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A Consensus-Based Single-Score for Life Cycle Assessment of Space Missions: Preliminary Results

Marnix Verkammen[1⋆], *Andrew R. Wilson*[2], *Guillermo Dominguez Calabuig*[2], *Alessandra Menicucci*[1],
Håkan Svedhem[1], *Mathieu Udriot*[3]

⋆ Corresponding author: m.h.g.verkammen@student.tudelft.nl
[1] Faculty of Aerospace Engineering of the Delft University of Technology: Kluyverweg 1, 2629 HS Delft, the Netherlands
[2] Aerospace Centre of Excellence, Department of Mechanical & Aerospace Engineering, University of Strathclyde: 75 Montrose Street, G1 1XJ, Glasgow, United Kingdom
[3] eSpace - EPFL Space Center: PPH 335 Station 13, CH-1015 Lausanne, Switzerland

Abstract

With a continuously growing number of satellites in orbit, it becomes increasingly important to assess their impacts on the Earth's environment in a standardised manner. While interest in Life Cycle Assessment (LCA) for space missions has gained in strength in the past few years - particularly in Europe - no consensus has yet been reached on a single-score LCA system. In parallel however, scoring systems for other sustainability aspects have been defined and are increasingly being used in the industry.

A notable example is that of the Swiss-based Space Sustainability Rating (SSR) non-profit organization. It aims to incentivise sustainable behaviors in space through a quantitative and qualitative assessment of the sustainability level of a mission. Several criteria are considered for this such as collision avoidance, post-mission disposal strategy, compliance to existing space debris mitigation standards, detectability and trackability, data sharing, and readiness level to active removal.

This paper presents the preliminary results of a feasibility study for creating a single-score LCA module of the SSR. The focus of the study lies in the identification of the initial inputs and the methodology to assess them, as well as the weighting method to reach a single-score. A global survey, with a European focus, has been conducted for this study and its conclusions are used to provide an initial discussion on the weighting method to be used.

Overall, this paper highlights the importance of an easy-to-understand LCA tool for space systems. It shows the necessity for a tool that is implementable during the design phase of the mission, to incentivise space actors to opt for more sustainable materials and designs, and to reassess their logistics. To that effect, this paper presents a literature review about LCA, explores consensus-based weights for a single score, highlights perceived benefits and drawbacks of doing a space LCA, investigates new weights for SSR and underlines the main aspects which still need further development and investigation.

1. Introduction

Sustainability is an increasingly important global topic, with the space sector now also making concentrated efforts to operate in a more environment-friendly way. To quantify the environmental impacts of space systems, Life Cycle Assessment (LCA) was identified as the most appropriate methodology by the European Space Agency (ESA). With ESA at the helm, the European space sector seems to be at the forefront of LCA implementation, while other parts of the world are beginning to follow suit. To enable a more simple use of LCA, efforts are being made to convert its multi-dimensional results into an easy-to-understand and acceptable single-score, useful for eco-design.

However, the methodology for generating such a single-score has been controversial within the space industry, as it inevitably involves a certain degree of subjectivity. This paper aims to provide an approach to limit this through a consensus-based approach which involves seeking expert opinions within the space sector through a survey and presenting its preliminary conclusions. Moreover, the survey aims to shed light on the segments and life cycle phases of a space mission which are considered to have the greatest environmental impact, as well as on the drivers and inhibitors behind space LCA.

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This research is part of a Master's Thesis at the Delft University of Technology [1] which is being conducted in collaboration with the Space Sustainability Rating initiative and the eSpace Center of the Swiss Federal Institute of Technology in Lausanne (EPFL). The paper presents the preliminary findings of this research - the final and more detailed results of which can be found in the thesis once published. However, this paper is split into six sections, with the first providing the introduction. A background on sustainability worldwide and efforts made in the space industry is presented in Section 2. The procedure, rationale and contents of the survey are presented in Section 3, while the results are shown in Section 4. A discussion on the findings is provided in Section 5, ahead of a final conclusion for this paper in Section 6.

2. Background

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 were some of the first wake-up calls on the vulnerability of our planet to anthropogenic loadings [2]. Recent findings suggest that failure to make drastic changes in current practices and policies over the next two decades, could result in the sixth mass extinction, the onset of which might already be visible [3].

Defining the term "sustainability" has been an interactive process, believed to evolve further depending on new environmental challenges societies will face [4]. A definition was 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" [5]. This was further refined by decomposing the concept of 'needs' into an environmental, a social and an economic dimension, which was most recently also written down in the 2015 Paris Agreements [6]. It resulted in an international agreement on actionable goals through the seventeen Sustainable Development Goals and their associated targets [7, 8], with the aim to limit the global temperature rise to 1.5 degrees above the pre-industrial times [9].

