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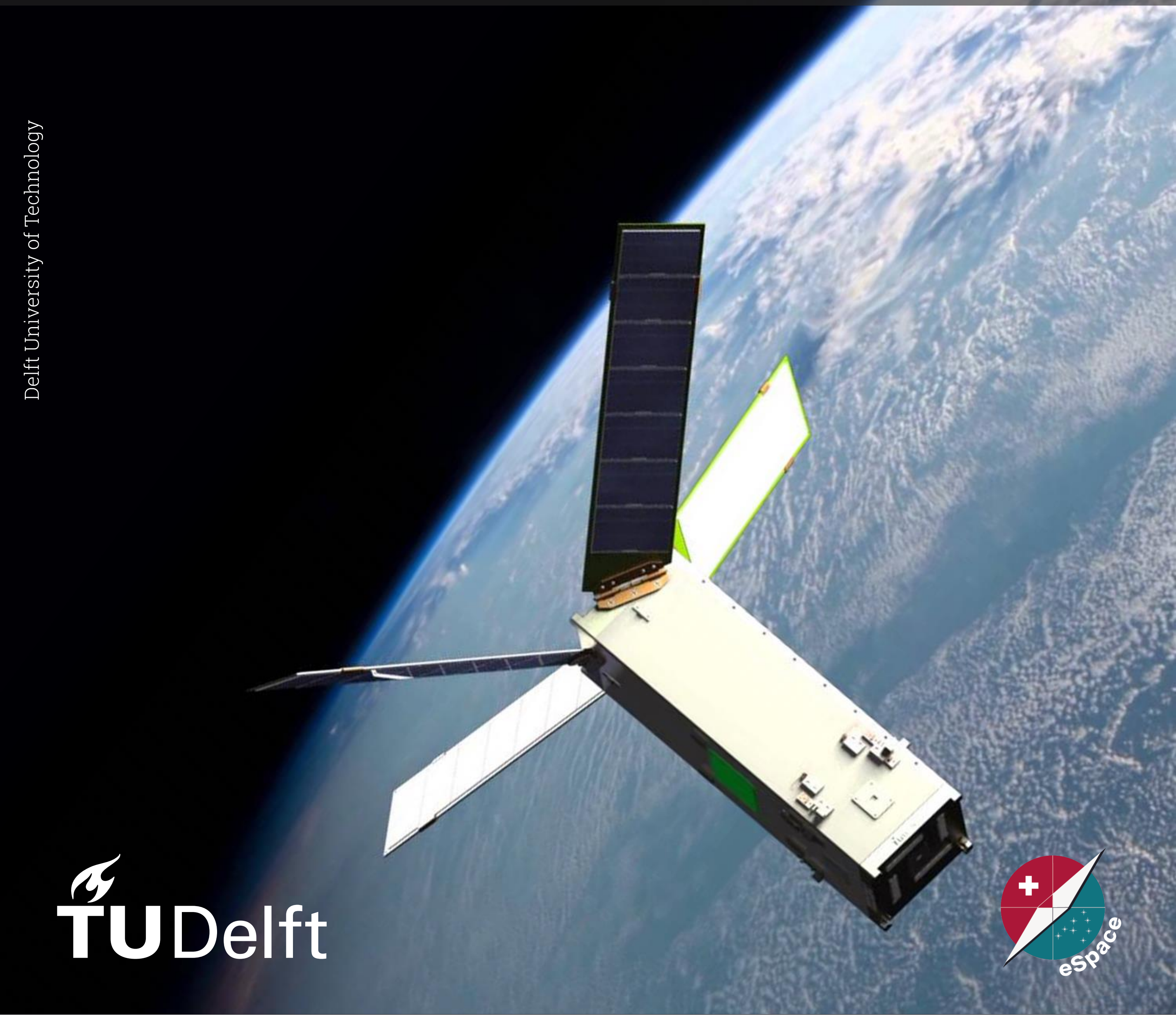

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by

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Cover: Still frame of a render video of Delfi-n3Xt in orbit, taken and modified from www.kijkmagazine.nl (accessed on 04/08/2023)

Preface

Dear Reader,

The space sector is a source of incredible awe, inspiration and motivation for young and old, as it enables us to pierce through the mysteries of our universe and life itself, one space mission at a time. Moreover, continued systematic data collection by the space sector is vital for a better understanding of how climate change affects our planet, bringing about actions to mitigate the effects of the rising temperatures. Admittedly, the space industry has an environmental impact on our Earth today, albeit only a fraction of that of the aviation industry.

However, projections for the planned future space activities suggest that the space industry's impacts will increase sharply in the coming decade. Major space missions involving vast numbers of launches and satellites are scheduled in the near future or are already ongoing. New nations and commercial companies are developing their own access to space. Once thought science-fiction, recreational space travel is increasingly common nowadays, albeit only in sub-orbital and low-Earth orbit at the time of writing. Commercial space stations are in their design and testing phases and sub-orbital travels from point A to point B on Earth are being proposed. In short, the space sector is seeing a booming growth and a diversification of its activities and thus in its impacts.

One of the core issues is that the sector is unique in its pollution of every part of the atmosphere and its highly specific use of toxic aerospace materials. On top of that, we merely have fragmentary understanding of the sector's impacts on the upper atmosphere during launch and re-entry. Actions towards a less environmentally taxing space sector should therefore be taken now, as early as possible, before the problem becomes too large to tackle.

My hope is that this thesis will bring some ideas for further discussions on how sustainability could be taken into consideration in an accessible way, during the design phase of a space mission. It would be presumptuous to write that this thesis solves the issue of the conception of a single space sustainability score, but it might add to the growing academic literature on the topic and perhaps provide new ideas to a future researcher.

To conclude, I would like to thank various people who enabled me to reache the point of writing this thesis. To begin, I am grateful to Dr. ir. Alessandra Menicucci and ir. Håkan Svedhem for their willingness to embark on this journey – first about clean space in general before settling on the new world of life cycle assessment – and supervise me. Similarly, I am thankful for the official supervision of Dr. Jean-Paul Kneib and the daily supervision of ir. Mathieu Udriot, as well as for the opportunity they gave me to complete my thesis at eSpace - EPFL Space Center. A warm thanks goes also to Dr.ir. Andrew R. Wilson and ir. Guillermo Dominguez Calabuig for their availability and help during the regular video-calls throughout my work. Moreover, my gratitude for the time given by the participants of the survey to fill in the questionnaires cannot be understated. Besides this, my parents' constant support in my study choices have been instrumental for the completion of this thesis.

Additionally, allow me to acknowledge the contributions of some specific friends. One of them is Bruno, whose contagious enthusiasm and mentoring with model airplanes was central in my choice for the study of aerospace engineering. Another one is Rebecca, who's help with getting me introduced to SSR and eSpace was pivotal for the topic of my thesis. More generally, I am appreciative of the support from everyone else throughout my studies.

Marnix Verkammen
Delft, October 2023

Summary

Background

Following preoccupying predictions on the consequences of human activity on our planet's ecosystem [81], various international agreements [9], [10] have resulted in Sustainable Development Goals [6], [11] which, amongst other, aim to limit the global temperature rise [7], [10], [11].

The internationally agreed methodology used to quantify the environmental impacts of a product or service is the Life Cycle Assessment (LCA) [4], [5]. It defines the precise scope and boundaries of the system, performs an inventory of all its processes and corresponding impacts, before presenting the total impacts in an understandable way. The latter is either done using the endpoint impact indicators, measuring directly the environmental damage done, or the midpoint impact indicators, measuring the intermediate effect.

Arguably, the European Union (EU) is at the forefront of LCA's implementation [98]. European industries are using a standardised LCA method for the assessment (and communication) of their products' or organisations' life cycle [14]: the Product Environmental Footprint (PEF). It mainly consists of a set of weighting factors aggregating the environmental midpoint impact categories into a single-score for decision-making purposes [18]. These impact categories relate to climate change, ozone depletion, human toxicity effects, particulate matter emissions (i.e. emissions leading to respiratory diseases), photochemical ozone formation (i.e. emissions creating, for instance, the so called "summer smog" and respiratory diseases), ionizing radiation (i.e. radiation increasing the risk of cancer), acidification (i.e. emissions leading to acid rain), eutrophication (i.e. an excess of nutrients in the soil or water), ecotoxicity (i.e. emissions of substances which are toxic to organisms), land and water use, and resource use.

The space industry works towards a simplified, single-score representation of the LCA results [43]. ESA, for instance, has devised its own initial set of weighting factors based on internal decisions and tests linked to an ESA-representative space mission [44], [45]. The University of Strathclyde develops its own single-score and database – the Strathclyde Space System Database (SSSD) – as a complement to ESA's approach, adding social and economic impact indicators [35], [36].

Moreover, the non-profit organisation Space Sustainability Rating (SSR) promotes sustainability in the sector [40] through a tiered scoring system which evaluates space operators on a range of modules such as the 'Mission Index'. This module pertains to the operator's collision avoidance capabilities [38], [41]. Other modules include topics such as the adherence to current regulations and the level of data sharing [38], [41]. The organisation is considering the addition of new modules, among which a LCA module, to expand its scope.

Problem statement and methodology

There is still a **lack of consensus on the LCA single-score methodology** [47], despite its acknowledged relevance for decision-making. The main reason being that the creation of such a methodology involves subjective judgement on the importance of each LCA output.

This thesis develops a consensus-based LCA single-score methodology and looks into implementing SSR's newly suggested LCA module. To that end, four steps are taken:

1. **International survey with space experts and space LCA experts to develop a single-score methodology.** Other key elements of the survey involve the assessment of the drivers (i.e. the reasons to do) and of the inhibitors (i.e. the reasons to avoid doing) of space LCA, the ranking of the current and future proposed SSR modules and the preferred presentation of the final simplified LCA results.
2. **Application of the resulting single-score methodology to a concrete space mission**, namely the the Delfi-n3Xt Cubesat launched by Delft University of Technology. The satellite's life cycle is modelled in Brightway2 [88], [101] using the Ecoinvent database, the ESA LCA Databases, and some parts of the SSSD.

3. **Calculation of the SSR score of the space mission using a revised weighting system**, by applying the weights of the modules, as extracted from the survey.
4. **Investigation into the implementation of a LCA single-score during concurrent and early design sessions**, based on discussions with practitioners in clean space and space mission early design.

Outcomes

Throughout four questionnaires, each participant ranked the PEF midpoint impact indicators as well as space-specific indicators from literature [46] according to their importance if used in a comparison between two designs of a same space mission. The impact indicators of climate change, ozone depletion and resource use of metals and minerals are ranked as the top three most important indicators when the launch segment is included in the LCA. If the latter is excluded, ozone depletion's importance reduces, in favour of fossil fuels resource use.

When comparing these findings with the indicators' ranking put forward by the general European industry [18], one notes an increase in importance given to ozone depletion for generic space missions. Moreover, a relative lower importance of Land Use for the space sector is observed.

To define the set of consensus-based weighting factors of space missions' LCA single-scores, the participants' ranking is aggregated into an initial space LCA weighting set shown below in Table 1. This is then multiplied by the robustness factors defined for the PEF [18], before being scaled to produce the final weighting set, also given in the table. The weighted impact indicators exclude any space-specific indicators [46], as there is limited scientific agreement on how the latter should be computed and interpreted. Moreover, the launch segment is excluded from the scope of this single-score LCA methodology because it is deemed that satellite designers have often limited control over the choice of the launcher and its environmental impacts.

Table 1: The weighting set defined through the survey, the robustness factors used and the final weighting factors recommended for the midpoint impact categories of space mission's LCA.
Note that the launch segment is excluded from the scope of the LCA for these weights and that a normalisation step (using the based on the Environmental Footprint of the average global person [97]) is needed before using the weights.

Midpoint impact indicator	Aggregated space LCA weighting set [%] (A)	Robustness factor from PEF (B)	Intermediate coefficients C=A*B	Final space LCA weighting factors (incl. robustness) C scaled to 100
Climate change.	9.66	0.87	8.41	**15.89**
Ozone depletion.	5.72	0.60	3.43	**6.49**
Human Toxicity - cancer effects.	8.04	0.17	1.37	**2.58**
Human Toxicity - non-cancer effects.	6.65	0.17	1.13	**2.14**
Particulate matter.	6.63	0.87	5.77	**10.90**
Ionizing radiation - human health.	6.32	0.47	2.97	**5.62**
Photochemical ozone formation - human health.	5.58	0.53	2.96	**5.59**
Acidification.	4.88	0.67	3.27	**6.18**
Eutrophication - terrestrial.	4.48	0.67	3.00	**5.67**
Eutrophication - freshwater.	4.61	0.47	2.16	**4.09**
Eutrophication - marine.	4.89	0.53	2.59	**4.90**
Ecotoxicity - freshwater.	5.32	0.17	0.90	**1.71**
Land use.	5.21	0.47	2.45	**4.63**
Water Use	5.49	0.47	2.58	**4.88**
Resource use: metals and minerals.	9.20	0.60	5.52	**10.43**
Resource use: fossil fuels.	7.33	0.60	4.40	**8.31**

This final weighting set is applied to TU Delft's Delfi-n3Xt CubeSat. The score, found to be 14.30, has a number of large contributors, namely marine eutrophication, fossil fuel use, metals and minerals resource use, climate change and freshwater ecotoxicity, in order of significance. Delfi-n3Xt's main hotspots (i.e. activities that cause significant impacts on one or more impact categories) are the office work during the feasibility and preliminay definition phase (i.e. Phase A+B) and the production and testing of the spacecraft in the qualification and production phase (i.e. Phase C+D).

To simulate the use of the single-score methodology at the design phase, Delfi-n3Xt's design is modified by swapping the lithium-ion (Li-ion) battery with a nickel metal hydride (NiMH) battery, which was also put forward during the CubeSat's real design phase. The resulting single-score of 15.97 is worse than the initial one, as the battery touches on many impact categories. Nevertheless, this lower score would have given the designers an additional argument against the NiMH battery, which proves the usefulness of the single-score for decision-making.

However, the survey participants bring some nuances to the way a LCA single-score result should be used. Regardless of the design stage, the majority of participants namely prefers combining the single-score and the results of either or both the mid- or endpoint indicators. At an early design stage, there is no particular preference between either or both the mid- or endpoint indicators as an addition to the single-score. In a detailed design stage, the preference leans towards adding the midpoint indicators, or both mid- and endpoint indicators, to the single-score. The participants mainly comment that one needs to balance the simplicity of a single score and the complexity of any of the impact category types based on the stage of the design and the specific goals of the LCA.

When asked about what the main reasons are for space industry players to perform LCAs, the survey participants highlight that it would boost environmental improvements in products and/or organisations, would allow the identification of environmental hotspots and would help adopting better environmental strategies. However, while the European industry is convinced that LCA should be performed because it would increase cooperation within a given company, increase sales and create new marketing opportunities [17], the participants of the survey disagree.

When questioned about reasons one would avoid doing LCA for space missions, the participants mention mainly the difficulty to collect life cycle data from the supplier and from the supply chain. Similarly, the uncertainties in the data quality assessment and evaluation, as well as the need for a significant amount of human resources are all highlighted as inhibitors for LCA.

Besides the LCA single-score, the SSR's rating system was also applied to Delfi-n3Xt and modified according to the survey's suggestions. The actual SSR score of Delfi-n3Xt is 46.76%, resulting in a bronze tier. The main contributor is the Mission Index module (weight of 50%), for which the CubeSat receives a score of 72.2%. With the survey participants recommending a more even spread of the modules' weights, the score lowers to 35.37%, below the Bronze Tier threshold. These results and the new choices of weights should however be discussed internally within SSR, as the participants may not have a full grasp of the modules' contents.

A final subject investigated during the thesis is the implementation of the LCA single-score during early design phases. Current early design sessions, such as concurrent design studies, do usually not yet implement LCA due to uncertainties of certain impacts of space missions (e.g. the impacts of high atmosphere emissions and re-entry). Further efforts need therefore to be put first into resolving these uncertainties. Afterwards, one could add a LCA expert or a trained systems engineer to the group of experts during such a concurrent design session. Also, the creation of LCA-related add-ons to system engineering tools would facilitate the implementation of LCA. In general, a transparent discussion and consensus on the single-score methodology is necessary prior to a complete implementation.

Conclusions and future steps

The set of weighting factors proposed in this thesis are thought to reflect well the main points of attention during a space mission's design. Amongst others, the emphasis on climate change reflects current environmental and political challenges, and the high weight for particulate matter shows the importance of the re-entry phase and its uncertain impact. Nevertheless, meta-studies ought to be made on the weighting factors proposed by this thesis, by ESA and by future initiatives, to derive a definitive set of weighting factors, agreed on by all.

Overall, this thesis aims to be an additional step in the space sector's efforts towards a general LCA single-score methodology. Current uncertainties and unknowns of space LCAs should be resolved prior to any early design implementations. One should develop implementations of the single-score and LCA into systems engineering tools and hands-on experience in the application of LCA in early design studies should be gained. Efforts should be pursued to enforce such application through agreements or regulations.

Contents

List of Figures

List of Tables

Nomenclature

Abbreviations

Below is a list of abbreviations used throughout this report:

Abbreviations related to Life Cycle Assessment and its methodology

E-LCA Environmental Life Cycle Assessment
LCA Life Cycle Assessment
LCC Life Cycle Costing
LCI Life Cycle Inventory analysis
LCIA Life Cycle Impact Assessment
LCSA Life Cycle Sustainability Assessment
S-LCA Social Life Cycle Assessment

Abbreviations of the subsystems and components of Delfi-n3Xt

ADCS Attitude Determination and Control System
AOCS Attitude and Orbit Control
BOP Bottom Panel
CDHS Command & Data Handling Subsystem
COMMS Communication Subsystem
DAB Deployment & Antenna Board
EPS Electrical Power Subsystem
G-EPS Global Electrical Power Subsystem
ITRX ISIS Transceiver
MAB Modular Antenna Box
MechS Mechanical Subsystem
OBC On-Board Computer
P/L External Payloads
PCB Printed Circuit Board
PTRX Primary Transceiver
SDM Solar cell Degradation Measurement experiment
STS Structural Subsystem
STX S-band transmitter
TCS Thermal Control Subsystem
TOP Top Panel

Abbreviations of the midpoint impact indicators

Ac Acidification
CC Climate change
Eu-Fw Eutrophication - freshwater
Eu-M Eutrophication - marine
Eu-T Eutrophication - terrestrial
Ex-Fw Ecotoxicity - freshwater
HT-CE Human Toxicity - cancer effects
HT-nCE Human Toxicity - non-cancer effects
IR-HH Ionizing radiation - human health
LU Land use
OD Ozone depletion
PM Particulate matter
POF-HH Photochemical ozone formation - human health
RU-FF Resource use: fossil fuels
RU-MM Resource use: metals and minerals

Abbreviations of the Space Sustainability Rating modules

ADOS Application to Design and Operation Standards
COLA Collision Avoidance Capability
DIT Detectability and Trackability
LVSR Launch Vehicle Sustainability Rating

Abbreviations of the location of the LCA datasets

CH Switzerland
GLO Global
RER Europe
ROW Rest-of-the-World

General abbreviations

AB Activity Browser
CDF Concurrent Design Facility
COP Conference of the Parties
CSID Clean Space Industry Days
EC European Commission
EF Environmental Footprint
EPFL École polytechnique fédérale de Lausanne
ESA the European Space Agency
EU European Union
FU Functional Unit
IC Integrated Circuit
ISO International Organization for Standardization
JRC Joint Research Centre
LEOP Launch and Early Operations Phase
Li-ion lithium-ion
MBSE Model-Based Systems Engineering
MPPT Maximum Power Point Tracking
NiMH nickel metal hydride
PEF Product Environmental Footprint
REACH Registration, Evaluation, Authorisation & Restriction of Chemicals
SDG Sustainable Development Goal
SSR Space Sustainability Rating
SSSD Strathclyde Space System Database
TTC Telemetry, Tracking, and Command
UN United Nations

Symbols

Below is a list of abbreviations used in equations throughout this report:

Symbol	Definition	Unit
d_{avg}	Average commute distance	km
d_{pers}	Number of kilometers.persons commuted	km.person
t_{d_w}	Days an employee works (these are the Julian days an employee *come to the office*)	day
$t_{d_{wg}}$	Working days (i.e. the number of days one has at least delivered one work-hour)	day
t_{h_w}	Work-hours (i.e. the number of hours one works	hour
t_y	Year (i.e. Julian year)	year
t_{y_w}	Work-year (i.e. the equivalent number of working days in one Julian year)	year

1 Introduction

Given the alarming predictions of global temperature rise and associated climate change, efforts are underway around the globe to reduce environmental impacts. More sustainable practices are being adopted through international agreements and local regulations. While they often exempted the space sector in the past due to its unique environmental impacts (e.g. emissions in the higher atmosphere during the launch event and re-entry), these agreements and new ones are progressively adapted to the sector constraints. Their implementation is growing, as is shown through an increased adherence to deorbiting guidelines and through the rising importance of the non-profit organisation Space Sustainability Rating which encourages space actors to design and implement sustainable space missions.

The pragmatic methodology for gauging the environmental impacts of Life Cycle Assessment (LCA) makes it a logical tool to use in this context. Its use is getting increasingly better as the space-specific LCA uncertainties and unknowns are being researched and solved. Moreover, guidelines have been released by the European Space Agency (ESA) on best practices for space LCAs.

Nevertheless, the complicated and long list of outputs of a LCA is considered by some as inadequate for the large design space of early-design sessions. Therefore, initial work is underway on creating a convenient and easy-to-understand way of represent the LCA results, namely a single-score LCA output. This is being done by the the European Space Agency (ESA) with its ESA Space Systems LCA Guidelines and its ESA LCA Database, as well as by the University of Strathclyde with its Strathclyde Space System Database (SSSD)

However, such a score is riddled by subjective weights and would need a large consensus to be accepted internationally. That is why this thesis precisely focuses on reaching such a consensus-based LCA single-score. For this, a number of smaller steps are defined, to provide more complete results. These steps are translated into the sub-questions shown below.

Research questions

Main Research Question: *What is the process for the calculation of a Life-Cycle Assessment single-score of a space mission in each design phase?*

Sub-Questions:
- What are the most relevant Environmental Impact Indicators for a representative Space Industry player?
- Which aspects need be added to the ESA LCA Database and to what extend would the Strathclyde Space System Database (SSSD) be relevant?
- How can the LCA single-score be integrated in Space Sustainability Rating's current rating system?
- How could the LCA single-score be included in early-stage concurrent design exercises?

To provide a structured answer to these questions, this thesis is subdivided into sections that build on one another. The background on sustainability in the general industry and in the space sector is provided in Chapter 2 and Chapter 3, respectively. The methodology followed during the thesis is detailed in Chapter 4. The outcomes are shown in Chapter 5 and Chapter 6. The relevant discussions are given in Chapter 7 and the conclusions and future outlook are penned down in Chapter 8. At the end of the report, a number of appendixes are placed as support.

2 Sustainability across industries

International concern about the negative effects of human activity on our planet's ecosystem has grown drastically in recent years. Early reports, such as the Club of Rome's 1972 report, served as first wake-up calls on the vulnerability of our planet to anthropogenic loadings [91]. Recent findings suggest that failure to make drastic changes in current practices and policies over the next two decades, may result in the sixth mass extinction, the onset of which some claim is already visible [81].

Awareness of the issue has increased worldwide in the last decades. As early as in 1987, it was remarked that the 1970s saw a doubling in the number of people who suffered from natural disasters compared to the 1960s [13]. Global warming was already discussed and predictions for drastic increases in fossil fuel needs by the 2030s were made [13].

To provide a better understanding of the historical and current status on sustainability in the general industry worldwide, this chapter first dives into the major historic sustainability agreements in Section 2.1. The developments of LCA as the mainstream tool to quantify sustainability and its methodology are discussed in Section 2.2. The European Commission's efforts to standardise LCA across the European industry through the Product Environmental Footprint is covered in Section 2.3.

2.1. Definition of sustainability and major historic agreements

Defining the term 'sustainability' has been an iterative process and continues to be so. It is believed to inevitably evolve further, as new environmental challenges will be faced by societies around the world [96]. A definition was nevertheless penned down in the Brundtland Report of 1987, referring to sustainable development as one which "meets the needs of the present without compromising the ability of future generations to meet their own needs" [13].

In that same year, the first major agreement was concluded between countries on changing certain practices in the name of sustainability, namely the Montreal Protocol on Substances that Deplete the Ozone Layer. It is aimed at the protection of the stratospheric ozone layer by phasing out and eventually stopping the production and consumption of ozone-depleting substances [9]. This proved to be a tremendously successful collective effort, as evidence nowadays suggest that the hole in the ozone layer continues to shrink every year [80].

The definition of sustainability has been further refined by decomposing the concept of 'needs' into an environmental, a social and an economic dimension, which has most recently been written down in the 2015 Paris Agreements [10]. Signed by 194 parties (193 states and the European Union), it aims to be the first step towards a net-zero emission world [8]. Its main objective is to work towards keeping the global temperature rise below 2 degrees Celsius compared to the pre-industrial levels [10], [11]. A further strengthening of this objective was achieved during the COP26 in 2021 in Glasgow, where the participating countries affirmed their ambition to limit the temperature rise to only 1.5 degrees above the pre-industrial era, as well as to phase-down the use of coal power [7].

This agreement resulted in an international approval on actionable goals through the seventeen Sustainable Development Goals (SDGs) [6], [11]. They expand upon the Millennium Development Goals, expired in 2015 [6] and have have 169 associated targets outlined in the 2030 Agenda [11].

2.2. Life Cycle Assessment as a tool to quantify sustainability

Companies or entities across industries ought to be able to assess the extent to which a certain environmental objective is achieved, or to substantiate a claim of sustainability on a product or service, as a consequence of the sustainability agreements mentioned in Section 2.1. Indeed, one ought to avoid any greenwashing, i.e. "the practice of making unclear or not well-substantiated environmental claims" [85]. The Life Cycle Assessment (LCA) methodology was developed for that reason.

The first LCA studies were conducted in 1969 and the early 1970s. Initially used to address environmental concerns around waste and packaging, LCA proliferated following the oil crisis, and eventually expanded into most (if not all) the other industries [90]. This has led to the mature and comprehensive methodology it is today, compiling and evaluating the inputs, outputs and the environmental impacts of products and services throughout their lifetime [90], [4].

The LCA methodology is defined through two international standards by the International Organization for Standardization (ISO). ISO 14040:2006 provides the principles and framework [4] whilst ISO 14044:2006 provides the requirements and guidelines [5].

International use and adoption of this methodology has grown, with the EU arguably being its front runner when considering the scale of European LCA policy implementation and the extent to which other countries draw inspiration from it [98]. Numerous studies indeed show the implementation and development of LCA in policies and policy development in countries such as the USA, Japan, China, Thailand, Mexico, Chile, Colombia, Brazil [98].

2.2.1. The Life Cycle Assessment procedure

LCA is a systematic approach that is defined in a standard framework, as discussed above and visualised in Figure 2.1 below. As highlighted in section 4.1.5 of the ISO 14040:2006 [4] and shown by the arrows in the below figure, the LCA process has an iterative nature to it which is needed to ensure that the study and reported results are comprehensive and consistent enough. Nevertheless, it can be said to have four main stages: Goal and Scope definition, Life Cycle Inventory analysis (LCI), Life Cycle Impact Assessment (LCIA) and the Interpretation.

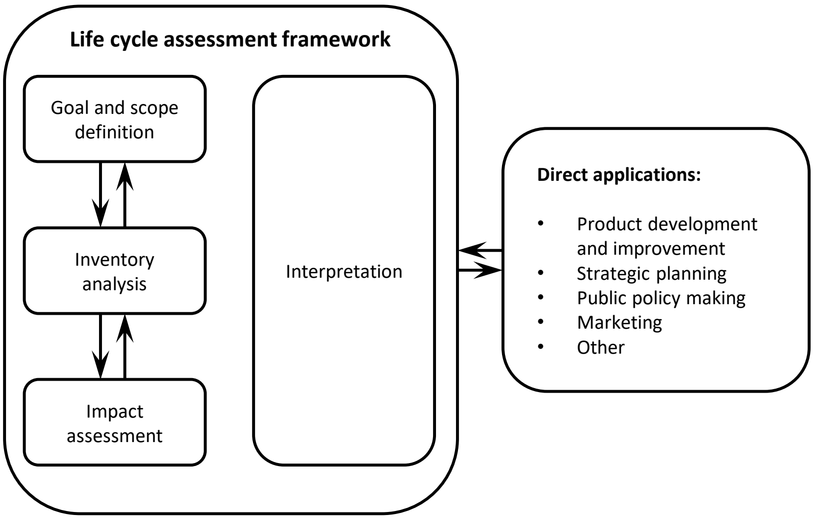


Figure 2.1: Life Cycle Assessment framework methodology and its applications. Taken from ISO 4040:2006 [4]

The **Goal and Scope definition** is key to any LCA, as it determines the intended application, the reasons for making the study, its target audience and whether or not the results are to be used for comparative assertions disclosed to the public [4]. It defines various items detailed in the ISO 14040:2006, among which the assessed product system, the study's functional unit, system boundaries, chosen impact categories and allocation procedures as well as the assumptions. This phase is crucial since the precision of its goal and scope will define the quality of the results in later phases [5].

The **LCI phase** consists of collecting relevant data and defining the calculation procedures to quantify the product system's relevant input and output flows [4]. The input flows include those related to the energy and raw materials needed as well as some physical inputs, and the output ones refer to the product, any waste, emissions and other environmental aspects [4]. These input and output flows are then allocated to processes in the product system using well defined allocation procedures [5]. The data related to these inputs and outputs can be collected directly, or taken from a public source, in which case reference to these data sources should be made [5].

The **LCIA phase**'s aim is to compute the potential environmental impacts of the product system based on the LCI results. To that purpose, specific impact categories are chosen, such as the ones proposed by Product Environmental Footprint (PEF) discussed further in Section 2.2.3, as well as their associated characterization model [4]. A reasoning behind the choice of impact categories and associated modelling methods always ought to be given, as it introduces some form of subjectivity according to ISO 14040:2006 [4].

The **Interpretation phase** comprises the analysis of the findings from the LCIA, based on the goal and the scope of the study [4]. It aims to identify the relevant environmental issues found in the LCI and LCIA phases and ensures that the analysis is complete and consistentent [4]. Moreover, the Interpretation phase includes providing comments on the LCA conclusions by discussing the particular study's limitations, performing some sensitivity checks and highlighting some recommendations [5].

One should note that Figure 2.1 does not show the **Reporting stage**, which nevertheless is considered an "internal part" of any LCA according to the ISO standards [4]. This phase allows an adequate communication of the results to the intended audience and should be transparent about the assumptions made, the choice of data and methods, as well as about the limitations of the LCA study [5]. Besides this, any modifications to the initial scope of the study should be reported and the system boundaries should be made clear. If the report is to be shared to a third-party (e.g. the public, or any other party different from the initial target audience), some additional detailing needs to be done to ensure that the reader has a full grasp on the study performed [5].

The entire LCA framework shown in Figure 2.1 is meant to define the steps needed to ensure the study is used correctly for real-world applications. The list of applications on the figure is non-exhaustive, as is shown in the Annex A of ISO 14040:2006, which points out a few other applications. Amongst them, and most notably for this thesis report, are the "environmental labels and declarations," "integration of environmental aspects into product design and development" and "environmental communication" [4].

2.2.2. Functional Unit

Defined as a "quantified performance of a product system for use as a reference unit" by the ISO 14040:2006 standard [4], the Functional Unit (FU) is essential for any LCA. Written down during the Goal and Scope phase, it serves as the reference to which one normalises the input and output data [5]. As such, it defines precisely what the study is about and how the conclusions should be interpreted.

In some cases, the product or process studied in the LCA may have more than one function. An example found in literature [90] is for instance that of a study comparing wood and concrete floor constructions. One may set up a FU based on their load bearing capacity if one is interested in the structural aspect of each construction. However, one could also be interested in comparing their quantitative noise reduction functions or their fire protection qualities [90].

For comparative studies, a LCA practitioner may therefore choose to tolerate differences in these properties and comment on them during the Interpretation and Reporting phase, or may try to make the two constructions functionally equal by adding constraints within the functional unit. While the latter choice seems more complete, it could lead to unreasonable assumptions and require some compromises [90]. As such, one must take great care when choosing a FU and sufficient arguments should be provided for the final choice.

2.2.3. Impact categories indicators

Impact categories, representing the environmental issues which one aims to assess during the LCIA [4], can be defined by the LCA practitioner based on the Goal and the Scope of the study [5]. To quantify them, an impact category indicator is to be chosen for each of them. These categories and indicators should be internationally accepted [5] and be selected to ensure a sufficient completeness of the study and a reasonable level of feasibility (i.e. there should not be too many categories) [90].

The impact categories indicators can be subdivided into midpoint and endpoint indicators. While both aim to quantify the amount of environmental stress, one could state that they quantify it at different levels. To illustrate this, Figure 2.2 shows where each of these two indicators lie in the cause-effect chain of the degradation, by human activities, of the so-called "Area of Protection," which can be human health, natural environment and natural resources. The endpoint indicators directly measure the damage done, while the midpoint indicators measure the intermediate step of the impacts such as global warming, ozone depletion, water use, etc. Thus, midpoint indicators are more closely linked to the elementary flows (i.e. inputs and outputs, or emissions and extractions) whereas endpoint indicators are more in-line with the damage on the area of protection [29].

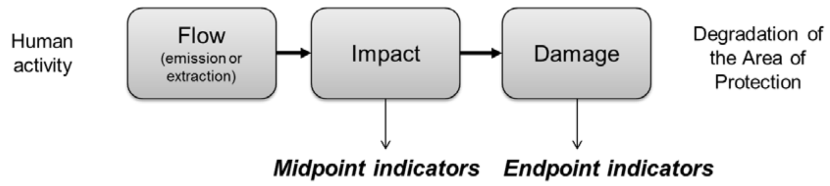


Figure 2.2: Connection between the midpoint and endpoint indicators in LCA. Taken from [29]

Figure 2.3 shows how the midpoint indicators can be transformed into the endpoint indicators. This transformation relies on some "complicated weighting factors and assumptions" [29]. While these precise midpoint indicators are slightly different from the ones used in the rest of this report, the figure does give insight into the types of midpoint indicators that ‘make up’ each endpoint indicator.

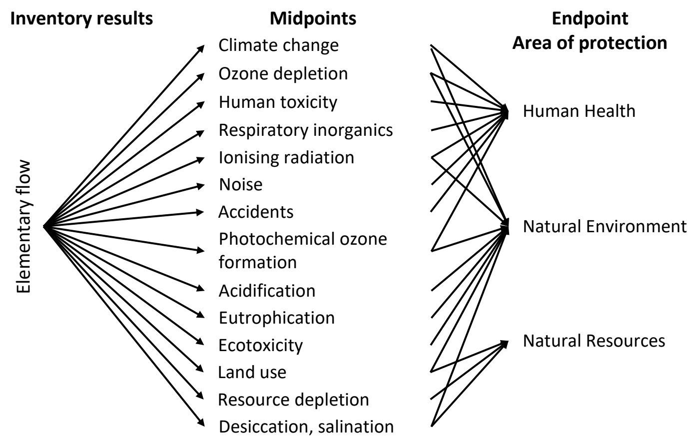


Figure 2.3: Schematic visualisation of the link between the midpoint and endpoint indicators. Taken from [29]

In the two subsections below, the meaning of the most commonly used indicators is given, while a more in-depth definition can be found in Appendix A. The indicators discussed in the following subsection are the ones most often used in a European LCA – if not also in other parts of the world – as they are used for the PEF. Below this subsection, the list of the space-specific impact indicators suggested in literature is given in the subsection.

Meaning of the midpoint indicators

An explanation on the meaning of the 16 commonly used midpoint impact categories is summarised below, based on their definition from the final report on the assessment of different communication vehicles for providing Environmental Footprint information on pages 113-115 [19]. These categories are used throughout this thesis as they are commonly used on a European level as well as internationally.

- **Climate change, total:** Emission of greenhouse gases changing temperature and the climate for the worse, impacting indirectly on the ecosystems, on natural resources and people’s health.
- **Ozone depletion:** Emissions damaging the ozone layer leading to increased ultraviolet radiation resulting in skin cancer.
- **Human Toxicity - cancer effects:** Emissions of toxic substances leading to an increased risk of cancer, for instance, through the air we breathe and indirectly through the food we eat and the water we drink.

- **Human Toxicity - non-cancer effects:** Emissions of toxic substances damaging people's health, for instance, through the air we breathe and also indirectly through the food we eat and the water we drink.
- **Particulate matter:** Emissions of tiny particle, for instance, leading to respiratory diseases and the so-called "winter smog".
- **Ionizing radiation, human health:** Radiation ("radioactivity") increasing the risk of cancer.
- **Photochemical ozone formation, human health:** Emissions creating, for instance, the so called "summer smog" and respiratory diseases.
- **Acidification:** Emission of substance leading, for instance, to acid rain and poorer quality of air, water and soil.
- **Eutrophication - terrestrial:** Too many nutrients in the environment, for instance by overuse of fertilisers in farming, upsetting the balance of nature.
- **Eutrophication - freshwater:** Too many nutrients in freshwater, for instance by the overuse of fertilisers in farming and release of wastewater, upsetting the balance of nature, e.g. leading to algal blooms and killing fish.
- **Eutrophication - marine:** Too many nutrients in marine water, for instance due to overuse of fertilisers in farming and release of wastewater, upsetting the balance of nature and leading to algal blooms in seawater.
- **Ecotoxicity - freshwater:** Emission of toxic substances that are a danger to organisms like fish, algae and other organisms living in fresh water.
- **Land use:** Use of land and soil endanger, such as soil fertility as well as the well-being and survival of some animals and plant species.
- **Water Use:** The use of freshwater affects its availability for future uses
- **Resource use: metals and minerals:** Use of minerals, metals and other resources in products reducing their availability for future uses.
- **Resource use: fossil fuels:** Use of fossil fuels, reducing their availability for future uses.

Meaning of the Endpoint indicators

An explanation on the meaning of the 3 endpoint categories can be found below. These are mentioned by ISO 14040:2006 and the definitions shown below have been taken from the final report on the assessment of different communication vehicles for providing Environmental Footprint information on page 94 [19].

- **Human Health.** The negative effects on people's health, for instance, as a consequence of chemicals or radiation emitted during the life cycle of a product or indirectly as consequence of climate change
- **Natural Environment.** The negative effects on the function and structure of natural ecosystems, for instance, as a consequence of the emission of chemicals or physical interventions that take place during the life cycle of a product
- **Natural Resources.** The negative effects, for instance, to the use of physical resources such as energy, metals and minerals and water, which results in a decrease in the availability of the total resource stock, as physical resources can be finite and non-renewable.

2.3. European standard in normalising and weighting of the results: the Product Environmental Footprint

As a common method for the assessment and communication of the life cycle performance of products and/or organisations across the European Union (EU), the Joint Research Centre (JRC) of the European Commission (EC) has devised a weight for each midpoint impact category, so as to transform them into single-score. That is, weights are developed for each midpoint impact category, as shown in Table 2.1 below, by combining answers from both survey results from the public and LCA experts worldwide, as well as from webinars with impact assessment experts. The JRC also takes into account the robustness of each impact category, by assessing the completeness of the data sets used for the normalisation as well as the data quality and robustness of input data for normalisation. This is all consolidated in the PEF approach [17], [19].

Table 2.1: PEF's midpoint impact categories weighting factors, as defined by the Joint Research Centre of the the European Commission [19]

Midpoint impact category	**PEF final weighting factors [%] (incl. robustness)**
Climate change	21.06
Ozone depletion	6.31
Human toxicity, cancer effects	2.13
Human toxicity, non-cancer effects	1.84
Particulate matter	8.96
Ionizing radiation, human health	5.01
Photochemical ozone formation, human health	4.78
Acidification	6.20
Eutrophication, terrestrial	3.71
Eutrophication, freshwater	2.80
Eutrophication, marine	1.92
Ecotoxicity freshwater	1.92
Land use	7.94
Water use	8.51
Resource use: metals and minerals	7.55
Resource use: fossil fuels	8.32

However, the JRC notes that "any weighting scheme is not mainly natural science based but inherently involves value choices that will depend on policy, cultural and other preferences and value systems" [19]. They argue that reaching a final overall consensus would therefore be difficult to achieve, as is the case for other multicriteria approaches besides LCA. This is further reinforced by Clause 4.4.5 of ISO 14044:2006, which prohibits the use of weighting in comparative assertions, when the intention is to disclose the conclusions to the public [5].

Nevertheless, the JRC does see weighting as "essential to further aggregate information with the objective to provide better support in complex decision situations" [19]. Indeed, while critical voices were raised during the PEF's conception regarding the use of a single-score method in LCA, most did conclude that such a method would be necessary, amongst others, for decision-making purposes [43]. It is argued that "carefully performed single-score results" in comparative LCAs are preferred over "single-issue results" such as carbon footprints, as the latter neglect potentially important environmental aspects [43].

3

Sustainability in the space sector

In parallel to the increased actions on sustainability in the general industries worldwide, the space sector is also more keen to act in a more sustainable way. While the focus so far lies mainly on the space debris issue, the topic of environmental sustainability as a whole has gained increased importance in the space sector these past few years. With the ever-growing number of satellites being launched as shown in Figure 3.1, space debris mitigation measures have been developed and are increasingly being adhered to [22]. A similar growth in adherence to sustainability practices pertaining to the terrestrial environment can be seen in space missions.

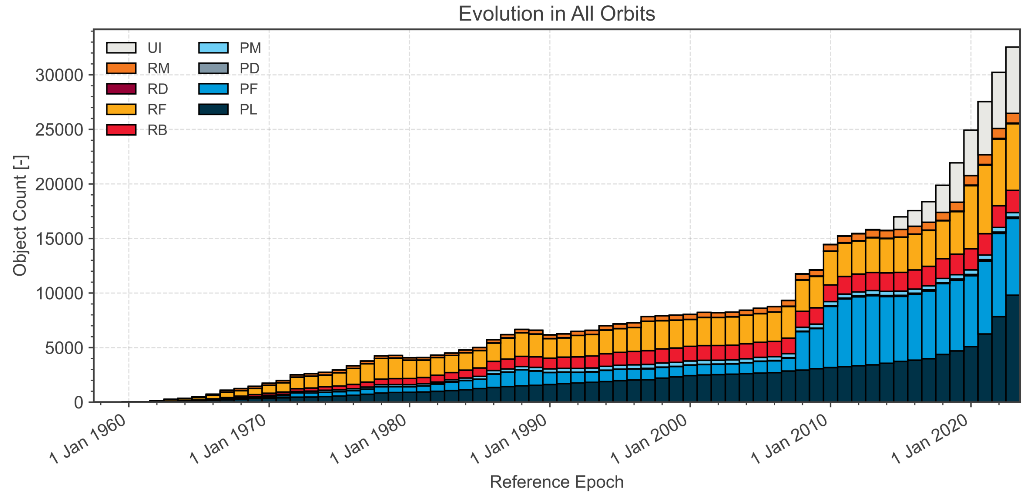


Figure 3.1: Evolution of the number of objects[1] counted in space over the past years. Taken from ESA's annual space environment report [22].

This chapter dives deeper into this increasing implementation of sustainability in the space sector and into the ongoing developments to develop best practices for space-specific LCA. Section 3.1 highlights the uniqueness of the environmental impacts of the space sector and the consequences for future space activities. A closer look at the developments in sustainability within the space sector in Europe and abroad is given in respectively Section 3.2 and Section 3.3. ESA's Space Systems LCA Guidelines are discussed in Section 3.4. Past efforts in simplifying the LCA into a single-score are summarised in Section 3.5. The history and current working of the Space Sustainability Rating is provided in Section 3.6

[1]The acronyms shown in the figure refer to the following types of objects [22]:

UI: Unidentified
RM: Rocket Mission Related Object
RD: Rocket Debris
RF: Rocket Fragmentation Debris
RB: Rocket Body
PM: Payload Mission Related Object
PD: Payload Debris
PF: Payload Fragmentation Debris
PL: Payload

3.1. The uniqueness and future predictions of the space sector's environmental impact

While the current environmental impacts of the space industry are relatively small, planned future space activities (e.g. satellite constellations, space tourism, space-based-solar-power, Moon and Mars missions) will increase those drastically. The current space activities' impacts are estimated to be less than 0.1% of the Annual Global Impacts [79], but certain aspects such as the effects of stratospheric release of particles are already a cause for concern [79]. However, even when considering a scenario of a low growth of future space activities, the space sector will likely already have caused enough ozone depletion by 2050 – at least 6% of the Annual Global Impact [92] – that it will be subjected to scrutiny of the various national and international ozone protection schemes. Thus, already with this conservative scenario, some activities of the space sector will face an increased pressure to consider their environmental impacts [92].

One ought to add to this the fact that the space sector is unique in its impacts compared to other industries. This is mainly due to specific aspects relating to the design, production, utilisation and disposal [24], [27], [29]. The design phase is usually particularly long, with movements of people across large distances or between countries for multinational mission contracts. The production is often very limited compared to a typical mass-producing commercial industry and it requires materials and a production process that are unique to the space sector. The testing and assembly facilities are generally dedicated to the sector and may have high power demands. The utilisation phase spans a long time (i.e. approaching twenty years for conventional missions) and is also marked by a brief moment of significant particle emissions in the higher atmosphere during launch and re-entry.

Despite the warning signs relating to the consequences of future space activities and the space industry's unique environmental impacts, the sector has traditionally been exempted from the major sustainability agreements [35]. However, this is currently changing, as space sustainability guidelines and regulations are more and more agreed upon. This process arguably started with the approval of the United Nations' Guidelines for the Long-Term Sustainability of Outer Space Activities [3] in 2019. The guidelines provide advice for policies and regulations on a number of topics, such as "space activities; safety of space operations; international cooperation, capacity-building and awareness; and scientific and technical research and development" [3], [12].

Also within the space sector, LCA is considered as the main tool to quantify sustainability and the impacts, as recommended by the Guidelines for these United Nation's guidelines [3]. Research of 2019 shows that the number of LCA-related documents in the industry increased from only 9 publications between 2009 and 2014 to 32 publications between 2015 and 2018 [30]. This growth has continued in recent years, in view of the various recent references used in this thesis and the growth in importance of the ESA Clean Space Industry Days [21].

3.2. Sustainability and LCA in the European space sector

A forerunner in terms of Space sustainability is arguably Europe, in particular through the European Space Agency (ESA). Their Clean Space Initiative started in 2009 with the ECOSAT Study in their Concurrent Design Facility (CDF) [24]. From thereon, it expanded into three main branches: Management of End-of-Life, In-Orbit Servicing and Ecodesign. The former two have the respective aims of developing technologies to avoid the creation of space debris, and of removing and servicing debris and spacecraft from orbit [23]. The latter branch – Ecodesign – is of greater interest for this thesis, as it focuses in ingraining environmental sustainability within the design of space missions [23].

ESA aims to be the main hub for the European space sector with regards to sustainability. It releases each year information on the space environment and global adherence to the space debris mitigation guidelines through their Space Environmental Report [22]. Moreover, the agency published (and are in the process of updating [27] after extensive feedback [26], [28], [31]) the Space Systems Life Cycle Assessment Guidelines [29] in 2016, henceforth referred to as ESA LCA Guidelines. This document defines the methodology for space-specific LCA within the European space sector. Furthermore ESA organises the yearly Clean Space Industry Days (CSID), which they describe as having become "the central forum for European industry working on designing and building sustainable missions" [21]. In short, ESA focuses more and more on its own sustainability [20] and that of the sector, thus aiming to lead by example.

To build on the LCA methodology provided by ESA, a number of research organisations and space industry actors are developing their own complementary approaches and/or practices [26]. Whilst some developed these for internal use only, others such as the University of Strathclyde's 'Strathclyde Space System Database (SSSD)' have been made open-source. Beyond complementing ESA's LCA methodology, the SSSD is aimed towards integrating space Life Cycle Sustainability Assessment (LCSA) into the concurrent design process. [36] This includes environmental impacts through Environmental Life Cycle Assessment (E-LCA), referred to as LCA in this paper, as well as social impacts through Social Life Cycle Assessment (S-LCA) and economic ones through Life Cycle Costing (LCC) [36]. LCSA aims to provide a more comprehensive and integrated view of sustainability by evaluating the trade-offs and synergies between environmental, social, and economic factors [89].

3.3. Sustainability and LCA in the space sector worldwide

While Europe seems to be the centre of development in space-related LCA, other parts of the world, specifically the United States, do not seem to have been equally motivated to act. It is reported that only a limited number of space LCA studies have been conducted in the country, which were mostly limited to a small scope or are "embryonic and not well aligned with best practices" [34]. It is argued that this could be the consequence of the uncommonness of LCA in the broader American industries [33], [34]. A significant cultural shift is thought to be necessary to prevent the US from falling behind Europe even further and to put in peril its space industry's large international trade [33], [34]. It is in sharp contrast with the European space sector, where LCA is mainstream enough for it to become a major – if not mandatory – part of any space mission's development [34].

In other parts of the world, similar efforts ought to be made by researchers and governments to enable the implementation of LCA. In New Zealand for instance, the growing space industry faces increasing environmental concerns, leading some academics to recommend further research efforts in order to implement LCA policies tailored for the sector [32]. In China, while a plan to decarbonise its economy by 2060 has been signed, no specific measures have been taken yet for its large space industry. Nevertheless, it is argued that the comparatively authoritarian top-down economy could allow for a much more rapid implementation of environmental policies than in Western countries [33].

3.4. ESA's Space Systems LCA Guidelines

ESA is the authority to follow with regards to recommendations on how to perform LCA on a full space system in Europe. As mentioned above, its Space Systems LCA Guidelines published in 2016 provide the reference for this. In Section 3.4.1, the LCA boundaries suggested by ESA are discussed. The recommended FU is highlighted in Section 3.4.2 and a brief discussion is given in Section 3.4.3 on midpoint indicators suggested in literature for space applications.

3.4.1. Recommended System Boundaries for space missions, according to the ESA LCA Guidelines

ESA's LCA Guidelines follow the international standards [4], [5] with regards to the definition of system boundaries, while adapting them slightly to accommodate for the specificities of the space sector. Its scope is defined per design phase and per segment of the space mission. This is concisely shown in Figure 3.2 below.

The ESA Guidelines do suggest a cut-off rule based on a mass-criterion when it is not possible or not desired to model some parts of the space mission. This rule recommends to exclude from the LCA scope any material or sub-assembly inputs which constitute less than 5% of the total mass, provided that all of the following statements are true [29]. Any deviation from this rule should be "properly justified" according to the ESA LCA Guidelines. Below are the satements that must be true [29]:

- No data is available
- There is no particular high environmental or health risk associated with their production, use or end-of-life, according to the EC's directives
- It is not identified by the EU as a critical raw material, nor is it included in the Registration, Evaluation, Authorisation & Restriction of Chemicals (REACH) Annex XIV 'Authorisation List'.

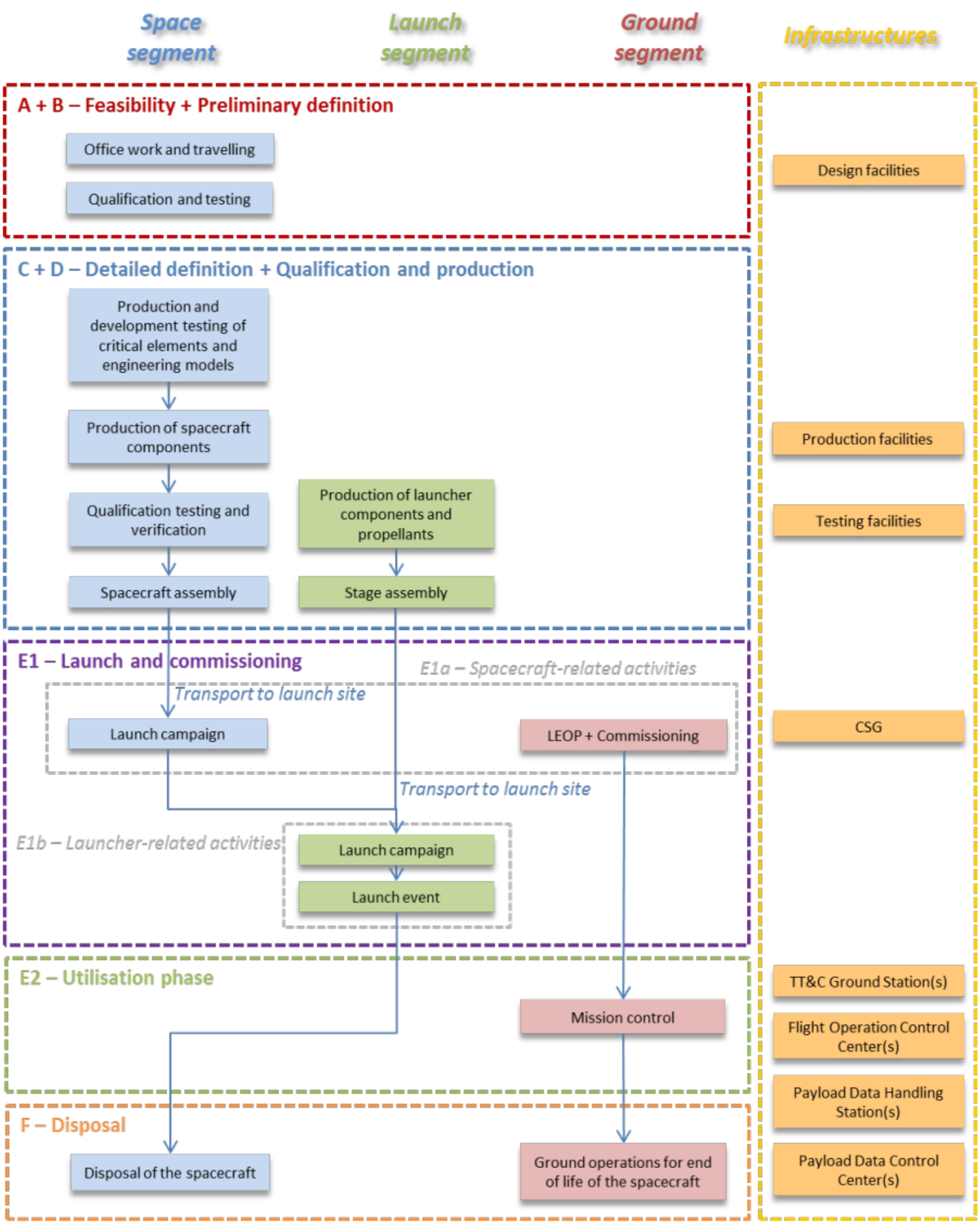


Figure 3.2: Space mission system boundaries as defined by the ESA LCA Guidelines, from which it has been taken [29]. Note that CSG stands for *Centre Spatial Guyanais* (Guiana Space Centre) and could be replaced by "Launch Centre."

3.4.2. Recommended Functional Unit

In its Guidelines, ESA admits that conceiving a FU which allows for a comparison between space missions is "very difficult," as few space missions have the same function [29]. On a European level, discussions are held between stakeholders and the space industry on, amongst others, the topic of creating a dedicated FU per mission class [15], [35].

Nevertheless, ESA recommends the following FU for space missions in general: "To fulfil the requirements of the specification of the equipment/component/material/process in question" [29]. These requirements ought then to be specified and depend upon the space mission and the segment studied. Note that the FU does not consider a case where the space mission would fail early, and thus exclude any risk consideration: it is assumed that the mission goes perfectly as expected.

For only the Space segment, this FU could translate into "one space mission in fulfilment of its requirements" [29]. A launcher might have a FU as follows: "To place a payload of X tons maximum [in single launch configuration and Y tons maximum in dual launch configuration] into orbit Z" [29]. The Ground Segment, if studied on its own, might be given the following FU: "To fulfil the ground segment requirements of the specification of the mission in study" [29]. Similarly, FUs could be specified if only subsystems, components or equipment are studied.

3.4.3. Space-specific midpoint indicators

Due to the uniqueness of the space sector in terms of LCA, some ink has flown on the topic of creating additional space-specific midpoint indicators. That is, arguments have been made in ESA's LCA Guidelines [29] as well as in research articles [46] that one should add midpoint indicators besides the PEF midpoint indicators to better encompass the full impacts caused by a space mission. In particular, the launch and re-entry processes are quoted alongside the use of certain chemicals as reasons to enlarge the scope of PEF's environmental assessments [29], [46].

