely available. As such, the percentage of SSSD social indicators which can be used at country-level within each stakeholder category is outlined in Figure 4.14 below.

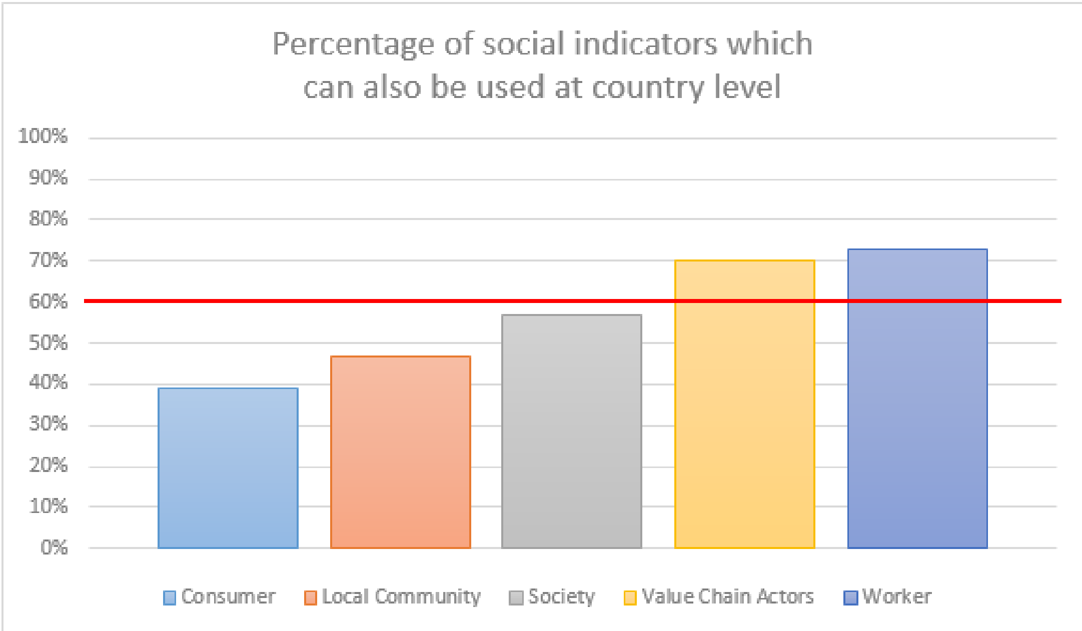


Figure 4.14: Percentage of SSSD social indicators which can also be used at country-level

In order to conduct a valid and meaningful case study, only stakeholder categories containing social indicators where 60% or more could be used at country-level were considered within this analysis. As such, this meant that for the purpose of this case study, social LCI data has been gathered using a country-level perspective for the stakeholder categories of value chain actors (VCAs) and workers. The collected data was obtained from freely available sources. For example, when collecting LCI data for the ‘Gender wage gap’ social indicator, the EC report entitled ‘2018 Report on equality between women and men in the EU’ was used as a reference [305]. According to this report, the gender wage gap in France was 15.2% in 2016. Using the evaluation scheme for this indicator outlined in Appendix A, then this LCI data can be classed as ‘Medium Risk’. Using the baseline social LCIA method outlined within Subsection 4.4.3, the LCIA results can then be calculated. These can be seen in Table 4.20 below for each stakeholder category and subcategory.

Table 4.20: Social LCIA Results for a 1 kg Battery Module Produced in France

Stakeholder Categories, Subcategories & Indicators	A Raw Score	B A x AV	C B x FU
► **VALUE CHAIN ACTORS**	**16.67**	**8.33**	**1,332.80**
↳ Fair Competition	0.00	0.00	0.00
↳ Promoting Social Responsibility	26.67	3.33	532.80
↳ Respect of Intellectual Property Rights	20.00	2.50	400.00
↳ Supplier Relationships	20.00	2.50	400.00
► **WORKER**	**36.67**	**18.33**	**2,932.80**
↳ Child Labour	0.00	0.00	0.00
↳ Equal Opportunities/Discrimination	40.00	2.22	355.20
↳ Fair Salary	26.67	1.48	236.80
↳ Forced Labour	20.00	1.11	177.60
↳ Freedom of Association & Collective Bargaining	40.00	2.22	355.20
↳ Health & Safety	90.00	5.00	800.00
↳ Social Benefits/Social Security	70.00	3.89	622.40
↳ Wellbeing of Staff	10.00	0.56	89.60
↳ Working Hours	33.33	1.85	296.00
SOCIAL SCORE	**53.34**	**26.67**	**4,265.60**
Activity variable (AV): Single Score Contribution to process			
Functional unit (FU): 1 kg battery module taking 160 hours to produce			

In addition to these LCIA results, the SDGs that are affected by this process can also be outlined as part of the decision-making criteria in line with the 2030 Agenda [4]. This unweighted approach was based on the SDGs which were attributed to each social indicator as detailed in Appendix A. As such, Figure 4.15 below provides the social LCIA results based on the ‘Affected SDGs’ social LCIA method for the production & manufacturing of a 1 kg spacecraft battery module in France.

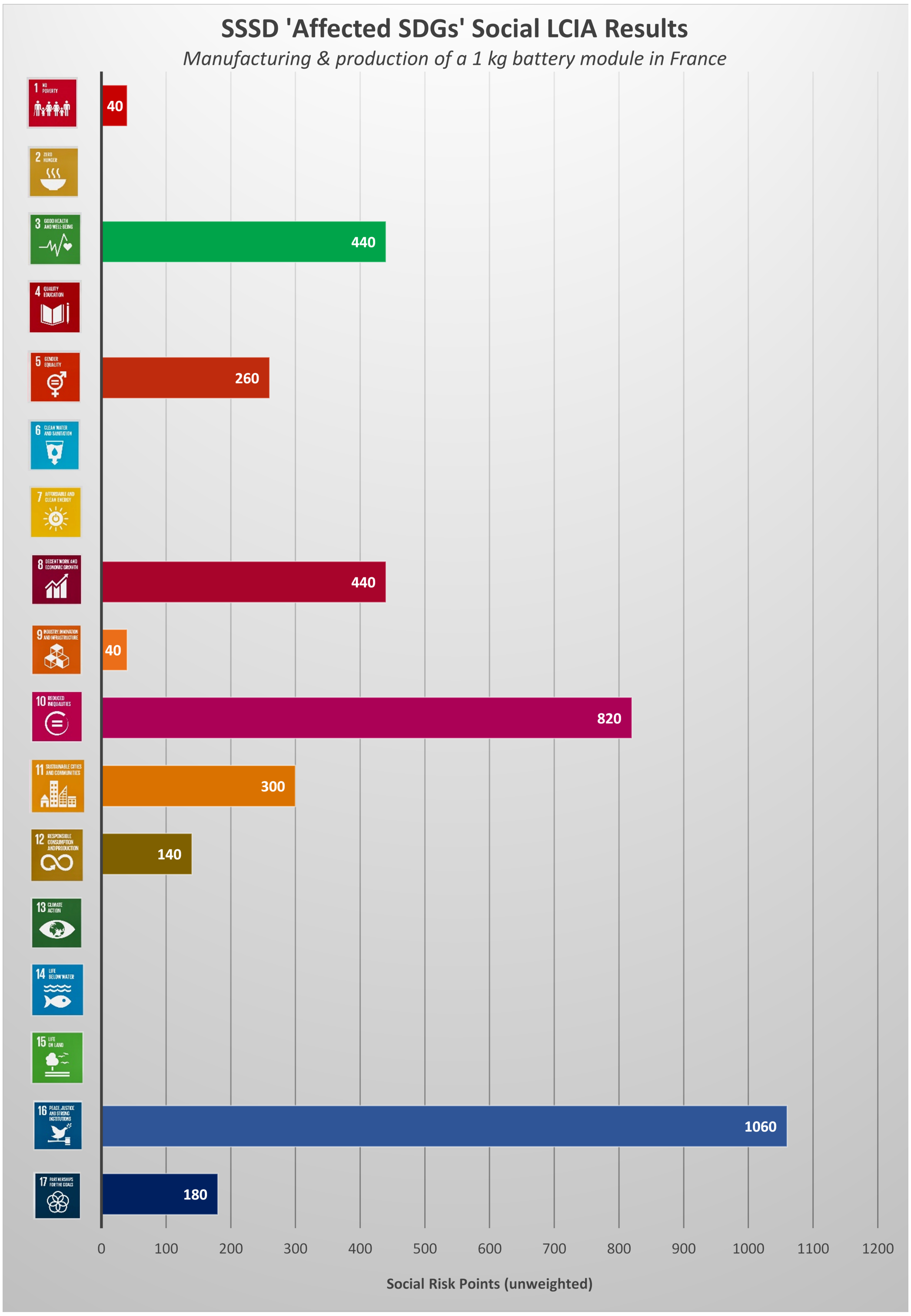


Figure 4.15: SSSD 'Affected SDGs' Social LCIA Results for the Production & Manufacturing of a 1 kg Battery Module in France

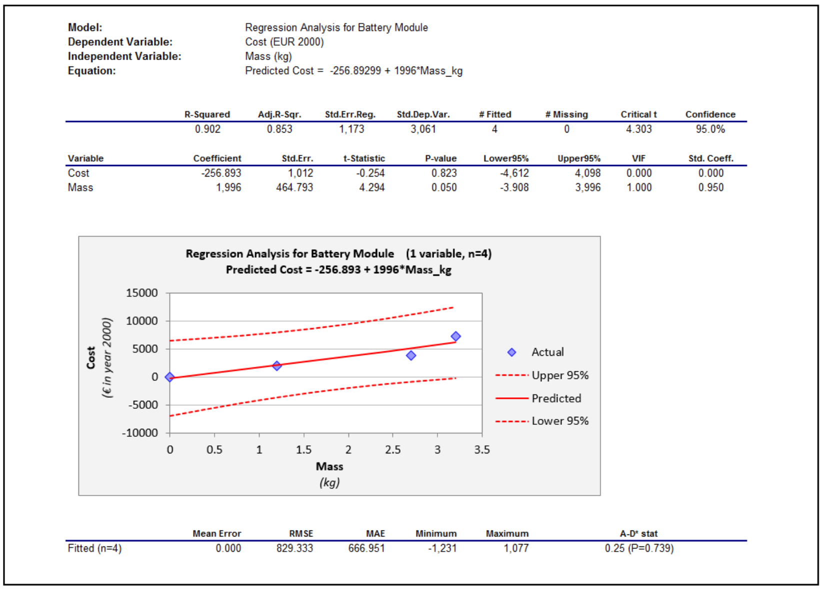
Overall, it was found that 68.75% of the social impact score is attributable to the workers stakeholder category. Of the nine subcategories it contains, health & safety is alone responsible for 27.3% of this impact. The reason for this poor score is due to the rate of fatal accidents, near misses and non-fatal accidents in the workplace in France. The LCI data was gathered based on a 2016 Health and Safety Executive report entitled 'Health and Safety statistics in the United Kingdom, 2019 - Comparison with the European Union' [306]. As such, it was found that out of all EU-28 nations, France was the fourth worst for fatal accidents (~3.5 incidences per 100,000 employees), fifth worst for near misses (~35,000 incidences per 100,000 employees) and third worst for non-fatal accidents (~3,000 incidences per 100,000 employees). As such, this attributed the maximum score based on the risk bands contained within these evaluation schemes. This indicates that these social indicators are particular social hotspots of within the LCIA results. However, when looking at the SDGs, SDG 3 (Good Health and Well-Being) was equally the most impacted goal after SDG 10 (Reduce Inequalities) and SDG 16 (Peace, Justice and Strong Institutions). This may be somewhat surprising since the health and safety impact subcategory was identified as a social hotspot since it scored so highly. This is primarily due to two reasons. Firstly, it can be seen in Appendix A that SDGs 10 and 16 are also influenced by each of these social indicators. Secondly, according to this appendix, SDGs 10 and 16 also have the most social indicators attributed to them as a whole, meaning that they have more potential to accrue a higher social score.

In terms of cost LCI data, information was obtained from freely available internet sources and through general price enquires. This means that generated cost estimation is applicable to the entire spacecraft battery model rather than its particular components. The reason for this was due to the level of detail required to generate such a cost estimation, which is not practical when considering specific spacecraft equipment. From this, three data reference points were identified which can facilitate a regression analysis. For confidentiality purposes, the supplier and products selected as data reference points have not been listed by name. Instead, they will be referred to as Company A, Company B and Company C. Since the data reference points consisted of two different currencies, this meant that the cost data was normalised to the SSSD base metric (the value of the euro in the year 2000) before it could be analysed. This information can be visualised in Table 4.21 below.

Table 4.21: LCI Cost Data for Battery Module

Organisation	Battery Mass	Cost in local currency	Conversion to baseline currency
A	1.2 kg	2,395.00 GBP	2,035.03 EUR (2000)
B	2.7 kg	5,915.00 USD	3,901.56 EUR (2000)
C	3.2 kg	10,515.00 USD	7,207.24 EUR (2000)

The normalised data was then input to RegressIt v3.4.1 [299] to analyse the data for candidate relationships and perform the regression analysis. This software plotted the normalised data onto a scattergraph, including a data entry at the point of origin (0,0) as a point of reference. The regression analysis generated a CER based on a line fit plot. This can be found in Figure 4.16 below along with a summary table of coefficients and P values. This relationship was then verified and accepted for use within the LCI dataset. No complexity factor was added since the battery module was modelled at TRL 9.



Model:	Regression Analysis for Battery Module
Dependent Variable:	Cost (EUR 2000)
Independent Variable:	Mass (kg)
Equation:	Predicted Cost = -256.89299 + 1996*Mass_kg

R-Squared	Adj.R-Sqr.	Std.Err.Reg.	Std.Dep.Var.	# Fitted	# Missing	Critical t	Confidence
0.902	0.853	1,173	3,061	4	0	4.303	95.0%

Variable	Coefficient	Std.Err.	t-Statistic	P-value	Lower95%	Upper95%	VIF	Std. Coeff.
Cost	-256.893	1,012	-0.254	0.823	-4,612	4,098	0.000	0.000
Mass	1,996	464.793	4.294	0.050	-3.908	3,996	1.000	0.950

	Mean Error	RMSE	MAE	Minimum	Maximum	A-D* stat
Fitted (n=4)	0.000	829.333	666.951	-1,231	1,077	0.25 (P=0.739)

Figure 4.16: Regression Analysis for Battery Module

Overall, by applying the CER outlined in Figure 4.16, it can be seen that the production & manufacturing cost of a 1 kg battery module is 1739.10701 EUR (2000). Transportation costs have been excluded from this analysis as it was considered outside the scope of study.

In conclusion, the social and economic LCIA impacts (including hotspots) from the production & manufacturing of a 1 kg spacecraft battery module in France have been identified. This practical example has provided a succinct overview of the S-LCA and LCC methodologies as they are applied within the SSSD. However, as these assessments are not completely separate entities, an impact in one assessment may very well have ramification within another assessment. For this reason, the use of MCDA is extremely important in order to compare these different assessments and visualise how decisions in one may have impacts on another.

4.5 Applying the MCDA Approach

According to Klöpffer who first consolidated the LCSA methodology, two options can be used on which to analyse LCSA results [10]. The first method views E-LCA, S-LCA and LCC as standalone assessment whilst the second method uses S-LCA and LCC results as separate impact categories within E-LCA. The SSSD has been created to facilitate both of these options. However, these methods make it difficult to gauge the relative importance of each sustainability aspect or how they interact with one another based on product design choices. In accordance with the space-specific LCSA framework outlined in Subsection 3.5.4, if the SSSD is to be used within sustainable design sessions then MCDA is necessary to determine the severity of the LCIA results relating to each sustainability aspect.

Prior to MCDA, it is important that normalisation and weighting of LCIA results takes place. As discussed in Subsection 3.5.3, NFs and WFs from a variety of sources can be used to generate a score reflecting performance for each sustainability aspect. However, since ESA aligns their work on E-LCA so closely with the EC, the method adopted by the Clean Space Initiative to generate an E-LCA single score was investigated further, as specified within the space-specific LCSA framework. In this regard, ESA proposed applying JRC PEF normalisation values [250] to convert LCIA results for each environmental impact category into EU equivalents then to apply the recommended JRC meta-weighting factors [252] to reach a single score. Although this technique was not specifically proposed within the ESA E-LCA guidelines, adopting such an approach within the SSSD may provide a robust and consistent approach for MCDA which aligns closely with the recommended PEFCRs [114] and ESA's single score method. The possibility of tailoring this approach towards social and economic criteria is investigated further in the following subsections.

4.5.1 Normalisation Method

Whilst absolute values provide robust and scientific LCIA results, by themselves they are not sufficient to communicate multi-criteria sustainability information. Normalised values provide a scale on which to gauge impacts which can be useful when communicating LCIA results to non-experts in order to provide more context to absolute values [253, 307]. This is also an important technique for aggregating results into common units which is required for MCDA to occur [308]. This is typically achieved by quantifying the contribution of a unit of pollutant or resource use to the total current load/pressure in a region per year. This approach has been applied within the SSSD in order to facilitate MCDA.

The recommended JRC PEF NFs which were applied within the SSSD were released in 2014 and are relevant to the EU-27 in 2010 (see Table 3.3). They relate to the total domestic impact of the EU-27 and impact per EU citizen across a wide range of impact categories. This is because domestic figures for 2010 were considered to be the most robust for this kind of application at the time of publication [250]. Additionally, the JRC also published a set of recommended planetary boundaries in 2016 [251]. This concept was introduced in 2009 by Rockström et al. [309]. This identified nine critical planetary boundaries in an attempt to define environmental limits within which humanity can safely operate to maintain a sustainable human presence on Earth. These provide an interesting alternative to traditional NFs but have not been selected for consideration within the SSSD since they cover less impact categories. Therefore, in order to align with ESA, the default method selected for use within the SSSD is impact per EU citizen taken from the recommended JRC PEF NFs [33]. More information relating to this method is provided in Subsection 3.5.3.

As such, a NF factor is provided for 10 out of the 11 ILCD compliant SSSD E-LCA impact categories. The impact category missing is marine ecotoxicity since no normalisation value is provided by the JRC for this impact category [250]. Additionally, the NF for water consumption was also used due to the considered transparency of the environmental model applied by the SSSD. A NF for air acidification was also applied by converting the units of the proposed normalised value outlined by the JRC (measured in mol H^+ eq.) to kg SO_2 eq. as used by the SSSD (i.e. 0.032 kg SO_2 eq. / mol H^+ eq.). This means that in total, 11 SSSD impact categories were considered as part of normalisation procedures. However, whilst this method provides NFs for E-LCA impact categories, if the three sustainability dimensions are to be balanced, each must undergo normalisation.

Very few normalisation approaches have been proposed for S-LCA and those which do mostly relate to economic values. None of these were considered appropriate for application within the SSSD. For this reason, a new normalisation method for S-LCA was formed based on SSSD single score method which closely aligns with the JRC PEF approach. This was calculated based on findings by PwC which suggest that just 28% of global companies have set quantitative targets which are linked to their societal impact for at least one KPI in 2016 [310]. Therefore, a social score of 72.00 was used to represent the average social score of an organisation. This was then multiplied by the total number of active EU-28 entities (27 million) to generate a total social score of 1.944 billion for all EU entities in one hour [311]. This was then multiplied by the total number of hours in one year to produce an annual social score. Finally, the figure was then divided by the EU-28 population in 2016 (5.10E+08) to get the average share of total annual European organisational social score per EU citizen (3.34E+04) [312]. This NF can be seen in Table 4.22 below. The adopted technique provides a very generic and approximate NF which is plagued with uncertainty. However, given the availability of data, this was the best approach which could be formulated. As such, the formulation of a more appropriate or scientifically robust S-LCA NF is recommended for future work. This may also incorporate a methodological shift towards using the SDGs as the baseline social LCIA approach meaning that an altogether different NF would need to be calculated.

Table 4.22: S-LCA normalisation factors within the SSSD (adapted from [310–312])

Impact Category	Unit	Social Score per European Citizen (2016)	Total European Social Score (2016)	Overall Robustness
Social Impacts	Social Score	3.34E+04	2.55E+14	Very Low

In a similar manner, the adopted normalisation procedure for LCC was calculated by multiplying the GDP per capita by the average tax rate of EU-28 nations in 2015 [313]. These values were then converted into the value of the euro in the year 2000 by taking into account exchange rates and inflation. Therefore, this approach provides a NF relevant to the total taxation per EU citizen in 2015 which can be seen in Table 4.23 below. As such, the NF should be applied to costs only and not revenues. Although this approach can be considered to be more accurate and relevant, exclusively measuring costs means that any revenues applied within the SSSD may need to be scoped out of the analysis if this approach is to be applied. However, whilst the overall robustness of this approach is relatively high since it provides a verifiable metric on which to benchmark LCC results, its comparability to the E-LCA NFs used within the SSSD could be considered rudimentary. Therefore, it is recommended that alternatives to this normalisation procedure for LCC are investigated to ascertain whether a more appropriate NF could be identified.

Table 4.23: LCC normalisation factors within the SSSD (adapted from [312, 313])

Impact Category	Unit	Taxation per European Citizen (2015)	Total European Taxation (2015)	Overall Robustness
Costing Impacts	€ 2000	8.55E+03	4.36E+12	High

4.5.2 Weighting Method

Weighting can be used to express the relationship between measured impacts and politically determined emission or consumption targets [314]. Weighting is also typically applied on normalised results to produce a single score for each assessment type. For this reason, WFs have been applied within the SSSD to aggregate normalised results based on their relative importance. In this sense, since S-LCA and LCC are used as impact categories in themselves, a WF is not required and hence they have both automatically been assigned a value of 1.00E+00.

The JRC meta-weighting factors provide a range of WFs for E-LCA impact categories based on their robustness and relative importance (i.e. the severity of the threat) from a European context [252]. These factors provide the magnitude of the of each impact category to the problem overall, as identified in Table 3.4. However, as can be seen from this table, the number and types of impact categories do not correlate with selected impact categories outlined in the above subsection. For this reason, the JRC meta-weighting method must be adapted within the SSSD based on the impact categories used for MCDA. Two options were considered for this. The first refers to a baseline option where all 11 impact categories are used for MCDA. The second refers to an alternative method where only the impact categories identified by ESA as being hotspots for space missions are used [33]. In this regard, the WFs for each impact category were reformulated across these two options so that their sum was equal to 1.00E+00. This allowed the E-LCA results to be diluted to the relevancy of one impact category, enabling environmental results to be more comparable to S-LCA and LCC. These adapted JRC WFs for both options can now be considered for use within the SSSD. More information relating to this method is provided in Subsection 4.5.3 below.

4.5.3 Multi-Attribute Value Theory

The described normalisation and weighting methods can be applied to the LCIA results within the SSSD in order to generate a score which reflects the performance of the system under study. This is a crucial part of the MAVT equation outlined in Subsection

3.5.3 and measures normalised and weighted results in terms of impact magnitude per EU citizen. As such, an overview of the adopted normalisation and weighting methods for each impact category is provided in Table 4.24 below. This is relevant for all 11 impact categories as well as the 5 impact categories identified by ESA's Clean Space Initiative as being 'hotspots' for space missions.

Table 4.24: Normalisation and Weighting Procedures within the SSSD (adapted from [250, 252, 310–313])

Impact Category	Reference Unit	Normalisation Factors		Weighting Factors		
		JRC (point of ref.)	SSSD (JRC, adapted)	JRC (point of ref.)	SSSD Baseline Method (JRC, adapted)	SSSD Hotspot Method (JRC, adapted)
Acidification – Air Acidification Potential	kg SO_2 eq.	1.51E+00	1.51E+00	6.20E+00	8.72E-02	-
Climate Change – Global Warming Potential 100a	kg CO_2 eq.	9.22E+03	9.22E+03	2.11E+01	2.96E-01	5.44E-01
Economic Impact – Single Score	EUR 2000	-	-8.55E+03	-	1.00E+00	1.00E+00
Eutrophication – Freshwater Eutrophication Potential	kg P eq.	1.48E+00	1.48E+00	2.80E+00	3.94E-02	-
Eutrophication – Marine Eutrophication Potential	kg N eq.	1.69E+01	1.69E+01	2.96E+00	4.16E-02	-
Ionising Radiation – Ionising Radiation Potential	kg U-235 eq.	1.13E+03	1.13E+03	5.01E+00	7.05E-02	-
Ozone Depletion – Ozone Depletion Potential (Steady State)	kg CFC-11 eq.	2.16E-02	2.16E-02	6.31E+00	8.88E-02	1.63E-01
Photochemical Oxidation – Photochemical Oxidation Potential	kg NMVOC	3.17E+01	3.17E+01	4.78E+00	6.73E-02	-
Resource Depletion – Mineral Resource Depletion Potential	kg Sb eq.	1.01E-01	1.01E-01	7.55E+00	1.06E-01	1.95E-01
Social Impact – Single Score	Social Score	-	3.34E+04	-	1.00E+00	1.00E+00
Toxicity – Freshwater Aquatic Ecotoxicity	PAF.m^3.day	8.74E+03	8.74E+03	1.92E+00	2.70E-02	4.96E-02
Toxicity – Human Toxicity	cases	5.70E-04	5.70E-04	3.97E+00	5.59E-02	4.76E-02
Water Consumption – Water Depletion Potential	m^3	8.14E+01	8.14E+01	8.51E+00	1.20E-01	-

With the score reflecting performance now calculated, a WF needs to be applied in order to 'balance' and set a general importance level to each sustainability dimension. A plausible method to achieve this is to follow political decision processes. Currently, the most important political decision process on a global scale is the definition of the SDGs by the UN [4]. This is because each of the 193 UN Member States who adopted the Agenda are expected to use these goals, targets and indicators in order to frame their agendas and political policies to 2030. Therefore, since the SDGs are aimed at tackling global problems by balancing the three dimensions of sustainability, the number of goals dedicated to each sustainability pillar could potentially provide a reasonable assumption concerning the current internationally accepted level of concern for each dimension. Diaz-Sarachaga et al. [315] groups the 17 SDGs and their associated 169 targets into environmental, social, economic and governance categories, and uses the Delphi methodology to highlight the percentage of goals/targets dedicated to each sustainability dimension as illustrated in Figure 4.17 below.

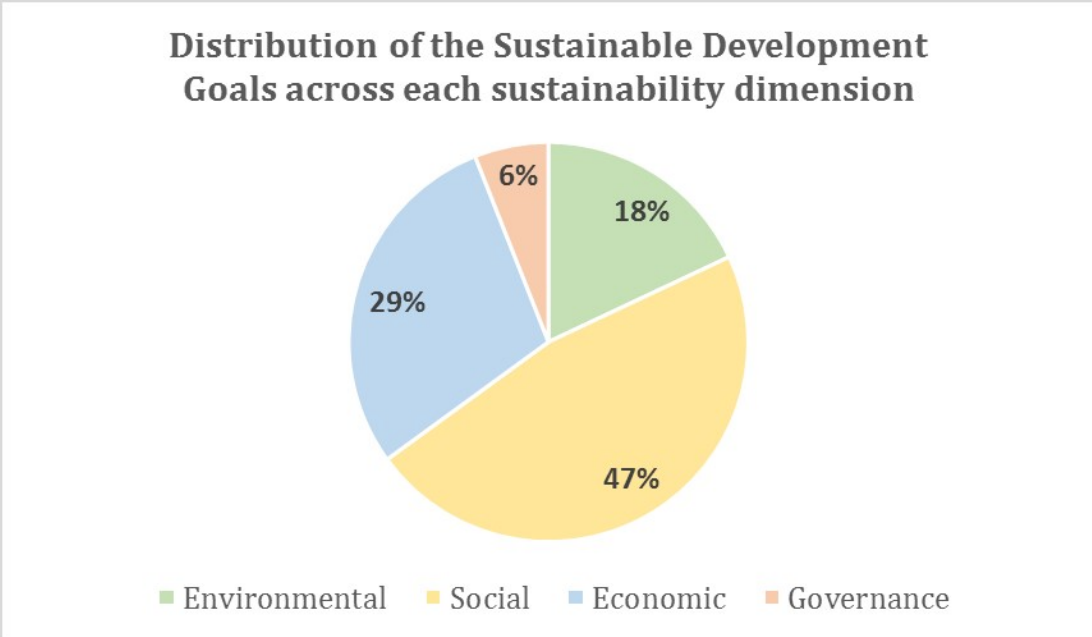


Figure 4.17: Distribution of the SDGs across each sustainability dimension [315]

In terms of MCDA, the results from this exercise can then be used as WFs to assign the level of importance placed upon each sustainability aspect within LCSA. This could be considered as a good method of evaluating the severity of each sustainability aspect within LCSA since it can also be used to come to a single score sustainability result. Using the information above, WFs were applied as a percentage (0-1) as illustrated in Table 4.25 below. These can be considered to be the MCDA WFs for LCSA, where the social and governance categories are grouped as one.

Table 4.25: SSSD Weighting Factors for each Sustainability Dimension within MCDA (adapted from [315])

Environment	Social/Governance	Economic
0.18	0.53	0.29

These figures can then be applied within Equation 3.7 for E-LCA, S-LCA and LCC to generate single score results for each aspect of sustainability. In this case, $v_i(a)$ is the normalised and/or weighted score reflecting performance of each sustainability aspect and w_i is the weighted set of values outlined in Table 4.25 which were derived from the 2030 Agenda [4]. Since these are all measured in the same units (importance of impact magnitude per EU citizen) then the total of all of these aspects provides a single sustainability score. This can be used to highlight which sustainability aspect receives the most impact whilst identifying the significance of design choices on each sustainability aspect between iterations. The SSSD has applied this equation as a normalisation and weighting set within its LCIA methods for the 11 impact categories applied and the 5 hotspot impact categories identified by ESA. An example of this application is provided in the following subsection.

4.5.4 Results & Discussion

To provide an overview of this method and its use within the SSSD, the LCIA results generated from the battery module example provided in Subsection 4.4.6 can be used as a case study. As such, the table below provides an overview of the LCIA results achieved during this process. It also provides the normalisation and weighting factors which were then applied based on the methods outlined in the above subsections to generate a score reflecting the performance for each option (see Table 4.24).

Table 4.26: Normalised and Weighted LCIA results of a 1 kg battery module

Impact Category	Reference Unit	LCIA Result	Score Reflecting Performance (All)	Score Reflecting Performance (Hotspots)
Acidification - Air Acidification Potential	kg SO_2 eq	1.18E-01	6.83E-03	-
Climate Change - Global Warming Potential 100a	kg CO_2 eq	1.76E+01	5.66E-04	1.04E-03
Economic Impact - Single Score	EUR 2000	-1.74E+03	2.03E-01	2.03E-01
Eutrophication - Freshwater Eutrophication Potential	kg P eq	4.25E-02	1.13E-03	-
Eutrophication - Marine Eutrophication Potential	kg N eq	2.07E-02	5.10E-05	-
Ionising Radiation - Ionising Radiation Potential	kg U235 eq	6.80E+00	4.25E-04	-
Ozone Depletion - Ozone Depletion Potential (Steady State)	kg CFC-11 eq	1.58E-06	6.52E-06	1.20E-05
Photochemical Oxidation - Photochemical Oxidation Potential	kg NMVOC	6.49E-02	1.38E-04	-
Resource Depletion - Mineral Resource Depletion Potential	kg Sb eq	1.54E-02	1.62E-02	2.98E-02
Social Impact - Single Score	Social Score	4.27E+03	1.28E-01	1.28E-01
Toxicity - Freshwater Aquatic Ecotoxicity	PAF.m^3.day	7.45E+02	2.30E-03	4.23E-03
Toxicity - Human Toxicity	cases	6.38E-05	6.69E-03	5.69E-03
Water Consumption - Water Depletion Potential	m^3	1.83E+02	2.69E-01	-

The scores reflecting performance for both options were then used in conjunction with the SSSD WFs for each sustainability dimension within MCDA as outlined in Table 4.25. Applying these figures within Equation 3.7 for both options allowed a single sustainability score to be achieved for the battery module. These results are outlined in Figure 4.18.

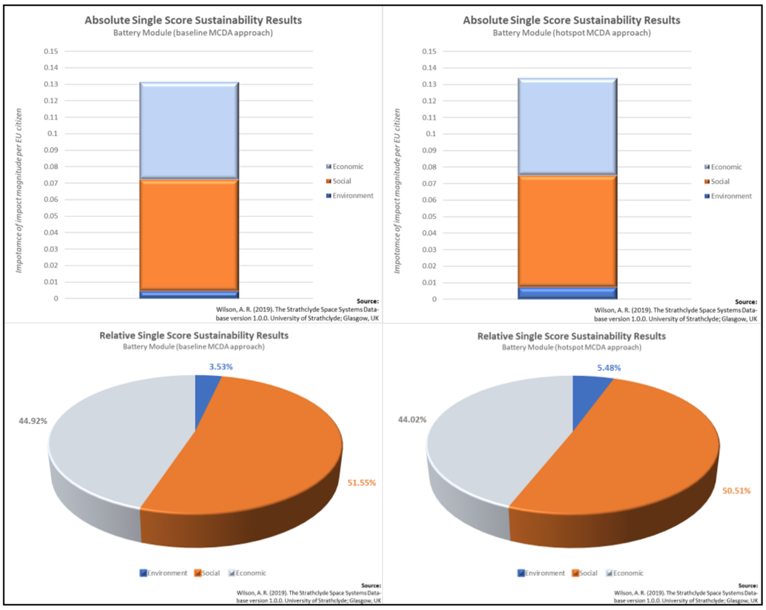


Figure 4.18: LCSA results of a 1 kg battery module

The results indicate that the environmental dimension of this spacecraft component is not as much an area of concern as the social or economic dimensions. This is due to the long development cycle involved and unique components required, which increases the cost and the number of stakeholders, actors and representatives involved in the design. As such, this puts an added emphasis on addressing the hotspots identified during the S-LCA and LCC LCIA results within Subsection 4.4.6. Interestingly, although the ESA hotspot approach produces the higher environmental impact of the two approaches (particularly due to mineral resource depletion stemming from the extraction of tantalum for the electronic components), the highest scoring impact category for the environmental dimension was found within the baseline option due to water consumption. The majority of this water consumption (88%) comes from turbine use in production & manufacturing of the aluminium casing, li-ion cells and other electronic components. Overall, this would indicate that water consumption is a considerable E-LCA hotspot for the battery module. 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. However, as much as 40% of fabrication plants do not recycle water meaning that worldwide power generation is currently responsible for between 3% and 10% of total global water withdrawals and consumption [316]. For this reason, further investment in water recycling may be required within these facilities in the future in order to lower these impacts in a cost-effective manner which keeps operational costs to a minimum.

Although the social and economic inventory data did not change depending on which weighting method was used to generate a score reflecting performance, it does demonstrate how decision-making can cause shifts in levels of importance. This highlights that considering ramifications of methodological choices is critical in order to avoid potential green-washing. Additionally, it could also be argued that it is equally as important to examine how decisions in one assessment might affect another. Although this was not specifically demonstrated within this case study, this could be addressed by targeting identified hotspots. For example, under the workers stakeholder category, the social hotspot of health & safety could be addressed by introducing more stringent health & safety training for employees prior to work commencing. This might mean that it could take longer to manufacture and produce the battery, creating additional costs (such as the training course fee and employee salaries) which must also be taken into account. If this training is assumed to last sixteen hours at a cost of 150 EUR in 2017, then according to the SSSD the additional cost would be around 499.86 EUR 2000 if three employees attended. This represents 28.74% of the current cost. Theorising that this training reduced the risk of accidents to very low levels, then this would see the relative social single score of the baseline option fall to 43.36% (from 51.55%) whilst the relative economic single score of the baseline option would rise to 54.32% (from 44.92%). Therefore, this demonstrates how a small change can massively impact the entire sustainability score across each sustainability aspect. For this reason, it can be seen that trade-offs should not only occur between impact categories, but also between sustainability dimensions. However, it should be noted that this example was applied based on the results of the S-LCA case study outlined in Subsection 4.4.6 which adopted a country-level perspective. At the same time, this approach is not directly applicable for use at this level in comparison to organisational-level which has far more relevancy since organisations have more control over implementing improvement measures. As such, for the purposes of this given example, it was assumed that the S-LCA results were generated on a organisational-level rather than at country-level purely to demonstrate the importance of interactions between sustainability dimensions.

In conclusion, the adopted approach is particularly useful for identifying which sustainability aspect is most important to address when considering relative scores. In this regard, the identified hotspots within the most impacting sustainability aspects (which were found before normalisation or weighting took place), can be targeted for mitigation. Additionally, this approach gives more context to the LCSA results and can aid engineers understanding of sustainability, particularly in relation to the implications of their design choices. However, with regards to absolute scores, the scale of impact is not straightforward or easy to understand. In this regard, although the measurement scale is based on importance of impact magnitude per EU citizen, there is no consensus on what a good or bad score on this scale might be. For this reason, it is suggested that as this technique is applied more, good and bad scores should be benchmarked and used as a basis for comparison between similar missions or spacecraft components to indicate their relative performance.

4.6 Database Logistics

When LCIs are selected for use within a study, it is important that users have a clear understanding of what that data represents and how reliable it is in the context of their study. In this regard, it is important to clearly communicate database information through dataset documentation and logistics [128]. In a perfect database, all information required to describe the quality and usability of each dataset for a given purpose would be included within such documentation. However, this level of detail for large databases is generally considered to be impractical due to cost and time considerations. Nevertheless, this communication is particularly important in the case of the SSSD since it is intended to be used widely by the space industry in the future. As a result of the development of the activities described in the previous three sections, all logistics relating to the SSSD are described below including database limitations, dataset information & documentation, data review and database management.

4.6.1 Database Limitations

The SSSD has provided a set of new LCI datasets, LCIA methods and MCDA approaches which accords to the space-specific LCSA framework. This is the first time that an LCSA platform has been developed for use within the space sector. This provides decision-makers with the necessary tools to measure, reduce and report on the life cycle environmental, social and economic impacts of space missions for the first time.