This section dives into the development of LCA to quantify sustainability in Section 2.1 and into the European standardised single-score of the Product Environmental Footprint in Section 2.2. A closer look at LCA in the space sector and at efforts to simplify space LCA's results in a single-score are provided in Section 2.3 and Section 2.4 respectively. A brief description of the SSR non-profit organisation is given in Section 2.5

2.1 Life Cycle Assessment as a tool to quantify sustainability

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. This has led to the mature and comprehensive methodology it is today, compiling and evaluating the inputs, outputs and the environmental impacts of a product/service throughout its lifetime [10].

The LCA methodology is set out in two international standards. ISO 14040:2006 provides the principles and framework [11] whilst ISO 14044:2006 provides the requirements and guidelines [12]. As far as the reporting of the results is concerned, the second standard states that practitioners can choose the impact categories they find relevant, provided appropriate arguments are given and international practices are mostly followed [11]. For this paper, the midpoint categories defined by the European Union (EU), discussed in Section 2.2, are used.

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 [13]. 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 [13].

2.2 European standard in normalising and weighting of the results: the Product Environmental Footprint (PEF)

In order to create a common method for the assessment and communication of the life cycle performance of products and/or organisations across the EU, the Joint Research Center (JRC) of the European Commission devised a weight for each midpoint impact category, so as to transform them into single-score. That is, they developed weights for each category, shown in Table 1, 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 took 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 Product Environmental Footprint (PEF) approach [14, 15].

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Midpoint impact category	PEF weight	Midpoint impact category	PEF weight
Climate change	12.90	Acidification	4.94
Ozone depletion	5.58	Eutrophication, terrestrial	2.95
Human toxicity, cancer effects	6.80	Eutrophication, freshwater	3.19
Human toxicity, non-cancer effects	5.88	Eutrophication, marine	2.94
Particulate matter	5.49	Ecotoxicity freshwater	6.12
Ionizing radiation, human health	5.7	Land use	9.69
Photochemical ozone formation, human health	4.76	Water use	9.04

Table 1: PEF weights, as defined by the European Commission's Joint Research Center [15]

2.3 Life cycle Assessment in the space sector

The space sector is unique compared to other industries because of specific aspects relating to the design, production, utilisation and disposal. The design phase is usually particularly long, with movements of people across large distances or between countries for multinational mission contracts. The production often is very limited compared to a typical mass-producing commercial industry and requires materials and a production process unique to the space sectors. The testing and assembly facilities are generally dedicated to the sector and may have high power demands. The utilisation phase spans a long time - 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 [16, 17, 18].

Despite the space sector being exempted from historical climate agreements due to its unique specificities, sustainability is increasingly on the agenda. LCA is also considered as the main tool, as recommended by the Guidelines for the Long-term Sustainability of Outer Space Activities by the Committee on the Peaceful Uses of Outer Space's Guidelines [19]. 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 [20] . This growth in recent years is likely to have continued.

2.3.1 Europe at the leading edge of space LCA

In order to provide guiding principles for LCA practices in the European space industry, ESA developed a common framework on space sustainability. It includes the publication of ESA's Space System LCA Guidelines and their database [17], in which a methodology is set out on how to perform a space LCA and on what scope should be chosen per design phase. It defines the environmental indicators which ought to be assessed, and provides rules on how to do so. Moreover, it defines two general functional units, depending on the intended scope of the LCA, and highlights the importance of good communication of a LCA's end results. A new version of the Guidelines is being developed [21], while extensive feedback is being given on the current document, mainly regarding availability of precise data for LCA and some uncertainties depending on the design phase [22, 23, 24].

To improve 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 [24]. Whilst some developed these for internal use only, others such as the University of Strathclyde's 'Strathclyde Space Systems Database (SSSD)' have been made open-source. Beyond complementing ESA's LCA methodology, the SSSD is aimed towards performing integrating space Life Cycle Sustainability Assessment (LCSA) into the concurrent design process. [25] This includes environmental impacts through Environmental-LCA (E-LCA), referred to as LCA in this paper, as well as social impacts through Social-LCA (S-LCA) and economic ones through Life Cycle Costing (LCC) [25]. 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. [26]

2.3.2 Global efforts towards space LCA implementation

While Europe seems to be the centre of development in space-related LCA, other parts of the world have not yet made an equal amount of progress in the topic. In the United States of America (USA), only a limited number of studies have been conducted, most of which were limited to a small scope or could be considered as being unaligned with international best practices [27]. It is argued that this could be the consequence of the uncommonness of LCA in the broader American industries, and that a significant cultural shift would be needed to prevent the US from falling behind Europe even further and to put in peril its space industry's large international trade [27, 28]. In New Zealand, 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 [29]. In China, while a plan to carbonise its

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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 [28].

2.4 Past efforts in simplifying the reporting of space LCA results

ESA's LCA handbook highlights that careful reporting of LCA results is key to avoid green-washing (i.e. when a 'green' or 'sustainable' label is used on a design without clear evidence). It focuses on the reporting of all relevant impact categories, in absolute values where possible, or in relative values if some data is confidential [17]. 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' [30].

In parallel these guidelines and recommendations, efforts have been put forward to devise a method for computing a single-score from the LCA results. Section 2.4.1 shows work done within ESA's Clean Space Office and Section 2.4.2 highlights the work of the University of Strathclyde.