The suggested additional space-specific midpoint indicators are listed below, alongside a brief explanation of their meaning [46]:

- **Mass left in Space.** Total mass of space hardware remaining in orbit at the end of the mission
- **Al2O3 emissions in air.** Emissions in air of alumine during launch event
- **Orbital resource depletion.** Space debris crossing the orbital resource
- **Critical raw material use.** Risk posed to the supply chain when using specific raw material, which may either be available in limited quantities or may be (or become) difficult to obtain due to geopolitical reasons.
- **Re-entry smoke particle generation.** Particles and smoke released in the upper layers of the atmosphere during re-entry.
- **Cumulative energy demand.** Primary energy consumption
- **Total mass disposed in ocean.** Mass left in the oceans after re-entry
- **Restricted substance use.** Risk assessment

3.5. Past efforts in simplifying the reporting of space LCA results

The ESA LCA Guidelines highlights that careful reporting of LCA results is key to avoid greenwashing. It focuses on the reporting of all relevant impact categories, in absolute values where possible, or in relative values if some data are confidential [29]. During the 2022 ESA Clean Space Industry Days (CSID), other suggestions were made to use equivalent analogies for the environmental impacts of space missions (e.g. the number of return trips from Paris to New York of an entire A380, for a measure of climate change impacts), as a means to communicate the environmental impacts more effectively in the midst of the discussions about becoming 'climate-neutral' or about 'resource circularity' [25].

In parallel to these guidelines and recommendations, efforts have been made to devise a method for computing a single-score from the LCA results. Section 3.5.1 shows work done within ESA's Clean Space Office and Section 3.5.2 highlights the work of the University of Strathclyde.

3.5.1. ESA's work towards a single-score LCA result

Work done as part of an internship at the ESA Clean Space office [45] aimed to find a single-score computation method to explicitly mark a space system as "sustainable". To do so, three approaches were investigated: using the PEF weights without any modification to the rest of the LCA procedure, using the PEF weights but with a so-called "space normalisation" based on the reference mission of GreenSat, and adapting the PEF weights to something considered more suitable to the space sector [45] below. The advantages and disadvantages that were found for each method are summarised in Table 3.1. While these conclusions are interesting, one could criticise the fact that the "space normalisation" computations are not readily publicly available, and thus cannot be checked externally. Moreover, the adapted weights were set based on a priority score decided upon by a relatively small group of individuals, all within the Clean Space Office. Therefore, a lack of broader consultation can be noted, potentially resulting in a biased set of weights.

Table 3.1: Advantages and disadvantages of three single-score computation methodologies defined by the ESA Clean Space Office. Taken and slightly modified from the 2023 PEGASUS paper [45] and the ESA Clean Space Office intern's report [44].

	Advantages	Disadvantages
PEF	• Simple to apply • Standard methodology in the EU • Easy to compare with other industries	• Do not take into account the space industry's specificities • Method is developed for mass production • Climate change and energy carriers are addressed as the main issues (21% and 8.3% weight resp.)
PEF with "space normalisation"	• Normalisation is more representative of a space mission • The single-score is better distributed among impact categories	• Climate change and energy carriers are addressed as the main issues (21% and 8.3% weight resp.) • Difficult to find a representative space mission • Ozone depletion might be too much emphasised (thus impacting launchers more) • Less comparable
PEF with adapted weights	• Weighting can be adapted to the space industry's priorities • Single-score is more representative of a space mission	• Weights need to be unequivocally defined • Less comparable

3.5.2. The University of Strathclyde's work towards a single-score LCA result

During the development of the SSSD, the use of a single-score was looked into to reduce the learning curve for engineers and prevent the cherry-picking of impact categories to address. In this regard, a method for deriving a single-score rating was developed using Multi-Criteria Decision Analysis (MCDA), which can be applied to transform multidimensional results into a single number. This is primarily based on already established normalisation and weighting factors as well as custom-made ones for the social and economic criteria [35].

The SSSD single-score is computed by multiplying the normalised results across each midpoint impact category with a weighting factor. The former is calculated using the raw results generated by the SSSD life cycle tool, which is then normalised based on the recommended normalisation approach from the Product Environment Footprint (PEF) [14], according to the 'EU-27 domestic inventory' in 2010 per EU citizen. Alternatively, larger analyses use the planetary boundary approach, defined by the Joint European Research Centre (JRC). The weighting factors for each impact category are taken from the recommended weighting values provided by the JRC [18] and reformulated to make the sum of the impact categories equate to 100% [47].

The SSSD has already been used in several studies, some of which calculate a single-score. This includes three Phase 0/A SmallSat concurrent design studies aimed at generating more sustainable design concepts [47]. However, it is argued that to make the single-score more relevant to the space sector, commonly agreed upon space specific normalisation/weighting factors should be developed by a consortium of relevant stakeholders [47].

3.6. The Space Sustainability Rating organisation and rating system

One organisation which aims to promote and incentivise sustainable practices across the space industry is the Space Sustainability Rating (SSR). Grown from a consortium composed of the World Economic Forum, ESA, the Massachusetts Institute of Technology, BryceTech as well as the University of Texas at

Austin, SSR was hosted in eSpace - EPFL Space Center before becoming a non-profit organisation [39], [40].

SSR's scoring system builds on the sustainability concepts devised in 2019 by the United Nation Committee on Peaceful Uses of Outer Space [39]. It aims to "quantify and measure sustainability decisions taken by operators" [41] through a tiered scoring system shown in Figure 3.3 below. With a range between Bronze (40-55%), Silver (55-70%), Gold (70-80%) and Platinum (80-100%), the score intends to reward operators who take actions that result in a more sustainable impact [38], [41]. An additional so-called 'Bonus "Step" indicator' represents the steps that could be taken by the operators to improve their mission even further mainly in fields which are "still emerging, or are too new to be defined in rigid terms in the SSR tiers" [38].

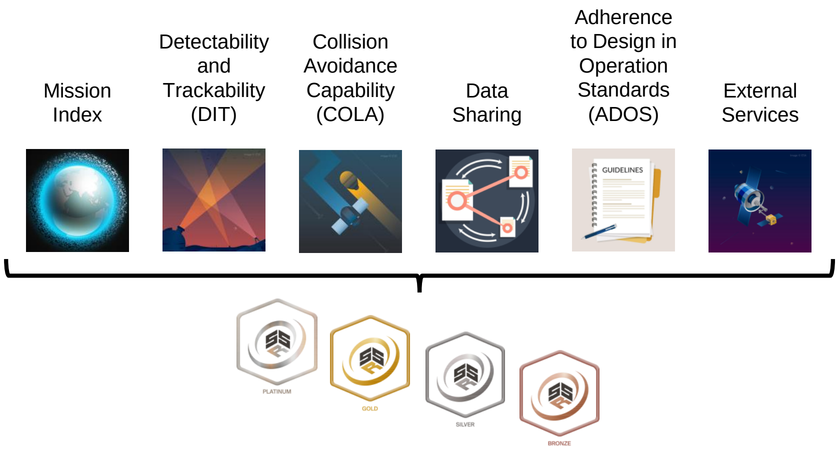


Figure 3.3: Simple representation of the SSR tiered scoring process. Images taken from [39]

The simple representation shows the tiered score created by combining six modules which SSR has developed over the past years. To realise this global score, each module's individual score is calculated and normalised, and the level of data verification is assessed, before weighing the combined scores [38]. A description of each module is given below [38], [41]:

- **Mission index:** quantifies the amount of "harmful physical interference" in orbit, as a result of the design, the mission operations, collision avoidance measures and End-of-Life disposal strategy.
- **Detectability and Trackability (DIT):** deals with the small objects which might not be reliably tracked and could create a risk to other objects in space.
- **Collision Avoidance Capability (COLA):** assessed by means of a questionnaire, it is aimed at highlighting the steps that could be taken by operators to lower the risks of accidental collisions with debris and operating objects.
- **Data Sharing:** evaluates the quantity of relevant information that is being shared between operators with a range of communities, as well as the extent to which this information contributes to the safety in the space environment.
- **Application to Design and Operation Standards (ADOS):** assesses the level to which the space actor adheres where possible to standardisation concepts in the design as well as operations.
- **External Services:** considers the level at which the mission design would allow for close proximity operations, as these might improve space sustainability. This topic is however highly dependent on the mission, resulting in the External Services to be considered within the bonus rating.

While the system is operational and in use since 2022, with prior Beta-tests performed in 2021-2022 [40], SSR is looking into expanding its modules beyond the topics cited above. Work is currently underway on the potential modules listed below [39], with the important comment that not each module will necessarily make integral part of SSR eventually. There are for instance discussions on keeping the LVSR module as a separate rating, dedicated to launchers [42]. Similarly, some of these modules could become bonus modules, as is the case currently for the External Services module.

- **Launch Vehicle Sustainability Rating (LVSR):** assessing the impacts of launch vehicles.

- **Dark & Quite skies module:** assessing the extent to which the mission causes issues for terrestrial astronomical and radio-astronomical observations
- **Life Cycle Assessment module:** assessing the environmental impacts of a space mission over the course of its life-cycle.

This last potential future module is the most relevant for this report. Interesting to remark is that in the original plan for SSR, this LCA module was not included. Instead of it, the LCA impact categories 'ozone depletion' and 'land and water contamination' were noted down [39] as potential topics to look into. This reflects what SSR considered to be important in terms of environmental sustainability on Earth of space missions.

4
Methodology

This chapter discusses in detail the methodology used in this thesis to answer the research questions. First, a survey, discussed in Section 4.1, is performed to gain essential insights. One of these insights leads directly to the creation of the single-score weighting set, as explained in Section 4.2. Then, the Life Cycle Assessment of Delfi-n3Xt is presented, with methodology detailed in Section 4.3. That same section also gives insights into how the satellite's LCA single-score is computed and how modifications are made to the design to simulate some ecodesign. After this, the SSR score of the Delfi-n3Xt is computed, both with SSR's current weights of their modules and with new weights, as reported in Section 4.4. The last step taken in this thesis is the discussion with practitioners in clean space and space mission early design, on how LCA could be implemented in the early design stages. This is described in Section 4.5.

4.1. International survey to reach a consensus

This section covers the methodology behind the survey, with its goal being described in Section 4.1.1. The use of the DELPHI method as an inspiration behind the methodology is discussed in Section 4.1.2 and the overall procedure followed is highlighted in Section 4.1.3. A detailed look at the recruitment of the participants is given in Section 4.1.4 and the content of the questionnaires themselves are explained in Section 4.1.5.

4.1.1. Objectives of the survey

The survey has two major objectives. The first one is to gain a better understanding of where and when a space mission has the highest environmental impact according to the observations and expertise of the space industry and academics. The second major objective of the survey is to understand which environmental impact indicators would be prioritised during a trade-off between two space mission concepts or designs. By converting the ranking into weights, the survey implicitly seek a consensus on weights of each midpoint impact category. Thus, both the perceived environmental hotspots of space missions and the most needed environmental aspects for a space mission's design are assessed.

Moreover, the survey has secondary objectives, meant to shine light on other aspects related to sustainability in the space sector. Firstly, the survey aims to pinpoint which which of ESA's defined [29] phases (i.e. Phase A, B, C, D, E1, E2 and F) and segments (i.e. Space, Launch, Ground Segment and Infrastructure) of a space mission are considered to cause the highest environmental impact. Secondly, the survey attempts to map the space industry's and academics' reasons to do (i.e. the drivers) or not to do (i.e. the inhibitors) a life cycle assessments, and their opinion regarding the current practices in their respective sectors. Thirdly, the survey is to provide an updated weighting system for Space Sustainability Rating's current and future modules.

4.1.2. DELPHI method

The major part of the survey is inspired by the DELPHI methodology, developed in the 1950s and 1960s in the USA. It is meant to systematically distill the opinions of a panel of experts into a general and reliable consensus, through a series of questionnaires and intermediate feedback on the general opinions

[48]. First used for predictions of future scientific and technological developments in the context of the Cold War, the DELPHI method has nowadays been applied to a plethora of topics (e.g. economic trends, health, education, etc) [48], [51], including recently the environmental impact of commercial space transportation activities in the USA [94].

One of the main benefits of this method is that it does make use of the advantage of group interactions and knowledge exchange between experts, while minimizing the negative impacts of such interactions. The experts are able to share their knowledge but the anonymity granted by the questionnaires and the controlled feedback prevents any particular individual to socially dominate the discussion, as could be the case in a face-to-face setting [49], [51]. Moreover, combining this with the multiple iterations of questionnaires, the theory and research suggest that the median answer of the panel of experts tends to move towards the true answer [51].

There are also some drawbacks to the DELPHI method noted in literature. As experienced during the work leading up to this paper, one of these drawbacks pertains to fact that it is quite resource intensive from the perspective of the organisers. The administration necessary to ensure all participants answer, the subsequent analysis of their answers and the modification of the questionnaires based on it are quite burdensome [49], [51]. Another drawback is the inconclusiveness on the superiority of the final average answers of a small panel of experts in literature, compared to that of a much larger group of 'non-expert' ones [51]. Nevertheless, it is argued that topics of high uncertainty and speculation, traditionally investigated with this method, do in fact require an expert panel [50], which tends to be small.

For the survey presented in this report, the DELPHI method is used for the two major goals described in Section 4.1.1: the environmental hotspots' identification and the weighting of impact categories. Using a DELPHI method for these was considered better than a traditional survey (i.e. without the feedback and iterations) given the complexity and subjectivity of these topics and the need for people with sufficient expertise. The opinion of a single expert would not be enough for robust conclusions, and a large number of participants with little knowledge would be impractical within the given time frame.The other topics of the survey are presented to the panelists in a more traditional survey format, as no or little feedback on their answers is given to them.

4.1.3. General procedure followed for the survey

The participants are given the three questionnaires shown in Appendix I over the span of four weeks, followed by a fourth one almost a month later, also shown in the same Appendix. They thus have about a week to answer each of the first three questionnaires, keeping the topics and their answers fresh in their minds. The fourth questionnaire is given for completion without an urgent deadline and is meant to address the topic of the ranking of the water use indicator, omitted in the other questionnaires.

The survey itself is fully anonymous as per the DELPHI methodology, but a possibility to link answers of a panellist between questionnaires without revealing their identity is used. Best efforts are put into guaranteeing the anonymity by strongly discouraging the panellists to disclose any personal or identifiable information while completing the questionnaires. Moreover, each panellist has a random Unique Code of 12 characters[1] (letters and numbers) enabling the linking of answers between questionnaires. The panellist are made aware of the privacy and data protection efforts through the email attached in Appendix H, sent to each panellists prior to the survey.

Answers are processed and the feedback is written before writing and subsequently send out the next questionnaire. With each questionnaire intended to last on average only 20 to 25 minutes per panellist, the feedback provided to the panellists on the preceding questionnaire is mainly limited to the questions pertaining the two main goals of the survey, described in Section 4.1.1.

4.1.4. Recruitment of the expert panel

The size of the expert panel is based on suggestions emanating from the DELPHI method. Most sources advise a minimum panel size of 7 experts [49], [51], while the recommended upper-bound of a DELPHI research is most often placed at 20 to 25 people [51]. Occasional sources suggest a panel in excess of a hundred experts [49], which, for the purposes of this survey, is deemed impractical and non-productive. Considering the subjectiveness of the questions to be asked, a larger panel size was preferred, to provide

[1]This Unique Code was created using the online code generator `https://generate.codes/` (accessed last on 20/08/2023). The choice of 12 characters was deemed sufficient to make memorisation difficult. Thus, it was deemed to prevent well enough recognising a code and linking it with the individual panellist.

a sufficient significance and acceptance of the results for the wider space industry. Thus the maximum total panel size is set to 40 panellists. The final number of panellists who responded to the questionnaire is 30, which is deemed sufficient to provide significantly relevant answers.

The individual panellists participating in the survey have been recruited with care, based on their expertise level. It is deemed important for the relevance of the survey's conclusions to select at least 7 experienced panelists per segment of a space mission (i.e. space, launch, ground and infrastructure segment). The potential panellists have been shortlisted based on the individuals' reputation (e.g. the relevance of their publications or that of their current or past professional position) and the knowledge level in space sustainability and LCA - a solid knowledge therein being preferred, with a handful of exceptions. Where possible, an introduction through a common acquaintance has been used instead of cold emailing.

The other factor considered during the recruitment process is the geographic location of the potential panellists. While the focus is mainly on the European space industry (including the United Kingdom), panellists from North America, Oceania and Asia are also recruited. This broadens the inputs and makes the conclusions more interesting for the international space industry as a whole.

While the participation to the survey is completely anonymous, some participants have allowed the citation of their workplace or general work experience, to give readers more insight into the types of professional backgrounds of the expert panel. The list of the companies or institutions where those panellists work is as follows:

- Airbus Defence and Space
- ArianeGroup
- EPFL, the Swiss Federal Institute of Technology in Lausanne
- European Space Agency
- German Aerospace Center
- Independent consultant
- Paul Scherrer Institut
- Space Sustainability Rating
- Te Punaha Atea - Space Institute of the University of Auckland
- Thales Alenia Space
- University of Auckland
- University of Stuttgart

It is important to underline that the answers of the vast majority of the panellists are based on personal experience and expertise, as opposed to the employer's policies or practices. The survey results should therefore not be considered as a direct reflection of the company or institution. Moreover, note that this list is non-exhaustive.

4.1.5. Conception of the questionnaires

As mentioned in Section 4.1.3, the survey is split up in three questionnaires (with an added fourth one for completeness), each reiterating the questions pertaining to the primary goals discussed in Section 4.1.1, following up on the average answers to the preceding questionnaire. The space mission's environmental hotspots identification is the main topic of the first questionnaire and a reflection on the average answers is obtained through the second one. No further questions are asked in later questionnaires, as the outcome is found to be quite clear and the limited questionnaire time requires prioritisation on the primary objectives.

Alongside this, the importance ranking of each impact indicator is asked for in all three questionnaires in the case two mission designs are to be compared. In the first one, only the internationally recognised impact indicators discussed in Section 2.2.3 are to be ranked. The second questionnaire adds the impact categories of 'mass left in space' and 'Al_2O_3 emissions in the air', based on a majority of suggestions to add them. The final questionnaire adds all the other impact categories suggested in literature [46]: orbital resource depletion, critical raw material use, re-entry smoke particle generation, cumulative energy demand, total mass disposed in ocean and restricted substance use (international substitute to the REACH substance use, for European readers).

Besides pursuing the primary objectives, each questionnaire also touches upon the secondary objectives and other topics. A portion of the first questionnaire is dedicated to obtaining personal information on the panellists, including their geographic location and their field of expertise. In the subsequent questionnaire, an insight is gained into the reasons for or against doing a LCA in the space sector (i.e. the drivers and inhibitors). The third questionnaire investigates the way the SSR's modules would be weighted, both for the current modules, as well as the newly suggested ones (such as the LCA module).

4.2. Creation of the space LCA single-score weighting set

With the survey performed and its conclusions drawn, the second major part of this thesis is to devise the weighting set for the space LCA single-score. For this, it is chosen to only consider impact categories recommended by PEF and to exclude the space segment from the scope. The reason behind this choice is three-fold:

1. The proposed space-specific impact categories do not yet have a clear and readily-available definition or implementation. Thus, they are not yet usable at the time of writing.
2. Adhering to PEF's recommended impact categories will ensure some level of comparability between the space industry and other industries. Although, it should be noted that the weights for space LCA are different from that of PEF.
3. The omission of the space segment reflects the fact that satellite operators often only have authority over the satellite's design and its overall life-cycle. The choice of the launcher is frequently mainly dictated by financial or political reasons. It is considered that, when environmental reasons are also taken into account, there are few actions the operator can take to reduce the impacts of the launch segment.

To calculate the final weighting set, the relative importance of the midpoint impact categories are first aggregated into initial space LCA weighting sets. For this, the average scores given by the panellists to each PEF impact indicator are obtained and scaled to sum up to 100%. After this, robustness factors are applied to each of them. These factors are conceived by the JRC and essentially ensure that impact categories with greater certainty in their outcomes have a higher weight compared to the results from impact categories that are less robust. The last step is to scale the intermediate weights to 100, i.e. to make their sum equate 100.

The resulting set of weights is then used for the calculation of Delfi-n3Xt's LCA single-score as discussed in Section 4.3.9. This is done after its life cycle is assessed, as discussed in Section 4.3 below, and the results are normalised (also described in Section 4.3.9).

4.3. Life Cycle Assessment of the Delfi-n3Xt mission

The third major part of this thesis is the LCA of an existing satellite, chosen to be the Delfi-n3Xt. Performing a concrete LCA is a means of testing the single-score weights' outcomes.

Therefore, this section provides insights into the methodology followed for the LCA of Delfi-N3Xt. It highlights the reasoning behind the choice of Delfi-n3Xt in Section 4.3.1 and the LCA software in Section 4.3.3. The goal and the scope of the LCA are discussed in Section 4.3.4 through the chosen FU and system boundary. The assumptions made for the LCA and the datasets used are listed respectively in Section 4.3.6 and Section 4.3.7. Details on the LCI modelling are provided in Section 4.3.8. Finally, the procedure followed to perform some ecodesign is discussed in Section 4.3.9.

4.3.1. Choice of Delfi-n3Xt as the satellite to study

A number of satellites are considered as study cases for the LCA in this thesis. The most obvious options are the ones from TU Delft's Delfi program. Extensive archival documentation is indeed available on them and many of the project managers of each satellite can still be approached within TU Delft for information. Other alternatives came from EPFL's past space mission.

In a bid to produce research in phase with the recent developments of the program, the freshly launched Delfi-PQ [54], [61] is the first option looked into. Given that one of the supervisors of this thesis, Dr. ir. Alessandra Menicucci, is the project manager of the Delfi program and led the Delfi-PQ system Engineering team, the obtention of information on the satellite would appear relatively straightforward. However, Delfi-PQ's PocketCube[2] form factor is not deemed to be sufficiently representative for the majority of the SmallSats launched at the moment. A CubeSat[3] form factor is much more common and would serve as a better satellite type to perform a LCA.

[2]A PocketQube is a satellite with a form-factor based on unit cubes of 5x5x5 cm (one eighth the volume of a Unit of a CubeSat). These cubes can be stacked to form a two, three, etc Unit PocketQube, similar to the workings of a CubeSat.

[3]A CubeSat is satellites with a form-factor based on cubes of 10x10x10 cm, called Units. When its body size is that of only one Unit, the CubeSat is called a 1U Cubesat. In the case of Delfi-C3 and Delfi-n3Xt, the size is that of the 3 Units (30x10x10 cm in total) approximately

For the above reasons, TU Delft's first satellite, Delfi-C3, is to be considered as a good candidate, if not for its simplicity compared to current SmallSats. Its 3U CubeSat form-factor aligns well with current trends and its simplicity – its lack of thrusters or batteries – would make a LCA relatively easy. However, it is exactly the latter argument which serves as a reason not to choose this satellite. The Delfi-C3 is thought to be too simple and thus not representative enough for current CubeSat missions.

Therefore, the Delfi-n3Xt is the chosen candidate. It has the same benefits relating to its form-factor as the Delfi-C3 while incorporating some elements more commonly found on current CubeSat missions, such as microthrusters – albeit as a payload – and batteries. Moreover, the documentation can easily be accessed through a TU Delft internal Cloud storage and the satellite's project manager and lead systems engineer, Dr. ir. Jasper Bouwmeester, can be (and has been) reached out to easily.

A notable mention should be made on to the fourth option briefly considered, yet rejected: the SwissCube[4]. Given the collaboration with eSpace - EPFL Space Center for this thesis, the 1U CubeSat launched by the university has been considered. A negative point, however, is that its form factor may not be the most representative of current commercial and governmental CubeSat launches. Moreover, it is unsure to what extent the required documentation can be found in EPFL's archives. As such, this cubesat is not selected for the LCA.

4.3.2. Background on the Delfi-n3Xt cubesat

The Delfi-n3Xt satellite, shown in Figure 4.1, is a product of the Delfi program. The latter, started in 2004 at the Delft University of Technology [54], mainly has an educational goal with the design, launch and operation of its CubeSats and PocketQube satellites [54]. The program's first satellite, Delfi-C3, was meant to highlight the benefits of CubeSats beyond its educational aspects, by showing how cost-effective a technology demonstration can be on such platforms [54]. Subsequently, the Delfi-n3Xt and Delfi-PQ missions would expand on this goal, with the popularity of CubeSat growing and it technology improving.

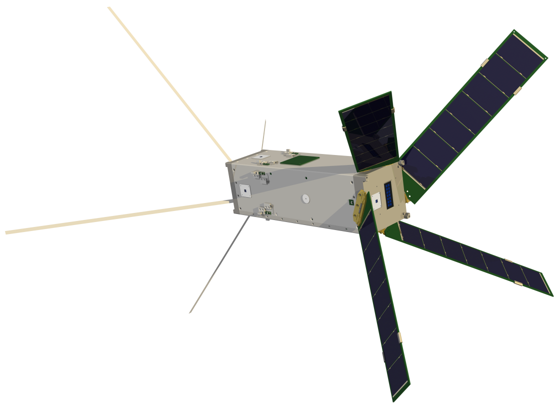


Figure 4.1: Artist render of Delfi-n3Xt. Taken from [54].

Overall, the following three general mission objectives are upheld across all missions [54]:

- **Education:** "To provide students optimal preparation for careers in space industry including improvement of engineering skills, team skills, scientific writing, communication and general understanding of all aspects of a real space project."
- **Technology Demonstration:** "To perform demonstration of small innovative space technology emerging from within TU Delft and external partners in the space sector."
- **Small Satellite Bus Development:** "To enable novel applications with (distributed networks) of very small satellites which are not yet feasible in terms of technology and/or cost-effectiveness with the state-of-the-art technology."

Below, a high-level overview of Delfi-n3Xt is given. Figure 4.3.2 discusses the history of the satellite, from its design until the launch and the loss of contact. A general peek into the mission's requirements is given in Figure 4.3.2. The design and the components of Delfi-n3Xt are focused on in Figure 4.3.2 and some clarification is given in Figure 4.3.2 on the ground segment and the infrastructure used throughout the CubeSat's life cycle.

History and current status of Delfi n3Xt's mission

The design of Delfi-n3Xt started in November 2007, with the aim to launch it no earlier than in 2010 [57]. The launch finally occurred on the 21st of November 2013 with a Dnepr rocket at the air base of

[4]More information on the SwissCube can be found here: `https://archiveweb.epfl.ch/swisscube.epfl.ch/` (accessed on 25/08/2023)

Dombarovsky in Russia [59], [62]. With a well-prepared Launch and Early Operations Phase (LEOP) [72], a signal could immediately be received [62] and telemetry showed a good deployment and nominal operations of the satellite. The satellite performed successfully the various in-orbit demonstration it was designed for during three months following the launch. Upon performing a transponder test on the 20^{th} of February 2014, the satellite fell silent and no data could be received anymore [59], [62], despite calls to the radio amateur community for help [52]. Despite this, the mission was considered a success, as it completed all its major objectives and enabled many students to graduate.

Given its "very low chance" of producing a signal again [62], the fact that it did come "back to life" [55] seven years later, on the 9^{th} of February 2021, was thus seen as an opportunity to perform a few more experiments and learn about the evolution of the satellite. Four months later, the signal was again lost and has not yet been regained since (according to the mission's project manager Dr. ir. Jasper Bouwmeester, interviewed for this thesis).

Requirements of Delfi n3Xt's mission

From the detailed list in Table D.1 of Appendix D, some of the relevant mission's requirements are highlighted in this section. On a high level, it is important to note that one of the satellite's core mission goals is to "facilitate educational goals", as well as to make technological progress with regards to Delfi C3 [59], [70]. The satellite is to host and test two payloads from external partners, as well as two other payload experiments. It is constrained by a 3kg mass limit as well as a 100mm x 100mm x 340.5mm size limit [70]. Regarding the timespan of the mission, the minimum operational lifetime of the bus systems (i.e the systems which support the payloads) is set to at least 3 months, even if a single point failure or a failure of a component occurs [70].

Design of Delfi n3Xt

With its size of 100mm x 100mm x 340.5mm [74] and a final mass of 2.865 kg [64], the CubeSat managed to stick to the dimensional requirements and fit all the required subsystems. The latter are the Communication Subsystem (COMMS), the Command & Data Handling Subsystem (CDHS), the Attitude Determination and Control System (ADCS), the Electrical Power Subsystem (EPS), the Mechanical Subsystem (MechS), the Structural Subsystem (STS), the Thermal Control Subsystem (TCS) and the External Payloads (P/L).

Figure 4.2 shows the components of each of these subsystems, as they are integrated in the satellite. The subsystems of ADCS is readily visible on the figure and is made up of a magnetorquer, a reaction wheel and a sun sensor. The EPS can also be seen on the figure except for its solar panels. The COMMS is composed of the Deployment & Antenna Board (DAB), the Primary Transceiver (PTRX) and the S-band transmitter (STX), as well as the Modular Antenna Box (MAB) which is not visible in the figure. The CDHS is made up by the On-Board Computer (OBC), and the MechS refers to the deployment hinges of the solar panels. The STS contains the Top Panel (TOP), Bottom Panel (BOP), as well as the midplane standoffs and the outer structure, not shown in the figure. The TCS is only composed of a thermal control tape to regulate the temperature. More details on the subsystems and their components' weights can be found in Table D.2 in Appendix D.

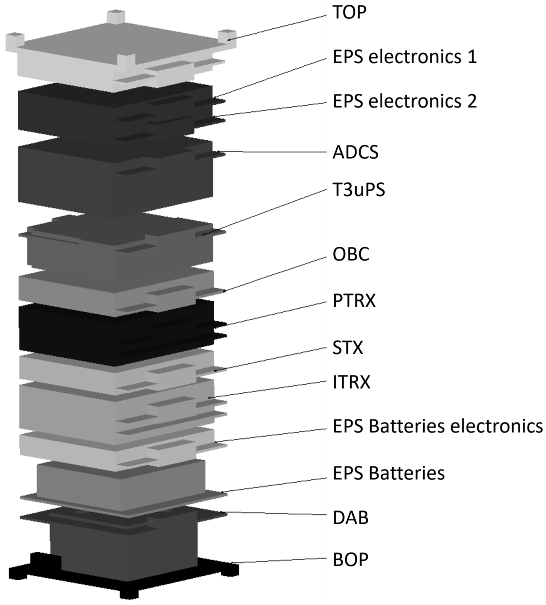


Figure 4.2: Components of Delfi-n3Xt. Modified from [62].

For the Payload, there are a total of 4 payloads and experiments placed onboard of the satellite [59], [62], despite five being deveoped at the earlier design stages [53]. The ones onboard of the satellite are listed below

- **The cool gas micro-propulsion system $T^3\mu$PS:** developed by TNO[5], TU Delft and the University of Twente, this payload is meant to demonstrate thrust generation for orbit and positional correction. Its eight cold gas generators store nitrogen in a solidified form and transform it into gas through a temporary heating. The resulting pressure increase can then be transformed into thrust by opening the valve and releasing the nitrogen.
- **The Solar cell Degradation Measurement experiment (SDM):** The TU Delft's micro-manufacturing lab Else Kooi Lab (EKL)[6] – formerly known as Dimes Technology Centre – developed this payload to measure the change in performance and degradation of silicon solar cells. For this, fourteen small solar cells are monitored as they get exposed to the radiation and temperature changes of space.
- **The ISIS Transceiver (ITRX)** developed by ISISPACE[7], this transceiver module is based on Delfi-C3's transceiver module [53] and was to be qualified and tested on Delfi-n3Xt.
- **The Linear Transponder:** This electronic component could also be considered a payload or an experiment since it mainly serves a third-party, namely the radio amateur community. This transponder is identical to the one on Delfi-C3 [53] and allows radio amateurs to receive telemetry data and forward this to the Delfi-n3Xt team.

Ground Segment and Infrastructure used

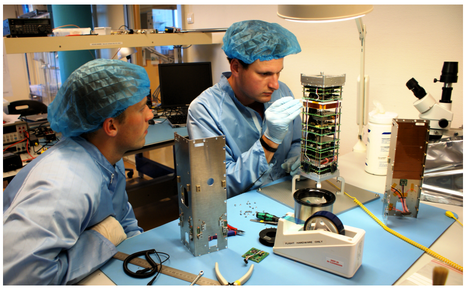


Figure 4.3: Integration of Delfi-n3Xt in the cleanroom of TU Delft's Aerospace Faculy. Taken and slightly cropped from [54].

For the LCA performed in this thesis, it is relevant to note which infrastructure is used by the designers and mission operators. During the design process of the satellite, the students and staff used mainly the facilities provided by the TU Delft. That is, offices within the Aerospace faculty were used, including the university's desktops or the students laptops. While some small tests were performed without the need of a cleanroom, the designers and assemblers of the satellite used almost solely the cleanroom situated on the 8^{th} floor of the faculty. This ISO 8, class 100,000 cleanroom was established in 2005 and is used by various students and researchers to build and test hardware [56]. An image of engineers working in the cleanroom is given in Figure 4.3.

Also the specifics of the ground station are relevant for the LCA. TU Delft has a ground station on the roof of the faculty of Electrical Engineering, Mathematics and Computer Science (i.e. the highest building on campus). On it, there are antennas and complementary radio equipment for satellite communication from VHF to S-band. Within the control room, the telemetry is acquired and and commands can be sent to the satellites. The ground station is used by the various satellite missions of TU Delft [56].

4.3.3. LCA Software used: Brightway2

While there exist many LCA software used by practitioners worldwide (e.g. SimaPro[8], GaBi[9], and OpenLCA[10]), the Brightway2 software was chosen for the LCA of Delfi-n3Xt. Developed since 2012 as an open source LCA framework, this software has seen increased uses within the research community [101]. It is the open-source aspect of the software, as well as its wide range of use-cases found in literature [101] that form the main reasons for choosing it for this thesis. No fees are to be paid in order to have certain databases imported or converted onto it and there is an active community of developers

[5] TNO is the Dutch Organization for Applied Scientific Research (or in Dutch: *Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek*). More information can be found on their website: `https://www.tno.nl/nl/` (accessed on 10/09/2023)
[6] More information on the lab can be found on their website `https://www.tudelft.nl/en/eemcs/research/facilities/else-kooi-lab/` (accessed on 10/09/2023)
[7] Created by some of the students who developed Delfi-C3, ISISPACE (Innovative Solutions In Space) specialises in the design and manufacturing of CubeSats. More information can be found on their website: `https://www.isispace.nl/` (accessed on 10/09/2023)
[8] More information on SimaPro can be found on their website: `https://simapro.com/` (Accessed on 10/09/2023)
[9] More information on GaBi (or 'Product Sustainability Solutions Software' as it is currently called) can be found here: `https://sphera.com/product-sustainability-software/` (Accessed on 10/09/2023)
[10] More information on OpenLCA can be found on their website: `https://www.openlca.org/` (Accessed on 10/09/2023)

to whom questions can be asked. Thus, any future researcher could easily download the software and reproduce or improve the calculations shown in this report, without further complications.

To easily interact with Brightway2, the so-called 'Activity Browser (AB)' is used. Intended to provide a graphical user interface to Brightway2 and to be an extendable open-source LCA software for novel and complex modeling approaches [88], [101], it was found to be the most easy-to-use method for Delfi-n3Xt's LCA modelling. It facilitates the management of LCA projects and databases, modeling of LCIs, visual exploration of the latter through a 'graph explorer,' parametrization of inputs and outputs, model scenarios if desired and it can perform and display the LCA calculations [101].

4.3.4. Goal and scope

The Goal and Scope of Delfi-n3Xt's LCA defines the outcome of the assessment, and is thus important. In this Section, the functional unit used for the LCA is described, as well as the system boundaries.

Functional Unit (FU)

The FU chosen for Delfi-n3Xt follows the ESA LCA Guidelines [29] and its general FU for the Space Segment, as described in Section 3.4.2. As such, Delfi-n3Xt's FU is as follows: "One Delfi-n3Xt space mission in fulfilment of its requirements." As discussed below, this means that the space segment, ground segment and some infrastructure are taken into account.

The requirements mentioned in the FU relate to the satellite's requirements of which a subset is shown in Table D.1. In particular, requirement SAT.2-C02, regarding the nominal operational mission time of 3 months is key. For the purposes of the LCA, it is assumed that the satellite operates indeed for 3 months, with data transmission and ground segment operations during that time span. After those months, the mission is considered over for the purposes of this LCA. Therefore, the loss of signal after the mission's first three months and subsequent re-acquisition of signal 7 year later, discussed in Figure 4.3.2, are disregarding for the LCA.

In short, this FU would effectively simulate the way in which the LCA could have been done during Delfi-n3Xt's design phase, if sustainability would have been taken into consideration. Indeed, the designers would not have expected a revival seven years after the nominal mission lifetime and the subsequent continuation of the mission. In a sense, this FU thus simulates the implementation of sustainability considerations during the design phase.

System Boundary

The general target of the LCA is to include as many of the aspects of a space mission's life cycle defined by ESA [29] as possible. The reason for this is that the results and the LCA single-score of Delfi-n3Xt would then be most representative for space missions in general and could be used most easily as a comparison for other studies. Therefore, investigations were made into the feasibility of including all the aspects shown in the diagram of Figure 3.2.

However, time constraints and the nonexistence of a LCA model of the Dnepr launcher (the launcher of Delfi-n3Xt) led to the exclusion of the launch segment from the scope of Delfi-n3Xt's LCA. Reliable data on the Dnepr launcher's assembly and launch campaign could not easily be found and reaching out to Roscosmos was deemed to have little chance of succeeding and would be too time-consuming. Also, despite SSSD's efforts in modelling various launchers (including the Soyuz-FG launcher), the Dnepr has not yet been modeled. Therefore, it was chosen to exclude the launch segment.

In fact, one could argue that the exclusion of the launch segment is a logical choice in the context of a satellite's LCA single-score and a satellite operator's SSR score with a LCA module. Indeed, a satellite operator has in general little agency over the environmental impact of the launcher. While a choice of launcher can be made, political or economical reasons often play a major role, if it isn't based on launch performance requirements. It would be difficult to paint a clear picture of a satellite's impacts while including the launch segment, as the latter usually dominates some impact categories, such as ozone depletion [44], [47]. For SSR's future LCA module, it would also not make sense to include the launch segment into a score which is mainly dedicated to a satellite, knowing that a module dedicated to the launcher (the LVSR) is being developed. Therefore, to future-proof the single-score methodology developed in this thesis (for a possible inclusion into SSR's LCA module) and to only assess the satellite's life-cycle, the launch segment is removed. The launcher might always be studied separately afterwards.

Moreover, regarding the scope of Delfi-n3Xt's LCA, the infrastructure is also set outside of the system boundary, although some aspects of it are implicitly taken into account. In Phases E2 and F, Delfi-n3Xt's infrastructure is simply not as complex as the one proposed by ESA and can thus implicitly be addressed within the mission control's and ground operation's office work activities (see Section 4.3.8 for more details on the activities). The same is true for the design facilities which are in fact merely offices in the Aerospace Faculty. Similarly, the production and testing facilities (i.e. the cleanroom of the faculty) of the mission are implicitly included in the form of a 'cleanroom activity'. Lastly, the limited information on the launch station makes the choice to exclude it from the LCA straightforward. Thus, the infrastructure is not considered as a segment on its own, but it is simplified and included with other segments' activities, with the exception of the launch station.

Consequently, one obtains a system boundary which includes the space segment and the ground segment explicitly, and some parts of the infrastructure in an implicit way. This is represented by Figure 4.4, in which the greyed out activities represent the ones which are excluded or only implicitly included.

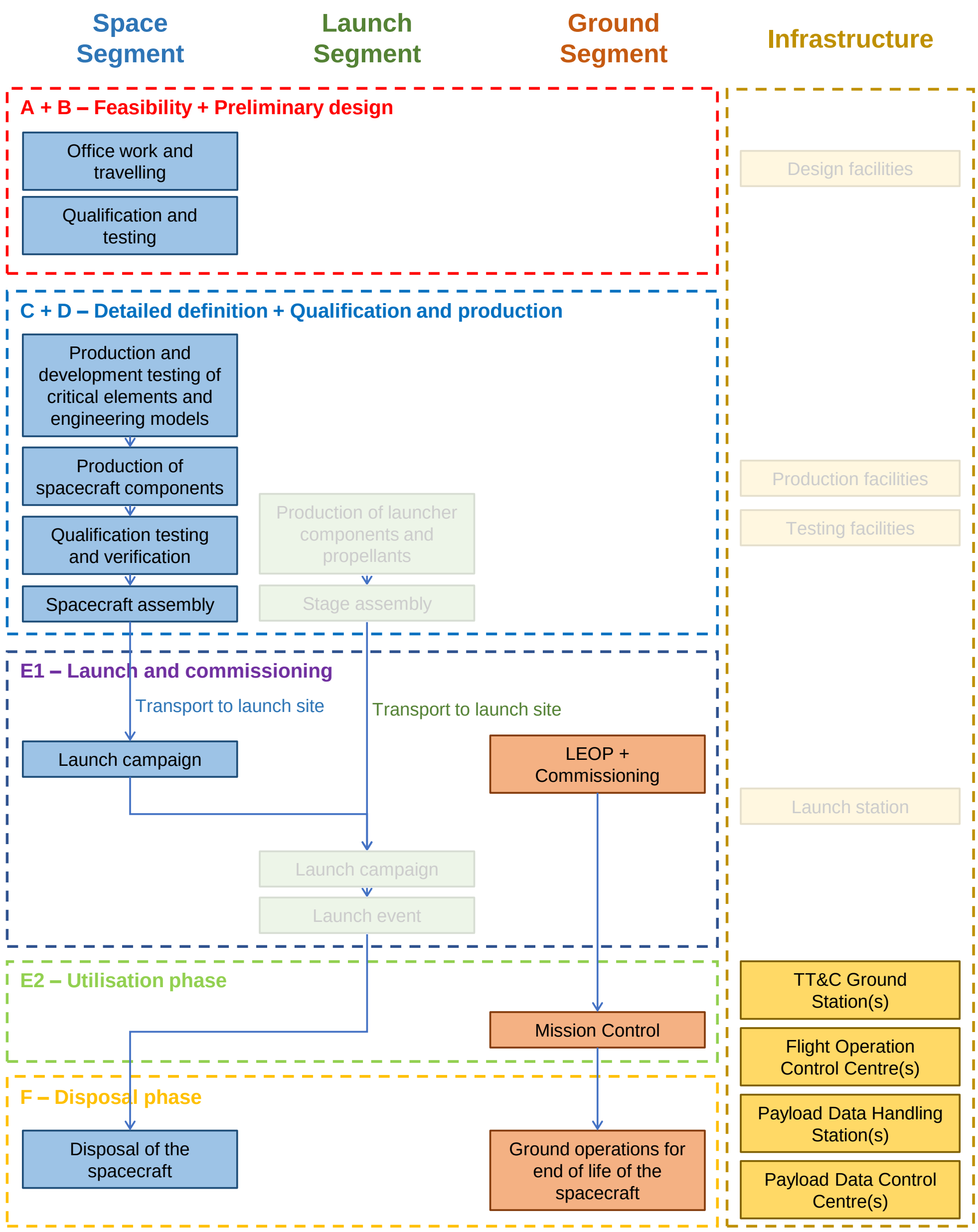


Figure 4.4: Delfi-n3Xt's system boundaries for its LCA. The lighter blocks are considered out of scope for the LCA. This figure has been modified from the ESA LCA Guidelines [29].

4.3.5. Impact categories and associated Life Cycle Impact Assessment method

While the decision relating to the impact categories is rather straightforward, the selection of the most appropriate LCIA method requires more reflection. Below, a rational is given for both of these choices.

The options for the impact categories are rather restricted, as the space-specific midpoint impact indicators – suggested in literature and discussed in Section 3.4.3 – are still under development and not yet readily available at the time of writing. As such, the generic impact categories found in the PEF and discussed in Section 2.2.3 are to be used. These impact categories which are broadly adopted enable one to create results that are easily understandable. Moreover, these impact categories match with the ones proposed to the expert panel in the survey (omitting, of course, the space-specific categories).

However, the choice of the LCIA characterisation model is more delicate, as the ESA LCA Guidelines are about to be updated – supposedly within months following the publication of this thesis, according to various reliable sources. The selection of a model which is currently not endorsed by Guidelines or which the updated Guidelines will not favour would likely result in a rapid obsolescence of any conclusions drawn in this thesis. The goal is therefore to apply a model that leans towards both current and upcoming practices in space LCA.

To solve this conundrum, a source closely involved with the development of the new ESA LCA Guidelines and LCIA characterisation model was asked for recommendations. While the ESA LCA Guidelines suggest to use a mixture of various models (with a slight preponderance of the ReCiPe 2016 LCIA model) depending on the impact indicator [29], the source mentioned that the ReCiPe 2016 LCIA model could be considered as the overarching model for the 2016 Guidelines. Regarding the updated Guidelines however, the source mentioned that the impact categories from the third version of the Environmental Footprint (EF) would be used as a basis, with some space-specific alterations. Thus the choice to be made would be between ReCiPe 2016 and EF v3.0.

To be as relevant as possible for future readers, the EF v3.0 LCIA characterisation model was picked. It remains to be seen how many modifications will be made for the space LCA, but this selection may be the most future-proof. Thus, the chosen impact categories and their respective units can be seen in Table 4.1.

Table 4.1: Chosen Impact categories and associated units for Delfi-n3Xt's LCA. These names and unites are taken from the EF v3.0 LCIA model proposed within Brigtway2.

Name taken from the EF v3.0 LCIA characterisation model	Unit
EF v3.0, acidification, accumulated exceedance (AE)	mol H+-Eq
EF v3.0, climate change, global warming potential (GWP100)	kg CO2-Eq
EF v3.0, ecotoxicity: freshwater, comparative toxic unit for ecosystems (CTUe)	CTUe
EF v3.0, energy resources: non-renewable, abiotic depletion potential (ADP): fossil fuels	MJ, net calorific value
EF v3.0, eutrophication: freshwater, fraction of nutrients reaching freshwater end compartment (P)	kg P-Eq
EF v3.0, eutrophication: marine, fraction of nutrients reaching marine end compartment (N)	kg N-Eq
EF v3.0, eutrophication: terrestrial, accumulated exceedance (AE)	mol N-Eq
EF v3.0, human toxicity: carcinogenic, comparative toxic unit for human (CTUh)	CTUh
EF v3.0, human toxicity: carcinogenic, organics, comparative toxic unit for human (CTUh)	CTUh
EF v3.0, human toxicity: non-carcinogenic, comparative toxic unit for human (CTUh)	CTUh
EF v3.0, ionising radiation: human health, human exposure efficiency relative to u235	kBq U235-Eq
EF v3.0, land use, soil quality index	dimensionless
EF v3.0, material resources: metals/minerals, abiotic depletion potential (ADP): elements (ultimate reserves)	kg Sb-Eq
EF v3.0, ozone depletion, ozone depletion potential (ODP)	kg CFC-11-Eq
EF v3.0, water use, user deprivation potential (deprivation-weighted water consumption)	m3 world eq. deprived

While the JRC provides more detailed information on the characterisation factors of these impact categories [16] and Appendix A provides a description of each impact indicator, certain units in Table 4.1 may be explained further here. One may note that many units are expressed in a "substance equivalent" unit, such as CO2-Eq, or P-Eq. These refer to the agglomeration of the impact of various substances' emissions, to represent it into an equivalent impact of a single substance. Climate Change is for instance expressed in kg CO2-Eq, which in fact takes into account emissions of CO2, methane and other gases.

The units of CTUh and CTUe are so-called Comparative Toxic Units for human and for ecosystems respectively. CTUh represents the estimated increase in disease cases in the total human population per unit mass of a chemical emitted (cases per kilogram) [99]. CTUe is similar, but applied to the ecosystem: it represents an estimate of the fraction of species that are potentially affected per unit of mass of chemical emitted [99].

The unit for Water Use represents the "cubic meter consumed on average in the world" [102] by the system studied. The 'average' refers to the fact that the relative availability of water in each area of the world is taken into account [78]. Thus, the unit is not the exact volume of water consumed by the system, but rather a comparative unit.

4.3.6. Assumptions

To perform any LCA study, a number of assumptions on the product or service studied ought to be made. For Delfi-n3Xt, these assumptions can be found in the tables below. An attempt was made to subdivide them in a comprehensible manner, along with documentation of the required rational for each of them. The full details on the reasoning behind each assumption can be found in Appendix E.

The general assumptions pertaining to the high-level overview of the Delfi-mission and to general matters can be seen in Table 4.2, with a fully detailed rational in Table E.1. In these assumptions, some definitions are put in place amongst others regarding work-hours, work-days[11] and work-years[12]. Moreover, some assumptions are given regarding the amount of time students, staff and the external consultant worked on the mission.

Table 4.2: General (GE) assumptions for the LCA of Delfi-n3Xt.

ID	Assumption	Short Rational
GE.01	No infrastructure used for assembly or testing will be included in the LCA	Facilities are used for multiple missions and educational projects [56].
GE.02	Per work-year, it is assumed that there are 225 work-days	Based on the Dutch government's website [93].
GE.03	Per work-day, it is assumed there are 8 work-hours	Personal choice/experience
GE.04	Students have contributed to the equivalent of 35 work-years during the first 5 years (i.e. Phase A+B and part of C+D).	Meeting with Dr.ir. Jasper Bouwmeester
GE.05	So-called "Full-time students" have contributed to the equivalent of 2.5 work-years during the last half-year prior to the launch (i.e. Phase C+D).	Meeting with Dr.ir. Jasper Bouwmeester
GE.06	An external consultant worked the equivalent of 1 work-year near the end of the project's design phase (i.e. Phase C+D)	Meeting with Dr.ir. Jasper Bouwmeester
GE.07	The TU Delft staff contributed in total 10 work-years	Meeting with Dr.ir. Jasper Bouwmeester
GE.08	It is assumed that during the Launch and Early Operations Phase (LEOP) (i.e. in Phase E1) 16 work-hours are spent by students	Personal choice/reasoning and internal documentation [72].
GE.09	It is assumed that one student contributed to the ground station operations and data handling during 425 work-hours	Meeting with Dr.ir. Jasper Bouwmeester

[11]The distinction between 'work-day' and 'working day' should be clear to the reader: the former refers to the equivalent number of days an employee would work for a given number of 'work-hours' and the latter represent the number of days the employee actually works. For a full-time employee, those two values would be identical, while for an employee working only half-time, the calculated number of work-days would be half of their number of working days.

[12]A similar distinction as that between 'work-day' and 'working day' should be made for 'work-year' and 'working year'. The same reasoning applies. Thus, for a full-time employee, the values of 'work-year' and 'working year' would be identical, while for an employee working only half-time, the calculated number of work-years would be half of their number of working years.

The assumptions related to Phase A+B can be found in Table 4.3. It shows the assumed allocation of work-years by both students and staff to the Phase A+B, as well as the fraction of that time spent in the office with a laptop or a desktop. Moreover, assumptions needed for the calculations of the number of commutes, as well as assumptions on the chosen vehicle for commutes are shown in the table. A fully detailed rational is given in Table E.2.

Table 4.3: Assumptions on Phase A+B for the LCA of Delfi-n3Xt.

ID	Assumption	Short Rational
AB.01	45% of the student's 35 work-years discussed in Assumption GE.04 (i.e. 15.75 work-years) is attributed to Phase A+B Office Work.	Personal choice/reasoning
AB.02	50% of the staff's 10 work-years discussed in Assumption GE.07 (i.e. 5 work-years) is attributed to Phase A+B Office Work.	Personal choice/reasoning
AB.03	An assumption on the percentage of the work-days spent on a desktop during Phase A+B is shown below: • students: 10% • staff: 90%	Personal choice/reasoning
AB.04	An assumption on the percentage of working days spent on a laptop during Phase A+B is shown below: • students: 80% • staff: 0%	Personal choice/reasoning
AB.05	The remaining percentage of working days from Assumptions GE.06 and GE.07 is considered to be spent on testing or miscellaneous tasks	Personal choice/reasoning
AB.06	For the purposes of the calculations of commutes to and from the office, all students are assumed to perform 4 work-hours day per day.	Personal choice/reasoning
AB.07	For the purposes of calculations of commutes to and from the office, the staff is assumed to perform 8 work-hours day per day.	Personal choice/reasoning
AB.08	The commute of both students and staff is assumed to done by bike, with an average one way distance of 3.5km (thus 7km back and forth)	Personal experience

The assumptions made for the LCA of Phase C+D can be found in Table 4.4. It shows assumptions similar to those made for Phase A+B, i.e. the allocated work-years of each group of persons working on the mission, their time spent on desktops and laptops and information on the commute type and frequency. A fully detailed rational is given in Table E.3.

Table 4.4: Assumptions on Phase C+D for the LCA of Delfi-n3Xt.

ID	Assumption	Short Rational
CD.01	55% of the student's 35 work-years discussed in Assumption GE.04 (i.e.19.25 work-years)is attributed to Phase C+D Office Work	Personal choice/reasoning
CD.02	50% of the staff's 10 work-years discussed in Assumption GE.07 (i.e. 5 work-years) is attributed to Phase C+D Office Work.	
CD.03	100% of the "Full-time student's" 2.5 work-years discussed in Assumption GE.05 is attributed to Phase C+D Office Work.	Personal choice/reasoning
CD.04	100% of the external consultant's 1 work-year discussed in Assumption GE.06 is attributed Phase C+D Office Work.	Personal choice/reasoning

Table 4.4: Assumptions on Phase C+D for the LCA of Delfi-n3Xt (cont.).

ID	Assumption	Short Rational
CD.05	An assumption on the percentage of the work-days spent on a desktop during Phase C+D is shown below: • students: 7% • staff: 80% • external consultant: 95%	Personal choice/reasoning
CD.06	An assumption on the percentage of working days spent on a laptop during PhaseC+D is shown below: • students: 60% • staff: 0% • external consultant: 0%	Personal choice/reasoning
CD.07	The remaining percentage of working days from Assumptions GE.06 and GE.07 is considered to be spent on testing or miscellaneous tasks	Personal choice/reasoning
CD.08	For the purposes of the calculations of commutes to and from the office, the students are assumed to perform 4 work-hours day per day.	Personal choice/reasoning
CD.09	For the purposes of the calculations of commutes to and from the office, the "Full-time students" discussed in Assumption GE.05 are assumed to perform 8 work-hours day per day.	Personal choice/reasoning
CD.10	For the purposes of calculations of commutes to and from the office, the staff is assumed to perform 8 work-hours day per day.	Personal choice/reasoning
CD.11	For the purposes of calculations of commutes to and from the office, the external consultant are assumed to perform 6 work-hours day per day.	Personal choice/reasoning

The assumptions made for the LCA of Phase E1 can be found in Table 4.5. It shows assumptions related mainly to the Clean Room operations required during Delfi-n3Xt's assembly and related to its transport to the launch site. A fully detailed rational is given in Table E.4.

Table 4.5: Assumptions on Phase E1 for the LCA of Delfi-n3Xt.

ID	Assumption	Short Rational
E1.01	Each Delfi-n3Xt Flight Model required 40 hours of Clean Room Operations	Personal choice/reasoning
E1.02	Each Delfi-n3Xt Prototype required 5 hours of Clean Room Operation	Personal choice/reasoning
E1.03	The transport of the Delfi-n3Xt CubeSat to the launch site happened by road.	Meeting with Dr.ir. Jasper Bouwmeester

The assumptions made for the LCA of Phase E2 can be found in Table 4.6. It shows assumptions regarding the operations of the ground station. A fully detailed rational is given in Table E.5.

Table 4.6: Assumptions on Phase E2 for the LCA of Delfi-n3Xt.

ID	Assumption	Short Rational
E2.01	For the purposes of the calculations of commutes to and from the ground station, the student mentionned in Assumption GE.09 is assumed to perform 4.5 work-hours day per day.	Personal choice/reasoning
E2.02	The commute of the student is assumed to done by bike, with an average one way distance of 3.5km (thus 7km back and forth)	Personal experience

Table 4.7: Assumptions on Phase E2 for the LCA of Delfi-n3Xt (cont.).

ID	Assumption	Short Rational
E2.03	LEOP is effectively office work from a Desktop, in the Ground Station	Personal choice/reasoning

To keep the same table format as for the other phases, the assumption made for the LCA of Phase F can be found in Table 4.6. It pertains to the amount of the satellite which survives re-entry. A fully detailed rational is given in Table E.5.

Table 4.8: Assumptions on Phase F for the LCA of Delfi-n3Xt.

ID	Assumption	Short Rational
F.01	0% of the spacecraft is assumed to survive the re-entry	Literature [87]

4.3.7. Databases imported and created for the LCA

A good understanding of the imported and created datasets for Delfi-n3Xt's LCA is essential for a good understanding of the next sections on the LCA modelling of the Cubesat. To that end, Table 4.9 shows the datasets used in Brightway2 and mentioned throughout the tables of the next sections. It shows whether or not each dataset is imported or created and it provides a brief explanation on each dataset.