Despite this, no software model will be released without its limitations. For this reason, it is important to outline these to allow potential users to have a clear understanding of any potential constraints. As such, all limitations which have been identified within the SSSD have been listed below:

- The SSSD is significantly smaller than the ESA E-LCA database (<25% the size).
- The use of Ecoinvent as a background inventory limits the SSSD's use as an open-source and free software model (see Subsection 4.6.4).
- The data contained within the SSSD is mainly based on secondary sources.
- In some cases, LCI datasets may generalise data (e.g. launch event processes) which was driven by a lack of available or reliable data.
- Due to a lack of scientific research on some topics, characterised results could not always be achieved meaning that placeholder flow indicators have to be used instead.
- Whilst data quality has been included within each LCI dataset, since system processes have been used, this means that uncertainty analysis is currently unable to be calculated at system level.
- Full results disclosure from the validation exercise is not permitted due to a confidentiality agreement which is in place with ESA.
- Launch segment LCI datasets at ESA were highly confidential meaning that SSSD launch segment LCI datasets could not be validated during the validation exercise.
- Validation procedures have not yet been conducted for social or economic criteria.
- No data has currently been included within the social LCI due to a lack of willingness from organisations to contribute data.

- The benchmarks used in the evaluation scheme of each social indicator require consistent checks and reviews due to potential shifts and changes which may ensue as the SDGs begin to be realised.
- Costing data is open to subjectivity and will require constant updating due to potential changes in supply and demand, inflation, exchange rates, devaluation or other shifts in economic processes.
- Since only 13 out of the 25 E-LCA midpoint impact categories (including S-LCA and LCC as single scores) are considered as part of the MCDA approach, this omission has great potential to divert focus away from other potential meaningful impacts.
- The normalisation procedures used within E-LCA are not completely comparable to those which are used for within S-LCA and LCC which could have significant ramifications for the significance levels of each sustainability dimension within the LCSA results generated through MCDA.
- Absolute MCDA results as a single score may be difficult for non-LCSA experts to understand.

Each of these are discussed further in Chapter 8 in order to provide a critical appraisal and interpretation with regards to the extent that these limitations impact the implementation of LCSA within the space sector. This helps to form a programme of work which can address all of the identified limitations highlighted throughout this research as a whole.

4.6.2 Dataset Information & Documentation

As recommended within the UNEP/SETAC 'Global Guidance Principles for Life Cycle Assessment Databases' [128], the SSSD has been created based on a systematic hierarchical structure. Additionally, each LCI dataset has been given a unique ID that includes a version number as well as a process description. Each dataset is contained in relevant folders and has been given a basic name to reflect the process it describes. All custom-made SSSD datasets have been created robustly and transparently, and contains the following information:

- General information
- Administrative information
- Modelling & validation information
- Allocation information

Each LCIA dataset contains the above information which describes the scope & intended application of the dataset including the quantitative reference, mathematical relationship of data, the allocation procedure adopted, access & use restrictions including copyright information, data source information, sampling period & procedures, data quality information and the process for evaluation & validation. This means that each dataset can be seen to comply with the UNEP/SETAC 'Global Guidance Principles for Life Cycle Assessment Databases' [128] whilst also fulfilling user expectations relating to database information.

In terms of additional documentation, a 48-page user guide was developed. This document provides assistance to individuals who wish to run E-LCA, S-LCA, LCC and/or LCSAs of space systems using the SSSD. The document also provides information on access & use restrictions of data, additional features and services available, key information and planned future updates. It does not generally provide an overview of the methodology relating to the development of the tool. This thesis has been made available for this purpose to provide users with an in-depth review of SSSD development and use. All SSSD content which is currently available is listed in Appendix B.

4.6.3 Data Review

To fully comply with the UNEP/SETAC 'Global Guidance Principles for Life Cycle Assessment Databases' [128], it is critical that a data review should occur. This is a fundamental aspect of database development which ensures that data quality and characteristics of each dataset is consistent with the database general requirements whilst also ensuring that sufficient information is provided to support users who wish to apply the database or individual datasets within their study.

As mentioned within Subsections 4.3.4 and 4.4.5, the SSSD has already undergone validation procedures. The outcome of this project is documented within the 'ESA LCI

Validation Project Report' [281] and a short specific validation statement was created for each dataset within the SSSD. However, issuing validity statements was not possible for S-LCA or LCC datasets. As such, a secondary validation exercise will be sought in the near future to compliment and provide additional assurance whilst also checking the validity of LCI datasets which could not be assessed. It is proposed that the results of this process will be implemented within the next version of the SSSD.

4.6.4 Database Management

The UNEP/SETAC 'Global Guidance Principles for Life Cycle Assessment Databases' states that publicly released databases require defined roles [128]. Since the SSSD was developed as part of this project, the database manager, owner, generator/developer and documenter is the current author. Contact information for support can be found within the 'Strathclyde Space Systems Database User Guide'. The copyright of all SSSD datasets remains with the database manager and the University of Strathclyde, as defined within the 'Strathclyde Space Systems Database End-User Licence Agreement'. Any new updates or revisions to datasets within the SSSD will be documented within subsequent versions of the user guide. All foreseen near-term updates and planned future developments are outlined in Section 7.4. The current version of the SSSD is v1.0.0.

It is intended that the SSSD will become a free, open-source tool. As such, all of its resources are provided through the Strathclyde Mechanical and Aerospace Research Toolboxes (SMART) on GitHub whilst other supporting documents are available on the University of Strathclyde's research information portal (Pure). 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 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. Thereby the SSSD can assist in this process by evaluating the environmental, social and economic aspects of a variety of space systems for the development of next generation sustainable space systems.

All SMART toolboxes are released open-source to the scientific community under the Mozilla Public License version 2.0. The only exception to this is the SSSD itself since it is supported by a commercial background database (Ecoinvent v3.3 & v2.2). Due to these dependencies, this means that the database can only be made available on request subject to conditions. These conditions mean that potential users must be able provide evidence that they hold a current and valid Ecoinvent licence for the stated background inventory versions or greater before access can be granted to the SSSD. Before this approach is implemented, an agreement is being sought with Ecoinvent in this regard so as not to breach their End-User Licence Agreement. This may eventually involve integrating the SSSD as part of future versions of the Ecoinvent database. Whilst these restrictions may be seen to go against the open-source and free software definitions, the SSSD itself has been developed to comply as closely as possible with these definitions despite being unavoidably based upon a closed-source plugin to enable its functionality. As such, the SSSD will not be made openly accessible within SMART. Instead, it has been stored within Pure with restricted visibility for long-term preservation. The remainder of this thesis will discuss the SSSD on the basis that an agreement can be reached with Ecoinvent and the SSSD becomes a free, open-source tool in the future as intended (subject to conditions).

The other resources contained within SMART encompass an end-user licence agreement to facilitate access to the SSSD, a 48-page user guide providing a basic overview of the SSSD as well as acting as a point of reference for SSSD users and a Sustainable Design Workbook for interfacing the SSSD with the OCDT. The supporting documents available on Pure refer to this thesis and a set of conference papers relating to SSSD development and use. An overview of all SSSD content that is currently available is listed in Appendix B which includes all resources, supporting documents and a list of services provided by the University of Strathclyde for SSSD support.

Finally, the SSSD is also covered by a Data Management Plan which provides information regarding the public availability of the SSSD including all restrictions as documented above. The plan also seeks to mitigate potential database security threats relating to these restrictions such as legitimate privilege abuse or data breaches. Other themes which are also addressed within this plan relate to data collection, documentation & metadata, ethics & legal compliance, storage & backup, database security, data sharing and responsibilities & resources. This plan was submitted to and approved by the research funders outlined in Section 1.6.

4.7 Chapter Summary

This chapter has described the methodology adopted by the SSSD which has been built to enable the proposed space-specific LCSA framework outlined in Subsection 3.5.4. Through the provision of case studies as examples, the successful implementation of this database as a facilitator for the new space-specific LCSA framework was demonstrated. As such, the open-source release of this database may encourage the space sector to become more accountable and responsible for their operations by assisting decision-makers in choosing the most suitable technologies and products based on multiple sustainability parameters/criteria.

Chapter 5

Integration into the Mission Design Process

5.1 Chapter Overview

One of the primary goals of the SSSD is to scientifically quantify the sustainability impacts of space systems in order to inform decision-makers of the environmental, social and economic consequences of design choices. In this regard, these results should assist decision-makers to identify potential hotspots in the life cycle of space missions and find solutions to lower these adverse sustainability impacts as far as practicably possible. For this reason, since adverse impacts are generally set by early design choices, it is recommended that the SSSD is used during Phase 0/Phase A space mission design sessions. As previously mentioned, this is because it is easier to modify adverse impacts the earlier into the design process that they are identified.

Based on this, methods to integrate the use of the SSSD into the concurrent design process of space missions will be investigated. Technically, the SSSD will be connected to the OCDT in order to facilitate the complete sharing of data. After this, the methodological issues involved with the sustainable design process (made possible by the previous step) are addressed based on a case study which is used as a part of alpha testing. This user acceptance testing also encapsulated comparability and functionality analyses before the SSSD could be tested within a real concurrent design environment.

These analyses were performed during the ESA LCI Validation Project, using Space Opera as a benchmark.

5.2 Connecting LCSA Software to a Design Model

If sustainable design is to be used within concurrent design sessions, it is vital that the software being used to facilitate this can be connected to and used in conjunction with the applied design model. Space Opera's inability to achieve this was one of the major drawbacks experienced during the HATHI mission design. Since one of the main goals of the SSSD is to be successfully integrated within concurrent design sessions, this process was conducted using a fully functioning CDF. The University of Strathclyde has its own CDF called the Concurrent & Collaborative Design Studio (CCDS) which opened in October 2015 and is used for all concurrent engineering activities within the university. This facility employs both the OCDT and Concurrent Design Platform 4 (CDP-4) developed by RHEA Group as concurrent design models. Although the OCDT has been used more frequently within the CCDS to date, the functionality of both tools are extremely similar, with the CDP-4 being 100% compatible with the OCDT [317]. As such, the process for connecting the SSSD to a design model has been described exclusively for the OCDT for simplification purposes.

The general concept to connect the SSSD to the OCDT has two parts. The first part involves manual manipulation of the design tool to enable it to host LCSA data. The second part involves creating a new data exchange interface which is compatible with both the sustainable design tool and concurrent design model to facilitate information retrieval and restitution between the two. The exact procedure adopted to accomplish each of these and address the technical issues documented during the HATHI study in Section 2.6 is outlined in the subsections below.

5.2.1 Design Model Manipulation

One of the major problems identified during the HATHI study was the inability of the OCDT to host E-LCA data. This is because the OCDT RDL follows the ECSS-

E-TM-10-25 Annex A standard which defines the parameter types that it hosts [152]. Unsurprisingly, this standard does not include E-LCA or LCSA parameter types within its metric system which is problematic for sustainable design. As the University of Strathclyde has its own CDF, these problems could be addressed locally through the creation of new LCSA parameters within the OCDT RDL for all the midpoint and endpoint impact categories indicated in Tables 4.3 and 4.4. These tables comprise of the full list of 25 E-LCA impact categories, including S-LCA and LCC as single scores in addition to the single scores generated by MCDA.

Before these impact categories were added as parameters, a new domain of expertise was created for LCSA within the OCDT server which can be assigned to any relevant person as their default domain. Alternatively, it can also be assigned to a person as a specific but secondary domain for a given CDF study [153]. This allows for all changes made by the assigned person within an engineering model to be clearly attributable to this domain. Whilst the OCDT uses a generic RDL based on ECSS-E-TM-10-25, each engineering model also has its own RDL [151]. Parameters can be created within either of these RDLs (along with other reference data) during the course of the study. ESA recommends that any new parameters created by a domain discipline expert should be examined by the systems team and promoted to the generic RDL at the earliest opportunity if they are found to be applicable for future studies [318]. As such, a range of parameters were added directly to the ECSS-E-TM-10-25 RDL within the CCDS using the OCDT administrators account to ensure that they are clearly visible and usable within future CDF studies rather than being specific to any given model template. The new parameters were created to reflect impact categories within the OCDT using appropriate measurement units and scales (as identified in Table 5.1). For each measurement unit, a simple unit was selected whilst a ratio scale was selected for each measurement scale using a ‘Real Number Set’. A parameter was defined for each of the 25 impact categories and 4 MCDA single score impact categories using a ‘Simple Quantity Kind’ as the parameter type. These choices which were selected for the measurement unit, measurement scale and parameter types were due to requirements stemming from the data exchange interface as defined in the following subsection. The short names for each of the 25 impact categories were then alphabetised (i.e. letters 'a' to 'y' were put at the front of each short name according to the alphabetical order of each impact category by long name). The single score impact categories were also alphabetised (i.e. letters 'za' to 'zd' according to the alphabetical order of each impact category by long name). This is also shown in Table 5.1 below. The reason for this step was also due to requirements stemming from the data exchange interface as defined in the following subsection.

Table 5.1: LCSA Parameters implemented within the OCDT

Parameter Name	Parameter Short Name	Parameter Type	Measurement Scale	Type of Measurement Scale	Measurement Unit
Midpoint Indicators					
Acidification – Air Acidification Potential	aAP	Simple Quantity Kind	kg SO2 eq	Ratio Scale	Simple Unit
Aluminium Oxide – Al2O3 Emissions in Air	bAl2O3	Simple Quantity Kind	kg Al2O3 eq	Ratio Scale	Simple Unit
Climate Change – Global Warming Potential 100a	cGWP	Simple Quantity Kind	Kg CO2 eq	Ratio Scale	Simple Unit
Critical Raw Materials – CRM Use Potential	dCRMUP	Simple Quantity Kind	kg	Ratio Scale	Simple Unit
Disposal – Mass Disposed in Ocean	eMDO	Simple Quantity Kind	kg	Ratio Scale	Simple Unit
Economic Impact – Economic Single Score	fEco	Simple Quantity Kind	EUR 2000	Ratio Scale	Simple Unit
Energy Consumption – Total Cumulative Energy Demand	gCED	Simple Quantity Kind	MJ	Ratio Scale	Simple Unit
Eutrophication – Freshwater Eutrophication Potential	hFEP	Simple Quantity Kind	kg P eq	Ratio Scale	Simple Unit
Eutrophication – Marine Eutrophication Potential	iMEP	Simple Quantity Kind	kg N eq	Ratio Scale	Simple Unit
Ionising Radiation – Ionising Radiation Potential	jIRP	Simple Quantity Kind	kg U235 eq	Ratio Scale	Simple Unit
Noise Pollution – Noise Creation Potential	kNCP	Simple Quantity Kind	Leq	Ratio Scale	Simple Unit
Orbital Risk – Space Debris Risk	lSDR	Simple Quantity Kind	Risk Level	Ratio Scale	Simple Unit
Orbital Space Use – Orbital Resource Depletion Potential	mORDP	Simple Quantity Kind	objects.m3.year	Ratio Scale	Simple Unit
Ozone Depletion – Ozone Depletion Potential	nODP	Simple Quantity Kind	kg CFC-11 eq	Ratio Scale	Simple Unit
Particulate Matter – Particulate Matter Formation Potential	oPMFP	Simple Quantity Kind	kg PM10 eq	Ratio Scale	Simple Unit
Photochemical Oxidation – Photochemical Oxidation Potential	pPCOP	Simple Quantity Kind	kg NMVOC	Ratio Scale	Simple Unit
Re-Entry Smoke Particles – RSP Creation Potential	qRSP	Simple Quantity Kind	kg RSP eq	Ratio Scale	Simple Unit
REACH Substances – Restricted & SVHC Use Potential	rRUP	Simple Quantity Kind	kg	Ratio Scale	Simple Unit
Resource Depletion – Fossil Resource Depletion Potential	sFRDP	Simple Quantity Kind	MJ fossil	Ratio Scale	Simple Unit
Resource Depletion – Mineral Resource Depletion Potential	tMRDP	Simple Quantity Kind	kg Sb eq	Ratio Scale	Simple Unit
Social Impact – Social Single Score	uSoc	Simple Quantity Kind	Score	Ratio Scale	Simple Unit
Toxicity – Freshwater Aquatic Ecotoxicity Potential	vFAETP	Simple Quantity Kind	PAF.m3.day	Ratio Scale	Simple Unit
Toxicity – Human Toxicity Potential	wHTP	Simple Quantity Kind	cases	Ratio Scale	Simple Unit
Toxicity – Marine Ecotoxicity Potential	xMETP	Simple Quantity Kind	kg 1,4-DB eq	Ratio Scale	Simple Unit
Water Consumption – Water Depletion Potential	yWDP	Simple Quantity Kind	m3	Ratio Scale	Simple Unit
Single Scores					
Costing Single Score	zaCOS	Simple Quantity Kind	Importance of Impact per EU Citizen	Ratio Scale	Simple Unit
Environmental Single Score	zbENV	Simple Quantity Kind	Importance of Impact per EU Citizen	Ratio Scale	Simple Unit
Social Single Score	zcSOC	Simple Quantity Kind	Importance of Impact per EU Citizen	Ratio Scale	Simple Unit
Sustainability Single Score	zdSUS	Simple Quantity Kind	Importance of Impact per EU Citizen	Ratio Scale	Simple Unit

Now that LCSA parameters have been created within the OCDT, they can then be added to specific OCDT engineering models to facilitate the sustainable design discipline of space missions. To do this, parameters can be dragged into relevant LCSA element definitions and/or parameter groups for the selected engineering model. As the LCIA results of the SSSD allow for a detailed breakdown, these results could be attributed to the entire mission, mission phases or individual subsystems within the OCDT (depending on the level of study specificity required). This is discussed in further detail in Section 5.3.

5.2.2 Creating a Data Exchange Interface

The biggest problem encountered during the HATHI study related to Space Opera's failure to interface with the OCDT. In particular, a decentralisation error stemming from bugs within the automatic import/export algorithm function meant that data retrieval and restitution was not possible between the OCDT and Space Opera. Additionally, these results could also not be exported as a Microsoft Excel file due to bugs within the Space Opera tool. Together with the OCDT's inability to host E-LCA data, this ultimately meant that other discipline experts were not aware of the impact of their design choices in real-time. As a result, the study was extensively hindered to a point where the assessment was considered incomplete. Therefore, it is crucial that alternative methods are sought to facilitate this data exchange between the SSSD and the OCDT.

To overcome these issues, a domain-specific tool adapter is required which uses an Excel or representational state transfer (REST)/JSON interface for connection to the web-service processor and subsequently the OCDT database (see Figure 2.12). This adapter must be able to interface with the SSSD and OCDT whilst also maintaining compliance with a number of standards including the ISO 10303 standards for computer-interpretable representation and exchange of product manufacturing information, the ISO 13584 standards on industrial automation systems and integration - parts library, the ISO 15926 RDL standards and the ISO/TS 14048:2002 standard for LCA data documentation format [319]. This approach differs from the one adopted by Space Opera since ESA's methodology was to create a direct connection to the web-service processor without the need for a domain-specific tool adapter [154]. This difference in method was primarily due to project time-constraints which meant that developing an automatic import/export algorithm or creating secondary software for sustainable design was not possible. Whilst a similar approach is being considered for future use within the SSSD to enable quicker, more efficient and streamlined analyses, the problems experienced by Space Opera cast doubts on the applicability of this method in the first instance. For this reason, a more simplistic approach was developed instead.

Since the OCDT was created using a simple Excel-based user interface to facilitate quick and effective concurrent design, an Excel-based domain-specific tool adapter was considered for the data exchange interface of the SSSD. This decision was made to reduce the learning curve for engineers as far practically possible by limiting the need for additional training [320]. Since openLCA supports an export function which converts LCIA results of complete product systems from ZOLCA format to xlsx format [119], a new sustainable design workbook was created exclusively for the LCSA discipline. This makes inserting these numbers into the OCDT straightforward since the new workbook can be used to exchange data between the SSSD and OCDT by copying the LCIA results contained within the exported openLCA output file to the new sustainable design workbook. As such, this links the SSSD and OCDT by allowing exported LCIA results to be deposited to the OCDT server whilst important design information can also be retrieved from the server within the workbook. The pushing and pulling of data via a domain-specific Microsoft Excel workbook is typically how other disciplines create a link with the OCDT server [141,146,321]. This three step process has therefore been replicated for the new LCSA discipline and can be visualised in Figure 5.1 below.

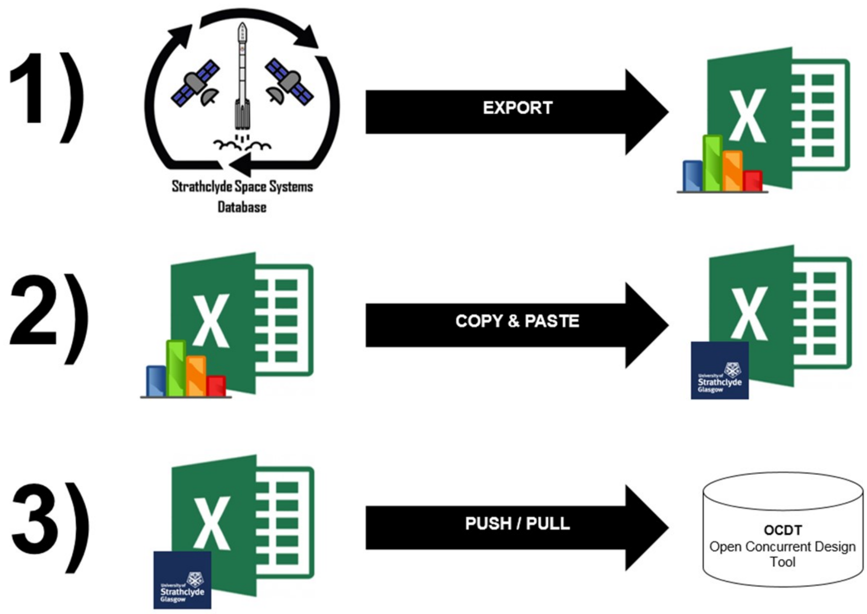


Figure 5.1: Restitution of SSSD LCIA Results to the OCDT Database

The new sustainable design workbook has been built to accommodate sustainable design for dynamic elements and a full space mission as defined within the system boundary of the ESA E-LCA guidelines. It is compatible with the SSSD E-LCA midpoint LCIA method (which includes S-LCA and LCC as single scores). The exported LCIA results which were generated using this method are exported from openLCA alphabetically according to impact category name. In comparison, the OCDT alphabetises parameters by their short name within element definitions and parameter groups of engineering models. As such, the newly created parameters within the OCDT were alphabetised by their short name (as described in the subsection above) in order to appear in the same order when used in an engineering model as within the exported openLCA file. This means that copy and pasting results between the two files is straightforward, since a 'simple quantity kind' was used for all parameter types. Additionally, since normalisation & weighting results are not possible through the openLCA Excel export [119], this information has been added to the SSSD Workbook for the 5 ESA hotspot impact categories and those listed within the MAVT technique outlined in Section 4.5 (including the custom-made S-LCA and LCC methods). This has been linked to the LCIA results cells to which information will be copied so that the information input from the SSSD E-LCA midpoint LCIA method will automatically generate single score results. The LCIA results from this tab can then be linked to the OCDT by the push/pull function whilst other element definitions of interest can be subscribed to. Further instructions on this can be found within the SSSD User Guide.

5.2.3 Discussion of Findings

Although a more simplistic method was adopted than Space Opera, all the technical issues experienced during the HATHI mission design have been addressed. This method also aligns more succinctly with the direction of the aerospace industry and their use of Excel-based modelling within concurrent engineering sessions to drive design.

With regards to interfacing with the OCDT, a new sustainable design workbook was created to avoid the possibility of a decentralisation error caused by data exchange formatting. Through openLCA's ability to export with excel, this simplifies the data exchange process. Based on a case study used for alpha testing (see Section 5.3), this process allows for the complete sharing of data. This indicates that the SSSD is working as intended by facilitating sustainable design within the concurrent design process whilst maintaining compliance with various data exchange standards.

5.3 Sustainable Design within Concurrent Engineering

The SSSD has been developed to maintain consistency with the new space-specific LCSA framework proposed and outlined in Subsection 3.5.4. However, in addition to its development, consistency with this framework must also be extended to the SSSD's methodology when it is applied in concurrent engineering activities. Although this framework was developed for space-specific LCSA rather than sustainable design, tailoring this methodology towards sustainable design applications has numerous advantages. In particular, it allows for LCE to take place by assisting engineers to improve the environmental, social and economic performance of space missions without reducing quality or performance. This can be used to create a competitive advantage by assisting in the development of more sustainable and innovative work processes, facilitated through the detection of significant or distinct life cycle issues and risks.

In this regard, since a connection has now been established between the SSSD and OCDT using a domain-specific tool adapter as the data exchange interface, it is important to determine how the SSSD can assist in the delivery of sustainable design within the concurrent design process and in what ways it can influence space system design. It was clear that Space Opera experienced several methodological challenges during the HATHI mission design as documented in Subsection 2.6.3. Addressing these issues allows the SSSD to be integrated into the concurrent design sessions successfully, using a methodology that is consistent with the new space-specific LCSA framework outlined in Subsection 3.5.4. The exact procedure adopted to facilitate sustainable design using the SSSD and address the methodological issues documented during the HATHI study is outlined in the subsections below.

5.3.1 Application & Performance

Although sustainable design has thus far never been applied to concurrent design, ecodesign has. Despite the distinct differences deriving from modelling each sustainability aspect within the space-specific LCSA framework as outlined in Subsection 3.5.4, it can be argued that the sustainable design process is extremely similar to the ecodesign process. This is because ecodesign and sustainable design are systematic procedures rather than a methodology like LCSA [156]. Therefore, it is reasonable to assume that the sustainable design process of space systems should be based on the ecodesign process already defined by ESA. As stated in Section 5.2, this is facilitated by creating a working connection between a space-specific ecodesign tool and the OCDT. Since the SSSD has already established this connection, it is important to define the methodological approach to be adopted which governs the SSSD's application within the concurrent design process to facilitate sustainable design.

Building upon the approach defined by the Space Opera developers for integrating ecodesign into the concurrent design process [32, 105], sustainable design is principally based on information provided to the OCDT server by other disciplines. Parameters input by these disciplines which contain relevant information for sustainable design should be identified and subscribed to. This data can then be pulled to the sustainable design workbook and used within the SSSD. This dynamic element data can be applied within relevant SSSD processes in conjunction with other generic data (i.e. static elements) and methodologies (such as S-LCA LCI data if being applied). The LCI results are then run through a calculation engine contained within the SSSD to produce LCIA results using the SSSD E-LCA midpoint LCIA method. These results can then be exported to excel and copied into the sustainable design workbook to facilitate MCDA before being deposited on the OCDT server following the same method as outlined in Figure 2.12. The other disciplines can then use these sustainability results to refine the spacecraft design further to reduce the overall environmental, social and economic impacts of the mission. An overview of this process is provided in Figure 5.2 below whilst step-by-step instructions on its application is provided within the SSSD user guide.

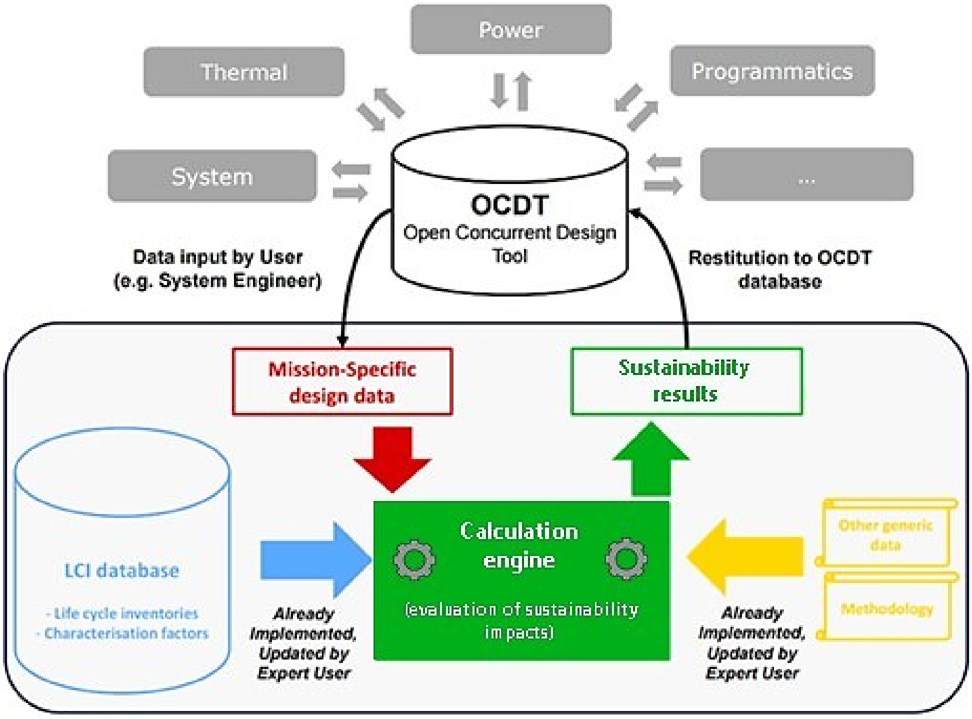


Figure 5.2: The sustainable design processes for space systems (adapted from [32,105])

However, as evidenced during the HATHI mission design, not all methodological issues relating to ecodesign have been addressed since this is still a very new concept within the space industry. Therefore, it is suggested that the sustainable design process of space missions should follow the process outlined in Figure 2.12 as closely as possible whilst addressing firstly the problems identified during the HATHI mission design and secondly any other sustainability issues deriving from the use of the SSSD. To do this, the SSSD was internally trialled during its development within the CCDS by using the FireSat mission example outlined within Larson & Wertz to create a new OCDT engineering model [203]. The purpose of this mission was to detect, identify, and monitor forest fires throughout the USA (including Alaska and Hawaii) in near real time. This CDF session was used for educational purposes as a precursor to the MÌOS mission (outlined in Section 6.2) to familiarise study participants with the OCDT and concurrent design approach.

The sustainable design process began within the SSSD once relevant data from selected disciplines was uploaded to the newly created FireSat engineering model. Since the SSSD does not currently support an automatic import/export algorithm, this means that each spacecraft component contained on the OCDT and its value had to be manually added to the SSSD. Although this is not a complex procedure and solves the decentralisation issue experienced by Space Opera during the HATHI mission design, it was extremely time consuming which only intensified as the design became more advanced. There was also a risk that this laborious and tedious process would require duplication with only slight variations if alternative designs were to be considered within the SSSD. However, this is currently an unavoidable feature of the SSSD.

Another issue relating to the application of the SSSD concerned the use of mass margins. Within concurrent engineering studies, ESA apply mass margins within spacecraft mass budgets by using the ESA CDF mass margin philosophy standard [167]. According to this standard, the recommended mass margins are 5% for COTS items, 10% for COTS items requiring minor modifications and 20% for new items or items requiring major modifications/re-design. The information contained within the mass budget of a given space mission design is generally the most useful information for the dynamic elements of the LCSA discipline [32]. However, in addition to this margin at equipment/component level, the ESA standard recommends a further 20% mass margin at system level [167]. Whilst the OCDT may, in some cases, contain input data for all spacecraft components with mass margins included at equipment/component level, it rarely includes system level mass margins [33]. This was the case during the FireSat training, which was highly problematic because this omission meant that 20% of the potential impacts arising for dynamic elements would be absent from the final LCIA results. As such, the SSSD used the openLCA parameter field to address this by multiplying the value of each spacecraft component input to the SSSD from the OCDT by a predefined mass margin parameter (in this case '1.2' to represent the additional 20% margin) so that each component also included mass margins at system level. Based on this, it is recommended that a new parameter is added to the SSSD's parameter field within future CDF studies by the LCSA discipline expert to represent the required spacecraft mass margins.

Moreover, it is important to clarify to study participants exactly what type of additional data they may be required to provided for the sustainable design discipline. Although the SSSD has self-contained LCI datasets, additional information was considered advantageous to assist with the social and economic analyses. Typically, social information which may need to be communicated to the LCSA expert relates to the name of the organisation where a component was sourced or the country where it was produced or manufactured. This would allow the most relevant social LCI dataset to be used (assuming social LCI datasets have been generated). In terms of costing information, although not essential, providing specific component costs (including their TRL level) allows for a more accurate build-up of the LCC results. Nonetheless, through the use of CERs, costing information has already been mapped in relation to component mass. For this reason, it can be seen that the SSSD has been designed to limit the amount of additional information required to be provided by other discipline experts (see Table 3.5). However, this approach assumes that the SSSD contains readily available information (particularly for S-LCA) which can be applied to all scenarios. Difficulties in motivating stakeholders to provide such data for social impact indicators has already been seen to be a major drawback of this thesis work. This type of problem was also observed by ESA for environmental indicators (where there is already a standardised method established) [33]. As such, requests for additional data may be met with further push-back. This creates a real problem relating to how best gain stakeholder, designer or managerial commitment to the LCSA discipline. Overcoming this issue may be key to streamlining the wide-spread application of sustainable design within the space industry in the future.

Another problem discovered during the FireSat training which affects the implementation of sustainable design is specificity of results. To that effect, the SSSD workbook allows LCIA results to be broken down at either mission level or for dynamic elements only. This is similar to the results produced by Space Opera within the HATHI mission design. Despite this, the SSSD is able to provide fully transparent and robust non-characterised results for any flow within the entire database at a variety of levels from mission to activity element level. The reason for this restriction within the sustainable design workbook is because result breakdown to component/equipment level within the OCDT is not practical due to time constraints concerning the handling of multiple parameters and the need for several LCSA analyses. However, this creates a problem as study participants will not be able to see potential hotspots within the design. As such, it is suggested that poorly performing components with respect to the dynamic elements are communicated to the responsible discipline team verbally in a clear and time effective manner.

In this regard, the communication and presentation of results within concurrent design sessions was another major issue. In particular, this relates to the timing of these elements, and whether this should occur during or between design iterations. Due to the functionality of Space Opera, ESA stated that the intention of the tool was for it to be used between design iterations to inform study participants of the design impact of the previous iteration [34]. However, this approach greatly restricts the flow of information and number of opportunities granted to engineers to modify the design with respect to identified hotspots. As such, the SSSD aims to actively contribute to each iteration of the concurrent design session by actively depositing real-time data to the OCDT. During the FireSat training, LCSA data was firstly added for 'static elements' where possible until design information relating to 'dynamic elements' began to be input to OCDT server by other disciplines. This information was used to provide engineers with an understanding of the 'build-up' of adverse impacts generated by the on-going design. Since most SSSD 'dynamic element' processes require mass data of each equipment/component, a completed mass budget is extremely important for LCSA results. As such, it is also extremely important that results of the final design are obtained from the finalised iteration of the engineering model and mass budget. Therefore, whilst it is imperative that sustainable design results are communicated in real-time as a discipline in its own right, it is recommended that results should also be reported at the close of each iteration as part of the system budgets. As such, to facilitate this, the engineering model should not be completely closed by the OCDT administrator in order to allow final LCSA results to be uploaded for information and documentation purposes.

5.3.2 Influence on Space System Design

Despite the seemingly robust approach for space-specific sustainable design outlined in the previous subsection (including its recommendations), its success cannot be assumed without considering its influence on the concurrent design process. In order to gauge this, it is important to look at both the positive and/or negative influences that this new sustainable design method has on space system design. As such, the quality of results generated by the LCSA discipline using the SSSD and their capacity to aid decision-making during the FireSat training were noted and deliberated below.

Firstly, the sustainable design workbook dictates the use of a particular LCIA method which leaves little room for alternative approaches to be applied unless the workbook is adapted. The reason for this selection is because the SSSD E-LCA mid-point LCIA method is the most compatible with MCDA which is applied through the sustainable design workbook. Besides the clear focus this places on E-LCA results, it also means that there are a total of 25 impact categories to generate results for. Although S-LCA and LCC are used as single score results within this LCIA method to reduce the number of impact categories, it can be argued that the sheer number of impact categories may still leave engineers overloaded with information. This is due to variances in impact results between iterations (i.e. the LCIA results for some impacts categories may observably decrease whilst others increase) which may leave engineers wondering which impact categories emphasis should be placed on. MCDA deals with this by splitting results into environment, social, economic and sustainability single scores. This significantly reduces the number of impact categories and groups them into understandable issues based on the concept of TBL sustainability. However, this can be seen to be introducing subjectivity and uncertainty to the analysis [32]. Despite this, the concept of equally weighting social, economic and environmental spheres (as presented within the Barbier diagram [9]) has become synonymous with the term ‘weak TBL sustainability’. This is because the approach is seen to enable the sacrifice of the environment for the sake of economic gains. As such, weighting of each dimension within the SSSD is based on the contents of the 2030 Agenda; the most dominant political framework for sustainability currently in existence. This approach can therefore be described as 'strong TBL sustainability' since it highlights the importance of respecting environmental limits regardless of social or economic progress [322].

Additionally, it was clear during the FireSat training that study participants were unclear on the scoring of both the SSSD E-LCA midpoint LCIA method and MCDA results relating to what represented a 'reasonable' or 'bad' score. This suggests that clear verbal communication from the LCSA expert is still required within the concurrent design process to provide information to relevant disciplines on poorly performing space systems based on the gravity of impacts outlined within the LCIA and MCDA results. Alternatively, the relative contribution of each sustainability aspect could be used instead of an absolute value in future mission design sessions. The success of this process is key to sustainable space system design and can be evidenced by the reduction of adverse sustainability impacts between design iterations.