Table 4.9: Datasets imported and created in Brightway2 for Delfi-n3Xt's LCA.

Name in Brightway2	Imported or self-created?	Further explanation
biosphere3	Imported	This is the **dataset of the elementary flows**. It is automatically imported when creating a Brightway2 project within the AB. It is mainly used n the 'cutoff391' and 'ESA LCA External 1.1.8a' dataset
cutoff391	Imported	This is the **dataset of Ecoinvent V3.91, with Cut-Off allocation method**. This is used for most activities that are created for Delfi-n3Xt, be it in the datasets 'ESA Guidelines', 'SSSD specific flows', 'Delfi n3Xt' or 'Space Mission Phases'.
ESA LCA External 1.1.8a	Imported	This is the **public access dataset provided by ESA**, alongside its LCA Guidelines.
ESA Guidelines	Created	This dataset **includes specific activities** which were not found in 'ESA LCA External 1.1.8a', but were **described in the ESA LCA Guidelines**' Appendixes. Thus, it copies some of these ESA activities with a more Dutch accent (e.g. in the electricity provision, etc).
SSSD specific flows	Created	This dataset includes useful **activities defined by SSSD**. Most notable, it include the activity pertaining to a satellite's re-entry.
Delfi n3Xt	Created	This dataset contains activities related to the **components and subsystems of the Delfi-n3Xt satellite**.
Space Mission Phases	Created	This dataset contains the **activities of the life-cycle phases, per segment**. A overview of these activities is given in Figure F.1.

4.3.8. Life Cycle Inventory analysis

The structure of the LCI of the Delfi-n3Xt mission is heavily inspired by SSSD's proposed structure, which in turn is derived from the ESA LCA Guidelines. In its description of a space mission's LCI, the latter decomposes a space mission into levels, each of which go deeper into each space mission's segments. However, in the ESA External database, such a decomposition is not modeled, leaving the

LCA practitioner free in their LCI approach. Therefore, the SSSD's tier-style approach [35], which more or less follows the ESA Guidelines.

The tier system implemented in SSSD and suggested in the ESA LCA Guidelines works as follows [29], [35], [36]. Level 1 represents the whole life-cycle of the entire mission and Level 2 contains the five phases given by ESA in their Guidelines [29] and shown in Figure 3.2. Level 3 subdivides these phases into their respective activities. Those activities get subdivided further into elements in Level 4. Level 5 is reserved for the so-called 'background inventory' which contains LCI datasets from the ESA External database and Ecoinvent, as well as any custom-created datasets.

The structure of the Delfi-n3xt LCI model is shown up to Level 3 in Figure 4.5, with each of the activities left open for further elaboration in the subsections below. One should note that each activity shown in this figure is inserted with an amount of 1 'unit' into the activity of the level below within the Brightway2 LCA tool. That is, the activity "Phase A+B" contains 1 unit of "Phase A+B - Office Work" and 1 unit of "Phase A+B - Travel." Similarly, the activity "Whole mission" contains 1 unit of "Phase A+B", 1 unit of "Phase C+D" and so on. The same could be written for each other activity.

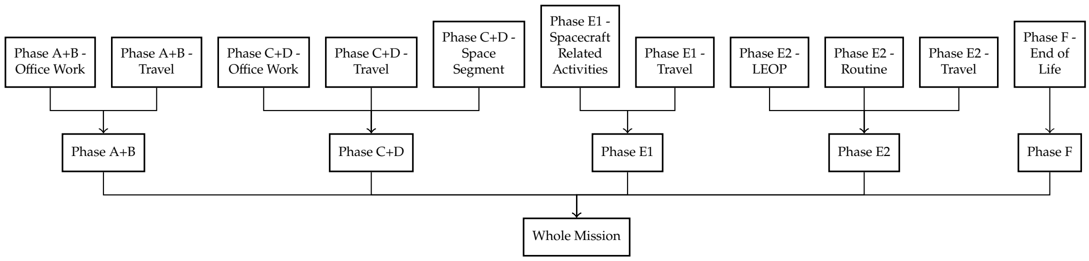


Figure 4.5: Overview of the LCI model of the Delfi-n3Xt space mission up to Level 3. Each of these blocks represent an activity as modeled within Brightway2 and is further expanded in Levels 4 and 5.

The subsections below unfold further the Level 3 activities shown in Figure 4.5. Where required a reference is made to Appendix F for further discussions on some of sub-activities.

Phase A+B - Office Work

The office work during Phase A+B is calculated based on the modelling of office work done within SSSD and shown in Table F.1, as well as on the assumed work-years discussed in Assumptions AB.01 and AB.02 in Table 4.3. A distinction is made between the students and the staff, since they have different numbers of work-years allocated to this Phase. Moreover, as shown in the former table and discussed further in Section E.2, a distinction is made between Office Work with a desktop and Office Work with a laptop.

The calculation of the Work-Hours of students or staff can be straightforwardly calculated using Equation 4.1 and Assumption GE.02 and GE.03. In essence, the computation is done through a multiplication between the work-years (t_{y_w}) of the student or staff, the number of working days ($t_{d_{wg}}$) per year (t_y) and the number of work-hours (t_{h_w}) per day ($t_{d_{wg}}$). The value of t_{y_w} is dependant on whether the person is a staff or student, hence it is left as a variable in the equation. One should note that the outcome of the equation should be multiplied by the percentage of work-days spent on either desktops or laptops, to find their appropriate work-hours.

$$\begin{aligned} t_{h_w} &= t_{y_w} * \left(\frac{t_{d_{wg}}}{t_y}\right) * \left(\frac{t_{h_w}}{t_{d_{wg}}}\right) \\ &= t_{y_w} * (225) * (8) \\ &= 1,800 t_{y_w} \end{aligned} \tag{4.1}$$

The results are summarised in Table 4.10. It shows both the distinction between the student's and the staff's working hours for the case with and without a desktop, as well as the summed up total for each case. Note that the location Global (GLO) is used, as that matches the SSSD definition of the Office Work activity. The final values inputted in Brightway2 are those of the combined Total hours for the Office Work with Desktop and the combined total hours for the Office Work with Laptop.

Table 4.10: High-level inputs for Phase A+B - Office Work. Note that the grayed cells are the values inputted in Brightway2.

Amount	Total	Units	Origin	Product	Activity	Location	Database
2,835		work-hours	Students	Office Work with desktop	Phase A+B - Office Work - Desktop	GLO	Space mission phases
8,100		work-hours	Staff				
	10,935	work-hours	Total				
22,680		work-hours	Students	Office Work with laptop	Phase A+B - Office Work - Laptop	GLO	Space mission phases
0		work-hours	Staff				
	22,680	work-hours	Total				

Phase A+B - Travel

The travel during Phase A+B is based on the assumptions discussed in Table 4.3 and in detail in Section E.2. In particular, the calculation of the passenger-kilometers rely on the assumed commuting distance and the assumption that the overwhelming majority of all commutes are done by bike.

The exact computation is done using Assumption AB.08 and Equation 4.2 where,

- d_{avg} is the average commute distance,
- t_{h_w} is the number of work-hours
- and $\frac{t_{h_w}}{t_{d_w}}$ is the number of working hours per day the staff or student actually works (see Assumption AB.06 and AB.07)

$$\begin{aligned} d_{pers} &= d_{avg}\left(\frac{t_{h_w}}{\left\lceil \frac{t_{h_w}}{t_{d_w}} \right\rceil}\right) \\ &= 7 * \left(\frac{t_{h_w}}{\left\lceil \frac{t_{h_w}}{t_{d_w}} \right\rceil}\right) \end{aligned} \tag{4.2}$$

The results are shown in Table 4.11, divided per student and staff travel. It is only the combined total which is used as inputs in Brightway2. Note that the location Rest-of-the-World (ROW) is chosen for the Ecoinvent activity, as it approaches the European activity the best given the alternatives [84]. The alternatives were Switzerland (CH) and GLO.

Table 4.11: High-level inputs for Phase A+B - Travel. Note that the grayed cells are the values inputted in Brightway2.

Amount	Total	Units	Origin	Product	Activity	Location	Database
49,613		person km	Students	transport, passenger, bicycle	transport, passenger, bicycle	RoW	cutoff391
7,875		person km	Staff				
	57,488	person km	Total				

Phase C+D - Office Work

Office Work for Phase C+D is modeled similarly to that of Phase A+B and The values inputted in Brightway2 for this Phase are shown in the grayed Total rows in Table 4.12. A detailed breakdown on the substructure of the Office Work is shown in Table F.1. Note that the the office work is not not only split up between the students and the staff, but also between the full-time students and the external consultant, as discussed in Table 4.4.

Table 4.12: High-level inputs for Phase C+D - Office Work. Note that the grayed cells are the values inputted in Brightway2.

Amount	Total	Units	Origin	Product	Activity	Location	Database
2,426		work-hours	Students	Office Work with desktop	Phase C+D - Office Work - Desktop	GLO	Space mission phases
315		work-hours	Full-time Students				
7,200		work-hours	Staff				
1,710		work-hours	External Consultant				
	9,941	work-hours	Total				
20,790		work-hours	Students	Office Work with laptop	Phase C+D - Office Work - Laptop	GLO	Space mission phases
2,700		work-hours	Full-time Students				
0		work-hours	Staff				
0		work-hours	External Consultant				
	23,490	work-hours	Total				

Phase C+D - Travel

The person.kilometers of Phase C+D's travels are modeled similarly to those of Phase A+B. The values inputted in Brightway2 for this Phase are shown in the grayed row of Table 4.13. Similar to the Phase C+D - Office-Work, the travel is calculated with the travel of the students, the staff, the full-time students and the external consultant, as discussed in Table 4.4.

Table 4.13: High-level inputs for Phase C+D - Travel. Note that the grayed cells are the values inputted in Brightway2.

Amount	Total	Units	Origin	Product	Activity	Location	Database
60,638		person km	Students	transport, passenger, bicycle	transport, passenger, bicycle	RoW	cutoff391
3,938		person km	Full-time Students				
7,875		person km	Staff				
2,100		person km	External Consultant				
	74,550	person km	Total				

Phase C+D - Space Segment: Spacecraft Production

An overview of the way the Space Segment of Phase C+D is modeled can be seen in Figure 4.6. Made up of the Spacecraft Production and the Spacecraft testing, the Space Segment of Phase C+D is dependent on the modeling of the Delfi-n3Xt satellite itself (seen in duplicate on top of the figure) and on the modelling of the selected tests, discussedd in the subsection below and in Figure 4.7. For the Spacecraft Production, it is worth noting that not only the Flight Model is accounted for, but also the the Prototypes.

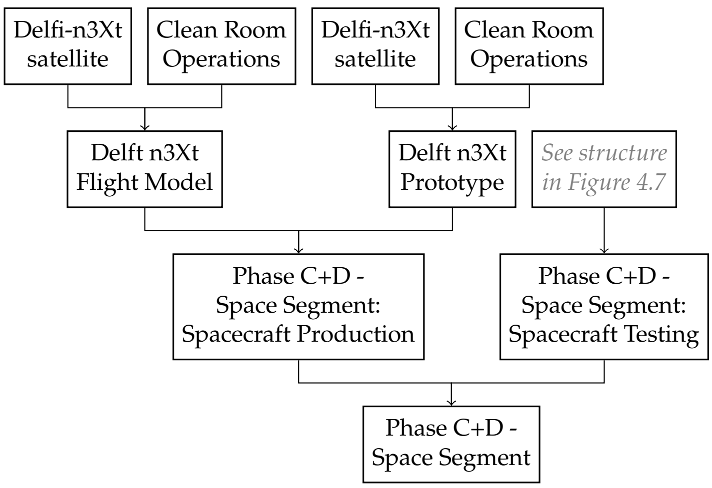


Figure 4.6: Overview of the LCI of "Phase C+D - Space Segment: Spacecraft Production". Note that the two "Delfi-n3Xt satellite" blocks are identical, as are the two "Clean Room Operations".

The exact LCI of the Spacecraft Production can be seen in Table 4.14, showing the number of flight models and prototypes that were considered. The choice to assume that an equivalent amount of six prototypes were made in the prototyping and production phase stems from discussions with Dr.ir. Jasper Bouwmeester. This number seems to match somewhat with the number of spare parts listed in Delfi-n3Xt's internal documentation [65], which only take into account the list of parts at the start of the final assembly phase – not showing the number of prototypes needed beforehand.

Table 4.14: Definition of the "Phase C+D - Space Segment: Assembly, Integration & Testing: Spacecraft Production" for a FU of one complete production phase.

Amount	Unit	Product	Activity	Location	Database
1	unit	Delfi-n3Xt Flight Model	Delfi-n3Xt Flight Model	GLO	Delfi n3Xt
6	unit	Delfi n3Xt Prototype	Delfi n3Xt Prototype	GLO	Delfi n3Xt

A 'unit' of the Delfi-n3Xt's Flight model and Prototype consists of a "Delfi-n3Xt satellite" product and the "Clean Room Operations" activity. The former is in both cases set to 3 kg. The latter is set to 40 hours in the case of the Flight Model and 5 hours in the case of the Prototype, as per Assumption E1.01 and E1.02. Note that the "Clean Room Operations" activity is copied from the SSSD's activity called "Clean Room Fuelling", which resembles closely to ESA's Clean Room related activities. The one used for Delfi-n3Xt has been modified to include electricity mixes from the Netherlands.

The exact subdivision of such a "Delfi-n3Xt satellite" product is shown in Table 4.15. For a FU of 1kg of satellite, with the proportional masses of each product (aka 'subsystems' of Delfi-n3Xt) being derived from the Mass Budget (see Table D.2) found in the internal documentations of the satellite [64]. More details regarding the modelling of each susbystem can be found in Appendix F

Table 4.15: Definition of the Delfi-n3Xt satellite for a FU of 1kg of satellite. The proportions of masses is derived from the Mass budget in Table D.2.

Amount	Unit	Product	Activity	Location	Database
0.112361	kg	ADCS - Attitude Determination & Control Subsystem	ADCS - Attitude Determination & Control Subsystem	GLO	Delfi n3Xt
0.016064	kg	CDHS - Command & Data Handling Subsystem	CDHS - Command & Data Handling Subsystem	GLO	Delfi n3Xt
0.080215	kg	COMMS - Communication Subsystem	COMMS - Communication Subsystem	GLO	Delfi n3Xt
0.34201	kg	EPS - Electrical Power Subsystem	EPS - Electrical Power Subsystem	GLO	Delfi n3Xt
0.037319	kg	MechS - Mechanical Subsystem	MechS - Mechanical Subsystem	GLO	Delfi n3Xt
0.277522	kg	STS - Structural Subsystem	STS - Structural Subsystem	GLO	Delfi n3Xt
0.018239	kg	TCS - Thermal Control Subsystem	TCS - Thermal Control Subsystem	GLO	Delfi n3Xt
0.10196	kg	P/L - External Payloads	P/L - External Payloads	GLO	Delfi n3Xt
0.01431	kg	Cable Harness	Cable Harness	GLO	Delfi n3Xt

Phase C+D - Space Segment: Spacecraft Testing

Besides the spacecraft manufacturing aspects, also some spacecraft testing elements are included in the LCA. From the various internal documentation received, it is clear that a wide range of tests were performed on the whole system, as well as on subsystems and components. These include quick checks of the Printed Circuit Boards (PCBs) or solar panels using voltmeters, multi-meters or other electronics testing devices, as well as more elaborate tests involving thermal-vacuum chambers, solar simulators and other devices. Given that the internal documentation of the tests are test plans written somewhat "on-the-go" with the intention to be used by the author or by their close colleagues, they are not always perfectly easy to understand for an outsider. Moreover, given the time gap since the last tests (more than 10 years ago, at the time of writing, the exact details of each test are somewhat lost in between the imperfect test plans and the students who performed the tests and who have graduated from university some time ago. Time constraints did also not allow an exhaustive search for information for each test.

Thus, specific tests mentioned in the documentation are selected when sufficient data are available and when they are thought to have relatively significant impacts. These are shown in Figure 4.7 and are comprised of long-duration thermal-vacuum tests; chosen because of their high consumption of energy and other resource. Small tests, such as quick calibration of the reaction wheels or PCB power and data checks are ignored for the LCA because of their short time and low resource consumption. Some tests which are ignored for the LCA but which could have had some impacts are tests involving the short uses of the thermal-vacuum chamber (e.g. around one hour), the sun simulator and vibration tables. However, no precise LCI-related information could be found regarding the latter two and the former is thought to have limited impacts.

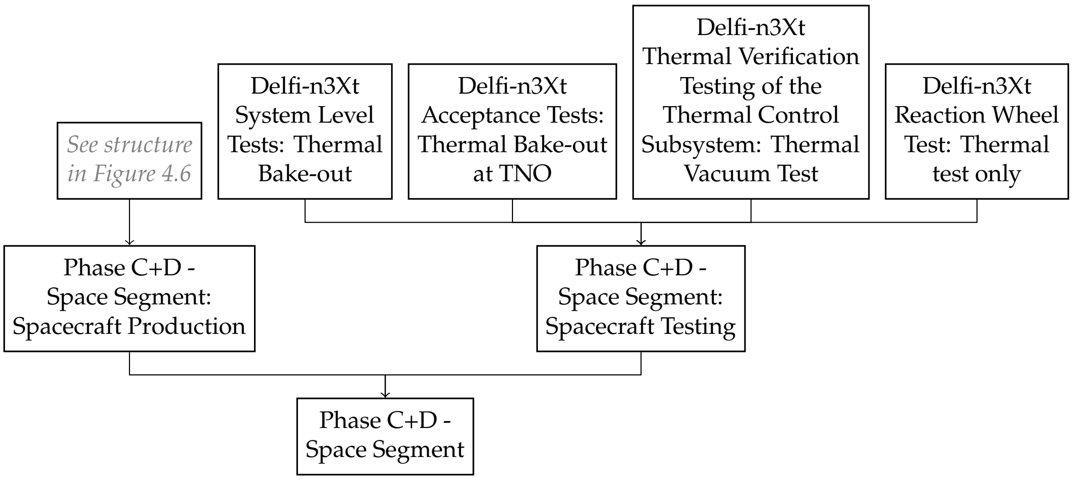


Figure 4.7: Overview of the LCI of "Phase C+D - Space Segment: Spacecraft Testing".

The exact way in which these tests are inserted into Brightway2 is shown in Table 4.16, with further detailed explanations in Section F.4. That is, from the internal documentation, it is found that the thermal bake-out activity of the Delfi-n3Xt's System Level Test and the Acceptance Test lasted 5 hours [75] and 24 hours [75], respectively. The use of the thermal-vacuum chamber for the thermal control subsystem's verification tests lasted 11 hours according to internal documentations found [76]. And, a thermal test of the reaction wheels done in a thermal-vacuum chamber lasted 22 hours [77].

Table 4.16: Definition of the Delfi-n3Xt satellite for a FU of 1kg of satellite. The proportions of masses is derived from the Mass budget in Table D.2.

Amount	Unit	Product	Activity	Location	Database
5	hour	Delfi-n3XT System Level Tests: Thermal Bake-Out	Delfi-n3XT System Level Tests: Thermal Bake-Out	GLO	Delfi n3Xt
24	hour	Delfi-n3XT Acceptance Tests: Thermal Bake-Out at TNO	Delfi-n3XT Acceptance Tests: Thermal Bake-Out at TNO	GLO	Delfi n3Xt
11	hour	Delfi-n3XT Thermal Verification Testing of the Thermal Control Subsystem: Thermal Vacuum test	Delfi-n3XT Thermal Verification Testing of the Thermal Control Subsystem: Thermal Vacuum test	GLO	Delfi n3Xt
22	hour	Delfi-n3XT Reaction Wheel Test: Thermal test only	Delfi-n3XT Reaction Wheel Test: Thermal test only	GLO	Delfi n3Xt

Phase E1 - Spacecraft Related Activities

An overview of Phase E1 - Spacecraft Related Activities can be seen in Figure 4.8. For the purposes of Delfi-n3Xt, only LEOP and the transportation to the launch site are modelled, as the ESA-proposed 'Commissioning' activity [29] was assumed to be insignificant for this mission. Indeed, the Routine activity in Phase E2 (see the subsections below) rapidly takes over after launch, until the end of the mission.

For simplicity reasons, the LEOP activity is modeled as a simple Office Work, identical to that described in Table F.1, with a total of 16 work-hours as discussed in Assumption GE.08. It was decided not to include in LEOP the LCI activities of 'Telemetry, Tracking, and Command (TTC) Ground station Use,' proposed within the ESA LCA Database, since the Ground Station of TU Delft is rather basic as it does not seem to have extensive TTC capabilities [56].

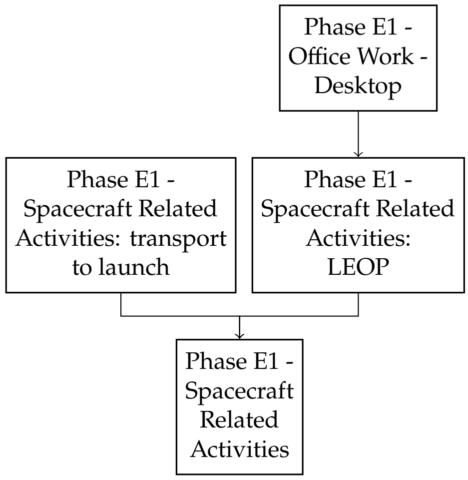


Figure 4.8: Overview of the LCI of "Phase E1 - Spacecraft Related Activities"

The transportation to the launch site is modeled quite straightforwardly based on information given by Dr. ir. Jasper Bouwmeester. As shown in Assumption E1.03, it was done by road, from Delft to the launch site of the Dnepr, Delfi-n3Xt's launcher, at the air base of Dombarovsky in Russia. By means of Google Maps, it was found that the travelled distance would have been 4358km. As a result, the transportation activity is modeled as shown in Table 4.17, where this distance has been multiplied by the satellite's mass.

Table 4.17: Definition of "Phase E1 - Spacecraft Related Activities: transport to launch" for a FU of one Delfi-n3Xt satellite being transported from Delft to the air base of Dombarovsky.

Amount	Unit	Product	Activity	Location	Database
13.074	ton*kilometer	transport, freight, lorry 3.5-7.5 metric ton, EURO4	market for transport, freight, lorry 3.5-7.5 metric ton, EURO4	RER	cutoff391

Phase E1 - LEOP

The LEOP activity in Phase E1 is simplified to the Office Work activity, as written in the Assumption E1.03. This is modeled identically to the way the other office works are modeled, as described in the sections above. For complete clarity and consistency with previous sections, Table 4.18 shows the exact input in Brightway2 for the LEOP activity.

Table 4.18: High-level inputs for Phase E1 - LEOP.

Amount	Unit	Product	Activity	Location	Database
16	work-hours	Office Work with desktop	Phase E2 - Office Work - Desktop	GLO	Space mission phases

Phase E2 - Routine

The Routine during Delfi-n3Xt's mission time is modelled as Office Work done by the student in charge of this phase of the mission. A mixture of work on a desktop and a laptop is considered. The resulting values inputted in Brightway2 can be seen in Table 4.19. For further clarifications on the contents of the Office Work activity, one can review the description in the sections above.

Table 4.19: High-level inputs for Phase E2 - Routine.

Amount	Unit	Product	Activity	Location	Database
25.3	work-hours	Office Work with desktop	Phase E2 - Office Work - Desktop	GLO	Space mission phases
202.5	work-hours	Office Work with laptop	Phase E2 - Office Work - Laptop	GLO	Space mission phases

Phase E2 - Travel
The travel of Phase C+D is modeled similarly to those of Phase A+B described in Table 4.3.8. The value inputted in Brightway2 for this Phase is shown Table 4.13 and are based on Assumptions E2.02.

Table 4.20: High-level inputs for Phase E2 - Travel.

Amount	Unit	Product	Activity	Location	Database
394	person km	transport, passenger, bicycle	transport, passenger, bicycle	RoW	cutoff391

Phase F - End of Life
The End-of-Life is modelled identically to the SSSD's implementation of it in its version 1.0.2 (the latest at the time of this thesis). That is, the various particles which the developers of the SSSD consider to be emitted by a satellite during re-entry are inserted in the Biosphere Flows (as opposed to the Technosphere Flows for the modelling of the previous activities). While SSSD has models of the re-entry with a survivability of the materials of 0% up to 100%, it is assumed that no part of Delfi-n3Xt survives its re-entry, as seems to be the case for CubeSats in literature [87]. Thus, the Biosphere Flows inserted into Brightway2 for the Re-Entry activity are taken from SSSD's activity "Re-entry: ~0% of materials survive", as shown in Table 4.21.

Table 4.21: Definition of "Re-entry: ~0% of materials survive" for a FU of 1kg of satellite.
Note that these are biosphere flows and that the proportions of masses is copied from SSSD's definition of this activity.

Amount	Unit	Flow Name	Compartment	Database
0.28929	kilogram	Aluminium III	air - lower stratosphere + upper troposphere	biosphere3
0.00357	kilogram	Carbon monoxide, fossil	air - lower stratosphere + upper troposphere	biosphere3
0.00714	kilogram	Chromium III	air - lower stratosphere + upper troposphere	biosphere3
0.01429	kilogram	Copper ion	air - lower stratosphere + upper troposphere	biosphere3
0.05714	kilogram	Iron ion	air - lower stratosphere + upper troposphere	biosphere3
0.00357	kilogram	Magnesium	air - lower stratosphere + upper troposphere	biosphere3
0.03214	kilogram	Nickel II	air - lower stratosphere + upper troposphere	biosphere3
0.02857	kilogram	Silicon	air - lower stratosphere + upper troposphere	biosphere3
0.01786	kilogram	Titanium ion	air - lower stratosphere + upper troposphere	biosphere3

4.3.9. Calculation of Delfi-n3Xt's LCA single-score and ecodesign

With the above LCA methodology set out, the LCA single-score of Delfi-n3xt can be calculated. For this, the LCA outcomes ought to be normalised before the single-score weights (computed with the methodology discussed in Section 4.2) are applied. Following this, a brief ecodesign effort is made to test the usefulness of such a single-score.

It is chosen to normalise the outcome of Delfi-n3Xt's LCA in terms of Environmental Footprint (EF) per person globally, given that this thesis aims to create a single-score calculation procedure which could be applied internationally, beyond Europe. The normalisation factors are taken from the JRC technical report on global normalisation factors for the EF and LCA [97]. After this, the weights can be applied to compute the single-score.

To provide a use-case for the single-score, the design of the Delfi-n3Xt CubeSat is slightly modified, simulating the ecodesign process. Discussed in more detail in Section 6.4, a search for those potential design changes is first done, before settling on a change contemplated by the designers themselves, namely a change in battery technology. With this, a new single-score is calculated and conclusions are drawn on its usefulness for single-score purposes.

4.4. Space Sustainability Rating score for Delfi-n3XT

Besides Delfi-n3Xt's LCA, a SSR score is also calculated for the mission. Such a score and that of the modules which it is composed of provide the opportunity to test the new weights proposed by the expert panel throughout the survey. This in turn would allow a discussion on how LCA could be included in the SSR, as part of the research questions.

The exact calculation of each of the modules' scores is left to the SSR team, with whom a close collaboration is maintained throughout the thesis. To perform said calculation, the team requires a set of answers in their online questionnaire used for the SSR rating of all space operators. The full questionnaire with answers provided to SSR is shown in Appendix C and summarised below.

In the questionnaire's section on the "Mission Index" and the "Collision Avoidance Capabilities", most inputs are based on documentation and well-known facts about Delfi-n3Xt. The data about the orbit's characteristics are derived from literature on the CubeSat [62] and compared to currently tracked data. The post-mission disposal rate is set to 100% as per SSR's recommendations for Delfi-n3Xt's case. Any possibilities of the Delfi-n3Xt team to coordinate with space operators regarding close encounters and collision avoidance is considered nonexistent due to lack of explicit mentions of it in the documentation. Moreover, for the same reasons and because of the fact that the Delfi Ground Station does not have extensive satellite tracking infrastructure [56], it is assumed that the satellite's team was reliant on third party SSA providers for their orbital state knowledge.

In the section of the "Collision Avoidance Capability", the answers are based on the extent to which the demanded data was found to be available in literature. For instance, no plan on the publishing of collision avoidance information or on updating the rest of the world on the satellite's mission information could be found. However, the satellite's characteristics are shared in various articles and websites, resulting in a set of answers which reflect this.

The answers on "Data Sharing" follow a similar methodology as those on "Collision Avoidance Capability". Any of the suggested information for the Collision Avoidance Coordination (i.e. contact information and their response time in case of a close approach) and the Satellite Mission Information (i.e. updated ephemeris, covariance, trajectory, etc) were not found to be shared explicitly by the team of Delfi-n3Xt. However, the information related to the Satellite Characterization (i.e. mass, manoeuvrability, etc) are publicly available, resulting in the corresponding answer.

The "Detectability and Trackability" section and the "External Services" sections were filled in rapidly thanks to the availability of information on their topics. For the first section, the geometry and orbital data were inputted based identically on questions in previous sections. The question about tracking of the satellite was answered identically to the similar question in the "Collision Avoidance Capabilities" section (i.e., the team was reliant on external SSA services), with the addition of the early tracking done during LEOP [72]. In the second section (i.e. the "External Services" one), all the answers were negative ones for on-orbit life-extension features and active debris removal.

The answers in the section on "Adherence to Design and Operation Standards" are based on the contents of the various standards looked at. Based on results of a simulation performed by the SSR team with ESA's DRAMA tool[13] of Delfi-n3Xt's orbital decay, it was found that Delfi-n3Xt does not comply with the requirement of its deorbiting after 25 years as imposed by the United Nations (UN)'s

[13]DRAMA (Debris Risk Assessment and Mitigation Analysis) is a tool which can calculate the compliance of a space mission with space debris mitigation standards. More information here: `https://sdup.esoc.esa.int/` (Accessed on 10/09/2023)

agreements on sustainable use of outer space. The simulation found a deorbiting time in the order of 27 years. Besides this, the various other guidelines were looked at and assessed to provide answers in the questionnaire.

4.5. Investigation of possibilities for Life Cycle Assessment during early design

In order to do a preliminary investigation into how LCA could be implemented during the early design stages of a mission, two approaches are taken. Firstly, questions are asked to students who completed a CDF study [82] as part of a lecture at EPFL. Secondly, an interview with someone both knowledgeable in Concurrent Design and Clean Space is conducted.

During the concurrent design course followed by the EPFL students, observations are made on whether or not sustainability would have been taken into account. The study itself revolves around the design of a SmallSat constellation deployer in Lunar Orbit [82]. While the topic is somewhat different from the earth orbiting satellite missions mainly considered for the single-score LCA of this thesis, the study and the student's choice to include or neglect sustainability is nevertheless instructive. At the end of the study, the students are asked whether or not they included sustainability and how they would include it (more) in a future study.

To gain more concrete opinions on how LCA could be included during early design phases, ir. Lorenz Affentranger is interviewed. With his expertise overlapping the fields of clean space, concurrent design and system engineering, he is thought to be able to provide relevant insights. He is asked to look into the contents of concurrent design studies in ESA's CDF and into the extent to which sustainability is considered an important topic. He is also asked how LCA could be included in the process and what he considers to be the biggest hurdles for it to overcome.

5

Survey Results

This chapter summarises the findings from the survey and the conclusions that can be drawn from them. It offers a more complete view on the outcomes of the survey than the EUCASS-CEAS conference proceeding on the survey's preliminary findings could show [1]. More answers are collected compared to the paper and more space is available to dive into all of the questionnaires questions. The totality of the answers are recorded and published in the *4TU.ResearchData* data repository [2].

This chapter starts with a detailed characterisation of the panellists in Figure 5.3 to assess the trustworthiness of their answers. The larger sustainability picture is then viewed through the panellists' eyes in Section 5.2, where the commitment on – and relevance of – sustainability in the sector is checked. Thereafter, Section 5.3 gives insights into the reasons for or against doing LCA in the space sector. The endpoint and midpoint impact indicators considered to be the biggest hotspots for space missions are discussed in Section 5.4 and Section 5.5 respectively. Below this, the ranking of midpoint indicator per importance level is displayed in Section 5.6 and a discussion is held in Section 5.7 on the panellists' preferred way of presenting the results of a LCA. New weights for the current and future SSR modules are put forward in Section 5.8 before a summary of some of the panellists' final comments on the survey is given in Section 5.9.

5.1. Demography of the expert panel

The first questionnaire, shown in Section I.1, covers the background of the panellists and of their workplace. This gives insight into their expertise on LCA and the extent to which their professional environment has a focus on sustainability. The collection of such data is needed to put the answers of the panelist into their individual contexts throughout the questionnaires.

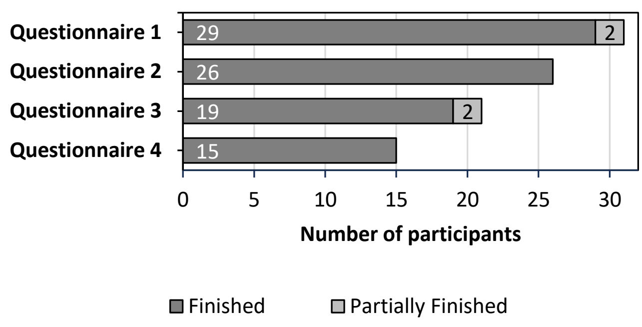


Figure 5.1: Number of panellists who completely or partially finished each questionnaire.

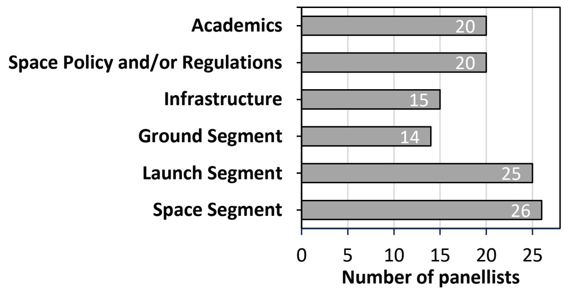
Moreover, this information on the demography of the panellists is important to justify the level of relevance of the survey's findings, given that the number of participants to each subsequent questionnaire got gradually smaller. Figure 5.1 shows that, despite tedious efforts of encouraging the experts to participate to every questionnaire, the size of the panel decreased from 31 in the first questionnaire to 21 in the third one. And, the later submission of the fourth questionnaire caused a further reduction to 15 panellists who answered.

Thus, to provide the necessary background on the panelists, the next parts discuss the demography of the expert panel. Section 5.1.2 shows the expertise of the panellists in LCA-related concepts. Section 5.1.4

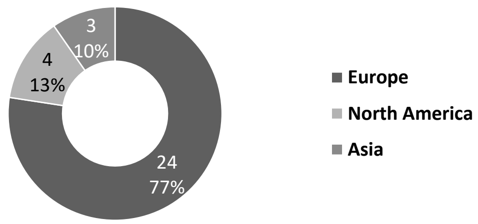
discusses the professional environment of the panellists and its focus on sustainability.

5.1.1. Panellists' knowledge in the space sector and their geographical distribuion

The results of the knowledge distribution within the panel of experts can is shown in Figure 5.2a. Note that the figure also shows, for completeness' sake, the number of participants knowledgeable or experienced in space policies or regulation and in the academic world. This bar chart is built by aggregating answers of the panellists, where each panellist is considered *experienced* or *knowledgeable* if they answered that the proposed sector matches "somewhat" or "perfectly" with their current of past experience, as opposed to "not at all". This shows that a majority of panellists is knowledgeable in the Space and Launch Segment, while a lesser, yet still significant, portion of them has knowledge or experience in the Ground Segment and/or Infrastructure.



(a) Number of experts experienced and/or knowledgeable in each segment, aggregated based on the panellists' answers (n = 31 answers).



(b) Distribution in the location of the workplace (n = 31 answers). The top number is the number of panellists, while the bottom one is the percentage of them.

Figure 5.2: Information on the panelists' knowledge in each segment, and on their location. This data is computed based on the answers to the first questionnaire.

The other factor considered during the recruitment process is the geographic location of the potential panellists. While the focus is mainly on the European space industry (including the United Kingdom), panellists from elsewhere were also recruited. Figure 5.2b shows that nearly one fourth of the panellist are from Asia and North America. Nevertheless, the lack South American and African representation could be criticised, since those continents have of rising - or well-established - space industry [83], [100].

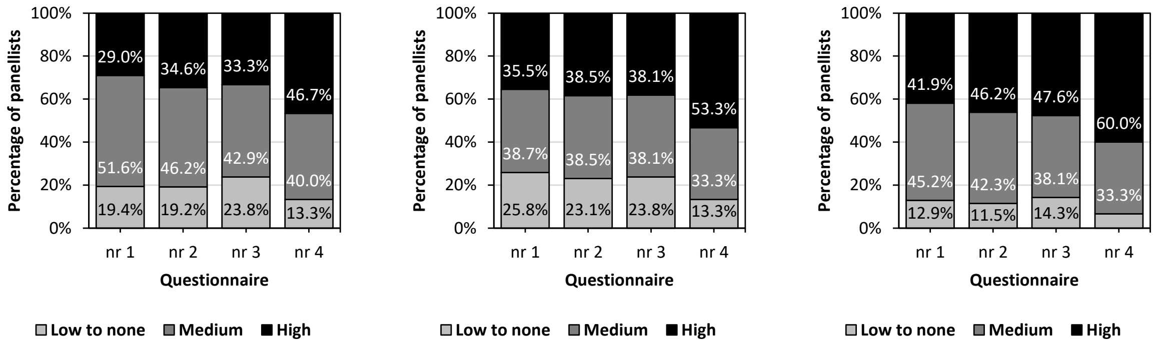
5.1.2. Panellists' knowledge on LCA

As explained in Section 4.1.4, the recruitment of the panellists focuses on space actors with knowledge in sustainability and preferably also LCA. While Figure 5.2a shows the diverse professional backgrounds of the panellists, Figure 5.3 shows the distribution in LCA expertise across the panel and throughout the questionnaires. It shows the panel's relative knowledge in impact categories, the LCA methodology and the interpretation of LCA results. The sub-figures are created by linking the answer to this question on the panellists' knowledge with the Individual Code each panellists received prior to the survey. With that, it was possible to verify for every questionnaire which of these Individual Codes have been inputted and what their knowledge level is.

One may note from the sub-figures that over 70% of the panellists have at least some working – if not expert – knowledge in each of these three topics. The outcomes of a LCA seem to be fully within working and expert knowledge of the panellists, with the exception of no more than 14.3% of them (i.e. 3 panellists in Questionnaire 3). With regards to the evolution of relative knowledge over the questionnaires, the least knowledgeable panellists seem to have proportionally stopped participating in most of the questionnaires. In general, it should be underlined that the panellists with proportionally lesser knowledge in specific LCA topics were recruited for their other fields of expertise, such as system engineering, space systems or space policies with some sustainability touches.

5.1.3. Panellists' knowledge in the midpoint categories

To gain a better judgement of the expertise which the panellists use to make judgements about the importance of each impact categories, they were asked about their level of knowledge of these categories. Figure 5.4 shows the distribution of the level of knowledge within the panel for each impact indicator. It shows this distribution of the panellists participating to the first questionnaire as well as that of the ones

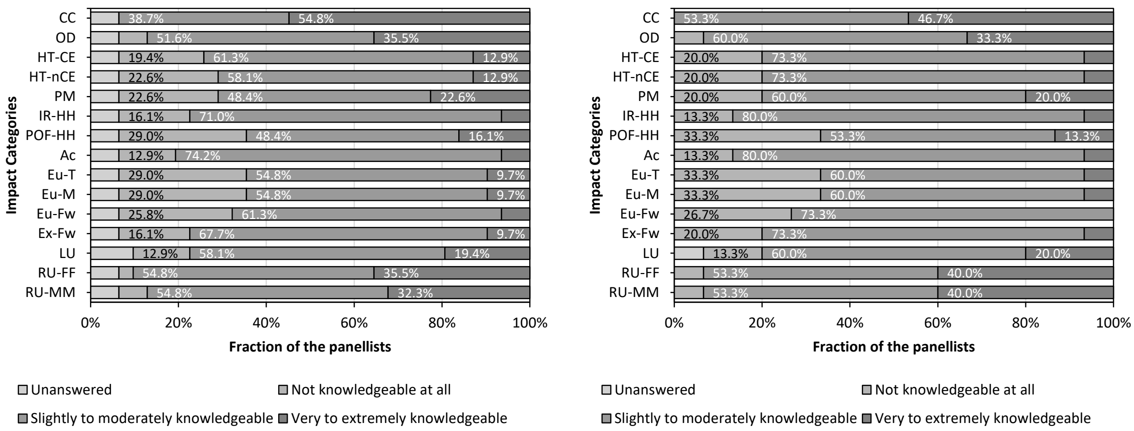


(a) Expertise on LCA's impact categories. **(b)** Expertise on the LCA methodology. **(c)** Expertise on interpreting LCA results.

Figure 5.3: Overview of the relative expertise on LCA of the expert panel, across the Questionnaires (n = 31 panellists). Note the meaning of each of the expertise levels: "Low to none" means that the panelist never dealt with the topic or only has an awareness of it. "Medium" expertise refers to a working knowledge with an occasional application of it. "High" expertise translates into a deep to expert knowledge of the topic with frequent application of it.

participating to the fourth one, to highlight any changes due to the reduction of number of panellists. These plots are created similarly to those in Figure 5.3, by linking the answer to this question with the Individual Code of each panellists and verifying for each questionnaire which of these Individual Codes has been inputted and what their knowledge level is.

It can be noted that the majority of the panellists – 64.5% of them or more, depending on the category – have at least a slight or moderate knowledge of each of the impact indicators. Some impact indicators, such as Climate change (CC), Ozone depletion (OD), Resource use: fossil fuels (RU-FF) and Resource use: metals and minerals (RU-MM), are quite well known, with over 87.1% of the panellists (depending on the category) having at least a 'slight' knowledge level and a minimum of 32.3% of them having a very good knowledge in the first questionnaire's expert panel. The Climate Change impact category stands out, with 54.8% of the panellists in the first questionnaire stating that they are very to extremely knowledgeable on the topic. Some of the impact categories on which the panellists across the two questionnaires have a lower knowledge are the categories of Particulate matter (PM), Ionizing radiation - human health (IR-HH), Photochemical ozone formation - human health (POF-HH), Eutrophication - terrestrial (Eu-T), Eutrophication - marine (Eu-M) and Eutrophication - freshwater (Eu-Fw).



(a) Knowledge level of the panellists of questionnaire 1. **(b)** Knowledge level of the panellists of questionnaire 4.

Figure 5.4: Knowledge level of the panellists on the impact categories.
Note that the acronyms for the impact categories have the following meaning: CC, Climate change; OD, Ozone depletion; HT-CE, Human Toxicity - cancer effects; HT-nCE, Human Toxicity - non-cancer effects; PM, PM; IR-HH, Ionizing radiation - human health; POF-HH, Photochemical ozone formation - human health; Ac, Acidification; Eu-T, Eutrophication - terrestrial; Eu-M, Eutrophication - marine; Eu-Fw, Eutrophication - freshwater; Ex-Fw, Ecotoxicity - freshwater; LU, Land use; WU, Water Use; RU-FF, Resource use: fossil fuels; RU-MM, Resource use: metals and minerals.

With regards to any variations caused by the reduction of the panel size, one observes from the figure that the distribution of knowledge levels remain approximately unchanged in questionnaire 4. The same impact categories mentioned above stand out as being the most and least understood by the panellists. One small difference which could be noted is the fact that the panellists who had high to excellent knowledge on the Eutrification - Freshwater impact category have not participated anymore. From further analysis, it seems to have been a gradual reduction of the proportion of panellists with such a high knowledge in that impact category: in questionnaire 2 and 3, they made up respectively 3.8% and 0% of the panel.

5.1.4. Panellists' professional environment and its focus on sustainability

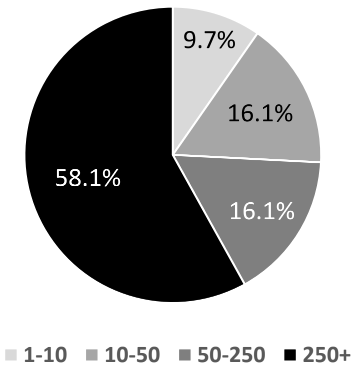


Figure 5.5: Size of the workplace of the panellists of the first questionnaire (n = 31 panellists).

The professional environments of the panellists could give an indication as to what type of experience they have and how they view the space sector (discussed in Section 5.2). The financial means and human resources of a smaller company or research institution could sway in a specific direction the point of view of a panellist working there. The same could be said for a panellist at a more financially and humanly resourceful workplace.

The distribution of the sizes of workplaces of the panellists is given in Figure 5.5. The panel is mainly composed of people working in a large organisation of over 250 people. It can be assumed that they consist mainly of some of the panellists who identified themselves in Figure 5.2a as academics and thus work at universities or research organisations, as well as some engineers who work at larger corporations. Almost one third of the panel is made up of people working at companies or institutions of medium size (i.e. between 10 and 250 people) and less than 10% of the panellists have a small professional environment.

To gain insight into the extent to which their place of employment puts resources into any sustainability topics, the panellists were asked to indicate what – if any – type of sustainability efforts are done. They could choose between space-related sustainability and office-work sustainability, while leaving the interpretation of these two areas open. The result is shown in Figure 5.6 and suggests that almost 75% of the panellists' workplaces put dedicated resources into some form of sustainability. There seems to be slightly less space-related sustainability focus than office-work related focus.

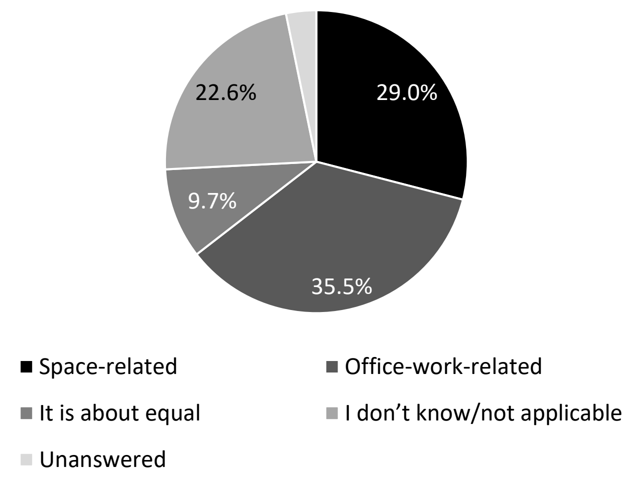


Figure 5.6: Topic of sustainability focused on at the panellists' workplace (n = 31 panellists).

Some of the panellists provided comments in the dedicated text box on their interpretation of those two focus areas. From the few comments given, it seems that the 'space-related' sustainability was understood by some as the efforts toward a least environmental taxing process of manufacturing, assembling testing, launching , orbiting and re-entering of a space mission. A single comment on the subject suggested that the panellist writing it interpreted the 'office-work related' sustainability as the sustainability aspects of anything that concerns strictly the work done in the office.

As a follow-up, the panellists could indicate how many people are dedicated to these sustainability matters at their workplace. The split is rather equal with 1-2 employees mentioned by 8 panellists, 3-10 employees mentioned by 8 other panelists and 10+ employees mentioned by 7 other panelists. As such, from the panellists indicating some form of focus on sustainability, one has a rather large range of possible numbers of employees dedicated to the environmental issues.

Overall, this section has shown that the panellists come from workplaces of different sizes, with some focus of sustainability in most cases and with a big variation in the amount of human resources dedicated to these sustainability issues. This diversified information could be relevant when considering some of the answers to the other questions.

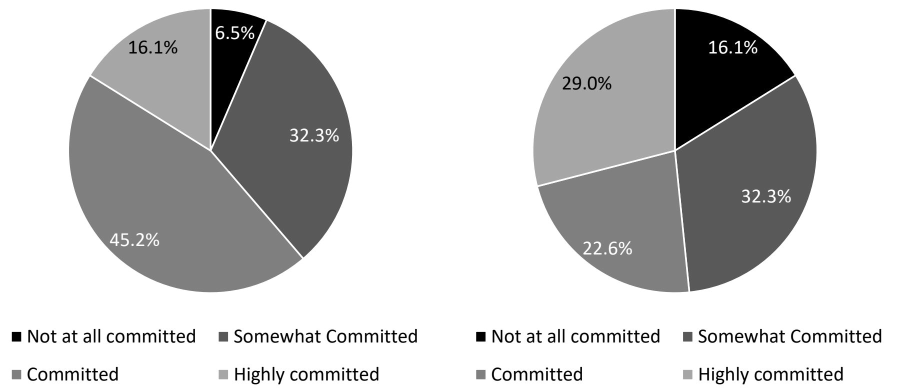
5.2. Views on how sustainability is approached in the space sector

In the first questionnaire, the panellists were given the opportunity to judge the commitment towards sustainability and relevance of it within their workplace (i.e. the organisation at which they work now - or have worked at if they are retired) and of their specific sector of expertise (i.e. the sector(s) in which they are most experienced, as listed in Figure 5.2a). Section 5.2.1 shows their view on the commitment of the sector and Section 5.2.2 shows their view on the relevance of sustainability within the sector.

5.2.1. Commitment of the space sector towards sustainability

The summary of the panelists' opinions on the commitment to sustainable of their workplace and sector of expertise is shown in Figure 5.7. The majority state that their workplace is committed in taking actions favourable for sustainability. The general view of a committed workplace seems unchanged when decomposing it further by their sector of expertise.

When the panelists were asked to look beyond commitment of their workplace towards that of their sector of expertise, the opinions are slightly more divided, as shown in Figure 5.7b. More panellists answered that their sector is "not at all" or only "somewhat" committed towards sustainability. Further analysis shows that 33% of the 12 panellists 'expert' in the space segment marked their commitment level to be between "not at all" and "somewhat". For the Launch Segment, the same low commitment level is observed by 18.2% of 11 panellists expert in this segment. It is not possible to make a reasonable assessment of the commitment of Ground Segment and the Infrastructure according to the panellists, as only 1 and 2 panellist, respectively, stated to be expert in those segments.



(a) Panellists' opinion on their workplace's level of commitment (n = 31 panellists).

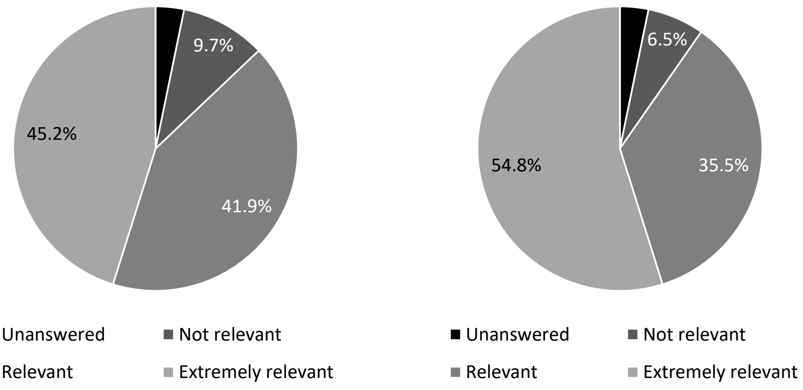
(b) Panellists' opinion on their sector of expertise's level of commitment (n = 31 panellists).

Figure 5.7: View of the panellists on the level of commitment towards sustainability of their own workplace and their sector of expertise.

5.2.2. Relevance of sustainability in the space sector

Besides the question on the space sector's commitment towards sustainability, the panellists received a question on their view of the relevance of sustainability within the sector. The summary of their answers is shown in Figure 5.8.

It is clear from the sub-figures that sustainability is important according to the panellists. Almost all panellists state that their workplace considers sustainability as a relevant topic to work on. For their specific sector of expertise, almost all panellists also state that sustainability is important. It is interesting to note that there is a slight increase in the level of relevance sustainability has for the sector of expertise compared to the panellists' workplaces.



(a) Panellists' opinion on the relevance of sustainability for their workplace (n = 31 panellists).

(b) Panellists' opinion on the relevance of sustainability for their sector of expertise (n = 31 panellists).

Figure 5.8: View of the panellists on relevance of sustainability for the space industry.

5.2.3. Discussion on how sustainability is approached in the space sector

Within the dedicated comment text box, several key themes emerge regarding the role of sustainability in academia and the space industry. Academia is recognized as a leader in addressing societal challenges, including those related to space, the environment, and the economy. Some organizations, particularly Small and Medium Enterprises (SME), are said to face significant costs when tackling environmental issues, emphasizing the importance of supportive policies.

Many panellists noted the strong commitment to sustainability of their workplace. Most mention the more conventional efforts such as a reduction in travels, efforts to reduce energy consumption in offices and limited plastic use during work hours. Except for the few workplaces which fully commit on it, most are said to lack the emphasis on space-specific sustainability, other than space debris in some cases.

There is a shared understanding that a business-as-usual approach is insufficient to address challenges such as space debris and climate change; greater commitment and focus are needed. Nevertheless, changes toward sustainability are said to often be prompted by regulations and commercial pressures, while self-initiative is less common unless employee health for instance is directly threatened. Moreover, a full understanding of environmental issues caused by the organization or sector are said to be lacking.

These comments collectively highlight the increasing importance of sustainability within academia and the space sector and the need for comprehensive and proactive efforts to address environmental challenges.

5.3. Drivers and inhibitors of space LCA

As mentioned in Section 4.1.5, the expert panel is questioned on the reasons why they think the space industry does or doesn't do a LCA. They are given a number of statements to which they could answer that they "disagree," "somewhat agree" or "agree". The statements are heavily inspired on question asked during a study across the European general industry (involving mostly sectors outside the space industry), looking at the best way of communicating information on the Environmental Footprint [17]. This study is part of the European Joint Research Centre's (JRC) development of Europe's weighting approach for the Product/Organisation Environmental Footprint (PEF) [19]. Figure 5.9 and Section 5.3.2 show respectively the drivers and inhibitors of LCA for a space mission.

5.3.1. Drivers of LCA in the space industry

The statements given to the panellists and the final results of their answers on the drivers for (i.e. reasons to do) a LCA are shown in Figure 5.9. All panellists either agree or somewhat agree that a LCA would drive environmental improvements in products and/or organisations and would allow the identification of environmental hotspots. Moreover, the benefits for the environmental strategies to be adopted, the increase in awareness around environmental issues, the improvement of best practices and the gain in reputation are almost unanimously subscribed to by the panellists. On the bottom of the figure, it could be noted that the panellists are not fully convinced that LCA would increase cooperation within the same company, improve relations with suppliers, increase sales or create new marketing opportunities.

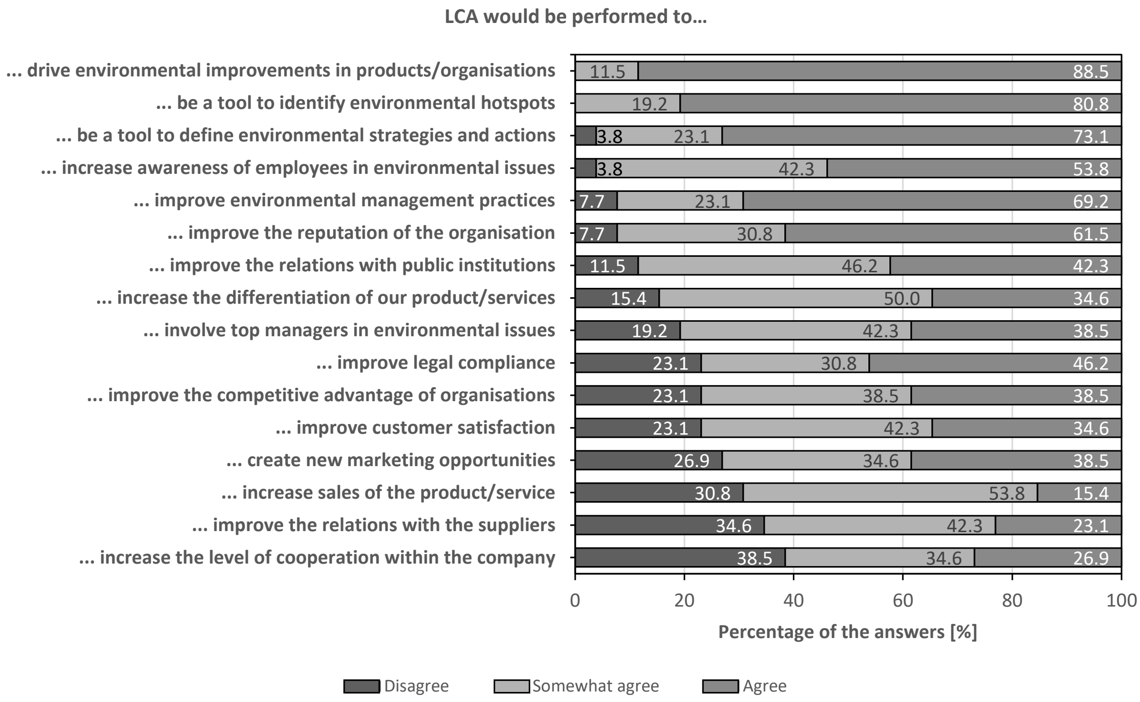


Figure 5.9: LCA drivers as given by the expert panel (n = 26 answers).

There are some noteworthy similarities and differences in the prioritisation by the panellists of the drivers compared to those of the full European industry [17]. The European industry's first, third and fourth drivers are also found somewhat high in the ranking of the expert panel, namely the statement that LCA would improve the environmental management practices, that it would increases awareness of employees in environmental issues and that it improves the reputation of the organisation. The idea that LCA would improve customer satisfaction - ranked as the second most important in Europe [17] - seems to have little importance in the space sector. Similarly, other drivers related to sales, marketing, competitiveness and legal compliance have been raked much lower by the expert panel, compared to the European findings. In contrast, the idea that LCA would be a tool to define environmental strategies and actions is much more agreed upon by the expert panel than by the European industry.

5.3.2. Inhibitors of LCA in the space industry

The inhibitors of (i.e. reasons against doing) a LCA and the statements proposed are shown in Figure 5.10. The percentage of panellists choosing the "disagree" option shows that less of a consensus is found. Nevertheless, it is clear that the difficulty of data collection from the supplier and supply chain, the difficulty in the data quality assessment and evaluation, as well as the need for a significant amount of human resources are all highlighted as inhibitors for LCA. It is relevant to note that the panel disagrees with the suggestion that the software would be too expensive, that the system boundaries, the analysis' scope and the functional unit would be difficult to define, or that the interpretation of the results would cause any issue.

Some similarities and differences can be noted between the answers of the panel of experts and the findings from the survey on the full European industry [17]. The first nine reasons given by the panel for not performing a LCA seem to match quite well with the most agreed upon inhibitors by the European industry. However, the idea that it would be difficult to define the system boundaries and the the LCA scope, ranked sixth and ninth out of seventeen by the European industry, are ranked significantly lower by the the panel.

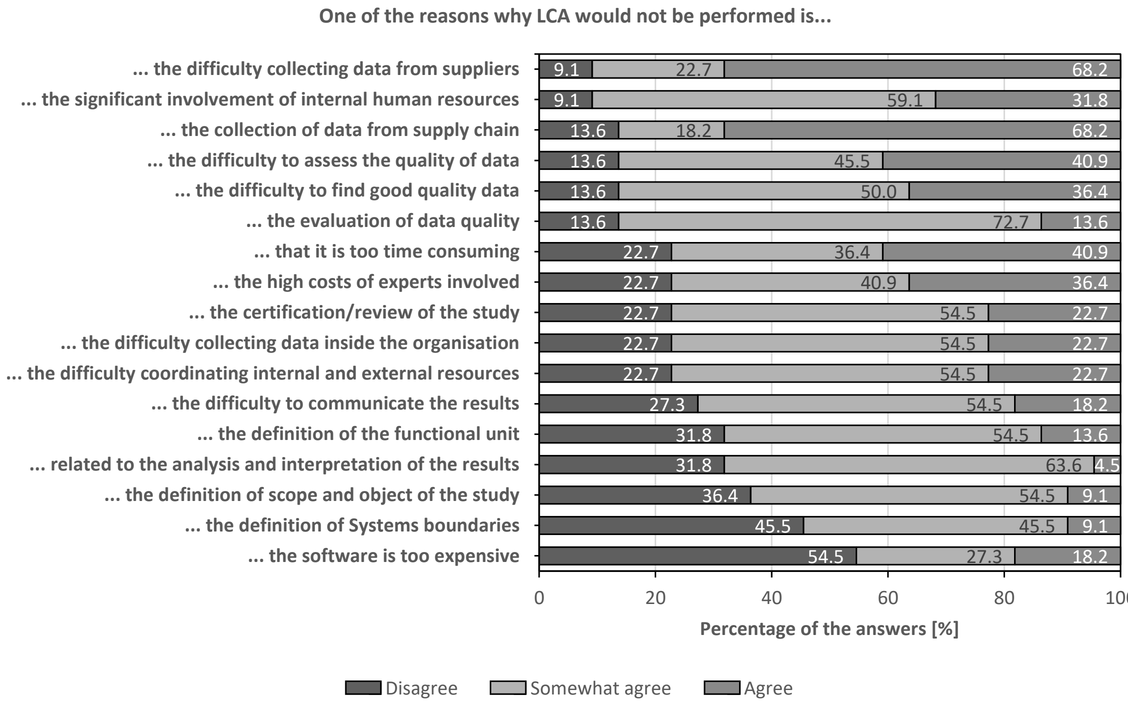


Figure 5.10: LCA inhibitors as given by the expert panel (n = 26 answers).

A special comment is made by one of the panellists at the end of the third questionnaire on another inhibitor for space LCA: the incompleteness of the current databases. In particular, the comment states that it becomes difficult for companies to perform very quantitative LCAs if their value chain is unwilling to partner or share data to conduct the LCA. The panelist states that ESA's LCA database cannot fully provide all the data needed as it was developed with confidential data based on large European space companies (the panellist mentions Arianne Group). This is not specific and tailored enough to make a LCA "as quantitative as proper LCA should be". Nevertheless, the panellist concludes with high hopes on the updated ESA Database, in which there will hopefully be more data which are more comprehensive.

5.4. Ranking of endpoint indicators for space LCA

As an experiment to understand which endpoint indicator is most affected by space missions, the panellists have to answer a question on the area of highest impact of space missions. In questionnaire 1, the panellists were asked to identify on which of the three indicators a "generic space mission" tends to have the highest impact. This impact category would be given a score of 100 points. The next most impacted indicator would be ranked relative to this, and so on.

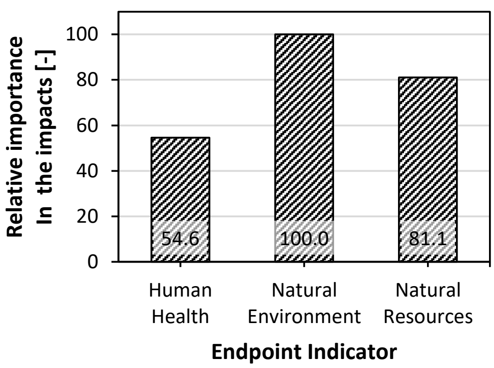


Figure 5.11: Average ranking of the impact of a space mission in terms of endpoint indicators, normalised to make the highest ranking equate to the value of 100% (n = 31 panellists).

The averaged results of the answers are shown in Figure 5.11, after a normalisation which makes the value of the highest impact equate to 100 points. The panellists consider the natural environment as being the most impacted by space missions, followed relatively closely by the indicator of natural resources. The impact of space missions on human health is considered to be almost half of that of natural environment.

The spread of the answers is more pronounced for the natural resources and human health indicators than for the natural environment one. The standard deviation (i.e. an indicator for the spread) of natural resources is 28.2. The standard deviations of natural resources and human health are 28.2 and 33.9 respectively.

The panellists' comments reveal several key insights on their reasoning. For Natural Resources for instance, panelists express concerns about resource depletion, driven by the high demand for rare materials and minerals in the space industry. The manufacturing and launch phases are identified as critical stages impacting natural resources.

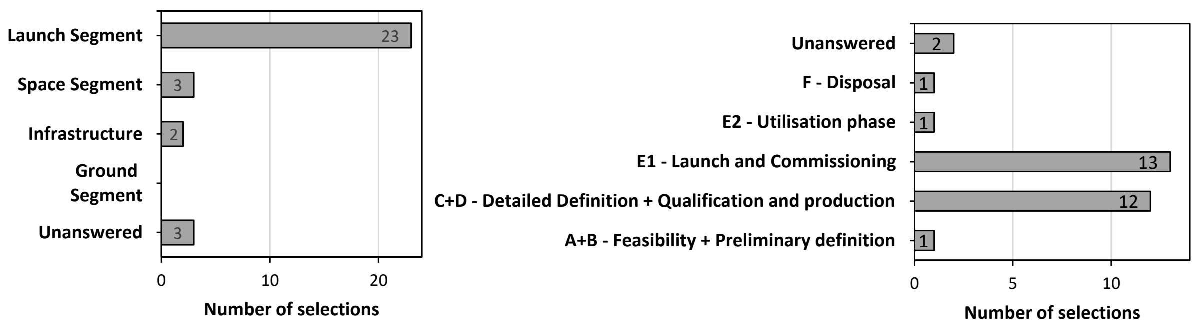
For Human Health impacts, panelists recognize potential risks such as exposure to toxic substances, radiation, and even falling debris. However, they also emphasize that safety regulations help mitigate these risks, and emissions during launch events are generally considered less harmful to human health.

The Natural Environment indicator emerges as the most impacted indicator according to the majority of panelists. They point to visible effects on ecosystems around launch sites such as the death of fish, disturbance of insects and changes of other habitats near the launch site. Moreover, they express concerns about emissions, climate change, ozone depletion, and potential harm to endangered species and water sources.

When asked if they have enough information at their disposal to provide the answer, approximately one third answers positively, while the remaining 2 thirds elaborates on the shortcomings. The panellists who state that no extra information is needed mainly argued that their answers are in line with what they thought to be conclusions for any average space mission. The negative responses, however, highlight a desire for more specific mission details and data in order to conduct a more precise assessment. Some panelists acknowledge that their rankings are based on general considerations and call for more research in certain areas related to space missions (e.g. the impact of rare materials and of propellants, etc).

5.5. Hotspot identification of space mission phases and segments with highest environmental impact

As discussed in Section 4.1.5, during the first questionnaire, the panellists are asked to indicate which phase and segment of a space mission have the highest environmental impact. They can select only one of each, based on their experience. The number of times each segment and phase was selected are reflected in Figure 5.12a and Figure 5.12b, respectively. From the former, it is clear that the launch segment is considered to have the greatest environmental impact compared to the other segment. The latter figure shows that the launch and commissioning phase (E1), as well as the detailed definition and qualification ones (C+D) stand out in terms of estimated environmental impact



(a) Number of selections of the segment of highest impact (n = 29 answers).

(b) Number of selection of the phase of highest impact (n = 29 answers).

Figure 5.12: Aggregation of the number of selections of the phase and segment with the highest impact.

The main arguments for the phase C+D selection are the length of the design phase, the manufacturing and the use of aerospace-specific material and related minerals. A remark is also made about inconsistencies which have existed between LCA researchers in the past, where some consider that all impacts related to the launcher (i.e. production, launch campaign, launch event and re-entry) belong to phase E1, while others consider the impacts due to their manufacturing and propellant production to fit in phase C+D. Regarding the choice for phase E1, the main arguments are the emissions related to the launch event, including those in the upper atmosphere. Overall, it is remarked that such a choice would require one to know which exact impact category one focuses most for a more accurate answer.

Regarding the choice for the launch segment, the main arguments include the significant difference in mass between a launcher and the satellite it launches, the launcher's and its propellant's manufacturing, as well as the emissions into the higher atmosphere. Similarly for the choice between the phases of a space mission, some panellists mention that more information should have been provided on which environmental impact category one is looking at.

5.6. Ranking of midpoint indicators for space LCA

Assuming two similar designs for space missions are to be compared from an environmental impact point of view, the expert panel has been asked to indicate which midpoint indicators they think are most important to look at. In the first questionnaire, the space mission is defined as a "generic space mission", but based on feedback, this is refined to a "single Earth orbiting satellite mission" and an "Earth-orbiting constellation mission" in the subsequent two questionnaires. For those two questionnaires, the suggested midpoint indicators from literature are added, as described in Section 4.1.5. Moreover, while the first two questionnaires do not indicate how the impacts are assessed, the third questionnaire specifies that the impacts would be computed as impacts per mass of the satellite(s) put in space. Lastly, also in the third questionnaire, the panellists are asked to return to the generic space mission, but with the extra assignment that the launch segment should be excluded from the LCA scope.

The panellists are asked to provide a relative ranking, assigning a score of 100 to the impact indicator they consider one should most look into. The score of the other impact indicators would be relative to that most important one. Thus, if the second most important indicator would be considered only half as important, then it would be given a score of 50, and so on. The final average scoring of the midpoint impact indicators can be seen in Table 5.1. The weights calculated based on these scores are equally shown in the table, alongside the PEF weights, modified proportionally to remove the impact indicator of Water Use, omitted from this study.

While a more detailed look into the table is given in the next paragraph, it is relevant to note the variations in the standard deviation (indicating the spread) of the answers across the panel. The first two questionnaires results in an average standard deviation around 29, ±1 depending on the space mission type. The single Earth orbiting satellite and the constellation mission of the third questionnaire sees a reduction of the average standard deviation to 28.3 and 26.6 respectively. The last generic mission ranking has a standard deviation of 33.3. The Climate Change, Ozone Depletion, Metals and Mineral Resource Use, Fossil Fuel Resource Use and the Mass left in Space impact indicators enjoy the smallest standard deviation for all three questionnaires, with their average values throughout the questionnaire of 17.7, 22.4, 23.6, 25.0, 21.28 respectively. Among the impact categories with the highest standard deviations, the Ionization Radiation - Human Health stands out, along with Critical raw material Use and Re-Entry Smoke Particle Generation, with their respective averages at 36.4, 35.5 and 34.5.

Some aspects are worth observing from the scores in Table 5.1. The impact indicators of Climate Change, Ozone Depletion and Resource Use of Metals and Minerals are persistently ranked as the top three most important indicators, except for Ozone Depletion in the case of the general space mission evaluated without the launch segment. Among the additional impact indicators, the Mass Left in Space, Al_2O_3 Emissions in Air, and Orbital Resource Depletion are ranked highly, with a spike in importance when a constellation is considered as space mission. Some of the lower ranking indicators are consistently the three impact categories related to Eutrophication, as well as the Photochemical Ozone Formation - Human Health, the Acidification and the Freshwater Ecotoxicity. Regarding the change in method of calculating the impacts (i.e. no indication given or the specification that impacts would be calculated per mass of the satellite), no major variations can be noted.

Considering the calculated weights, it is interesting to compare them with the aggregated weighting sets proposed by PEF (i.e. before the robustness factor is taken into account [19]). In the case where no space-specific impact categories are looked at, the general trends of PEF are being followed, despite slight variations in the final values of the weight. Notable however, is the relative increase in weight of the Ozone Depletion and metals and minerals resource use, as well as the decrease in weight of the land use. For the cases where more and more space-specific impact categories are considered, the PEF-defined categories seem to be more or less followed proportionally, with the same exceptions for Ozone depletion and Land Use.

Table 5.1: Average scores given to each midpoint indicator throughout the four questionnaires, based on a specific given space mission type, an indication on how the impacts are computed and on which segments are considered. The colour of each cell is proportional to the size of the weight and the score, with darker grey indicating a high number and light grey a low number. The number of answers n for each question is also provided in the first line of the table.

	PEF's aggregated weighting set [19]	Questionnaire 1: Generic mission (n = 31 answers)		Questionnaire 2: Single satellite (n = 26 answers)		Questionnaire 2: Constellation (n = 17 answers)		Questionnaire 3: Single satellite, impacts/mass of satellite (n = 21 answers)		Questionnaire 3: Constellation, impacts/mass of satellite (n = 11 answers)		Questionnaire 3: Generic mission, impacts/mass of satellite without Space Segment (n = 16 answers)	
Midpoint impact indicator		Avg Score	Computed Weight [%]	Avg Score	Computed Weight [%]	Avg Score	Computed Weight [%]	Avg Score	Computed Weight [%]	Avg Score	Computed Weight [%]	Avg Score	Computed Weight [%]
Climate change.	12.9	95.6	9.3	87.4	8.29	91.1	8.28	95.3	6.33	92	6.06	81.6	5.94
Ozone depletion.	5.58	89.6	8.72	87.2	8.27	90.9	8.27	90.3	6	87.2	5.75	48.3	3.51
Human Toxicity - cancer effects.	6.8	65.7	6.39	65.2	6.18	52.6	4.78	65.7	4.37	58.3	3.84	67.9	4.94
Human Toxicity - non-cancer effects.	5.88	60.4	5.88	56.5	5.36	49.9	4.54	57.3	3.81	44.2	2.91	56.2	4.09
Particulate matter.	5.49	63.9	6.22	63.5	6.02	63.8	5.8	67.6	4.49	63	4.15	56	4.07
Ionizing radiation - human health.	5.7	58.3	5.67	53.7	5.09	60.4	5.49	55.7	3.7	52.8	3.48	53.4	3.88
Photochemical ozone formation - human health.	4.76	53.7	5.23	45.8	4.34	53.4	4.86	54.4	3.62	43.5	2.87	47.1	3.43
Acidification.	4.94	55.1	5.36	46.1	4.37	50.1	4.56	44.3	2.94	36.5	2.41	41.2	3
Eutrophication - terrestrial.	2.95	48.2	4.69	42.7	4.05	44.5	4.05	38	2.53	33.3	2.19	37.8	2.75
Eutrophication - freshwater.	3.19	49.5	4.82	41.5	3.94	43.9	3.99	38.5	2.56	32.9	2.17	38.9	2.83
Eutrophication - marine.	2.94	48.9	4.76	40.2	3.81	44.1	4.01	37.6	2.5	36.5	2.41	41.3	3
Ecotoxicity - freshwater.	6.12	61.8	6.01	50.4	4.78	47.9	4.36	44.5	2.96	39.5	2.6	44.9	3.27
Land use.	9.04	55.8	5.43	53.1	5.04	48.6	4.42	45.5	3.02	47.1	3.1	44	3.2
Water Use	9.69	60.1[a]	5.85	NA[a]	NA	NA[a]	NA	58.1[a]	3.86	64[a]	4.22	46.4[a]	3.38
Resource use: metals and minerals.	6.68	82.7	8.05	84.3	8	92.4	8.4	83	5.52	87.5	5.77	77.7	5.65
Resource use: fossil fuels.	7.37	78.2	7.61	80.4	7.63	83.6	7.6	75.8	5.04	72.6	4.78	61.9	4.5
Mass left in space	NA	NA	NA	79.8	7.57	96.9	8.81	73.7	4.9	99.1	6.53	79	5.75
Al2O3 emissions in air	NA	NA	NA	76.6	7.26	85.5	7.78	84	5.58	91.9	6.06	44.8	3.26
Orbital resource depletion	NA	NA	NA	NA	NA	NA	NA	77.9	5.18	97	6.39	79.6	5.79
Critical raw material use	NA	NA	NA	NA	NA	NA	NA	69.7	4.63	75.6	4.98	69.1	5.03
Re-entry smoke particle generation	NA	NA	NA	NA	NA	NA	NA	61.1	4.06	66	4.35	67.9	4.94
Cumulative energy demand	NA	NA	NA	NA	NA	NA	NA	66.1	4.39	66.8	4.4	63	4.58
Total mass disposed in ocean	NA	NA	NA	NA	NA	NA	NA	54.5	3.62	56.5	3.72	55.9	4.07
Restricted substance use	NA	NA	NA	NA	NA	NA	NA	66.2	4.4	73.5	4.84	70.9	5.16

[a] Given that the Water Use ranking was asked for in a fourth, separate questionnaire, a total of n = 15 panellists provided their input, as opposed to the values provided in the first row. For the constellation mission case of questionnaire 3, there were n = 3 panellists who gave an input. Also noteworthy are the cells with NA, which correspond to the questions that were not asked in the questionnaire 4.

5.7. Preferred presentation of a space LCA result

In the second questionnaire, the panellists are asked to indicate how they would prefer the space results to be shown to them when making a choice between two designs of a same space mission. To understand better if the phase of the design would influence the preferred representation of the results, they are asked to complete this exercise for an early design phase of a space mission, as well as for a detailed design phase. No indication with regards to the space mission type is provided. The results of their answers can be seen in Figure 5.13

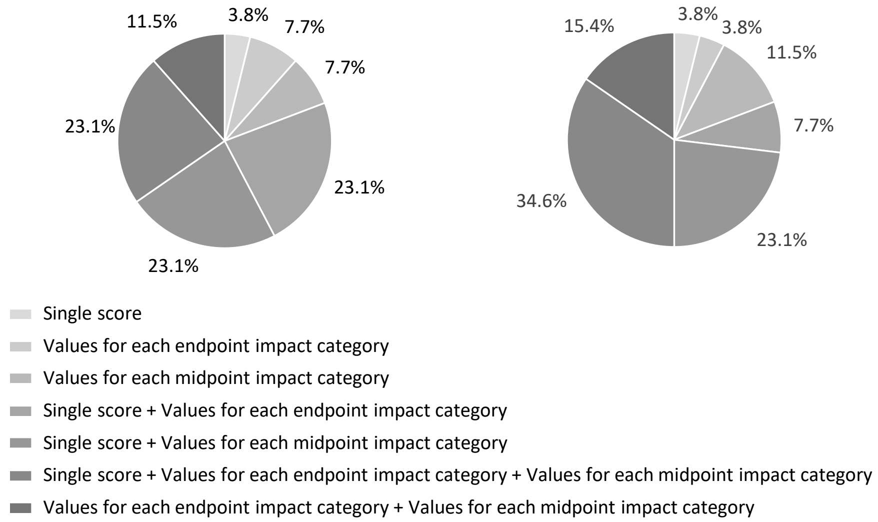


Figure 5.13: Preferred presentation of a space LCA results per the panellists' answers (n = 26 panellists). On the left pie chart, the distribution of the preferred presentation during early design is shown. The right pie chart shows it for detailed design phase.

The figure shows mixed preferences and small differences between design phases. The majority of the panellists – 65.4% and 69.2% in the early and detailed design phase, respectively – prefer a single-score with the addition of values from the midpoint and/or endpoint impact categories. For the early design stage, there is no particular preference between adding the values of the midpoint or endpoint indicators or both, as equal fractions of the panellists choose each option. On the neighbouring pie chart however, the endpoint indicators as an addition to the single-score seem less liked for the detailed design and a slight predilection can be observed for both impact categories to be shown with the single-score. In both design stages, a notable portion of the panellists – 11.5% and 15.4% for the early and late design phase respectively – are in favour of only showing the values for the mid- and endpoint impact categories.

In their comments, the panellists recognize the importance of both single scores and mid- and endpoint impact categories but note the need to balance simplicity and complexity based on the phase of the design and the specific goals of the LCA. Some mention that having all the midpoint results would be too many points to look at for a trade-off during the earlier design phases, yet also a single score may end up in information getting lost. Multiple comments are made on the idea that more detailed LCA results could be shown as the design phase progresses, with very little detail (i.e. something resembling a single-score) at early design and a more extensive listing of the results (for instance the midpoint indicators) during more detailed design phases.

The expert panel is given the opportunity to comment on any changes in their answer in case a specific mission type would have been suggested. An almost unanimous "no" is provided by the panellists, with little argumentation. Among the three comments somewhat in favour of modifying the LCA results representation, one panellist writes that a differentiation per segment could be envisaged. In particular, the launcher segment is mentioned with the argumentation that specific launchers already in operation for some time have enough available data for a highly detailed LCA, and thus a more detailed representation of the results (i.e. through the midpoint indicators instead or in addition of the single-score or end-point ones). However, this suggestion of the panellist refers to a LCA done after the design phase and falls a bit outside of the scope of the original question.

When asked if they have enough information to decide on the best representation of LCA results, panellists have mixed opinions and comments. A note is made that the answer would depend on who would use the LCA results: a single-score is most useful to the "deciders" while more details would benefit the "specialists", writes one of the panellists. The issue of the subjectivity of the weights associated with a single-score calculation is also brought up, with a special warning that care should be taken to make sure some consensus on it is reached. Moreover, a more general comment is made on the readiness of the space sector for devising a LCA single-score. The panellist who gives this comment and chooses the representation of LCA through values of both mid- and endpoint indicators, argues that the sector is not ready yet because of the uncertainties in LCA (the ones mentioned are high altitude atmospheric impacts on climate and ozone) and some unexplored effects of space-specific materials. They also mention the immature (as of now) single-score methodology and the lack of some LCA processes as reasons why a single-score cannot yet be designed for the moment.

5.8. Ranking of Space Sustainability Rating's modules

In the third questionnaire, the panellists are requested to rank the modules assessed and proposed by SSR. As a means of background, they are given brief descriptions of each module, similar to the ones in Section 3.6, as shown in Section I.3. The Dark and Quiet Skies module is split into two separate modules (Dark Skies and Quiet Skies) to see if any variation in importance between them is indicated.

A first ranking of only the current modules is asked for, after which a new ranking combining both the current and the future modules is done. The panellists are asked to provide a relative ranking, identical to the one of the midpoint indicators, as described in Section 4.1.5. The weights computed from the average final scoring of the current modules and the current and future modules can be seen in Table 5.2, SSR's current weights. The second column is adapted to accommodate for the fact that External Services is currently a bonus module. Thus the column allows for a better comparison with the current state.

Table 5.2: Comparison of the current SSR weight with the average weights proposed by the expert panel, for the current modules with and without the module of External Services, as well as for the current and future modules.

	SSR's Weights	Jury's weight of current modules excluding External Services (n = 18 answers)	Jury's weight of current modules including External Services (n = 18 answers)	Jury's weight with future modules (n = 16 answers)
Mission Index	50	22.9	20.0	12.0
DIT	12	18.7	16.4	9.3
COLA	16.5	19.7	17.2	10.7
Data Sharing	16.5	18.6	16.2	8.5
ADOS	5	20.1	17.5	10.6
External Services	Bonus	Bonus	12.7	7.1
LCA Module	NA	NA	NA	12.2
LVSR	NA	NA	NA	10.6
Dark Skies Module	NA	NA	NA	9.6
Quiet Skies Module	NA	NA	NA	9.5

Certain aspects stand out from the data collected. Firstly, it is worth noting that the standard deviation (or spread) of the scores given is relatively small (only 18.8 compared to the average of 24.7) for the mission index when only looking at the current modules, as well as for the LCA module when also considering the future modules (only 17.8 compared too the average of 28.2). The Mission Index's standard deviation when considering all current and future proposed modules is 24.9 – a significant increase compared to the case where only the current modules are considered. Moreover, from the current modules' ranking, the weights of all modules seem quite close, except for the External Services one, which appears not to be considered that important. A similar conclusion regarding the External Services module can be made when considering all current and future modules. However, in this case, the LCA module and the Mission Index seem to be considered most important.

A significant difference with the original SSR weights can be observed. Most notable of which is the fact that the Mission index does not take up half of the final score anymore, and that the other modules are much more spread out. In the case where all the current and future modules are looked at, the weights seem more or less evenly distributed, without any drastic differences - except perhaps for the External Services Module. Notable as well is the relative low weight for the Data sharing module in the case where all the modules are considered. Moreover, while the LVSR module has a high weight assigned to it, one should note that this component of the rating might in fact be a stand-alone rating, separate from the current SSR, as discussions are being held at the time of writing.

5.9. General comments of the panellists about the survey

At the end of the third questionnaire, the panellists are asked for any general comments on the survey. Some comments were given on the length of the questionnaires as they took a bit more time to complete than panellists expected – which makes the author even more grateful for the time taken by each panellist. A remark is made that the matter of ranking the impact categories leans sometimes more toward being a political matter rather than a purely scientific one.

A broader statement is made by one panellists who considers that the ongoing environmental changes on our planet (i.e. climate change and the increase in global temperatures) may one day prevent any further developments in space activities except the ones they view as the most critical ones (i.e. meteorology, ecological survey, atmosphere observations, telecommunications, etc.). It is argued that these "essential applications" can only be maintained if international regulations are agreed upon, including regulations on how to assess the environmental impacts.

5.10. The overall recommended weights for a space LCA single-score

With the results of the survey, the recommended weights can now be calculated. Section 5.10.1 shows the recommended weights and discusses the way they are calculated. Section 5.10.2 provides a comparison between the proposed weights and those created by PEF and ESA.

5.10.1. Proposed weights for single-score space life cycle assessments

Upon consideration of the results shown in Table 5.1, recommendations can be made with regards to weights for a single-score space LCA. For this, it is chosen to only consider impact categories recommended by PEF and to exclude the Launch Segment from the scope. The reason behind this choice is three-fold:

1. The proposed space-specific impact categories do not yet have a clear and readily-available definition or implementation. Thus, they are not yet usable at the time of writing.
2. Adhering to PEF's recommended impact categories will ensure some level of comparability between the space industry and other industries. Although, it should be noted that the weights for space LCA are different from that of PEF.
3. The omission of the Launch Segment reflects the fact that satellite operators often only have authority over the satellite's design and its overall life-cycle, as opposed to the launcher. The choice of the launcher is frequently mainly dictated by financial or political reasons. It is considered that, when environmental reasons are also taken into account, there are few actions the operator can take to reduce the impacts of the launch segment.

Thus, the last column of Table 5.1 is used to compute the final weighting factors. Firstly, the aggregated space LCA weighting set is obtained after removing the space-specific impact categories from the average scores in the table and scaling them to 100. The result is shown in the second column of Table 5.3.

After this, robustness factors are applied to each of them. These factors are conceived by the JRC [19] and shown in the third column of Table 5.3. In essence, they ensure that impact categories with greater certainty in their outcomes have a higher weight compared to the results from impact categories that are less robust. The resulting intermediate coefficients, shown in the fourth column, are thus slightly less reliant on pure subjectivity alone.

The last step to reach the final space LCA weighting factors is to scale them to 100, i.e. to make their sum equate 100. The result is shown in the last column of Table 5.3. Note that the layout of this table is identical to that of JRC's report [19], for increased comparability between that report and this thesis.

Table 5.3: The recommended weighting set, robustness factors and final weighting factors for the midpoint impact categories.

Midpoint impact indicator	Aggregated space LCA weighting set (%) (A)	Robustness factor [19] (B)	Intermediate coefficients C=A*B	Final space LCA weighting factors (incl. robustness) (%) C scaled to 100
Climate change.	9.66	0.87	8.41	**15.89**
Ozone depletion.	5.72	0.60	3.43	**6.49**
Human Toxicity - cancer effects.	8.04	0.17	1.37	**2.58**
Human Toxicity - non-cancer effects.	6.65	0.17	1.13	**2.14**
Particulate matter.	6.63	0.87	5.77	**10.90**
Ionizing radiation - human health.	6.32	0.47	2.97	**5.62**
Photochemical ozone formation - human health.	5.58	0.53	2.96	**5.59**
Acidification.	4.88	0.67	3.27	**6.18**
Eutrophication - terrestrial.	4.48	0.67	3.00	**5.67**
Eutrophication - freshwater.	4.61	0.47	2.16	**4.09**
Eutrophication - marine.	4.89	0.53	2.59	**4.90**
Ecotoxicity - freshwater.	5.32	0.17	0.90	**1.71**
Land use.	5.21	0.47	2.45	**4.63**
Water Use	5.49	0.47	2.58	**4.88**
Resource use: metals and minerals.	9.20	0.60	5.52	**10.43**
Resource use: fossil fuels.	7.33	0.60	4.40	**8.31**

5.10.2. Comparison of the recommended weights with PEF's and ESA's weights

For the interested reader, a comparison between the final weighting factors proposed in this thesis with those of proposed in PEF [19] and by ESA [44] is shown in Table 5.4. The cells are given a more or less dark gray colour depending on the relative value of the proposed weight. This enables a more convenient comparison of the highest and lowest values between the three propositions.

Table 5.4: Comparison of the proposed space LCA weighting factors with the weighting factors proposed by PEF and ESA. The color of each cell is proportional to the size of the weights of either PEF, ESA or of the ones proposed in this thesis. Darker grey indicating a high number and light grey a low number.

Midpoint impact indicator	Final space LCA weighting factors (incl. robustness)	PEF final weighting factors [19]	ESA proposed weighting factors [44]
Climate change.	**15.89**	12.90	11.76
Ozone depletion.	**6.49**	5.58	11.76
Human Toxicity - cancer effects.	**2.58**	6.80	2.35
Human Toxicity - non-cancer effects.	**2.14**	5.88	2.35
Particulate matter.	**10.90**	5.49	2.35
Ionizing radiation - human health.	**5.62**	5.70	4.71
Photochemical ozone formation - human health.	**5.59**	4.76	7.06
Acidification.	**6.18**	4.94	7.06
Eutrophication - terrestrial.	**5.67**	2.95	5.88
Eutrophication - freshwater.	**4.09**	3.19	5.88
Eutrophication - marine.	**4.90**	2.94	5.88
Ecotoxicity - freshwater.	**1.71**	6.12	5.88
Land use.	**4.63**	9.04	4.71
Water Use	**4.88**	9.69	2.35
Resource use: metals and minerals.	**10.43**	6.68	10.59
Resource use: fossil fuels.	**8.31**	7.37	9.41

Overall, one may note that the distribution of the proposed weighting factors resembles more closely that of the ones proposed by ESA than the ones PEF puts forward. While a focus on Climate Change is present in all three, one recognises that ESA's focus on the two Resource Use indicators and their disregard of the Human Toxicity indicator is similar to the one in this thesis' proposed weighting factors. One larger difference between ESA's weights and those proposed in this thesis is ESA's relatively bigger focus on Ozone Depletion. As a possible explanation, one ought to remember that ESA's weights aim to encompass the launch segment as well [44]. Another significant difference is the Particulate Matter impact category which is highly considered in this thesis' weighting factors, but barely in ESA's.

It is interesting to focus on some of the differences of the final space LCA weighting factors and PEF's final weighting factors. Most notably, the land and water use are much more heavily considered in PEF than for the space LCA weights. The same could be written about the Human Toxicity impact indicators. Besides this, PEF considers freshwater ecotoxicity to be much more important than what results from the weights of this thesis. Regarding resource use, one may remark that PEF finds this indicator important, although relatively lesser than what is the case of the space LCA weighting factors.

6 Delfi-n3Xt's LCA and SSR results

Having summarised the inputs of the survey in Chapter 5 and defined recommended weighting factors for a space LCA single-score in Section 5.10, this chapter delves into the computation of the LCA single-score of Delfi-n3Xt. First, the unnormalised impacts are shown in Section 6.1, based on the LCA modeling described in Section 4.3. The result of the application of the normalisation factors are shown in Section 6.2. From there, the single-score is computed in Section 6.3 using the weighting factors recommended in Section 5.10. Section 6.4 shows efforts made to simulate some basic ecodesign.

Moreover, this chapter explores Delfi-n3Xt SSR score. Section 4.4 shows the score compute with SSR's current weights. The effect of the newly suggested weights of Section 5.8 onto the SSR score of Delfi-3Xt is investigated in Section 6.5.2.

6.1. Unnormalised impacts of Delfi-n3Xt

The Impacts of Delfi-n3Xt's life-cycle, as modelled in Section 4.3, are shown in Table 6.1 and can also be found in the *4TU.ResearchData* data repository [2]. The impacts are divided per impact indicator and Phase of the life cycle. A total impact per Phase is also shown.

Table 6.1: Impact of Delphi-n3Xt, divided by impact category and mission phase.

Impact category	**Phase A+B**	**Phase C+D**	**Phase E1**	**Phase E2**	**Phase F**	**Total**	**Unit**
CC	7.45E+04	3.90E+04	2.36E+01	2.25E+02	1.68E-02	**1.14E+05**	kg CO2-Eq
OD	1.22E-02	1.14E-02	5.38E-06	7.40E-05	0.00E+00	**2.36E-02**	kg CFC-11-Eq
HT-CE	2.95E-05	1.79E-05	9.99E-09	8.83E-08	3.52E-06	**5.10E-05**	CTUh
HT-nCE	5.40E-04	2.47E-04	2.08E-07	8.80E-07	1.57E-07	**7.88E-04**	CTUh
PM	1.45E-03	1.33E-03	6.95E-07	3.71E-06	0.00E+00	**2.79E-03**	disease incidence
IR-HH	1.21E+04	7.25E+03	3.27E+00	4.05E+01	0.00E+00	**1.94E+04**	kBq U235-Eq
POF-HH	1.64E+02	2.29E+02	7.75E-02	5.12E-01	4.88E-04	**3.93E+02**	kg NMVOC-Eq
Ac	1.98E+02	2.74E+02	7.16E-02	5.76E-01	0.00E+00	**4.73E+02**	mol H+-Eq
Eu-T	4.71E+02	1.04E+03	2.01E-01	1.23E+00	0.00E+00	**1.51E+03**	mol N-Eq
Eu-M	3.34E+01	6.39E+01	1.32E-02	2.19E-02	0.00E+00	**9.74E+01**	kg N-Eq
Eu-Fw	2.55E+01	1.55E+01	5.93E-03	6.71E-02	0.00E+00	**4.11E+01**	kg P-Eq
Ex-Fw	9.00E+05	3.84E+05	2.57E+02	1.70E+03	1.67E+05	**1.45E+06**	CTUe
LU	7.36E+05	1.33E+05	1.01E+02	8.14E+02	0.00E+00	**8.70E+05**	-
WU	2.23E+04	1.03E+04	5.12E+00	6.16E+01	0.00E+00	**3.27E+04**	m3 world eq. deprived
RU-FF	1.25E+06	7.07E+05	4.04E+02	4.16E+03	0.00E+00	**1.96E+06**	MJ, net calorific value
RU-MM	5.65E-01	1.25E+00	3.36E-04	2.94E-03	0.00E+00	**1.82E+00**	kg Sb-Eq

The acronyms for the Impact categories have the following meaning: CC, Climate change; OD, Ozone depletion; HT-CE, Human Toxicity - cancer effects; HT-nCE, Human Toxicity - non-cancer effects; PM, Particulate matter; IR-HH, Ionizing radiation - human health; POF-HH, Photochemical ozone formation - human health; Ac, Acidification; Eu-T, Eutrophication - terrestrial; Eu-M, Eutrophication - marine; Eu-Fw, Eutrophication - freshwater; Ex-Fw, Ecotoxicity - freshwater; LU, Land use; WU, Water Use; RU-FF, Resource use: fossil fuels; RU-MM, Resource use: metals and minerals.

To give an intuitive impression of the relative importance of each life cycle phase, a visual representation of their relative impacts can be seen in Figure 6.1. From the figure, one may note that Phase A+B and C+D make up almost the entirety of the impacts. Some small portion of them is taken by Phase F in two impact categories, but its impact is 0% or close to 0% in all other categories. The impacts of Phase E1 take up less than 0.03% of the total impact in each category. Phase E2 's impacts are slightly higher, yet still below 0.32% for all impact categories.

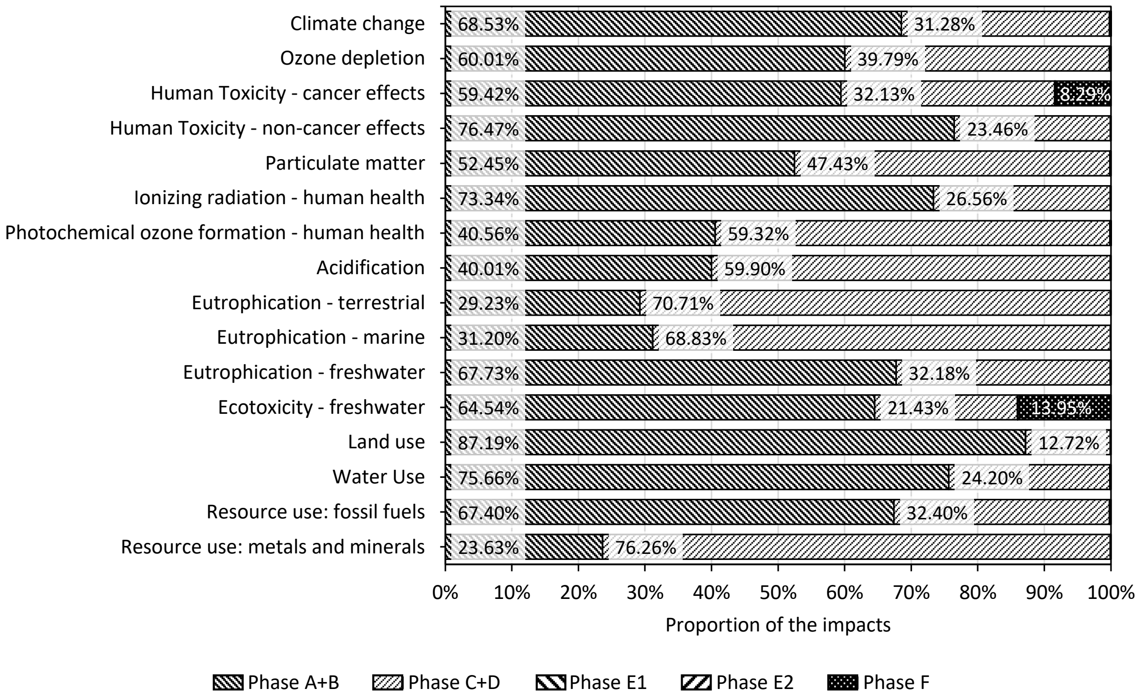


Figure 6.1: Relative impacts of each Phase of the Delfi-n3Xt mission.

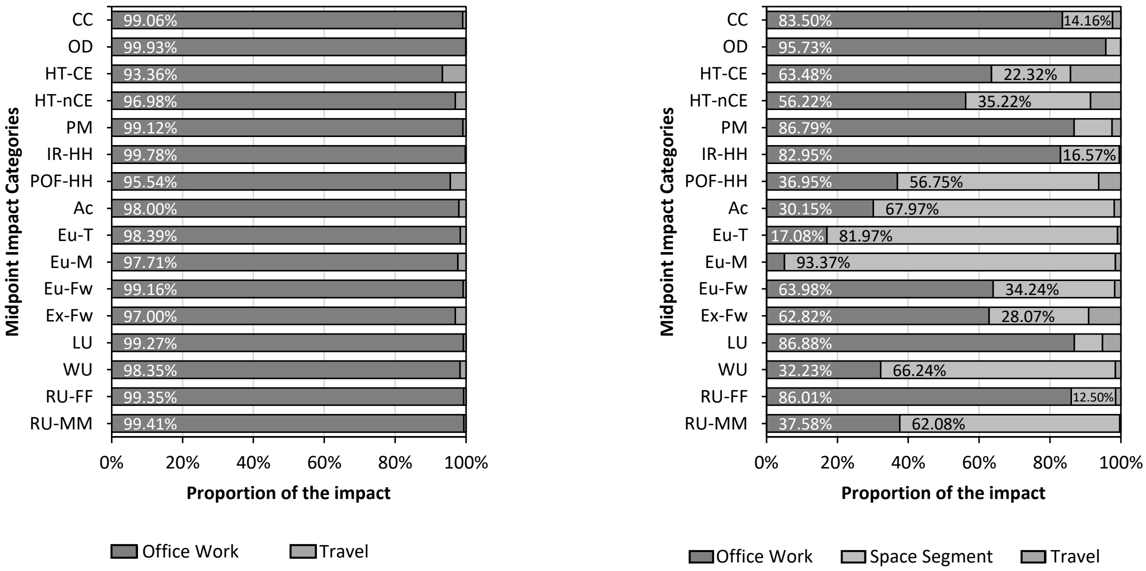
A more detailed analysis of the composition of the impacts of Phase A+B and Phase C+D is given in Figure 6.2. It must be written that the Phase C+D Office Work is found to have positive impacts on the Marine Eutrophication due to waste water treatment, but for the purposes of the figures, the impacts have been inserted as if they were negative (i.e. bad for the environment). It can be noted that the travel component represents only a minor part of the impacts – even negligible in the case of Phase A+B. Office Work represents almost all of the impacts of Phase A+B and a large part of Phase C+D. The space segment activities in Phase C+D make up a large part of the impacts and, for some impact indicators, even almost the majority of the impacts. This gives insight into which activities of the most impact-full phases of Delfi-n3Xt cause the biggest environmental impacts.

Upon closer inspection, additional conclusions could be drawn with regards to hotspots within the Space Segment activities. In terrestrial and marine eutrophication, acidification and photochemical ozone formation, the Clean Room operations dominate the space segment's impacts, with a relative proportion of the impacts between 81% and 95%. For freshwater eutrophication and the metals and minerals resource use, the electronic units make up 67% and 73% of the impacts respectively, combining the low and high Integrated Circuit (IC) electronics' impacts. In the case of freshwater ecotoxicity, the solar panels seem to be the largest contributor to the impacts: 41% of the impacts.

6.2. Normalised impacts of Delfi-n3Xt

With the above LCA results, it is now possible to normalise the impacts, as an intermediate step before the single-score calculation and as a means to compare the impact categories between themselves. It is chosen to normalise in terms of Environmental Footprint (EF) per person globally, as discussed in Section 4.3.9. The resulting normalisation is shown in Table 6.2.

It is clear from the numbers shown in the table that some impact categories stand out more than



(a) Relative impacts of the components of Phase A+B.

(b) Relative impacts of the components of Phase C+D.

Figure 6.2: Closer look at the relative importance of the components of Phases A+B and C+D.
For a description of the impact indicator's acronyms used in the figure, see the note below Table 6.1. Note that the impact indicators have the same order in this figure as in Figure 6.1.

others. The Delfi-n3Xt mission, as modelled in this thesis, seems to have a high relative impact compared to an average global person in the fossil fuels resource use, the land use, the freshwater ecotoxicity and the climate change. The impact categories with the lowest impact categories are the ones related to human health and to particulate matter, where only a small fraction of the EF of an average person is noted.

Table 6.2: Normalised impacts of Defi-n3Xt.

Midpoint impact category	Impact [EF per person]
Climate change	1.13E+01
Ozone depletion	4.51E-07
Human Toxicity - cancer effects	5.06E-09
Human Toxicity - non-cancer effects	6.56E-08
Particulate matter	2.80E-07
Ionizing radiation - human health	1.23E+00
Photochemical ozone formation - human health	4.09E-02
Acidification	4.61E-02
Eutrophication - terrestrial	1.62E-01
Eutrophication - marine	9.67E-03
Eutrophication - freshwater	3.32E-03
Ecotoxicity - freshwater	1.42E+02
Land use	9.63E+01
Water Use	2.77E+00
Resource use: fossil fuels	1.83E+02
Resource use: metals and minerals	1.56E-04

6.3. LCA single-score of Delfi-n3Xt

With the above normalised values for each impact category, the weighting factors shown in Table 5.3 are now applied to compute Delfi-n3Xt's single score. For comparison purposes, the same has been done with PEF's and ESA's weights. These calculations are also recorded in the *4TU.ResearchData* data repository [2], which can be accessed for further clarification. All three single scores are listed in Table 6.3 and they show some differences in values. The recommended single-score methodology results a score of 14.30, which is the lowest one of the three. ESA's methodology appears to produce the highest score for the case of Delfi-n3Xt.

Table 6.3: Delfi-n3Xt single-score compared with the one from ESA's and PEF's single-score methodology.

	Single-score [-]
Score based on recommended weighting factors	14.30
Score based on PEF's [19] weighting factors	16.00
Score based on ESA's [44] weighting factors	20.17

To study the differences in the scores, the relative contribution of the the impacts of each impact category is shown in Figure 6.3 for each single-core methodology.

The figure indicates that for the recommended single-score methodology, the marine eutrophication, freshwater ecotoxicity fossil fuel and metals & minerals resource use and climate change contribute the most to the single score, with 32.27%, 29.52%, 12.37%, 9.61%, and 6.61% of the single-score's composition, respectively. The same five impact categories contribute the most, although in different proportions, to the single-score calculated through PEF's and ESA's weighting factors. These differences in final proportions, due to the different weighting factors, are the cause for the differences in single-score values.

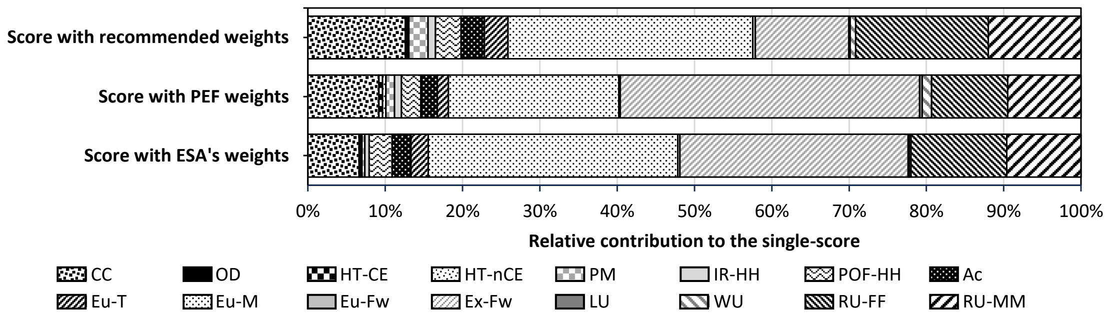


Figure 6.3: Contributions of the impacts of each impact category to Delfi-n3Xt's proposed single-score, as well its ESA and PEF single scores. That is, the relative values of the normalised impacts are multiplied by the weighting factors of each of these methodologies.
Note that the impact categories are shown in the plot in the same order as the legend. That is, the first category shown is 'Climate change (CC)', followed by 'Ozone depletion (OD)', etc. until 'Resource use: metals and minerals (RU-MM)'

6.4. Ecodesign of Delfi-n3Xt

Some ecodesign attempts are made on Delfi-n3Xt, with limited success. Investigations are made into the LCA activities that could be changed in a realistic way, while preferably having the highest impacts on the single-score. For this, the contributions, shown in Figure 6.3, of each impact category to the single-score and the LCA hotspots discussed in Section 6.1 are used as a basis to work from.

6.4.1. Attempts at tackling the single-score's hotspots

The first approach is to look at the biggest contributor to the single-score, i.e. the marine eutrophication. For this impact category, Phase A+B's Office Work and C+D's space segment have the largest impact, as can be seen in Figure 6.2. In particular, the activity related to electricity is the hotspot (57.4% of its impacts) of Phase A+B Office work and the cleanroom activity is the hotspot for Phase C+D Space Segment (93% of it impacts). Unfortunately, it does not make sense to modify these two hotspots as they are modeled based on external datasets and any modification would not be based on real first-hand data and could thus not be justified. The only recommendation one could make to designers starting a new CubeSat mission is to attempt to limit the number of hours in the cleanroom and limit the electricity consumption at the office

Then, the freshwater ecotoxicity impact category is investigated. As visible from Figure 6.1, Phase A+B, C+D and F are the biggest contributors in decreasing order. Starting with Phase F, it is decided not to modify its flows, since the ones used are taken from the SSSD and no other sources could be found to provide better ones. Such a modification would also not be in line with the concept of ecodesigning, but rather in line with the action of improving the LCA databases used for Delfi-n3Xt's LCA. For Phases A+B and C+D, Figure 6.2 shows that Office Work plays a major role, however no modifications to it is done for reasons explained above. In the space segment, the solar panels are found to have the biggest impacts, as discussed in Section 6.1. It is however not possible to choose cells with lower impacts, as the choice was limited to the one provided by ESA's Database and no time was available to develop a custom dataset. Reducing the size of the panels is also unrealistic, given the satellite's power needs. There is therefore no optimisation done with regards to Delfi-n3Xt's solar panels.

The other impact categories with the largest contributions are also looked at, but few modifications could be made to the CubeSat itself. As shown in Figure 6.1, the impact categories of climate change and fossil fuel use are mainly dictated by the office work activity. For reasons explained above, it is not realistic to make any changes to it, only recommendations could be made to future mission designers. For the metals and minerals resource use indicator, the electronics of the CubeSat are found to have the biggest contribution (around 50% of Phase C+D's contribution). However, it is impossible to reduce the number of electronics used, as the designers of Delfi-n3Xt are assumed to have limited their mass as much as possible already. One could possibly consider improving the way the electronic units are modeled in Brightway2, however any departure from ESA's general dataset would need to be justified with first-hand data which is not available in time.

6.4.2. Basic ecodesign by changing the battery

With those major hotspots in the single-score investigated, the focus is now on a smaller, yet more practical, aspect of the CubeSat that could be changed: the battery. It is observed that certain battery technologies were investigated during the real design phase, before settling on the lithium-ion (Li-ion) technology [73]. In particular a nickel metal hydride (NiMH) battery is ranked high among the options due to its high specific energy [73]. Since this battery type is also available in Ecoinvent's Cut-Off database, it is easy to swap the Li-ion battery in the battery case with a NiMH one. For simplicity reasons, the same mass of battery is preserved for the new battery, although the higher specific energy might enable the designers to reduce the mass during a real design stage.

After calculations of the environmental impacts and their conversion into a new single-score, it is found that the CubeSat would now receive a score of 15.97. That is a higher and thus worse score than Delfi-n3Xt's original single-score of 14.30. It represents an increase in score of 11.7%.

Despite the fact that the battery makes up only 7.2% of the total mass of the satellite, it seems like a change in its technology has drastic effects for the impacts as well as for the single-score specifically. All the impact categories are affected. The changes can be studied in Table 6.4.

The most heavily weighted impact categories seem to generate only a relatively small difference, while categories with more intermediate to small weights see large changes. The heavily weighted categories of climate change, particulate matter and resource use see an increase in normalised impacts between 18 and 39%. This undoubtedly contributes heavily to the increase in the score, but extremely high increases in categories with somewhat intermediate weights must also have contributed to it. Those categories are in particular ozone depletion, freshwater eutrophication and land use, with their respective 524%, 252% and 21250% increase.

One should however stay sceptical and verify these findings. The value of the land use impact's difference as well as that of the other two very high differences, may be surprising given the relatively small mass fraction of the battery. This should incite a deeper investigation. Due to limited time, this was not possible for this thesis. However, one may note that the NiMH battery production activity was taken from the Ecoinvent database, whereas the one of the Li-ion battery's production was borrowed from the ESA LCA Database. There may be different assumptions underlying each of these two activities and the fact that the Ecoinvent database is not at all tailored to the space industry could be contributing factors to the observed differences in normalised impacts.

Nevertheless, this small experiment of changing a component of the CubeSat's design does show that the proposed single-score could be a useful tool to make a choice between two design options. If designers would have had access to this LCA and single-score methodology, they could have used the above conclusions as argumentation in their choice between batteries. In this case, it would have suggested them to abandon the NiMH battery and favour the less impactful Li-ion battery, which they coincidentally did using more hard engineering reasoning.

Table 6.4: Changes in the normalised impacts after swapping the battery technology in Delfi-n3Xt.

Midpoint Impact Categories	Original normalised impacts [EF per person]	New normalised impacts [EF per person]	Difference [%]
Climate change	1.13E+01	1.35E+01	19.51
Ozone depletion	1.62E-01	1.01E+00	524.26
Human Toxicity - cancer effects	1.10E+00	1.32E+00	19.70
Human Toxicity - non-cancer effects	1.16E+00	1.66E+00	42.99
Particulate matter	3.27E+00	3.89E+00	18.83
Ionizing radiation - human health	2.45E+00	4.60E+00	87.75
Photochemical ozone formation - human health	8.45E+00	9.69E+00	14.67
Acidification	6.97E+00	8.53E+00	22.39
Eutrophication - terrestrial	7.70E+00	8.52E+00	10.72
Eutrophication - marine	1.11E+02	5.60E+01	-49.42
Eutrophication - freshwater	9.86E-01	3.47E+00	251.97
Ecotoxicity - freshwater	1.01E+02	6.22E-01	-99.39
Land use	5.78E-01	1.23E+02	21,249.93
Water Use	2.02E+00	2.84E+00	40.50
Resource use: fossil fuels	2.36E+01	3.00E+01	27.21
Resource use: metals and minerals	2.06E+01	2.86E+01	38.89

6.5. Space Sustainability Rating of Delfi-n3Xt

Upon submitting to the SSR team the answers of the questionnaire discussed in Section 4.4, a SSR score for the Delfi-n3Xt satellite is computed and a report is given. The latter can be found in Appendix G and the former is discussed below in Section 6.5.1, alongside a discussion of changed SSR weights in Section 6.5.2. One should note that the report copied in the appendix is tailored to the Delfi mission, as it has slightly been simplified compared to ones sent to other space operators.

6.5.1. Delfi-n3Xt SSR score

The SSR score of Delfi-n3Xt is found to be 46.76%, as shown in the 'Tier Score' of Figure 6.4, extracted from the SSR Score Report. Despite being on the somewhat lower range of the possibilities, this score does fall in the Bronze Tier for which a a score between 40% and 55% is needed [41].