When generating LCIA results within the SSSD, a complete product tree is also generated. This product tree built for the engineering model can also be used to trace the most impacting areas of each impact category to their root causes. This is particularly useful for identifying sustainability hotspots and communicating these to relevant design disciplines. However, based on this, it can be seen that the launch segment generally masks the impact of the space segment for the majority of impact categories across the whole mission. This is similar to what was observed within the LCC results during the FireSat training, where a large proportion of the cost came from the acquisition of the launcher. Although such findings highly depend on the goal and scope definition (which can be adjusted to suit study specificities), this may have serious implications for the sustainable design process of spacecraft at mission level. In this regard, implemented improvements may become insignificant or unobservable (particularly in SmallSats) in comparison to the launcher impacts if a system boundary consisting of the ground, launch and space segment is adopted, as outlined in Figure 2.4. To address this, ESA are currently in the process of adopting an approach that is goal dependent (i.e. if ecodesign is applied, all elements that cannot be affected by the satellite design are not taken into account) [33]. This highlights the importance of including results for dynamic elements only within the newly developed sustainable design workbook. Additionally, the tracing of social impacts could not occur during the FireSat training due to a lack of social LCI data whilst MCDA results cannot be traced back to their root causes as easily since no product tree can be built in openLCA with respect to normalisation and weighting criteria. Due to this, it can be argued that the E-LCA midpoint LCIA results (including S-LCA and LCC as single score results) are more important to address since these provide more scientifically correct results whilst each impact category can also be traced across the full product tree. Based on this, if seeking to improve MCDA results, lowering the adverse sustainability impacts produced by the SSSD E-LCA midpoint LCIA impact categories which contribute to the single score result should be seen as the emphasis and motivation of the LCSA expert. In particular, the results from the FireSat training highlighted that there is a distinct emphasis on environmental impacts which also lends weight to the usefulness of the SSSD E-LCA midpoint LCIA method due to its focus on environmental impact categories.

Since the FireSat training session was merely an educational exercise for students (acting as precursor to the MÌOS mission outlined in Chapter 6), it was not considered appropriate to examine the how the integration of sustainable design affected the group dynamic in this instance. As such, it can be considered that the influence of this process on team behaviour and design choices is yet to be examined. This issue will be addressed in the following chapter where sustainable design is applied within real concurrent engineering sessions.

5.3.3 Discussion of Findings

Overall, the methodological approach allows LCE to be applied within the concurrent design process of space missions for the first time by balancing "the three dimensions of sustainable development" in line with the 2030 Agenda [4]. However, it was found that adding new design elements and updating these were extremely time consuming. The manual nature of this process also provides more scope for human error to occur. Whilst the approach adopted by the SSSD is also functional, this lends weight to the required use of an automatic import/export algorithm. As such, this is considered as a basis for future work (see Section 7.4).

In relation to the influence of the SSSD on concurrent design, it is clear from the findings of this process that the method adopted to integrate MCDA results into concurrent design severely limits the choice of applicable LCIA methods as a means to communicate results to participants. The intention behind this was to maintain a focus on E-LCA whilst providing additional supporting information regarding social and economic impacts and the use of MCDA. Additionally, it was found that study participants were unsure of the link between these three sustainability aspects due to the data exchange format and needed clarification on the MCDA measurement scale. This is perhaps due to the novelty of the discipline within the space sector but means that careful communication is required by the LCSA expert to convey these results to other disciplines in order to facilitate sustainable design.

In this regard, the SSSD was developed so that all LCI data and LCIA methods along its product tree were fully observable. This transparency means that life cycle impacts can be traced, unlike Space Opera where LCI and LCIA information is hidden. Although this provides users with an in-depth overview of all impacts and their root causes, this level of detail cannot be input to the OCDT since a space-related LCSA product system will typically consist of some several thousand flows as inputs and outputs. This emphasises the need for careful communication of results. Particularly, it relates to sustainability hotspots of particular spacecraft elements and the timing of results presentations as identified within Section 5.3.1. This is not too problematic since the process is an inherent part of concurrent design, which is to facilitate dialogue between key decision-makers and discipline experts simultaneously.

It was found that consideration of mass margins is crucial within LCSA as this is often applied at equipment and system level. Without making such a provision, a significant proportion of LCIA impacts may be omitted from the analysis. However, mass margins (at least at system level) are not typically applied within the OCDT. As such, the discipline heavily relies on the provision of an updated mass budget by the systems engineer and close relationship with this person is recommended. This allows this element of space system design to be considered within the SSSD as required if applying ESA's mass margin philosophy.

Finally, if the launch segment masks the relative contribution of other mission segments for so many impact categories in E-LCA then it raises the question whether ecodesign is a worthwhile endeavour since this process typically focuses exclusively on dynamic elements of an entire space mission. Although this depends on the goal and scope definition, in this regard, it could be argued that the impacts of launchers should be the sole focus of ecodesign within the industry and ecodesign of spacecraft be disregarded. However, when considering other aspects such as cost and particularly social impacts, then spacecraft dynamic elements have a much larger relative contribution. This is demonstrated within Chapter 6 which highlights the importance of using sustainable design within the concurrent design process of space missions to also consider social and economic impacts. S-LCA impacts are very similar for launcher and spacecraft. This is because launchers are built using familiar processes and standardised testing. In comparison, spacecraft have a significantly lower mass to build but use specific components and testing which are very labour and time intensive.

5.4 Operability & Dependability for Sustainable Design

In order to evidence the practicality and versatility of the SSSD as a sustainable design tool, its operability and dependability must be quantifiably measured. To determine this, the SSSD was benchmarked against Space Opera by assessing its comparability and functionality. This work was conducted as part of the ESA LCI Validation Project to provide additional support to validation procedures.

In this regard, the comparability analysis has been conducted to determine differences in LCIA results between the SSSD and Space Opera whilst the functionality analysis has been conducted to identify potential software issues. The results from the comparability assessment can be used to support validation claims for LCI datasets where issuing a validation statement was not possible (e.g. launch segment processes due to confidentiality issues). Additionally, functionality testing results can also be used to determine the strength of the SSSD's integration into the concurrent design process whilst also providing a problem report which can be used to frame recommendations for future software development. The results from both of these analyses are provided, discussed and evaluated in the following subsections.

5.4.1 Comparability Analysis

Comparative studies are a common practice in E-LCA. Both of the ISO 14040:2006 and 14044:2006 standards [5,6] provide strict rules on how to properly conduct a comparative E-LCA whilst the ESA Space System E-LCA Guidelines provide guidance on how to apply this to space [30]. However, comparative E-LCAs have additional requirements when being used for validation purposes. The GHG Protocol specifies that a margin of error should be applied when there are unacceptable differences in results generated via a comparative assessment [323]. However, no literature could be found on applying this to an E-LCA when considering multi-criteria indicators. This is problematic because whilst some indicators may be within an applied acceptable margin of error, others may not. This means that not only does a margin of error need to be set, but also what constitutes an area of significant difference in LCIA results.

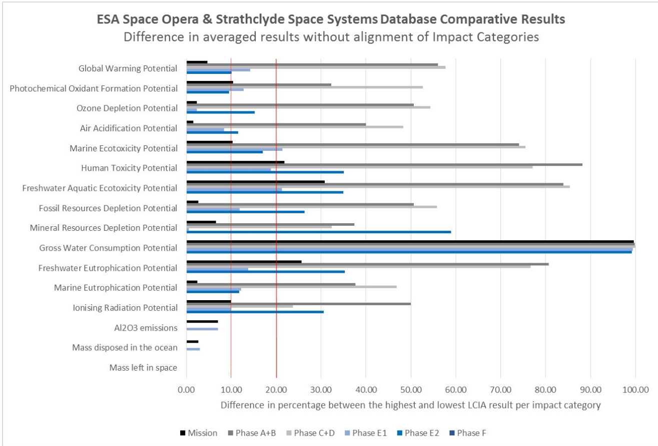
Despite the usefulness of such comparisons, Madushela et al. warns that studies which make use of secondary data should indicate potential margins of error in the data, or at least be transparent about their values [324]. For this reason, it is highly advisable for comparative validation studies to include an acceptable margin of error when looking into differences between results. However, there is currently no internationally accepted margin of error for environmental assessments since these depend highly on the type, context and content of a given study. To address this, based on literature reviews, Berg suggests that a potential maximum acceptable margin of error for E-LCAs which should be used during conceptual design studies lies at ±10-20% [325]. The adoption of such a margin and its transparent communication allows such studies to maintain accuracy in reporting their results. This is particularly important given that the GHG Protocol reports that one of the most significant limitations of environmental inventories involves the collection of high quality activity data [9]. To ensure that data quality is not compromised, the GHG Protocol recommends a range of data validation methods. This includes the suggestion of comparing activity data with multiple reference sources and testing its applicability through validation tests, including consistency and completeness checks. It also notes that results which differ by over 10% may warrant further investigation (although this figure was used merely as an example). No suggested margin of error is given within the GHG Protocol since the most applicable margin of error will depend on individual study characteristics. However, this 10% margin of error for inventory gathering has been taken as a reference figure by many organisations in recent years. For example, the UN have adopted it to assist with data validation procedures when they conduct their annual GHG inventory data collection across the UN-system [326]. Similar to this, ESA utilises a mass margin philosophy in their concurrent engineering studies and industrial activities to ensure that space missions and activities are designed with an appropriate level uncertainty/error included. This typically means that during conceptual design sessions (Phases 0/A) a 20% system level margin is added to the nominal dry mass at launch [167].

No literature could be found on areas of significant difference for E-LCA (i.e. the amount of impact categories that differ by more than the applied margin of error which would lead to the LCI dataset being questioned). However, after consultation with various E-LCA experts who have worked with ESA and at Glasgow Caledonian University, a good assumption might be differences in LCIA results of ≥10% for 50% of impact categories as a lower limit and/or ≥20% for 25% of impact categories as an upper limit [327]. This assumption has been adopted as part of this study as a measure of result comparability and to define areas of significant difference. The results from this process will be used to distinguish the acceptability of results and indicate potential areas which may require further investigation.

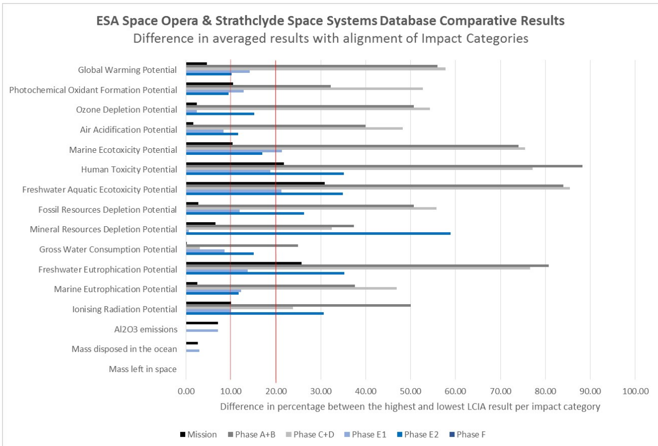
The goal of this assessment was to investigate the average difference in LCIA results (with and without alignment of LCIA impact categories) of three space missions with identical input values run through both the SSSD and Space Opera ecodesign tools simultaneously. This was conducted as part of the ESA LCI Validation Project between 17 September 2018 and 14 December 2018. As such, the adopted methodological approach must ensure consistency which includes at the minimum the adoption of the same goal & scope (including FU and system boundary), identical LCI datasets used by each tool (e.g. the use of man-hours in Phase A+B for both tools), and the same input values used by each tool for all LCI datasets under each specific study. Consideration must also be provided for the use of LCIA methods (impact categories, indicators and characterisation models) used by each tool. Since Space Opera contains only environmental data, only E-LCA impact categories were able to be compared. The selected FU and system boundary for all three studies are based on the ESA E-LCA guidelines [30]. As such, the FU was set as 'one space mission in fulfilment of its requirements' whilst the system boundary covers the ground segment, launch segment and space segment across all mission phases as can be seen in Figure 2.4. The selected space missions were purely fictitious, based on engineering models already contained within Space Opera. The datasets of both the SSSD and Space Opera were used as the LCIs of the study. Space Opera currently uses its own inventories developed from Astra1N and MetOp-A data, which draw on the ESA E-LCA Database for space-specific LCI datasets relating to materials & manufacturing processes and propellants & pressurants [33]. The SSSD LCI was primarily created based on experimentation, literature reviews and expert input. Input values used for all LCI datasets used in both the SSSD and Space Opera ecodesign tool are identical. These LCI dataset input values can be found in Appendix 9.4 of the 'ESA Life Cycle Inventory (LCI) Validation Report' [281]. This report is classified as confidential and is accessible to authorised persons only. The LCIA methods used by each tool including the impact categories, indicators and characterisation models were guided by the ESA E-LCA guidelines [30]. The results note all areas of significant difference in LCIA results between the ecodesign tools for all three space missions. In this regard, areas of significant difference are defined according to the margin of errors stated earlier. As agreed with ESA, the absolute results from these comparisons will be kept confidential. Significant issues encountered during the comparison process have also been documented. Completeness, sensitivity and consistency checks including uncertainty analysis could not take place due to bugs within the Space Opera tool (which have been noted with respect to the functionality testing in Subsection 5.4.2).

Figure 5.3 provides the results from this process. These results show the average difference in percentage between the highest and lowest LCIA result per impact category across the three generic missions when comparing the LCIA results of Space Opera to the SSSD. In particular, Figure 5.3(a) provides results relating to the absolute average difference that users will experience when using the SSSD in comparison to Space Opera at system and phase level. Figure 5.3(b) provides results relating to the average difference that users will experience with aligned LCIA methods when using the SSSD in comparison to Space Opera at system and phase level. Indeed, the only difference between Figure 5.3(a) and Figure 5.3(b) relates to the Gross Water Consumption impact category. In Figure 5.3(a), two completely different LCIA methods were being used (i.e. 'Ecoinvent, Cumulative energy demand' for Space Opera compared to 'ReCiPe Midpoint (H)' for the SSSD). In Figure 5.3(b), the Gross Water Consumption impact category within the SSSD was changed to match the LCIA method implemented by Space Opera. Additionally, the IPCC 2007 model was used for climate change by Space Opera in both figures whilst the IPCC 2013 model was used for the SSSD.

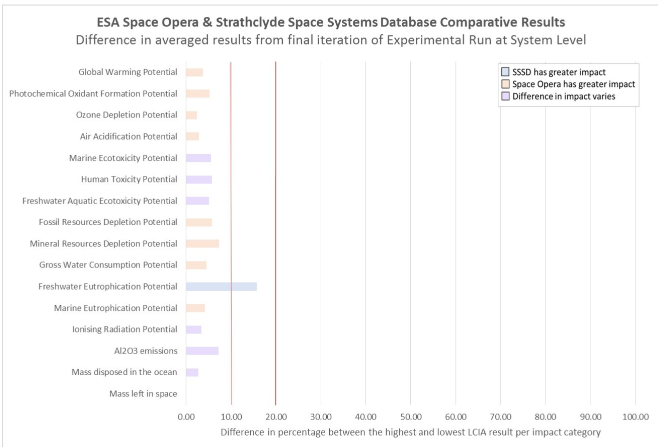
With regards to Figure 5.3(b), out of 16 impact categories 10 have a difference of less than 10% whilst 13 have a difference of less than 20%. This means that 3 out of the 16 impact categories have a difference of over 20%. These impact categories are Human Toxicity, Freshwater Aquatic Ecotoxicity, and Freshwater Eutrophication. Of these, Freshwater Aquatic Ecotoxicity has the largest difference in results at 30.86%, closely followed by Freshwater Eutrophication at 25.69% and then by Human Toxicity at 21.80%. In addition to these, the impact categories which have between a 10% and 20% difference in results are Ionising Radiation, Marine Ecotoxicity, and Photochemical Oxidant Formation. In fact, each of these just narrowly breaches the lower limit, with differences of 10.00%, 10.36% and 10.47% respectively. The overall margin of error was also calculated for each mission in terms of the average percentage in difference between results across all impact categories. This showed that the average difference in results was 7.61% for Generic Mission One, 4.55% for Generic Mission Two, and 14.21% for Generic Mission Three which led to an overall system level average of 8.79%. The overall averaged difference in results for all 3 generic missions at phase level was also calculated. This showed that the greatest impact comes from Phase A+B at 44.17%,



(a) Absolute difference



(b) Methodological alignment



(c) Final iteration of experimental run

Figure 5.3: Averaged difference in LCIA results between Space Opera and the SSSD

followed by Phase C+D at 43.11%. Phase E2 and Phase E1 falls within the accepted upper boundary limit at 19.47% and 10.40% whilst there is no difference in results at Phase F.

The aforementioned results were then used within an experimental run to frame the root cause of the areas of significant difference. As such, results were generated for the average difference in LCIA results with alignment of LCIA impact categories where additional criteria that has not been considered in the LCI datasets of both tools has been removed. The outcome of this was to test the influence of the man-hours & travel, ground segment, launch segment and space segment separately. As such, Figure 5.3(c) shows the averaged results from the final iteration of the experimental run at system level. In this case, the results show the comparison when all process flows other than electricity consumption are removed from the SSSD for man-hours during Phases A+B and C+D. This figure provides the absolute difference in LCIA results between the SSSD and Space Opera at mission level by identifying which tool's results were higher or lower across each impact category at mission level. Although at mission level the averaged iteration result does not fall into the category of a significant difference, the result can also be broken down into mission segments. As a result, it was found that each one of these falls into this category meaning that the LCI of each should be investigated.

The overall averaged results for all three generic missions at system level show that from sixteen impact categories, fifteen have a difference of less than 10% whilst only one has a difference of between 10-20%. This impact category is Freshwater Eutrophication which has a difference of 15.69%. The overall margin of error was also calculated for each mission in terms of the average percentage in difference between results across all impact categories. This showed that the average difference in results was 2.99% for Generic Mission One, 4.78% for Generic Mission Two, and 7.30% for Generic Mission Three which led to an overall system level average of 5.02%. The overall averaged difference in results for all 3 generic missions in terms of each segment was also calculated. This showed that the greatest impact comes from man-hours + travel at 39.28%, followed by the space segment at 27.29%. The ground segment and launch segment both falls within the accepted upper boundary limit at 19.47% and 10.33% respectively.

On analysis of these results per mission segment, it was found that although man-hours datasets were aligned to include only electricity processes, man-hours + travel still account for the largest difference in LCIA results. Excluding impact categories with null values, the SSSD predicted a higher impact for every impact category for man-hours + travel except for Ionising Radiation where the predicted difference varies. In terms of the space segment, when considering only the production and manufacturing of spacecraft components, the difference in LCIA results falls to 20.56% from 27.92%. This means that AIT along with the manufacturing and production of propellants and pressurants cause a considerable difference in results, particularly since the LCIA results are in general higher than the production and manufacturing of spacecraft components across all impact categories. Excluding impact categories with null values, the SSSD predicted a higher impact for the toxicity impact categories as well as Gross Water Consumption, Freshwater Eutrophication and Ionising Radiation. Space Opera predicted a higher impact across the other impact categories. In terms of ground segment, there seems to be large differences in electricity processes which are reduced with the inclusion of other elements such as natural gas consumption, water consumption and waste. Global Warming, Photochemical Oxidant Formation and Air Acidification produce varied differences whilst Space Opera predicted larger difference across Ozone Depletion, Fossil Resources Depletion and Gross Water Consumption. The SSSD predicted higher differences for all remaining impact categories when excluding the impact categories with null values. The launch segment was the most impacting segment but where there was least difference with regards to the segments. In this regard, when excluding the impact categories with null values, Space Opera predicted a higher difference in LCIA results across all impact categories except for Al_2O_3 emissions and Mass disposed in ocean where varied differences occurred. Greater details of these differences are provided in the ESA LCI Validation Project Report Presentation [281]. Overall, the number of impact categories for each segment which cause significant differences are documented in Table 5.2 below.

Table 5.2: Breakdown of differences in LCIA results between the SSSD & Space Opera by mission segment

Segment	Impact Categories at or above 10%	Impact Categories at or above 20%
Man-hours + Travel	12/16 (75.00%)	11/16 (68.75%)
Ground Segment	12/16 (75.00%)	6/16 (37.50%)
Launch Segment	9/16 (56.25%)	2/16 (12.50%)
Space Segment	12/16 (75.00%)	11/16 (68.75%)
Mission Level	1/16 (6.25%)	0/16 (0.00%)

According to the applied margin of errors, the information provided in the table above shows that all mission segments (excluding mission level) can be categorised as an area of significant difference. For this reason, it is important to investigate why these differences in LCIA results occurred. From the analysis, several areas of interest have been noted with regards to the LCI inputs. These are summarised below:

- Electricity consumption processes.
- Spacecraft AIT processes.
- Spacecraft production & manufacturing of propellants & pressurants processes.

In terms of the interpretation, no significant issues were identified in terms of the E-LCA studies. The only issues encountered related to the functionality of Space Opera (see Subsection 5.4.2). Similarly, uncertainty analysis and data quality analysis could not take place due to bugs in the Space Opera ecodesign tool and since uncertainty and data quality matrices were only at flow level within the SSSD at the time of this study.

5.4.2 Functionality Analysis

The functionality and performance of the SSSD was tested in comparison to Space Opera in order to identify potential software issues. A SWOT analysis was then used to frame a list of recommendations providing potentially implementable improvement measures for each tool. A SWOT analysis is a strategic analysis technique used for macro evaluations of internal factors (strengths & weaknesses) and external factors (opportunities & threats) [328]. They tend not to focus on specific issues or details but instead create a roadmap which can be used as a basis for more specific analyses in the future. This took place at ESTEC as part of the LCI Validation Project between ESA and the University of Strathclyde in order to highlight factors which may add or deduct value.

This approach was selected based on a study by Jannisar et al. who investigated testing techniques for software development based on a SWOT analysis [329]. Specifically, they suggest that despite the use of verification and validation approaches to assure product quality, defect-free software is not very often achieved. This implies that functionality testing could also be considered as a crucial component of software validation procedures. They also suggested that for subjective assessment of software testing strategies, a SWOT analysis can be used to highlight the strengths, weaknesses, opportunities and threats of available techniques that might eventually improve an organisation's future decisions. This suggests that the SWOT analysis could also be used as a problem report to frame recommendations for future software development. Pesce et al. consider this as one of the best methods to determine functionality and performance issues associated to a software, particularly as one of the main advantages of using a SWOT analysis is that it requires little cost and can be applied to address complex situations [330]. Additionally, Gürel & Tat argue that SWOT analyses should not be seen as a mere list-making exercise, but be used to build a story about the product or process and what action is required [328]. This highlights the importance of successfully aligning internal activities with external realities.

The comparison ran a single ecodesign assessment of a post-CDF study (extracted from the OCDT) called the Large Observatory For x-ray Timing (LOFT) between Monday 12th November 2018 and Friday 23rd November 2018 through both the SSSD and Space Opera. This study was selected for comparison since the intended CDF study (Design for Recycle) which this comparison was to be based on was postponed until 2019. However, it was also found during the assessment that bugs in the Space Opera tool meant that creating a new product system in Space Opera was not possible, which would have immobilised its potential use in a real CDF session anyway. Instead, this meant that the testing took place from studies already implemented in Space Opera which had extracted engineering models already implemented from the OCDT. As such, the LOFT engineering model was selected for comparison since it was used as a test case during Space Opera's development. This means that all necessary information and data has already been extracted from the OCDT to Space Opera and is contained within an existing product system. As such, should a deserialisation error occur, then Space Opera already has the information included within it to continue the functionality testing.

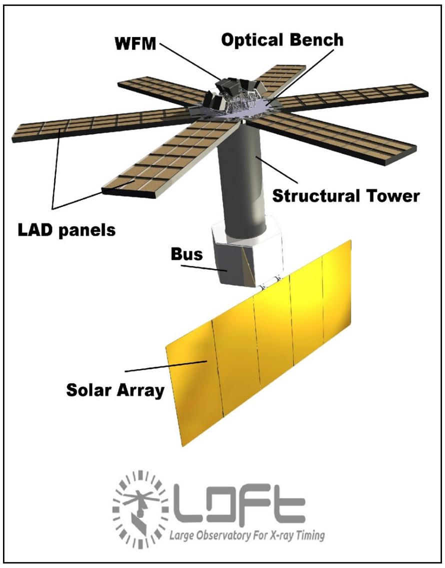


Figure 5.4: Selected engineering model selected for functionality testing [331]

Once the comparison was made, an assessment was conducted on the successes and failures of both tools. Although the functionality testing was based on a comparative study of a single mission, the focus was on the usability of both tools rather than the results. As such, the E-LCA inputs and results from this study have not been recorded (i.e. it was outside the scope of study). The main issues identified during this process were recorded and are listed in Table 5.3 below. This table documents a unique issue identifier number which lists the issues (by number) and by tool (letter). It also describes the finding in terms of identified successes and failures of each tool and a description of these. Overall 14 thematic issues were identified relating to the successes and failures of both Space Opera and the SSSD.

Table 5.3: Qualitative Performance Comparison between Space Opera & the SSSD

Space Opera		SSSD	
Issue No.	***Description of Finding***	***Issue No.***	***Description of Finding***
A1	A new product system cannot be created within Space Opera due to a '500 Internal Server Error'.	*B1*	Each ZOLCA file can be easily imported as a new product system.
A2	Modelling of default and alternative scenarios possible within one product system. Can easily add further scenarios.	*B2*	Modelling of baseline and backup options possible within one product system. Creating additional options possible but laborious.
A3	The tool is web-based and requires connection to the ESA vcdf server in order to work.	*B3*	No internet required and no server access required until LCI results have been exported (OCDT server). As documented in Issue B4, this is currently impossible to do directly.
A4	Due to Issue A1, OCDT importing could not be tested. Instead an already imported OCDT model was used. ESA experts state that under normal circumstances, this import can either take up to half a day or not import at all due to a deserialisation error. As such, the deposition of LCA data to the OCDT could also not be tested.	*B4*	It is not yet possible to import OCDT models to the SSSD. This is planned future work. Instead, datasets have to be added to product systems manually which is majorly laborious. Similarly, it can also not export LCA data to the OCDT. To get around this problem, LCA data can be exported as an Excel file and linked to a custom-made Excel LCA Workbook which connects to the OCDT.
A5	Space Opera (in theory) should implement an automatic interface between the ESA LCA database and OCDT through an import algorithm. However, at present, Space Opera is not linked to the ESA LCA database or its inventories.	*B5*	The SSSD has been developed for use as both an LCA database and an ecodesign tool meaning no access to remote inventories is required since they are already integrated.
A6	Space Opera currently uses its own inventories developed from Sentinel 3B and Astra 1N data. The LCI datasets are implemented directly and include characterised results and not elementary flows based on Ecoinvent v2.2.	*B6*	Since the SSSD has been designed to be an open source tool, the LCIs can be seen visibly including elementary flows. These inventories have been developed within the tool and are based on experimentation, literature reviews and expert input based on Ecoinvent v2.2 & 3.3 and ELCD v3.2.
A7	Excluding data extracted from the OCDT (i.e. payload and platform), all LCI datasets which are part of the product tree are static and new processes which are not already part of the product tree cannot be added. In some cases drop-down lists are applied to specific LCI activity.	*B7*	Although recommended LCI datasets are mapped out in the product tree, these are fluid and can be easily changed, added to or excluded at user discretion – not just by LCI processes included in the product tree.
A8	Formulas used for inventory input seems to be mapped from an external source which cannot be accessed. Changing formulas leads to null-value LCIA results.	*B8*	Formulas used for inventory input is mapped out and can be visibly seen and/or changed by the user.
A9	Space Opera only has chemical propulsion available for section. Additionally, bi-propellant cannot be selected either.	*B9*	Bi-propellant can be selected within the SSSD but electric propulsion has not yet been modelled.
A10	Red flags were present for vast majority of spacecraft components meaning that parameter values could not be extracted from the OCDT. This meant that LCIA results could not be generated.	*B10*	Input values for LCI processes requires manual entry by the user which can be a very lengthy and laborious task (coupled with also the need to manually add each component) depending on how detailed the spacecraft design is.
A11	LCIA results lack breakdown past category headings listed within the product tree.	*B11*	LCIA results provide a detailed breakdown of each LCI dataset to elementary flows.
A12	LCIA results provide environmental impacts at midpoint, endpoint, normalised and single score.	*B12*	LCIA results provide environmental, social, and economic impacts at midpoint, endpoint, single score and sustainability single score.
A13	Uncertainties remain constant throughout the study and not influenced by LCI datasets. Data quality analysis is also not included.	*B13*	Uncertainties and data quality analysis are still in the process of being implemented within the SSSD.
A14	When attempting to export results via excel an error occurs due to a '500 Internal Server Error'. Additionally, when trying to export via email, the email does not arrive.	*B14*	Results export is possible via Excel but is in a particular format which is not compatible with the OCDT (see Issue B4).

The aforementioned assessment was used to frame a SWOT analysis and provide a list of recommendations which suggests potential implementable improvement measures for both tools. The magnitude of all the issues identified in Table 5.3 were qualitatively evaluated through value judgement in order to frame the SWOT analysis which can be found in Table 5.4 below.

Table 5.4: SWOT Analysis Results

(a) SWOT Analysis of Space Opera

Strengths	Weaknesses
• Modelling of various scenarios possible. • Connecting to the OCDT allows for the quick and effective measurement of environmental impacts without adding a resource burden. • First ever space-specific inventories to have been created based on primary data. • Inventories provide input over a wide-range of spacecraft components and other space-specific processes. • Modelled to be highly user friendly for systematic implementation of space LCA during CDF studies. • LCIA results highly useful to assist decision-making and ecodesign. • Potentially confidential data contained within inventories remains restricted even to the user.	• New product system cannot be created. • OCDT model cannot be imported due to a decentralisation error. • Inventories not connected to ESA LCA database and uses an outdated background database. • Inventory based on specific missions. • Difficult to deviate from default product tree. • LCI inventory processes not detailed and cannot be changed or manipulated. • Restricted dataset selection from drop-downs. • Deserialisation error means LCIA results of spacecraft components cannot be generated. • LCIA results lack detailed breakdown. • Only characterised results are visible and not elementary flows. • Uncertainty analysis is non-functional and data quality analysis is not included. • Exporting LCIA results is not possible.
Opportunities	**Threats**
• First tool of its type to exist worldwide. • User handbook available. • Importance of ecodesign rising externally and ESA are seen as leaders in field. • Ecodesign may become a requirement within CDF sessions in ESA.	• Tool currently not available to industry. • Numerous bugs in tool has meant that no successful demonstrations have ever taken place and as such the tool does not get used. • Lack of time within ESA and a lack of funding for the tool's development.

(b) SWOT Analysis of the SSSD

Strengths	Weaknesses
• New product systems can be easily created. • Does not rely on third party tools/processes (i.e. no internet or server connection required). • All inventories are transparent and visible within the tool. • The LCI datasets used are fluid and can be easily changed, including their formulas. • LCIA results are extremely detailed from mission level results to elementary flows. • The SSSD is currently the only tool in existence to measure the life cycle impacts relating to all sustainability dimensions (environment, society and economy) for space systems.	• Modelling of various scenarios possible but difficult if required beyond two design scenarios. • OCDT model currently cannot be imported. • Inventories have been created from a variety of sources (not all primary) and the background database used is now outdated. • The SSSD has much less LCI datasets than Space Opera and these are also much more generic. • Manual entry required for spacecraft components and values which is time consuming. • Its use requires due care and attention by user which should be guided by the user handbook. • Uncertainty analysis and data quality analysis is not yet possible. • Whilst the LCIA results are capable of being exported, they require manual manipulation to convert them into a usable format.
Opportunities	**Threats**
• Tool to be made available to industry open-source subject to an end-user licence agreement with paid-for add-ons. • User handbook and Ecodesign Excel Workbook available. • Ecodesign has become a requirement for CDF studies at the University of Strathclyde. • The SSSD has a 6 year future plan where future PhD students will work to further its development.	• Proof of concept already achieved for a post-mission analysis and CDF study. • Only a handful of students will work on the development of the SSSD and their success will largely depend on available funding (which is not yet defined). • For the environmental dimension, this could be seen to be duplicating work already done by ESA.

Based on the SWOT analysis, value judgement was again used to identify potential areas of improvement for the SSSD. This formed a list of potential implementable improvement measures which are discussed further in Section 7.3 and Section 7.4.

5.4.3 Discussion of Findings

Although the majority of LCI datasets were validated, careful communication of results is required since the comparability analysis highlights that the sum of all mission segments play a larger role in 'levelling out' mission level LCIA results in comparison to Space Opera (i.e. suppressing differences). Since so many LCI datasets have been validated, it raises a question as to why there were such vast observable differences in LCIA results for some segments within the E-LCA comparisons. As such, these results can be considered alongside the LCI validation investigation results to help to identify why these differences occur, particularly for the noted areas of interest. From this qualitative exercise, it is hypothesised that this is due to a number of reasons including:

- Outdated background databases.
- Accuracy of characterisation factors.
- Accumulation of LCI differences in upstream / downstream datasets coupled with slight LCI differences in foreground datasets.
- Large LCI differences in foreground datasets.

With particular reference to the first point, whilst running the GreenSat ESA E-LCA study, Thales Alenia Space found that differences in LCIA results ranged from -50% to +159% per impact category when using Ecoinvent v2.2 compared to v3.2. When integrating the ESA E-LCA database into Ecoinvent v3.2 they found that this difference widened to between -50% and +179% [83, 332]. Since Space Opera is based on Ecoinvent v3.2 and the SSSD is based on Ecoinvent v3.3 & v2.2, this suggests that variations in database versions could be a major contributor to the difference in LCIA results which were observed during the project.

The second point relates to observed differences in characterised results. It is theorised that this may have occurred due to two reasons. The first involves variances in LCIA models (e.g. IPCC 2007 used by Space Opera and IPCC 2013 used by the SSSD). This has the potential to cause considerable differences in LCIA results due to the different or updated CFs used. The second reason related to which elementary flows have been included as part of Space Opera's characterised LCIA results. No documentation could be found relating to this which causes great uncertainty.

With regard to the last two points, since the FU and system boundaries for each E-LCA comparison are directly aligned (including LCI dataset inputs and LCIA methods), this suggests that result variance could also be caused by differences in input data or values contained within each LCI dataset process. This could also relate to differences in location or the materials, processes or services used. For example, when considering the LCI dataset for a 1 m^3 spacecraft container it was found that Space Opera focuses on one made from steel whilst the SSSD is based on aluminium [281]. As this difference was identified, this LCI dataset was not used within comparability analysis. However, unnoticed differences in other LCI datasets have the potential to cause vast variances in LCIA results. Such differences will only be amplified if used in downstream processes where slight variances occur regarding input values of upstream processes. This could not be tested since the Space Opera LCI is currently not connected to the ESA E-LCA Database whilst inventory inputs and outputs remain 'hidden'.

In terms of limitations to the analysis, new scenarios could not be created meaning that a study model which already had OCDT import information had to be adopted for use. Using a previously imported study model limited which spacecraft components could be analysed. This problem was unavoidable. Additionally, Space Opera could not break results down past phase level so the impacts of specific LCI datasets could not be directly investigated. To address this, datasets were systematically removed from the analysis to investigate individually. Through experimental run iterations, the effect of this highlighted their impact at mission level. Uncertainty and data quality analysis could also not be conducted due to bugs within Space Opera and since the SSSD did not have data quality matrices in place at flow level. However, this was not considered to be a major limitation for the purposes of this comparison.

Despite these limitations, it was considered that accurate and representative comparisons were achieved which have been communicated clearly and without bias. Errors were also scoped out in the LCIA methods within the SSSD and unit allocations of LCI datasets were also refined within the SSSD to be more comparable. As such, this approach is capable of identifying LCI datasets which have the potential to cause large differences in results at system level and limits the risk of the validator not detecting a material discrepancy over a very large system.

With regards to the functionality analysis, no major issues were identified within the SSSD that would prevent the tool from transitioning towards beta testing. Overall, the analysis highlighted the fact that whilst the SSSD provides a far more simplistic method for facilitating sustainable design, it eliminates the need for an import/export algorithm which is a major bug plaguing the use of Space Opera at present. However, one of the main drawbacks of this approach is that it is far more labour intensive than Space Opera and provides scope for human error. Additionally, the SSSD is not as large or as reliable as Space Opera and uncertainty analysis is currently not possible at system level. Overall, when comparing these findings against the criteria-based assessment to measure software quality outlined within the ISO/IEC 25010:2011 Systems and software engineering — Systems and software Quality Requirements and Evaluation (SQuaRE) — System and software quality models standard [333], it was found that usability, sustainability and maintainability of the SSSD was sufficiently defined.

In terms of analysis limitations, bugs in Space Opera meant that a new study could not be started. This meant that studies had to be based on previously successfully imported OCDT models and could not take place in a CDF study meaning that the strengths and weaknesses of the OCDT import algorithm could not be determined. However, besides this, particular strengths and weaknesses of both tools were noted and a detailed SWOT analysis of both tools was produced to provide a report to ESA and the University of Strathclyde on the successes and problems of both tools. Recommendations on implementable improvement measures for each tool were also issued for their continued development. These are discussed further in Section 7.3 and Section 7.4.

Both of these analyses were completed within the time frame of the project and to an acceptable standard to ESA and the University of Strathclyde [281]. The project has indicated the strengths of each tool and provided additional evidence to support an essential requirement of the ISO 14040:2006 & 14044:2006 standards in terms of data quality and validation. The results from both analyses (combined with the LCI validation results) demonstrate that the SSSD can be considered to be a valid, practical and dependable sustainable design tool for use within concurrent engineering sessions of space missions. In this regard, in addition to the identified similarities and differences between each tool, the project has also highlighted many previously unknown areas of weaknesses which can be improved upon for future use. The results from this process can also be used to update SSSD LCI datasets and processes which either displayed a limited level of assurance or could not be validated. As such, it is suggested that ESA do the same for Space Opera and the ESA E-LCA Database.