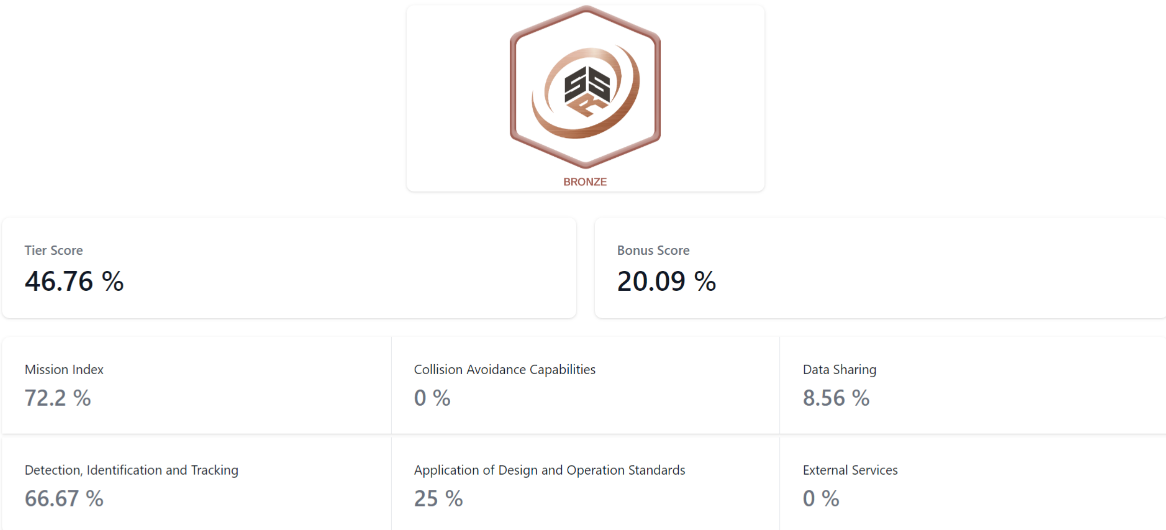


Figure 6.4: Delfi-n3Xt's 'score card' provided by SSSR, showing its SSR overal and bonus score, as well as its score for each module

This score can be explained by the scores of each module. Given its large weight in the SSR methodology, the relatively high score of 72.2%, the Mission Index is a major component of Delfi-n3Xt's final SSR score. The score of 0% of the Collision Avoidance Capability is a logical consequence of the lack of any non-payload thruster elements of the CubeSat. The fact that the team of Delfi-n3Xt only shares a limited amount of SSR's recommended shareable data results in the low score of 8.56% of the Data Sharing modules. The score of 66.67% for the DIT stems from a calculation done by SSR and from the fact that the CubeSat's team kept track of the satellite's orbital state within the first few days after launch. The low ADOS score of 25% can mainly be explained through the lack of adherence to the guidelines of de-orbiting one's satellite after 25 years. This lack might stem from the fact that awareness around such guidelines was not as high in 2013 as it is today. And, while not contributing to the main score but only to the bonus one, the External Services do not have any percentage score, as no measures pertaining to them were taken for the CubeSat. More information is provided in the SSR report, in Appendix G.

6.5.2. Modification of the SSR weights

The Delfi-n3Xt's modules score can now be weighted in a different way than the standard SSR weighting system to observe and discuss any changes in the outcome. For the purposes of this thesis, the weights proposed by the panellists were used to that effect. Specifically the weights listed in the second column of Table 5.2 are used. The resulting new total SSR score is shown in Table 6.5 and found to be 35.37%.

Table 6.5: Calculation of the SSR score and the score based on the suggested weights.
The 'SSR weighted scores' are computed by applying the SSR weights shown in the first column of Table 5.2 to the Module Scores.
The 'Newly weighted scores' are computed by applying the first suggested weights as given in the second column of Table 5.2 by the panellists.

SSR Modules	**Modules score [%]**	**SSR weighted score [%]**	**Newly weighted score [%]**
Mission Index	72.2	36.10	16.53
COLA	0	0	0
Data Sharing	8.56	1.41	1.72
DIT	66.67	8.00	12.47
ADOS	25	1.25	4.65
External Services	0	0 (Bonus score)	0 (Bonus score)
	Total:	**46.76**	**35.37**

This newly found score would not fall in any of the tiers, as a minimum score of 40% is needed for Bronze, the lowest tier. Such a reduction in score can be explained by the fact that the new weights could be described as having been flattened between one another. The high spike in importance for the Mission Index is not present anymore, lowering its – previously significant – impact on the final score. All other modules have in comparison gained more importance. And, given these modules' relative low individual scores, the final total score gets reduced.

7 Discussion

The results found in this thesis ought to be discussed further to fully understand the nuances. Section 7.1 focuses on some of the findings of the survey: the drivers and inhibitors of space LCA, the SSR module weights and the midpoint indicator weights. Section 7.2 gives further comments on the final LCA weighting set proposed in this thesis. A reflection on Delfi-n3Xt's LCA rsults and single-score is given in Section 7.3 and Section 7.4 respectively. The same is done for its SSR rating in Section 7.5, before remarks are made in Section 7.6 on the possibilities of implementing LCA in early design.

7.1. Notable findings from the survey

The survey provides key information useful for the space industry at large, given the expertise of the panellists and the chosen survey method. This section discusses in more detail some of the findings, namely in respectively Section 7.1.1, Section 7.1.2 and Section 7.1.3, the drivers and inhibitors of space LCA are discussed, the weights for SSR modules are looked at and the weights of the midpoint indicators are elaborated upon.

7.1.1. Drivers and inhibitors of a space LCA

One should evaluate the conclusions drawn from the drivers and inhibitors with care, given the limited size and the bias of the expert panel's demography. As mentioned in Section 4.1.1, the main objective of the survey pertains to the rating of the midpoint indicators, for which the DELPHI method would be ideal. The estimation of space LCA's drivers and inhibitors should be more individuals within the space industry, with backgrounds also outside the field of LCA, including the marketing and business sectors.

It is interesting that the commercial drivers (marketing opportunities, sales increase, competitive advantage, customer satisfaction) are ranked that low compared to the European general industry's opinion, while the more pure environmental calculation drivers are considered to be much more important. One possible explanation for that could be the demographic of the panellists, which did not include any salesperson within a company. Moreover, the panellists were asked to answer based on their own experience, which is mainly technical, as opposed to being asked to answer from the perspective of the company. Nevertheless, the results shown in this paper are thought to be a good indication as to which factors could incite the space industry to perform more LCA.

Similarly, the background of the experts could also explain the low ranking of the inhibitors pertaining to the definition of LCA-related elements itself (e.g. scope and system boundaries), compared to that of the European general industry's average opinion. A more diverse group of participants to a survey might find these aspects more difficult and thus rank them as a greater inhibitor for LCA. Nonetheless, the fact that people with experiences in LCA do consider these aspects to be major inhibitors shows that the definition of a LCA for the space sector is not that much more difficult than the definition of any other LCA.

The fact that data collection and the judgement of the data's quality rank among the biggest inhibitors for a LCA in the space industry seems to match well with remarks in literature. The lack or the incompleteness of space-specific LCA databases is often given as a major drawback for the performance of LCA on a space-related topic. Likewise, the lack of information on the data's quality or the need to use proxy data is regularly mentioned.

7.1.2. SSR modules weights

The outcomes of the weighting of SSR's current modules as well as that of it's current and future modules could be an interesting point of reference for a future version of the rating. Slight modifications of the proposed weights in Table 5.2 could provide a more transparent method of creating the final SSR score, although a full assessment of the resulting new score calculation should be performed. The reasoning behind the choice of SSR's current weights are not fully disclosed in literature, with only a mention of an assignment of a three tier importance level to each module [37], and some iterations on it [38].

However, if one looks at the distinct high weight of the future LCA module compared to the others, one could argue that a larger number of people with different backgrounds within the space industry should be consulted for a final set of weights decided upon by the community. The high for this module is likely biased given the background of the expert panels and the fact that the survey's subject is LCA. One could envision a future discussion with experts, where the workings of the modules are discussed in much more depth before asking to rank them.

Moreover, the Dark Skies and the Quit Skies modules will likely be combined into a single module: "Dark and Quiet Skies module". Thus, the weights of each of these two topics should be merged, by averaging their scores and then computing their weights. This paper presents them as separate topics, to investigate if there would be any significant difference in perceived importance between them.

Lastly, one should be aware of the shortcomings of this survey with respect to the weights of the SSR modules. Besides the likely bias introduced regarding the LCA module, one should note that only a handful of the participants knew in some detail the workings of each module. In the survey, the modules were only described using SSR's general description [41], which may not have been sufficient to gain enough insights for a thorough weighting. This can be deduced from the relatively equal distribution of the weights, suggesting that panellists might not have had enough information to make a distinct differentiation.

7.1.3. Weighting of the environmental midpoint indicators

The fact that few participants choose to modify their ranking of impact categories of the single satellite mission for the constellation mission, and the similarities between their scores for the PEF-defined impact categories of a single satellite mission and a constellation mission could indicate that a single-score weighting across all mission types would be feasible. Nevertheless differences in the space specific impact categories such as the one of Mass left in Space, Orbital Resource Depletion and Al_3O_2 emissions do exist. To create a single-score weighting valid for all mission types, these difference would need to be ironed out (e.g. through averaging their scores).

The significant differences found between PEF weights and the weights through the panellists' inputs confirms the uniqueness of the space industry and its need to have a different means of aggregating the LCA results. One could make the case that, for instance, the relative increase in the Ozone Depletion category's weight and the decrease in the one of Land Use could reflect the fact that the space industry emits emissions ozone-depleting directly into the upper atmosphere and that it might need less land compared to more general industries. The results shown are therefore useful for a first version of a single-score computation methodology.

However, this difference between PEF and the proposed weights could also highlight the limits of the knowledge on the exact environmental impacts of space missions of the scientific community and by extension the panellists. For instance, there is no definitive answer yet to the extent to which the upper atmosphere is impacted by launches and atmospheric re-entry. As a consequence, there is also little insights on how to compare these within a life cycle framework. In addition, there might still be large uncertainties in the current LCA datasets which need further assessment.

Thus, despite the panellists' expertise, there is still a generalised lack of knowledge on the environmental impacts of spaceflight, which might have affected their answers and the conclusion of this paper. This can be further supported by the fact that the standard deviations in the scores did not decrease significantly throughout the three questionnaires, indicating a certain disparity of opinions and possible lack of consensus. In contrast, the fact that the standard deviation for Climate change and orbital resource depletion are constantly drastically lower than other impact categories might be a reflection of political directives or of an international awareness, rather than a reflection of conclusions from scientific research. Overall, this has a impact on the conception of space policies related to environmental impacts and eco-design, where one might be basing certain guidelines on inconclusive or debated findings.

Besides this, the fact that the weights diverge thus from the PEF weights would mean an increased difficulty in comparing the impacts of a space mission with that of any other system or process in the general industry. Therefore, care should be taken in the communication of the results of a space mission's environmental single-score if these proposed weights are to be implemented. One should, regardless of the industry, consider the Clause 4.4.5 of ISO 14044 [5], which warns that a comparison between any two weighted LCA results of a product or process (e.g. two single-score results) should not be disclosed to the public.

7.2. Proposed space LCA single-score weighting factors

The proposed LCA weighting factors for a single-score, discussed in Section 5.10, remain somewhat subjectively chosen despite the effort put into providing a clear reasoning for their values. It is nevertheless thought by the author that the final set of factors do reflect well the points of focus during the design of a satellite. Climate Change being the most important is logical, give the current global temperature rise and the political incentive worldwide to tackle the climate change crisis. The further emphasis of Particulate Matter highlights the importance of the re-entry stage and encompasses the fact that there is limited knowledge about it at the moment. One can also justify the high weights of the resource use indicators by the fact that space missions typically need very specific metals, minerals and fuels.

One ought to remember that the weighting factors proposed in this thesis are only meant for LCAs which exclude the launch segment. This explains the lack of emphasis for instance on Ozone Depletion which ESA gives a much greater weight. The exclusion of the launch segment follows from the findings in literature that launchers cause almost all impacts for specific indicators, when included in the LCA's scope. The lack of agency of a satellite operator over the ecodesigning of the chosen launcher is another reason to exclude launchers from early design LCAs, where only the satellite and its design and operation process can be altered.

7.3. Delfi-n3Xt's Life Cycle Assessment

It is clear that the LCA of Delfi-n3Xt was restricted by the available LCA databases, which has both benefits and drawbacks. Since no time was available during the thesis to develop any LCA processes and activities specific to Delfi-n3Xt's life cycle, only the ESA External database could be used, alongside the structure provided through the SSSD and the more generic Ecoinvent database. The great strength of this approach for the purposes of this thesis is that it mimics the way any average LCA practitioner would perform a LCA with the means available. More specifically, this approach simulates how one would do a LCA at the early design stages of a space mission, when specifics are not fully worked out yet.

However, as a result, the LCA of Delfi-n3Xt might not be as detailed or as tailored as one would ideally like it to be. Specific examples of LCA activities that are likely not perfectly in line with the CubeSat's life cycle are as follows (non-exhaustive list):

- The Clean Room activity is taken from the ESA database and is likely to be based on one of Guiana Space Centre's clean rooms. While the electricity mix was switched to those in the Netherlands, its consumption and any other flows are presumably based on the consumption and needs of the large Guyanese clean rooms. The small size, likely significant lower use of air conditioning and much lower cleanliness standard of Tu Delft's clean room will likely result in different flows.
- There is not enough transparency on the reference used for ESA's electronic units in their LCA Database. Presumably, most of ESA's LCA activities are modeled on medium to large spacecraft missions. It is therefore unclear if the electronic units would be different for small CubeSats.
- More insights need to be gained into SSSD's Office Work activity, to verify its similarities with the way the TU Delft students and staff do their office work. There may be major differences due to the specificities of the university's offices or their work practices. Nevertheless, it is thought that this activity serves well as an average Office Work to use.

- The modelling of the tests involving the thermal-vacuum chamber may not perfectly represent how TU Delft's thermal vacuum chamber works. It was modeled based on an off-the-shelf chamber found online[1] as it was not possible to investigate in time the exact specifications of the one in the Aerospace Faculty's clean room. Therefore, some of its flows may be off.
- The End-of-Life activity is based on the "experimental" implementation of it in SSSD. While the ESA LCA Guidelines stipulate that the end-of-life cannot be modeled yet due to lack of data [29], SSSD's version of the end-of-life did provide at least a starting point. The flows are likely underestimated and some may not be accounted for.

Overall, this simplification allows for a LCA of Delfi-n3Xt similar to one which could have been done during the design phases, but at the risk of not entirely (or sometimes wrongly) grasping the full impacts of the life cycle.

7.4. Delfi-n3Xt's LCA single-score and ecodesigning

The exercise of computing Delfi-n3Xt's single score and simulating some basic ecodesign approaches provides great insights into the usability of the single-score. It is clear that the single-score by itself is of little value, as it needs to be compared to the single-score of a slightly modified design to provide information. Only then can it be used to say that the first design is "better" for the environment than the other.

In the process of computing the single-score and using it to identify points of environmental improvements for the CubeSat, it becomes evident that other information might be useful too. Given the limited meaning conveyed by a single-score on its own, the decomposition of the impact categories' contribution to the score shown in Figure 6.3 is found useful to make an assessment on where to begin ecodesiging. Further tools such as the built-in Sankey Diagram feature of Brightway2 allows to further discover which activities cause the greatest impacts within each impact category.

Therefore, if one aims to pro-actively partake in ecodesigning, one needs some more tools than only the single-score calculation methodology. Such scenarios may be envisioned mainly during later design stages, where more time is available to dive into the details of the environmental impacts and use the findings to refine the design. For early-designs and CDF studies, it is the author's opinion that such proactive ecodesigning would only be possible if a dedicated LCA practitioner is present, in which case they have all the tools available to go into further detail where needed. A single-score would then only be a simple tool for preliminary assessments and for gaining an intuitive feeling of the sustainability level.

Nevertheless, value is seen in the use of only the single-score for less pro-active ecodesigning. That is, a single-score may be most convenient when it is used at the end of a minor design cycle to verify if the environmental impacts decreases or increases. Such a scenario could be comparable to the change in battery technology proposed for Delfi-n3Xt in this thesis (albeit with slightly more effort put into calculating the reduction of battery mass thanks to the increase in energy density, etc). Here, the designers would add environmental impacts to their trade-off criteria for the design option with the new battery type once that design is proposed and somewhat investigated. It is the author's opinion that this would be the most realistic scenario during early-design phases and especially CDF studies, as any average systems engineer with minimal training should be able to perform such a trade-off. This would be an even more obvious scenario if MBSE tools integrate some form of LCA, making the task even more simple for a systems engineer. While less proactive, such an approach does enable sustainability to be included from the earliest design phases without too big of an adjustment being needed.

7.5. Delfi-n3Xt's SSR rating

The Bronze label obtained for Delfi-n3Xt's SSR score is a good reflection of the nature of the mission, although one ought to put this in the perspective of its 2013 launch year. The fact that its orbit does not naturally allow for a deorbit within 25 years and that it does not have capabilities to deorbit itself decreases significantly its score. Yet, this was not such a stringent requirement at the time of launch. Moreover, the limited amount of data sharing might, as suggested in the SSR report in Appendix C, be a

[1]See the "Ideal Vacuum ExploraVAC Space Simulation TVAC Thermal Vacuum Test Chamber" for the exact model: `https://www.idealvac.com/Ideal-Vacuum-ExploraVAC-Space-Simulation-Test-Chamber/pp/P1012095AllOps=10-13-17-21-24-29-31-34-39-4-9OptQtys=1-1-1-1-1-1-1-1-1-1-1` (accessed 23/08/2023)

consequence of the lower priority this would have had at that time. In adition to this, its small size and relatively high orbit does not facilitate the CubeSat's detectability.

In Section 7.5.1 below, further discussion is provided on Delfi-n3Xt's new SSR score. The future and possibilities of SSR's proposed LCA module are commented on in Section 7.5.2

7.5.1. Delfi-n3Xt's new SSR score and the choice of weights

Regarding the new calculated score with the suggested weights, one could indefinitely debate the outcome and the values of the weights chosen for it. This has in part been shown in Section 7.1.2, but could be further elaborated on here.

While the exact choice of the weights will always remain subjective, one ought to keep in mind that the SSR is primarily aimed at capturing "different aspects of sustainability in space, considering both the impact on other operators and on the environment globally" [37]. Therefore, the rating is meant for the space environment, rather than the terrestrial environment. From that perspective, one should note that a significant reduction in the weight of the Mission Index module – arguable the most representative module of the space environment's sustainability – would go against SSR's aim. Thus, it is unlikely that SSR's consortium would settle on such a comparatively low weight of this module. As a result of this, the new SSR score of Delfi-n3Xt would not entirely be in line with probably future SSR score methodology.

Nevertheless, such changes in weights, where even the Mission Index will get a lower importance, will be necessary if SSR plans to implement a LCA, LVSR or Dark & Quiet Skies module. While it was not possible to include the LCA module during this thesis for reasons discussed in Section 7.5.2, nor any other new module, this initial experiment with new weights is a first step for SSR to look at possible modifications. After all, if SSR intends to expand its aim, it will eventually need to revise its weights.

7.5.2. LCA module and the other suggested new modules

None of SSR's suggested modules are looked at in the modified SSR rating of Delfi-n3Xt because they are considered out of scope of this thesis, preventing their suggested weights to be tested. For instance, the Dark & Quiet Skies module is not in-line with this LCA-focused thesis and requires a dedicated research. For the LVSR module, there are discussions within SSR to consider it as a separate rating system, given the fact that only the launcher is considered, instead of the full mission. While some LCA of launchers would be involved in the LVSR module, the scope of this module, with its questionnaire to launcher operators, requires its own thorough investigation as well. The LCA module is not touched upon for Delfi-n3Xt's modified score as it requires some maturation and further work, discussed below.

Indeed, while the topic of this thesis is environmental sustainability and life cycle assessment of space missions, the LCA module cannot yet be implemented within a new SSR score. This is because of the nature of the SSR which aims to create a score between 0 and 100% to represent how much a space operator adheres to sustainability principles. For this, one ought to define thresholds for 'good' and 'bad' LCA single-scores. There is currently a lack of data points to be able to draw such a conclusion, leading to the omission of the LCA module of Delfi-n3Xt's proposed new SSR score.

In order to implement such a LCA module within the SSR framework, three methods have been put forward to the SSR team as a result of this thesis. These methods are listed below and should be discussed by future researchers, as they each have conceptual advantages and drawbacks:

- Have representative missions (i.e. a single CubeSat mission, a constellation mission, a geostationary satellite mission, etc) for which threshold scores are defined. For each of these missions, a generic LCA should be created and improved and worsened, to extract the range of single-score LCAs to which the space operator's mission can then be compared.
- Have one single generic threshold score based on a generic mission. For this, the industry ought to be involved to obtain generalised data of the various types of space missions launched to create an "average" space mission. Similar efforts have been performed recently for launchers [86], enabling the LCA of a generic European launcher and its quantitative publication in literature.
- Base the score of SSR's LCA module on the ecodesign performed by the operator. That is, the LCA single-score of the initial design is compared with that of the final design. This logically implies that the SSR rating can only be performed at a later stage in the design process, although one could imagine it being performed with the view on future changes in the design proposed by the operator. This way of computing the score of the LCA module avoids any comparisons

between two completely different space systems (i.e. the one of the operator and the generic one), but requires a first 'bad version' to show improvements.

7.6. Life Cycle Assessment in early design

The use of LCA during the early design phases may prove to be most beneficial, as these phases have the highest effect on the designed space mission. Opinions on how to implement LCA in such phases are summarised in Section 7.6.1 and a brief discussion on this is provided in Section 7.6.2.

7.6.1. Collected opinions from an expert and students during a concurrent design study

To gain insights into the implementation of LCA in early design, the progress of a CDF study of EPFL students was followed from a distance and an expert in Concurrent Design and Systems Engineering was interviewed. The findings from the former can be found in the next sub-subsection and those of the latter are penned down in sub-subsection below it.

Insights from the EPFL student's CDF study

While the general progress of the students was followed throughout their CDF course, it was mainly during their final presentations that questions could be asked and insights in their implementation of sustainability could be gained. It was clear throughout their CDF that they were mostly focused on the technical aspects of their lunar satellite deployer mission [82] and that they were preoccupied with the workings of their concurrent engineering tool COMET[2]. Any sustainability considerations were not imposed by the instructors of the class as objectives of the CDF.

Thus, during the final presentation, the students indeed mentioned their lack of focus on sustainability aspects. They justified it by the limited amount of time allocated to the CDF and the fact that it was mainly tailored to a preliminary analysis of the system. They mentioned that if they would have been instructed to consider it more highly, they would have taken the time to also make an assessment of the sustainability of their system.

A more tangible and actionable point made by the students is the fact that they lack a "library of materials", as they call it, in which some sustainability factor is indicated per material choice. They argue that such a database would help them make more environmental choices with regards to the design of the satellite's structure and components.

In general, one could state that the above comments of the students only have anecdotal value, however it is the opinion of the author that they do reflect some truth experienced during CDF studies within the industry. Firstly, one can note that the students mainly understand the concept of 'sustainability' through a choice of materials, and that they disregard it during other design phases. Based on some discussions held during the 2022 CSID, this seems to be the default understanding of engineers who are not fully briefed on all the aspects of sustainability. Secondly, the lack of time allocated to any sustainability considerations due to a lack of focus on it seems to be also the case for the industry's CDFs, as can be inferred from the interview with ir. Lorenz Affentranger. And thirdly, Affentranger also mentions the lack of a so-called convenient "library of materials", or a user-friendly and detailed database to assess the environmental impact of the space system during the early design phases.

Insights from an expert in Concurrent Design and Systems Engineering

With the full interview written in Appendix B, some key points mentioned by ir. Lorenz Affentranger are highlighted below. The comments he makes emanate from his experience in the CDF section of ESA, joined after his two years as a trainee. While his main focus lies in the system engineering of ESA's Mars Exploration program, he also supports ESA's Clean Space office. As such, he has a good overview of both early design and clean space to provide comments.

From his comments, it is clear that CDF studies always have certain topics of focus. The financial budget of the mission is a reoccurring theme within those studies, as is the mass and volume budgets imposed by the launchers. They are complemented by typical systems engineering topics such as the

[2]More information on COMET can be found here: `https://www.rheagroup.com/services-solutions/system-engineering/concurrent-design/download-cdp4-comet/` (accessed on 25/08/2023)

mechanical, thermal, electrical, power subsystems or the payload. For all these topics, one or more dedicated experts are present at the CDF.

A topic which is almost never considered seems to be that of sustainability due to unknowns in the calculations. The only aspect of it which sometimes is mentioned during a study is that of space debris and its mitigation. Furthermore, anything related to the assessment of the environmental sustainability is usually not included in the study because of the many unknowns still present in the assessments of impacts of some parts of the life-cycle (most notably that of launch and re-entry according to literature [92], [35]). Therefore, Affentranger argues that one would risk to shift the burden from one impact indicator into another if ecodesign would nevertheless be applied with those unknowns.

He underlines as well that sustainability is not yet implemented in CDF studies because of a lack of a simple, understandable and accepted way to represent it. The design space of a CDF is so large that the addition of 15 or more impact indicators does not seem feasible according to him. Great care would need to be taken when implementing such a LCA singe-score since "there needs to be more than just a consensus between experts", according to him. There needs to be "a visibility over what goes into the single-score", such that it is clear to anyone interested how it has been derived.

With sustainability left out of CDF studies, ecodesign is often relegated to a design stage after the CDF, or requirements are simply imposed on subcontractors. For instance, Affentranger gives the example of potentially toxic propellants which might be chosen during a CDF. In such a case, the subcontractors would simply receive requirements on how to handle it. It seems therefore that it is not to be considered as a major point to improve during the CDF, but rather as something to be dealt with later on.

In order to include LCA more as a tool for the sustainability assessment more in CDF studies, Affentranger suggests one – or a combination of – the following actions to be taken:

- Include LCA into an already existing Model-Based Systems Engineering (MBSE) tool used during CDF studies. This could be, according to him, the SysML[3] based ones such as Cameo[4] or Enterprise Architect[5], or the COMET software mentioned for the student's CDF study. However, these tools first need to further develop in order to better match the space sector's systems engineering needs, according to Affentranger, before a LCA component should be added to them.
- Include one expert of sustainability and LCA within every CDF studies. Similar to experts in more technical or economical fields, such a sustainability expert would be dedicated to give inputs concerning the environmental impacts certain choices during the design would cause.
- Training one or more systems engineers on the concepts of sustainability and ecodesign. They would then directly implement their newfound knowledge into the systems engineering process, to help reach a space system with lower environmental impacts.

In addition to the above opinions and recommendations, Affentranger commented on the likelihood of the emergence of multiple LCA single-scores and of the benefits this could provide. Indeed, work by ESA [44], [45] and others [43], [46], [47] is underway and would result in slightly different methods of single-score calculations. Nevertheless, according to Affentranger, this would enable meta-studies to be performed, comparing every single-score. This, in turn, will allow the merging of all methods and the creation of a 'better' single-score.

To end the interview, Affentranger reminds one that a single-score should be used, in his opinion, to compare a space mission with an updated design of that same space mission. Comparing two different systems would not make sense and is not yet clearly defined, as the main purpose of a single-score would be to observe any gain in the sustainability score for an updated version of the design. This is also what ESA usually does, according to him.

7.6.2. Discussion on the use of LCA in Early-Design

While no hands-on experience was gained for this thesis, the suggestions made by ir. Lorenz Affentranger and the findings of EPFL students' CDF study provide good insights into an implementation of LCA

[3]SysML, or System Modelling Language, is a modelling language used in various applications such as most notably systems engineering. It is an extension of Unified Modelling Language (UML) and is originally developed as an open-source language. General information can be found on its Wikipedia page (`https://en.wikipedia.org/wiki/Systems_modeling_language`), on `https://sysml.org/` and in more specialised literature which the interested reader can readily find online.

[4]More information can be found here: `https://www.3ds.com/products-services/catia/products/no-magic/cameo-systems-modeler/` (accessed on 25/08/2023)

[5]More information can be found here: `https://sparxsystems.com/` (accessed on 25/08/2023)

during early design. It is clear from both sources that there is currently still a lack of education on sustainability of the engineers participating to the CDF. Moreover, there is a lack of easy-to-use tools which would enable a LCA to be readily implemented in the intense process of a CDF study. This all adds on to the fact that no time is currently allocated to any sustainability considerations during a CDF study.

Nevertheless, the author is optimistic that an implementation of LCA during a CDF study is possible, although it would take some time to fully develop and get accepted. On the short term, Affentranger's suggestion to bring in a LCA expert to CDF studies could be the fastest way to include sustainability from the earliest design phases. Training systems engineers would also be feasible in relatively short notice, although it should be noted that it may not be the most practical solution given their current high work-load. The inclusion of a LCA add-on to currently used MBSE tools would take more time, but would be the most convenient long-term solution in the author's opinion, along with the training of systems engineers.

However, any of these actions require initiative to be taken and policies to be imposed, which could face opposition due to the current uncertainties in specific life-cycles. It is therefore essential that the last wrinkles are ironed out of the impact assessments of phases such as the launch and re-entry before one can expect the broader industry to start fully trusting LCA during the early design stages. Experiments with LCA during CDF studies could – and in the author's opinion, should – be nonetheless performed to draw preliminary conclusions.

On a positive note, Affentranger's prediction of the multitude of single-scores which are expected to be conceived in the near-future is indeed good for the development of a commonly accepted and used LCA single-score. The meta-study suggested would enable greater transparency and acceptance of the calculation method. Hence, it is important to encourage the sector to look critically at the various single-scores in the process of being presented and suggest improvements all together.

Alongside the efforts of implementing LCA into the early design stages, one could also consider implementing the SSR rating during those early stages. While LCA's strength lies in the terrestrial environmental impacts of a space mission, SSR's focus is mainly on the sustainability of the orbital resources. Taking actions to limit the space debris creation and the risk a mission poses to other missions are best taken at the earliest stages possible. But, it is also acknowledged by the author that this would add another layer of complexity to the already complex early design phase.

8
Conclusion

This thesis presents the steps taken towards the creation and application of a consensus-based LCA single-score for space missions. The starting point is an international survey on, amongst others, the ranking of the impact indicators. From there, weighting factors for a space LCA single-score are distilled and compared with currently existing single-score methodologies. This single-score is then applied to the LCA of TU Delft's second CubeSat, Delfi-n3Xt, and attempts are made to investigate possibilities of improving its environmental impacts through basic ecodesign.

These efforts aim to encourage the implementation of sustainability measures early on in the design process of space missions. While there are still unknowns with regards to the specificities of the space sector's impacts, it is an additional step, along with other developments of LCA single-scores. With the rules, regulations and agreements that are developed in the field of space sustainability, this progress could help the industry to also include sustainability measures within its current practices.

The sub-questions and main question of this thesis are answered in more detail in Section 8.1 and Section 8.2, respectively. Some concluding remarks on the future outlook are given in Section 8.3

8.1. An answer to the sub-questions

There are four sub-questions to be answered in preparation to the main questions of this thesis.

What are the most relevant Environmental Impact Indicators for a representative Space Industry player?

It is clear that specific impact indicators stand out when comparing two designs of a same space mission, be it for political reasons or purely life cycle assessment ones. Climate change is the most important indicator according to the space sector, in part due to the current global temperature rise crisis and political agenda. Ozone Depletion also ranks high when the launch segment is included in the scope of the LCA, due to its impact on the upper atmosphere. The metals, minerals and fossil fuel resource use indicators complete the list of conventional impact indicators that are highly ranked. The use of materials or fuels that are unique to the space sector is often mentioned as an argument for this.

Some similarities and differences are notable between the space industry's ranking of important indicators and that of the general European industry (through PEF). The climate change indicator also ranks first, but ozone depletion is not as prominently highlighted by the general industry. Also, while considered important, the indicators of resource use do not seem to be quite as important for the European general industry as for its space industry. Interestingly, land and water use receive large weights by the general industry, while the space sector only accords them an average importance.

Among some of the newly proposed space-specific impact indicators, the mass left in space and the use of restricted substances seem to be considered as highly important indicators to look at. If the launch segment is included, the Al_2O_3 emissions in the air is also found to be highly relevant. When the mission is one of a constellation, the orbital resource depletion indicator equally joins the row of important space-specific indicators.

Which aspects need to be added to the ESA LCA Database and to what extend would the SSSD be relevant?

Throughout this thesis, it was found that working with both ESA's database and SSSD result in a more productive and faster LCA. SSSD's structure complements perfectly ESA's datasets and provides a great framework for the LCA to be built from. SSSD' modeling of certain activities such as Office Work and other office and datacenter related activities are lacking from ESA's database. The same could be said about the re-entry activity which is omitted in ESA's LCA database.

While some aspects of the SSSD are a good addition to the ESA database, one ought to note drawbacks of some of ESA's datasets. ESA's external LCA database's lack of transparency on the reason behind the modeling of certain activities hinder some reasoned customisation of specific activities. Moreover, this lack of transparency prevents one to verify if the datasets are also suitable to smaller satellite missions, compared to ESA's more conventional larger missions. Also, some of ESA's ground segment activities such as the ones related to the clean room operations may not be representative of average ground segments, but rather only of ESA's facilities. The database and its conclusions should therefore always be carefully assessed, with or without additions by SSSD.

How can the LCA single-score be integrated in Space Sustainability Rating's (SSR) current rating system?

While the exact methodology of the score of SSR's LCA module remains to be defined in the future, one could have a critical look at the SSR rating system as a whole. It is clear that the organisation would need to revise its weights if any module is to be added. While the survey's outcomes suggest weights of similar size of the LCA module and the other future proposed modules, SSR will need to assess it internally, as well as discuss publicly the reasoning behind their future final choice of the value.

In this report, three non-exhaustive suggestions are made for the calculation of the future LCA module, as listed below. Future research should investigate them further, and SSR should make a well argued decision.

- Define threshold values of LCA single-scores for various types of space missions (e.g. satellite constellation mission, geo-synchronous mission, single-satellite mission, etc). This range can then be converted into a scale from which the level of environmental impacts of each of SSR's assessed space mission type can be evaluated.
- Define threshold values of LCA single-scores for a generic space mission. With this, regardless of the mission type assessed by SSR, a scale can be created to evaluate the level of impacts of the assessed mission.
- Base the score of the LCA module on the extent to which ecodesign was used during the design process. A significant reduction in overal impacts in the new version of the design would then equate to a better score.

Regardless of the chosen methodology of the LCA module's score, SSR should exclude the launch segment from the LCA. With their proposed LVSR module, the launcher's sustainability impacts would already be accounted for elsewhere. Also, the lack of the satellite designer's control over the sustainability level of the launcher should not be a penalty for the LCA module score.

How could the LCA single-score be included in early-stage concurrent design exercises?

In this report, the interview of a Concurrent Design and Systems Engineering expert and the observation of students' CDF study provide key insights into a possible implementation of a LCA single-score into the concurrent design exercises. This could be done by adding a LCA expert to the group of experts during early design sessions, or by adding a systems engineer among the group of CDF participants more aware of environmental sustainability topics. The creation of LCA-related add-ons to MBSE tools used during CDF studies should facilitate the implementation of LCA even more.

Prior to the implementation by means of trained experts or MBSE tools, it is essential to reach a consensus on a single-score calculation for space LCAs. Indeed, to avoid increasing the size of the already large design space of an early design session, a simple metric for sustainability needs to be agreed on. For this, there needs to be great transparency about the internal reasoning and workings of the single-score.

8.2. An answer to the main question: What is the process for the calculation of a Life-Cycle Assessment single-score of a space mission in each design phase?

To calculate the single-score of space missions' life cycle assessments, the steps below ought to be followed.

1. **The LCA of the space mission must be performed.** To that effect, the designers should go into as much detail as their current design phase allows them to go. Where needed, assumptions should be made on for instance the number of work-hours, or specific components of the satellite. If the methodology proposed in this thesis is followed, the launch segment should be excluded because of its high impacts and the lack of the satellite designers' control over the launcher's sustainability.
2. **The outputs of the LCA should be normalised with respect to the Environmental Footprint of an average person globally.** The global normalisation factors for the Environmental Footprint given by the JRC [97] must be used for this if the weighting method of this thesis is followed.
3. **These normalised results are then to be weighted and converted into a single-score** through the preferred single-score calculation method. If the methodology proposed in this thesis is followed, one should use the weighting factors shown in Table 8.1

Table 8.1: The recommended weighting set for the calculation of LCA single-scores of space mission (without their launch segments)

Midpoint impact indicator	Final space LCA weighting factors (incl. robustness) [%]
Climate change.	15.89
Ozone depletion.	6.49
Human Toxicity - cancer effects.	2.58
Human Toxicity - non-cancer effects.	2.14
Particulate matter.	10.90
Ionizing radiation - human health.	5.62
Photochemical ozone formation - human health.	5.59
Acidification.	6.18
Eutrophication - terrestrial.	5.67
Eutrophication - freshwater.	4.09
Eutrophication - marine.	4.90
Ecotoxicity - freshwater.	1.71
Land use.	4.63
Water Use	4.88
Resource use: metals and minerals.	10.43
Resource use: fossil fuels.	8.31

While these three steps must be followed regardless of the design phase, the level of detail reached during each step is dependent on the knowledge at the specific design stage.

Based on the experience gained with Delfi-n3Xt, the usage of this single-score could either be done through a 'pro-active' ecodesign approach or through a more 'passive' one. A 'pro-active' ecodesign would involve not only recording single-score but also the relative contributions of each midpoint indicator, while using that information to guide the new design iteration. With that information, hotspots can be detected in the current design iteration, and can be worked on for the new one. A more 'passive' approach would mainly involve looking at the single-score of a previous iteration and the new one, to check if any improvements are made (i.e. the score becomes smaller). This is more simple compared to the inclusion of the assessment of midpoint indicators, and would mainly allow designers and systems engineers to decide to go ahead with the new design (e.g. if the single-score remains more or less constant or reduces) or ask them to make changes (e.g. if the score increased significantly). This approach would be feasible for non-LCA-trained systems engineers, ad may only require a more pro-active approach if the score significantly increases.

8.3. A future outlook

Overall, there are many reasons for the reader to pursue further research in the topic of a space LCA single-score. Firstly, the adoption of environmental practices in the space sector worldwide is only at its infancy, providing a window of opportunity to mold them through consensus-based international methods, such as that of a single-score. Secondly, the current uncertainties and unknowns of the environmental LCA of space missions are excellent fertile grounds for detailed research to sprout and grow towards the single-score methodology. And thirdly, the lack on international agreements on the methodology of a single-score calculation creates opportunities for global discussions and debates on the subject.

This thesis is only an additional step in the space sector's work towards the implementation of LCA in early design. Section 8.3.1 emphasises the developments in LCA of space mission that are needed for the purposes of a single-score. Efforts that ought to be undertaken for the latter are described in Section 8.3.2. The future work needed for SSR in their development of an expanded rating with new modules is touched upon in Section 8.3.3. Section 8.3.4 highlights what needs to be done for LCA and the LCA single-score to be implemented in the earlier design stages. And, points of improvement of this thesis' survey are discussed in Section 8.3.5.

8.3.1. Developments in LCA of space missions

There are still many unknowns and uncertainties in life cycle assessments of space missions that should addressed. Most notably, efforts focus on generating a better understanding of the impacts of launches and re-entries in the higher atmosphere. Once sufficient research is performed, general and openly available datasets should be created on these topics, to enable any practitioner to better model the full life cycle of their space mission.

Quantitative outcomes of life cycle assessments of space missions should be published more in literature or other readily available sources. With only relative impacts published, it is not easy to find reference cases of LCAs, which could be detrimental for productive academic progress. It also does not help with providing insights into how urgently the space sector needs to take action to prevent its environmental impact to grow too much.

8.3.2. Development of the space LCA single-score

The weighting factors for the single-score proposed in this thesis should be used on various real space missions to assess their outcomes. It would be interesting to consider various levels of detail of the LCA itself, to mimic the differences in detail resulting from the particular design phase one is in. Moreover, investigations on the outcomes of the single-score per mission type would create a understanding of its usability.

More LCAs and resulting single-scores should be computed and published. In particular, LCAs should be performed on a large variety of space mission types to develop a range of single-scores per mission type. This may in turn be used during a design phase to situate the single-score of a specific type of mission with respect to that of other missions of the similar type. This would help one acquire an intuition on the value of the single-score and might make the inclusion of the ecodesign process more straightforward. Moreover, it could provide some good references for meta-studies on the single-score calculation methods that will likely get developed around the world in the coming years.

With the likely creation of different single-score methodology, one should conduct meta-studies to assess each of the single-scores and to arrive to an accepted one. Care should be taken to make such a study fully transparent, to help the formation of a concensus on one particular set of weighting factors.

8.3.3. Developments for Space Sustainability Rating

If SSR is indeed to expand into new modules, a discussion with some level of transparency ought to be held on re-scaling the weights. Given SSR's current focus on the space environment, such an expansion would equate to a broadening of its objectives. This ought to be done carefully and with the adequate explanations and justification, as to avoid any confusion. The internal discussions on the possibility of including the LVSR module within SSR is one step in the right direction. A similar discussion could be held about the LCA module, to assess to what extent it should be a distinct rating, or a module which fits within the current SSR's scope. All of these open discussions – important for the international recognition of SSR's added value for operators – should be translated into research papers or other publicly available documents that can readily be accessed.

For the LCA module specifically, a critical assessment of the three implementation methods suggested in Section 7.5.2 should be performed and a choice ought to be made. There are advantages and disadvantages to each of the three methods, which should be laid out clearly. An argumentation – most likely a mix of qualitative and quantitative reasoning – should be given transparently, for interested readers to find.

8.3.4. Developments for LCA in early design phases

For LCA to be included in CDF studies and the early design stages, further research ought to be performed on the remaining uncertainties of the impacts of specific life cycle phases (e.g. the launch and re-entry phase). This will avoid unknowingly shifting the environmental burden from one impact category to another and will help spread the acceptance of LCA as a tool for early design.

Efforts should be directed towards the practical and technical implementation of LCA within the current structures of CDF studies and that of the early design phases. That is, systems engineers should be trained on – or at least made familiar with – key notions of sustainability and LCA. Also, where and when possible, sustainability or LCA experts should be added to the teams performing the CDF or early stage design studies. And on a longer-term, efforts should be directed towards the creation of plug-ins or add-ons to existing (and used) MBSE tools.

In general, there should be more lobbying within the various governments, space organisations and companies to consider sustainability aspects from the earliest design phases. This could take the form of a top-down approach, where ESA or the EU, in the case of Europe, impose this on the industry. It could also be a bottom-up approach where the industry imposes on itself the requirement to consider sustainability as early as possible.

8.3.5. Improvements of the surveys and questionnaires

A more detailed survey could be considered regarding the weighting of the environmental impact, as there were aspects omitted in this thesis' survey. To reduce ambiguity during the ranking of the midpoint indicators, the exact normalisation method to be considered could be mentioned. Similarly, a further division in mission types could be proposed to investigate any clear differences.

A new study similar to the one performed for this thesis should include even more international participants. In particular, it would be interesting to give a greater voice to emerging space nations, as well as to some more isolated space-faring countries. This would help assess any differences in perception of space sustainability.

Regarding the questions outside of the pure LCA topic, some new survey could also be performed. For example, for the question on the drivers and inhibitors of space LCA, more participants from diverging backgrounds (i.e. less technical backgrounds and more managerial ones) should give their opinions, in order to reduce any biases due to the high LCA expertise. Also, concerning the SSR weighting, more insights should be given on the methodology and meaning of each of the SSR modules, to attain a more conclusive consensus.

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A

Impact indicators

This appendix aims to bring together a relatively detailed description of the Midpoint and Endpoint indicators used in a Life Cycle Assessment (LCA). The PEF as well as the space-specific midpoint impact indicators are described in Section A.1 and the endpoint indicators are discussed in Section A.2.

A.1. Midpoint indicators

This section gives a closer look into the midpoint indicators for the interested reader. Section A.1.1 details the midpoint indicator defined by the PEF methodology and Section A.1.2 sheds light into the suggested impact indicators to be used specifically for space missions' LCAs.

A.1.1. PEF Midpoint indicators

Below is a detailed explanation of the midpoint indicators defined in PEF. This is also the detailed description the panellists had access to though a PDF file linked in the questionnaires, as shown in Appendix I. It is added to this report to give the reader more insight into the meaning of each midpoint indicator, as well as to show what the panellists could refer to during the survey.

Note that the description below is taken from the final report on the assessment of different communication vehicles for providing Environmental Footprint information on pages 113-115 [19].

- **Climate change.** Refers to the changes induced to the World's climate as a consequence of the emissions to the atmosphere of the so-called greenhouse gases, such as CO2, N2O, CH4. The Earth's atmosphere absorbs part of the energy emitted as infrared radiation from Earth towards space, and is thereby heated. This natural greenhouse effect leading to a warming of the atmosphere has been increased over the past few centuries by human activity leading to accumulation of such compounds as CO2, N2O, CH4 and halocarbons to the atmosphere. The most important human contribution to the emissions of greenhouse gases is attributed to the combustion of fossil fuels such as coal, oil and natural gas. The consequences include increased global average temperatures and sudden regional climatic changes.
- **Ozone depletion.** The stratospheric Ozone (O3) layer (that can stretch from ~ 8 km to ~ 50 km height) protects us from hazardous ultraviolet radiation (UV-B). Its depletion can have dangerous consequences in the form of increased frequency of skin cancer in humans and damage to plants. Stratospheric O3 is broken down as a consequence of man-made emissions of halocarbons (as CFCs and HCFCs), halons and other long-lived gases containing chloride and bromine. The ozone content of the stratosphere was therefore decreasing, and since 1985 a dramatic temporary thinning of the ozone layer, often referred to as "ozone hole", has been observed each year, over the South Pole. In recent years the problem has been reduced due to international ban of substances contributing to ozone depletion.
- **Human toxicity – cancer effects.** Chemicals emitted as a consequence of human activities can contribute to cancer in humans via exposure to the environment. For a substance to be regarded as contributing to human toxicity, it must of course cause cancer. In addition, also the substance's behavior has to be considered in that there can be several routes of exposure to humans. The most

important routes of exposure are via the air breathed in or via other materials ingested orally, e.g. food or water.

- **Human toxicity – non-cancer effects.** Chemicals emitted as a consequence of human activities can contribute to human toxicity via exposure to the environment. For a substance to be regarded as contributing to human toxicity, it must of course be poisonous to humans. In addition, also the substance's behavior has to be considered in that there can be several routes of exposure to humans. The most important routes of exposure looked at in those categories are via the air breathed in or via other materials ingested orally, e.g. food or water.
- **Particulate matter/respiratory inorganics.** Ambient concentrations of "dust" or particulate matter (PM) are elevated by emissions of primary and secondary particulates. The mechanism for the creation of secondary emissions involves emissions of SO2 and NOx that create sulphate and nitrate aerosols. Particulate matter is measured in a variety of ways: total suspended particulates (TSP), particulate matter less than 10 microns in diameter (PM10), particulate matter less than 2.5 microns in diameter (PM2.5) or particulate matter less than 0.1 microns in diameter (PM0.1). Usually, the smaller the particles are the more dangerous they are as they can get deeper into the lungs.
- **Ionising radiation, human health.** The exposure to ionising radiation ("radioactivity") can have impacts on human health. The modelling starts with releases at the point of emission, expressed as Becquerel (Bq). The exposure analysis calculates the dose that a human actually absorbs, given the radiation levels that are calculated in the fate analysis. The measure for the effective dose is the Sievert (Sv), based on human body equivalence factors for the different ionising radiation types. It is to be noted, that in Life Cycle Assessment and in the Environmental Footprint only emissions are taken into account that occur under normal operating conditions. The risks due to nuclear accidents are not covered by the EF.
- **Photochemical ozone formation, human health.** While a sufficiently high concentration of ozone up in the stratosphere (8-50 km) is vital to protect the earth from hazardous ultraviolet radiation (UV-B), ozone on the ground (in the troposphere) attacks organic compounds and especially the respiratory tract in humans. This leads to an increased frequency of problems of the respiratory tract in humans during periods of photochemical smog in cities ("summer smog"). When solvents and other volatile organic compounds (VOCs) are released to the atmosphere (e.g. by emissions from combustion processes), they can be degraded within a few days. The reaction involved is an oxidation, which occurs under the influence of light from the sun. In the presence of oxides of nitrogen (NOx) ozone can be formed. NOx are not consumed during ozone formation, but have a catalyst-like function. This process is termed photochemical ozone formation.
- **Acidification.** Acidification has contributed to a decline of coniferous forests and increased fish mortality. Acidification can be caused by emissions to air, water and soil. For instance when gaseous SO2 is released and reaches a water body, it reacts with H2O to form the acid H2SO4. When acids (and compounds that can be converted to acids) are emitted to the atmosphere and deposited in water and soil, the addition of hydrogen ions (H+) may result in a decrease in the pH of the water body. The most significant manmade sources of acidification are combustion processes in electricity, heating production and transport. The contribution to acidification is greatest when the fuels used contain a high content of sulphure.
- **Eutrophication – terrestrial.** Eutrophication is an impact on the ecosystems from substances containing nitrogen (N) or phosphorus (P). As a rule, the availability of one of these nutrients will be a limiting factor for growth in the ecosystem, and if this nutrient is added, the growth of algae or specific plants will be increased. On land, ecosystems which need an environment with only little nutrients are gradually disappearing mainly as a result of the addition of nitrogen (N). Oxides of nitrogen (NOX) from combustion processes are of significance for both aquatic and terrestrial ecosystems.
- **Eutrophication –freshwater.** Eutrophication is an impact on the ecosystems from substances containing nitrogen (N) or phosphorus (P). As a rule, the availability of one of these nutrients will be a limiting factor for growth in the ecosystem, and if this nutrient is added, the growth of algae or specific plants will be increased. In lakes and rivers this will be mainly due to the increase of phosphorus (P). Too rapid growth of algae can lead to situations without enough oxygen in the water for fish to survive once the algae die and are degraded (which consumes

oxygen). Emissions of nitrogen to the aquatic environment are caused largely by the agricultural use of fertilizers, but oxides of nitrogen from combustion processes are also of significance for both aquatic and terrestrial ecosystems. The most significant sources of emissions of phosphorus are sewage treatment plants for urban and industrial effluents and leaching from agricultural land.

- **Eutrophication – marine.** Eutrophication is an impact on the ecosystems from substances containing nitrogen (N) or phosphorus (P). As a rule, the availability of one of these nutrients will be a limiting factor for growth in the ecosystem, and if this nutrient is added, the growth of algae or specific plants will be increased. For the marine environment this will be mainly due to the increase of nitrogen (N). Emissions of nitrogen are caused largely by the agricultural use of fertilizers, but oxides of nitrogen from combustion processes are also of significance for both aquatic and terrestrial ecosystems.
- **Ecotoxicity – freshwater.** A substance contributing to ecotoxicity, affects the function and structure of the ecosystem by exerting toxic effects on the organisms which live in it. Toxic effects can occur as soon as the substances are released (acute ecotoxicity), or may appear after repeated or long-term exposure to the substances (chronic ecotoxicity). Chronic ecotoxicity is often caused by substances which have a low degradability in the environment and which can therefore remain for a long time after their emission (persistent substances). Some substances also have the tendency of accumulating in living organisms, so that tissues and organs can be exposed to concentrations of the substance which are far higher than the concentration in the surrounding environment. The chronic ecotoxicity of a compound is thus determined by its toxic effects, its biodegradability, and its ability of accumulating in living organisms.
- **Land use.** The impact category Land Use tries to estimate the damage to ecosystems due to the effects of occupation and transformation of land. Examples of land use are agricultural production, mineral extraction and human settlement. Transformation is the conversion of land from one use to another use. The impacts can be various such as loss of species, soil organic matter content or reduced primary production or loss of the soil itself ("erosion").
- **Resource use – water.** The withdrawal of water from lakes, rivers or groundwater can contribute to the "depletion" of the available water, while water itself is seen as a renewable resource. The impact category considers the availability or scarcity of water in the regions where the activity takes place, if this information is known.
- **Resource use –metals and minerals.** The earth contains a finite amount of nonrenewable resources, such as metals, minerals. The use of resources may lead to a decrease of availability of potential functions of resources.
- **Resource use –fossil fuels.** The earth contains a finite amount of non-renewable resources, such as fossil fuels like coal, oil and gas. The use of resources may lead to a decrease of availability of potential functions of resources.

A.1.2. Additional space-specific Midpoint impact indicators

Below is an explanation of the space-specific indicators suggested by literature [46]. The description below is slightly modified from the one the panellists were given, as shown in the transcripts of the questionnaires in Sections I.2 I.3, I.4. It is added here to give a more detailed insight into the meaning of these suggested impact categories, as well as to bundle this description with that of the other impact categories.

- **Al2O3 emissions.** Emissions in air of alumine during launch event.
- **Critical raw material use.** Supply risk.
- **Cumulative energy demand.** Primary energy consumption
- **Mass disposed in ocean, total.**
- **Mass left in space, total.** Total mass of space hardware remaining in orbit at the end of the mission.
- **Orbital resource depletion.** Space debris crossing the orbital resource
- **Re-entry smoke particle generation.**
- **REACH substance use.** Risk assessment

A.2. Endpoint indicators

Below is an explanation of the endpoint indicators defined in PEF. This is also the description the panellists received in the first questionnaire, as can be seen in in Section I.1. It is added in this appendix to give a concise overview of the impact indicators, be it the midpoint or the endpoint ones, as well as to show what the panellists could refer to during the survey.

Note that, similar to Section A.1.1, the description below is taken from the final report on the assessment of different communication vehicles for providing Environmental Footprint information on page 94 [19].

- **Human Health.** The negative effects on people's health, for instance, as a consequence of chemicals or radiation emitted during the life cycle of a product or indirectly as consequence of climate change
- **Natural Environment.** The negative effects on the function and structure of natural ecosystems, for instance, as a consequence of the emission of chemicals or physical interventions that take place during the life cycle of a product
- **Natural Resources.** The negative effects, for instance, to the use of physical resources such as energy, metals and minerals and water, which results in a decrease in the availability of the total resource stock, as physical resources can be finite and non-renewable.

B

Interview on LCA during Early and Concurrent Design

Below is the transcript of the interview conducted with ir. Lorenz Affentranger. Various repetition and pauses are filtered out to for the coherent text below. L. Affentranger also had the opportunity to make small clarifications and modificatiosn to the transcript.

Could you give some more information on your background?
I have a background in mechanical engineering and I mainly studied in Switzerland. So I don't have a space background.
I came to ESA at the end of 2019 as a trainee. For me it was specifically systems engineering on Mars missions. So I was in the human and Robotic Exploration Directorate working on Mars Sample return as a systems engineer.
After my two years training, I joined the Tech SYE section at ESA. That is what we call the CDF section and that is indeed where we do a lot of our preliminary assessments and preliminary feasibility studies for future missions at ESA, as well as for externals to ESA.
This is actually only a minor part of my responsibilities at the moment. I still continue to work as a systems engineer for Mars exploration. And I also support a lot the Clean Space Office of ESA on the life cycle assessment and Ecodesign activities, mainly focusing on the launcher segments of future launchers. I am working on green propulsion for in space transportation.

It is especially your experience with not only Clean Space, but also with CDF and Systems Engineering that interested me. This overlap can produce good insights for my thesis!
So, to begin on a more general level, I was wondering if there were topics that often reoccur in CDFs and are focused on a lot?
The financial aspect if of course included in all the studies and is a is a key part. We always work in the framework of a certain budgets that our customers will define. So I I think that is one of the key, if not most important, design factors when we perform those studies.
Then, the programmatic always also comes a little bit hand in hand with that. For instance, we ask ourselves what kind of launcher vehicle can we use in what time frame for such a mission? Or, what technology development would need to happen within that time frame? So, what Technology Readiness Level (TRL) would this mission be at, right now.
Besides that, there are the launch vehicle, of course too. This is one of the key drivers for every study, both for cost reasons and for mass restriction and volume restriction considerations
And from there on-wards, I would say the remaining classic system engineering trades are made per subsystem. That is the mechanical, thermal, electrical, power subsystem and so on. Based on the mission objectives, there will be a focus on a specific subsystem during the study.

Is sustainability ever an aspect that is considered in your past CDF studies, or the ones you know of from colleagues? Or is there a specific aspect of sustainability that is sometimes considered?
No, to my knowledge it has only been rarely considered and it my personal experience none of the studies in which I have been involved have considered it
But, the aspect of sustainability that might be considered in some cases is not necessarily related with Earth's biosphere, but it is more the space debris aspect. Each study does carry a requirement to comply with the European engineering standards (ECSS) regarding space debris.
And so if you think of LCA and EcoDesign, has only been done once in a dedicated study.

So, would you say that Ecodesign is more done later on in the design phase?
Yes, it will happen much later. EcoDesign is very reliant on having a proper and detailed LCA available. LCA methodology for the space sector is still being defined so going through a EcoDesign process is challenging (even for later stages).
The choice made during a CDF will be more based on current regulations for instance. So if we need a propellant that we know needs a special treatment or special handling, then we put requirements on our subcontractors to deal with this. This is the standard way for us to handle it.
So, we would rarely make a trade-off such as one where we say "ok, this is quite a toxic propellant, let's look at another one."

From what I know, the only CDF which really looked at sustainability is that of Ecosat many years ago – around 2008 or so. But, this one seemed to have sustainability as a main focus, didn't it?
Exactly. That would have been that that that the eco design and LCA aspect were looked at because that was the objective of the of the study itself.

Even though only space debris is sometimes looked at, if at all, would you say that there are aspects of sustainability that could be looked at a bit more during CDFs? That is, are there aspects that could be looked at in an in easy way in your opinion
Absolutely.
I think one easy win would be to develop tools for that purpose. The LCA tools which are linked to Model-Based Systems Engineering (MBSE) environments of the CDF, such that very little LCA knowledge is needed by the practitioner to actually perform the LCA and. This could be through an add-on to an existing tool, or one could make an argument for using another tool.
Another option could be to look at the experts within the CDF. So we have one expert per subsystem for each of the CDF's. For example, there are the classical experts on fields such as thermal or propulsion, as well as less classical one such as the costs scheduler, etc. And then we could think about including a subsystem which is 'sustainability' and whose expert participates equally to each of the session and tries to give insights on what the trade offs could be from a sustainability point of view.
A further option I see would be the training of the current system engineers to have a knowledge and know-how about LCA and Ecodesign.

You mentioned that adding a sustainability expert could be an option. But, why do you think it is not yet done currently in CDFs?
It's a good question. There are many question marks still on how to perform an LCA for space.
Of course there is the ESA handbook and the ESA database, but there are still aspects of the whole life cycle that we are just not aware of, at the time of a CDF study. We don't know what some of the impacts are. So if we start making trade-offs on sustainability aspects without having the full picture of what actually happens, we might make design choices which are wrong. You might make, what we call, burden shifting. So you would shift the burden somewhere where we actually don't yet have the knowledge on what would be happening there.
That is a reason.
Another reason – and I'm glad you're actually working on that – is the CDF and the design process already is a huge design space with a lot of variables. And currently as we see it at ESA, LCA is an additional 15 plus indicators which we need to look at. This doesn't – for now at least – seem feasible to implement in the in the design process.

I do recognise both the burden shifting concern and that of the additional indicators to look at also in the questionnaire I sent out. But, how do you feel about a single-score LCA in this context and how would you try to get it accepted and implemented within a CDF?
If you're introduce a single score there needs to be more than just a consensus between experts on what the weights are, in my opinion. And it's an open question. We are also looking at single scores at ESA or on have, as you saw at the at the industry week.
So you would you would also need to have a visibility over what goes into the single score. You need to make sure that if someone is interested to look into it that it's clear how it was derived. Both the how and why. Because if we now tell an engineer their system only has a environmental score of 2 rather than 10, It will take long for people to understand the why. Why does it have the score of this or that? What flows into there? Are there are error bars? If you if you use a different single score, how does my system compare to the other single score?
In my view there will be a number of single scores that will come on the market in the in the next couple of years. And that is good because there will be big differences between the single scores, which is a good starting point to make meta studies on those scores. For instance one would look at where do the different scores come from, why do they come from there and how can we can we converge towards using all of them in.
Look for instance at European Union's single score from PEF. They did a huge survey across industry and such to build the score.

If you would do a CDF with where sustainability is included, what would be the main things you would want to see in terms of the practical implementation of it?
I see it very much. that MBSE environments I was talking about because that's anyway. a direction we are going towards, in terms of having the entire system modelled. And I don't see it as being that complicated to find a way to connect that LCA tool or single-score or whatever.
Of course it cannot be a fully detailed LCA with SimaPro or some kind of similar tool because you simply at early stages don't have enough information yet. So you anyways need to use proxies (approximations) and all of this. But, if you have some simplified tool that that would be super beneficial for adoption.

Which kind of tools do you use at ESA for MBSE and which would you say sustainability has to be included into?
As ESA, we cannot the use one tool over the other. The customer can choose.
But the ones we use mostly are SysML based. So that would be a Cameo and Enterprise Architect. The other one is Comet, but it is a little bit limited in the in how you can design your system. And the last one is Capella.
I don't know if it's actually public information or not, but we did a trial a couple of years ago to do to include LCA into MBSE. It didn't caught on at the time because also the MBSE tools themselves need need further development purely from our system engineering perspective. So that's also need to keep in mind that those tools aren't yet so ready to fully be used use.

What do you mean when you say that these tools are not fully ready yet to be used?
It is more about the tool itself. Even for doing system engineering with it, ignoring sustainability for now, it needs further development. So before adding an LCA add on, we also need to fix the system engineering aspect of it.
That doesn't mean we cannot start with trials and so on a but it doesn't only depend on the LCA aspect.

Thank you for all the insights you have given! I have gone through the main questions. Would you like to add something?
It might be a good idea in general for your thesis, instead of comparing your CubeSat LCA with other CubeSats, you could compare it with your Cubesat itself with some fictive change to it. For instance the use of a carbon Fiber structures instead of an aluminium one. Then you can see if there is any gain in the score.
Comparing between two systems is also usually not what we do. We usually compare the system itself with what it could have been. We do this because we do not yet have a clear way – although we have some ideas – on how we could compare for instance two different CubeSats How would you marry the functional unit there?

C

Space Sustainability Rating inputs

The inputs provided for the SSR rating of Delfi-n3Xt is provided bellow. For questions requiring a numerical answer, the answer is provided next to the question. In the case questions have multiple choices as answers, all the choices provided by Space Sustainability Rating are listed and the chosen one(s) is (are) ticked.

C.1. Mission Index

C.1.1. Object Characteristsics

Number of satellites: 1
Verification Level: Authority
Mass (kg): 3.0
Verification Level: Authority
Cross-sectional area in randomly tumbling motion (m2): 0.075
Verification Level: Authority
Deployment duration (years): 1
Verification Level: Authority
Envisioned operational lifetime (years): 0.25
Verification Level: Authority

C.1.2. Operational orbit parameters

Mean operational altitude (km): 689
Verification Level: Authority
Inclination (deg): 97.8
Verification Level: Authority

C.1.3. Disposal strategy

Target end-of-life apogee (km): 599
Verification Level:
Target end-of-life perigee (km): 780
Verification Level: Authority
Expected Post-Mission Disposal success rate (%): 100
Verification Level: Authority

C.1.4. Collision Avoidance strategy

Is your spacecraft able to perform Collision avoidance maneuvers? No

C.2. Collision Avoidance Capabilities

C.2.1. Orbital state knowledge (during normal operations)

The operator:

- ☑ Relies on third party public SSA providers for state information
- ☐ Is maintaining the orbital position state knowledge of the object
- ☐ Complies with all the following:
  - The orbital state knowledge is maintained within 10km (in any directions)
  - The orbit determination is updated in case of a maneuver or another event
  - The covariance is characterised and validated
- ☐ Complies with all the following:
  - The orbital state knowledge is maintained within 1km (in any directions)
  - The orbit determination is updated in case of a maneuver or another event
  - The covariance is characterised and validated

Verification Level: N/A

C.2.2. Availability to coordinate

The operator:

- ☑ Is not able to coordinate
- ☐ Is able to coordinate in response of an emergency
- ☐ Is able to coordinate during set hours per day
- ☐ Has a system routine conjunction assessment and capabilities 24/24 (human or computer) leading to a near immediate coordination and reaction in case of an urgent issue

C.2.3. Capability to coordinate

The operator:

- ☑ Has no dedicated process for conjunction screening, assessment, or mitigation.
- ☐ Comply with all the following:
  - Has the capability to be contacted in case of close approach or emergency
  - Regularly screens obit and planned maneuvers from SSA sharing organizations and/or third-party SSA providers
- ☐ Comply with all the following:
  - Is capable of interpreting conjunction data messages to generate/screen mitigating maneuvers
  - Has a system for automated routine conjunction assessment
- ☐ Comply with all the following:
  - Has documented procedures for collision screening, assessment, and mitigation
  - Regularly screens operational spacecraft and planned maneuvers against SSA organization catalogue

Verification Level: N/A

C.2.4. Maneuver Capability

- ☑ Have no maneuver capabilities
- ☐ Are able to maneuver, any maneuver capability is considered appropriate for this input (including differential drag)
- ☐ Are able to maneuver with a reaction (at least Δv=1 cm/s) within 6 orbital revolutions
- ☐ Are able to maneuver with a reaction (at least Δv=1 cm/s) within 1 orbital revolution

Verification Level: N/A

C.2.5. Maintaining orbital state knowledge after the end of normal operations

[BONUS] The operator:

- ☑ Is not maintaining the orbital state knowledge after the end of operations
- ☐ Is maintaining the orbital state knowledge until atmospheric reentry, or disposal to a graveyard orbit
- ☐ Is maintaining the orbital state knowledge within 10km (in any directions) until atmospheric reentry, or disposal to a graveyard orbit
- ☐ Is maintaining the orbital state knowledge within 1km (in any directions) until atmospheric reentry, or disposal to a graveyard orbit

Verification Level: N/A

C.3. Collision Avoidance Capability

C.3.1. Collision Avoidance Coordination information

Publish and update collision avoidance contact Information (such as name(s), title(s), phone number(s), email address(s), list of controlled objects by NORAD ID or International Designator, languages spoken). The information is shared with:

☑ None of the stakeholders below
☐ SSA providers
☐ Other operators upon request
☐ Voluntary network of operations / stakeholders
☐ Public
Verification Level: N/A

Publish and update collision avoidance contact time zone/hours of operation. The information is shared with:

☑ None of the stakeholders below
☐ SSA providers
☐ Other operators upon request
☐ Voluntary network of operations / stakeholders
☐ Public
Verification Level: N/A

Publish and update COLA contact/coordination response time commitments. The information is shared with:

☑ None of the stakeholders below
☐ SSA providers
☐ Other operators upon request
☐ Voluntary network of operations / stakeholders
☐ Public
Verification Level: N/A

C.3.2. Satellite and Mission Information

Publish and update satellite ephemeris (including manoeuvres, for LEO: 7 days, MEO/GEO: 14 days into the future). Sharing archived data is encouraged, but not required. The information is shared with:

☑ None of the stakeholders below
☐ SSA providers
☐ Other operators upon request
☐ Voluntary network of operations / stakeholders
☐ Public
Verification Level: N/A

Publish and update covariance information. The information is shared with:

☑ None of the stakeholders below
☐ SSA providers
☐ Other operators upon request
☐ Voluntary network of operations / stakeholders
☐ Public
Verification Level: N/A

Publish and update covariance characterization/validation. The information is shared with:

☑ None of the stakeholders below
☐ SSA providers
☐ Other operators upon request
☐ Voluntary network of operations / stakeholders
☐ Public
Verification Level: N/A

Publish and update launch vehicle timing/trajectories (planned and actual). The information is shared with:

☑ None of the stakeholders below

- ☐ SSA providers
- ☐ Other operators upon request
- ☐ Voluntary network of operations / stakeholders
- ☐ Public

C.3.3. Satellite Characterization information

Publish and update satellite mass. The information is shared with:

- ☐ None of the stakeholders below
- ☐ SSA providers
- ☐ Other operators upon request
- ☐ Voluntary network of operations / stakeholders
- ☑ Public

Verification Level: Authority

Publish and update satellite manoeuvrability (manoeuvrable/non-manoeuvrable). The information is shared with:

- ☐ None of the stakeholders below
- ☐ SSA providers
- ☐ Other operators upon request
- ☐ Voluntary network of operations / stakeholders
- ☑ Public

Verification Level: Authority

Publish and update satellite manoeuvrability capability. The information is shared with:

- ☐ None of the stakeholders below
- ☐ SSA providers
- ☐ Other operators upon request
- ☐ Voluntary network of operations / stakeholders
- ☑ Public

Verification Level: Authority

Publish and update satellite operational status (operational/non-operational). The information is shared with:

- ☐ None of the stakeholders below
- ☐ SSA providers
- ☐ Other operators upon request
- ☐ Voluntary network of operations / stakeholders
- ☑ Public

Verification Level: Authority

C.3.4. Autonomous systems for satellite manoeuvering

Is your mission using autonomous systems (systems without a human in the loop) for satellite manoeuvring?

- ☐ Yes
- ☑ No

C.3.5. Other forms of data sharing (BONUS)

Radio-frequency information to support interference avoidance/mitigation/geolocation. The information is shared with:

- ☐ None of the stakeholders below
- ☐ SSA providers
- ☐ Other operators upon request
- ☐ Voluntary network of operations / stakeholders
- ☑ Public

Verification Level: Authority

Spacecraft anomaly information. The information is shared with:

- ☐ None of the stakeholders below
- ☐ SSA providers

- ☑ Other operators upon request
- ☐ Voluntary network of operations / stakeholders
- ☐ Public

Verification Level: Authority

Other datasets to support government/academic research. The information is shared with:

- ☐ None of the stakeholders below
- ☐ SSA providers
- ☑ Other operators upon request
- ☐ Voluntary network of operations / stakeholders
- ☐ Public

Verification Level: Authority

APIs or other means for automatic machine to machine access to above information. The information is shared with:

- ☑ None of the stakeholders below
- ☐ SSA providers
- ☐ Other operators upon request
- ☐ Voluntary network of operations / stakeholders
- ☐ Public

Verification Level: N/A

C.4. Data Sharing

C.4.1. Collision Avoidance Coordination information

Publish and update collision avoidance contact Information (such as name(s), title(s), phone number(s), email address(s), list of controlled objects by NORAD ID or International Designator, languages spoken). The information is shared with:

- ☑ None of the stakeholders below
- ☐ SSA providers
- ☐ Other operators upon request
- ☐ Voluntary network of operations / stakeholders
- ☐ Public

Verification Level: N/A

APIs or other means for automatic machine to machine access to above information. The information is shared with:Publish and update collision avoidance contact time zone/hours of operation. The information is shared with:

- ☑ None of the stakeholders below
- ☐ SSA providers
- ☐ Other operators upon request
- ☐ Voluntary network of operations / stakeholders
- ☐ Public

Verification Level: N/A

Publish and update COLA contact/coordination response time commitments. The information is shared with:

- ☑ None of the stakeholders below
- ☐ SSA providers
- ☐ Other operators upon request
- ☐ Voluntary network of operations / stakeholders
- ☐ Public

Verification Level: N/A

C.4.2. Satellite and Mission Information

Publish and update satellite ephemeris (including manoeuvres, for LEO: 7 days, MEO/GEO: 14 days into the future). Sharing archived data is encouraged, but not required. The information is shared with:

- ☑ None of the stakeholders below
- ☐ SSA providers

- ☐ Other operators upon request
- ☐ Voluntary network of operations / stakeholders
- ☐ Public

Verification Level: N/A

Publish and update covariance information. The information is shared with:

- ☑ None of the stakeholders below
- ☐ SSA providers
- ☐ Other operators upon request
- ☐ Voluntary network of operations / stakeholders
- ☐ Public

Verification Level: N/A

Publish and update covariance characterization/validation. The information is shared with:

- ☑ None of the stakeholders below
- ☐ SSA providers
- ☐ Other operators upon request
- ☐ Voluntary network of operations / stakeholders
- ☐ Public

Verification Level: N/A

Publish and update launch vehicle timing/trajectories (planned and actual). The information is shared with:

- ☑ None of the stakeholders below
- ☐ SSA providers
- ☐ Other operators upon request
- ☐ Voluntary network of operations / stakeholders
- ☐ Public

Verification Level: N/A

C.4.3. Satellite Characterization information

Publish and update satellite mass. The information is shared with:

- ☐ None of the stakeholders below
- ☐ SSA providers
- ☐ Other operators upon request
- ☐ Voluntary network of operations / stakeholders
- ☑ Public

Verification Level: Authority

Publish and update satellite manoeuvrability (manoeuvrable/non-manoeuvrable). The information is shared with:

- ☐ None of the stakeholders below
- ☐ SSA providers
- ☐ Other operators upon request
- ☐ Voluntary network of operations / stakeholders
- ☑ Public

Verification Level: Authority

Publish and update satellite manoeuvrability capability. The information is shared with:

- ☐ None of the stakeholders below
- ☐ SSA providers
- ☐ Other operators upon request
- ☐ Voluntary network of operations / stakeholders
- ☑ Public

Verification Level: Authority

Publish and update satellite operational status (operational/non-operational). The information is shared with:

- ☐ None of the stakeholders below
- ☐ SSA providers
- ☐ Other operators upon request

- ☐ Voluntary network of operations / stakeholders
- ☑ Public

Verification Level: Authority

C.4.4. Autonomous systems for satellite manoeuvering

Is your mission using autonomous systems (systems without a human in the loop) for satellite manoeuvring?

- ☐ Yes
- ☑ No

C.4.5. Other forms of data sharing (BONUS)

Radio-frequency information to support interference avoidance/mitigation/geolocation. The information is shared with:

- ☐ None of the stakeholders below
- ☐ SSA providers
- ☐ Other operators upon request
- ☐ Voluntary network of operations / stakeholders
- ☑ Public

Verification Level: Authority

Spacecraft anomaly information. The information is shared with:

- ☐ None of the stakeholders below
- ☐ SSA providers
- ☑ Other operators upon request
- ☐ Voluntary network of operations / stakeholders
- ☑ Public

Verification Level: Authority

Other datasets to support government/academic research. The information is shared with:

- ☐ None of the stakeholders below
- ☐ SSA providers
- ☑ Other operators upon request
- ☐ Voluntary network of operations / stakeholders
- ☑ Public

Verification Level: Authority

APIs or other means for automatic machine to machine access to above information. The information is shared with:

- ☑ None of the stakeholders below
- ☐ SSA providers
- ☐ Other operators upon request
- ☐ Voluntary network of operations / stakeholders
- ☐ Public

Verification Level: N/A

C.5. Detectability and Trackability

C.5.1. External geometry

Geometric Approximation and Dimensions

- ☑ Rectangular prism
- ☐ Cylinder
- ☐ Sphere

Dimension approximation: 100x100x340mm

Verification Level: Authority

C.5.2. Orbital Information

Operational apogee altitude: z_a km: 780

Verification Level: Authority

Operational perigee altitude: z_p km: 780
Verification Level: Authority
Inclination: i °: 97.8
Verification Level: Authority
Right Ascension of the Ascending node (RAAN): Ω **°:** 41
Verification Level: Authority
Argument of perigee: ω **°:** 187
Verification Level: Authority

C.5.3. Detectability, Identification and Tracking qualitative score

Do you track the resident space objects you operate? Select all that apply. Resident space object is tracked:

- ☐ Resident Space Object is not tracked
- ☑ Rely on Space-track or other third party public SSA providers
- ☑ Custody of operated satellites maintained within 14 days of deployment and thereafter
- ☑ Custody of operated satellites maintained within 1 day of deployment and thereafter

Verification Level: Authority

C.5.4. Bonus: Provide verifiable photometric/radiometric characterisation data on the satellite to the SSR evaluator

Have you provided the following characterisation data on the satellite to the SSR evaluator? Radiometric Data (average/max/min Radar Cross Section)

- ☐ Yes
- ☑ No

Verification Level: Authority

Photometric Data (average/max/min Visual Magnitude)

- ☐ Yes
- ☑ No

Verification Level: Authority

C.6. Application to Design and Operation Standards

C.6.1. National and international guidelines

Space debris mitigation guidelines (UNCOPUOS[1] or IADC[2])

- ☑ No compliance
- ☐ Compliant, mandatory adopted
- ☐ Compliant, voluntary adopted

Tailor: 0
Verification Level: N/A

Long-term sustainability guidelines (UNCOPUOS)

- ☐ No compliance
- ☐ Compliant, mandatory adopted
- ☑ Compliant, voluntary adopted

Tailor: 1
Verification Level: Authority

Space debris mitigation standards or verifiable laws (ISO 24113[3], or NASA ODMSP[4] or any national verifiable law)

- ☑ No compliance
- ☐ Compliant, mandatory adopted

[1]This is a hyperlink in the form, leading to the following link: https://www.unoosa.org/pdf/publications/st_space_49E.pdf

[2]This is a hyperlink in the form, leading to the following link: https://orbitaldebris.jsc.nasa.gov/library/iadc-space-debris-guidelines-revision-2.pdf

[3]This is a hyperlink in the form, leading to the following link: https://www.iso.org/standard/72383.html

[4]This is a hyperlink in the form, leading to the following link: https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf

☐ Compliant, voluntary adopted
Tailor: 0
Verification Level: N/A

Standardised operational products guidelines (CCSDS 502.0-B-2[5] on orbital data messages or 508.0-B-1[6] on conjunction data messages)

☑ No compliance
☐ Compliant, mandatory adopted
☐ Compliant, voluntary adopted
Tailor: 0
Verification Level: N/A

ITU regulations[7] on spectrum use

☐ No compliance
☑ Compliant, mandatory adopted
☐ Compliant, voluntary adopted
Tailor: 1
Verification Level: N/A

Does your mission include close proximity or rendez vous operations?

☐ Yes
☑ No

C.6.2. Other recommended best-practises

Does your spacecraft release debris in orbit as part of the operations?

☐ Yes
☑ No, or only smaller than 1mm

Is your payload registered by your launching state?

☑ Yes
☐ No

Level of minimization of the probability of explosion as part of the operational lifetime

☑ No action or analysis
☐ Yes, please enter a value of explosion probability

Spacecraft passivated after its operational lifetime

☑ No
☐ Yes
☐ Yes, with a near-controlled reentry

Launch vehicle passivated after its operational lifetime

☑ No
☐ Yes
☐ Yes, with a near-controlled reentry

The spacecraft uses a disposal orbit after its operational lifetime

☑ No
☐ Yes
☐ Yes, with a near-controlled reentry

The launch vehicle uses a disposal orbit after its operational lifetime

☑ No
☐ Yes
☐ Yes, with a near-controlled reentry

C.7. Inputs for the External Services module

On-orbit servicing features ?

☐ Yes
☑ No

[5]This is a hyperlink in the form, leading to the following link: `https://public.ccsds.org/Pubs/502x0b2c1e2.pdf`
[6]This is a hyperlink in the form, leading to the following link: `https://public.ccsds.org/Pubs/508x0b1e2c2.pdf`
[7]This is a hyperlink in the form, leading to the following link: `https://www.itu.int/en/publications/ITU-R/Pages/publications.aspx?lang=en&media=electronic&parent=R-REG-RR-2020`

Verification Level: N/A

Standardized interfaces?

☐ Yes
☑ No
Verification Level: N/A

Life extension services (non-contact support,inspection, refuelling, upgradability, orbit modification and maintenance) ?

☐ Yes
☑ No
Verification Level: N/A

External Active debris removal services ?

☐ Yes
☑ No
Verification Level: N/A

D

Detailed information on Delfi n3Xt

D.1. Relevant requirements

The list of requirements relevant to the LCA setup described in Section 4.3 is shown in Table D.1. This was used as the basis certain assumptions for the LCI.

Table D.1: Relevant requirements[1] of the Delfi-n3Xt mission, as taken from [70]

Requirement	Configuration Item	Description
MIS-F01	Delfi-n3Xt Mission	The mission shall facilitate two payloads from external partners.
MIS-F02	Delfi-n3Xt Mission	The mission shall facilitate bus advancements w.r.t. Delfi-C3.
MIS-F03	Delfi-n3Xt Mission	The mission shall facilitate additional experiments under condition that they do not drive the design or cause significant progress delays on the satellite or its subsystems.
MIS-G01	Delfi-n3Xt Mission	The mission shall facilitate educational goals.
SAT-C06	Delfi-n3Xt Satellite	All satellite systems shall be able to withstand the launch environment.
SAT-C07	Delfi-n3Xt Satellite	All satellite systems shall be able to withstand the space environment.
SAT-C09	Delfi-n3Xt Satellite	The total mass of the satellite shall be no more than 3.0 kg.
SAT.1-F01	Payloads	The payloads shall include the T3μPS thruster.
SAT.1-F02	Payloads	The payloads shall include the ITRX transceiver.
SAT.1-F03	Payloads	The payloads shall include the SDM experiment.
SAT.2-C02	Spacecraft Bus	All satellite bus systems shall guarantee a minimum operational life time of three months, also in case of a single point or component failure.
SAT.2-C03	Spacecraft Bus	All satellite systems shall be designed for a nominal operational life time of two years.
SAT.2-F01	Spacecraft Bus	The satellite bus shall facilitate the payloads.
SAT.2-F02	Spacecraft Bus	All satellite bus systems shall generate and provide housekeeping data when of interest to satellite operation.

[1]The requirement code is defined as follows: <Configuration Item> - <Requirement Type> . <Number>
The letters of the Requirement Types have the following meaning [70]:

C = Constraint ; this requirements puts constraints on a configuration item
F = Functional ; this requirement specifies the functionality of a configuration item
G = General ; this requirement is not belonging to any of the other categories
I = Interface ; this requirement specifies the (type of) interface of a configuration item
O = Operational ; this requirement specifies an operational mode
P = Performance ; this requirement specifies the (minimum) performance of a configuration item

Table D.1: Relevant requirements[2] of the Delfi-n3Xt mission (cont.).

Requirement	Configuration Item	Description
SAT.2.3-C01	Communication Subsystem (COMMS)	The frequencies for communicating with the satellite shall lie within the frequency bands allocated to the amateur satellite service
SAT.2.3-C02	Communication Subsystem (COMMS)	Any data transmitted to and from the satellite other than telecommands shall not be encrypted in any way
SAT.2.3-F03	Communication Subsystem (COMMS)	The COMMS shall provide a return service to the radio amateur community
SAT.2.4-C01	Structural Subsystem (STS)	The STS including solar panels, shall fit into an ISIPOD deployment canister.
SAT.2.4-C02	Structural Subsystem (STS)	The STS, excluding solar panels, shall fit within an envelope of 100 mm x 100 mm x 340.5 mm.
SAT.2.4-F01	Structural Subsystem (STS)	The STS shall be based on the design and dimensions of a three-unit CubeSat.
SAT.2.4-F04	Structural Subsystem (STS)	The STS shall be designed to withstand applied loads by the natural and induced environments to which it is exposed during its complete lifetime (manufacturing, assembly, testing, transport, launch, operations).

D.2. Delfi-n3Xt mass budget

The mass budget and actually measured mass of Delfi-n3Xt is shown in Table D.2. Note that the values for each subsystem (highlighted in gray) and their components (indented under the subsystem) are the final calculated masses prior to final assembly. They include any contingencies the designers may have accounted for. The 'Total Sum' is the sum of these calculated masses and the 'Total Measured' value is the actually measured mass after assembly.

Table D.2: Mass budget and mass measured of Delfi-n3Xt. Table taken and simplified from [64].

Subsystem	**Amount**	**Allocated mass [g]**
ADCS - Attitude Determination & Control Subsystem		320.4
Magnetorquer assembly	1	101.4
ADCS PCB	1	87.2
Reaction Wheel assembly	1	73.0
Sun sensors	6	58.8
CDHS - Command & Data Handling Subsystem		45.8
OBC	1	45.8
COMMS - Communication Subsystem		228.7
MABs	4	67.6
DAB	1	47.6
PTRX	1	65.0
STX Functional Board	1	13.7
STX Interface Board	1	34.8
EPS - Electrical Power Subsystem		975.1
Battery Box	1	273.9
Battery Management System Board	1	61.5
G-EPS MPPT Board	1	59.2
G-EPS Control & Regulation Board	1	59.3
Solar Panels	4	521.2
MechS - Mechanical Subsystem		106.4
Deployment Hinges	4	106.4
STS - Structural Subsystem		791.2
BOP + Kill Switches	1	121.9
Unsymmetrical U's + Hold Down Mechanisms + Wiring + Temperature sensors	1	386.2
TOP	1	160.9
Midplane Standoffs	8	11.0
Rods	4	86.4
Nuts, Bolts & Clamps	1	24.8
TCS - Thermal Control Subsystem		52.0
Thermal Control Tape	1	52.0
P/L - External Payloads		290.7
T3mPS	1	120.9
SDM	1	65.3
ITRX	1	62.5
Linear Transponder	1	42.0
Cable Harness		40.8
Flex-rigid PCB	1	30.1
Coax cables	5	10.7
	Total Sum	2851
	Total Measured	2865

E

Assumptions for the LCA of Delfi-n3Xt

This appendix gives a more detailed look at the rational behind the assumptions made in the modelling of Delfi-n3Xt's. It is complementary to the descriptions given in Section 4.3. If one desires further explanation of the reasoning behind an assumption in that section, one only has to look at the Assumption ID and find it in the table below.

E.1. Rational behind the general assumptions

Table E.1: Rational on the general assumptions for the LCA of Delfi-n3Xt

ID	Rational
GE.01	TU Delft's Clean Room and other infrastructure are open for students and student teams to be used [56]. Therefore it would be difficult to assess what fraction of its environmental impacts could be alloted to only Delfi-n3Xt's life cycle.
GE.02	This is based on the average of 250 business days per year and the fact that workers in the Netherlands are entitled to at least 20 days of annual leave and that there are 11 national holidays (which do not always end on business days) [93].
GE.03	This is a common amount of time spent at the office in the Netherlands (based on experience/common sense)
GE.04	Dr.ir. Jasper Bouwmeester mentioned that approximately 70 students worked on the Delfi-n3Xt project during 5 years, each working the equivalent of half a work-year.
GE.05	Dr.ir. Jasper Bouwmeester mentionned that 4-5 students worked full-time to complete the project in the last half year (here assumed to be 5 students)
GE.06	Dr.ir. Jasper Bouwmeester mentioned that a professional was hired for one year and a half towards the end, but worked approximately as 1 Full-Time Equivalent.
GE.07	Dr.ir. Jasper Bouwmeester mentionned that there were 5 staff members from the faculty involved, each of whom contributed the equivalent of 2 Full-Time Equivalent throughout the design phases.
GE.08	This assumption stems from documentation on the LEOP [72], were it is clear that multiple students are involved in this brief period of one day. This document is unclear on exactly how long each student is present and working but it does indicate the expected launch time at 08:10, Delfi-n3Xt's expected deployment at 8:50 and the times of reception of the eight first passes of the CubeSat until just over quarter past midnight. For this thesis, it is assumed that the students are not hard at work between passes, nor present until the last passes. Hence the chosen time
GE.09	Dr.ir. Jasper Bouwmeester mentioned that one student performed during 3 months the various routine ground station operations and data handling, for about 5 working-hours per day. To calculate the working days, the number of work-days in a year shown in Assumption GE.02 was divided by three. The work-hours are then found by multiplying this value with the 5 working-hours.

E.2. Rational behind the Phase A+B

Table E.2: Rational on the assumptions on Phase A+B for the LCA of Delfi-n3Xt

ID	Rational
AB.01	Dr.ir. Jasper Bouwmeester mentioned that, due to the educational nature of the project, it is difficult to assign what portion of the students' work could be considered preliminary versus detailed design. Frequent design changes were made between students and small tests were performed in between. Thus, an almost equal split of the working hours is chosen between Phase A+B and Phase C+D, with a small emphasis on the latter phase due to the many, relatively detailed, tests performed
AB.02	Similar reasoning as for Assumption AB.01, but the split is made equal as one cannot certainly say how the project planning was done
AB.03	It is assumed that students worked mostly on their own laptop, but might have needed a desktop for specific tasks or for when their laptop was unavailable. The staff tends to have their own desktop, hence the high percentage
AB.04	See rational of Assumption AB.04
AB.05	It is assumed that a relatively lower time was spent on prototyping and testing (and other miscellaneous activities) during Phase A+B. Especially the staff is assumed to mainly be focused on the surveillance of the students and the theoretical work.
AB.06	This number of working-hours per day is based on the fact that most (if not all) of the students combined work on Delfi-n3Xt with their own studies in some way.
AB.07	This number of working-hours per day is based on the fact that the staff should have been always present at the faculty, as not all students were likely to work on Delfi-n3Xt at the same time of the day.
AB.08	Both students and professors live close to the campus and faculty. Commutes are most often done with a bike, including those of the staff.

E.3. Rational behind the Phase C+D

Table E.3: Rational on the assumptions on Phase C+D for the LCA of Delfi-n3Xt

ID	Rational
CD.01	Dr.ir. Jasper Bouwmeester mentioned that, due to the educational nature of the project, it is difficult to assign what portion of the students' work could be considered preliminary versus detailed design. Frequent design changes were made between students and small tests were performed in between. Thus, an almost equal split of the working hours is chosen between Phase A+B and Phase C+D, with a small emphasis on the latter phase due to the many, relatively detailed, tests performed
CD.02	See the rational for Assumption AB.02
CD.03	This work is being performed at the end, as part of the final preparations before launch.
CD.04	This work is being performed at the end, as part of the final preparations before launch.
CD.05	Same rational as in Assumption AB.03 regarding the percentages of student and staff work on a desktop. Although the percentages are reduced to accommodate for the prototyping and testing. For the external consultant, it is assumed that they worked almost entirely on a desktop.
CD.06	Similar rational as in Assumption AB.04 for Phase A+B. More time is left for the manufacturing, testing and prototyping.
CD.07	Similar reasoning as in Assumption AB.05 for Phase A+B, however more time is now allocated to the testing and prototyping.
CD.08	This number of working-hours per day is based on the fact that most (if not all) of the students combined work on Delfi-n3Xt with their own studies in some way.

Table E.3: Rational on the assumptions on Phase C+D for the LCA of Delfi-n3Xt (cont.)

ID	Rational
CD.09	This number of working-hours per day is based on the information given by Dr.ir. Jasper Bouwmeester that these students worked full-time.
CD.10	This number of working-hours per day is based on the fact that the staff should have been always present at the faculty, as not all students were likely to work on Delfi-n3Xt at the same time of the day.
CD.11	This number of working-hours per day is based on a comment given by Dr.ir. Jasper Bouwmeester: he mentioned that the external consultant worked on the project for about 1.5 years in total, thus not entirely a full-time day at work

E.4. Rational behind the Phase E1

Table E.4: Rational on the assumptions on Phase E1 for the LCA of Delfi-n3Xt

ID	Rational
E1.01	The 40 hours spent in the cleanroom is set to take into account the assembly time of the satellite, as well as some minor tests done during the assembly. This time is deemed a good initial guess, based on the author's opinion.
E1.02	The 5 hours spent in the cleanroom for the prototype is deemed sufficient, as it is assumed that the prototype would mainly be tested through short and small tests and that not all tests ought to be performed in the cleanroom
E1.03	Dr. i. Jasper Bouwmeester mentioned that he satellite was transported by road towrds the launch site. A deditcated van was used for this, according to him.

E.5. Rational behind the Phase E2

Table E.5: Rational on the assumptions on Phase E2 for the LCA of Delfi-n3Xt

ID	Rational
E2.01	Based on estmates given by Dr.ir. Jasper Bouwmeester
E2.02	Both students and professors live close to the campus and faculty. Commutes are most often done with a bike, including those of the staff.
E2.03	This assumption simplifies the modeling of the Ground Station's use and is deemed to make sense: the Ground Station mainly contains desktops and screens, which the students are assumed to exclusively use.

E.6. Rational behind the Phase F

Table E.6: Rational on the assumptions on Phase F for the LCA of Delfi-n3Xt

ID	Rational
F.01	According to literature [87], satellites with a form-factor similar to a CubeSat do often not survive the re-entry.

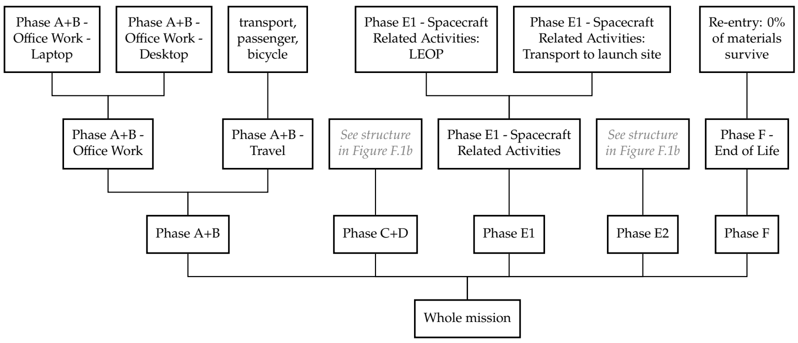
F

Detailed information on the Life Cycle Assessment

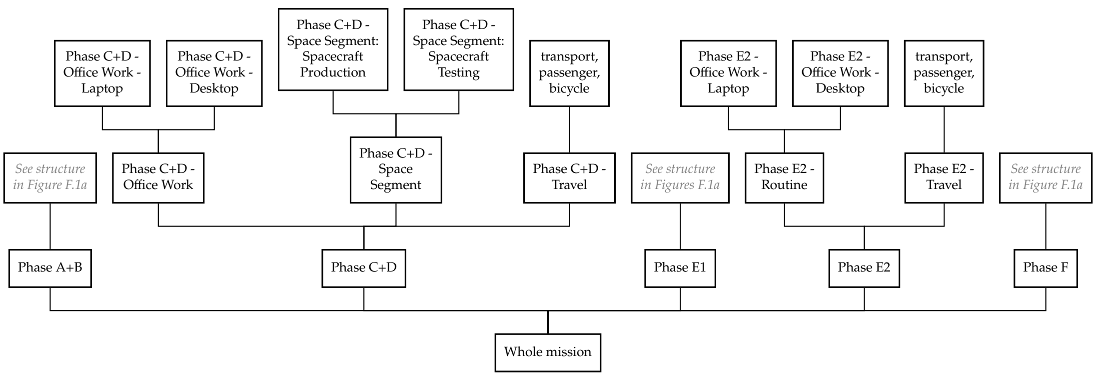
This Appendix provides more information on the Delfi-n3Xt's Life Cycle Assessment, and its LCI, as discussed in Section 4.3.

F.1. Structure of Delfi-n3Xt's Life Cycle Inventory analysis

As a complement to the description in Section 4.3.8 of the most important aspects of Delfi-n3Xt's modeling in Brightway2, Figure F.1 shows the structure of the LCI. The diagram goes up to level 4, as defined by the ESA LCA Guidelines. Differences between ESA Guideline's recommended structure can be noted, as only the elements within the scope of Delfi-n3Xt's LCA (as defined in Section 4.3.4) are modelled.



(a) Detailed structure of the Phases A+B, E1 and F



(b) Detailed structure of the Phase C+D and E2

Figure F.1: Structure of Delfi-n3Xt's LCI, up to Level 4. Note that the diagram has been split up in two sub-figures for layout purposes.

F.2. Modelling of Office Work for Phases A+B, C+D and E2

In order to create a complete and realistic LCI for the Office Work of Phases A+B, C+D and E1, inspiration is heavily taken from the SSSD's structure. Table F.1 shows exactly how SSSD defines Office work for Phase A+B, C+D and E1.

Table F.1: Standard Office Work definition from the SSSD in the Ecoinvent software. Note that this process is identical for "Phase A+B - Office Work: Man-hours" and "Phase C+D - Office Work: Man-hours". Taken from the SSSD

Amount	Units	Flow
0.85	h	use, computer, desktop with LCD monitor, active mode - RER
2.0	h	use, computer, desktop with LCD monitor, off mode - RER
0.15	h	use, computer, desktop with LCD monitor, sleep/standby mode - RER
0.025	h	use, IP network, videoconference - CH
0.03261	items	Water Bottle Production - RER
0.14423	kg	disposal, municipal solid waste, 22.9% water, to sanitary landfill - CH
0.01106	kg	paper, woodfree, uncoated, at regional storage - RER
0.01923	kg	use, printer, laser jet, colour, per kg printed paper - RER
0.01106	kg	waste paper, mixed, from public collection, for further treatment, RER
0.35144	kWh	cooling energy
2.86984	kWh	electricity, medium voltage, production RER, at grid - RER
1.98536	kWh	heat, natural gas at boiler condensing modulation >100kW - RER
0.01141	m3	treatment, sewage, to wastewater treatment, class 3 - CH

It was found that at least[1] the following flows are specific to SSSD. That is, they were conceived by the designers of SSSD, instead of by the Eco-invent managers for instance.

- "Water Bottle Production - RER"
- "electricity, medium voltage, production RER, at grid - RER"
- "treatment, sewage, to wastewater treatment, class 3 - CH"

The definition of the 'Water Bottle Production - RER' given by SSSD was reproduced into Brightway2 as much as possible. The SSSD implementation is identical to the one shown in a tutrial video by OpenLCA [95]. The interested reader could thus dive deeper into its definition by means of the video, if so desired.

F.3. Modelling of Phase C+D - Space Segment Spacecraft Production

While Figure F.1 falls short of detailing the components of the Spacecraft Production of Phase C+D, it is indicated in Section 4.3.8 that a Flight Model and Prototypes are made. Both of these have the same structure, and are composed of subsystems, components and the Clean Room activity. The subsections below dive in-depth in the modelling of these subsystems and components. The Clean Room activity's modeling is treated in Section F.5, further below.

F.3.1. ADCS - Attitude Determination & Control Subsystem

The ADCS is composed of the magnetorquer assembly, the ADCS PCB, the reaction wheel assembly and the suns sensor. The way each of these are modeled in Brightway2 is detailed in the sub-subsections and tables below.

Magnetorquer Assembly

Information on the magnetorquer, found in a Master's thesis [58], suggests that 2 magnetorquers are placed inside the structural subsystem, and a third one in the outer structure. No details are provided or could be directly found regarding the whole assembly. Therefore, the ESA LCA activity "Magnetorquer, adjusted for DQR | production" is assumed to cover well enough Delfi-n3Xt's magnetorquer assembly.

Thus, the way Delfi-n3Xt's magnetorquer assembly is modelled is simply shown in Table F.2, below

[1]It is possible that there were other SSSD-specific flows that were not identified. That could have happened if the SSD-specific flow resembled a lot the name and contents of a similar Eco-invent one.

Table F.2: Definition of the Delfi-n3Xt's magnetorquer assembly..

Amount	Unit	Product	Activity	Location	Database
1	kilogram	Magnetorquer, adjusted for DQR	Magnetorquer, adjusted for DQR | production	RER	ESA LCA External 1.1.8a

The Attitude Determination and Control System PCB

For PCB of the ADCS, one of the generic Electronic Unit models of ESA's Database is used. Specifically, the low IC variant is chosen, as per ESA's Guidelines [29]. The result is shown in Table F.3.

Table F.3: Definition of the Delfi-n3Xt's ADCS PCB.

Amount	Unit	Product	Activity	Location	Database
1	kilogram	Electronit Unit, Low IC, generic	Electronit Unit, Low IC, generic | production	RER	ESA LCA External 1.1.8a

Reaction wheel assembly

Little direct information on Delfi-n3Xt's reaction wheel assembly could be found. Therefore, ESA's database is used, as shown in Table F.4. It should be noted that the dataset in this table already includes the reaction wheel's casing according the ESA LCA Guidelines [29].

Table F.4: Definition of the Delfi-n3Xt's reaction wheel assembly.

Amount	Unit	Product	Activity	Location	Database
1	kilogram	Reaction wheel, adjusted for DQR	Reaction wheel, adjusted for DQR | generic production	RER	ESA LCA External 1.1.8a

Sun Sensor

Using data from internal documentation [63], a rough sizing of the sensor could be derived and the proportion of the mass of each component could be found. The documentation show that the sensor's housing is made up of the material PEEK[2] and that the remaining mass is taken up by the electronics. the high IC electronic unit is chosen as per ESA's Guidelines [29], resulting in the suns sensor's LCI model shown in Table F.5.

A special note should be made on the mass proportions in the table. These are based on a 9.8g sensor, as indicated in the Mass Budget (see Table D.2 and [64]). Nevertheless, the initial design mentions a first version of the sensor of 14g, with the expectation of a large mass reduction mainly due to a shrinking of the PCB [69]. Thus, the mass of the initial design's casing is kept for the LCI modelling, with the remaining mass from the 9.8g assumed to be dedicated to the electronics.

Table F.5: Definition of the Delfi-n3Xt's sun sensor. The proportion of each element is based on Delfi-n3Xt's design documentation [63].

Amount	Unit	Product	Activity	Location	Database
0.101707	kilogram	Poly Ether Ether Ketone (PEEK)	Poly Ether Ether Ketone (PEEK) | production	RER	ESA LCA External 1.1.8a
0.898293	kilogram	Electronit Unit, High IC, generic	Electronit Unit, High IC, generic | production	RER	ESA LCA External 1.1.8a

[2]Interested readers may find online more detailed descriptions of the material and its properties. A good introduction can be found on the material's Wikipedia page: `https://en.wikipedia.org/wiki/Polyether_ether_ketone` (accessed on 10/09/2023).

F.3.2. CDHS - Command & Data Handling Subsystem

For the modelling of Delfi-n3Xt's CDHS, the ESA LCA Guidelines's definition of the CDHS PCB [29] is copied, with some small modifications, as shown in Table F.6. Below is a list of the changes with their respective rational:

- The Aluminium Alloy is chosen within the Ecoinvent database as the best alternative to the one proposed by ESA (which was not found in Ecoinvent). It is mentioned in the description of the Ecoinvent activity that this alloy (and thus database) is mainly used for the aerospace sector.
- The transport is chosen as the best proxy, because ESA does not specify what class of lorry is used (EURO1, 2, 3, 4 or 5). The activity in Table F.6 is a mix of all classes.
- The "Cleaning with solvent" product [29] is modified from the "degreasing, metal part in alkaline bath" (at RER) of Ecoinvent, by removing the electricity from its Technosphere flows. This now matches with ESA's Guidelines
- The electricity choice is considered to be the best option, specific to the Dutch setting for Delfi-n3Xt.

Table F.6: Definition of the Delfi-n3Xt's OBC. The proportion of each element is taken from the ESA LCA Guidelines [29].

Amount	Unit	Product	Activity	Location	Database
0.2	kilogram	aluminium alloy, AlLi	aluminium alloy production, AlLi	RoW	cutoff391
0.8	kilogram	Electronit Unit, High IC, generic	Electronit Unit, High IC, generic | production	GLO	ESA LCA External 1.1.8a
1	ton kilometer	transport, freight, lorry, unspecified	market for transport, freight, lorry, unspecified	RER	cutoff391
0.2	kilogram	sheet rolling, aluminium	sheet rolling, aluminium	RER	cutoff391
0.0247	square meter	anodising, aluminium sheet	anodising, aluminium sheet	RER	cutoff391
0.0247	square meter	Cleaning with solvent	degreasing, metal part in alkaline bath WO Electricity Consumption	RER	ESA Guidelines
0.43	kilowatt hour	electricity, medium voltage	market for electricity, medium voltage	NL	cutoff391

F.3.3. COMMS - Communication Subsystem

The COMMS is composed of the Modular Antenna Box (MAB), the Deployment & Antenna Board (DAB), the Primary Transceiver (PTRX), the S-band transmitter (STX) and the STX Interface Board [64]. The sub-subsections below detail the way each of these components are modeled in Brightway2

Modular Antenna Boxes

Delfi-n3Xt's Modular Antenna Box (MAB) is modelled based on information from Delfi-C3's MAB, as they identical to each other if not for an additional bolt and hole in Delfi-n3Xt's MAB [63]. Thus, the mass budget of Delfi-C3 is used [66] to define the relative mass of the MAB's aluminium parts and the electronic units. That is, the MAB's box, bolts and antenna (measuring tapes) are assumed to be made up of aluminium. Note that, despite the acrylic which can be seen on Figure F.2, it is assumed that the final flight-ready MAB is made up of aluminium, as this seemed in the author's opinion more plausible (no direct source could be found on it). The electronic and RF connector mentioned in Delfi-C3's mass budget are considered to be part of the Electronic Unit. The resulting Brightway2 model of Delfi-n3xt's MAB is shown in Table F.7.

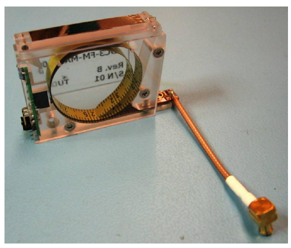


Figure F.2: Photo of Delfi-C3's Modular Antenna Box (MAB). Taken from [54].

It should be highlighted that no additional activity is applied to the aluminium (e.g. sheet rolling, milling, etc) due to the lack of any reliable source on the topic. The relatively low mass of the MAB – just under 2.4% of the CubeSat's total mass – may allow such simplifications, with limited consequences.

Table F.7: Definition of the Delfi-n3Xt's MABs. The proportion of each element is based on the mass budget of Delfi-C3's MABs [66].

Amount	Unit	Product	Activity	Location	Database
0.791925	kilogram	aluminium alloy, AlLi	aluminium alloy production, AlLi	RoW	cutoff391
0.20807	kilogram	Electronit Unit, High IC, generic	Electronit Unit, High IC, generic | production	GLO	ESA LCA External 1.1.8a

Deployment & Antenna Board

The Deployment and Antenna Board is in essence a PCB[67], thus an electronic unit. ESA's high IC electronic unit is chosen based on on ESA Guidelines' suggestion that high IC should selected for communication electronics [29]. Table F.8 summarises this concisely.

Table F.8: Definition of the Delfi-n3Xt's DAB.

Amount	Unit	Product	Activity	Location	Database
1	kilogram	Electronit Unit, High IC, generic	Electronit Unit, High IC, generic | production	GLO	ESA LCA External 1.1.8a

Primary Transceiver

The design the Primary Transceiver (PTRX) of Delfi-n3Xt is a small modification from the Radio Amateur Platform of Delfi-C3 [68], [62], which is an electronic unit. As per ESA LCA Guidelines, the high IC electronic unit is chosen to represent it, as summarised in Table F.9.

Table F.9: Definition of the Delfi-n3Xt's PTRX.

Amount	Unit	Product	Activity	Location	Database
1	kilogram	Electronit Unit, High IC, generic	Electronit Unit, High IC, generic | production	GLO	ESA LCA External 1.1.8a

S-Band Transmitter

For the same reasons as mentioned for the PTRX, the S-band transmitter (STX) can be considered an electronic unit with high IC. The way it is modelled in Brightway2 is summarised in Table F.10.

Table F.10: Definition of the Delfi-n3Xt's STX.

Amount	Unit	Product	Activity	Location	Database
1	kilogram	Electronit Unit, High IC, generic	Electronit Unit, High IC, generic | production	GLO	ESA LCA External 1.1.8a

STX Interface Board

The same reasoning as described for the primary transceiver can be applied for the STX interface board: it is to be modelled as an electronic unit with high IC. This is shown in Table F.11.

Table F.11: Definition of the Delfi-n3Xt's STX Interface Board.

Amount	Unit	Product	Activity	Location	Database
1	kilogram	Electronit Unit, High IC, generic	Electronit Unit, High IC, generic | production	GLO	ESA LCA External 1.1.8a

F.3.4. EPS - Electrical Power Subsystem

The Electrical Power Subsystem (EPS) of Delfi-n3Xt is composed of the Battery Box and its Management System Board, the Global Electrical Power Subsystem (G-EPS) Control and Regulation Board and the G-EPS Maximum Power Point Tracking (MPPT) Board, as shown in Figure F.3. Each of these are modelled in Brightway2 as shown in the sub-subsections below.

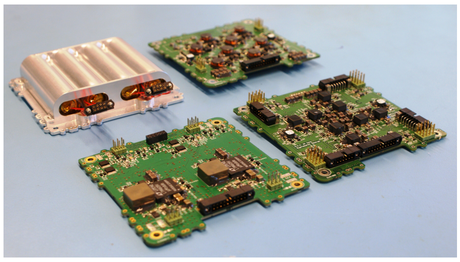


Figure F.3: Photo of Delfi-n3Xt's full Electrical Power Subsystem (EPS). Taken from [54].

Battery Box

The battery box is composed of the batteries and the casing. Four cylindrical Li-Ion batteries are used [62] with a total mass of 200g [73]. The battery casing is made out of aluminium [73]. Any electronics are ignored, as they seem to be accounted for in the Battery Management System Board, discussed in the sub-subsection below.

To model this in Brightway2, the ESA LCA Guideline on the "Battery assembly, Li-ion" product [29] is used, with some modifications. The relative masses of each element is adjusted to match the real masses of Delfi-n3Xt's Battery Box. Moreover, the "Battery Management System", suggested by ESA, has been removed. The result is shown in Table F.12.

Table F.12: Definition of the Delfi-n3Xt's Battery Box. The proportion of each element is taken from internal documentation [73].

Amount	Unit	Product	Activity	Location	Database
7.30E-01	kilogram	Battery cell, Li-ion	Battery cell, Li-ion | production	RER	ESA LCA External 1.1.8a
2.70E-01	kilogram	Battery casing, Li-ion battery	Battery casing, Li-ion battery | production	GLO	ESA LCA External 1.1.8a

Battery Management System Board

For the Battery Management System Board, it is chosen to use ESA's Electronic Unit product with a low IC. It was decided not to use ESA's defined "Battery management system, Li-ion battery" product as it seemed to cover less aspects than the low IC electronic unit. Table F.13 thus shows how Delfi-n3Xt's Battery Management System Board is modelled in Brightway2.

Table F.13: Definition of the Delfi-n3Xt's Battery Management System Board.

Amount	Unit	Product	Activity	Location	Database
1	kilogram	Electronit Unit, Low IC, generic	Electronit Unit, Low IC, generic | production	GLO	ESA LCA External 1.1.8a

G-EPS MPPT Board

The modelling of the G-EPS MPPT Board is straightforward, as it derives from the ESA LCA Guidelines on the use of low IC electronic units [29]. Table F.14 shows how it is modelled.

Table F.14: Definition of the Delfi-n3Xt's G-EPS MPPT Board.

Amount	Unit	Product	Activity	Location	Database
1	kilogram	Electronit Unit, Low IC, generic	Electronit Unit, Low IC, generic | production	GLO	ESA LCA External 1.1.8a

G-EPS Control & Regulation Board. This is

The same choice for low IC unit can be made for G-EPS Control & Regulation Board. This is shown in Table F.15.

Table F.15: Definition of the Delfi-n3Xt's G-EPS Control & Regulation Board.

Amount	Unit	Product	Activity	Location	Database
1	kilogram	Electronit Unit, Low IC, generic	Electronit Unit, Low IC, generic | production	GLO	ESA LCA External 1.1.8a

Solar Panels

The Solar Panels are modeled using ESA's defined product called "Solar cell, GaInP/GaAs, without wafer", as this matches the best with Delfi-n3Xt's solar panels. This is shown in Table F.16.

Table F.16: Definition of the Delfi-n3Xt's solar panels.

Amount	Unit	Product Activity	Location	Database	
1	square meter	Solar cell, GaInP/-GaAs, without wafer	Solar cell, GaInP/-GaAs, without wafer | production	GLO	ESA LCA External 1.1.8a

F.3.5. MechS - Mechanical Subsystem

Within the mass budget (see Table D.2 or [64]), only the solar panel deployment hinges are accounted for in the Mechanical Subsystem. Internal documentation [63] show that these are mainly composed of aluminium. This aluminium can be assumed to be essentially sheet rolled with some minor additional shaping process added. This is reflected in the way it is modelled in Brightway2, as shown in Table F.17.

Table F.17: Definition of the Delfi-n3Xt's Mechanical Subsystem.

Amount	Unit	Product Activity	Location	Database	
1	kilogram	aluminium alloy, AlLi	market for aluminium alloy, AlLi	GLO	cutoff391
1	kilogram	sheet rolling, aluminium	sheet rolling, aluminium	RER	cutoff391

F.3.6. STS - Structural Subsystem

The Structural Subsystem (STS) is composed of the elements shown in Figure F.4: the Bottom and Top Panels, the external panels, the midplane standoffs (between PCBs) and the rods, as well as some nuts and bolts. Each of these are modelled in Brightway2, as described below.

A general note can be made for all of these elements: they are made of aluminium [71], hence the choice of this material in the modelling.

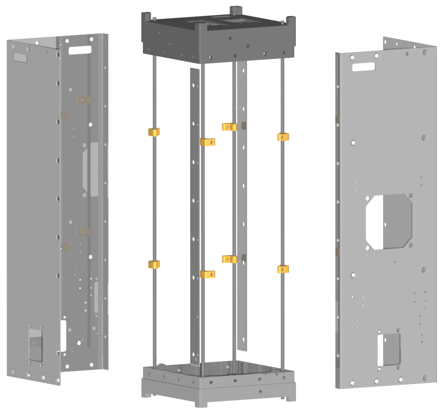


Figure F.4: Render of Delfi-n3Xt's Structural Subsystem. Taken from [71].