A letter provided by ESA giving permission to the current author to disclose the results generated during his time working with the Clean Space Initiative (between 17 September 2018 and 14 December 2018 at ESTEC in Noordwijk, Netherlands) in their current form as presented within this thesis is provided in Appendix C.

5.5 Chapter Summary

Methods to integrate the SSSD into the concurrent design process of space missions have been investigated. A more simplistic approach to establish a connection between the E-LCA database and OCDT was developed in comparison to Space Opera. However, as highlighted through the functionality analysis, this approach is capable of facilitating the complete sharing of data which is currently not the case with Space Opera due to the bugs that it contains. Methodologically, several challenges relating to the implementation of sustainable design have been outlined based on the findings from the alpha testing. Solutions have been suggested for these issues as a potential method to help streamline the application of the space-specific LCSA framework within concurrent design sessions. The comparability analysis highlighted that the LCIA results are very similar between the SSSD and Space Opera at system level, but greater disparities were obvious within other mission segments. As such, it was clear that the sum of these segments suppressed these differences. No significant functionality issues relating to the SSSD were identified meaning that the tool was considered to be ready for beta testing within a real concurrent design environment.

Chapter 6

Designing Sustainable Space Missions

6.1 Chapter Overview

The ability of the SSSD to function within a concurrent design session has been theoretically verified through alpha testing. However, in order for the SSSD to actively contribute to the sustainability remit, it is imperative that the tool is successfully integrated within early mission design sessions. This allows decision-makers to measure and address adverse life cycle sustainability impacts of design choices whilst directly addressing the issue of a lack of practical demonstrations showcasing best practice for LCSA identified in Subsection 3.5.1 as being a major methodological of LCSA.

As such, the SSSD has been applied within two real mission design sessions which were used as case studies in order to demonstrate the use of the SSSD as an enabler of the space-specific LCSA framework. These case studies are the MÌOS and NEACORE CDF studies which were designed at the University of Strathclyde's CCDS. The MÌOS case study was used as a first test case for the SSSD in a post-CDF scenario (i.e. providing results at the end of the study) before being used more systematically during the NEACORE mission. The results from these studies have been provided within this chapter in order to highlight the successful integration of the SSSD within the concurrent design process and its importance as a decision-making tool.

6.2 MÌOS Case Study

In September 2017, the University of Strathclyde participated in the first ESA Academy concurrent engineering challenge in order to teach students about the concurrent engineering approach. This was the first CDF study to be run within the CCDS, so also acted as a test case to assess the functionality of the facility. The challenge tasked students to design a small satellite mission to the Moon in order to collect data on the micrometeorite and radiation environment and detect the presence of water/ice on the Lunar South Pole in view of a future Moon base. Coming up against Universidad Politécnica de Madrid and Politecnico di Torino as well as a group of students led by a team of ESA experts, a group of 18 University of Strathclyde engineering students from across the Faculty of Engineering produced a solid and sound design concept called MÌOS (Moon Ice Observation Satellite) that satisfied all mission requirements (Table 6.1) with ample margins. At the final review, the University of Strathclyde were the only team with no major design flaws.

Table 6.1: Mission Objectives & Requirements for the MÌOS Mission

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

The final MÌOS Phase 0 Baseline design had a wet mass of 286.04 kg including mass margins and the launch adapter. According to the mission requirements, this was 13.96

kg within budget. The mission consists of a single satellite in a frozen lunar orbit with a maximum eclipse of 160 minutes. It is sun pointing for most of the lunar orbit with a minimum altitude of 82km and maximum altitude of 119 km at the Lunar South Pole. The mission concept uses a narrow angled camera for taking pictures of the water/ice content and a wide angled camera for the radiation/micrometeorite environment. The configuration of the components used can be seen in Figure 6.1 below.

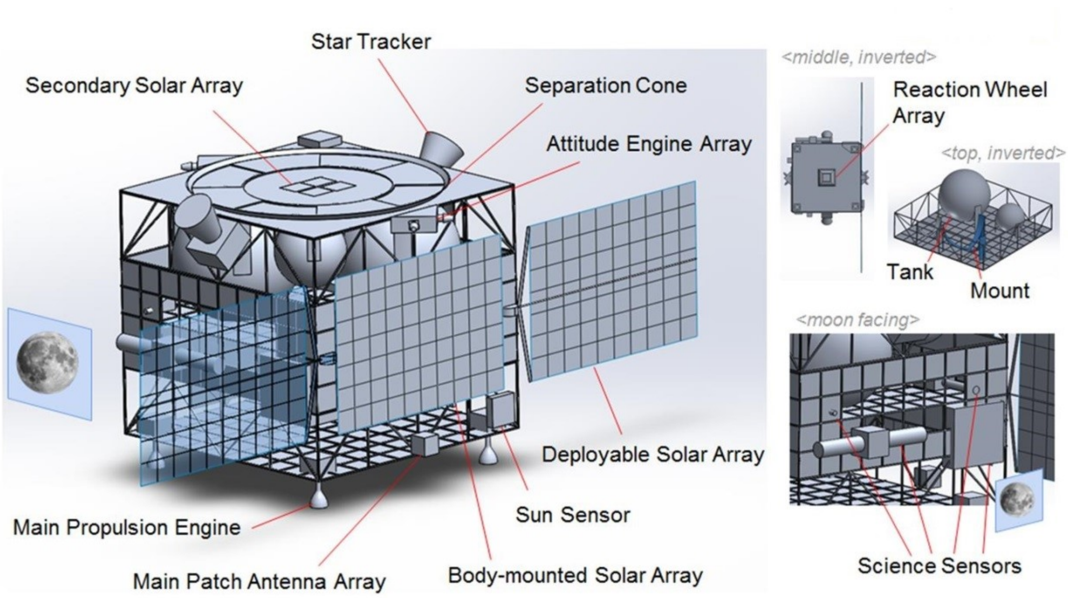


Figure 6.1: Final Phase 0 Baseline Design of the MÌOS Mission

This mission design was selected as a first test case for the SSSD to assess the sustainability impacts of a space mission. For this reason, a post-CDF LCSA study was performed in order to inform decision-makers of the potential sustainability impacts of the MÌOS concept before any further iterations/design sessions are to occur. As part of this study, the life cycle impacts of the MÌOS baseline design will firstly be investigated and then compared to an adaptation of the same model where two predetermined 'sustainable design' options have been implemented. The first of these options targets the most substantial hotspot within MÌOS baseline design identified from the greatest impacting sustainability dimension according to MCDA. The second was chosen by the Director of the Aerospace Centre of Excellence at the University of Strathclyde and involves replacing the propellant with a high performance green propellant (HPGP) to test if there is a case for this switch within future design sessions of the MÌOS mission. Therefore, the study will investigate the collective influence of these options on LCIA results across the dynamic elements and at mission level. As such, the purpose of the study is to test the ability of the SSSD to perform sustainable design whilst demonstrating the applicability of social and economic criteria within this process.

6.2.1 Scenario A: Baseline Design

As previously stated, the purpose of the study is to inform decision-makers of the potential sustainability impacts of the MÌOS concept before any further iterations/design sessions occur. The goal of Scenario A is to assess the full system level life cycle sustainability impacts of the MÌOS mission through a post-CDF LCSA study. The FU has been set as "one space mission in fulfilment of its requirements". The system boundary for Scenario A is identical to that of the one suggested by the ESA E-LCA guidelines as provided in Figure 2.4. The only exception to this is the production of launcher components & propellants and stage assembly which now occurs at Phase E1 where the launch segment was considered to enter the product system rather than at Phase C+D as outlined within the ESA E-LCA guidelines.

The SSSD was used to calculate both the LCI and LCIA results. For the static elements, data was collected primarily based on SSSD default values and well-judged estimations for the mission type established from the information collected during the HATHI study. Despite this, some static elements were influenced by the dynamic elements (e.g. location and use of ground stations) and mission requirements (e.g. type of launcher). In particular, to fulfil MIS-R-03 it was assumed that the MÌOS mission would be launched with the other three missions designed as part of the ESA Academy Concurrent Engineering Challenge. Therefore, the mission was attributed a 25% share of total launch segment impacts. For dynamic elements, the data collection was based on information contained within the MÌOS engineering model saved on the OCDT and the final presentation of the MÌOS mission. Mass margins were also included within the analysis at both system and subsystem level.

For the social impact, 31 different stakeholder groups were identified including the University of Strathclyde, ESA, ArianeGroup plus 28 other organisations. However, since the SSSD does not currently hold social LCI data, social impacts were calculated using freely-available averaged national-level data to represent organisations based on their country of operation. This was considered appropriate since Siebert et al. states that "an organisation's conduct is highly influenced by national and regional socio-economic conditions" [334]. Social impacts were calculated for all stakeholders for the stakeholder categories of 'worker' and 'value chain actors'. The reason for this is because S-LCA is applied at organisational-level meaning that it is likely that the stakeholder categories of consumer, local community, and society may have less direct impacts than worker and VCAs [335]. Despite this, the University of Strathclyde, ESA and ArianeGroup were calculated more fully based on online resources such as corporate sustainability reports where applicable.

Table 6.2: MÌOS mission baseline option E-LCA LCIA results

Impact Category	Result	Unit
Air acidification	6.18E+04	kg SO_2 eq.
Al_2O_3 emissions	3.96E+04	kg Al_2O_3
Climate change	1.12E+07	kg CO_2 eq.
Critical raw materials	5.81E+03	kg mass
Disposal to ocean	2.41E+04	kg mass
Economic impact	1.19E+08	EUR 2000
Energy consumption	2.22E+08	MJ
Eutrophication (freshwater)	6.72E+03	kg P eq.
Eutrophication (marine)	1.09E+04	kg N eq.
Ionising radiation	5.23E+06	kg U^{235} eq.
Ozone depletion	2.17E+04	kg CFC-11 eq.
Particulate matter formation	5.41E+04	kg PM_{10} eq.
Photochemical oxidation	3.08E+04	kg NMVOC
Re-entry smoke particles	0.00E+00	kg RSP
Resource depletion (fossil)	1.42E+08	MJ fossil
Resource depletion (mineral)	2.58E+05	kg Sb eq.
Social impact	7.70E+08	Social score
Toxicity (freshwater aquatic)	6.93E+07	PAF.m^3.day
Toxicity (human)	1.88E+03	cases
Toxicity (marine)	3.27E+10	kg 1,4-DB eq.
Water consumption	5.80E+07	m^3

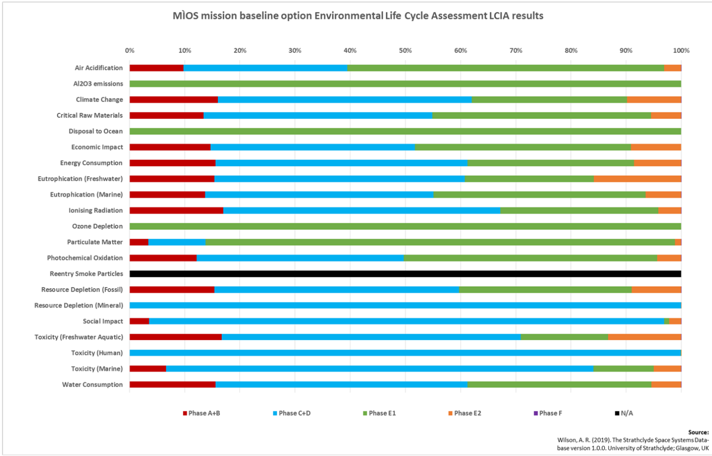
The selected E-LCA impact categories can be found in Table 6.2 above along with the LCIA results and their unit of measurement. Single score S-LCA and LCC results were also used as impact categories within the E-LCA since both assessment types are scored using a common unit of measurement. Whilst these results provide a good overview of the life cycle sustainability impacts of the MÌOS mission, to provide a better breakdown of the social and economic results, full LCIA results for each can be seen in Figure 6.2. In this regard, the social LCIA results provide results according to each stakeholder subcategory group whilst the economic LCIA results provide results according to types of cost.

From this, it is clear that by far the largest social impact comes from the 'Working Hours' stakeholder subcategory (which produces 29.30% of total social impact). This was based on a survey conducted as part of this research at the University of Strathclyde which found that the working hours of PhD students and academics within the Department of Mechanical & Aerospace Engineering was generally higher in real-terms than reported by the university. Whilst at ESA during the ESA LCI Validation Project, similar working patterns were also observed. This trend led to the establishment of a factor which was applied to average working times reported by each country based on OECD data [336]. As such, it was found that a very high risk factor was assigned to most countries which was the primary reason for this score. The highest VCA stakeholder subcategory was 'Promoting Social Responsibility' which produced 9.25% of the total social impact. This score was based on information contained within a report titled 'Global trends in sustainability reporting' which highlighted the number of reporting instruments identified by country [337].

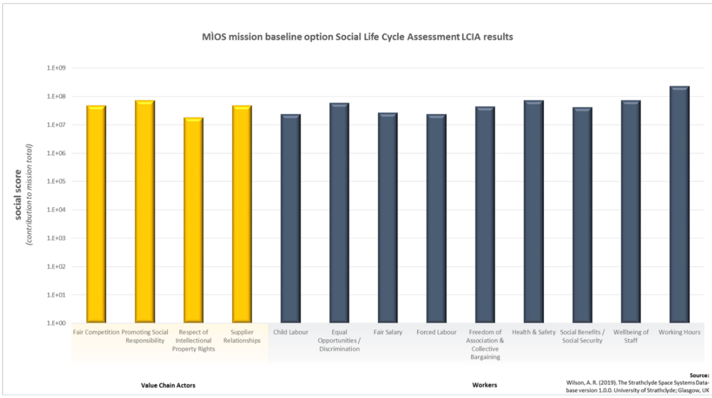
In relation to the SDG social LCIA method, the top 5 most affected SDGs represents 79.41% of the total social score. The most impacted was Goal 16 (Peace, Justice & Strong Institutions) which contributed 31.83% of this score. This was principally because this SDG was included within almost all VCA and worker social indicators. After this, Goal 8 (Decent Work & Economic Growth) and Goal 10 (Reduced Inequalities) produced 20.64% and 12.60% of the total social score. These are mainly driven by the worker stakeholder categories, although the VCA subcategory of 'Promoting

Social Responsibility' has a slight influence on these SDGs (<10% each). Therefore, it can be seen that Goal 8 and Goal 16 accrue >50% of the total social score. Somewhat unsurprisingly, both of these SDGs are the only ones to be included within the 'Working Hours' stakeholder subcategory which is another reason why these may have been more affected than others. Thereafter, Goal 17 (Partnerships for the Goals) is the fourth most affect SDG, providing 8.72% of the total social score. This SDG is driven completely exclusively by the VCA stakeholder categories since the goal is attributed to all VCA social indicators. Goal 12 (Responsible Consumption & Production) is the final goal to make up the top 5 most affected SDGs of the MÌOS mission. This contributed 5.62% respectively which is exclusively due to the 'Promoting Social Responsibility' and 'Supplier Relationships' VCA stakeholder subcategories. As such, these five SDGs could be seen as social hotspots of the MÌOS mission based on the SDG social LCIA method.

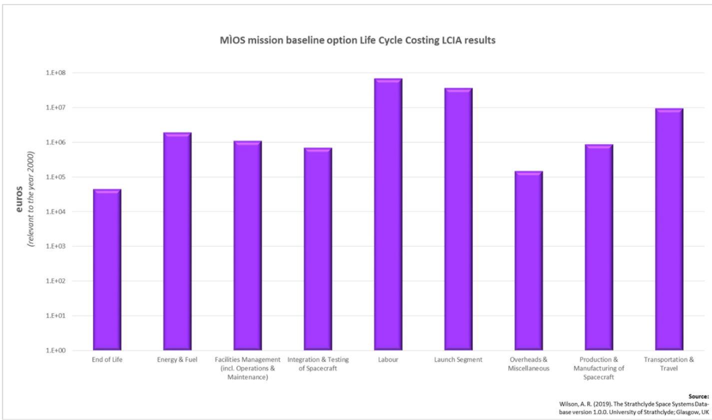
In comparison, it can be seen that the majority of costs arise from labour (6.89E+07 EUR 2000), closely followed by the launch segment (3.61E+07 EUR 2000) and transportation (9.30E+06 EUR 2000). The reason for the high cost of labour was directly attributable to ESA being assigned as the cost bearer since this was an ESA mission design study. As such, it was assumed that ESA would be responsible for the cost of the design and the production & manufacturing of the space mission. The cost of launch segment relates entirely to acquisition of the Ariane 5 ECA launcher which was the second most impacting cost element. However, this cost was somewhat minimised by the fact that the mission was attributed a 25% share of total launch segment impacts. This was because it was assumed that the MÌOS mission would be launched with the other three missions designed as part of the ESA Academy Concurrent Engineering Challenge in accordance with MIS-R-03. Transportation also had considerable costs attached to it. In this regard, the costs related to the shipping of both the spacecraft and launcher components to the ESA launch site in Kourou, French Guiana and the air travel involved for staff/expert participation in space mission design sessions and launch event activities. As such, these cost elements can be seen to be economic hotspots of the MÌOS mission.



(a) Environmental Life Cycle Assessment Results



(b) Social Life Cycle Assessment Results



(c) Life Cycle Costing Results

Figure 6.2: Life Cycle Impact Assessment Results of the MÌOS Mission

These results also acted as a first test case for applying MCDA at mission level. The MAVT technique was firstly applied to the five key environmental hotspots of space missions which were identified by the ESA Clean Space Initiative (climate change, fresh-water ecotoxicity, human toxicity, mineral resource depletion and ozone depletion) [33]. Using the adapted JRC environmental NFs contained within Table 4.24 for each of these impact categories, the impact per EU citizen could be obtained as a normalised value for E-LCA based on the annual impact magnitude per EU citizen. By multiplying these values with the reformulated EC's meta-weighting factors (re-weighted to reflect less impact categories) also contained within this table and the SSSD sustainable design workbook, a score reflecting performance for E-LCA was obtained. Similarly, normalisation was also applied to both the S-LCA and LCC single scores based on the values contained in Table 4.24. Using these figures as the score reflecting performance for each sustainability aspect, the MAVT technique could be applied with respect to the SDG WFs outlined in Table 4.25 which acted as the 'importance factor' of each pillar. Overall, it found that the final importance of impact magnitude per EU citizen for the entire sustainability score is 1.66E+05 which is composed of 1.50E+05 environmental impact, 1.22E+04 social impact and 4.04E+03 economic impact. An overview of these results for the MÌOS baseline design can be found below in Figure 6.3 in terms of relative and absolute scores.

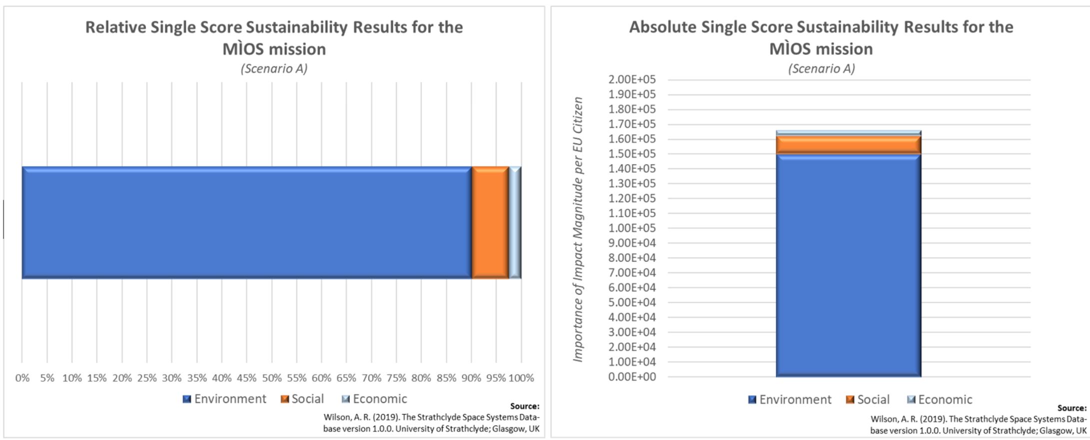


Figure 6.3: MÌOS Mission baseline option MCDA results

In terms of interpretation, the MCDA results clearly indicate that E-LCA should be considered to be the most important sustainability dimension to address. Environmentally, the majority of this impact came from mineral resource depletion (59.98%) which is directly attributable to the use of germanium in solar cells. Other high scoring impact categories were human toxicity (20.18%) and ozone depletion (19.71%). The former result is largely due to the manufacturing and production of the launcher propellants and dioxins released during the production & manufacturing of the germanium substrate for the solar arrays. The latter result was almost entirely due to the launch event. Both climate change and freshwater aquatic ecotoxicity scored less than 0.1% each, indicating that they should not be classed as hotspots. As such, it is recommended that the next iteration of the MÌOS study identifies and implements solutions to these established environmental concerns in line with the space-specific LCSA framework outlined within Subsection 3.5.4. In particular, since the production & manufacturing of the germanium substrate used within the solar arrays has been identified as the driving force behind these impacts, this hotspot has been selected as a target area for sustainable design measures within Scenario B. This is in addition to switching the propellant used to a HPGP (the other sustainable design option predefined as part of the study criteria). Therefore, according to the results of the MCDA approach, the sustainable design options which will be investigated within Scenario B relate purely to the environmental dimension of sustainability through the implementation of ecodesign solutions.

6.2.2 Scenario B: Sustainable Design

Based on the findings of Scenario A, the first ecodesign option specifically targets the germanium substrate used within the solar array. In particular, a triple-junction GalnP/GaAs/Ge solar cell was used within the MÌOS baseline design which had a mass of 18.84 kg (including mass margins) and conversion efficiency of 30%. However, as stated in Section 2.5, it is important to note that applying ecodesign through concurrent engineering is mostly applicable at system level. This means that addressing impacts at equipment, component & material is outside the scope of application. For this reason, since the germanium substrate of solar arrays was identified as the most contributing environmental hotspot, only reduction or replacement options of the entire subsystem can be considered as viable design alternatives. Besides the direct effect that such an approach could offer on the observed environmental impacts, it is also important to ascertain whether such changes will cause significant indirect alterations to different subsystems and the net impact that this will have at system level.

In terms of the second ecodesign option, the MÌOS mission contains 61.2 kg of hydrazine which is the traditional and most commonly used type of spacecraft propellant. However, hydrazine is particularly toxic and now contained on the candidate list of substances to be regulated under the EU's regulation concerning the REACH regulations [338]. In line with the growing push in recent years to find more environmentally benign alternatives to commonly used monopropellants, this means that phasing out hydrazine may become a priority for the space industry. In this regard, LMP-103S is a flight proven HPGP which is marketed as being much less toxic than hydrazine and also non-carcinogenic. More specifically, LMP-103S has a 6% higher specific impulse than hydrazine and is 24% more dense (values based on observations from the PRISMA mission, launched 15 June 2010 [339]). As such, it exhibits a 30% higher density impulse, meaning that less propellant is required in comparison to hydrazine. In relation to the MÌOS mission, this could offer an improved environmental performance through this direct propellant reduction. However, if less propellant is required then alterations or redesigns of other subsystems may be required which could also indirectly affect the overall spacecraft mass and environmental impacts.

Therefore, the goal of Scenario B is to assess the effects of implementing both of these ecodesign options on dynamic element results and the system level MCDA results of Scenario A. In terms of the dynamic elements, the FU has been set as "the production & manufacturing of spacecraft components and propellants". The system boundary therefore covers all material inputs, production & manufacturing processes and electricity consumption relating to the FU of each component and propellant, including waste disposal and transportation. The FU and system boundary for the system level MCDA results is identical to that of Scenario A. With reference to the

LCI, when redesigning the MÌOS mission to include both of these ecodesign improvement measures, there are a variety of different parameters that need to be considered. The required changes were assisted, analysed and verified by MÌOS study participants and saved as a backup to the MÌOS engineering model on the OCDT. This analysis was constructed based on dedicated LCI datasets contained within the SSSD. Most processes used were created based on secondary data (literature reviews), details of which can be found within the SSSD.

Internally, it was decided that a 20% reduction should be targeted for the mineral resource depletion and human toxicity impact categories within Scenario B in order to produce meaningful reductions. Clearly, this will most likely be driven by the first ecodesign option since it was found that these impact categories were the leading cause of the high MCDA score observed, primarily due to the germanium substrate within the solar array. In line with this requirement, the solar array was downsized by 21.71% from 18.84 kg to 14.75 kg. Directly, this simply reduces all environmental, social and economic impacts of that component by 21.71% since impacts of spacecraft components are scaled linearly within the SSSD according to mass. This cut in mass also led to further system redesigns including reductions to the solar array deployment mechanism, array tilt mechanism and torsion springs by around 8.31% on average. Additionally, the battery module was not resized to account for a decreased power supply since this was considered to be a systems issue. Instead, the power budget was balanced accordingly (e.g. deciding which equipment can be turned off and when to ensure sufficient charging of the battery module). Other options were investigated as alternatives to this mass reduction, such as replacing the triple-junction GalnP/GaAs/Ge solar cell with duel-junction cells and silicon-based cells. However, these options were found to provide only 78.34% and 93.24% of the conversion efficiency of the triple-junction GalnP/GaAs/Ge solar cell at the reduced mass size [340]. For this reason, solar array size reduction was considered as the more appropriate ecodesign measure. Therefore solar array replacement was discarded as an ecodesign option so that the technical performance of the system was not hindered any more than was absolutely necessary.

In terms of the second ecodesign option, since this is a replacement strategy, this will be addressed firstly through a direct comparison relating to the production & manufacturing process of 1 kg of hydrazine and LMP-103S to assess which is the more environmentally, socially and economically sensible choice. In this regard, the FU has been set as "the production & manufacturing of 1 kg of propellant". Similar to the dynamic elements, the system boundary therefore covers all material inputs, production & manufacturing processes and electricity consumption relating to the FU of each propellant, including waste disposal and transportation. Overall the LCIA results show that although LMP-103S is marketed as a viable green alternative to hydrazine, when comparing the production and manufacturing of 1 kg of LMP-103S to the production and manufacturing of 1kg of hydrazine using the SSSD, LMP-103S performed the worst on fifteen out of eighteen impact categories (see Figure 6.4). In particular, hydrazine actually offers average environmental savings of 43.10% per impact category and is significantly cheaper at 144.62 EUR 2000 per kg compared to 722.04 EUR 2000 per kg for LMP-103S. Despite this, LMP-103S has a 22.63% lower social score whilst the Freshwater Aquatic Ecotoxicity score is also lower by 92.28% which is the greatest difference in observed results across all impact categories.

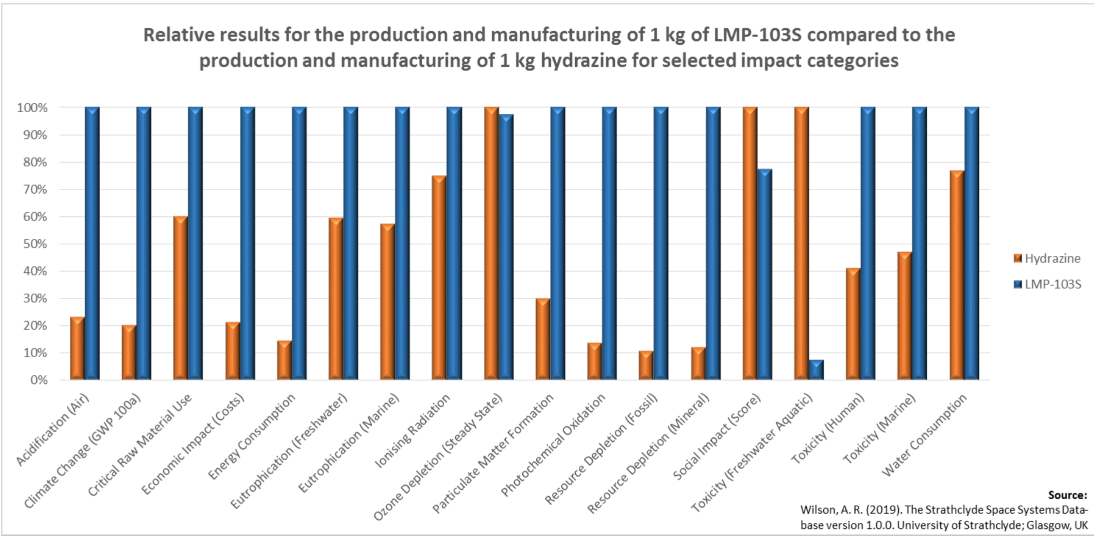


Figure 6.4: Relative results for the production and manufacturing of 1 kg of LMP-103S compared to the production and manufacturing of 1 kg of hydrazine for selected impact categories

The main reason for the poor performance of LMP-103S compared to hydrazine is primarily due to ammonium dinitramide production. In particular, the influence of nitric acid (from the production of potassium dinitramide), isopropanol and pentane leads to LMP-103S performing significantly worse environmentally than hydrazine when directly comparing the two propellants. These E-LCA results were verified and validated by ESA during the ESA LCI Validation Project. With regards to costs, hydrazine is 577.42 EUR 2000 cheaper per kg due to the fact that LMP-103S is not yet being mass produced. However, mass production is expected to significantly reduce this cost in the future. The social score is one of the only impact categories which LMP-103S scored better. This is primarily due to the risks involved with workers handling hydrazine which is highly toxic. Additionally, as LMP-103S is produced in Sweden and hydrazine is produced in Germany, the workers category of LMP-103S scored significantly better, particularly relating to wellbeing of staff (36.71%) and working hours (33.33%).

Therefore, at face value, these findings would suggest that replacing hydrazine with LMP-103S is unlikely to be a viable ecodesign option. However, this would depend on a variety of performance factors such as direct and indirect mass savings at system level. In this regard, it was found that due to the attributes of LMP-103S, 7% less propellant was required during the MÌOS mission meaning that 0.93 kg of the LMP-103S was required for every 1 kg of hydrazine. As such, this meant that 56.92 kg of LMP-103S was required for the mission compared to 61.2 kg of hydrazine. Based on Figure 6.4, this clearly shows that these mass savings are not enough to offer any significant direct environmental, social or economic benefits. However, as a predetermined requirement of Scenario B, LMP-103S was included within the system redesign regardless of this fact. Despite this, indirectly, this ecodesign option led to a downsizing of the propellant tank by 10.54% but an increase in thruster size by 11.89% due to the combustion temperatures of LMP-103S requiring the need for higher temperature resistant materials to be used [341].

Overall, the implementation of these ecodesign options led to average 'waterfall' mass savings of 5.05% meaning that the total spacecraft wet mass fell from 286.04 kg to 271.59 kg. Based on this redesign, the LCIA results of Scenario B can be seen in

Figure 6.5 below. These show that the MÌOS mission produces average environmental savings of 8.46% per impact category. As can be seen in the figure, the overall impact was reduced on thirteen out of eighteen impact categories whilst the score of only four impact category increased. Additionally, this led to a 26.64% better social performance and a reduction of 6.62E+04 EUR 2000 in costs. With regards to S-LCA, in addition to the direct savings which occur due to the use of LMP-103S, this lower value was particularly influenced by the linear nature of SSSD LCI datasets meaning that it is assumed that a lower mass equates to less time to manufacture and produce. The cost was also influenced by this, due to the nature of CERs.

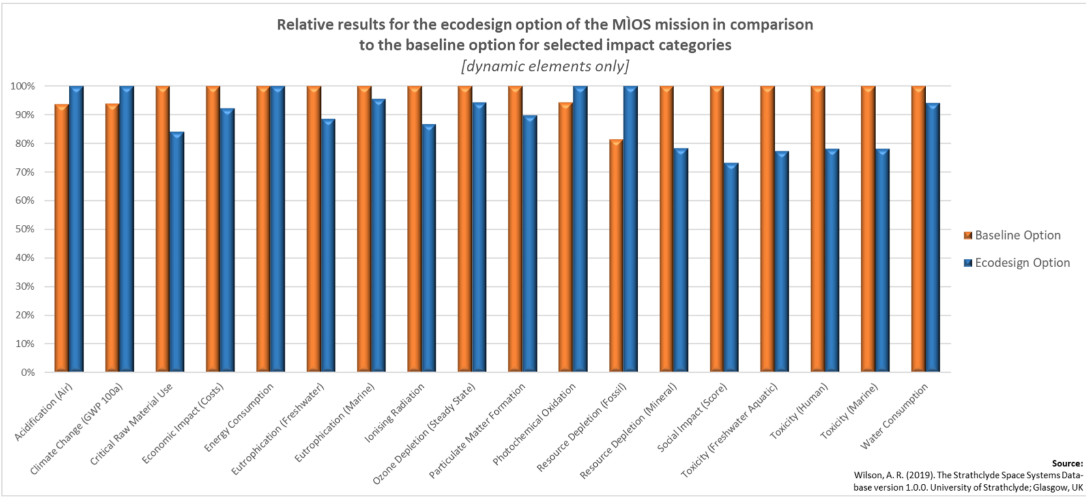


Figure 6.5: Relative results for the ecodesign option of the MÌOS mission in comparison to the baseline option for selected impact categories

As can be seen from these results, the implementation of these ecodesign options on the MÌOS baseline design has clear environmental, social and economic benefits within the dynamic elements. These results largely conform to ESA's findings which highlighted germanium as one of the most important environmental hotspots of space missions. Due to this, various reduction efforts are ongoing at ESA, including the requirement for recycling processes to be included within the strategy of the germanium wafer manufacturer [86]. Additionally, another important study in relation to the MÌOS mission is the GreenSat project which was conducted by Thales Alenia Space on behalf of ESA, concluding in 2019. This project sought to identify environmental hotspots of the Sentinel-3 mission and investigate potential ecodesign options to reduce its environmental footprint. One element examined by the study was the use of hydrazine in comparison to LMP-103S as an eco-design measure [342]. This design alternative was partly chosen based on the principles outlined by the MÌOS study, presented during the 8th International Systems & Concurrent Engineering for Space Applications Conference and the ESA Clean Space Industrial Days in 2018 [111, 332, 343]. Despite the higher theoretical efficiency of LMP-103S compared to hydrazine, it was found that this design solution generally produced greater impacts across the dynamic elements of the GreenSat study. However, it did minimise the obsolescence risks stemming from the REACH regulations and reduced the time that the satellite spent in clean rooms. Overall, this decreased environmental impacts across most impact categories at system level [344]. Although only dynamic elements were captured within Figure 6.5, such impacts can be seen to be captured within the MÌOS mission through the S-LCA results. Therefore, these studies somewhat provide added verification relating to the validity of the MÌOS LCIA results. However, with regards to the overall system level results of the MÌOS mission design, MCDA can also be applied as an additional step based on the 5 hotspot impact categories identified by ESA. The results of this process are provided in Figure 6.6 below.

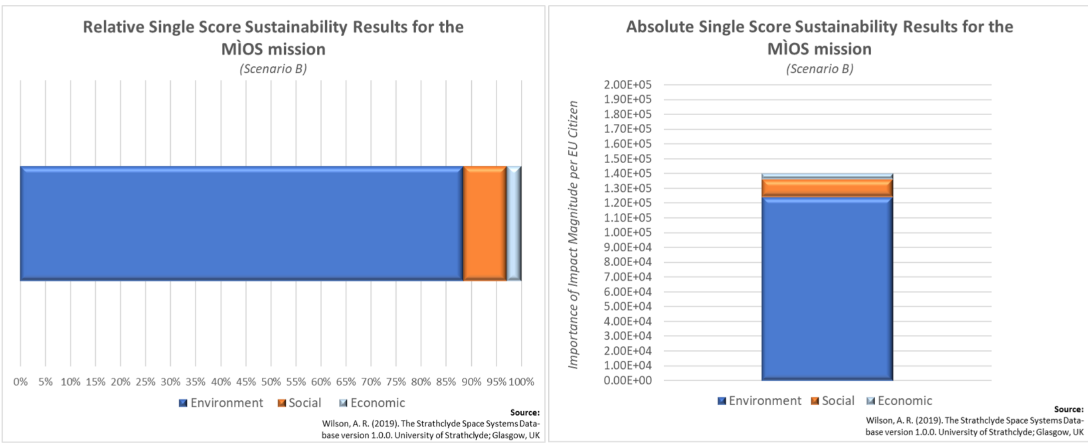


Figure 6.6: MÌOS Mission sustainable design option MCDA results

Overall, it is found that the final importance of impact magnitude per EU citizen for the entire sustainability score is 1.40E+05 which is composed of 1.24E+05 environmental impact, 1.22E+04 social impact and 4.03E+03 economic impact. As such, it can be seen that E-LCA should still be considered as the most important sustainability dimension to address within the next iteration of the MÌOS study. It was also found that the environmental hotspots identified within Scenario A are still the most impacting environmental contributors, despite having been significantly reduced. In particular, there were noticeable reductions within Freshwater Aquatic Ecotoxicity (0.08%), Human Toxicity (21.86%) and Mineral Resource Depletion (21.50%). These reductions relate to the downsizing of the solar array whilst the switch of propellants had no real influence on the result. Since these solar panels used germanium as a substrate, this downsizing meant that less of the substance was used which had a dramatic effect on Mineral Resource Depletion. Additionally, savings in the Human Toxicity impact category relate to lower levels of dioxins being released to air due to the production & manufacturing of the germanium substrate.

6.2.3 Comparative Results Analysis

Although Scenario B offers an improved performance in terms of LCSA results of the MÌOS mission, this is almost entirely due to the reduction of the solar array mass. In relation to the dynamic element results in Figure 6.5, it can be hypothesised that the replacement of hydrazine with LMP-103S actually suppressed the improvements of the first ecodesign option across most impact categories. However, proving this would be extremely challenging since tracing the full indirect impacts to a single ecodesign 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 (like a domino-effect). For example, within Scenario B of the MÌOS mission, the reaction wheels were reduced by 8.25% which was caused by changes to the centre of mass. As such, it is difficult to determine which ecodesign option primarily drove this change since both created reductions in system mass. However, together with the technical performance of spacecraft components, this demonstrates that the indirect effect of design changes are also a key parameter to consider when applying sustainable design to space systems. In this regard, space system components or equipment with poor environmental, social or economic credentials may, in some instances, offer a more sustainable alternative if they can provide an optimised performance at system level or are offset by other sustainable design decisions (as demonstrated within the MÌOS mission). This will not always be the case, but it highlights the importance that a change in design can indirectly have on LCIA results.

When comparing both scenarios at system level using MCDA, it can be seen that Scenario B has a 17.34% lower environmental score, a 0.82% lower social score and a 0.25% lower economic score. Ultimately, this led to an overall reduction of 15.66% in total sustainability score as can be visualised in Figure 6.7 below.

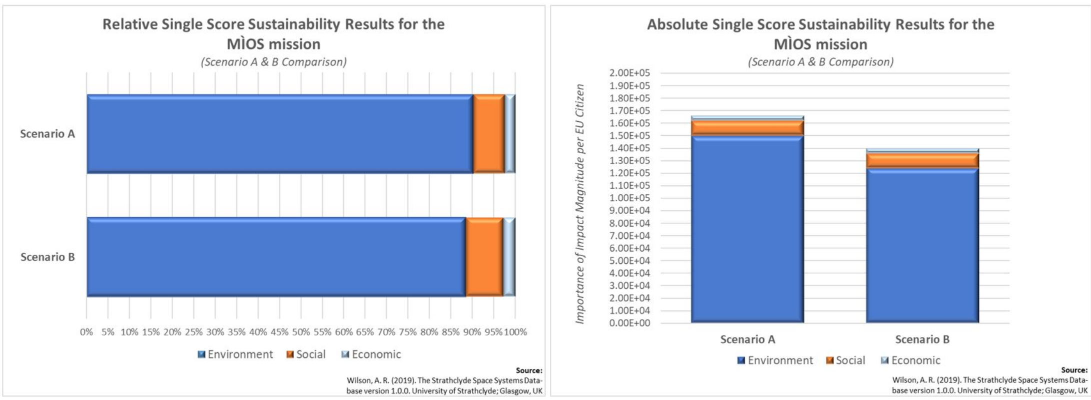


Figure 6.7: MÌOS Mission Scenario Comparison of MCDA results

In terms of limitations, a linking problem relating to the use of CERs was discovered during this study. The linking problem relates to the inability of upstream processes to refer to the applied parametric cost formulas due to the current functionality of openLCA. In this regard, upstream processes scaled the value produced by the formulas rather than only scaling the unit of measurement part of the formula to which costs are being compared (i.e. the quantitative reference). However, this issue was manually corrected using parametric cost formulas in downstream processes to work out the total cost with respect to the input values of the upstream process. As such, this calculated value was then input and scaled to the quantitative reference unit of the downstream process to reflect the scaling up required by the upstream process further along the product tree. Whilst this approach corrected the CER linking issue, it may be problematic if a component is used more than once within a study. Additionally, tracing the full space mission product tree was very time consuming and labour intensive. For this reason, solutions are currently being sought to amend this bug.

This study has demonstrated the significance of applying the sustainable design concept during early phase mission design sessions in order to measure and lower adverse sustainability impacts. It also highlights the applicability of the MCDA approach developed as part of the space-specific LCSA framework to address the multidimensional results of LCSA and reach conclusions. In particular, it is recommended that either the solar array size is reduced further or the germanium substrate is replaced, whilst additional efforts are made to minimise the other identified environmental hotspots within future design iterations. Additionally, whilst other HPGPs could be investigated for use within the MÌOS mission, switching propellants from hydrazine to LMP-103S should not considered as an ecodesign solution. As an outcome of this study, the Director of the Aerospace Centre of Excellence at the University of Strathclyde specifically requested that LCSA should be systematically included within all future space missions designed at the university.

6.3 NEACORE Case Study

With LCSA now included as a mandatory discipline within concurrent design sessions of space missions at the University of Strathclyde, the use of the SSSD could now be tested as part of the design disciplines within a CDF study. The selected study was the Nanosat Exploration of Asteroids by COllision and flyby REconnaissance (NEACORE) mission which acted as a feasibility study for a new concept of nanosatellite mission framework which is intended to allow reconnaissance of a large number of near Earth asteroids while minimising cost. The framework sought to include a significant profit margin for the organising body based on the sale of these nanosatellites to interested parties who would be able to choose their own targets and trajectories and receive all data gathered [345].

This CDF study was part of the first Strathclyde Concurrent Design Challenge which was established to familiarise PhD students with the CCDS at the University of Strathclyde by providing them with an opportunity to learn the concurrent engineering approach. The challenge was also used to trial the CDP-4 and to beta test several concurrent design tools developed at the University of Strathclyde. The mission objectives and requirements were developed with input from ESA, CNES, the Paris Observatory, the MILO Institute, Massachusetts Institute of Technology and various other parties due to their interest in the proposed mission concept. These are outlined in Table 6.3 below.

Table 6.3: Mission Objectives & Requirements for the NEACORE Mission

ID	Statement
MIS-OBJ-01	The mission shall perform several flybys around multiple objects of interests, Near Earth Objects (NEOs), with a nanosat, singular or multiple.
MIS-OBJ-02	The mission shall estimate the relative position, velocity and 2D shape of the objects of interest.
MIS-OBJ-03	An impact shall be performed to generate an observable plume in the case of a formation.
MIS-R-01	The platform shall be flexible and tailorable to different flybys mission scenarios.
MIS-R-02	The mission shall include one to six 12U spacecraft, launched on a single launcher, between 2022 and 2023.
MIS-R-03	Each spacecraft shall contain a camera, and either a LIDAR or a spectrometer. The measurements shall improve the ephemeris by an amount to be defined.
MIS-R-04	The mass budget per spacecraft, including margins, shall be limited to 24 kg. This excludes the upper stage, estimated to a weight of 135 kg (incl. margins) for the Phase 0.
MIS-R-05	The spacecraft volume shall be limited by the launcher envelope, considering that a maximum of 6 s/c with 6 upper stage shall be fitted inside this envelope.
MIS-R-06	Observational data shall be transmitted after each flyby. OBDH should allow the storage of all flyby data from the spacecraft and other spacecrafts of the mission, for the full mission duration.
MIS-R-07	Cost per mission shall be limited to $100M (including all spacecraft, launcher, upper stage and operations).
MIS-R-08	The mission shall rely on Low Thrust Propulsion.
MIS-R-09	The mission lifetime shall be between 3 and 6 years.
MIS-R-10	The bus design process shall indicate which systems can rely on COTS components and which will require novel developments.

Based on these requirements, a common spacecraft platform was designed with a total dry mass of 19.89 kg including a 10% system margin. Two different payloads were considered. The first comprises of LIDAR and a camera with a total dry mass of 2.95 kg including a 10% system margin. The second comprises of a spectrometer and camera with a total dry mass of 1.59 kg including a 10% system margin. When adding these payloads and the propellant mass (1.59 kg) to each option, the total wet mass is 24.44 kg for the LIDAR option and 23.07 kg for the spectrometer option. This also includes a 2% propellant margin. The final configuration of this design can be seen in Figure 6.8.

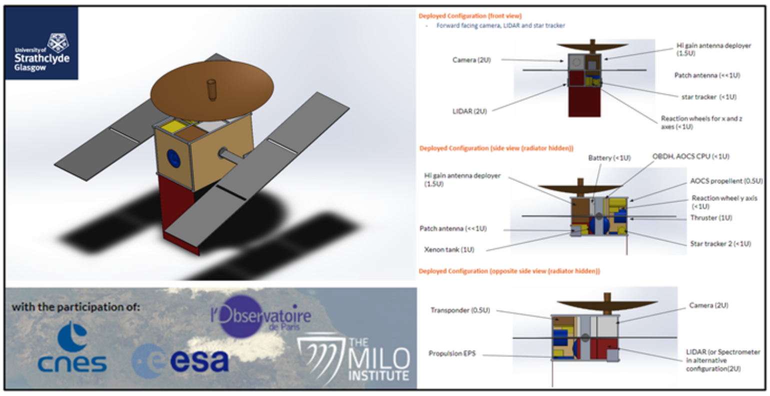


Figure 6.8: Final Phase 0 Baseline Design of the NEACORE mission

6.3.1 Goal & Scope Definition

The primary objective of the LCSA discipline within the NEACORE study was to identify and minimise adverse environmental, social and economic impacts of the entire mission without significantly compromising technical aspects. The LCSA was modelled following the procedures outlined in [4–6, 30, 114, 179, 181, 183, 184, 254]. The generated results are relevant for 6 spacecraft (including system and subsystem mass margins) launched on a dedicated PSLV-CA in 2022 for a mission duration of 4 years and 8 months. Based on this mission definition, the FU was determined to be 'the NEACORE mission in fulfilment of its requirements' for a system boundary covering all activities during each mission phase as outlined below.

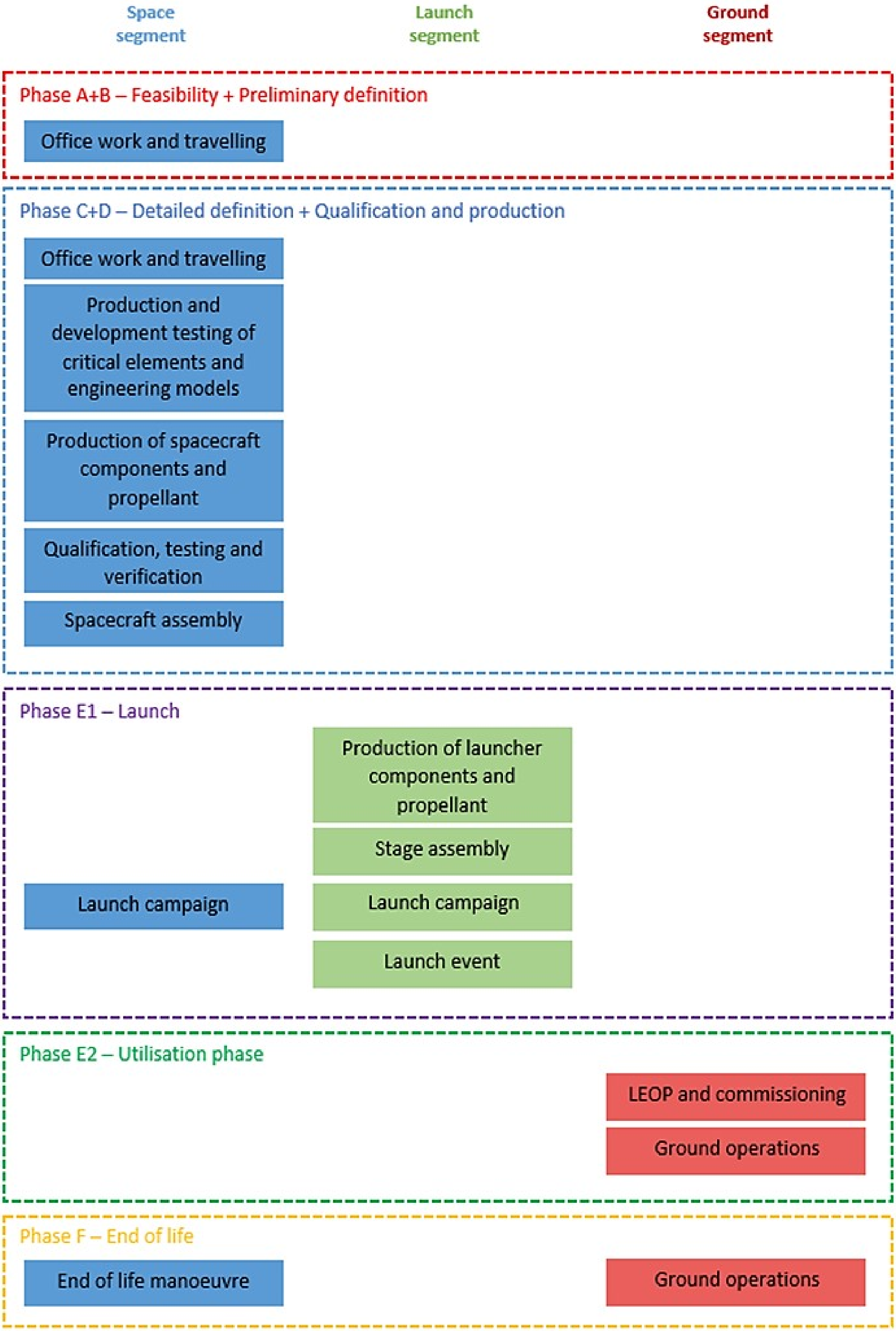


Figure 6.9: System Boundary of the NEACORE mission (adapted from [30])

6.3.2 Life Cycle Inventory Analysis

The data used in this study came directly from information deposited to the CDP-4 during the concurrent design session, expert knowledge and domain-specific default values. The inventory is based upon the use of six spacecraft which would be composed of three with LIDAR payloads and three with spectrometer payloads (i.e. a total mass of 142.52 kg). Social LCI data was gathered at national-level, in a similar manner to the MÌOS study for VCA stakeholder categories. Consideration was also provided to the CER linking error discovered during MÌOS testing to ensure that appropriate corrective measures were put in place to avoid generating vastly incorrect results.

6.3.3 Life Cycle Impact Assessment

The SSSD was also used for the LCIA. For E-LCA, the applied method is based on the SSSD E-LCA midpoint LCIA method with the inclusion of S-LCA and LCC as single score impact categories. The LCIA method used for S-LCA is based on the SSSD S-LCA stakeholder LCIA method. The LCC cost categories LCIA method has been applied for costing impacts.

To analyse the E-LCA results, the impact categories of climate change, freshwater aquatic ecotoxicity, human toxicity, mineral resource depletion and ozone depletion were selected for further investigation since they were identified by ESA's Clean Space Initiative as being 'hotspots' for space missions [33]. In terms of climate change, 37.39% of the impact is due to the carbon dioxide released as part of the launcher production and manufacturing. The launch campaign and AIT are responsible for 20.12% and 17.61% which is mostly due to carbon dioxide released from the use of electricity. For freshwater aquatic ecotoxicity, 34.75% of the total impact came from launcher production and manufacturing primarily due to the release of copper, vanadium and zinc ions. A further 19.99% was caused by the production and manufacturing of the launcher propellant due to sodium perchlorate manufacturing and nitrogen dioxide releases as well as electricity consumption and wastewater treatment. The spacecraft solar arrays alone are responsible for 99.77% of the human toxicity impact. This comes almost entirely from the dioxins and mercury released during the germanium substrate production and manufacturing. The germanium substrate is also responsible for 99.01% of the mineral resource depletion impact since it is a critical raw material. In terms of ozone depletion, the launch event is responsible for 99.99% of the impact, mainly due to ClO_x, HO_x, NO_x and HCl compound releases from the combustion of the solid propellant.

In terms of S-LCA, only the stakeholder categories of workers and VCAs were investigated. Overall, it was found that 85.94% of the total impact rose during Phase C+D. This was principally due to the number of VCAs involved in the production and manufacturing of the spacecraft over a period of two years. In particular, it was found that the VCA stakeholder subcategories of fair competition and supplier relationships scored highest amongst all 13 stakeholder subcategories. Fair competition contributed 15.12% of the total social score. Based on data held by the WEF [346], it was found that the reason for this was because many of the VCAs country of operation were ones in which there has been evidence of anti-competitive behaviour and are also more likely to breach competition laws. In terms of supplier relationships, the stakeholder subcategory contributed 15.02% to the total social score respectively. This was primarily caused by inconsistencies regarding payment to suppliers and sufficient lead times at national-level based on World Bank data [347]. In relation to the SDG social LCIA method, the top 5 most affected SDGs represent 76.66% of the total social score. In order of the most affected, these were Goal 16 (Peace, Justice & Strong Institutions), Goal 17 (Partnerships for the Goals), Goal 10 (Reduced Inequalities), Goal 8 (Decent Work & Economic Growth) and Goal 9 (Industry, Innovation & Infrastructure) which contributed 28.12%, 15.76%, 13.37%, 10.48% and 8.93% respectively. These findings draw many similarities to the results of the MÌOS mission within Section 6.2, since Goals 8, 10, 16 and 17 are all included as part of the top 5 most impacted SDGs across the life cycle of both missions. However, in particular, within the fair competition and supplier relationships stakeholder subcategories it was found that Goal 16 and Goal 17 were present for all social indicators whilst Goal 9 was present within all of the fair competition social indicators. This perhaps explains why these SDGs were some of the most affected.

As one of the main mission objectives of the NEACORE study was to keep the cost as low as possible, LCC played a particularly important role. It was found that the total cost of the mission would be 2.97E+07 EUR 2000 of which around 69% is directly attributable to the acquisition cost of the launcher and around 20% due to ground operations. When this is converted into present value USD then the result is 4.49E+07 USD 2019. Additionally, since the mission is for commercial purposes then two business models can be applied to account for revenues. In the first, the organising body would be responsible for all costs over the mission life cycle and sells to the customer with a 20% profit margin. In the second, the organising body would be responsible for all costs up to (and including) the launch and sells to the customer with a 20% profit margin. The customer would therefore be responsible for operation and end of life costs. These are outlined below along with the associated costs to the customer:

Table 6.4: Cost per spacecraft based on selected business models

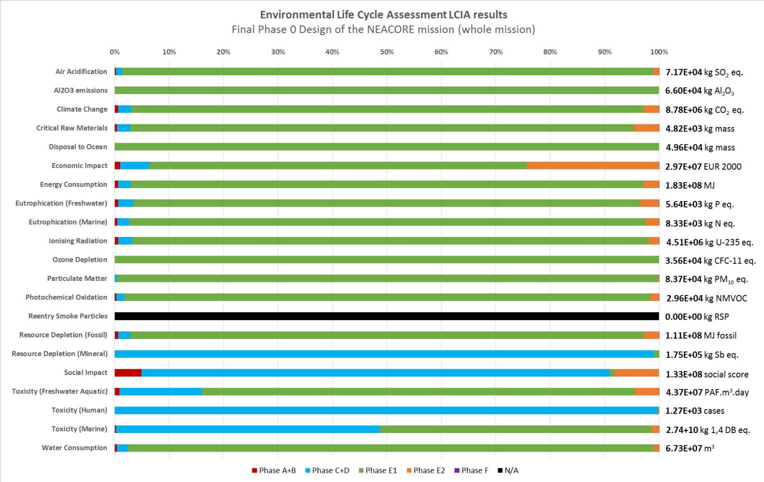
(a) Business Model A

Cost element	Cost per 6 spacecraft	Cost per spacecraft
Whole mission	$44,878,328.12	$7,479,721.36
20% profit margin	$8,975,665.62	$1,495,944.27
Total cost	**$53,853,993.75**	**$8,975,665.63**

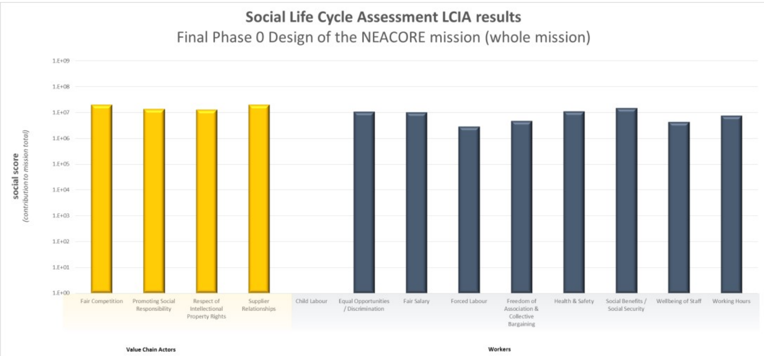
(b) Business Model B

Cost element	Cost per 6 spacecraft	Cost per spacecraft
Up to and incl. launch	$33,963,918.72	$5,660,653.12
20% profit margin	$6,792,783.74	$1,132,130.63
Total cost	**$40,756,702.46**	**$6,792,783.75**

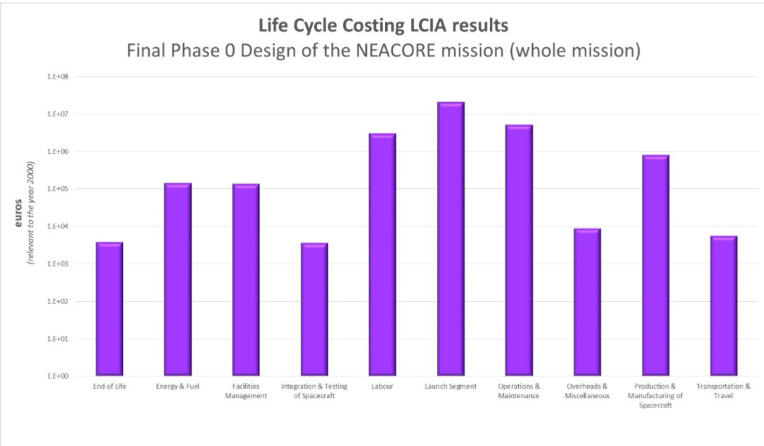
Despite the low cost of this mission, it is worth noting that the cost per spacecraft could be reduced even further if additional spacecraft were to be included as part of this mission and launched on-board the PSLV-CA. Additionally, since this evaluation is based purely on conventional LCC, these values do not take into consideration environmental remediation costs due to the environmental impact of the mission. If environmental LCC was also included within this analysis, then it would cost an additional $200,605.44 to offset the CO_2e emissions released from this mission alone based on the UK Government's Carbon Price Floor [348]. This equates to a cost of $33,434.24 per spacecraft which would only increase further if impacts identified by all other impact categories are also addressed.



(a) Environmental Life Cycle Assessment Results



(b) Social Life Cycle Assessment Results

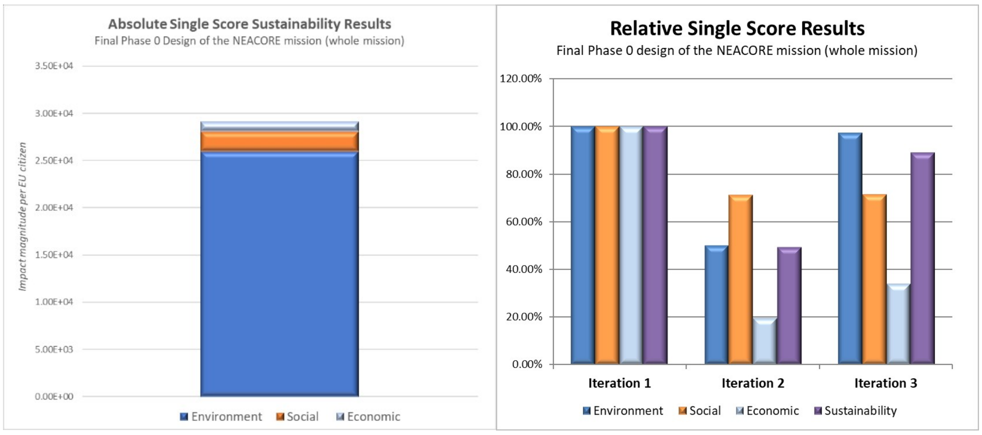


(c) Life Cycle Costing Results

Figure 6.10: Life Cycle Impact Assessment Results of the NEACORE Mission

6.3.4 Multi-Criteria Decision Analysis

Although each of these assessments can be viewed as standalone results, in order to gauge how the three sustainability dimensions interact with one another, MCDA was applied. This was based on the NFs and WFs for the 5 'hotspot' impact categories contained in Table 4.24. These were applied to these LCIA results before the MAVT method outlined in Equation 3.7 was used in conjunction with the WFs for each sustainability aspect outlined in Table 4.25. The proceeding MCDA results of the NEACORE mission which were generated using this method can be seen below.



(a) Absolute Results (b) Relative Results

Figure 6.11: Life Cycle Sustainability Assessment Results of the NEACORE Mission

6.3.5 Interpretation

Overall the results show that the environmental impacts are the most problematic of the three sustainability dimensions for the mission, contributing 89.26% of the single score sustainability impact. Whilst the impact categories of climate change and freshwater aquatic ecotoxicity amounted to just 0.1% of this score, mineral resource depletion account for 46.84% whilst ozone depletion and human toxicity corresponded to 37.28% and 15.78% respectively. This is primarily due to the launch vehicle and the use of germanium as a substrate in the solar array. For this reason, the environmental impacts were the most closely monitored with efforts made to lowering them as far as practically possible. Some of the ecodesign options considered included reducing the solar array size and switching the AOCS propellant from argon to AF-M315E which is a HPGP. As such, the solar array was reduced by 32.78% leading to vast single score environmental savings. However, it was found that the switching of propellants offered no significant environmental benefits. Additionally, the observable decrease between iteration 1 and 2 was due to more relevant data becoming available and the mission design becoming more defined. In particular, this involved an emphasis on reducing spacecraft mass as far as possible (including the solar arrays) to fulfil mission requirement MIS-R-04, which in the end was only partially achieved. The increase in environmental results from iteration 2 and 3 was due to a change in launcher for commercial reasons. The initial estimation was for piggy-backing on a Soyuz 2-1b launcher, assuming a 20% share in environmental, social and economic impact. This was then changed 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 1.

In conclusion, this was the first study to successfully integrate E-LCA, S-LCA and LCC collectively into the concurrent design process of a space mission worldwide, highlighting the usefulness of the discipline in determining adverse sustainability impacts during the concurrent design process and providing solutions to lower them. For the first time, it was evident that study participants were proactively eager to contribute in any way technically possible to lower their sustainability impacts, particularly relating to the environment. Dialogue between engineers and the LCSA expert allowed for various sustainable design solutions to be tested and compared. From this, it could be seen that these conversations dispersed amongst other discipline experts with regards to waterfall effects on system design and how other subsystems could contribute to the sustainable design process. As such, it was found that many disciplines were seeking advice from the LCSA expert on potential sustainable design measures that they could implement whilst other disciplines were proposing their own solutions for their subsystem. For example, the suggestion to switch the AOCS propellant was proposed exclusively by the AOCS discipline expert. Although it was unclear as to whether this change in participant behaviour was driven by results of the SSSD or society's perception with regards to sustainability issues, this clearly highlights the growing awareness concerning the importance of addressing sustainability issues amongst engineers and suggest a potential paradigm shift towards addressing such impacts within the space sector in the future.

The main limitations of this study stemmed from the generalisation and/or omission of certain LCI datasets from the SSSD due to their uniqueness (e.g. LIDAR) which meant that a best fit had to be chosen instead. Furthermore, since the SSSD also does not contain an S-LCA LCI it means that social impacts were measured at country-level which does not accurately reflect relevant stakeholders. Additionally, estimates for cost of operations ranged from $750 USD to €1,500 EUR per hour. This uncertainty meant that the total cost of operations for 6 spacecraft varied from $5.292M to $11.854M including a 20% margin. This was based on the total cost of ground station antenna usage, 10 thrust arcs and 4 flybys for a lifetime of 4 years and 8 months. For this reason, a conservative cost estimation of $960 per hour was applied based on NASA's Deep Space Network published formula, leading to a total cost of $7.292M [349]. Finally, normalisation and weighting applied during LCSA is less scientific and can add subjectivity to the outcome of the analysis. In particular, the E-LCA single score only considers certain hotspot impact categories which may obscure results.

Based on these findings and limitations, the following list of recommendations were set out by the LCSA discipline for future NEACORE design sessions:

- Launcher trade-offs should take place based on the environmental impact.
- The feasibility of using solar panels without germanium substrates (e.g. dual-junction GaAs arrays) should be examined.
- S-LCA should investigate the impacts at an organisational-level with stakeholder participation.
- Cost of operations needs to be more accurately estimated.
- Single score results should not be solely relied upon and should only be used for hotspot identification.

6.4 Chapter Summary

Using the SSSD as part of the MÌOS and NEACORE studies has allowed LCSA to be integrated into the concurrent design process of a space mission for the first time. These practical demonstrations showcased the importance of the LCSA discipline as a decision-making tool during space mission design, as facilitated by the space-specific LCSA framework and SSSD. Whilst one methodological issue was discovered relating to the linking of CERs between LCI datasets, overall the case studies have evidenced the applicability and usefulness of these two contributions to the space sector. In particular, it was found that the relative results from the MCDA analyses was a particularly useful mechanism for translating results to study participants. Overall, the results have indicated a clear shift in participant perception relating to the importance of addressing sustainability issues in comparison to the HATHI mission.

Chapter 7

Significance & Evaluation of Findings

7.1 Chapter Overview

Since the application of the space-specific LCSA framework has now been demonstrated through the SSSD within real concurrent design sessions, it is now important that the significance of this attainment is appropriately evaluated. This allows results to be benchmarked and justified whilst also providing context to the findings of this research. This can also be used to help form a programme of work for future improvement.

Therefore, this chapter will indicate the significance of annual environmental, social and economic impacts of the space activities based on previous studies conducted using the new space-specific LCSA database. The proposed contributions of this research outlined within Section 1.3 will then be discussed in order to determine whether the stated objectives of this study were met. Planned future work is then outlined based on this evaluation.

7.2 Sustainability Impact of the Space Sector

As a result of this work, the new space-specific LCSA framework and LCSA database can be used in conjunction with the sustainable design results outlined throughout this thesis to provide a first order approximation regarding the sustainability impact of the space sector for the first time. This has been included as an evaluation procedure in order to measure the significance of the sector's sustainability impact, whilst justifying and evidencing the appropriateness of space-specific LCSA and the SSSD.

As such, a streamlined LCSA was adopted to make this exercise more manageable. Although these assessment types continue to follow the same standards and principles as E-LCA (as adopted within the space-specific LCSA framework), there are a number of differences. In particular, they are less accurate since their purpose is to reduce the time required to make an assessment [350]. According to Airbus, a streamlined E-LCA can be achieved in a number of ways including by limiting the scope, using generalised or qualitative data, removing upstream and/or downstream components or using specific impact categories [351]. In this methodology, the simplification lies in the use of generalised data and the fact that very specific evaluations have been used to represent very broad and complex industrial activities. This is explained further in Subsection 7.2.1 below.

The calculation provides a rough approximation for annual sustainability impacts of space missions over two scenarios. The first is based on all documented space activities occurring in 2018 whilst the second refers to a situation where there is a significant rise in the number of launches in the short to medium term future. This latter point was investigated due to the considerable efforts being made to provide affordable access to space in the future, meaning that the prospect of mega constellations, space tourism and Moon/Mars colonisation could begin to establish themselves within the next couple of decades [352]. The LCIA results for each scenario have been compared against normalised values to portray their severity. In this regard, the contribution of selected impact categories have been measured against total annual worldwide impacts relative to 2010 [249] and planetary boundaries [251]. These results formed the basis for the evaluation, showcasing the capabilities of the SSSD whilst providing an indication of the severity levels of space activities for the first time. Additionally, it should be duly noted that these analyses only measure the impacts of space missions and do not represent the impact of the entire space industry (i.e. the system boundary does not consider regular day-to-day activities that are not directly attributable to the life cycle of all space missions in a given year of launch).

7.2.1 Calculation Procedure & Results

The goal of this analysis is to identify the annual sustainability impacts of space missions over two scenarios. The first scenario refers to the full life cycle impacts from all space missions launched throughout the 2018 calendar year. This takes into account the 114 recorded launches and the 452 satellites placed in orbit [353, 354]. The second scenario refers to the full life cycle impacts from scaling the first scenario to account for affordable access to space and the prospect of mega constellations, space tourism and Moon/Mars colonisation. Under this scenario, 750 launches are assumed in one calendar year with 5,000 spacecraft being placed in orbit. The FU for both scenarios has been defined as 'one year of global space missions in fulfilment of their requirements'. The adopted system boundary covers the ground, launch and space segments outlined in Figure 2.4. Although this system boundary is generally seen to be applicable to one space mission, within this study it refers to the sum of impacts deriving from all space missions within one calendar year.

The underlying assumptions for the LCI calculation of both scenarios were based on a literature review of space activities in 2018. Gathered LCI data was either used directly or by applying methods of extrapolation. S-LCA data was also included in this analysis, using averaged values obtained during the MÌOS and NEACORE missions based on a national-level perspective for the VCAs and workers stakeholder categories. This involved collecting data for 10 different countries. The life cycle impact of all space missions launched in 2018 was calculated and used to represent the annual impact. It is within this context that LCI data began to be generated, as documented for scenario one below.

In terms of the space segment, the LCI data for man-hours and travel were based on default SSSD values which were originally obtained from expert input during the HATHI study. These figures were then multiplied by the number of space missions launched in 2018 as identified during the literature review. In this regard, according to UNOOSA's 'Online Index of Object Launched into Outer Space', 452 objects were placed into orbit in 2018 [354]. Through the extrapolation of data contained within the Union of Concerned Scientists Satellite Database [355], it was found that the average mass of these objects was 617.41 kg per spacecraft. Therefore, based on these figures, it can be postulated that the total mass of spacecraft put into orbit in 2018 is 279,069.32 kg. The LCIA results relating to the manufacturing and production of the MÌOS and NEACORE missions were then scaled to 1 kg and averaged before being multiplied by this figure to provide an approximation relating to the sustainability impacts of this activity. It was also estimated that an average of 5 spacecraft models would be created per space mission using a 1:1 mass ratio. In a similar manner to man-hours and travel, AIT and spacecraft activities during the launch campaign were calculated based on SSSD default values using the number of space missions launched in 2018. The manufacturing and production of spacecraft propellants and pressurants including their management were based on averaged propellant mass to spacecraft dry mass ratio observed during the MÌOS and NEACORE missions. This was then scaled to 452 spacecraft. All propellants and pressurants listed within the SSSD were applied within this analysis using the following breakdown: Helium (30%), N_2 (10%), HPGP (5%), Hydrazine (30%), MMH (10%), MON-3 (10%) and Chemical-Electric propulsion systems using Xenon (5%).

With regards to the launch segment, according to the 2018 Space Launch Report, 114 launches occurred in the calendar year of 2018 [353]. Of these, 111 were successful. A breakdown of these orbital launches by launcher type is provided in Figure 7.1 below. The launchers indicated in orange means that the SSSD contains specific data within it relating to that launcher type. This provides a 46.5% coverage. However, it should be noted that 33.33% of these successful orbital launches relate specifically to the Long March launcher for which the SSSD does not contain data. For each launcher where this is the case, the generic launcher processes were used as input based on the appropriate stage masses and propellant volumes for each launcher type found through a literature review.

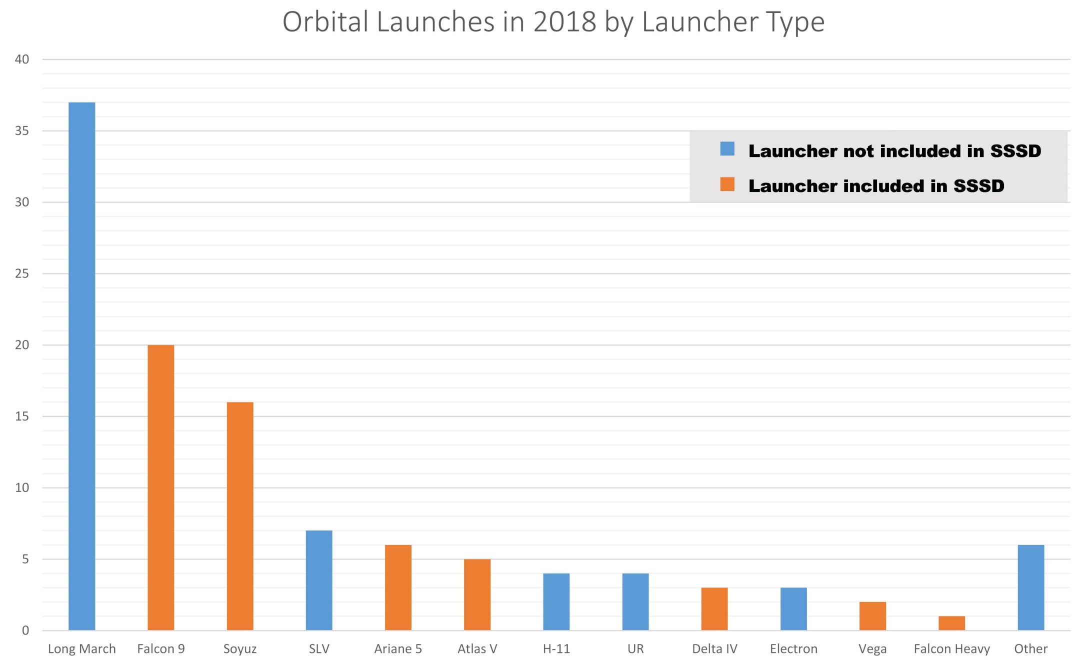


Figure 7.1: Orbital Launches in 2018 by Launcher Type (adapted from [353])

The LCI of the launch segment was therefore calculated by scaling this data to the total number of launches per launcher type. This includes the manufacturing and production of each launcher and its propellants. AIT and the launch campaign were calculated based on SSSD default values using the total number of launches in 2018 to scale up these activities. The launch event was calculated using the same scaling method as the manufacturing and production activities within relevant SSSD launcher processes. For launchers not included within the SSSD, values obtained during the literature review were used within 'Launch event by propellant type' processes for the masses of the observed propellant types of each launcher. This also included the total mass disposed to the ocean from spent launcher stages. However, it is important to note that eleven out of the twenty Falcon 9 launches used reusable rocket stages [353]. This was also factored into the calculation.

Looking at ground segment, averaged values obtained during the MÌOS and NEA-CORE missions were used to portray the use of ground stations and control centres during launch & early orbit phase (LEOP), commissioning, routine and ground operations at the end of life. A 10-year average mission lifetime was assumed for each space mission meaning that the MÌOS and NEACORE were scaled to this reference. It was also assumed that none of the spacecraft were systematically salvaged after re-entry. According to ESA, about 20-40% of large spacecraft typically survives re-entry to reach Earth's surface [356]. As such, it was considered that 70% of spacecraft components would burn-up on re-entry whilst 30% impact water bodies. Since no data could be found on the number of planned re-entries for the 2018 missions, a 100% re-entry rate was assumed as a worst case scenario.