Bottom Panel and Kill Switches

The BOP is presumed to be manufactured from a metal block, which is milled to the correct specifications. To model this, the advice given in the description of Ecoinvent's "aluminium removed by milling, small parts" activity is fllowed, which states that 23% of the material can be assumed to be removed during the milling process when no further information is given[3].

[3]See www.globallcadataaccess.org for the full description (accessed on 10/09/2023)

The BOP aluminium part is said to have received an "Alodine 1500" surface treatment [71]. This is modelled as ESA's activity of "Anodizing, aluminum, 2 sides". As an input for the surface area, the top surface area of the CubeSat (100x100mm) is used twice.

The proportion of mass of the electronics units also present in the BOP [71] is based on engineering intuition. The result is show in Table F.18

Table F.18: Definition of the Delfi-n3Xt's BOP and Kill Switches. The proportion of each element is taken from Delfi-n3Xt's design documentation [71].

Amount	Unit	Product	Activity	Location	Database
0.95	kilogram	aluminium alloy, AlLi	market for aluminium alloy, AlLi	GLO	cutoff391
0.2185	kilogram	aluminium removed by milling, small parts	aluminium milling, small parts	RER	cutoff391
0.05	kilogram	Electronit Unit, Low IC, generic	Electronit Unit, Low IC, generic | production	GLO	ESA LCA External 1.1.8a
0.01	square meter	Anodizing, aluminum, 2 sides	Anodizing, aluminum, 2 sides | processing	RER	ESA LCA External 1.1.8a

External panels, wiring and temperature sensors

For these elements, the mass proportions are based on engineering intuition as no direct source could be found. The same proxy for anodisation as for the BOP is used for the metal shets of the external panels. The area is based on the side area of the satellite (100x340mm), which is then multiplied by 8 (i.e. both sides of each side of the satellite). The result is shown in Table F.19.

Table F.19: Definition of the Delfi-n3Xt's external panels, wiring and temperature sensors.

Amount	Unit	Product Activity	Location	Database	
0.8	kilogram	aluminium alloy, AlLi	market for aluminium alloy, AlLi	GLO	cutoff391
0.8	kilogram	sheet rolling, aluminium	sheet rolling, aluminium	RER	cutoff391
0.05	kilogram	Electronit Unit, Low IC, generic	Electronit Unit, Low IC, generic | production	GLO	ESA LCA External 1.1.8a
0.15	kilogram	Shielded jacketed single wire [mass], AWG 14	Shielded jacketed single wire [mass], AWG 14 | production	GLO	ESA LCA External 1.1.8a
0.272	square meter	Anodizing, aluminum, 2 sides	Anodizing, aluminum, 2 sides | processing	RER	ESA LCA External 1.1.8a

Top Panel

The reasoning behind the way the TOP is modelled in Brightway2 is idetical to that of the modelling of the BOP. Thus, the result is shown in Table F.20.

Table F.20: Definition of the Delfi-n3Xt's Top Panel.

Amount	Unit	Product Activity	Location	Database	
1	kilogram	aluminium alloy, AlLi	market for aluminium alloy, AlLi	GLO	cutoff391
0.23	kilogram	aluminium removed by milling, small parts	aluminium milling, small parts	RER	cutoff391
0.01	square meter	Anodizing, aluminum, 2 sides	Anodizing, aluminum, 2 sides | processing	RER	ESA LCA External 1.1.8a

Midplane Standoffs

Unclear what material it is made out of, but DNX-TUD-SE-1056 mentions "PCB Stand-Off" which are made at a metal manufacturer in Groningen. Therefore, it is assumed that these Midplane Standoffs are made of aluminium Also unclear how they are made. BBut, does not matter too much given their very low weight.

Table F.21: Definition of the Delfi-n3Xt's Midplane Standoffs.

Amount	Unit	Product	Activity	Location	Database
1	kilogram	aluminium alloy, AlLi	market for aluminium alloy, AlLi	GLO	cutoff391

Rods

It is unclear how the rods are exactly manufactured. Hence the lack of any process added to the aluminium alloy. Moreover, the rod's mass relatively low fraction of the Cubesat's mass may be an argument as to why the manufacturing process might not have a major impact on the final LCA results. Therefore, the rods were simply modeled as shown in Table F.22.

Table F.22: Definition of the Delfi-n3Xt's rods.

Amount	Unit	Product	Activity	Location	Database
1	kilogram	aluminium alloy, AlLi	market for aluminium alloy, AlLi	GLO	cutoff391

Nuts, Bolts & Clamps

A similar argumentation as given for the rods can be made for the nuts, bolts and clamps. Thus, they are modeled as shown in Table F.23.

Table F.23: Definition of the Delfi-n3Xt's nuts, bolts and clamps.

Amount	Unit	Product	Activity	Location	Database
1	kilogram	aluminium alloy, AlLi	market for aluminium alloy, AlLi	GLO	cutoff391

F.3.7. P/L - External Payloads

The External Payloads (P/L) are the T3μPS, the ITRX, the Linear Transponder and the SDM. All but the last payload are modelled in Brightway2 as shown in the sub-subsections below. An explanation on why the SDM is not included is given in Section 4.3.

T3μPS

Literature [59], [60] states that the T3μPS paload, shown in Figure F.5, has 8 cool gas generators with each 0.3 grams of liquid nitrogen. Combining this information with the total mass of the T3μPS [64], a mass fraction could be set and is shown in Table F.24.

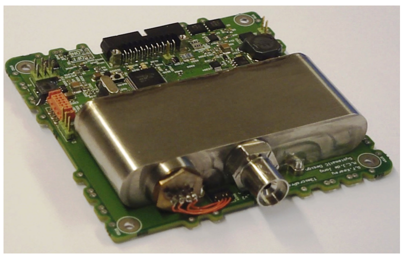


Figure F.5: Photo of Delfi-n3Xt's T3μPS payload. Taken from [54].

For small gas tanks, a volume could be determined using a figure in internal documentation. However, no aluminium tank could be found in ESA's LCA Database. Also, it would be complicated to model in detail such tanks from Ecoinvent data. Thus, the proxy of a titanium spherical tank is used from ESA's Database. This is also shown in Table F.24.

For the electronics, a engineering guess on its mass compared to the total mass is made using the images, renders and diagrams of payload. This results in the mass fraction shown in Table F.24.

Table F.24: Definition of the Delfi-n3Xt's T3μPS payload.

Amount	Unit	Product	Activity	Location	Database
1.99E-02	kilogram	nitrogen, liquid	market for nitrogen, liquid	RER	cutoff391
1.00E-04	cubic meter	Spherical Tank, Titanium primary, average	Spherical Tank, Titanium primary, average | production	RER	ESA LCA External 1.1.8a
0.25	kilogram	Electronit Unit, Low IC, generic	Electronit Unit, Low IC, generic | production	GLO	ESA LCA External 1.1.8a

ITRX (ISIS Transceiver)
The ITRX is simply modelled as an electronic unit. It is chosen to use the high IC version following ESA LCA Guidelines which state that transceiver electronics can be considered to have high IC [29]. The result is shown in Table F.25.

Table F.25: Definition of the Delfi-n3Xt's ITRX (ISIS Transceiver).

Amount	Unit	Product	Activity	Location	Database
1	kilogram	Electronit Unit, High IC, generic	Electronit Unit, High IC, generic | production	GLO	ESA LCA External 1.1.8a

Linear Transponder
The modelling of the Linear Transponder is identical to that of the ITRX. The same reasoning applies, resulting in the inputs shown in Table F.26.

Table F.26: Definition of the Delfi-n3Xt's Linear Transponder.

Amount	Unit	Product	Activity	Location	Database
1	kilogram	Electronit Unit, High IC, generic	Electronit Unit, High IC, generic | production	GLO	ESA LCA External 1.1.8a

F.3.8. Cable Harness

The so-called Cable Harness comprises all the flex-rigid PCBs and the coax cables used in Delfi-n3Xt. They are both modelled within Brightway2. A description of each is given below.

Flex-rigid PCB
The best way found to model the flex-rigid PCBs is to combine single wires and low IC electronic units. Since it is unclear how to exactly distribute the mass between these two elements, it is chosen to split it equally. This is also shown in Table F.27.

Table F.27: Definition of the Delfi-n3Xt's flex-rigid PCB.

Amount	Unit	Product	Activity	Location	Database
0.5	kilogram	Single wire [mass], AWG 26	Single wire [mass], AWG 26 | production	GLO	ESA LCA External 1.1.8a
0.5	kilogram	Electronit Unit, Low IC, generic	Electronit Unit, Low IC, generic | production	GLO	ESA LCA External 1.1.8a

Coax Cable
The coax cable is assumed to be equivalent to ESA Database's shielded jacketed single wire with a size of AWG 20. Thus, Table F.28 reflects the inputs into Brightway2.

Table F.28: Definition of the Delfi-n3Xt's coax cables.

Amount	Unit	Product	Activity	Location	Database
1	kilogram	Shielded jacketed single wire [mass], AWG 20	Shielded jacketed single wire [mass], AWG 20 | production	GLO	ESA LCA External 1.1.8a

F.4. Modelling of Phase C+D - Space Segment: Spacecraft Testing

Internal documentation provides detailed information on a range of tests performed on Delfi-n3xt and its individual components. This includes small tests with voltmeters to make sure all electronic circuits function as designed, to tests involving thermal-vacuum chamber and other devices. A selection of these is made based

The tests considered to have the highest potential of causing significant impacts are selected based on engineering intuition. These are the Defi-n3Xt Acceptance Test, the Reaction Wheel Test, the System Level Test and the Thermal Verification Test. Each of these are modelled as described in the sub-subsections below.

Delfi-n3XT Acceptance Tests: Thermal Bake-Out at TNO

The modelling of this test is done with a unit of one hour of testing. For this, a readily available commercial thermal-vacuum chamber (the *ExploraVAC Space Simulation TVAC*[4]) resembling the Aerospace Faculty's chamber (in the author's opinion) was taken as a reference. Its power and nitrogen consumption is taken and used for the Acceptance Test. Given that the Aerospace Faculty's thermal-vacuum chamber is in the cleanroom, the cleanroom operations are also included in the Brightway2 model. This results in the inputs shown in Table F.29

Table F.29: Definition of the Delfi-n3XT Acceptance Tests (Thermal Bake-Out at TNO).

Amount	Unit	Product	Activity	Location	Database
11	kilowatt hour	electricity, medium voltage	market for electricity, medium voltage	NL	cutoff391
0.5	kilogram	nitrogen, liquid	market for nitrogen, liquid	RER	cutoff391
1	hour	Clean room operations	Clean room operations	GLO	SSSD specific flows

System Level Tests (Thermal Bake-Out)

The system level test involves similar activities as Delfi-n3Xt's acceptance test. The same reasoning therefore apply, resulting in Table F.30.

Table F.30: Definition of the Delfi-n3XT System Level Tests (Thermal Bake-Out).

Amount	Unit	Product	Activity	Location	Database
11	kilowatt hour	electricity, medium voltage	market for electricity, medium voltage	NL	cutoff391
0.5	kilogram	nitrogen, liquid	market for nitrogen, liquid	RER	cutoff391
1	hour	Clean room operations	Clean room operations	GLO	SSSD specific flows

Thermal Verification Testing of the Thermal Control Subsystem (Thermal Vacuum test)

The thermal verification tests involve similar activities as Delfi-n3Xt's acceptance test. The same reasoning therefore apply, resulting in Table F.31.

[4]For more information on the chamber, see the webshop's page: https://www.idealvac.com/Ideal-Vacuum-ExploraVAC-Space-Simulation-Test-Chamber/pp/P1012095AllOps=10-13-17-21-24-29-31-34-39-4-9OptQtys=1-1-1-1-1-1-1-1-1-1-1

Table F.31: Definition of the Thermal Verification Testing of the Thermal Control Subsystem (Thermal Vacuum test).

Amount	Unit	Product	Activity	Location	Database
11	kilowatt hour	electricity, medium voltage	market for electricity, medium voltage	NL	cutoff391
0.5	kilogram	nitrogen, liquid	market for nitrogen, liquid	RER	cutoff391
1	hour	Clean room operations	Clean room operations	GLO	SSSD specific flows

Reaction Wheel Test: Thermal test

For the reaction wheel test, the thermal-vacuum chamber is only heated and does not create a vacuum. Therefore, compared to the Brightway2 inputs for the acceptance test, no liquid nitrogen is needed. This results in the inputs shown in Table F.32

Table F.32: Definition of the Delfi-n3Xt's Delfi-n3XT Reaction Wheel Test (thermal test).

Amount	Unit	Product	Activity	Location	Database
11	kilowatt hour	electricity, medium voltage	market for electricity, medium voltage	NL	cutoff391
1	hour	Clean room operations	Clean room operations	GLO	SSSD specific flows

F.5. Modelling of the Clean Room Activities

The clean room activities are modelled using SSSD's "Clean Room Fuelling" activity, which is, itself, based on one of ESA's clean room activities. The values are copied directy from SSSD and the activities are matched as much as possible, with small adaptations to fit better the Dutch electricity mix. The resulting inputs are shown in Table F.33.

Table F.33: Definition of the Delfi-n3Xt's Clean Room Activities.

Amount	Unit	Product	Activity	Location	Database
2.68E-03	kilogram	synthetic rubber	synthetic rubber production	RER	cutoff391
7.78E-03	kilogram	nylon 6	nylon 6 production	RER	cutoff391
2.61E-03	kilogram	steel, low-alloyed	steel production, electric, low-alloyed	Europe without Switzerland and Austria	cutoff391
5.44E-04	kilogram	polycarbonate	polycarbonate production	RER	cutoff391
4.57E-05	unit	air filter, central unit, 600 m3/h	air filter production, central unit, 600 m3/h	RoW	cutoff391
1.09E-05	unit	ventilation control and wiring, central unit	market for ventilation control and wiring, central unit	GLO	cutoff391
-1.36E-02	kilogram	municipal solid waste	treatment of municipal solid waste, incineration	RoW	cutoff391
3.10E+01	kilowatt hour	electricity, high voltage	market for electricity, high voltage	NL	cutoff391
5.00E-04	kilowatt hour	electricity, low voltage	market for electricity, low voltage	NL	cutoff391
7.50E+00	kilowatt hour	electricity, medium voltage	market for electricity, medium voltage	NL	cutoff391

G
Delfi-n3Xt's SSR score report

In the next pages, SSR's report on the score of Delfi-n3Xt is provided. This report has been simplified for the purposes of this thesis, but remains representative of the type of information an operator would get upon completing a SSR rating.

Space Sustainability Rating

Delfi-n3Xt rating

Version	Date	Remark
1.0	23/08/2023	Initial issue

Disclaimer

This document is provided as part of tailored rating delivered to the Delfi-n3Xt mission performed during a master thesis of a TU Delft University student. Its content is not representative of the feedback report provided to satellite operators under contracted service agreements as the rating was performed pro-bono and with a reduced scope (no recommendations, nor extensive data verification process).

Operator:	**TU Delft**
Mission:	**Delfi-n3Xt**
Phase:	**End of primary mission, natural decay**
Date of issue:	**23/08/2023**
Latest Revision:	**23/08/2023**

Achieved Score: 46.76% - Bronze Rating, No bonus stars

BRONZE

Tier Score 46.76 %	Bonus Score 20.09 %

Mission Index 72.2 %	Collision Avoidance Capabilities 0 %	Data Sharing 8.56 %
Detection, Identification and Tracking 66.67 %	Application of Design and Operation Standards 25 %	External Services 0 %

Figure 1: Delfi-n3Xt score per module

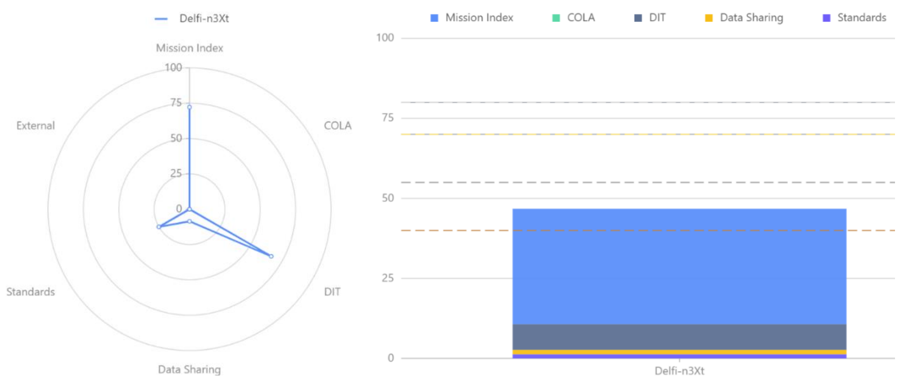


Figure 2: Delfi-n3Xt score per module (web chart, left) and cumulated score (bar chart, right)

Highlights:

- Orbital considerations: Delfi-n3Xt was inserted in 2013 in an orbit with a perigee of 599 km and an apogee of 780 km and has no propulsion capabilities for disposal purposes. An orbital lifetime of 27 years was computed using the ESA DRAMA software tool (Figure 3), showing that orbit is not naturally compliant to best-practise stating that the orbital lifetime of an object should be limited to 25 years after the end of the primary mission (as stated in IADC 5.3.2). As such, the SSR score for the mission is limited in several modules, including:
  - Application of Design and Operation Standards: the mission does not meet the requirements of several space debris mitigation guidelines and criteria (launcher and satellite passivation and disposal, characterisation of the explosion probability).
  - Relative part of the mission index: A dedicated section on the mission index is detailed below.

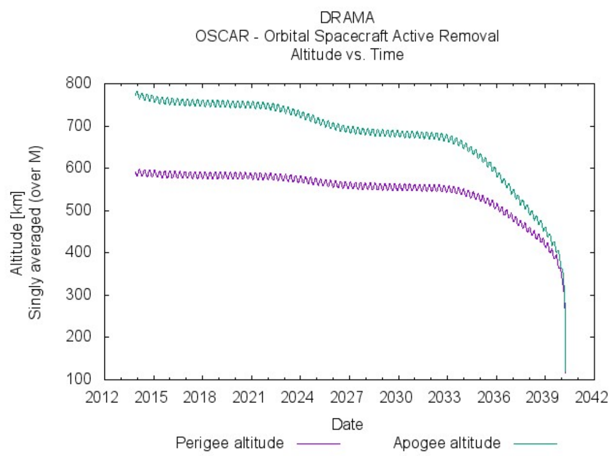


Figure 3: Delfi-n3Xt natural decay propagation (Drama - OSCAR software used for propagation). The total orbital lifetime exceeds 25 years.

- Mission index analysis: The cross-sectional area of the spacecraft being low ($0.075m^2$ in randomly tumbling motion), both the collision probability of collision and the severity of a collision are low. As such, the absolute part of the mission index achieves the maximal score (the mission uses less than 0.001% of the total available yearly index capacity). However, the orbital lifetime of the spacecraft exceeds the 25 years rule guidelines. The relative index part of the module compares the actual absolute index I_{abs} to the same mission, complying with the best-practises for disposal I_{ref} (i.e., disposal in 25 years, with a 90% success rate). Delfi-n3Xt mission's relative index ($I_{rel} = I_{abs}/I_{ref}$) is above one, showing that the mission's actual disposal scenario implies a higher index (i.e., a higher risk), than the reference scenario corresponding to the minimal compliance to internationally endorsed best-practises. This result in a penalization on the relative part of the index. As a consequence, despite the low collision probability of the mission over its lifetime, the mission not meeting the guidelines for disposal standards prevents it for scoring the maximum score on the module.

- Collision Avoidance: The Delfi-n3Xt mission does not have any propulsion capabilities that can be used for collision avoidance, hence limiting the score that can be achieved in the collision avoidance capabilities module.

- Data Sharing: A limited set of information is shared with SSA providers or other operators, limiting the score on this module. One could suppose that data sharing was not considered a priority at the date of launch (2013) or was harder to achieve as the sharing infrastructures were either not developed nor widely used. However, the spacecraft will remain in orbit for more than 27 years, stressing the need for updating sharing practises and transparency of terminated mission.

- Detectability, Trackability: As the spacecraft is rather small (3U CubeSat) and operated on a 600/780 km elliptical orbit in Low Earth Orbit (LEO), simulations show that detecting and tracking the satellite is not straightforward, but can be achieved. The score for these categories is 50% (both for both trackability and detectability aspects). Additionally, the spacecraft was effectively tracked by the operator relatively quickly after its deployment, leading to a DIT score of 66% thanks to the questionnaire part of the module.

- General comment: Delfi-n3Xt mission achieves a bronze rating with a score of 46.76%. The mission meets the pre-requisite requirements to apply for an SSR. The SSR applicant demonstrates willingness to increase mission's sustainability. However, current sustainable practices still need to be incorporated into the mission.

H

Human Research considerations of the Survey

In accordance with the Human Research Ethics Committee of the Delft University of technology, certain measures were taken to ensure the protection of the data as much as possible. To that end, to ensure that each participant to the survey was well aware of the risks as well as of the measures taken to mitigate them, the email to invite them to participate to each questionnaire was carefully drafted with all necessary information. Below can be seen the generic email sent to all participants to invite them to participate in the first questionnaire.

Dear << INSERT TITLE>> << INSERT NAME >>,

You are invited to participate in a research study titled “Feasibility of a Single-Score Life-Cycle Assessment for Space Missions”. This study is done as part of my MSc Thesis for the TU Delft, under supervision of Dr. Alessandra Menicucci and Ir. Håkan Svedhem. The thesis is performed in collaboration with Space Sustainability Rating, a non-profit organisation and the EPFL Space Center, located at the Swiss Federal Institute of Technology (EPFL) in Switzerland.

Below is a detailed explanation of the goal and procedure of the survey, along with that of the way your privacy and the data is being managed. The way the results will be published and how you can participate are also described. Finally, you will find a link to the first questionnaire at the bottom of this mail.

Goal and Procedure of the Survey

The purpose of this research study is to **understand the general opinion of the space sector on what aspects of sustainability are deemed most critical for space missions**, and to reach a common consensus on the matter. This is the first of three questionnaires, each of which will take you approximately **20 minutes** to complete. The data will be used as part of a MSc thesis where it will support the argumentation made in there, as well as part of a research paper to be published for the 10th EUCASS conference this July.

I will be asking you to provide **your own personal opinion** on each of the questions, based on your background, knowledge, experience and/or expertise. Some questions on your background and expertise will first be asked, to enable a more interesting division of the answers in the analysis after the survey. You can then expect questions related to the ranking of the environmental impact indicators based on various scenarios and assumptions. Some questions related to the space sustainability rating and other miscellaneous aspects on, for instance, your sector’s attitude towards sustainability will also be asked throughout the questionnaires.

You can expect to receive each questionnaire around the following dates (some slight changes may occur):

- Questionnaire 1: Thu. 25th of May
- Questionnaire 2: Mon. 5th of June
- Questionnaire 3: Mon 12th of June

Privacy and Data Management

To the best of my ability **your answers in this study will remain confidential**. I will minimize any risks by collecting as little personal information as possible: no IP addresses, nor any information that could identify you as an individual (i.e. name, age, exact address, email address, etc) will be asked for or recorded during the survey. Your name and email address, collected when reaching out to you with the request to participate to the survey, are kept in a secure data storage hosted by the TU Delft. They will only be used for administrative purposes (i.e. to send you the questionnaires) and will be deleted as soon as they are not needed anymore (after the last questionnaire).

You will receive a **Unique Code** (see the bottom of this mail) which you will have to input at the start of each questionnaire. It will **allow me to link together the answers you provide in each of the three questionnaires**, such that the correct analysis can be performed. This code is individually made for you and stored securely in the above-mentioned data storage of the TU Delft and deleted as soon as it is not needed anymore (after the third questionnaire). It will NOT be used to investigate your individual answers during the analysis, nor will it be used to link your set of answers to you personally in the final report.

The answers you provide will thus be fully anonymised and will be stored and analysed as such. The tool used to collect them is the Qualtrics, an online software considered the most secure and safe one by the TU Delft. During and after the research, your answers will be stored in TU Delft's secure database and only accessible by me and my supervisors. **The data will eventually be transferred to the international data repository for science, engineering and design, 4TU.ResearchData** (https://data.4tu.nl/) , located in the Netherlands and meant for future reproducibility by other interested researchers. As such, the answers will be considered Open Data and be licenced as Creative Commons Attribution (CC-BY). Besides this, your anonymous answers will **also be transferred to the secure Swiss database storage platform SWIFT** (https://www.switch.ch/), **where only Space Sustainability Rating will have access**. The data will be classified as Open Data.

Publication of the Results

Within the **thesis report** and **research paper**, the best efforts will be put into preserving your anonymity. Your personal name will not be disclosed within the list of participants. **Only if you explicitly agree to it** (in a future email exchange), **the company or institution in which you work may be named**, without any mention of your role within it. While you may have been reached through a network of someone else, it won't be disclosed whose network was used, to minimize the chances that you could be tagged as a participant a posteriori. Moreover, the answers will always be analysed as part of all the other answers, avoiding as much as possible to analyse a single (anonymous) set of answers.

Participation

Your participation in this study is entirely voluntary and you can withdraw at any time. Since the answers to questionnaire will be anonymous, **it will not be possible for you to request me after the questionnaires to delete the answers you provided** (as I would not be able to identify them). While it is encouraged to answer all questions to provide the best data possible, you are **free to omit any questions**.

If you have any questions, concerns or complaints regarding the survey and how the data will be used and stored, do reach out to me through email to m.h.g.verkammen@student.tudelft.nl. For any urgent matters, you may also call me: << INSERT PHONE NR >>.

Giving Consent and Accessing the Questionnaire

To confirm you agree with the above Statement and to be redirected to the questionnaire, please copy the following link in your browser: << INSERT URL >>

Your Unique Code (to be filled in at the start of each questionnaire) is: << INSERT UNIQUE CODE >>

Thank you for participating to this first questionnaire.

With kind regards,

Marnix Verkammen
MSc Thesis student

TU Delft **Faculty of Aerospace Engineering/ Dept. Space Engineering**
Kluyverweg 1, 2629 HS Delft
The Netherlands

T << INSERT PHONE NR >>

I
Questionnaires

This appendix contains copies of the questionnaires sent to the expert panellists. The layout shown below differs somewhat from the one seen by the panellists, as the questionnaires were downloaded in a MS Word format from the survey tool Qualtrix, before being converted in PDFs and inserted here.

One may note the regular gray horizontal lines with a text starting with "Start of Block" in the same colour. This indicates that within the Qualtrix environment seen by the panellists, a new page (or "Block", in qualtrix's terminology) would have started. Indeed, the questionnaire were split up in multiple pages, but the panellists were able to move back to the previous one.

Equally noteworthy are the "« INSERT LINK »" text seen sporadically each copy of the questionnaires. This is a modification from the original Qualtrix questionnaire, as this text were links which would have lead panellists to a copy of the email with the privacy and security statements (shown in Appendix H) or the simplified description of the Midpoint indicators given in the bullet points of Figure 2.2.3.

A last aspect to notice is the sliders of the various questions where a ranking is requested. They were by default moved entirely to the right (a score of 100%) to make the ranking more intuitive. Moreover, whenever moved, the sliders showed the value of its current position.

I.1. Questionnaire 1

Space Sustainability Questionnaire 1

Start of Block: Default Question Block

Dear participant,

Thank you, once again, for participating to this survey on the environmental sustainability of space missions, as part of a MSc thesis research at the Delft University of Technology.

By proceeding with this survey and questionnaire, **you declare giving your consent** with regards to the purpose of this survey as well as the privacy and security statements given in the email.
If you like to review this, you may look back at the email, or look at the document linked here: « INSERT LINK »

This questionnaire contains **5 parts, each with 5 to 7 questions**. It is aimed at understanding your expertise, your opinion on current sustainability efforts and your initial assessment of the aspects of sustainability on a space mission has the biggest impact.
As mentioned in the emails, **you are free to skip questions if you prefer**, although complete answers are of course preferable.

The most noteworthy results of this questionnaire will be shown to you at the beginning of next questionnaire and will be further built upon in the next questionnaires.

This Questionnaire should take **approximately 20 minutes**.

Please provide below your Individual Code (see email)**.**
Note: as mentioned in the email exchanges, this code will only be used to link your answers of this questionnaire with that of the subsequent ones. It will NOT be used during the analysis, nor will it be used to disclose your individual answers in the final thesis. Moreover, the list with names and corresponding Individual Codes will be deleted as soon as they are not relevant (after the third survey).

Click or tap here to enter text.

____

Page 1 of 17

End of Block: Default Question Block

Start of Block: Block 1

Part 1/5: Personal Background

These first few questions are aimed at understanding your background, current type of job and level of expertise in environmental sustainability. They will be used to classify your answers, for a more detailed and fairer analysis. **NO personal data** (name, age, current company, etc) which could directly link you to these answers **will be collected during this or subsequent questionnaires.** Moreover, you are asked to avoid mentioning any of such information in these and upcoming questions, in order to avoid a traceability to you personally. The goal is to obtain a fully anonymous set of answers which can be assessed with as little bias as possible.

While a complete set of answers is preferable, if you consider any of these questions to be too personal or if you prefer not to answer some, you are of course free to skip some questions.

What is your level of expertise in the following domains?

	Low to none (e.g. never dealt with it, or basic awareness of some topics)	**Medium** (e.g. working knowledge with occasional application of it)	**High** (e.g. deep to expert knowledge with frequent application of it)
The methodology of an Environmental Life-Cycle Assessment. (i.e. the way one performs a LCA)	☐	☐	☐
The results of an Environmental Life-Cycle Assessment and their interpretations (i.e. the meaning of the results of a LCA, and how one should interpret them)	☐	☐	☐
Environmental impact categories (i.e. the categories displayed as part of the result of a LCA, and the way these categories have been defined)	☐	☐	☐

To what extent would you say that these sectors of the space industry describe your current or past experience?

	Not well at all. I do not touch on this subject at all, or at least barely.	**Somewhat.** There is an overlap with this field in my work	**Perfectly.** This is what I am focused on.
Operations of a Ground Station or Mission Control Centre	☐	☐	☐
Operations within an Integration and Test Facilities	☐	☐	☐
Operations of Launch Facilities	☐	☐	☐
Design of components/subsystem/systems for the Space Segment (i.e. for spacecrafts etc)	☐	☐	☐
Design of components/subsystem/systems for the Launch Segment (i.e. for launchers etc)	☐	☐	☐
Design of components/subsystem/systems for the Ground Segment (i.e. for ground stations/mission controls of for launch platforms, or test facilities)	☐	☐	☐
Manufacturing and/or Testing components/subs-systems for Space Missions (i.e.instruments or sub-system manufacturing/testing)	☐	☐	☐
Systems Manufacturing and/or Testing for Space Missions (i.e.satellite or launcher manufacturing/testing)	☐	☐	☐
Academia (research in a specific field)	☐	☐	☐
Space Policy and/or Regulations	☐	☐	☐
General Engineering outside of the space sector	☐	☐	☐

If none of the sectors above fit well with your work, please (briefly) describe below what kind of topics you are (generally) working on.
Please, do not mention any specifics which could make me identify you, such as the company/organisation you work for, or the name of the project you work on.

If you indicated that you work in academia, please provide (concisely) the main focus(es) of your research:
Please, do not mention any specifics which could make me identify you, such as the company/organisation you work for, or the name of the project you work on.

Which part of the world are you mainly working from nowadays?

- ☐ Africa
- ☐ Asia + Oceania
- ☐ Europe
- ☐ North America
- ☐ South America

End of Block: Block 1

Start of Block: Block 2

Part 2/5: Sector and organisation background

This section is aimed at better **understanding your work sector** (or the past one, if you are retired), and their perspective and actions towards environmental sustainability.
Please answer it to the best of your knowledge. If you are unsure about some answers, you will be able to express this in a dedicated textbox.

How many employees work at your company/institution/organisation?
☐ 1-10
☐ 10-50
☐ 50-250
☐ 250+

Does your company/institution/organisation have a person with explicit responsibility for environmental issues (for space sector specific activities as well as office-related activities)**? If so, how many?**
☐ Yes: 1-2
☐ Yes: 3-5
☐ Yes: 5-10
☐ Yes: 10+
☐ No

Are the majority of the persons mentioned above working on space sector specific sustainability, or on office-related sustainability?
☐ Majority works on space-related sustainability
☐ Majority works on office-work-related sustainability
☐ It is about equal
☐ I don't know/not applicable (e.g. since nobody works on sustainability specifically)

Would you like to comment on your previous answer? If yes, please do so here.

How would you judge the extent of commitment towards environmental sustainability shown by your organisation and your sector of expertise?
Note: as mentioned earlier, no information about the name of your organisation will be collected throughout these questionnaires. There exists therefore no direct link between the answer you would provide here and your organisation.

	Not at all committed	**Somewhat committed**	**Committed**	**Highly committed**
Your organisation (i.e. the organisation at which you work now - or have worked at if you are retired)	☐	☐	☐	☐
Your sector of expertise (i.e. the sector discussed in the previous section - the sector(s) in which you are most experienced)	☐	☐	☐	☐

How relevant are environmental concerns to your organisation and your sector of expertise today?
Note: as mentioned earlier, no information about the name of your organisation will be collected throughout these questionnaires. This question is mainly meant to gauge your personal point of view.

	Not relevant. No (special) commitment is needed	**Relevant** Commitment is needed (and/or is already present)	**Extremely relevant** A high (increase in) commitment is needed
Your organisation (i.e. the organisation at which you work now - or have worked at if you are retired)	☐	☐	☐
Your sector of expertise (i.e. the sector discussed in the previous section - the sector(s) in which you are most experienced)	☐	☐	☐

Could you please (briefly) explain why you answered as you did in the last question?

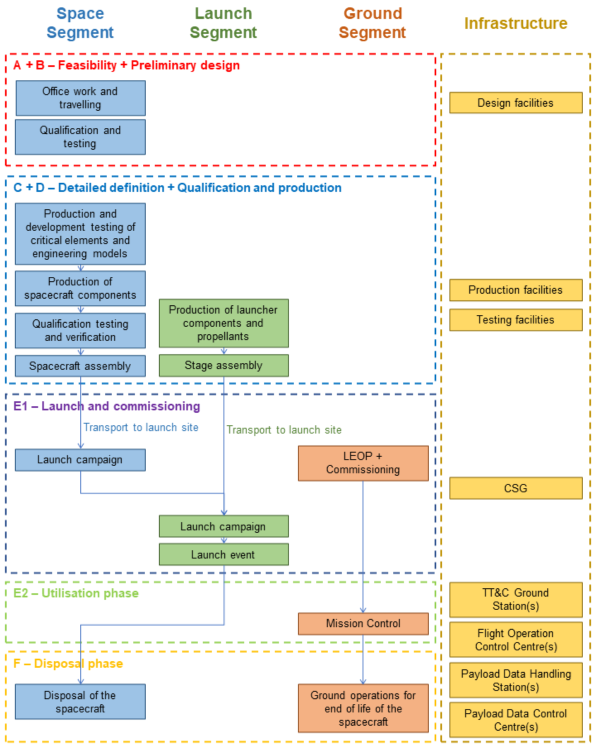
End of Block: Block 2

Start of Block: Block 3

Part 3/5: Rating Environmental Sustainability Hotspots per Phase and Segment

To perform a Life-Cycle Assessment of any product or service, one must identify the various **stages of the life-cycle** which have negative environmental impacts. The European Space Agency (ESA) has divided the life-cycle of a space mission into stages ranging from the feasibility and preliminary design definition, all the way to the utilisation phase and the disposal. To subdivide these further and analyse them in more detail, ESA has decomposed them into **segments**: space, launch and ground segment, as well as the required infrastructure.

This can all be seen in the image (adapted from ESA LCA Handbook 2016) below:



In which the above life-cycle phase would you argue that your personal expertise is the highest?
That is, on which of these phases have you worked the most (be it on a sustainability matter, regular engineering problem, or other)
Multiple answers are possible.

☐ A+B - Feasibility + Preliminary definition
☐ C+D - Detailed Definition + Qualification and production
☐ E1 - Launch and Commissioning
☐ E2 - Utilisation phase
☐ F - Disposal

Based on your experience, during which of these life-cycle phases does a generic space mission have the highest environmental impact?
Please only select one. In the next question, you may discuss more on this choice and on whether or not others should also be considered.

☐ A+B - Feasibility + Preliminary definition
☐ C+D - Detailed Definition + Qualification and production
☐ E1 - Launch and Commissioning
☐ E2 - Utilisation phase
☐ F - Disposal

Why did you choose that stage as the one with the highest environmental impact in the previous question?

Based on your experience, in which of these segments does a generic space mission have the highest environmental impact?
Please only select one. In the next question, you may discuss more on this choice and on whether or not others should also be considered.

☐ Space Segment
☐ Launch Segment
☐ Ground Segment
☐ Infrastructure

Why did you choose that segment as the one with the highest environmental impact in the previous question?

Did you have enough information on the space mission to provide an accurate assessment regarding the segment and life-cycle?
If yes, explain what information(s), if any, would make your answers change, and how it would change. If no, please explain briefly why your choice would remain the same.

End of Block: Block 3

Start of Block: Block 4

Part 4/5: Prioritisation of endpoint environmental indicators

One way of presenting the results of a product's or service's Life-Cycle-Assessment (LCA) is the use of so-called "**endpoint indicators**." Explained in more detail below, these indicators condense the LCA results into the **direct effect of the product or service on the environment**. They show generally the effect on Human Health, the Natural Environment and on the Natural Ressources and might be **more intuitive to understand** than the indicators described in the next Part.

Below is a detailed description of each of these environmental endpoint indicators:

- **Human Health.** The negative effects on people's health, for instance, as a consequence of chemicals or radiation emitted during the life cycle of a product or indirectly as consequence of climate change
- **Natural Environment**. The negative effects on the function and structure of natural ecosystems, for instance, as a consequence of the emission of chemicals or physical interventions that take place during the lifecycle of a product
- **Natural Resources.** The negative effects, for instance, to the use of physical resources such as energy, metals and minerals and water, which results in a decrease in the availability of the total resource stock, as physical resources can be finite and non-renewable.

How would you define the impact a generic space mission has on each of the three endpoint indicators?
Please assign a score of 100 to the one you think has the highest level of concern. How many points would you give the one you would rank second? If you think it is half as important, give it a score of about 50. If you think it is nearly as important, give it a score of about 90. Now, what about the third impact? How does that compare with the first one?
Note: Please click and drag the slider to indicate the score, also when indicating a score of 100

Example: you may think that a generic space mission has the most impact on Natural Ressources (score of 100), followed very closely by Human Health (score of 90). But, you may think that the impact on the Natural Environment is much more negligible, less than half of the impact on Natural Ressources (score for Natural Environment: 40).

- **Human Health:** Click or tap here to enter text.
- **Natural Environment**: Click or tap here to enter text.
- **Natural Resources:** Click or tap here to enter text.

Could you please provide briefly your reasoning or some comments for your answers above?

Did you have enough information on the space mission to provide an accurate assessment?
If no, explain what information(s), if any, would make your answers change, and how it would change. If yes, please explain briefly why your choice would remain the same.

End of Block: Block 4

Start of Block: Block 5

Part 5/5: Prioritisation of environmental impact categories

The outcome of a life-cycle assessment is most commonly a range of **midpoint impact categories** which are analysed individually, to indicate in detail where the impact is highest, where it comes from and what should be modified first to create the biggest improvements. The European Union has identified the following categories.
A shortened description can be found next to each, along with a longer description if you are not entirely familiar with the indicator:

- **Climate change, total.** Emission of greenhouse gases changing temperature and the climate for the worse, impacting indirectly on the ecosystems, on natural resources and your health.
- **Ozone depletion.** Emissions damaging the ozone layer leading to increased ultraviolet radiation resulting in skin cancer.
- **Human Toxicity - cancer effects.** Emissions of toxic substances leading to an increased risk of cancer, for instance, through the air we breathe and indirectly through the food we eat and the water we drink.
- **Human Toxicity - non-cancer effects.** Emissions of toxic substances damaging your health, for instance, through the air we breathe and also indirectly through the food we eat and the water we drink.
- **Particulate matter.** Emissions of tiny particle, for instance, leading to respiratory diseases and the so-called “winter smog”.
- **Ionizing radiation, human health.** Radiation ("radioactivity") increasing the risk of cancer.
- **Photochemical ozone formation., human health.** Emissions creating, for instance, the so called “summer smog” and respiratory diseases.
- **Acidification.** Emission of substance leading, for instance, to acid rain and poorer quality of air, water and soil.
- **Eutrophication - terrestrial.** Too many nutrients in the environment, for instance by overuse of fertilisers in farming, upsetting the balance of nature.
- **Eutrophication - freshwater.** Too many nutrients in freshwater, for instance by the overuse of fertilisers in farming and release of wastewater, upsetting the balance of nature, e.g. leading to algal blooms and killing fish.
- **Eutrophication - marine.** Too many nutrients in marine water, for instance due to overuse of fertilisers in farming and release of wastewater, upsetting the balance of nature and leading to algal blooms in seawater.
- **Ecotoxicity - freshwater.** Emission of toxic substances that are a danger to organisms like fish, algae and other organisms living in fresh water.

- **Land use.** Use of land and soil endanger, such as soil fertility as well as the wellbeing and survival of some animals and plant species.
- **Resource use: metals and minerals.** Use of minerals, metals and other resources in products reducing their availability for future uses.
- **Resource use: fossil fuels.** Use of fossil fuels, reducing their availability for future uses.

If you need a more detailed description of each of these impact categories, open the document linked here: « INSERT LINK »

How knowledgeable are you in each of these impact categories?
That is: how would you consider your level of understanding and expertise for each of them?

	Not knowledgeable at all	**Slightly knowledgeable**	**Moderately knowledgeable**	**Very knowledgeable**	**Extremely knowledgeable**
Climate change.	☐	☐	☐	☐	☐
Ozone depletion.	☐	☐	☐	☐	☐
Human Toxicity - cancer effects.	☐	☐	☒	☐	☐
Human Toxicity - non-cancer effects.	☐	☐	☐	☐	☐
Particulate matter.	☐	☐	☐	☐	☐
Ionizing radiation - human health.	☐	☐	☐	☐	☐
Photochemical ozone formation - human health.	☐	☐	☐	☐	☐
Acidification.	☐	☐	☐	☐	☐
Eutrophication terrestrial.	☐	☐	☐	☐	☐
Eutrophication - freshwater.	☐	☐	☐	☐	☐

Eutrophication - marine.	☐	☐	☐	☐	☐
Ecotoxicity - freshwater.	☐	☐	☐	☐	☐
Land use.	☐	☐	☐	☐	☐
Resource use: metals and minerals.	☐	☐	☐	☐	☐
Resource use: fossil fuels.	☐	☐	☐	☐	☐

Based on your experience, which categories would you consider to be hotspots for an average space mission? That is: on which category does an average space mission have the highest impact?
Please select up to 7 categories

☐ Climate change.
☐ Ozone depletion.
☐ Human Toxicity - cancer effects.
☐ Human Toxicity - non-cancer effects.
☐ Particulate matter.
☐ Ionizing radiation - human health.
☐ Photochemical ozone formation - human health.
☐ Acidification.
☐ Eutrophication - terrestrial.
☐ Eutrophication - freshwater.
☐ Eutrophication - marine.
☐ Ecotoxicity - freshwater.
☐ Land use.
☐ Resource use: metals and minerals.
☐ Resource use: fossil fuels.

Could you provide a brief reasoning behind the choice of environmental hotspots?

Did you have enough information on the space mission to provide an accurate assessment?
If no, explain what information(s), if any, would make your answers change, and how it would change. If yes, please explain briefly why your choice would remain the same.

Now, assume that you are comparing the life-cycle assessment results of two variations of a space mission in order to choose which one to design further and eventually launch.

For this decision process, to what extent would you find a given indicator more important than another? Please rank them according to their relative importance in such a decision process.

That is, give the most important impact category a score of 100. If you find that the next category is only half as important, give it a score of 50. And so on.
If you consider some categories completely unimportant, give them a score of 0. If, otherwise, you think two or more categories have the same level of importance compared to the most important one, give them the same score. Similarly, you may also provide a score of 100 to multiple categories if they are equally high important in this decision process, according to you.
Note: Please click and drag the slider to indicate the score, also when indicating a score of 100

An example could be:
Acidification : 100
Resource use - metals and minerals : 100
Ecotoxicity - freshwater : 85
Human Toxicity - non-cancer effects : 45
All the rest are considered unimportant: score of 0

	0	50	100
Climate change			
Ozone depletion			
Human Toxicity - cancer effects			
Human Toxicity - non-cancer effects			
Particulate matter			
Ionizing radiation - human health			
Photochemical ozone formation - human health			
Acidification			
Eutrophication – terrestrial			
Eutrophication – freshwater			
Eutrophication – marine			
Land use			
Resource use: metals and minerals			
Resource use: fossil fuels			

Could you provide a brief reasoning behind the ranking of some of these categories?

Based on the description of the different impact categories and based on your knowledge, do you think these environmental impact categories describe fully the environmental sustainability of space missions?
If yes, please explain. If no, please provide what you consider to be lacking.

End of Block: Block 5

I.2. Questionnaire 2

Space Sustainability Questionnaire 2

Start of Block: Default Question Block

Dear participant,

Thank you, once again, for participating to this survey on the environmental sustainability of space missions, as part of a MSc thesis research at the Delft University of Technology. This is the **second questionnaire** of the survey.

By proceeding with this survey and questionnaire, **you declare giving your consent** with regards to the purpose of this survey as well as the privacy and security statements given in the email.
If you like to review this, you may look back at the email, or look at the document linked here:
« INSERT LINK »

This questionnaire contains **4 parts, each with 2 to 7 questions**. It is aimed at understanding your expertise, your opinion on current sustainability efforts and your initial assessment of the aspects of sustainability on a space mission has the biggest impact.
As mentioned in the emails, **you are free to skip questions if you prefer**, although complete answers are of course preferable.

The most noteworthy results of this questionnaire will be shown to you at the beginning of next questionnaire and will be further built upon in the next questionnaires.

This Questionnaire should take **approximately 20 minutes**.

Please provide below your *Individual Code* (see email)**.**
Note: as mentioned in the email exchanges, this code will only be used to link your answers of this questionnaire with that of the subsequent ones. It will NOT be used during the analysis, nor will it be used to disclose your individual answers in the final thesis. Moreover, the list with names and corresponding Individual Codes will be deleted as soon as they are not relevant (after the third survey).

Click or tap here to enter text.

Please only proceed to the next parts if you completed the first questionnaire. Refer to the first invitation email to find your link to the first questionnaire, if you have not filled it in yet.

Page 1 of 19

End of Block: Default Question Block

Start of Block: Block 1

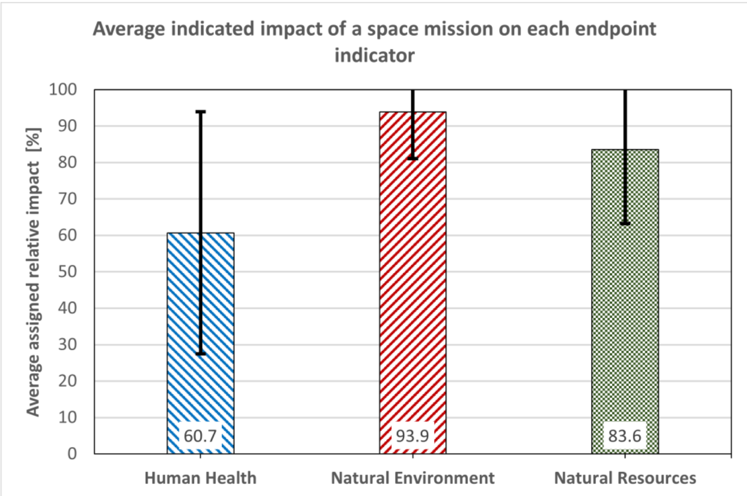
Part 1/4: Relevant feedback from the previous survey

In this Part, you will find a summary of the relevant answers you and the other participants gave in the previous questionnaire, as well as some questions for you to reflect on the findings. Please study the figures and tables, ad answer the questions based on your opinion and knowledge.

The data shown below is the summary of the answers of 24 participants in total, with various expertise. While the final number of recorded answers is expected to rise since a few participants have not yet responded, the data provided is relevant enough to make first conclusions.

In the first questionnaire, you were asked the following question: "***How would you define the impact a generic space mission has on each of the three endpoint indicators?***"

The figure below summarizes the average of all participants' answers through the bar chart, as well as each answer's standard deviation (an indication of the spread of the answers compared to the average).
It clearly shows that the participants estimated the **Natural Environment** and the **Natural Resources** to be **more impacted** by a generic space mission than Human Health. It also shows that there is a significant variation in the answers, particularly for the Human Health indicator.



A more in-depth analysis of the answers is shown in the table below. Note that the Median Score refers to the "middle value" amongst all the answers provided.

Endpoint indicators	Average score	Median Score	Standard Deviation
Human Health	45.5	35	32.7
Natural Environment	85.8	90	20.5
Natural Resources	71.5	71	26.9

Does this outcome match your own opinion on a generic space mission's endpoint indicator's hotspots based on your experience? Please elaborate.

Some of the remarks made on each Endpoint impact category are summarised below:

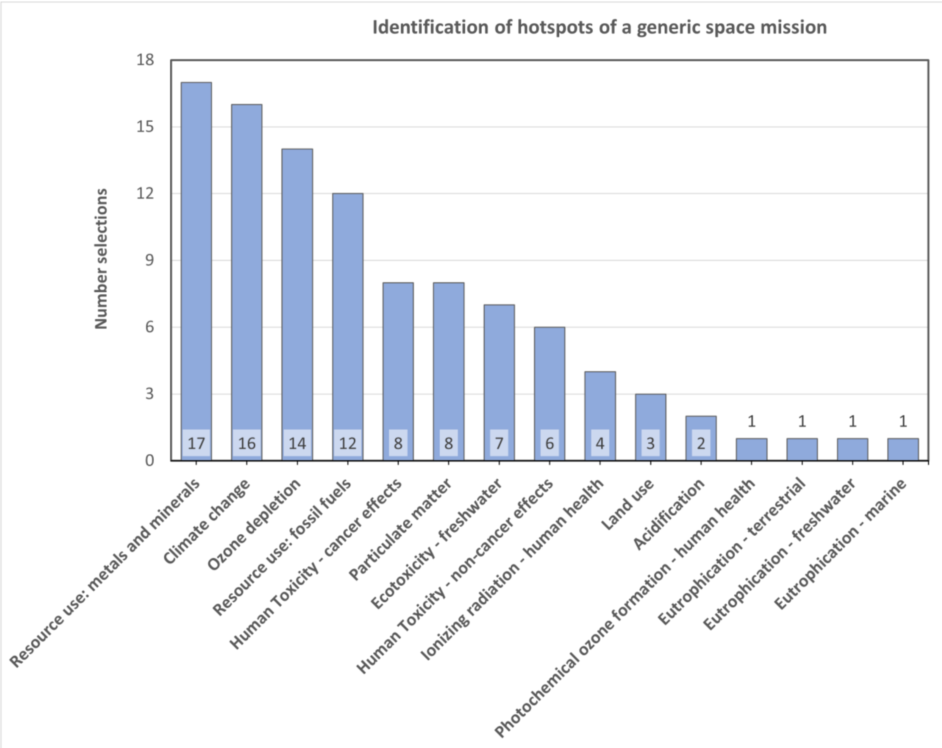
1. Natural Resources:
    - There is a depletion of natural resources in the space sector: rare metals, propellant, fossil fuels, and high material loss during production.
    - High-performance materials and rare minerals are used in the production phase of space missions
    - Resources can hardly be recovered and reused after re-entry
2. Environmental Impact:
    - Launch sites affect the surrounding ecosystems (habitat change, animal disturbances, emissions, pollution)
    - Re-entry of objects can have high impacts as well.
    - Manufacturing of satellites, rocket launches, and reentry negatively affect the natural environment on regional and global scales
3. Human Health:
    - Toxic substances and radiation are the main contributors to Human Health impacts.
    - Some argue that the Human Health impacts are lower than in other industries.
    - There are already mitigation measures and regulations in place for the relevant workers.

Moreover, some participants argue that the depletion of natural resources may be a more important topic compared to the impacts on the natural environment/ They write that natural resources may not recover, in contrast to the natural environment which can slowly recover over time

Do you agree with the above arguments, or are there points you consider missing or wrong? Elaborate.
Which of these points do you agree most with?

In the first questionnaire, you were asked the following question: "***Based on your experience, which categories would you consider to be hotspots for an average space mission?***"

The figure below summarizes the accumulated number of selections of hotspot indicators by all the participants combined. They are sorted in a decreasing order, showing that there are **four obvious hotspots** according to the participants: **Metals and Minerals Resource Use, Climate Change, Ozone Depletion and Fossil Fuels Resource Use**. Beyond that, the four indicators from Human Toxicity - Cancer Effects to Ionizing Radiation - Human Health seem to still be considered relevant hotspots, but much less than the first four. The last indicator seem not to constitute major hotspots.



Does this outcome match your own opinion on a generic space mission's midpoint indicator's hotspots based on your experience? Please elaborate.

Some of the participants gave comments on their selection or on similar topics. Some of the most recurring or interesting comments are summarized below:

1. Climate Change: It is considered by some a significant concern due to indirect emissions from workforce activities, launch vehicle operations, and the demise of orbital objects. The space industry's emissions in all layers of the atmosphere are mentioned as a unique contributor to climate change with potential long-term impacts.
2. Ozone Depletion: Given that launch vehicles and re-entering objects emit substances directly in the higher layers of our atmosphere and the ozone layer, Ozone Depletion is considered by some as an important factor
3. Resource Use: A few participant note that the space industry typically has a high consumption of rare materials and chemical propellants, which contribute to resource use concerns.
4. Human Health: While some participants acknowledge the potential for impacts on human health due to toxic substances, they generally consider it less significant compared to other environmental concerns mentioned. Substances associated with the production of space missions, such as polymers and toxic metals, are cited as potential sources of human toxicity.
5. Land Use: A few participants suggested that future space missions may involve the use of bio-sourced materials, such as bio-methane, which could impact land use.

Do you agree with the above arguments, or are there points you consider missing or wrong? Elaborate.
Which of these points do you agree most with?

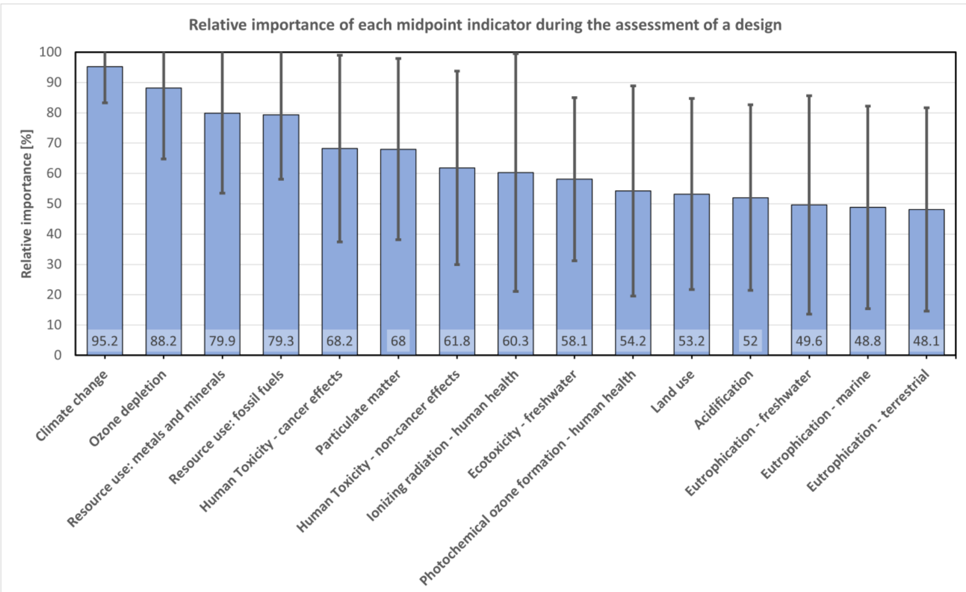
In the first questionnaire, you were asked the following question: ***"Assuming use during design proces, rank midpoint indicators. For this decision process, to what extent would you find a given indicator more important than another? "***

The figure below summarizes the average scores of each midpoint indicators assigned by the participants, with the standard deviation (an indication of the spread of the answers compared to the average) depicted by the error bar. They are sorted in a decreasing order.