The LCI of the second scenario considered the scaling up of space sector activities due to ease of access to space. Under this scenario, the analysis assumed 750 launches take place in one calendar year whilst 5,000 spacecraft with an average mass of 1,000 kg were placed in orbit with an average mission lifetime of 10 years. This means that a total mass of 5,000,000 kg will be placed in orbit. Due to the prospect of mega-constellations encapsulating a large proportion of this mass (where the baseline is typically an electric propulsion), the following breakdown was assumed: Helium (15%), N_2 (5%), HPGP (5%), Hydrazine (15%), MMH (5%), MON-3 (5%) and Chemical-Electric propulsion systems using Xenon (50%). A 50% reuse of launcher components was also considered which lessens the potential impact of production & manufacturing of launchers and disposal to the ocean. These guesstimates are aligned with observable trends relating to the potential future direction of space industry development [352]. These figures were then applied within the first scenario, replacing the other previously stated figures and assumptions. Although this clearly does not provide a completely accurate overview of the potential activities that may occur due to mega-constellations, space tourism and Moon/Mars colonisation, it avoids attempts at predicting future space activities and the precise processes involved whilst continuing to scale up impacts to account for increased launches and space system development.

The LCIA results of each scenario were calculated using the SSSD E-LCA midpoint LCIA method (including S-LCA and LCC as single scores). Overall, results were generated for 21 out of the 25 impact categories. An overview of these are provided below in Table 7.1 below.

Table 7.1: SSSD LCIA Results of Both Scenarios

Impact Category	Reference Unit	LCIA Results	
		Scenario 1	Scenario 2
Acidification - Air Acidification Potential	kg SO_2 eq	2.86E+07	6.10E+08
Aluminium Oxide - Al_2O_3 Emissions in Air	kg Al_2O_3	2.49E+06	1.64E+07
Climate Change - Global Warming Potential 100a	kg CO_2 eq	5.96E+09	1.20E+11
Critical Raw Materials - CRM Use Potential	kg mass	3.54E+06	1.41E+08
Disposal - Mass Disposed in the Ocean	kg mass	3.43E+06	1.25E+07
Economic Impact - Single Score	EUR 2000	-4.38E+10	-5.28E+11
Energy Consumption - Total Cumulative Energy Demand	MJ	1.32E+11	2.32E+12
Eutrophication - Freshwater Eutrophication Potential	kg P eq	2.92E+06	1.03E+08
Eutrophication - Marine Eutrophication Potential	kg N eq	5.50E+06	1.11E+08
Ionising Radiation - Ionising Radiation Potential	kg U235 eq	2.72E+09	5.07E+10
Noise Pollution - Noise Creation Potential	Av Leq / Cat	-	-
Orbital Risk - Space Debris Risk	Index Score	-	-
Orbital Space Use - Orbital Resource Depletion Potential	objects.m^3.year	-	-
Ozone Depletion - Ozone Depletion Potential (Steady State)	kg CFC-11 eq	1.25E+06	8.26E+06
Particulate Matter - Particulate Matter Formation Potential	kg PM10 eq	1.43E+07	2.89E+08
Photochemical Oxidation - Photochemical Oxidation Potential	kg NMVOC	1.95E+07	3.71E+08
Re-entry Smoke Particles - RSP Creation Potential	kg RSP eq	1.95E+05	3.50E+06
REACH Substances - Restricted & SVHC Use Potential	kg mass	-	-
Resource Depletion - Fossil Resource Depletion Potential	MJ fossil	9.61E+10	1.55E+12
Resource Depletion - Mineral Resource Depletion Potential	kg Sb eq	2.15E+09	3.86E+10
Social Impact - Single Score	Social Score	7.72E+11	8.53E+12
Toxicity - Freshwater Aquatic Ecotoxicity	PAF.m^3.day	9.77E+10	2.66E+12
Toxicity - Human Toxicity	cases	1.58E+07	2.83E+08
Toxicity - Marine Ecotoxicity	kg 1,4-db eq	1.70E+14	3.19E+15
Water Consumption - Water Depletion Potential	m^3	3.58E+10	1.20E+12

Based on these results, three categories of particular interest are air acidification, freshwater aquatic ecotoxicity and ozone depletion due to their impacts compared to NFs outlined in Table 4.24. In terms of air acidification, within scenario 1, it can be seen that the production & manufacturing of launcher propellants is responsible for the greatest impact (38.81%). However, this shifts to the production & manufacturing of spacecraft propellants in scenario 2 (68.03%) due to the amount of sulphur dioxide, nitrogen oxides and ammonia released as part of the cryogenic air separation process for the chemical-electric propulsion system. A similar result is found within the freshwater aquatic ecotoxicity impact category where the greatest impact for scenario 1 came from the production & manufacturing of spacecraft components (68.68%), most notably due to the release of arsenic, mercury and dioxins to air from germanium production & manufacturing. However, scenario 2 also sees production & manufacturing of spacecraft propellants produce the greatest impact (47.76%) due to the release of chromium VI along with copper, nickel, vanadium and zinc ions to groundwater during the cryogenic air separation process for the chemical-electric propulsion system. As such, it can be determined that the cryogenic air separation process could be a considerable environmental hotspot for future space missions, which draws similarities to the findings of Pettersen et al. [93, 94]. For ozone depletion, the impact comes almost entirely from ClO_x, NO_x, HO_x and HCl emissions of the launch event (99.97% for scenario 1 and 99.88% for scenario 2).

In terms of social and economic impacts, the majority of the S-LCA score was generated within Phase C+D (83.34% in the first scenario and 87.71% in the second scenario). This is primarily due to the high levels of organisational involvement within this phase which would clearly drive an organisation S-LCA score. In terms of LCC, the total cost of Scenario 1 was 4.38E+10 EUR 2000 which increased to 5.28E+11 EUR 2000 in Scenario 2. This is primarily due to additional research & development activities together with increased levels of production & manufacturing in line with new space developments as part of Scenario 2. Additionally, the relative share of costs across Phase E1 and Phase E2 fell from 17.96% to 10.76% between Scenario 1 and Scenario 2. This is mainly due to cheaper access to space, which is envisioned as part of Scenario 2 in addition to the fact that a proportionally smaller workforce is required for satellite operations per mission. These social and economic results are discussed in more detail in Subsection 7.2.2.

The NFs which were applied followed a global perspective since the impact of worldwide space missions was being measured. For E-LCA, these were based on JRC global domestic NFs outlined in Table 3.3. These can mapped against estimated planetary boundaries also found within this table. It was found that eight of the E-LCA impact categories correlate with planetary boundaries and global NFs. However, it should be noted that the planetary boundary defined for water consumption was considered to be impractically low, so the planetary boundary adopted for this impact category is based on the NF value proposed by Bjorn & Hauschild instead [357]. The NFs applied for S-LCA and LCC was based on the exact same method, but scaled up to represent worldwide impacts [358, 359]. The NFs factors applied to represent planetary boundaries was based on the maximum potential social score for all organisations within one year for S-LCA and total worldwide GDP in 2016 for LCC [358, 360]. An overview of these NFs and planetary boundaries can be found in Table 7.2 below.

Table 7.2: Applied Normalisation Factors for Space Sector Impact Analysis [249, 251, 347, 357–359]

(a) E-LCA

Impact Category	Unit	Total Worldwide Emissions (2010)	Estimated Planetary Boundaries	One Planet Living	Overall Robustness
Air Acidification	kg SO_2 eq.	1.23E+10	3.20E+10	0.38	High
Climate Change	kg CO_2 eq.	5.79E+13	6.79E+12	8.53	Very High
Eutrophication (Freshwater)	kg P eq.	5.06E+09	5.79E+09	0.87	Medium to Low
Eutrophication (Marine)	kg N eq.	1.95E+11	2.00E+11	0.98	Medium to Low
Ozone Depletion	kg CFC-11 eq.	1.61E+08	5.38E+08	0.30	Medium
Photochemical Oxidation	kg NMVOC	2.80E+11	2.62E+10	10.96	Medium
Toxicity (Freshwater Aquatic)	PAF.m^3.day	8.15E+13	1.31E+14	0.62	Low
Water Consumption	m^3	7.91E+13	1.04E+14	0.76	Medium to Low

(b) S-LCA

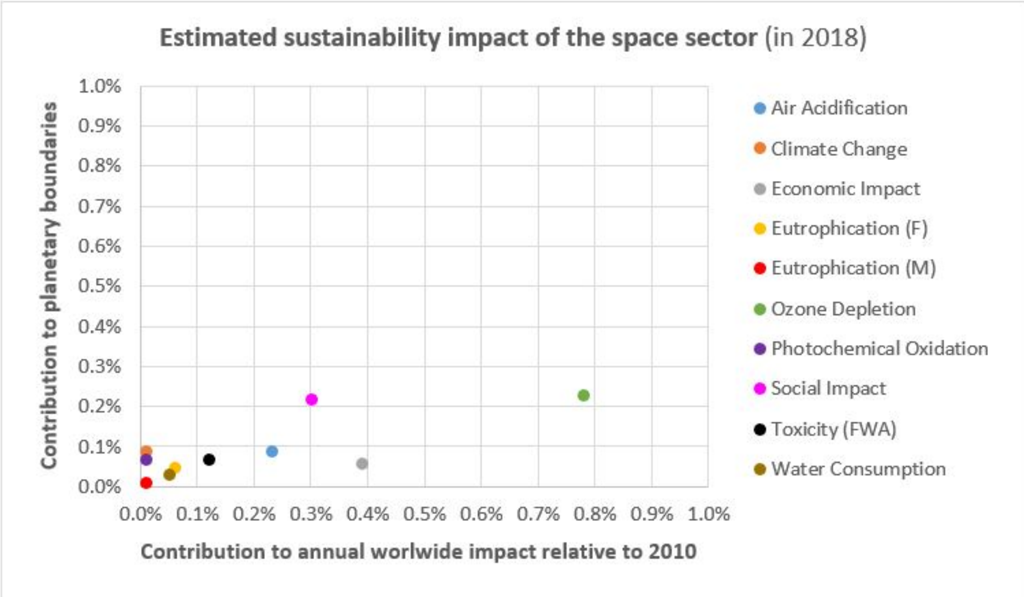
Impact Category	Unit	Total Worldwide Social Score (2016)	Maximum Potential Social Score (2016)	Overall Robustness
Social Impact	social score	2.55E+14	3.54E+14	Very Low

(c) LCC

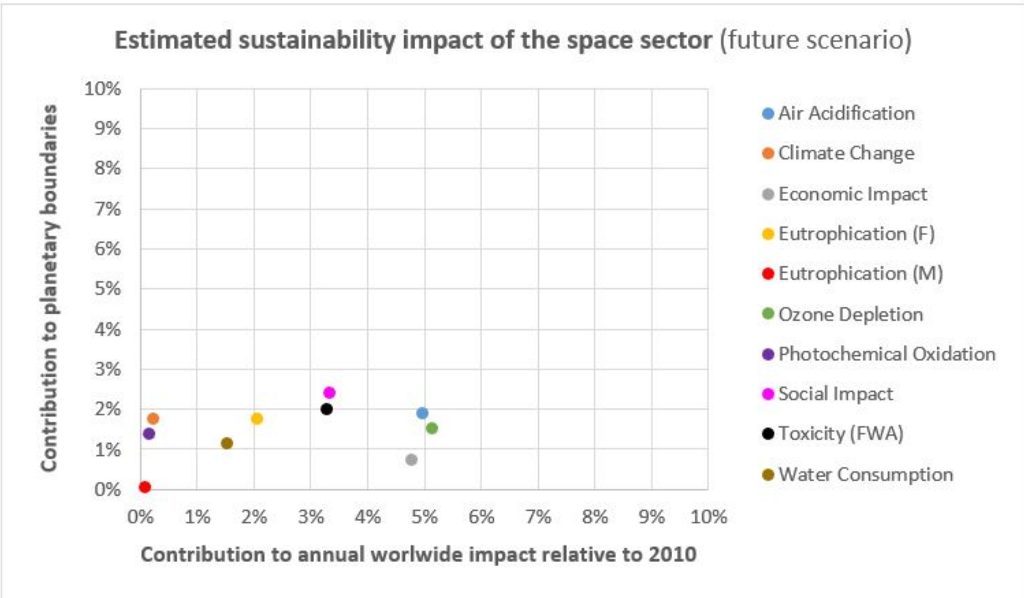
Impact Category	Unit	Total Worldwide Taxation (2015)	Total Worldwide GDP (2015)	Overall Robustness
Economic Impact	EUR: Year 2000	1.11E+13	6.84E+13	High

Based on these NFs, it can be seen that a large coverage of the ILCD compliant SSSD E-LCA impact categories are included within this analysis. However, it can be considered that a major limitation of this approach is the omission of the human toxicity and mineral resource depletion from Table 7.2(a), despite these representing two of ESA's five hotspot impact categories. This is a considerable exclusion since the MÌOS and NEACORE studies have demonstrated the significance of these impact categories to the environmental single score generated through MCDA. The reason for this is because no planetary boundary value is available for either of these impact categories. This is primarily due to gaps in knowledge caused by incomplete emissions accounting and issues associated with modelling exercises which has meant that assigning an unequivocal level of pressure due to human activities was not possible and hence a measurable ecological threshold could not be determined [251]. Although defining planetary boundaries for both of these environmental issues is still a topic of discussion, without such a threshold, a NF could not be provided for either impact category. Therefore, the statistical power of this approach could be considered to be reduced since the proportion of impact categories excluded from the analysis has the distinct possibility to produce larger standard errors. Whilst this may limit confidence levels of the analysis by overlooking particularly meaningful impacts, it was an unavoidable feature of this modelling approach.

The LCIA results of both scenarios can then be mapped against these NFs to highlight the contribution of each impact category to planetary boundaries and the annual worldwide impact of 2010. It can be argued that the space sector's contribution to planetary boundaries is the most important performance indicator since it measures impacts with regard to safe operating thresholds/tipping points of the Earth system (i.e. the severity). However, assessing this against the space sector's contribution to worldwide impacts indicates where the impacts of space activities place in relation to the sum of all other anthropogenic activities (i.e. the contribution). Considering these together provides an outline of the relative performance of the space sector with regards to the significance of its sustainability impacts. An overview of these results is provided in Figure 7.2 below. In particular, Figure 7.2(a) provides the estimate for the life cycle sustainability impact of all worldwide space missions launched in the year 2018. In comparison, Figure 7.2(b) provides this estimate for the future scenario, where 750 launches are assumed in one calendar year to deliver a total of 5,000 spacecraft into orbit.



(a) Scenario 1



(b) Scenario 2

Figure 7.2: Estimated Sustainability Impact of the Space Sector

7.2.2 Evaluation & Discussion

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

In terms of climate change, 84.90% of the total LCIA result for 2018 came from the production & manufacturing of spacecraft and launcher components and propellants (which includes their management, handling and storage). This impact was primarily due to the CO_2 released during heat and electricity consumption. Overall, this analysis estimates that total global contribution of space missions towards climate change is just 0.01% of total emissions for the 2018 scenario and 0.21% for the future scenario. For reference, this equates to 54 days and 1,082 days of daily averaged GHG emissions in Scotland for 2017 [361]. Whilst this would indicate that the overall impact is insignificant in comparison to other sectors, in comparison to the global aviation industry (which currently accounts for between 2-3% of all anthropogenic CO_2 emissions) [282], this is a particularly alarming result. In this regard, the International Civil Aviation Organization reported that 38 million flights departed in 2018 [362]. This compares to just 114 launches in the same year [353], indicating that the impact per launch vehicle is several orders of magnitude greater than that of an aircraft. The influence on planetary boundaries is much greater, with a 0.09% contribution for the 2018 scenario and 1.77% for the future scenario. This highlights the urgent need for addressing climate change since more CO_2e is currently being emitted than the planet can cope with to restore its natural equilibrium. The breach of this planetary threshold outlined in Table 7.2 reaffirms the urgency of the high WF placed on the impact category during MCDA.

Additionally, 99.97% of the observed ozone depletion impact in 2018 comes from the launch segment during Phase E1. Contrary to the WMO assessment on ozone depletion which predicts that rocket launches have a small effect on total stratospheric ozone (causing much less than 0.1% loss) [288], this analysis estimates that total annual ozone destruction caused by global launches in 2018 could be on the order of about 0.78% of total emissions which leads to a 0.23% contribution to the planetary boundary. The WMO report goes on to suggest that modern space industry developments could lead to a more significant increase in launcher exhaust emissions than reported in previous assessments. In this regard, under the future scenario, this analysis estimates an impact of 5.13% of total emissions which leads to a 1.54% contribution to the planetary boundary. However, it is important to note that existing gaps in knowledge relating to the chemical, radiative and dynamical impacts of launcher exhaust products on the global stratosphere meant that CFs with regards to altitude of emissions could not be formulated within the SSSD. This omission limits the confidence level of these ozone predictions. It is expected that the significance of these impacts would considerably decrease with the application of altitude-dependant CFs.

The S-LCA results indicated that the 2018 scenario would contribute 0.30% of the total 2016 worldwide social score and 0.22% of the maximum potential social score. In comparison, the future scenario would contribute 3.32% of the total 2016 worldwide social score and 2.43% of the maximum potential social score. Of this impact, 83.34% arose during Phase C+D for the 2018 scenario, rising to 87.71% for the future scenario. This was due to a 50% launcher reuse considered as part of this scenario meaning less production & manufacturing time was being spent on launchers, which came into the system boundary during Phase E1. Overall, it was found that the total social score achieved was primarily due to the number of organisations which were involved in the supply chain to manufacture, produce and test spacecraft components. In particular, the large influence of US-based organisations within the space sector defined this result. This is because at national-level, US-based organisations scored the 7th worst out of the 10 countries where LCI data was gathered. Primarily, this was due to the high social scores achieved for the stakeholder subcategories of fair competition and equal opportunities/discrimination. For example, the high score within this latter point was primarily achieved because of the large gender pay gap present in the country. According to the Bureau of Labor Statistics, an average woman's unadjusted annual salary falls between 78% and 82% of that of the average man's [363,364]. This therefore attributed the maximum score for this social indicator. However, these S-LCA results are clearly the most contentious out of all the other impact categories since specific organisational data has not been used.

When considering LCC, it was found that the total costs associated with the 2018 scenario was 0.39% of global taxation in 2015 and 0.06% of worldwide GDP. In terms of the future scenario, it was found that the total costs would equate to 4.76% of global taxation in 2015 and 0.77% of worldwide GDP. These results were then compared to global satellite industry revenues for 2018 as reported by the Satellite Industry Association [176]. Within this report, it was found that the global space economy was worth $360 billion of which 77% was related to the satellite industry. When excluding satellite service revenues from this analysis, it was found that the total revenues for satellite manufacturing, the launcher industry and ground equipment, was $151 billion. This equates to 9.36E+10 EUR (2000). In comparison to 2015 worldwide GDP, this equates to 0.14%. This is comparable to the result generated within this analysis for the 2018 scenario since this figure reflects costs, whilst the result obtained from the Satellite Industry Association document reflects revenues. As such, a higher value was expected to be obtained within this document to reflect profit margins which in this case averages at 29.03% for the space sector. However, it should be noted that the GNSS ground segment equipment contributed 61.83% of satellite manufacturing, the launcher industry and ground equipment revenue within the Satellite Industry Association report. In this regard, it can be determined that this operation has a large influence on results and the fact that this was not specifically considered within the analysis due to the generalisation of the LCI may be what is causing this high profit margin. Despite this, the similarity and clear correlation between the figures contained within this analysis and the Satellite Industry Association report adds credibility to the general accuracy of the generated results.

When applying MCDA using the baseline approach to the LCIA results displayed in Table 7.1, it was found that the relative results relating to the importance of impact magnitude per EU citizen for the 2018 scenario was 98.13% for E-LCA, 1.67% for S-LCA and 0.20% for LCC. The majority of this score for the environmental dimension comes from mineral resource depletion (56.83%) and human toxicity (41.66%), reemphasising the significance of excluding these hotspot impact categories as part of this analysis. However, as previously discussed, this was unavoidable. When re-weighting the environmental WFs used in the MCDA baseline approach for the 2018 scenario to only include the impact categories included within this analysis, it was found that the relative results changed to 51.32% for E-LCA, 43.42% for S-LCA and 5.26% for LCC. In this case, it was found that the results of the environmental dimension were most impacted by water consumption. Despite the significant shift in results, this could indicate that over the life cycle of a space mission, environmental impacts may remain the most important sustainability aspect to address during the sustainable design process. Moreover, it also highlights the significance of the mineral resource depletion and human toxicity impact categories on MCDA results, demonstrating that the environmental and societal dimensions would be far more comparable if these impact categories were excluded from the analysis. As such, it could be argued that perhaps more robust NFs may need to be formulated for S-LCA and LCC in order to be more comparable to E-LCA during MCDA, especially considering where each impact category placed with respect to annual worldwide impacts and planetary boundaries within Figure 7.2.

In terms of limitations, the main drawback of this analysis was its generalisation. In particular, specific spacecraft and components were not analysed due to a lack of data and time constraints. To overcome this, averages were taken from the MÌOS and NEACORE mission which may not be the most representative choice for representing the sustainability impacts of all space missions in 2018. Additionally, European manufacturing and production processes have been used to represent all spacecraft manufacturing which is over-simplistic whilst the production & manufacturing of lunar/mars modules or different launchers were not considered within the future scenario. Finally, the MCDA values obtained still refer to Europe due to their nature whilst this takes a global perspective. However, since a streamlined LCSA was adopted, these limitations and methodological choices were deemed acceptable for this analysis in order to provide a first order overview of annual life cycle sustainability results from space activities. As such, a more detailed analysis is recommended within the future if data becomes available.

Based on this analysis, it can be concluded that although the space industry's contribution to adverse sustainability impacts is minimal at present, these impacts may become more meaningful with the scaling up of space activities in the near to medium term future. In such an event, scientifically quantifying and reducing environmental, social and economic impacts of space missions will become an increasingly more important subject within the industry and will likely become a mandatory component of space mission design. For this reason, it can be predicted that the use of space-specific E-LCA/LCSA will become ever more prevalent within this process over the next decade. The SSSD and LCSA framework presented within this body of work provide the first stepping stones for industry to begin applying space-specific sustainable design within a concurrent engineering environment. In particular, the SSSD provides the means on which to apply and further this framework, and may be released freely to the space community in the future. This means that its future use will be largely dictated by space industry demand and the perceived importance of reducing adverse sustainability impacts of space missions. Fortunately, a shift in perceptions relating to this level of importance has already been witnessed during the NEACORE mission, as documented within Subsection 6.3.5.

7.3 Evaluation of Contribution to the Field

The aim of this research was to successfully transition the E-LCA methodology for space systems towards a more holistic approach of sustainability assessment which aligns with the global aspirations envisaged within the 2030 Agenda. To achieve this, four objectives were outlined which this body of work sought to address. As stated in Section 1.3, in fulfilment of the aim and objectives, it can be considered that two primary outputs have been achieved as contributions to the field. The first relates to the new framework developed for LCSA of space systems. The second is the creation of a new tool to assist the space industry apply sustainability assessments of space systems for the first time. For this reason, it can be considered that the novelty of this research does not exclusively lie in the development of the framework, but on its application through the SSSD.

This research sought to deliver these contributions by addressing the stated objectives outlined in Section 1.4. Therefore, consideration must be given as to whether or not these objectives were achieved. As such, each contribution will be discussed and evaluated (including miscellaneous contributions uncovered as part of the findings of this research) with regard to the objectives in order to determine their importance to the field. Effectively, this will help to emphasise the scientific contributions of this research.

7.3.1 Space-Specific LCSA Framework

The first study output was the proposal of a new space-specific LCSA framework and methodology based on best practice. It was considered that the first objective related to this study output. It sought to identify and critically review current practice relating to E-LCA within the space sector and sustainability assessment more widely, including gaps in knowledge, in order to develop a space-specific LCSA framework and methodology. To achieve this objective, firstly a literature review was conducted which examined current methods for conducting E-LCA and ecodesign of space systems before going on to examine the strengths and weaknesses of the Space Opera ecodesign tool based on its integration within a real concurrent design study. Another literature review was then conducted which critically reviewed the current LCSA approach and methodologies for applying social and economic criteria within space missions. Collectively, this led to the formation of the new space-specific LCSA framework which provides methodological guidance relating to best practice for the aggregation of E-LCA, S-LCA and LCC within one single space-specific assessment.

The literature review found a distinct lack of research relating to space-specific E-LCA, with most of the available literature presenting limited information due to confidentiality concerns. Therefore, the current practice relating to E-LCA within the space sector was primarily focused on ESA and the formation of their space E-LCA framework. The application of this developed approach was then tested during the HATHI mission which highlighted some critical technical issues relating to its implementation. The lessons learned from this process were used to frame applied methods for integrating the new LCSA database into the concurrent design process as part of the third objective. However, since these issues were related almost entirely to tool functionality, the established methodology was considered to be robust enough on which to base social and economic criteria.

In this regard, it was found that the current approach applied within the space industry for modelling costs was highly applicable to LCSA since it generally followed a product life cycle assessment model, in a similar manner to E-LCA. This meant that very little adaption was required for adoption within the framework. In comparison, social impact modelling was lacking within the space sector. As such, an entirely new approach had to be developed for S-LCA which was forced to follow an organisational life cycle assessment model due to its nature. This created problems relating to inventory data since there was a clear lack of willingness from organisations to contribute data. However, since it is expected that organisations should apply data related to their own supply chain, this was not considered to be a hindrance. It was suggested that social indicators were developed based on the SDG targets and indicators meaning the contents of the 2030 Agenda can be directly considered within this assessment.

Based on these approaches, a method which considers how each sustainability dimension interacts with one another was required to aid the decision-making process. In this regard, MCDA was deemed crucial to balance the results stemming from the selected environmental, social and economic models, as required by the 2030 Agenda. This developed approach presented a method for measuring sustainability impacts in order to better determine the most critical sustainability hotspots to address.

Therefore, these approaches were collectively fed into the creation of the new space-specific LCSA framework to aid hotspot identification and reduction. With the development of new social indicators and MCDA WFs based on SDG targets and indicators (as applied within the SSSD which should be seen as an extension of this methodology), it is clear that this framework successfully aligns with the 2030 Agenda. As such, it can be considered that the first objective has been successfully achieved. However, the relative success of this framework is dependent on its use within concurrent design sessions, as determined by the other three objectives.

7.3.2 Space-Specific LCSA Database

The second study output was the development of the first ever life cycle sustainability database for space-based applications. It was considered that the second, third and fourth objectives related to this study output. The second objective was to create a fully functioning and robust life cycle database for space systems which facilitates a transition from the traditional form of environmental assessment to a more encompassing and fully integrated sustainability assessment with respect to the 2030 Agenda. The third objective was to investigate and apply methods enabling the new life cycle database to be used within the concurrent design process of space missions. The fourth objective aimed to demonstrate the appropriateness of the developed LCSA framework and methodology by applying the new life cycle database within the concurrent design process of space missions using practical case studies as test cases.

For the second objective to be realised, a new LCSA database was developed within openLCA. This sought to specifically apply the principles of the space-specific LCSA framework, created as part of the first objective. The database integrated social and economic criteria into E-LCA LCI datasets and developed new E-LCA, S-LCA and LCC LCIA methods. The environmental criteria held within 30% of SSSD LCI datasets were also validated through the ESA LCI Validation Project. S-LCA and LCC were applied in accordance to the space-specific LCSA framework. In particular, social indicators were developed based on the SDG targets and indicators meaning the contents of 2030 Agenda can be directly considered within this assessment. MCDA was also based on this framework, using the percentage of SDG targets and indicators attributable to each sustainability aspect as a method for weighting in order to balance the three dimensions. Case studies were used to provide examples of dataset implementation and MCDA since the SSSD was too large to individually detail the development of each LCI dataset and LCIA method. These helped to highlight the robustness and functionality of the database for transitioning E-LCA of space missions towards LCSA. The consideration of the SDGs within S-LCA and the weighting approach developed for the MCDA approach directly aligns this database with the 2030 Agenda. As such, it can be considered that the second objective has been successfully met.

To achieve the third objective, methods for integrating the new LCSA database into the concurrent design process to facilitate sustainable design was identified, discussed and developed. As such, a connection was established between the OCDT and SSSD through manipulation of the design model to host LCSA data and through the creation of a new sustainable design workbook as a data exchange interface. This was then examined within a precursor CDF test as part of alpha testing, highlighting that this connection was functioning as expected. During alpha testing, the SSSD was inspected with regards to how it can assist in the delivery of sustainable design within the concurrent design process and in what ways it can influence space system design. No major issues were identified, however easily implementable solutions were proposed for any problems unearthed. A comparability and functionality analysis was also conducted using the Space Opera ecodesign tool as a baseline for final data quality and validation checks before use within real CDF studies. This provided added verification relating to the robustness and functionality of the tool, indicating its successful integration into the concurrent design process. Based on this, it can be considered that the third objective has been fulfilled.

Accomplishment of the fourth objective was dependent on the successful demonstration of the new LCSA database within the concurrent design process as an enabler of sustainable design. This was based on two CDF case studies of space missions designed at the University of Strathclyde to specifically address one of the most commonly cited methodological problems relating to LCSA documented in Subsection 3.5.1. This was the first time that LCSA had ever been applied to space systems, which sought to provide proof of concept relating to the feasibility and usefulness of the space-specific LCSA framework and the SSSD for application within the space sector. The results from both of these studies have highlighted the life cycle sustainability impacts for the first time. In particular, the application of S-LCA added an additional layer of depth to these analyses by determining the most affected SDGs in terms of the VCAs and worker stakeholder categories. Additionally, MCDA proved to be an extremely useful tool in identifying which hotspots are more important to address across each sustainability dimension, in accordance with the 2030 Agenda. As such, these practical demonstrations showcased the importance of the LCSA discipline as a decision-making tool during space mission design, as facilitated by the space-specific LCSA framework and the SSSD. For this reason, it is contemplated that the fourth objective has been adequately addressed.

7.3.3 Miscellaneous

Besides the achievement of the objectives discussed in the subsections above, there were also several miscellaneous achievements that were produced as a result of this research. Running alongside the development of the space-specific LCSA framework and database, three additional deliverables were generated. These are:

- An EULA which can be used to obtain permission to use the SSSD.
- An Sustainable Design Workbook for integrating LCSA results into a CDF study.
- A User Guide to provide assistance to users of the SSSD.

The locations of each of these deliverables is outlined in Appendix B. Each can be seen as a crucial component of the space-specific LCSA framework and database which are critical to the successful application of sustainable design within the space sector. These have been discussed more fully in Section 4.6.

Another key contribution to the field was made during the ESA LCI Validation Project. In this regard, a cross-validation approach was conducted using the ESA E-LCA database and Space Opera. Besides the benefits of this project to the development of the SSSD, the exercise also allowed a range of ESA LCI datasets to be validated for the first time and a range of bugs to be identified within the Space Opera tool. This external validation allowed a level of confidence to be instilled in the quality of data held within the ESA E-LCA database and allows ESA to fully align with the validation requirement as part of the ISO 14040:2006 and 14044:2006 standards [5, 6]. With reference to the latter point, this helped to frame a supplementary report to the problem report submitted to ESA as part of the HATHI study. The findings contained within this report will now form a basis for a small contract to the Space Opera developers in order to debug the tool so that it is fully operational for systematic use within future CDF studies.

Whilst the successful integration of the space-specific LCSA framework within concurrent design sessions through the use of the SSSD is commendable, it is also important to address the findings from these studies. One particularly important finding in this regard related to the MÌOS study. The results suggest that decisions to replace existing technologies with new and more sustainable alternatives should not be based solely on comparative one-for-one analyses of environmental, social and/or economic aspects. Instead, it is imperative 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. Although during the MÌOS mission it was actually found that switching propellants from hydrazine to LMP-103S generated a poorer environmental impact at system level in comparison to the baseline design, these impacts were more than offset by the net savings from the solar array mass reduction. Despite this solution not offering an enhanced environmental performance at system level, it does demonstrate the importance of taking into account the net effects of sustainable design decisions due to potential indirect savings or gains which are generated through system redesign. Therefore, it can be concluded that completely replacing technologies that perform worse one-for-one without any technical consideration is an inattentive and poor sustainable design choice. As such, a shift in FU may be required to reflect this (e.g. the FU for propellants could be changed from mass to specific impulse in line with the FU of Pettersen et al. [94]).

The outcomes of including S-LCA and LCC data within a common space-specific LCSA framework is also important to quantify. In terms of S-LCA, it was found that Goal 8 (Decent Work & Economic Growth), Goal 10 (Reduced Inequalities), Goal 16 (Peace, Justice & Strong Institutions) and Goal 17 (Partnerships for the Goals) were all included within the top 5 most impacted SDGs of both the MÌOS and NEACORE missions. These represent four of the top 5 most relevant SDGs identified for a space-specific S-LCA outlined in Subsection 4.4.1, with the only difference being the inclusion of Goal 12 (Responsible Consumption & Production) and Goal 9 (Industry, Innovation & Infrastructure) as the fifth most affected SDG within the MÌOS and NEACORE missions, replacing Goal 11 (Sustainable Cities & Communities). There could be numerous reasons for this, such as Goal 11 mainly being driven by other stakeholder categories not included within these analyses. However, this does indicate that Goals 8, 10, 16 and 17 could potentially be considered as social hotspots of space missions, at least for the workers and VCAs stakeholder categories. In terms of LCC, the drivers for the cost were generally determined to be labour, launcher acquisition and cost of operations (although this will depend on the goal and scope definition). This is because, when combined, these cost elements represented 89.14% of the total cost of the MÌOS mission and 96.13% of the NEACORE mission. As such, these could be classed as considerable economic hotspots of space missions.

Interestingly, when calculating MCDA results of both the MÌOS and NEACORE missions, it can be observed that the environmental impact produces a far greater share of the sustainability score. Within this sustainability aspect, the same hotspots were identified which relate to the use of germanium as a substrate within solar arrays for human toxicity and mineral resource depletion and the release of ClO_x, NO_x, HO_x and HCl during the launch event for ozone depletion. Within these missions, these impact categories vastly contributed to the total score of the environmental dimension (near 100%) to an extent where if they were excluded from the analysis then the environmental dimension of the MCDA results would be far more comparable to the social and economic aspects. This raises the question: is this just a coincidence or is the environmental dimension truly the most important sustainability dimension to address? If this is the case, it could worth conducting future E-LCA/LCSA studies to investigate whether these environmental hotspots are common across all space missions and how they could be addressed.

Lastly, a first order approximation regarding the sustainability impact of the space sector was produced. This provides a general indication of the space sector's total contribution toward the annual worldwide impacts of all anthropogenic activities, measured against the severity of this contribution. The outcome of this exercise is extremely important as it benchmarks the footprint of the space sector for the first time. This could also be used as a base for reformulating the WFs applied during MCDA, based on the contribution and severity of the threat relating to each impact category. Furthermore, the scaling up of current space activities within a future scenario to reflect projected trends of the space sector highlights the importance of addressing sustainability impacts within the industry, evidencing the usefulness of the new space-specific LCSA framework and database as a tool to address such impacts.

7.4 Future Work

Despite the achievement of the aim and objectives, it is crucial that the space-specific LCSA framework and database continually improves. This relates to the recurrent development, maintenance and revision of these elements to ensure their long-term use within the space industry. In this regard, based on some of the developed methodological approaches generated as part of this research, this section will briefly discuss some potentially interesting research topics which are worth investigating further, before going on to outline any foreseen near-term future applications of this research.

7.4.1 Refinement of the Space-Specific LCSA Framework

In a similar manner to ISO standards, since the space-specific LCSA framework has no predefined lifetime, it is important that a periodic review is conducted. This ensures that the framework continues to align with life cycle methodologies and guidelines even if these have been updated whilst also taking into account advances in life cycle modelling of space systems. This maintains consistency by continuing to reflect best practice in line with latest technological developments and market trends.

As such, a cyclical refinement process was developed based on a realist evaluation approach to ensure that the space-specific LCSA framework is fit for purpose [365]. This process is outlined in Figure 7.3 below. However, it should be noted that the application of this refinement process is also dependant on updates and modifications made to the SSSD, as specified in Subsection 7.4.2 below. Any updates to the framework will be communicated in revised versions of the SSSD User Guide.

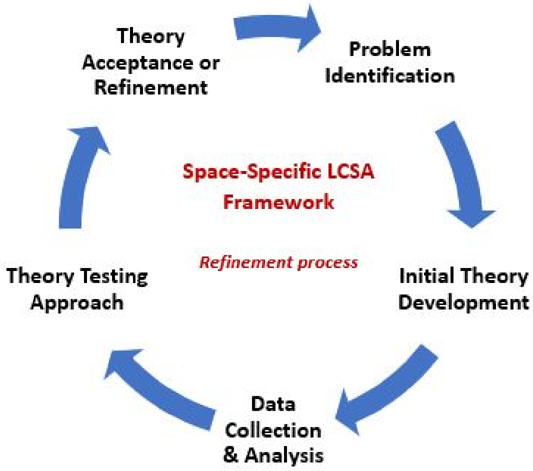


Figure 7.3: Space-Specific LCSA Framework Refinement Process (adapted from [365])

An example of such a change which may be considered within the next cycle is the alignment of the social scoring system to align with the developed WEF space sustainability rating once it is released (problem identification). This may involve investigating the possibility of a move towards using the affected SDGs LCIA method as the SSSD's baseline (initial theory development). The reason why this was not initially selected as the baseline was due to the disparity regarding the number of SDGs covered by the developed social indicators (see Appendix A). As such, an equal weighting approach could be adopted in the future to redefine this where each SDG is weighted evenly regardless of the number of social indicators attributed to each one (data manipulation). If this offers an optimised method for calculating social results (theory testing) then the theory can be accepted. If not, then the theory may need to be redefined based on the problem identified.