From the figure, it is clear that there is a significant spread of answers given. Nevertheless, one may reach the conclusion that the following indicators are most important (i.e. a score above 65%) during a design phase, according to the participants:

- Climate change
- Ozone depletion
- Resource use: metals and minerals
- Resource use: fossil fuels
- Human Toxicity - cancer effects
- Particulate matter

The other indicators are quite close as well, although there is a clear reduction in importance for the second half of the indicators.



Some of the most recurring note-worthy comments made by the participants are listed below:

1. Climate Change: Climate change is consistently recognized as a significant concern associated with space missions. Some participants emphasize the wide-ranging impacts on humans, animals, vegetation, landscapes, and weather and a few mention the political interest in ranking it higher. Other participants .
2. Ozone Depletion: Participants mostly mention the high altitude emissions as a mai factor in ozone depletion
3. Resource Use: Participants highlight the use of minerals, metals, and other scarce resources in space missions.
4. Human Health: Some participants prioritize human health as the topmost concern, others weigh its impact against other factors.
5. Land Use: The land use associated with spaceports and the protection of nearby habitats is mentioned as an important consideration. Future fuels, such as sustainable aviation fuels (SAFs), and the location of some space facilities near nature are also highlighted.
6. Eutrophication: Some participants consider it less significant in the context of space missions, while others describe it as a factor that some may have limited knowledge.

Do you agree with the ranking and the above arguments? Elaborate.

Note: A brief summary on each impact category, as shown in the previous questionnaire, is given below

In the first questionnaire, you were asked the following question: "***Based on the description of the different impact categories and based on your knowledge, do you think these environmental impact categories describe fully the environmental sustainability of space missions?***"

Below are some of the suggested additional impact categories:

1. Space Debris: Several participants highlight the need to consider the impacts of space debris, such as the risks associated with debris accumulation and potential collisions.
    - This could be represented by the impact indicator described in ESA's 2016 LCA Handbook: **Mass left in Space**. It is described as: "Total mass of space hardware remaining in orbit at the end of the mission"
2. High Altitude Atmospheric Impacts: Mentioned by a limited number of participants, this category refers to the impacts that space missions can have on the atmosphere at high altitudes, potentially including effects on ozone depletion or other atmospheric processes.

- A possibility if to represent this by the impact indicator described in ESA's 2016 LCA Handbook: **Al2O3 emissions in air**. It is described as: "Emissions in air of alumine during launch event"

3. Orbital Resources: One participant suggests considering useful orbits and frequencies as natural resources in the context of space missions.
4. Light Pollution: A limited number of participants identified the absence of a category related to light pollution, which can arise from space missions and affect astronomical observations or ecological systems.
5. Biodiversity: One participant suggests that considering the impacts on biodiversity, particularly in relation to land use, could be relevant for a more comprehensive assessment.

Do you agree with the suggested new types of impact categories? Which of these (if any) do you agree most with? Please also comment on the necessity of each suggested impact category, based on your experience.

Are there any other impact categories that should be added and considered for a generic space mission?

As a general reminder for all the above questions, below is a short description of each impact category:

- **Climate change, total.** Emission of greenhouse gases changing temperature and the climate for the worse, impacting indirectly on the ecosystems, on natural resources and your health.
- **Ozone depletion.** Emissions damaging the ozone layer leading to increased ultraviolet radiation resulting in skin cancer.
- **Human Toxicity - cancer effects.** Emissions of toxic substances leading to an increased risk of cancer, for instance, through the air we breathe and indirectly through the food we eat and the water we drink.
- **Human Toxicity - non-cancer effects.** Emissions of toxic substances damaging your health, for instance, through the air we breathe and also indirectly through the food we eat and the water we drink.
- **Particulate matter.** Emissions of tiny particle, for instance, leading to respiratory diseases and the so-called “winter smog”.

- **Ionizing radiation, human health.** Radiation ("radioactivity") increasing the risk of cancer.
- **Photochemical ozone formation., human health.** Emissions creating, for instance, the so called “summer smog” and respiratory diseases.
- **Acidification.** Emission of substance leading, for instance, to acid rain and poorer quality of air, water and soil.
- **Eutrophication - terrestrial.** Too many nutrients in the environment, for instance by overuse of fertilisers in farming, upsetting the balance of nature.
- **Eutrophication - freshwater.** Too many nutrients in freshwater, for instance by the overuse of fertilisers in farming and release of wastewater, upsetting the balance of nature, e.g. leading to algal blooms and killing fish.
- **Eutrophication - marine.** Too many nutrients in marine water, for instance due to overuse of fertilisers in farming and release of wastewater, upsetting the balance of nature and leading to algal blooms in seawater.
- **Ecotoxicity - freshwater.** Emission of toxic substances that are a danger to organisms like fish, algae and other organisms living in fresh water.
- **Land use.** Use of land and soil endanger, such as soil fertility as well as the wellbeing and survival of some animals and plant species.
- **Resource use: metals and minerals.** Use of minerals, metals and other resources in products reducing their availability for future uses.
- **Resource use: fossil fuels.** Use of fossil fuels, reducing their availability for future uses

End of Block: Block 1

Start of Block: Block 2

Part 2/4: Prioritisation of Midpoint indicators during the design phase, for two types of space missions.

Based on the comments of the participants, the "generic space mission" discussed in the previous questionnaire is now detailed further in this questionnaire. Two main mission types around Earth were distilled from your comments: a **single spacecraft in orbit around Earth** and **an Earth-orbiting constellation mission**.

In this section, you will be asked to indicate in what impact indicator you would find most important to assess in order to make a decision between potential mission designs.

Below is a brief summary of each indicator. Note that the ESA defined **mass left in space** and **Al2O3 emissions in air** are also added.

- **Climate change, total.** Emission of greenhouse gases changing temperature and the climate for the worse, impacting indirectly on the ecosystems, on natural resources and your health.
- **Ozone depletion.** Emissions damaging the ozone layer leading to increased ultraviolet radiation resulting in skin cancer.
- **Human Toxicity - cancer effects.** Emissions of toxic substances leading to an increased risk of cancer, for instance, through the air we breathe and indirectly through the food we eat and the water we drink.
- **Human Toxicity - non-cancer effects.** Emissions of toxic substances damaging your health, for instance, through the air we breathe and also indirectly through the food we eat and the water we drink.
- **Particulate matter.** Emissions of tiny particle, for instance, leading to respiratory diseases and the so-called “winter smog”.
- **Ionizing radiation, human health.** Radiation ("radioactivity") increasing the risk of cancer.
- **Photochemical ozone formation., human health.** Emissions creating, for instance, the so called “summer smog” and respiratory diseases.
- **Acidification.** Emission of substance leading, for instance, to acid rain and poorer quality of air, water and soil.
- **Eutrophication - terrestrial.** Too many nutrients in the environment, for instance by overuse of fertilisers in farming, upsetting the balance of nature.
- **Eutrophication - freshwater.** Too many nutrients in freshwater, for instance by the overuse of fertilisers in farming and release of wastewater, upsetting the balance of nature, e.g. leading to algal blooms and killing fish.

- **Eutrophication - marine.** Too many nutrients in marine water, for instance due to overuse of fertilisers in farming and release of wastewater, upsetting the balance of nature and leading to algal blooms in seawater.
- **Ecotoxicity - freshwater.** Emission of toxic substances that are a danger to organisms like fish, algae and other organisms living in fresh water.
- **Land use.** Use of land and soil endanger, such as soil fertility as well as the wellbeing and survival of some animals and plant species.
- **Resource use: metals and minerals.** Use of minerals, metals and other resources in products reducing their availability for future uses.
- **Resource use: fossil fuels.** Use of fossil fuels, reducing their availability for future uses.
- **Mass left in Space:** Total mass of space hardware remaining in orbit at the end of the mission
- **Al2O3 emissions in air**: Emissions in air of alumine during launch event

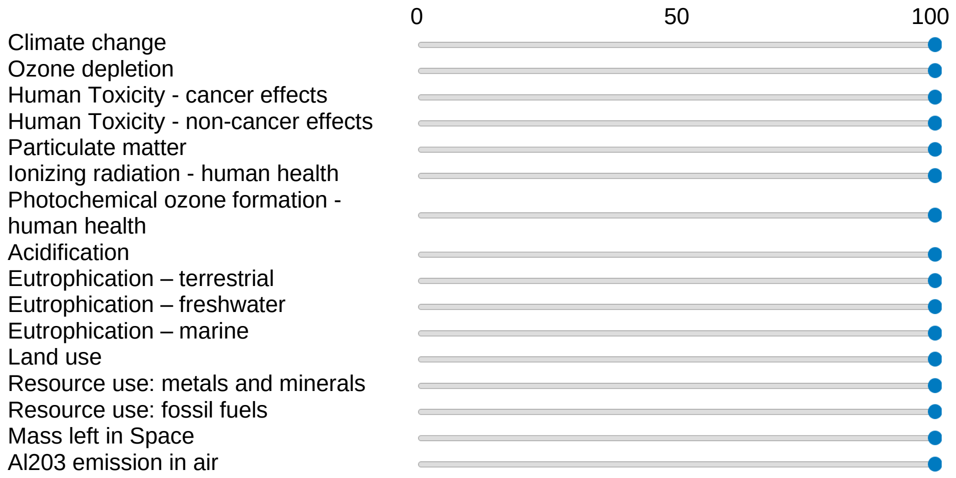
---

Assume that you are comparing the life-cycle assessment results of two variations of the **single spacecraft in Earth orbit mission** in order to choose which one to design further and eventually launch.

For this decision process, to what extent would you find a given indicator more important than another? Please rank them according to their relative importance in such a decision process.

That is, give the most important impact category a score of 100. If you find that the next category is only half as important, give it a score of 50. And so on.
If you consider some categories completely unimportant, give them a score of 0. If, otherwise, you think two or more categories have the same level of importance compared to the most important one, give them the same score. Similarly, you may also provide a score of 100 to multiple categories if they are equally high important in this decision process, according to you.
Note: Please click and drag the slider to indicate the score, also when indicating a score of 100

An example could be:
Acidification : 100
Resource use - metals and minerals : 100
Ecotoxicity - freshwater : 85
Human Toxicity - non-cancer effects : 45
All the rest are considered unimportant: score of 0



Based on your experience, do you think you would find (slightly) different impact indicators more important during the design phase of a single spacecraft mission in Earth orbit compared to an Earth-orbiting constellation?

☐ Yes

☐ No

If you answered Yes to the above question, please answer this question. Else, disregard it

Assume that you are comparing the life-cycle assessment results of two variations of the **Earth-orbiting constellation** in order to choose which one to design further and eventually launch.

For this decision process, to what extent would you find a given indicator more important than another? Please rank them according to their relative importance in such a decision process.

That is, give the most important impact category a score of 100. If you find that the next category is only half as important, give it a score of 50. And so on.
If you consider some categories completely unimportant, give them a score of 0. If, otherwise, you think two or more categories have the same level of importance compared to the most important one, give them the same score. Similarly, you may also provide a score of 100 to multiple categories if they are equally high important in this decision process, according to you.
Note: Please click and drag the slider to indicate the score, also when indicating a score of 100

An example could be:
Acidification : 100

Resource use - metals and minerals : 100
Ecotoxicity - freshwater : 85
Human Toxicity - non-cancer effects : 45
All the rest are considered unimportant: score of 0

0 50 100

Climate change
Ozone depletion
Human Toxicity - cancer effects
Human Toxicity - non-cancer effects
Particulate matter
Ionizing radiation - human health
Photochemical ozone formation - human health
Acidification
Eutrophication – terrestrial
Eutrophication – freshwater
Eutrophication – marine
Land use
Resource use: metals and minerals
Resource use: fossil fuels
Mass left in Space
Al203 emission in air

Could you provide a brief reasoning behind the ranking of some of these categories?

Did you have enough information on the two space mission to provide an accurate assessment? In your answer, please compare the level of information these space missions' specification (i.e. "single spacecraft in Earth Orbit" and "Earth-orbiting constellation") has brought, compared to the "generic space mission" specified in the first questionnaire.

If no, explain what information(s), if any, would make your answers change, <u>and how (much) it would change</u>. If yes, please explain briefly why your choice would remain the same.

End of Block: Block 2

Start of Block: Block 3

Part 3/4: Preferred representation of the results of a Life-Cycle Assessment during the mission design

This Part of the Questionnaire investigates how one should best present the results of a Life-Cycle Assessment, for it to be useful during various stages of the design. Below, the "generic space mission" is used again throughout the questions

The options include:

- **Values** for each **Endpoint Impact Category**: Human Health, Natural Environment, Natural Resources.
- **Values** for each **Midpoint Impact Category**: Climate change, Acidification., Eutrophication, Land use, Ozone depletion, Human Toxicity, Particulate matter, Ionizing radiation, Photochemical ozone formation, Resource use, and possibly (some of) the proposed indicators from the previous section
- A **Single Score** (presented as a value in an understandable unit e.g. Co2 eq/citizen, or as a percentage of some standard design or concept)

Assume that a Life-cycle Assessment is being performed at an **early design phase (Phase 0 or A)** for two options of a mission design of a **generic space mission**. Thus many details of the design are still uncertain and not fully defined.

How would you prefer the output of the LCA to be, in order to make a choice between the two designs? That is, what information would be sufficient and most useful from the outputs of the LCA for you to make a qualitative decision?

☐ Single score
☐ Values for each endpoint impact category (Human Health, Natural Environment, Natural Resources)
☐ Values for each midpoint impact category (Climate change, Acidification., Eutrophication, Land use, Ozone depletion, Human Toxicity, Particulate matter, Ionizing radiation, Photochemical ozone formation, Resource use, and possibly (some of) the proposed indicators from the previous section)
☐ Single score + Values for each endpoint impact category
☐ Single score + Values for each midpoint impact category
☐ Single score + Values for each endpoint impact category + Values for each midpoint impact category
☐ Values for each endpoint impact category + Values for each midpoint impact category

---

Assume that a Life-cycle Assessment is being performed at a **detailed design phase** for two options of a mission design of a **generic space mission**. Thus almost all aspects of the mission have been defined.

How would you prefer the output of the LCA to be, in order to make a choice between the two designs? That is, what information would be sufficient and most useful from the outputs of the LCA for you to make a qualitative decision?

☐ Single score
☐ Values for each endpoint impact category (Human Health, Natural Environment, Natural Resources)
☐ Values for each midpoint impact category (Climate change, Acidification., Eutrophication, Land use, Ozone depletion, Human Toxicity, Particulate matter, Ionizing radiation, Photochemical ozone formation, Resource use, and possibly (some of) the proposed indicators from the previous section)
☐ Single score + Values for each endpoint impact category
☐ Single score + Values for each midpoint impact category
☐ Single score + Values for each endpoint impact category + Values for each midpoint impact category
☐ Values for each endpoint impact category + Values for each midpoint impact category

Would your answers to the above two questions be dependent on the type of the mission? Please elaborate.

That is: If a specific mission type would have been provided (single satellite, constellation, etc), do you think you would have answered differently?

Could you comment on your choice of LCA result representation for each of these two design phases?
If there is a difference or if they are identical, please give your reasoning.

Did you have enough information to make a choice? Please elaborate

End of Block: Block 3

Start of Block: Block 4

Part 4/4: Pros and Cons of performing a LCA

With Life-Cycle Assessment gaining in popularity, various studies have attempted to map the reasons why one would want, or not want, to perform a LCA. Particularly the European Commission's Joint Research Centre has conducted such a widespread survey within the European general industry (see "Assessment of different communication vehicles for providing Environmental Footprint information" by F. Lupiáñez-Villanueva et al, 2021).

The Space Sector has not enjoyed such a detailed study, to my knowledge. Therefore, this section is meant to gain some first insights behind the drivers and inhibitors of space LCA.

Please answer the following questions relative to your own background and expertise.

LCA Drivers:
Please indicate to what extent you agree with the following statements on why LCA would be performed in your sector of expertise in the space sector.

LCA would be performed to...

	Disagree	Somewhat agree	Agree
... improve environmental management practices	☐	☐	☐
... improve customer satisfaction	☐	☐	☐
... increase awareness of employees in environmental issues	☐	☐	☐
... improve the reputation of the organization	☐	☐	☐
... increase the differentiation of our product/services	☐	☐	☐
... improve legal compliance	☐	☐	☐

... drive environmental improvements in products/organisations	☐	☐	☐
... be a tool to define environmental strategies and actions	☐	☐	☐
... increase sales of the product/service	☐	☐	☐
... create new marketing opportunities	☐	☐	☐
... improve the competitive advantage of organisations	☐	☐	☐
... involve top managers in environmental issues	☐	☐	☐
... increase the level of cooperation within the company	☐	☐	☐
... be a tool to identify environmental hotspots	☐	☐	☐
... improve the relations with the suppliers	☐	☐	☐
... improve the relations with public institutions	☐	☐	☐

<u>LCA Inhibitors:</u>

Please indicate to what extent you agree with the following statements why LCA would not be perform within your sector of expertise in the space sector.

One of the reasons why LCA would not be performed is...

	Disagree	Somewhat agree	Agree
... the high costs of experts involved	☐	☐	☐
... the difficulty collecting data from suppliers	☐	☐	☐
... the significant involvement of internal human ressources	☐	☐	☐
... the collection of data from supply chain	☐	☐	☐
... the difficulty to assess the quality of data	☐	☐	☐
... the definition of Systems boundaries	☐	☐	☐
... the difficult to find good quality data	☐	☐	☐
... that it is too time consuming	☐	☐	☐
... the definition of scope and object of the study	☐	☐	☐
... the certification/review of the study	☐	☐	☐
... the difficulty collecting data inside the organisation	☐	☐	☐
... the evaluation of data quality	☐	☐	☐
... related to the analysis and interpretation of the results	☐	☐	☐
... the definition of the functional unit	☐	☐	☐

... the software is too expensive	☐	☐	☐
... the difficulty coordinating internal and external resources	☐	☐	☐
... the difficulty to communicate the results	☐	☐	☐

End of Block: Block 4

I.3. Questionnaire 3

Space Sustainability Questionnaire 3

Start of Block: Default Question Block

Dear participant,

Thank you, once again, for participating to this survey on the environmental sustainability of space missions, as part of a MSc thesis research at the Delft University of Technology. This is the **third and last questionnaire** of the survey.

By proceeding with this survey and questionnaire, **you declare giving your consent** with regards to the purpose of this survey as well as the privacy and security statements given in the email.
If you like to review this, you may look back at the email, or look at the document linked here: « INSERT LINK »

This questionnaire contains 5 **parts, each with 2 to 6 questions**. The goal of this survey is to get closer to a common consensus.
As mentioned in the emails, **you are free to skip questions if you prefer**, although complete answers are of course preferable.

The most noteworthy results of this questionnaire will be shown to you at the beginning of next questionnaire and will be further built upon in the next questionnaires.

This Questionnaire should take **approximately 20-25 minutes**.

Please provide below your *Individual Code* (see email)**.**
Note: as mentioned in the email exchanges, this code will only be used to link your answers of this questionnaire with that of the subsequent ones. It will NOT be used during the analysis, nor will it be used to disclose your individual answers in the final thesis. Moreover, the list with names and corresponding Individual Codes will be deleted as soon as they are not relevant (after the third survey).

Please only proceed to the next parts if you completed the first two questionnaires. Refer to emails to find your link to those questionnaires, if you have not filled them in yet.

End of Block: Default Question Block

Start of Block: Block 1

Part 1/5: Relevant feedback from the previous survey

In this Part, you will find a summary of the relevant answers you and the other participants gave in the previous questionnaire, as well as some questions for you to reflect on the findings. Please study the figures and tables, and answer the questions based on your opinion and knowledge.

The data shown below is the summary of the answers of 22 participants or less (as is detailed for each summary below), with various expertise. While the final number of recorded answers is expected to rise since a few participants have not yet responded, the data provided is relevant enough to make first conclusions.

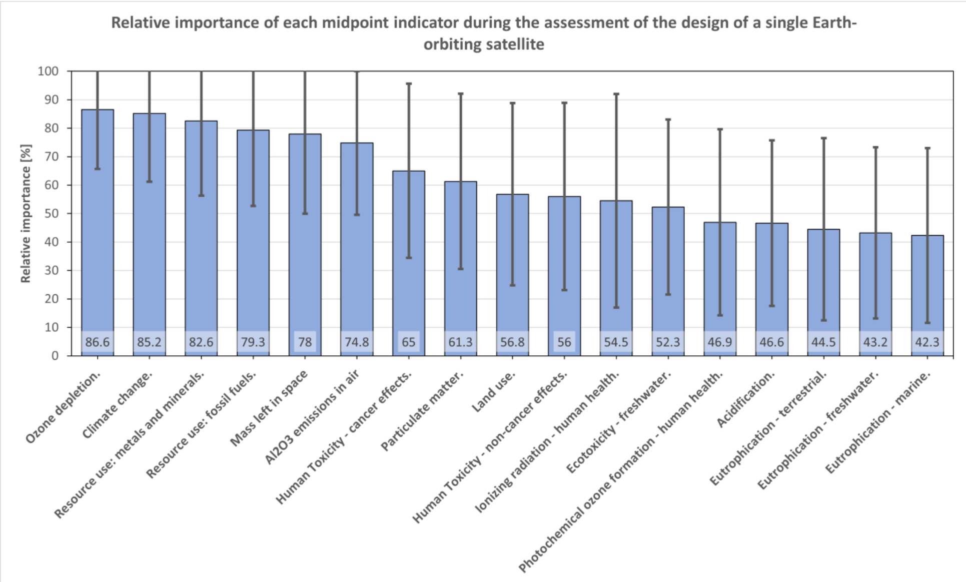
In the second questionnaire, you were asked the following question (paraphrased): "***In the decision process between two similar concepts for a <u>single Earth-orbiting satellite</u> space mission,*** to what extent would you find a given indicator more important than another?"

The figure below summarizes the average of all 22 participants' answers through the bar chart, as well as each answer's standard deviation (an indication of the spread of the answers compared to the average).

From the figure, it is clear that there is a significant spread of answers given. Nevertheless, one may reach the conclusion that the following indicators are most important (i.e. a score above 65%) during a design phase, according to the participants:

- Ozone depletion
- Climate change
- Resource use: metals and minerals
- Resource use: fossil fuels
- Mass left in Space
- Al203 emissions in air

The other indicators are quite close as well, although there is a clear reduction in importance for the second half of the indicators.



Half of the participants noted that they would prioritize (slightly) different Midpoint impact indicators for an Earth-orbiting constellation mission.

The figure below summarizes the average of the 11 participants' answers regarding their prioritization. It also shows each answer's standard deviation (an indication of the spread of the answers compared to the average).

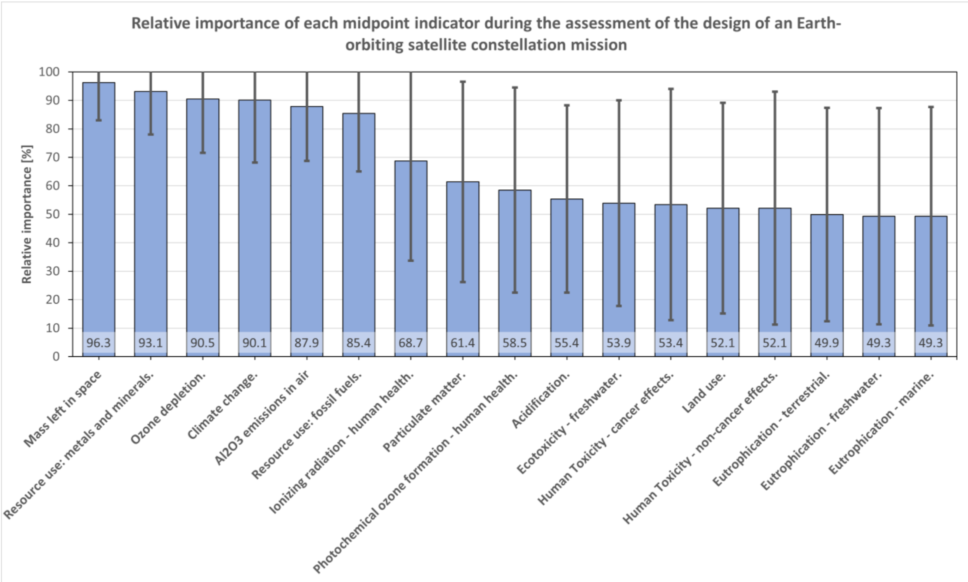
From the figure, it is clear that there is a significant spread of answers given (perhaps accentuated due to the lower number of participants who answered). Nevertheless, one may reach the conclusion that the following indicators are most important (i.e. a score above 65%) during a design phase, according to the participants:

- Mass left in Space
- Resource use: metals and minerals
- Ozone depletion
- Climate change
- Al203 emissions in air
- Resource use: fossil fuels
- Ionizing radiation - human health

Note that the first six indicators seem to have limited spread in answers compared to the other ones, and that there is a clear reduction in importance for the second half of the indicators.

It seems therefore that Mass left in Space and Ressource use (metals and minerals), as well as

Al203 emissions have gained some more importance



Does the above outcome for both mission types match your own opinion on the prioritisation of the midpoint indicators, based on your experience? Do particularly note the differences between each of the space missions.

In the previous Questionnaire, participants were subsequently asked the following question: "Could you provide a brief reasoning behind the ranking of some of these categories?"

Below is a summary of some of the points made regarding the differences between the two mission types:

- Most participants highlighted that there are **large similarities** between which impact categories one would find important for a single satellite mission versus a constellation.
- Many participants suggested that the increased number of satellites and debris of a constellations would cause **greater potential for collisions**, as well as an increase in **objects that re-enter**. Thus, they argued it is important to look at the Mass left in Space.

- Many participants underlined that a constellation would result in a higher number of launches, therefore an increased the **emissions in the upper atmosphere** (Al203 emissions amongst others)
- Constellation also require more **raw materials** and increased **production**, thus some participants stated that Ressource Use and Human toxicity should be prioritised further.

Do you agree with the above arguments, or are there points you consider missing or wrong? Elaborate.
Which of these points do you agree most with?

When asked whether or not enough information was provided for an accurate assessment, the opinions varied. Below is a summary of the points raised:

- Some indicated that dividing the "generic mission" into a single satellite mission and a constellation mission provided a bit more clarity.
- Others mentioned that the mission types were still too vague.
    1. It was highlighted by some participants that more quantitative data was needed, since no indication on the mass of the spacecraft(s) was provided, nor the number of satellites, type of orbit(s).
    2. Another suggestion made by one of the participants is to clarify whether the impacts are assessed as the total, overall, impacts, or rather as the impacts per mass of spacecraft launched

Do you agree with some of the above arguments? Which of these points do you agree most with? Elaborate.

During the suggestion round in the last questionnaire, you were asked whether or not the suggested additional Midpoint impact categories would be useful for the assessment of a space mission. While only "Mass left in Space" and "AL203 emission in air" were used for future analysis, the participants re-iterated that there should be other Midpoint impact categories included. Below is a summary of the re-emphasized suggestions:

1. An impact category or flow indicator to emphasize the fact that **orbits** could also be considered as "**ressources**" which can be depleted due to missions or space debris.
2. An impact category or flow indicator to highlight the **critical raw material use** for a space mission.
3. An impact category or flow indicator for the **re-entry particle and smoke creation**
4. An impact category or flow indicator **total cumulated energy** needed for the full life-cycle
5. An impact category or flow indicator regarding the **mass disposed in ocean** (in addition to the mass in space)
6. An impact category or flow indicator to show the extent to which **restricted substances** (as defined by the local regulatory body, such as REACH in the European Union) are used.

Which of these additional categories or flow indicators do you consider relevant, in addition to the mass left in space and Al2O3 emissions in air?
Please select as many as you like.

- ☐ Orbital resource depletion (3)
- ☐ Critical raw material use (4)
- ☐ Re-entry smoke particle generation (5)
- ☐ Cumulative energy demand (6)
- ☐ Total mass disposed in ocean (7)
- ☐ Restricted substance use (8)

Would you like to comment on your choice or on any impact categories that are mission?
Please do so here.

End of Block: Block 1

Start of Block: Block 3

Part 2/5: Updated prioritisation of Midpoint indicators during the design phase, for two types of space missions.

In this section, you will be asked to rank the importance of each midpoint indicator for each space mission again, using the feedback from Part 1. Note: you may at all times revert back to Part 1, if desired.

In order to provide way of ranking the midpoint categories that is more uniform between participants, it will be assumed that **the impacts of the full mission are assessed per unit of mass of spacecraft launched**. This, in fact, is one of the suggestions made by the participants, as shown in the previous Part of this Questionnaire. This reduces the effects of the spacecraft's size, mass and number, but would change the impacts computed in each category.

Please answer the question below based on your knowledge and the feedback you read previously. The objective would be to see if this allows one to approach a consensus even more.

Below is a brief summary of each indicator. Note that the newly suggested indicators and flows are also added.

- **Climate change, total.** Emission of greenhouse gases changing temperature and the climate for the worse, impacting indirectly on the ecosystems, on natural resources and your health.
- **Ozone depletion.** Emissions damaging the ozone layer leading to increased ultraviolet radiation resulting in skin cancer.
- **Human Toxicity - cancer effects.** Emissions of toxic substances leading to an increased risk of cancer, for instance, through the air we breathe and indirectly through the food we eat and the water we drink.
- **Human Toxicity - non-cancer effects.** Emissions of toxic substances damaging your health, for instance, through the air we breathe and also indirectly through the food we eat and the water we drink.
- **Particulate matter.** Emissions of tiny particle, for instance, leading to respiratory diseases and the so-called “winter smog”.
- **Ionizing radiation, human health.** Radiation ("radioactivity") increasing the risk of cancer.
- **Photochemical ozone formation., human health.** Emissions creating, for instance, the so called “summer smog” and respiratory diseases.

- **Acidification.** Emission of substance leading, for instance, to acid rain and poorer quality of air, water and soil.
- **Eutrophication - terrestrial.** Too many nutrients in the environment, for instance by overuse of fertilisers in farming, upsetting the balance of nature.
- **Eutrophication - freshwater.** Too many nutrients in freshwater, for instance by the overuse of fertilisers in farming and release of wastewater, upsetting the balance of nature, e.g. leading to algal blooms and killing fish.
- **Eutrophication - marine.** Too many nutrients in marine water, for instance due to overuse of fertilisers in farming and release of wastewater, upsetting the balance of nature and leading to algal blooms in seawater.
- **Ecotoxicity - freshwater.** Emission of toxic substances that are a danger to organisms like fish, algae and other organisms living in fresh water.
- **Land use.** Use of land and soil endanger, such as soil fertility as well as the wellbeing and survival of some animals and plant species.
- **Resource use: metals and minerals.** Use of minerals, metals and other resources in products reducing their availability for future uses.
- **Resource use: fossil fuels.** Use of fossil fuels, reducing their availability for future uses.
- **Mass left in Space:** Total mass of space hardware remaining in orbit at the end of the mission
- **Al2O3 emissions in air**: Emissions in air of alumine during launch event
- **Orbital resource depletion:** Space debris crossing the orbital resource
- **Critical raw material use:** Supply risk
- **Re-entry smoke particle generation**
- **Cumulative energy demand:** Primary energy consumption
- **Total mass disposed in ocean**
- **Restricted substance use:** Risk assessment

Assume that you are comparing the life-cycle assessment results of two variations of the **single spacecraft in Earth orbit mission** in order to choose which one to design further and eventually launch.

For this decision process, to what extent would you find a given indicator more important than another? Please rank them according to their relative importance in such a decision process.

That is, give the most important impact category a score of 100. If you find that the next category is only half as important, give it a score of 50. And so on.
If you consider some categories completely unimportant, give them a score of 0. If, otherwise, you think two or more categories have the same level of importance compared to the most important one, give them the same score. Similarly, you may also provide a score of 100 to multiple categories if they are equally high important in this decision process, according to you.
Note: Please click and drag the slider to indicate the score, also when indicating a score of 100

An example could be:
Acidification : 100
Resource use - metals and minerals : 100
Ecotoxicity - freshwater : 85
Human Toxicity - non-cancer effects : 45
All the rest are considered unimportant: score of 0

	0	50	100
Climate change			
Ozone depletion			
Human Toxicity - cancer effects			
Human Toxicity - non-cancer effects			
Particulate matter			
Ionizing radiation - human health			
Photochemical ozone formation - human health			
Acidification			
Eutrophication – terrestrial			
Eutrophication – freshwater			
Eutrophication – marine			
Land use			
Resource use: metals and minerals			
Resource use: fossil fuels			
Mass left in Space			
Al203 emission in air			
Orbital resource depletion			
Critical raw material use			
Cumulative energy demand			
Total mass disposed in ocean			
Restricted substance use			

Based on your experience and on the previous feedback, do you think you would find (slightly) different impact indicators more important during the design phase of a single spacecraft mission in Earth orbit compared to an Earth-orbiting constellation?

- ☐ Yes
- ☐ No

If you answered Yes to the above question, please answer this question. Else, disregard it

Assume that you are comparing the life-cycle assessment results of two variations of the **Earth-orbiting constellation** in order to choose which one to design further and eventually launch.

For this decision process, to what extent would you find a given indicator more important than another? Please rank them according to their relative importance in such a decision process.

That is, give the most important impact category a score of 100. If you find that the next category is only half as important, give it a score of 50. And so on.
If you consider some categories completely unimportant, give them a score of 0. If, otherwise, you think two or more categories have the same level of importance compared to the most important one, give them the same score. Similarly, you may also provide a score of 100 to multiple categories if they are equally high important in this decision process, according to you.
Note: Please click and drag the slider to indicate the score, also when indicating a score of 100

An example could be:
Acidification : 100
Resource use - metals and minerals : 100
Ecotoxicity - freshwater : 85
Human Toxicity - non-cancer effects : 45
All the rest are considered unimportant: score of 0

	0	50	100
Climate change			
Ozone depletion			
Human Toxicity - cancer effects			
Human Toxicity - non-cancer effects			
Particulate matter			
Ionizing radiation - human health			
Photochemical ozone formation - human health			
Acidification			
Eutrophication – terrestrial			
Eutrophication – freshwater			
Eutrophication – marine			
Land use			
Resource use: metals and minerals			
Resource use: fossil fuels			
Mass left in Space			
Al203 emission in air			
Orbital resource depletion			
Critical raw material use			
Cumulative energy demand			
Total mass disposed in ocean			
Restricted substance use			

Could you provide a brief reasoning behind the ranking of some of these categories?

Would you like to comment on any the level of information provided to you? Did you have enough information on the two space mission and the assessment of the impact categories to provide an accurate judgement?

End of Block: Block 3

Start of Block: Block 3

Part 3/5: Prioritisation of Midpoint indicators without the launch segment

In this section, you will be asked to indicate which impact indicators you would find the most important, if the launch segment would be omitted from the space mission's Life-Cycle Assessment. This is done because most of the participants indicated in the first questionnaire that the launch segment would be a major cause of environmental impacts most space missions' LCA.

As such, assume that **the launch, the launcher and the launcher's production and testing are excluded from the LCA**. Please consider again a **generic space mission** and the fact that the **impacts would be assessed per mass of spacecraft**. You will have the opportunity to comment on any changes you would expect if a more specific mission would have been used as an example.

Thus, assume that you are comparing the life-cycle assessment results of two variations of a **generic space mission** in order to choose which one to design further and eventually launch.

For this decision process, to what extent would you find a given indicator more important than another? Please rank them according to their relative importance in such a decision process.

That is, give the most important impact category a score of 100. If you find that the next category is only half as important, give it a score of 50. And so on.
If you consider some categories completely unimportant, give them a score of 0. If, otherwise, you think two or more categories have the same level of importance compared to the most important one, give them the same score. Similarly, you may also provide a score of 100 to multiple categories if they are equally high important in this decision process, according to you.
Note: Please click and drag the slider to indicate the score, also when indicating a score of 100

An example could be:
Acidification : 100
Resource use - metals and minerals : 100
Ecotoxicity - freshwater : 85
Human Toxicity - non-cancer effects : 45
All the rest are considered unimportant: score of 0

Climate change
Ozone depletion
Human Toxicity - cancer effects
Human Toxicity - non-cancer effects
Particulate matter
Ionizing radiation - human health
Photochemical ozone formation - human health
Acidification
Eutrophication – terrestrial
Eutrophication – freshwater
Eutrophication – marine
Land use
Resource use: metals and minerals
Resource use: fossil fuels
Mass left in Space
Al203 emission in air
Orbital resource depletion
Critical raw material use
Cumulative energy demand
Total mass disposed in ocean
Restricted substance use

Would you like to comment on your ranking of the midpoint indicators and flows? How (if at all) would your ranking have changed per mission type? Please elaborate

End of Block: Block 3

Start of Block: Block 1

Part 4/5: General rating of a space mission - Beyond environmental sustainability

While performed as part of a MSc thesis at the Delft University of Technology, this thesis research is also done in collaboration with Space Sustainability Rating (SSR), located in Lausanne, Switzerland. Their fully operational space mission rating system already includes various topics (e.g. space debris potential, adherence to end-of-life guidelines, transparency in data sharing, etc) and is being used by a number of companies to understand, improve and communicate on the level of sustainability of their operations.

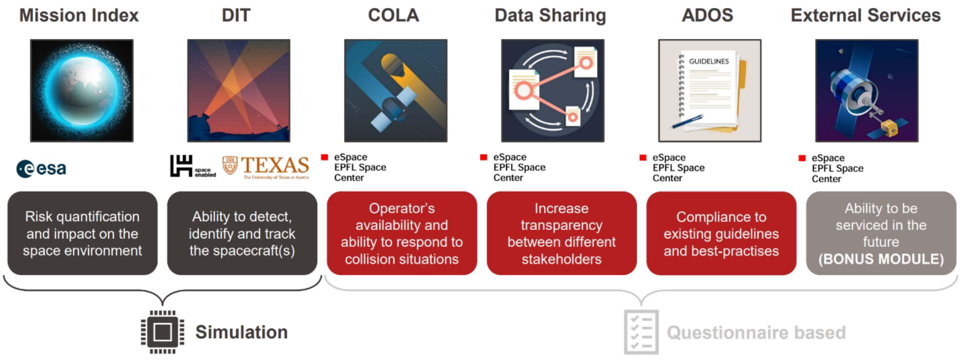
The SSR is a non-profit organization (which was hosted by the EPFL Space Center before transitioning to an independent structure) currently investigating the possibility of adding an LCA module in the rating system to make the assessment ever more comprehensive and relevant .

As such, this Part of the questionnaire requires you to give your input on how you would see the LCA module and other modules in development would best be weighted together.

A compact visualization of the current modules is shown in the image below. These modules are evaluated using a simulation and/or answers from questionnaires as indicated on the image. Additionally, an analysis is done on the level of verifiability of the data provided and the level of verification by technical authorities. Then, finally, all the results are weighted and aggregated into a final score with associated tiers (Bronze, Silver, Gold and Platinum).

An explanation of the abbreviations shown is given here:

- DIT: Detectability, Identification, and Trackability
- COLA: COLision Avoidance Capabilities
- ADOS: Application of Design and Operation Standards



Below is a more detailed description of each of the current modules, taken from SSR's website. For a deeper dive into this, you may look at SSR's webpage on the topic.

- **Mission index:** Any mission and object associated therewith leaves a trace in orbit. In the best case, it is only using a portion of the space environment, sustainably. In the worst case, it will cause harmful interference with other objects in the environment. This module quantifies the level of harmful physical interference caused by the planned design and mission operations considering mission characteristics, collision avoidance strategy, and post mission disposal strategy.
- **Detectability, Identification & Trackability (DIT):** Small objects, which might be operational but cannot be reliably included in space surveillance and tracking products, form a risk to other objects in the space environment. Moreover, identification is required for registration and liability purposes. This module aims to cover these aspects. As space surveillance and tracking capabilities improve and become more accurate in tracking satellites, this module is expected to undergo updates with each SSR version.
- **Collision Avoidance Capabilities (COLA):** In absence of a perfect space surveillance capability and depending on the operators' capabilities, there are various ways a mission can choose to operate in a congested environment. This module aims to emphasise the steps which can be taken by operators to reduce the risk of accidental collision with debris and among active operators.
- **Data Sharing:** Sharing of space situational awareness and other information by operators is critical to space safety. At the same time, some operators have sensitivities about sharing certain kinds of information. In other cases, operators simply do not share certain information, but have no particular objection to potentially doing so. This module quantifies the amount of relevant information an operator shares with various communities and the contribution of this information to spaceflight safety.
- **Application of Design & Operations Standards (ADOS):** Successfully addressing the problem of space sustainability when it comes to avoiding the creation of space debris and operating in congested environments can only be achieved by means of common

understanding and objectives. As such, a part of the SSR's emphasis is placed on the adoption of standardisation concepts in design and operations where possible.

- **External Services:** Innovations taking place in the area of close proximity operations have the potential to improve space sustainability and as such are of interest. However, their application can be widely different for individual mission concepts. Thus, they are considered relevant for **bonus ratings**. As external services develop and are successfully proven and utilized, the External Services module of the SSR will be updated accordingly.

If you were to define the weighting of the current modules, how much importance would you give to each each module? Please answer this question bearing in mind your experience and knowledge of the space sector, and in a way that the weighting would be applicable for most types of Earth orbiting space mission.

Give the most important module a score of 100. If you find that the next module is only half as important, give it a score of 50. And so on.
If you consider some module(s) completely unimportant, give them a score of 0. If, otherwise, you think two or more modules have the same level of importance compared to the most important one, give them the same score. Similarly, you may also provide a score of 100 to multiple modules if they are of equally high importance.
Note: Please click and drag the slider to indicate the score, also when indicating a score of 100

An example could be:
ADOS : 100
Data sharing : 100
DIT : 85
COLA : 45
All the rest are considered unimportant: score of 0

	0	50	100
Mission index			
Detectability, Identification, and Trackability (DIT)			
COLision Avoidance Capabilities (COLA)			
Data Sharing			
Application of Design and Operation Standards (ADOS)			
External Services			

Could you provide a brief reasoning behind the ranking of some of these modules?

There are currently efforts underway to develop more modules to extend the rating further. Below is a short description of each of these additional modules that are being developed:

- **LCA Module:** The assessment of the impact of a space mission through the LCA methodology
- **Launch Vehicle Sustainability Rating Module:** The assessment of the sustainability of launch vehicles (rockets, space planes and other more novel techniques), by means of a questionnaire.
- **Dark Skies Module:** The assessment of a space mission's impact on optical astronomy from Earth.
- **Quite Skies Modules:** The assessment of a space mission's impact on radio-astronomy from Earth.

The goal would be to combine (some of) the additional modules to the current modules in some way. This could be as part of the core modules used for the final score, or in the shape of bonus modules, used for an additional bonus score.

If you were to define the weighting of all these modules compared to one another, how much importance would you give to each each module? Please answer this question bearing in mind your experience and knowledge of the space sector, and in a way that the weighting would be applicable for most types of Earth orbiting space mission.

Give the most important module a score of 100. If you find that the next module is only half as important, give it a score of 50. And so on.
If you consider some module(s) completely unimportant, give them a score of 0. If, otherwise, you think two or more modules have the same level of importance compared to the most important one, give them the same score. Similarly, you may also provide a score of 100 to multiple modules if they are of equally high importance.
Note: Please click and drag the slider to indicate the score, also when indicating a score of 100

An example could be:
ADOS : 100
Dark Skies Module : 100
DIT : 85
COLA : 45
All the rest are considered unimportant: score of 0

	0	50	100
Mission index			
Detectability, Identification, and Trackability (DIT)			
COLision Avoidance Capabilities (COLA)			
Data Sharing			
Application of Design and Operation Standards (ADOS)			
External Services			
LCA Module			
Launch Vehicle Sustainability Rating Module			
Dark Skies Module			
Quite Skies Module			

Could you provide a brief reasoning behind the ranking of some of these modules?

End of Block: Block 1

Start of Block: Block 5

Part 5/5: Commenting and authorization to give contact details to SSR

Thank you very much for taking part of this survey. Your contribution is highly valued and will provide important insights into sustainability of space missions and on how to create a single score.

Would you like to provide any comment or feedback on the survey, its expected results, the procedure or any other topic? Feel free to do so here

Since this is the very last Part of the questionnaire, you are be given the option to indicate whether or not you allow me to cite your participation using your company or organisation's name (as in: "an employee of <this company> participated in the survey"). Moreover, you will be able to indicate if you want to receive the conclusions of this study and whether you would allow Space Sustainability Rating (SSR) to have your contact details for future use.

If you answer yes to any (or all) of these question, you will be redirected to a new mini-questionnaire upon clicking the NEXT button (the button with the arrow, on the bottom right). This mini-questionnaire will ask you for your name, title and email address in order for this to be either forwarded to SSR or used to send you the conclusion of this study.

Note that your contact details are not asked directly within this questionnaire because of the anonymity constraint. The new mini-questionnaire will not be linked in any way to this one, thus preserving the anonymity of your answers here.

In order to give weight to your participation in this survey and to the study as a whole, would you allow me to mention your company's name (or the name of any organisation you feel most affiliated with) as having participated to the survey?
You can expect the EUCASS paper or the MSc thesis document to list the companies/organisations where the participants (who allowed this to be mentioned), are from. This would likely be in the form of a brief bullet point list, or in one sentence.

- ☐ Yes
- ☐ No

Would you like to receive the conclusions of this survey in the future?
This would likely be in the form of a paper for the upcoming EUCASS conference (9-13th July). If major new findings are made, you might also receive the final thesis report (expected in September).

- ☐ Yes
- ☐ No

Do you allow Space Sustainability Rating (SSR) to have your contact details?
SSR is always keen on engaging with sustainability-oriented space actors, allowing to build a strong network pushing for the sustainability of space activities. They might reach out to you to propose you to participate in the future rating's development discussions, or for possibilities to use the Space Sustainability Rating. They will not use it to send you unnecessary spam emails.

- ☐ Yes
- ☐ No

End of Block: Block 5

I.4. Questionnaire 4

Space Sustainability Questionnaire 2

Start of Block: Default Question Block

Dear participant,

Thank you, once again, for participating to this survey on the environmental sustainability of space missions, as part of a MSc thesis research at the Delft University of Technology. This is the **second questionnaire** of the survey.

By proceeding with this survey and questionnaire, **you declare giving your consent** with regards to the purpose of this survey as well as the privacy and security statements given in the email.
If you like to review this, you may look back at the email, or look at the document linked here:
« INSERT LINK »

This questionnaire contains **4 parts, each with 2 to 7 questions**. It is aimed at understanding your expertise, your opinion on current sustainability efforts and your initial assessment of the aspects of sustainability on a space mission has the biggest impact.
As mentioned in the emails, **you are free to skip questions if you prefer**, although complete answers are of course preferable.

The most noteworthy results of this questionnaire will be shown to you at the beginning of next questionnaire and will be further built upon in the next questionnaires.

This Questionnaire should take **approximately 20 minutes**.

Please provide below your *Individual Code* (see email)**.**
Note: as mentioned in the email exchanges, this code will only be used to link your answers of this questionnaire with that of the subsequent ones. It will NOT be used during the analysis, nor will it be used to disclose your individual answers in the final thesis. Moreover, the list with names and corresponding Individual Codes will be deleted as soon as they are not relevant (after the third survey).

Click or tap here to enter text.

Please only proceed to the next parts if you completed the first questionnaire. Refer to the first invitation email to find your link to the first questionnaire, if you have not filled it in yet.

End of Block: Default Question Block

Start of Block: Block 1

Part 1/1: Including Water Use

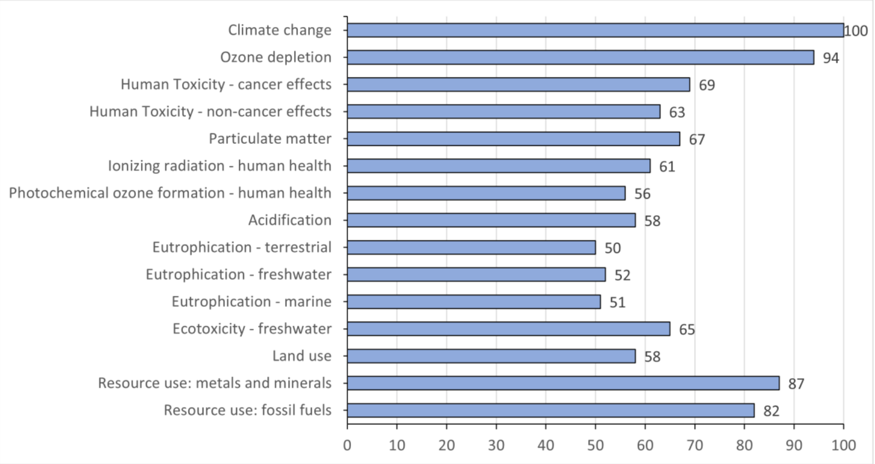
In this section, you are asked to **rank the importance of Water Use compared to the other midpoint indicators**. For this, you are shown below the the average ranking of each midpoint indicator, based on the answers of the participants in previous survey.
Below, you are asked to provide this ranking for 4 cases where the impacts are caculated per mass of the satellite:

- A generic mission, with the launch segment A generic mission without the launch segment
- A single-satellite mission, with launch segment
- A single-satellite mission, with launch segment

Generic mission with launch segment

In Questionnaire 1, you were asked to assume that a comparison of the life-cycle assessment results between two variations of a **generic space mission,** including the launch segment, is to be done to choose one to design further and eventually launch.
The question asked was: "**For this decision process, to what extent would you find a given indicator more important than another?** Please rank them according to their relative importance in such a decision process."

Below is the average scores the participants have given to each impact categories. Note that only the standard PEF impact categories were given in that questionnaire.



If you need a more detailed description of each of these impact categories (including the space-specific ones, added in the next questions), open the document linked below: « INSERT LINK »

Given the above scores, **what score would you give to Water Use**, in terms of its importance in the comparison between the two generic mission design variants?

As a reminder, the scoring works as follows: the most important impact category has a score of 100, and the next most important one has a score proportional to that. If one finds that the next category is only half as important, one gives it a score of 50. And so on.

If some categories are considered completely unimportant, a score of 0 is to be given. If, otherwise, two or more categories are considered to have the same level of importance compared to the most important one, they are given the same score. Similarly, one may also provide a score of 100 to multiple categories if they are equally high important in this decision process.

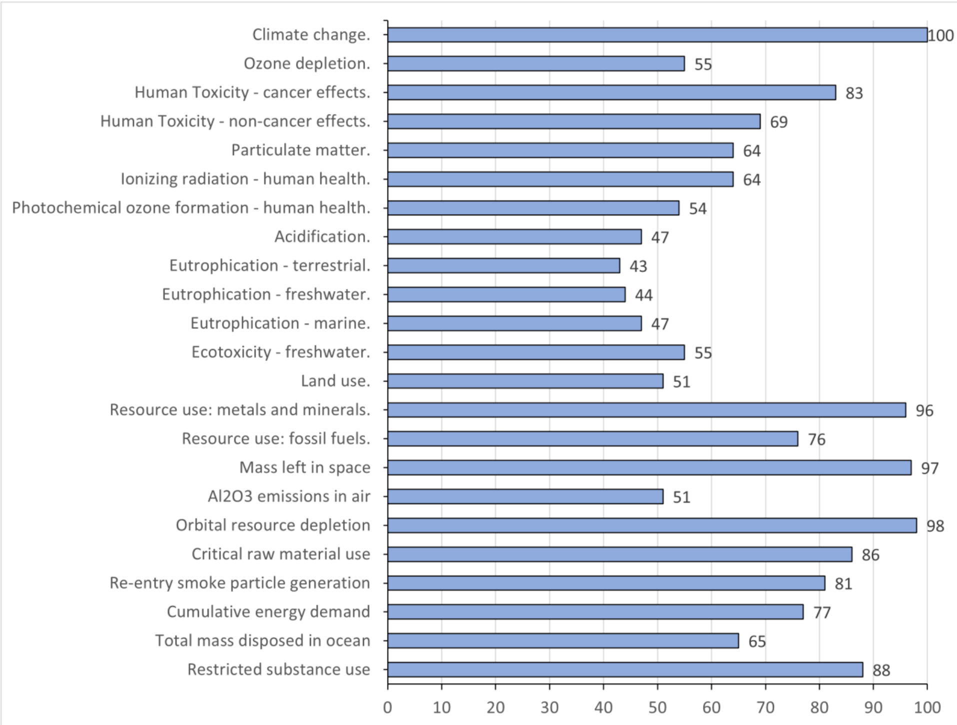
Note: Please click and drag the slider to indicate the score, also when indicating a score of 100

	0	50	100
Water Use			

Generic mission without launch segment

In Questionnaire 3, you were asked to assume a similar comparison of the LCA results between two variations of a **generic space mission**, but without the launch segment
Again, the question asked was: "**For this decision process, to what extent would you find a given indicator more important than another?** Please rank them according to their relative importance in such a decision process."

Below is the average scores the participants have given to each impact categories.



Given the above scores, **what score would you give to Water Use**, in terms of its importance in the comparison between the two generic mission design variants? Note that the impacts are here assumed to be calculated as **impacts/mass of the satellite launched**.

The scoring works identically to the previous question
Note: Please click and drag the slider to indicate the score, also when indicating a score of 100

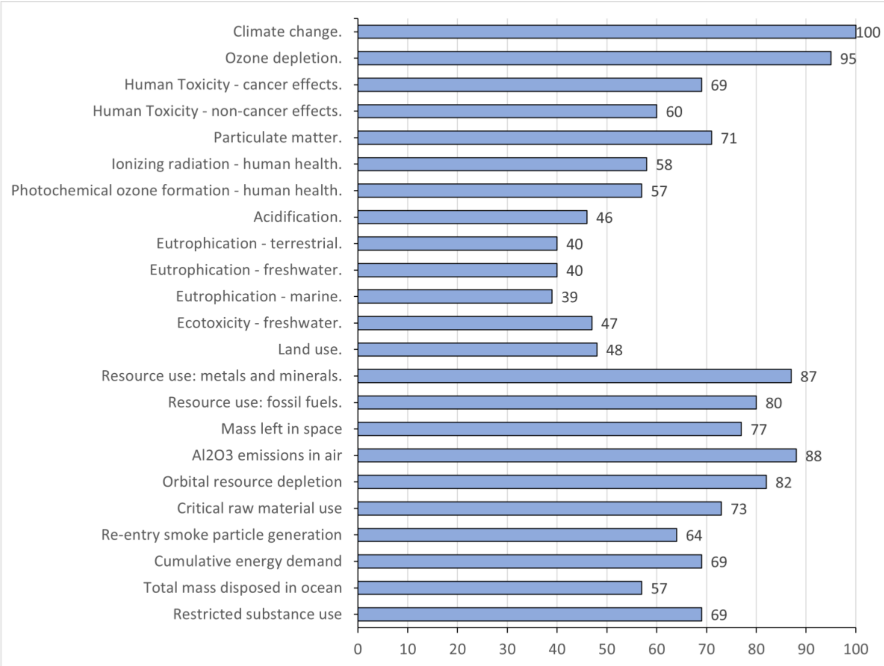
	0	50	100
Water Use			

Page 4 of 6

Single-Satellite mission with launch segment

In Questionnaire 3, you were asked to assume a similar comparison of the LCA results between two variations of a **single-satellite space mission**, with the launch segment
The question asked was: "**For this decision process, to what extent would you find a given indicator more important than another?** Please rank them according to their relative importance in such a decision process."

Below is the average scores the participants have given to each impact categories.



Given the above scores, **what score would you give to Water Use**, in terms of its importance in the comparison between the two single-satellite mission design variants? Note that the impacts are here assumed to be calculated as **impacts/mass of the satellite launched**

The scoring works identically to the previous question
Note: Please click and drag the slider to indicate the score, also when indicating a score of 100

0 50 100

Water Use

Page 5 of 6

Constellation mission with launch segment

Based on your experience, do you think you would find score Water Use (slightly) differently during the design phase of a single spacecraft mission in Earth orbit compared to an Earth-orbiting constellation?

☐ Yes
☐ No

If you answered Yes to the above question, please answer this question. Else, disregard it

Please indicate **how you would score Water Use for a constellation mission**, in terms of its importance in the comparison between the two constellation mission design variants? Note that the impacts are here assumed to be calculated as **impacts/mass of the satellite launched**.

The scoring works identically to the previous question
Note: Please click and drag the slider to indicate the score, also when indicating a score of 100

	0	50	100
Water Use			

General Comment

Would you like to comment on your previous scorings?

End of Block: Block 1