7.4.2 Further Development of the SSSD

In order to continue developing the SSSD, a programme of work relating to the data analytics process has been formulated. This refers to all planned work in the short to medium term and can be seen in Figure 7.4 below. This proposed programme of work contributed towards the formation of recommendations in Section 8.4 which can be used to further the development of LCSA within the space sector.

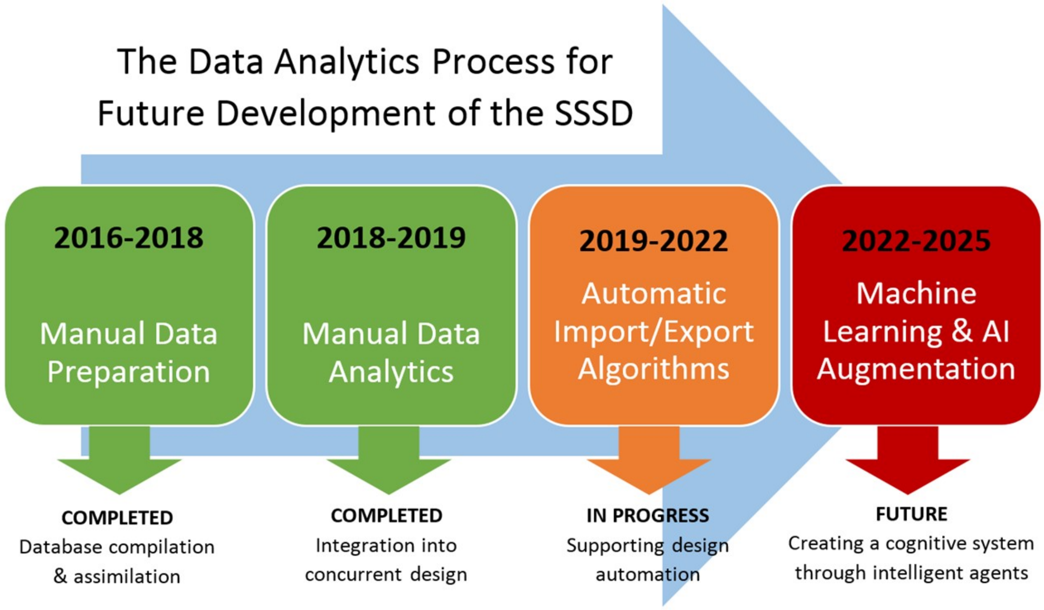


Figure 7.4: Proposed Data Analytics Process for Future Development of the SSSD

Although the manual data preparation and analytics are classed as 'completed', it is expected that these phases will follow a continual improvement cycle. As such, according to the outcome of the 'ESA Life Cycle Inventory (LCI) Validation Report', it is intended that the SSSD will continue to be modified, updated and developed on a regular basis, with a particular emphasis on LCI datasets and LCIA methods when more reliable data becomes available. This also incorporates any methodological changes that may be required as a part of the space-specific LCSA framework refinement, the provision of social LCI datasets, full implementation of all LCIA methods listed in Table 4.3, fixing of the CER linking issue and the inclusion of more extensive MCDA techniques within LCIA methods. To facilitate these latter two points, the applicability of employing the openLCA collaboration server will be investigated so that multiple users can operate and commit any changes made within the local version of the database to a central server in order to synchronise data [366]. It is also intended that the SSSD will go through a harmonisation exercise in the near-future to name each LCI dataset in a consistent way. Since no standard, joint convention or internationally accepted method currently exists between database developers which dictates how to define the name for datasets, the Ecoinvent format is proposed for future harmonisation of the SSSD as Ecoinvent is the largest and the most common background database used by the E-LCA community.

The next step is to implement automatic import/export algorithms to support design automation. To do this, it is proposed that an application programming interface (API) will be created which automates the sustainable design process within concurrent engineering sessions and allows other SMART software programmes to communicate with one another. Similar to the intended functions of Space Opera, in this sense, the API will establish a working connection between the SSSD and OCDT to allow for complete sharing of data through an automatic import/export algorithm with various flexible parameters. The possibility of applying this to multiple design tools (other than the OCDT and CDP4) will also be investigated. Additionally, it is intended that the API will also allow the SSSD to communicate with different tools within SMART and to support design automation of complex space systems using one or multiple performance criteria. This is based on evidence-based optimisation with evidence network models where a generic or complex system can be represented as a network, where each node is a subsystem and information is shared through links between subsystems [367]. This will facilitate effective communication between SMART tools, using the SSSD as part of this optimisation criteria.

After the API is created, the next step scheduled is to integrate automation and artificial intelligence (AI) methods to automatically predict environmental impacts of space systems within the sustainable design process using a cognitive system of intelligent agents. Based on the work of Haapala et al. [368], the methodology proposed for this in the first instance is a morphological matrix-based approach to automatically predict life cycle impacts of mission designs based on information contained within SSSD datasets and OCDT design repository data. In this regard, a concept generation algorithm will be implemented which relates SSSD datasets to OCDT data and translates this into a function adjacency matrix. This matrix will then undergo a series of multiplications to map design impacts and highlight potential hotspots. However, an eventual transition to artificial intelligence is envisioned to synthesise potential solutions for these identified design hotspots. In a similar manner to the methodology proposed by Nabavi-Pelesaraei et al. [369], this will likely be based on artificial neural networks. Additional learning algorithms can then be implemented in Matlab or Python to train these artificial neural networks to identify appropriate solutions to these identified sustainability hotpots outlined within the API using a morphological matrix-based approach [370–372]. Therefore, this new learning surrogate LCSA model will allow potential optimised solutions to be mapped whilst filtering out infeasible component-to-component connections based on the OCDT repository data.

The output from this will be a set of concept variants which can be used by engineers to lower potential sustainability impacts across the entire system with respect to MCDA without negatively affecting performance. In this regard Kraines et al. developed a knowledge-based system that leverages ontologies to merge expert knowledge into a single platform [373]. A similar approach could be adopted for the transfer of knowledge between disparate disciplines engaged in the design process to communicate this information. The neural network may also be used to identify any similarities and differences between new and previous design iterations. Therefore, the combination of these automated and AI approaches allows analyses to made which avoid sub-optimisation and problem shifting to create space products which fulfils market demand in a more sustainable way [374].

7.4.3 Future Research Application

From January 2019, the SSSD has been requested by a number of organisations to provide data pertaining to the life cycle environmental, social and economic impacts of their space mission designs within concurrent engineering sessions. One example of this is the proposed Phase A SPACE Canada mission. SPACE Canada are a not-for-profit organisation dedicated to promoting, supporting and encouraging international dialogue on SBSP through research, education and commercialisation. Their proposed mission is called the 'SPACE Canada SBSP LEO Constellation Demonstration Project' which aims to demonstrate technologies related to SBSP for the first time through a pathfinder mission to be launched into LEO before 2030.

The SBSP concept aims to provide an alternative renewable energy source to conventional ground-based solar power by capturing solar power in space and wirelessly transmitting it back to Earth where it can be harnessed [66]. However, no in-orbit demonstrations have ever taken place due to the high initial upfront cost. SBSP has also traditionally been marketed as a green technology since there are no conceivable emissions attributable to its utilisation. However, this ignores the environmental impacts arising from other areas of its life cycle which reemphasises the need for E-LCA to be conducted on this technology. Despite this, very few E-LCA studies have ever taken place for SBSP. Those that do adopt an EEIO analysis and limit the scope exclusively to CO_2 emissions [375, 376]. This has meant that there has been no scientific evidence robust enough to support such an environmental claim, or indeed to justify any kind of environmental declaration.

As such, SPACE Canada partially funded this research in order to create a tool which can be used in a CDF session to quantitatively and scientifically gauge the life cycle environmental and costing impacts of the mission in order to address the green marketing claim and to potentially justify mission funding. For this reason, the SPACE Canada mission seeks to develop a low-cost, environmentally-friendly demonstration mission as proof of concept which is intended to act as a catalyst for the technology to be utilised for disaster relief and/or as an alternative clean energy solution. Therefore, a key component of this project is to apply the SSSD during early design phases primarily to assess environmental and costing impacts as well as social aspects to ensure that the mission is as sustainable as it can possibly be.

In addition to its use within concurrent design, it can be reported that several requests for access to the SSSD have already been registered at the University of Strathclyde. In particular, researchers in Australia and the USA have stated that they wish to use the SSSD to investigate life cycle impacts of asteroid mining. This reaffirms the benefit of the SSSD to the space industry and highlights the growing responsibility of the sector with regards to addressing the impacts of their activities. As such, if an agreement can be reached with Ecoinvent, it is expected that the use of the SSSD will begin and continue to grow within the space sector. It is hoped that in conjunction with the space-specific LCSA framework, this will help to facilitate streamlined decision-making and monitoring in a more systematic and coordinated fashion which accords with the renewed vision of sustainability outlined in the 2030 Agenda.

In this regard, whilst ESA is currently not pursuing LCSA themselves, it is something that they may consider moving towards in the next few years. Moreover, the Clean Space Initiative has already expressed an interest in potentially combining the SSSD with the ESA E-LCA database at some point in the near future [33]. Although this was stated in an unofficial capacity, it demonstrates the importance and influence of this research within the space sector. The rationale behind this is to facilitate the aggregation of all space-specific life cycle approaches, assessment types and methodologies in one centralised location. In this regard, it would perhaps be advantageous for an international protocol to be developed which governs the harmonisation of E-LCA/LCSA for space technologies. Such an approach may allow the topic to be advanced further in a more coordinated and streamlined manner.

7.5 Chapter Summary

The contribution and significance of annual environmental, social and economic impacts of space activities have been outlined. This benchmarked the impacts of these for the first time, highlighting the importance of the space-specific LCSA framework and database in controlling such impacts. The proposed contributions of this research were then discussed. From this, it was determined that the stated aim and objectives of this study were suitably satisfied. This indicates that the space-specific LCSA framework and database are now ready for public dissemination if an agreement can be reached with Ecoinvent. As such, planned future work was outlined with a view of ensuring the long-term use of these elements within the space industry.

Chapter 8

Conclusion, Limitations & Recommendations

8.1 Chapter Overview

The final chapter will draw conclusions from this research based on the scientific contributions to knowledge outlined in the previous chapter. Limitations indicated throughout this thesis will also be discussed in more detail in order to frame a list of recommendations as a basis for future research on the topic of space-specific LCSA.

8.2 Conclusion

This research has presented a new and verified approach for integrating social and economic principles into life cycle modelling of space systems for concurrent design applications. In particular, the establishment of a new space-specific LCSA framework provides a credible and compelling new method of streamlining decision-making for sustainability in a more systematic and coordinated fashion. However, the novelty of this research does not exclusively lie in the development of the framework, but on its application through the new space-specific LCSA database. This database provides a set of consolidated LCI datasets and LCIA methods for LCSA which can be used within the space industry to allow the sector to become more accountable and responsible for their operations by taking into account the full spectrum of life cycle impacts and sustainability issues associated with the operation of space systems. Assuming that an agreement can be reached with Ecoinvent, it can be used to bridge the gap between the lack of process-based life cycle databases for space systems and the public dissemination of the ESA tools.

The aim of this study was to successfully transition the E-LCA methodology for space systems towards a more holistic approach of sustainability assessment which aligns with the global aspirations envisaged within the 2030 Agenda for Sustainable Development. As such, alignment of this methodology to the 2030 Agenda was particularly important. In this regard, the SDGs have been integrated into the sustainable design process at a micro level through S-LCA social indicators whilst allowing the three dimensions of sustainability to be considered and balanced in accordance with the 2030 Agenda through MCDA. Therefore, this methodological choice means that the space-specific LCSA database can be used to influence design decisions in the frame of the most dominant political framework for sustainability currently in existence.

The space-specific LCSA database has been built so that it is capable of generating life cycle results within a product design scenario or more generally. The integration of this approach within the concurrent design processes is particularly useful since the majority of adverse sustainability impacts are set by choices made during early design stages. Since these impacts are easier to modify the earlier into the design process that they are identified, the integration of the space-specific LCSA database within space mission design sessions has great potential to influence the sustainability footprint of the space industry, which have been identified for the first time, mapping impact contribution against severity. From running the tool within two selected CDF studies, the importance of considering all three dimensions of sustainable development to assist decision-makers in creating next generation sustainable space systems has been demonstrated. In this regard, the inclusion of MCDA has helped to determine hotspots across each sustainability aspect and the mission as a whole, based on the 2030 Agenda. This was the first time that LCSA impacts have been modelled for space systems.

Due to the fulfilment of each study objective outlined in Section 7.3, it can be concluded that the initial aim of this research has been satisfied through the establishment of a new space-specific LCSA framework and methodology for space systems and the provision of a fully-functioning, validated and test-proven LCSA database which also acts as a sustainable design tool within concurrent engineering sessions of space missions. As such, it is hoped that these outputs will contribute to the global sustainability agenda by assisting decision-makers to design space missions that are not only cost-efficient, eco-efficient and socially responsible, but also ones that can easily justify and evidence their sustainability in the frame of the 2030 Agenda for Sustainable Development.

8.3 Limitations

Despite the fulfilment of the initial aim, limitations were prevalent during this research due to the nascent nature of the field. These limitations were documented throughout this body of work in order to put the research findings into context, interpret their validity and ascribe a credibility level to the resulting conclusions. Whilst measures were put in place to lessen the influence of these limitations, these could not always be completely overcome. The limitations presented within this thesis will therefore be discussed in more detail as a basis for future research on the topic so that any identified gaps in knowledge can be addressed.

Firstly, the availability of literature on E-LCA in the space sector was severely lacking and surrounded by confidentiality concerns whilst information on S-LCA of space systems was completely non-existent. This severely restricted the foundations on which this research could be based. However, it was considered that a sufficient amount of literature was able to be obtained which could be used as a basis on which new or adapted LCSA methodologies could be formed.

Access to primary data was highly restricted which meant that the data contained within the SSSD is mainly based on secondary sources. This data collection and deployment process made developing the SSSD highly resource and time intensive which severely restricted the number of datasets and competing LCIA methods which could be generated. To ease this process, the ELCD and Ecoinvent were used as a background inventory. However, it was found that this severely limited the SSSD's use as an open-source and free software model. To counter this, provisions are being put into place which will allow the SSSD to be remain freely available to the wider space community subject to certain conditions in order to maintain compliance with the Ecoinvent terms and conditions of use (see Subsection 4.6.4).

Due to lack of available or reliable data, many LCI datasets used generalised data (e.g. launch event processes). This was particularly prevalent in the sustainability footprint analysis of the space sector. As such, careful interpretation of results is advised if further studies are to be based on this output. Additionally, the lack of scientific research on some topics meant that characterised results could not always be achieved meaning that placeholder flow indicators had to be used instead. Although this limits the contribution of such flows to the other impact categories, it ensures that vital impact areas are not overlooked.

Whilst data quality has been included within each LCI dataset, since system processes have been used, this means that uncertainty analysis is currently unable to be calculated at system level. This is particularly problematic when considering the generalisation of LCI datasets. To counter this, the pedigree approach was applied at process level to provide qualitative information regarding data quality. In terms of validation, the exercise undertaken with ESA provided a 30% coverage of SSSD LCI datasets which were validated. This did not include launch segment LCI datasets since these datasets were classed as highly confidential at ESA meaning that they could not be validated during the validation exercise. To counter this, a comparability analysis was conducted which suggests the alignment of these LCI datasets. Validation procedures for social or economic criteria have not yet taken place due to a lack of data which can be compared. This limits the validity of results for these two assessments. Full results disclosure from the ESA validation exercise is not permitted due to a confidentiality agreement which is in place with ESA. However, the resulting report has been retained internally for documentation purposes.

Due to the problems stated for S-LCA in Section 3.5, a completely new approach has been adopted meaning that appraisal of this method is perhaps needed by independent experts. This has not yet occurred, however feedback from industry experts provided during conferences has been fed back into the development of this method. However, an obvious drawback of this approach is the level of specificity required to conduct the S-LCA proposed by the space-specific LCSA framework. Since an organisational approach was developed, the SSSD currently contains no social data. This is due to a lack of willingness from organisations to contribute data. However, this was not considered to be a hindrance since it is expected that organisations should apply data related to their own supply chain but is an extremely time consuming task for the S-LCA practitioner to facilitate. Additionally, the benchmarks used in the evaluation scheme of each social indicator require consistent checks and reviews due to potential political and/or regulatory shifts, cultural changes, overpopulation, migration, etc. However, it could be argued that this is perhaps an unavoidable aspect of S-LCA.

Costing data is also open to subjectivity and will require constant updating due to potential changes in supply and demand, inflation, exchange rates, devaluation or other shifts in economic processes. Additionally, a major bug was discovered during the MÌOS mission concerning a linking issue of CERs during vertical aggregation. Manual corrective measures were put in place during these studies to avoid generating vastly incorrect results but this issue is still prevalent.

Only 13 out of the 25 E-LCA midpoint impact categories (including S-LCA and LCC as single scores) are considered as part of the MCDA approach due to the availability of normalised and weighted values. This has the potential to shift focus away from other potential meaningful impacts and may lead to a level of predetermined importance of particular impact categories in comparison to others which can cause a burden shifting effect. Additionally, it may be difficult for non-LCSA experts to interpret absolute MCDA results as a single score. As such, relative results may present a better approach.

Although the SSSD can be run independently of concurrent design studies, it also has the capability to act as a plug-in to the OCDT in order to simply exchange information. As such, when integrating the SSSD into concurrent design, a far more simplistic approach developed than Space Opera. This method is far more time consuming and labour intensive which opens up the possibility to human error. Despite this, the approach eliminates the possibility of decentralisation errors occurring as experienced by Space Opera. It was found that not all necessary components were included within the SSSD during the MÌOS and NEACORE studies. To counter this, a best fit alternative had to be chosen instead. Although spacecraft components will continue to be added to the SSSD, a complete coverage of all components is unlikely during a mission design session due to the specialised and often unique nature of components within the space sector. It was also found that it was difficult to model more than two scenarios within the SSSD, which restricted its functionality as a comparative tool. However, as the ESA E-LCA guidelines do not recommended comparisons take place between different space missions due to inherent variations in mission design and goals, it can be considered that a comparison of two different design options is sufficient for use within the SSSD.

Finally, it could be argued that the creation of E-LCA LCI datasets is duplicating the work of ESA. However, since the ESA E-LCA database is currently only available under contract, the development of the SSSD was deemed necessary in order to integrate social and economic criteria. Therefore, the SSSD provides a more transparent and open outlook with regards to its methodology and acts as the only LCSA database for space systems in existence.

8.4 Recommendations

The novelty of the work presented within this thesis means that further development is required in order to streamline its use within the space sector. The following recommendations have been provided as a basis for future research on the topic of space-specific LCSA in order to address the limitations listed in Section 8.3 above and further consolidate/advance this work:

- Future E-LCA/LCSA research within the space sector should strive to limit the amount of information which is bound by confidentiality agreements.
- Further research into the environmental impacts of space missions is required for a deeper analysis and to fill gaps in data. Specifically, it was found that

there are particular gaps involving atmospheric re-entry and deep sea ecology impacts. Therefore, the effects of satellite re-entry on the upper atmosphere could be investigated in more depth to characterise the behaviour, fate and composition of RSPs including their influence on Earth's atmosphere, propagated over a period of time. In terms of deep sea ecology impacts, the environmental and biological effects of disposed launcher and satellite bodies in zones where residues are known to fall back could also be characterised. In this regard, data could be collected for metal and non-metal degradation behaviour with respect to specific local environmental conditions such as ocean depth and oxygen availability. Other studies could also be conducted into impacts from unexpected circumstances such as launcher explosions, to cover a wide range of scenarios.

- Further research into S-LCA is required at a general level and within the space industry. In particular, this relates to the selection of appropriate social indicators, scoring mechanisms and evaluation scheme benchmarks. In this regard, it may be advantageous to align the S-LCA approach for space systems with the space sustainability rating system developed by the WEF once it is published.
- Regular refinement and elaboration of the proposed space-specific LCSA framework should occur, as mentioned in Subsection 7.4.1. This should include consistent review of the S-LCA evaluation scheme benchmarks due to potential political and/or regulatory shifts, cultural changes, overpopulation, migration, etc.
- The programme of work outlined in Subsection 7.4.2 should be followed in order to ensure the continued development of the SSSD. This includes the provision of new and updated LCI datasets if more specific data becomes available. In this regard, attempts to include organisational or national-level S-LCA data should be pursued whilst efforts should be made to fix the LCC CER linking problem identified during the MÌOS study.
- Potential pathways which could allow the SSSD to be made widely available to industry should be explored in order to provide the space sector with a set of consolidated LCSA datasets for space systems. This should take into account the

most appropriate legalities and mechanisms to ensure compliance and accountability with respect to expected codes of conduct.

- A transition from data quality information at system level using the pedigree approach to flow level should be pursued for all SSSD LCI datasets. Further validation procedures should also be conducted for LCI datasets which could not be validated. This also includes validation all social and economic data.
- A more appropriate and scientifically robust S-LCA normalisation method should be sought for MCDA. Additionally, it would be useful to develop a new set of NFs and WFs for all impact categories within the SSSD E-LCA midpoint LCIA method (including S-LCA and LCC as single scores) to create a score reflecting performance within MCDA which considers all 25 impact categories.
- Future LCSA concurrent design studies of space missions should be based on the space-specific LCSA framework. However, in addition to the complete sharing of data within mission design sessions, verbal communication and interpretation of results to non-LCSA experts is also crucial if sustainable design is to occur.
- More research should be conducted into the inter-relationship between static and dynamic elements within space mission design.
- The identification of sustainability hotspots using MCDA could be worth investigating to assess if there are any commonalities or recurrences between mission types.
- The sustainability impact of the space sector outlined in Section 7.2 provides a first order approximation of the sustainability footprint of the space sector using a highly simplified methodology. As such, a more detailed sustainability footprint analysis should be conducted if data becomes available.
- More demonstrations of LCSA applied within the space sector is required to streamline this approach within the industry. The space-specific LCSA framework and database presented by this research can act as the foundations for this.
- An international protocol should be established which governs the harmonisation of E-LCA/LCSA for space technologies.

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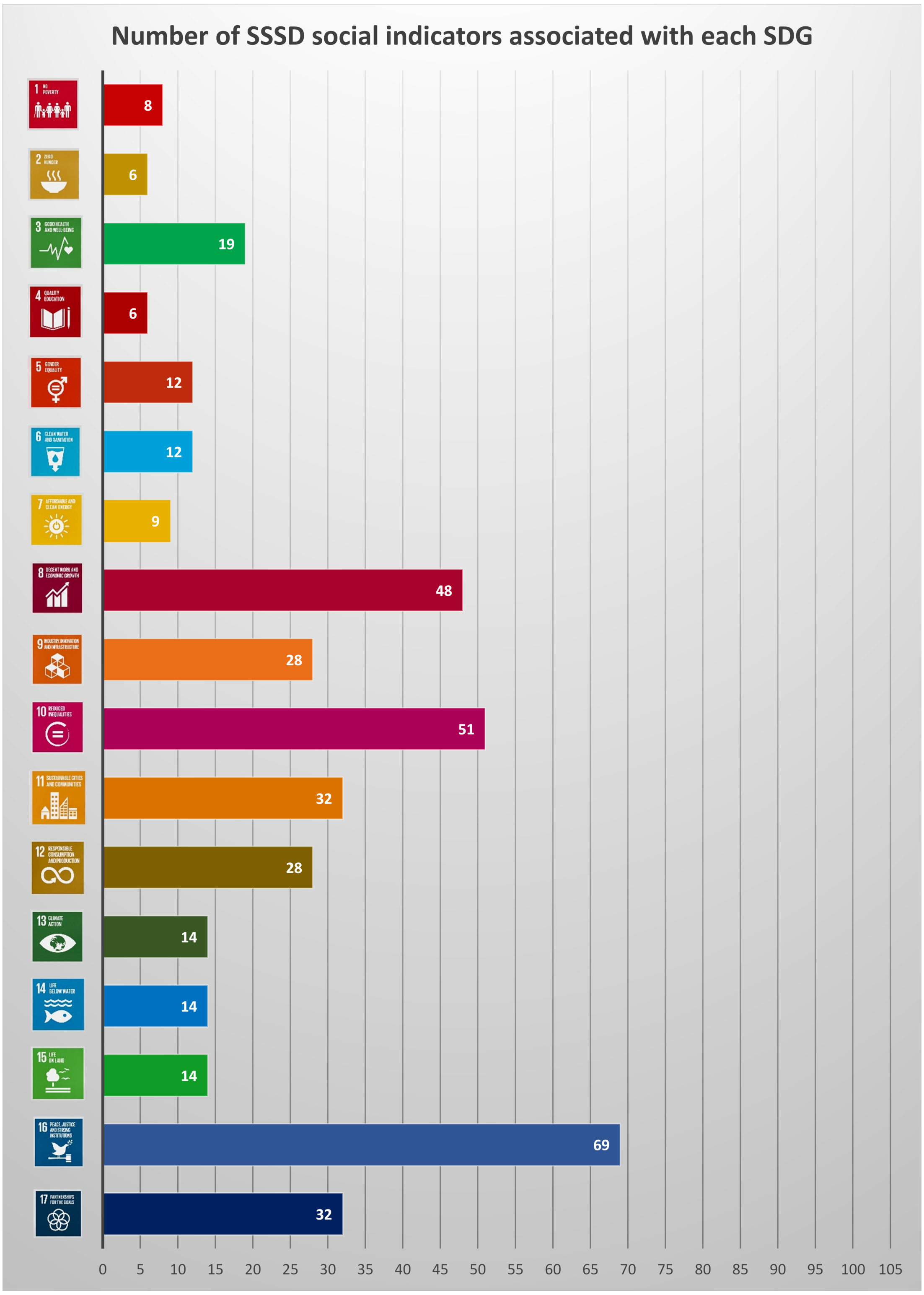
Appendices

A List of SSSD Social Indicators

A1 Overview of SSSD stakeholder categories and subcategories

Stakeholder Categories & Subcategories	Indicator Information		
	Number of Indicators	Indicator Activity Variable (Single Score Contribution to Process) (%)	Comments
Consumer			
Consumer Privacy	3	1.11111	-
End of Life Responsibility	2	1.66666	-
Feedback Mechanism	3	1.11111	-
Health & Safety	3	1.11111	-
Product/Service Competency	3	1.11111	New Stakeholder Subcategory
Transparency	4	0.83333	-
Local Community			
Access to Immaterial Resources	4	0.55555	-
Access to Material Resources	3	0.74074	-
Community Engagement	4	0.55555	-
Cultural Heritage	3	0.74074	-
Delocalisation & Migration	3	0.74074	-
Local Employment	2	1.11111	-
Respect of Indigenous Rights	3	0.74074	-
Safe & Healthy Living Conditions	4	0.55555	-
Secure Living Conditions	4	0.55555	-
Society			
Contribution to Economic Development	4	1.00000	-
Corruption	2	2.00000	-
Prevention & Mitigation of Armed Conflicts	2	2.00000	-
Public Commitments to Sustainability Issues	3	1.33333	-
Technology Development	3	1.33333	-
Value Chain Actors			
Fair competition	2	2.50000	-
Promoting Social Responsibility	3	1.66666	-
Respect of Intellectual Property Rights	2	2.50000	-
Supplier Relationships	3	1.66666	-
Worker			
Child Labour	3	0.74074	-
Equal Opportunities/Discrimination	4	0.55555	-
Fair Salary	4	0.55555	-
Forced Labour	2	1.11111	-
Freedom of Association & Collective Bargaining	2	1.11111	-
Health & Safety	7	0.31746	-
Social Benefits/Social Security	3	0.74074	-
Wellbeing of Staff	5	0.44444	New Stakeholder Subcategory
Working Hours	3	0.74074	-
TOTAL	**(105)**	**99.99972**	-

A2 Number of SSSD social indicators associated with each SDG



A3 List of SSSD social indicators for Consumer (C)

Consumer Privacy (C.1)

1. Amount spent on consumer privacy
2. Number of privacy breaches & complaints received with number of legal actions
3. Organisational practice with regards to data protection legislation

End of Life Responsibility (C.2)

1. Average incidents of non-compliance with proper disposal/labelling practices
2. Organisational practice with regards to consumer end of life options

Feedback Mechanism (C.3)

1. Improvement measures for customer feedback & satisfaction level practices
2. Presence of feedback mechanisms to gather information/opinion
3. Total number of complaints versus percentage of complaints resolved

Health & Safety (C.4)

1. Complaints made regarding consumer health & safety
2. Health & safety information provided to consumers
3. Measures in place to address consumer health & safety

Product/Service Competency (C.5)

1. Intrinsic product value
2. Product legacy
3. Product quality

Transparency (C.6)

1. Company rating in sustainability indices
2. Full disclosure within performance reports including sustainability & project...
3. Measures to foster accountability with number of certifications & labels obtained
4. Non-compliance regarding transparency & consumer complaints

A4 List of SSSD social indicators for Local Community (L)

Access to Immaterial Resources (L.1)

1. Community education initiatives
2. Freedom of expression in country of operation
3. Public access to information in country of operation
4. Success of patents & copyrights system to protect intellectual property

Access to Material Resources (L.2)

1. Certified Environmental Management System
2. Levels of land use, water use & natural resource extraction
3. Organisational infrastructure with mutual community access & benefit

Community Engagement (L.3)

1. Charitable giving & tackling of social problems
2. Diversity of engaged stakeholder groups
3. Number & quality of meetings with local community
4. Strength of written policies & mechanisms for community engagement

Cultural Heritage (L.4)

1. Efforts to preserve & protect cultural heritage
2. Strength of written policies & mechanisms for cultural heritage
3. Total expenditure on cultural heritage

Delocalisation & Migration (L.5)

1. Integration of migrant workers into the local community
2. Net migration rate
3. Transaction costs of migrant remittances

Local Employment (L.6)

1. Locally hired workforce
2. Local procurement

Respect of Indigenous Rights (L.7)

1. Levels of discrimination against indigenous community members
2. Number & quality of meetings with indigenous community members
3. Strength of written policies & mechanisms to protect indigenous rights

Safe & Healthy Living Conditions (L.8)

1. Application of best practice/breaches of laws & regulations
2. Burden of disease/pollution levels within country of operation
3. Community based projects to secure safe & healthy living conditions
4. Efforts to minimise use of hazardous materials, substances & processes

Secure Living Conditions (L.9)

1. Policies related to private security personnel
2. Rate of causalities/injuries ascribed to the organisation
3. State of hired/sub-contracted security staff
4. State of security & human rights in country of operation

A5 List of SSSD social indicators for Society (S)

Contribution to Economic Development (S.1)

1. Contribution to economic development & commercial enterprise
2. Job creation
3. Percentage of annual spending on educational opportunities
4. Resource allocation to impoverished areas

Corruption (S.2)

1. Active involvement of entities in corruption/bribery
2. Corruption perceptions/allegations

Prevention & Mitigation of Armed Conflicts (S.3)

1. Business conducted within countries where armed conflicts are present
2. Product association with weapons

Public Commitments to Sustainability Issues (S.4)

1. Complaints & accountability in sustainability reporting
2. Existence of & engagement in sustainability obligations
3. Robustness of monitoring & evaluation system for sustainability measures

Technology Development (S.5)

1. R&D spending
2. Technology readiness level & innovation
3. Technology transfer

A6 List of SSSD social indicators for Value Chain Actors (V)

Fair Competition (V.1)

1. Evidence of anti-competitive behaviour
2. Risk of breaking competition laws

Promoting Social Responsibility (V.2)

1. Integration of sustainability issues/policies amongst value chain actors
2. Levels of social responsibility along the supply chain
3. Rights of workers maintained

Respect of Intellectual Property Rights (V.3)

1. Infringement of intellectual property rights
2. Security offered by national intellectual property protection laws

Supplier Relationships (V.4)

1. Payments to suppliers
2. Sufficient lead time
3. Supplier relationship management survey scores

A7 List of SSSD social indicators for Workers (W)

Child Labour (W.1)

1. Amount of child labour
2. Number of children exposed to hazardous work
3. Total children in employment

Equal Opportunities/Discrimination (W.2)

1. Breakdown of employees by gender, age, race, ethnicity etc.
2. Complaints made regarding discrimination
3. Gender wage gap
4. Male-to-female worker ratio

Fair Salary (W.3)

1. Complaints regarding deductions in pay
2. Employees receiving minimum/living wage or less
3. Paid time off
4. Sector average annual wage

Forced Labour (W.4)

1. Percentage of forced labour
2. Voluntarily agreed upon employment terms & transparent contracts

Freedom of Association & Collective Bargaining (W.5)

1. Employees covered by collective bargaining
2. Employees which are members of trade unions or other organisations

Health & Safety (W.6)

1. Presence of sufficient policies & safety measures
2. Rate of fatal accidents at the workplace
3. Rate of near misses at the workplace
4. Rate of non-fatal accidents at the workplace
5. Success of mechanisms to fight violence/harassment
6. Suitable facilities
7. Suitable support mechanisms for health and wellbeing

Social Benefits/Social Security (W.7)

1. Comprehensive social benefit coverage
2. Comprehensive social security coverage
3. Evidence of violation of laws & employment regulations

Wellbeing of Staff (W.8)

1. Employee creativity
2. Employee productivity
3. Opportunities for professional growth
4. Staff morale
5. Total number of redundancies

Working Hours (W.9)

1. Average weekly working hours of employees
2. Respect of contractual agreements concerning working hours
3. Total number of workers on temporary, part time and/or zero hour contracts

A8 SSSD social indicator information

C.1.1

Evaluation Schemes: % of annual revenue spent on consumer privacy

Sources: Khan, M. (2017); Fortune (2018)

Affected SDGs: 16

C.1.2

Evaluation Schemes: (1) Score: Breaches per person; (2) Score: Complaints per person; (3) Score: Legal actions per person

Sources: Lord, N. (2017); United States Department of Health & Human Services (2017); United States Census Bureau (2017)

Affected SDGs: 16

C.1.3

Evaluation Schemes: Score: Organisational Data Protection compliance points

Sources: Wilson, A. R. (2019)

Affected SDGs: 16

C.2.1

Evaluation Schemes: % of annual waste disposal not compliant with applicable regulations

Sources: WHO (2015)

Affected SDGs: 12, 13, 14, 15, 17

C.2.2

Evaluation Schemes: Score: End of life options points

Sources: Wilson, A. R. (2019)

Affected SDGs: 12, 13, 14, 15, 17

C.3.1

Evaluation Schemes: Score: Customer feedback & satisfaction levels improvement points

Sources: Wilson, A. R. (2019)

Affected SDGs: 8, 16, 17

C.3.2

Evaluation Schemes: Score: Effectiveness of feedback mechanism type

Sources: Zajdo, C. (2018); Wilson, A. R. (2019)

Affected SDGs: 8, 16, 17

C.3.3

Evaluation Schemes: (1) Score: Number of complaints per 100,000 employees; (2) Score: % of customer complaints resolved within five working days

Sources: United States Equal Employment Opportunity Commission (2014); NASA (2016); Newell-Legner, R. (2008)

Affected SDGs: 8, 16, 17

C.4.1

Evaluation Schemes: Number of complaints per 100,000 employees

Sources: Health & Safety Executive (2017); Office for National Statistics (2018)

Affected SDGs: 3, 6, 7, 9, 10, 11, 16

C.4.2

Evaluation Schemes: Score: Quality of health & safety information provided by issues covered

Sources: Health & Safety Executive (2014)

Affected SDGs: 3, 6, 7, 9, 10, 11, 16

C.4.3

Evaluation Schemes: Score: Issues addressed to ensure consumer health & safety

Sources: Wilson, A. R. (2019)

Affected SDGs: 3, 6, 7, 9, 10, 11, 16

C.5.1

Evaluation Schemes: Average customer satisfaction levels

Sources: Institute of Customer Service (2016)

Affected SDGs: 8, 9, 10

C.5.2

Evaluation Schemes: Average long-term outcomes achieved

Sources: Wilson, A. R. (2019)

Affected SDGs: 8, 9, 10

C.5.3

Evaluation Schemes: Average number of goals & objectives met

Sources: Wilson, A. R. (2019)

Affected SDGs: 8, 9, 10

C.6.1

Evaluation Schemes: Average organisational placing within independent sustainability indices

Sources: Wilson, A. R. (2019)

Affected SDGs: 12, 13, 14, 15, 17

C.6.2

Evaluation Schemes: Score: Transparency disclosure points

Sources: Wilson, A. R. (2019)

Affected SDGs: 12, 13, 14, 15, 17

C.6.3

Evaluation Schemes: (1) Score: Accountability points; (2) Score: Certification & labels achieved

Sources: Ressler, C. (2013); Allison, C. & Carter, A. (2000)

Affected SDGs: 8, 9, 12, 16

C.6.4

Evaluation Schemes: (1) Score: Severity of non-compliance regarding transparency; (2) Score: Freedom of info requests completed outwith statutory timescales; (3) Score: Number of complaints regarding transparency as % of total
Sources: Wilson, A. R. (2019); Cabinet Office National Statistics (2018); Teffer, P. (2017)
Affected SDGs: 8, 9, 12, 16

L.1.1

Evaluation Schemes: Score: Community education initiative type
Sources: General Assembly resolution 71/313; Wilson, A. R. (2019)
Affected SDGs: 4, 10

L.1.2

Evaluation Schemes: Country score in Free Expression Index
Sources: Wike, R. & Simmons, K. (2015)
Affected SDGs: 5, 10, 11, 16

L.1.3

Evaluation Schemes: (1) Score: Country score in Global Right to Information Rating Map; (2) Score: Number of journalists kidnapped, killed, detained or missing annually
Sources: Access Info & Centre for Law and Democracy (2018); Reporters Without Borders (2017)
Affected SDGs: 9, 16

L.1.4

Evaluation Schemes: (1) Score: Annual number of patent filings per 100,000 employees; (2) Score: Annual number of copyright infringements per 100,000 employees
Sources: WIPO (2017); UK Office for National Statistics (2017); TRAC Reports (2016); Statista (2018)
Affected SDGs: 8, 9, 10, 16, 17

L.2.1

Evaluation Schemes: Stage & quality of organisational EMS

Sources: ISO Quality Services Ltd (2018); Wilson, A. R. (2019)

Affected SDGs: 12, 13, 14, 15, 16, 17

L.2.2

Evaluation Schemes: (1) Score: % of total national industrial land cover; (2) Score: % of total national freshwater withdrawals for industrial use; (3) Score: % of total national finite resource extraction for industrial use

Sources: European Commission (2017); World Bank (2018); OECD (2018)

Affected SDGs: 12, 13, 14, 15, 16, 17

L.2.3

Evaluation Schemes: Score: Shared community facility points met

Sources: Local Government Victoria (2010); Wilson, A. R. (2019)

Affected SDGs: 6, 7, 9, 10, 11

L.3.1

Evaluation Schemes: (1) Annual donation per employee; (2) Annual time dedicated per employee

Sources: NPT-UK (2018); UK Office for National Statistics (2017)

Affected SDGs: 1, 2, 3, 6, 7, 9, 10, 11

L.3.2

Evaluation Schemes: Representation as % of local community

Sources: Wilson, A. R. (2019); Office for National Statistics et al (2016)

Affected SDGs: 4, 5, 9, 10, 11, 12, 16

L.3.3

Evaluation Schemes: (1) Meeting regularity; (2) Score: Meeting quality

Sources: Local Government Association (2014); Right Track Associated (2017)

Affected SDGs: 4, 5, 9, 10, 11, 12, 16

L.3.4

Evaluation Schemes: Engagement monitoring & recognition

Sources: Wilson, A. R. (2019)

Affected SDGs: 4, 5, 9, 10, 11, 12, 17

L.4.1

Evaluation Schemes: Score: Points met for best practice initiatives

Sources: UNEP/SETAC (2013); Wilson, A. R. (2019)

Affected SDGs: 8, 11, 12, 13, 14, 15, 16

L.4.2

Evaluation Schemes: Score: Alignment with international standards

Sources: UNEP/SETAC (2013); Wilson, A. R. (2019)

Affected SDGs: 8, 11, 12, 13, 14, 15, 16

L.4.3

Evaluation Schemes: % of annual budget spent on cultural goods & services

Sources: European Commission (2016)

Affected SDGs: 8, 11, 12, 13, 14, 15, 16

L.5.1

Evaluation Schemes: Observation

Sources: European Commission (2016)

Affected SDGs: 8, 10, 11

L.5.2

Evaluation Schemes: Annual net migration rate per 100,000 inhabitants

Sources: European Commission (2017)

Affected SDGs: 8, 10, 11

L.5.3

Evaluation Schemes: Transaction costs as % of amount transferred

Sources: General Assembly resolution 69/313

Affected SDGs: 8, 10, 11

L.6.1

Evaluation Schemes: % of total workforce

Sources: UK Office for National Statistics (2017)

Affected SDGs: 8, 10, 11

L.6.2

Evaluation Schemes: % of supplier based spending

Sources: Cram (2012)

Affected SDGs: 8, 10, 11, 12

L.7.1

Evaluation Schemes: Complaints/incidents per 100,000 employees

Sources: World Bank (2018); Dodson, M. (1997)

Affected SDGs: 10, 11, 16

L.7.2

Evaluation Schemes: (1) Meeting regularity; (2) Score: Meeting quality

Sources: Local Government Association (2014); Right Track Associated (2017)

Affected SDGs: 8, 10, 11, 16, 17

L.7.3

Evaluation Schemes: Score: Alignment with international standards

Sources: UNEP/SETAC (2013); Wilson, A. R. (2019)

Affected SDGs: 8, 10, 11, 16, 17

L.8.1

Evaluation Schemes: (1) Score: Best practice points met; (2) Score: Severity of breach
Sources: Health & Safety Authority (2018); Wilson, A. R. (2019); Health & Safety Executive (2003)
Affected SDGs: 3, 9, 10, 11, 12, 16, 17

L.8.2

Evaluation Schemes: (1) Score: Average air pollution level by PM10 concentration; (2) Score: Average disease level by DALYs
Sources: Wheeler et al (1999); WHO (2015)
Affected SDGs: 1, 2, 3, 6, 13, 14, 15

L.8.3

Evaluation Schemes: Score: Issues addressed to secure public health & safety
Sources: Wilson, A. R. (2019)
Affected SDGs: 1, 2, 3, 6, 9, 10, 11, 12, 16, 17

L.8.4

Evaluation Schemes: Score: Hazardous waste minimisation
Sources: University of Iowa (2018)
Affected SDGs: 3, 12, 13, 14, 15, 16

L.9.1

Evaluation Schemes: Score: Core principle points met
Sources: ArcelorMittal (2011)
Affected SDGs: 1, 2, 5, 8, 11

L.9.2

Evaluation Schemes: (1) Annual casualties per 100,000 employees; (2) Annual injuries per 100,000 employees
Sources: UK Office for National Statistics (2017); Health & Safety Executive (2018); Trading Economics (2018); Health & Safety Authority (2014)
Affected SDGs: 3, 10, 11, 16

L.9.3

Evaluation Schemes: (1) Score: % of annual revenue spent on security; (2) Score: Complaints per 100,000 security employees

Sources: Institute of Finance & Management (2011); The Guardian (2011); G4S (2018)

Affected SDGs: 1, 2, 5, 8, 11

L.9.4

Evaluation Schemes: (1) Score: Human rights protection score; (2) Score: Military expenditure as % of GDP; (3) Score: Country Score in Global Peace Index

Sources: Roser, M. (2014); World Bank (2018); Institute for Economics & Peace (2018)

Affected SDGs: 1, 2, 4, 5, 8, 10, 11, 16

S.1.1

Evaluation Schemes: % of organisation economic growth per annum

Sources: IAEG-SGDs (2017); Trading Economics (2018)

Affected SDGs: 8, 9, 17

S.1.2

Evaluation Schemes: % of new jobs created in terms of total jobs

Sources: European Commission (2012)

Affected SDGs: 4, 8, 12

S.1.3

Evaluation Schemes: % of annual budget dedicated to education

Sources: NASA (2014); NASA (2015)

Affected SDGs: 4, 8,

S.1.4

Evaluation Schemes: % of annual budget dedicated to eradicating poverty

Sources: Greenberg (2017); World Bank (2018)

Affected SDGs: 1, 2, 3, 6, 7, 10, 11

S.2.1

Evaluation Schemes: Observation

Sources: Wilson, A. R. (2019)

Affected SDGs: 16

S.2.2

Evaluation Schemes: Perception/allegations per 100,000 employees

Sources: Serious Frauds Office (2015); UK Office for National Statistics (2017); Wilson, A. R. (2019); Helliwell, J., Layard, R. & Sachs, J. (eds.) (2017)

Affected SDGs: 16

S.3.1

Evaluation Schemes: (1) Total Product money flow; (2) Money flow per employee; (3) Country score in Global Peace Index

Sources: Stockholm International Peace Research Institute (2016); Institute for Economics & Peace (2018)

Affected SDGs: 16

S.3.2

Evaluation Schemes: (1) Score: Organisation's weapon association along supply chain; (2) Potential for product weaponisation

Sources: Wilson, A. R. (2019); Stockholm International Peace Research Institute (2016)

Affected SDGs: 16

S.4.1

Evaluation Schemes: (1) Level of complaints received regarding broken promises; (2) Progress reporting on sustainability measures

Sources: Wilson, A. R. (2019)

Affected SDGs: 12, 13, 14, 15, 16, 17

S.4.2

Evaluation Schemes: (1) % of targets met; (2) Strength of sustainability measures

Sources: Wilson, A. R. (2019)

Affected SDGs: 12, 13, 14, 15, 16, 17

S.4.3

Evaluation Schemes: Quality of the monitoring & evaluation scheme

Sources: Wilson, A. R. (2019)

Affected SDGs: 12, 13, 14, 15, 16, 17

S.5.1

Evaluation Schemes: R&D spending as % of product revenue/cost

Sources: PwC (2014)

Affected SDGs: 8, 9, 10, 16, 17

S.5.2

Evaluation Schemes: Score: TRL versus change in TRL

Sources: European Space Agency (2015)

Affected SDGs: 8, 9, 10, 16, 17

S.5.3

Evaluation Schemes: Annual number of transfers per employee

Sources: European Space Agency (2017); European Space Agency (2016); World Economic Forum (2017)

Affected SDGs: 8, 9, 10, 16, 17

V.1.1

Evaluation Schemes: Observation

Sources: Wilson, A. R. (2019)

Affected SDGs: 9, 16, 17

V.1.2

Evaluation Schemes: Observation

Sources: UK Government (2015)

Affected SDGs: 9, 16, 17

V.2.1

Evaluation Schemes: Observation

Sources: Bonini, S. & Görner, S. (2011)

Affected SDGs: 12, 16, 17

V.2.2

Evaluation Schemes: Score: Quality of initiatives & social responsibility practice

Sources: Caramela, S. (2016)

Affected SDGs: 12, 16, 17

V.2.3

Evaluation Schemes: % of total workforce

Sources: International Labour Organisation (2014)

Affected SDGs: 5, 8, 10, 12, 16, 17

V.3.1

Evaluation Schemes: % of money lost/gained through infringement

Sources: UK Government (2015)

Affected SDGs: 9, 16, 17

V.3.2

Evaluation Schemes: Scale

Sources: Rapp, R. & Rozek, R.P. (1990)

Affected SDGs: 9, 16, 17

V.4.1

Evaluation Schemes: % of late payments

Sources: Federation of Small Businesses (2011)

Affected SDGs: 12, 16, 17

V.4.2

Evaluation Schemes: % of projects completed on time

Sources: Wilson, A. R. (2019)

Affected SDGs: 12, 16, 17

V.4.3

Evaluation Schemes: Rating

Sources: Wilson, A. R. (2019)

Affected SDGs: 12, 16, 17

W.1.1

Evaluation Schemes: % of total workforce

Sources: International Labour Organisation (2011)

Affected SDGs: 8, 16

W.1.2

Evaluation Schemes: % of total workforce

Sources: International Labour Organisation (2011)

Affected SDGs: 8, 16

W.1.3

Evaluation Schemes: % of total workforce

Sources: International Labour Organisation (2011)

Affected SDGs: 8, 16

W.2.1

Evaluation Schemes: % of total workforce

Sources: UK Government (2016)

Affected SDGs: 5, 10, 16

W.2.2

Evaluation Schemes: Complaints received per 100,000 employees

Sources: UK Office for National Statistics (2017); UK Ministry of Justice (2012)

Affected SDGs: 5, 10, 16

W.2.3

Evaluation Schemes: Difference in earnings (%)

Sources: Ariane Hegewisch & Asha DuMonthier (2016)

Affected SDGs: 5, 10, 16

W.2.4

Evaluation Schemes: Male/female worker ratio

Sources: Institute of Engineering & Technology (2016); Bonnie Marcus (2014)

Affected SDGs: 5, 10, 16

W.3.1

Evaluation Schemes: Complaints received per 100,000 employees

Sources: UK Office for National Statistics (2017)

Affected SDGs: 8, 10

W.3.2

Evaluation Schemes: (1) % of total workforce (living wage); (2) % of total workforce (minimum wage)

Sources: UK Office for National Statistics (2015); Low Pay Commission (2017)

Affected SDGs: 1, 8, 10

W.3.3

Evaluation Schemes: Average annual paid time off per employee

Sources: Directive 2003/88/EC; Davis, C. (2013)

Affected SDGs: 8, 10

W.3.4

Evaluation Schemes: Average rate of pay per employee (GBP)

Sources: Payscale (2017)

Affected SDGs: 8, 10

W.4.1

Evaluation Schemes: Annual incidence per 100,000 employees

Sources: International Labour Organisation (2012)

Affected SDGs: 8, 16

W.4.2

Evaluation Schemes: Observation

Sources: UK Government (2017)

Affected SDGs: 8, 16

W.5.1

Evaluation Schemes: % of total workforce

Sources: Fulton, L. (2013)

Affected SDGs: 10, 16

W.5.2

Evaluation Schemes: % of total workforce

Sources: UK Government (2015)

Affected SDGs: 10, 16

W.6.1

Evaluation Schemes: Observation

Sources: Health & Safety Executive (2001)

Affected SDGs: 3, 6, 7, 9, 10, 11, 16

W.6.2

Evaluation Schemes: Annual incidence per 100,000 employees

Sources: European Commission (2017)

Affected SDGs: 3, 10, 11, 16

W.6.3

Evaluation Schemes: Annual incidence per 100,000 employees

Sources: Bird, F.E. Jr. & Germain, G.L (1996); British Glass (2015); European Commission (2017)

Affected SDGs: 3, 10, 11, 16

W.6.4

Evaluation Schemes: Annual incidence per 100,000 employees

Sources: European Commission (2017)

Affected SDGs: 3, 10, 11, 16

W.6.5

Evaluation Schemes: (1) % of total workforce exposed to violence; (2) % of total workforce exposed to harassment

Sources: Milczarek, M. (2010)

Affected SDGs: 5, 10, 16

W.6.6

Evaluation Schemes: Observation

Sources: International Labour Organisation (2014)

Affected SDGs: 3, 6, 7, 9, 10, 11, 16

W.6.7

Evaluation Schemes: Employee survey scores

Sources: Roger, S. (2011); Wilson, A. R. (2019)

Affected SDGs: 3, 6, 7, 9, 10, 11, 16

W.7.1

Evaluation Schemes: % of total workforce

Sources: Aon (2013)

Affected SDGs: 3, 8, 10, 16

W.7.2

Evaluation Schemes: % of total workforce

Sources: International Labour Organisation (2014)

Affected SDGs: 3, 8, 10, 16

W.7.3

Evaluation Schemes: Severity of violation

Sources: Wilson, A. R. (2019)

Affected SDGs: 3, 8, 10, 16

W.8.1

Evaluation Schemes: Annual no. of suggestions per 100,000 employees

Sources: Kolay, M.K. (2005)

Affected SDGs: 8

W.8.2

Evaluation Schemes: Annual value added per employee in EURO 2014

Sources: European Commission (2017)

Affected SDGs: 8

W.8.3

Evaluation Schemes: (1) % of employees gaining a pay rise or promotion; (2) % of employees meeting/exceeding performance targets

Sources: Wilson, R. (2019); European Commission (2016)

Affected SDGs: 8

W.8.4

Evaluation Schemes: Permanent staff retention rate

Sources: European Commission (2018)

Affected SDGs: 8

W.8.5

Evaluation Schemes: % of total workforce

Sources: UK Office for National Statistics (2018); UK Office for National Statistics (2017)

Affected SDGs: 1, 8

W.9.1

Evaluation Schemes: Hours per week

Sources: Mika Kivimäk et al (2015); EU Working Time Directive (2003/88/EC)

Affected SDGs: 8, 16

W.9.2

Evaluation Schemes: Average overtime (per worker or in hours)

Sources: Trades Union Congress (2016)

Affected SDGs: 8, 16

W.9.3

Evaluation Schemes: % of total workforce

Sources: UK Office for National Statistics (2017); UK Office for National Statistics (2015)

Affected SDGs: 8, 16

A9 Performance Criteria for each SSSD social indicator

Consumer

Indicator	No Risk (00.00)	V. Low Risk (20.00)	Low Risk (40.00)	Med Risk (60.00)	High Risk (80.00)	V. High Risk (100.00)
C.1.1	At or above 0.060%	0.048-0.060%	0.036-0.048%	0.024-0.036%	0.012-0.024	0.000-0.012%
C.1.2	0.00000 0.00000 0.00000	0.0000000-0.6250000 0.0000000-0.0009150 0.0000000-0.0001375	0.6250000-1.2500000 0.0009150-0.0018300 0.0001375-0.0002750	1.2500000-1.8750000 0.0018300-0.0027450 0.0002750-0.0004125	1.8750000-2.5000000 0.0027450-0.0036600 0.0004125-0.0005500	At or above 2.5000000 At or above 0.0036600 At or above 0.0005500
C.1.3	5 points	4 points	3 points	2 points	1 point	0 points
C.2.1	0-5%	5-10%	10-15%	15-20%	20-25%	At or above 25%
C.2.2	5 points or above	4 points	3 points	2 points	1 point	0 points
C.3.1	5 points	4 points	3 points	2 points	1 point	0 points
C.3.2	5 stars	4-5 stars	3-4 stars	2-3 stars	1-2 stars	0-1 stars
C.3.3	0-44 At 100.00%	44-88 97.75-100.00%	88-132 95.50-97.75%	132-176 93.25-95.50%	176-220 91.00-93.25%	At or above 220 At or below 91.00%
C.4.1	At 0.00	0.00-0.18	0.18-0.36	0.36-0.54	0.54-0.72	At or above 0.72
C.4.2	5 points	4 points	3 points	2 points	1 point	0 points
C.4.3	5 points or above	4 points	3 points	2 points	1 point	0 points
C.5.1	100.0000	76.1000-100.0000	71.8125-76.10000	68.2000-71.8125	34.1000-68.2000	0.0000-34.1000
C.5.2	Extremely positive	Positive	Neutral/slightly positive	Neutral/slightly negative	Negative	Extremely negative
C.5.3	100%	80-100%	60-80%	40-60%	20-40%	0-20%
C.6.1	Top organisation	Upper 0-20%	Upper 20-40%	Mid 40-60%	Lower 20-40%	Lower 0-20%
C.6.2	5 points or above	4 points	3 points	2 points	1 points	0 points
C.6.3	10 points 5 points	8-9 points 4 points	6-7 points 3 points	4-5 points 2 points	2-3 points 1 point	0-1 points 0 points
C.6.4	No evidence At 0.0% At 0.0%	Complaints received 0.0-2.0% 0.0-7.4%	Bad publicity 2.0-4.0% 7.4-14.8%	Org. investigated 4.0-6.0% 14.8-22.2%	Org. taken to court 6.0-8.0% 22.2-29.6%	Org. prosecuted At or above 8.0% At or above 29.6%

Local Community

Indicator	No Risk (00.00)	V. Low Risk (20.00)	Low Risk (40.00)	Med Risk (60.00)	High Risk (80.00)	V. High Risk (100.00)
L.1.1	5 points or more	4 points	3 points	2 points	1 point	0 points
L.1.2	At or above 5.7300	4.8125-5.7300	3.8950-4.8125	2.9775-3.8950	2.0600-2.9775	At or below 2.0600
L.1.3	At or above 136.00 At 0.00000 per 100,000 national population	110.25-136.00 0.00000-0.00149 per 100,000 national population	84.50-110.25 0.00149-0.00298 per 100,000 national population	58.75-84.50 0.00298-0.00447 per 100,000 national population	33.00-58.75 0.00447-0.00596 per 100,000 national population	At or below 33.00 At or above 0.00596 per 100,000
L.1.4	At or above 21.0 0.00-0.64	16.8-21.0 0.64-1.28	12.6-16.8 1.28-1.92	8.4-12.6 1.92-2.56	4.2-8.4 2.56-3.20	0.0-4.2 At or above 3.20
L.2.1	Obtained ISO 14001 certification	t Writing of Documentation stage for certificatio	t Initial Assessment stage for ceritficatio	EMS in place but not certified	In process of creating EMS	No EMS in place
L.2.2	0.00-0.66% 0.00-13.86% 0.00-13.20%	0.66-1.32% 13.86-27.72% 13.20-26.40%	1.32-1.98% 27.72-41.58% 26.40-39.60%	1.98-2.64% 41.58-55.44% 39.60-52.80%	2.64-3.30% 55.44-69.30% 52.80-66.00%	At or above 3.30% At or above 69.30% At or above 66.00%
L.2.3	5 points	4 points	3 points	2 points	1 point	0 points
L.3.1	At of above £11.00 At or above 13.5 mins	£8.80-11.00 10.8-13.5 mins	£6.60-8.80 8.1-10.8 mins	£4.40-6.60 5.4-8.1 mins	£2.20-4.40 2.7-5.4 mins	£0.00-2.20 0.0-2.7 mins
L.3.2	Age, Disability, LGBT, Race, Religion, Sex & Total	Age, Disability, LGBT, Race, Religion, Sex & Total	Age, Disability, LGBT, Race, Religion, Sex & Total	Age, Disability, LGBT, Race, Religion, Sex & Total	Age, Disability, LGBT, Race, Religion, Sex & Total	Age, Disability, LGBT, Race, Religion, Sex & Total
L.3.3	Weekly 4 points met	Bi-weekly 3 points met	Monthly 2 points met	Quarterly 1 point met	Annually 0 points met	Does not occur Does not occur
L.3.4	Monitoring in place & community awards	Policies in place & regular monitoring	ᵓolicies in place but no regular monitorinן	Contribution but no policies	No policies/mechanisms	Complaints received
L.4.1	At or above 5 points	4 points	3 points	2 points	1 point	0 points
L.4.2	13 to 14 points	10 to 12 points	7 to 9 points	4 to 6 points	1 to 3 points	At 0 points
L.4.3	At or above 3.60%	2.88-3.60%	2.16-2.88%	1.44-2.16%	0.72-1.44%	0.00-0.72%
L.5.1	5 criteria points	4 criteria points	3 criteria points	2 criteria points	1 criteria point	0 criteria points
L.5.2	0	0-95	95-190	190-285	285-380	At or above 380
L.5.3	Below 3.0%	3.0-3.5%	3.5-4.0%	4.0-4.5%	4.5-5.0%	At or above 5.0%
L.6.1	At 89.7%	67.3-89.7%; 89.7-92.3%	44.9-67.3%; 92.3-94.9%	22.4-44.9%; 94.9-97.4%	0-22.4%; 97.4-100%	At 0%; At 100%
L.6.2	At or above 10%	7.5-10%	5-7.5%	2.5-5%	0-2.5%	0%
L.7.1	At 0.00	0.00-0.55	0.55-1.10	1.10-1.65	1.65-2.20	At or above 2.20
L.7.2	Weekly 4 points met	Bi-weekly 3 points met	Monthly 2 points met	Quarterly 1 point met	Annually 0 points met	Does not occur Does not occur
L.7.3	13 to 14 points	10 to 12 points	7 to 9 points	4 to 6 points	1 to 3 points	At 0 points
L.8.1	At or above 5 points No breaches	4 points Claims or investigation made or in process	3 points Improvement/prohibition notice or other order	2 points Fine of up to £20,000	1 point Fine beyond £20,000	0 points Imprisonment
L.8.2	Pollution: At 0.0 Disease: At 0.0	Pollution: 0.0-14.0 Disease: 0.0-3634.1	Pollution: 14.0-28.0 Disease: 3634.2-7268.2	Pollution: 28.0-42.0 Disease: 7268.2-10902.3	Pollution: 42.0-56.0 Disease: 10902.3-14536.4	Pollution: At or above 56.0 Disease: At or above 14536.4
L.8.3	At or above 5 points	4 points	3 points	2 points	1 point	0 points
L.8.4	At or above 5 points	4 points	3 points	2 points	1 point	0 points
L.9.1	10	9	8	7	6	5 or under
L.9.2	At 0.00 At 0.00	0.00-0.03 0.00-4.75	0.03-0.06 4.75-9.50	0.06-0.09 9.50-14.25	0.09-0.12 14.25-19.00	At or above 0.12 At or above 19.00
L.9.3	At or above 3.370% 0.0-31.2	2.696-3.370% 31.2-62.4	2.022-2.696% 62.4-93.6	1.348-2.022% 93.6-124.8	0.674-1.348% 124.8-156.0	0.000-0.674% At or above 156.0
L.9.4	At 4 At or above 3.0% 1.0-1.5	2 to 4 2.4-3.0% 1.5-2.0	0 to 2 1.8-2.4% 2.0-2.5	0 to -2 1.2-1.8% 2.5-3.0	-2 to -4 0.6-1.2% 3.0-3.5	At -4 0.0-0.6% 3.5-4.0

Society

Indicator	No Risk (00.00)	V. Low Risk (20.00)	Low Risk (40.00)	Med Risk (60.00)	High Risk (80.00)	V. High Risk (100.00)
S.1.1	ELDCs: At or above 7.00% EMDCs: At or above 1.740%	ELDCs: 5.25-7.00% EMDCs: 1.305-1.740%	ELDCs: 3.50-5.25% EMDCs: 0.870-1.305%	ELDCS: 1.75-3.50% EMDCs: 0.435-0.870%	ELDCs: 0.00-1.75% EMDCs: 0.000-0.435%	ELDCs: At 0.00% EMDCs: At 0.000%
S.1.2	At or above 0.9%	0.6-0.9%	0.3-0.6%	0.0-0.3%	At 0.0%	A job loss rate
S.1.3	At or above 0.5300%	0.3975-0.5300%	0.2650-0.3975%	0.1325-0.2650%	0.0000-0.1325%	At 0.0000%
S.1.4	At or above 0.25%	0.20-0.25%	0.15-0.20%	0.10-0.15%	0.05-0.10%	0.00-0.05%
S.2.1	Measures/initiatives	No known involvement	Association through trade	Bad publicity	Taken to court	Proven guilty
S.2.2	0% 0	0-11.45% 0-0.01275	11.45-22.90% 0.01275-0.0255	22.90-34.35% 0.0255-0.03825	34.35-45.80% 0.03825-0.051	At or above 45.80% At or above 0.051
S.3.1	0.000% $0.00 1.0-1.5	0.000-0.575% $0.00-57.00 1.5-2.0	0.575-1.150% $57.00-114.00 2.0-2.5	1.150-1.725% $114.00-171.00 2.5-3.0	1.725-2.300% $171.00-228.00 3.0-3.5	At or above 2.300% At or above $228.00 3.5-4.0
S.3.2	0 No risk of weaponisation	0.0-0.2 May aid other weapons	0.2-0.4 Design prevents weaponisation	0.4-0.6 Could be used as weapon	0.6-0.8 Secondary use as weapon	0.8-1.0 Product is a weapon
S.4.1	No complaints Reports critically reviewed	Indiv. internal level Progress reports + improv.	Indiv. external level Public reports + progress	Local level Public reporting	National level Internal reporting	International level No reporting
S.4.2	100% International targets	80-100% Regional targets	60-80% National targets	40-60% Local targets	20-40% Internal targets	0-20% No targets
S.4.3	5 points	4 points	3 points	2 points	1 point	0 points
S.5.1	At or above 8.20%	6.15-8.20%	4.10-6.15%	2.05-4.10%	0.00-2.05%	0.00%
S.5.2	9-10	7-8	5-6	3-4	1-2	At 0
S.5.3	At or above 0.0100	0.0075-0.0100	0.0050-0.0075	0.0025-0.0050	0.000-0.0025	At 0.0000

Value Chain Actors

	No Risk (00.00)	V. Low Risk (20.00)	Low Risk (40.00)	Med Risk (60.00)	High Risk (80.00)	V. High Risk (100.00)
V.1.1	Measures/initiatives	No known involvement	Association through trade	Bad publicity	Taken to court	Proven guilty
V.1.2	No contact with competitors	0 points have occurred	1 point has occurred	2 points have occurred	3 points have occurred	4 or more points
V.2.1	Practice, Programme, Cert	Practice, Programme	Practice, No Programme	Activities, No Programme	No Activities, Programme	Nothing
V.2.2	11-12 points	9-10 points	7-8 points	5-6 points	3-4 points	0-2 points
V.2.3	0%	0-2.075%	2.075-4.15%	4.15-6.225%	6.225-8.3%	At or above 8.3%
V.3.1	0%	0.000-0.022%	0.022-0.044%	0.044-0.066%	0.066-0.88%	At or above 0.088%
V.3.2	No laws	Inadequate laws	Seriously flawed laws	Flaws in laws	Generally good laws	Fully consistent
V.4.1	Pri, Loc, Edu, Gov, EU	Pri, Loc, Edu, Gov, EU	Pri, Loc, Edu, Gov, EU	Pri, Loc, Edu, Gov, EU	Pri, Loc, Edu, Gov, EU	Pri, Loc, Edu, Gov, EU
V.4.2	100%	80-100%	60-80%	40-60%	20-40%	0-20%
V.4.3	5 stars	4 stars	3 stars	2 stars	1 star	0 stars

Workers

Indicator	No Risk (00.00)	V. Low Risk (20.00)	Low Risk (40.00)	Med Risk (60.00)	High Risk (80.00)	V. High Risk (100.00)
W.1.1	0%	0-2.65%	2.65-5.3%	5.3-7.95%	7.95-10.6%	Above 10.6%
W.1.2	0%	0-1.35%	1.35-2.7%	2.7-4.05%	4.05-5.4%	Above 5.4%
W.1.3	0%	0-4.175%	4.175-8.35%	8.35-12.525%	12.525-16.7%	Above 16.7%
W.2.1	Age, Disability, LGBT, Race, Religion, Sex & Total	Age, Disability, LGBT, Race, Religion, Sex & Total	Age, Disability, LGBT, Race, Religion, Sex & Total	Age, Disability, LGBT, Race, Religion, Sex & Total	Age, Disability, LGBT, Race, Religion, Sex & Total	Age, Disability, LGBT, Race, Religion, Sex & Total
W.2.2	Age, Disability, LGBT, Race, Religion, Sex & Total	Age, Disability, LGBT, Race, Religion, Sex & Total	Age, Disability, LGBT, Race, Religion, Sex & Total	Age, Disability, LGBT, Race, Religion, Sex & Total	Age, Disability, LGBT, Race, Religion, Sex & Total	Age, Disability, LGBT, Race, Religion, Sex & Total
W.2.3	0%	0-5.1%	5.1-10.2%	10.2-15.3%	15.3-20.4%	Above 20.4%
W.2.4	At or less than 75:25	75:25 to 80:20	80:20 to 85:15	85:15 to 90:10	90:10 to 95:5	95:5 to 100:0
W.3.1	0	0.0-43.5	43.5-87	87-130.5	130.5-174	Above 174
W.3.2	0.00% 0.00%	0.00-5.75% 0.00-3.25%	5.75-11.50% 3.25-6.50%	11.50-17.25% 6.50-9.75%	17.25-23.00% 9.75-13.00%	Above 23.00% Above 13.00%
W.3.3	34 days and above	32.5-34 days	31-32.5 days	29.5-31 days	28-29.5 days	Less than 28 days
W.3.4	At or above £54,834	£46,639.50-£54,834	£38,445-£46,639.50	£30,250.50-£38,445	£22,056-£30,250.50	At or below £22,056
W.4.1	0	0-7.5	7.5-15	15-22.5	22.5-30	Above 30
W.4.2	At or above 7 criteria	5-6 criteria	3-4 criteria	1-2 criteria	0 criteria met	No contract issued
W.5.1	At or above 62%	46.5-62%	31-46.5%	15.5-31%	0-15.5%	0%
W.5.2	At or above 24.7%	19.76-24.7%	14.82-19.76%	9.88-14.82%	4.94-9.88%	0-4.94%
W.6.1	Policies & safety measu	Policies & safety measu	Policies & safety measur	Policies & safety measure	Policies & safety measu	Completely inadequate
W.6.2	0	0-0.45	0.45-0.9	0.9-1.35	1.35-1.8	Above 1.8
W.6.3	0	0-6,250	6,250-12,500	12,500-18,750	18,750-25,000	Above 25,000
W.6.4	0	0-375	375-750	750-1,125	1,125-1,500	Above 1,500
W.6.5	0.00% (V) 0.00% (H)	0.00-1.50% (V) 0.00-1.25% (H)	1.50-3.00% (V) 1.25-2.50% (H)	3.00-4.50% (V) 2.50-3.75% (H)	4.50-6.00% (V) 3.75-5.00% (H)	At or above 6.00% (V) At or above 5.00% (H)
W.6.6	Facilities provided are o	Facilities provided mee	Facilities provided meet	Facilities provided meet r	Facilities provided fall b	Completely inadequate
W.6.7	10.0	7.5-10.0	5.0-7.5	2.5-5.0	0.0-2.5	0.0
W.7.1	100%	92.5-100%	85-92.5%	77.5-85%	70-77.5%	Below 70%
W.7.2	100%	81.75-100%	63.50-81.75%	45.25-63.50%	27-45.25%	Below 27%
W.7.3	No evidence	Worker complaints	Strike action occurred	Bad publicity	rganisation taken to cou	Organisation prosecuted
W.8.1	At or above 4929.80	3943.84-4929.80	2975.88-3943.84	1971.92-2957.88	985.96-1971.92	0.00-985.96
W.8.2	At or above 55	44-55	33-44	22-33	11-22	0-11
W.8.3	At or above 40% At 100%	32-40% 80-100%	24-32% 60-80%	16-24% 40-60%	8-16% 20-40%	0-20%
W.8.4	At or above 78.0%	62.4%-78.0%	46.8-62.4%	31.2-46.8%	15.6-31.2%	0-15.6%
W.8.5	0.0000%	0.0000-0.0902%	0.0902-0.1804%	0.1804-0.2706%	0.2706-0.3608%	At or above 0.3608%
W.9.1	35 hours or less	35-38.25 hours	38.25-41.5 hours	41.5-44.75 hours	44.75-48 hours	Over 48 hours
W.9.2	Workers: 0% Hours: 0 hours	Workers: 0-4.85% Hours: 0-1.925 hours	Workers: 4.85-9.7% Hours: 1.925-3.85 hours	Workers: 9.7-14.55% Hours: 3.85-5.775 hours	Workers: 14.55-19.4% Hours: 5.775-7.7 hours	Workers: Over 19.4% Hours: Over 7.7 hours
W.9.3	Temp: 0% PT: 0% Zero: 0%	Temp: 0-1.275% PT: 0-6.6% Zero: 0-0.6%	Temp: 1.275-2.55% PT: 6.6-13.2% Zero: 0.6-1.2%	Temp: 2.55-3.825% PT: 13.2-19.8% Zero: 1.2-1.8%	Temp: 3.825-5.1% PT: 19.8-26.4% Zero: 1.8-2.4%	Temp: Above 5.1% PT: Above 26.4% Zero: Above 2.4%

B List of Available Content for the SSSD

B1 Databases

<Available on request subject to conditions>

File type	File name	Comments
	The Strathclyde Space Systems Database – Version 1.0.0 *<strathclyde_space_systems_database_1_0_0.zolca>*	See the SSSD User Guide v1.0.0 for access criteria.

B2 Resources

<https://github.com/strath-ace>

File type	File name	Comments
	Strathclyde Space Systems Database Ecodesign Workbook – Version 1.0.0 *<strathclyde_space_systems_database_1_0_0_ecodesign.xlsx>*	To be used to integrate SSSD results into a CDF study.
	Strathclyde Space Systems Database End-User Licence Agreement – Version 1.0.0 *<strathclyde_space_systems_database_1_0_0_eula.pdf>*	To be signed before access to the SSSD can be granted.
	Strathclyde Space Systems Database User Guide – Version 1.0.0 *<strathclyde_space_systems_database_1_0_0_userguide.pdf>*	To provide assistance to users of the SSSD.

B3 Supporting Documents

<https://pureportal.strath.ac.uk/en/persons/andrew-wilson>

File type	File name	Comments
PDF	Advanced Methods of Life Cycle Assessment for Space Systems *<2019_andrewrosswilson_phd.pdf>*	PhD thesis outlining SSSD development & testing.
PDF	Nanospacecraft Exploration of Asteroids by Collision and flyby Reconnaissance (NEACORE) *<2019_walker_etal_lcpm2019.pdf>*	Paper compiling the results from the SSSD's first use in a CDF.
PDF	The Strathclyde Space Systems Database: A New Life Cycle Sustainability Assessment Tool for the Design of Next Genera… *<2018_wilson_etal_secesa2018.pdf>*	Paper providing the first space LCSA results using the SSSD.
PDF	Integrating Life Cycle Assessment of Space Systems into the Concurrent Design Process *<2017_wilson_vasile_iac2017.pdf>*	Paper publically unveiling the SSSD and its intended goals.

B4 Services

<https://www.strath.ac.uk/engineering/mechanicalaerospaceengineering/aerospacecentreofexcellence>

Provider	Service	Comments
University of Strathclyde Glasgow	SSSD Maintenance, Service & Technical Support *<Contact the University of Strathclyde for a price estimation>*	User assistance plus access to extensions & pro services.
University of Strathclyde Glasgow	Space-Specific LCSA Expert Hire *<Contact the University of Strathclyde for a price estimation>*	To hire an expert to run a specified space-specific LCSA study.
University of Strathclyde Glasgow	CCDS Hire for a CDF Study with a Space-Specific LCSA Expert *<Contact the University of Strathclyde for a price estimation>*	To hire the CCDS for a space-specific study with LCSA.

C ESA Letter of Authorisation for Results Disclosure

esa

University of Strathclyde
Dept. of Mechanical and Aerospace Engineering

Letter of Authorisation for Results Disclosure – Mr. Andrew Ross Wilson

2nd December 2019

To whom it may concern,

I, Dr. Luisa Innocenti, Head of the European Space Agency Clean Space Office, hereby authorise Mr. Andrew Ross Wilson to disclose the results generated during his time working with the European Space Agency as a Visiting Research Scientist between 17 September 2018 and 14 December 2018 (Ref: HIF-HO/CB/12.5/136) within his PhD thesis entitled 'Advanced Methods of Life Cycle Assessment for Space Systems', in the form presented to the Clean Space Office on 18th November 2019.

This authorisation is valid with immediate effect, until further written notice from the European Space Agency.

Luisa Innocenti

Respectfully yours,

Luisa Innocenti

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