2.4.1 ESA's work towards a single-score LCA result

Work done as part of an internship at the ESA Clean Space office [31] aimed to find a single-score computation method to explicitly define a space system 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 so-called "space normalisation", based on the reference mission of GreenSat, and adapting the PEF weights to something considered more suited to the space sector [31]. The advantages and disadvantages that were found for each method are summarised in Table 2. 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 single or very small group of people, all within the Clean Space Office. Therefore, a lack of a broader consultation for this can be noted, potentially resulting in a biased set of weights.

	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

Table 2: Advantages and disadvantages of the single-score computation of ESA Clean Space Office, as taken from the 2023 PEGASUS paper [31], with modifications based on the internship report [32].

2.4.2 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 investigated to reduce the leaning curve for engineers and prevent the cherry-picking of impact categories to address. In this regard, a method for deriving a single-score

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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 [33].

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) [34], 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 [35] and reformulated to make the sum of the impact categories equate to 100% [36].

The SSSD has already been used in several studies, some of which a single-score rating was calculated. This includes three Phase 0/A SmallSat concurrent design studies aimed at generating more sustainable design concepts. [36] 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 [36].

2.5 Space Sustainability Rating

One organisation which aims to promote and incentivise sustainable practices across the space industry is 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 [37, 38].

It developed a rating system for modules on space debris potential (Mission Index), detectability and trackability (DIT), collision avoidance capability (COLA), data sharing (Data Sharing), adherence to design an operation standards (ADOS) and possibility for external services in-orbit (External Services). Through a process of the evaluation of the modules, their scores' normalisation, an assessment of the level of data verification, and eventually a weighting, a score from 0 to 1 (or in percentages) is calculated for each module, to which a tier score (i.e. Bronze, Silver, Gold, Platinum) is associated [39, 40]. The system is operational and in use since 2022, with prior Beta-tests performed in 2021-2022 [37]. SSR is looking into expanding its modules beyond the topics cited above and is currently developing a module on launch vehicle sustainability (LVSR), on dark and quiet skies, as well as on LCA [38]. It must be noted that not all these modules would make integral part of SSR, as there are for instance discussions on keeping the LVSR module as a separate rating, dedicated to launchers [41]. Similarly, some of these modules could become bonus modules, as is the case currently for the External Services module.

3. Survey Methodology

This section dives into the methodology behind the survey, with its goal being described in Section 3.1. The use of the DELPHI method as an inspiration behind the methodology is discussed in Section 3.2, while the overall procedure followed is highlighted in Section 3.3. A detailed look at the recruitment of the participants is given in Section 3.4 and the content of the questionnaires themselves are highlighted in Section 3.5.

3.1 Goal of the survey

The survey performed as part of this paper and broader MSc thesis [1] 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 aspects of sustainability would be prioritised during a trade-off between two space mission concepts or designs. By converting their ranking into proportional weights, the survey implicitly seeks for 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. For both of these objectives, the main focus lies on the European space industry's perception, although a comparison with industries abroad is also deemed interesting.

Next to this, 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 phase (i.e. Phase A, B, C, D, E1, E2 and F) and segment (i.e. Space, Launch, Ground Segment and Infrastructure) of a space mission, as defined by ESA [17], are considered to cause the highest environmental impact. Secondly, the survey attempts to map the space industry's and academics' arguments in favour or against the performance of life cycle assessments, and their opinion regarding the

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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.

3.2 The DELPHI method as inspiration for the survey methodology

A portion of the survey is heavily inspired by the DELPHI method, a methodology developed in the 1950s and 1960s in the USA. It was originally used 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 [42]. Initially 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 diverging topics (e.g. economic trends, health, education, etc) [42, 43], including recently the environmental impact of commercial space transportation activities in the USA [44].

One of the main benefits of this method over others 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[43, 45]. 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[43].

There are some drawbacks to the DELPHI method noted in literature. As was also 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. This is due to the administration to ensure all participants answer, the analysis of their answers and the creation of the various questionnaires based on it [43, 45]. 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[43]. Nevertheless, it is argued that topics of high uncertainty and speculation, traditionally investigated with this method, do in fact require an expert panel [46], which tends to be small in number of panelists.

For the survey presented in this paper, the DELPHI method is used for the two major goals described in Section 3.1: 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 thus the need for people with sufficient knowledge. 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 frameThe 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.

3.3 General procedure followed for the survey

The participants were given three questionnaire over the span of three weeks and half approximately. Thus, except for unique cases, they were given around a week to answer each questionnaire, keeping the topics and their answers fresh in their minds. Within that time frame, the answers were processed, the feedback was written and the questionnaires were adapted. With each questionnaire intended to last on average only 20 to 25 minutes per panellist, the feedback provided was mainly limited to the questions pertaining the two main goals of the survey, described in Section 3.1.

With most of the execution happening during the month preceding the 10th EUCASS conference for which this paper is written, the analysis of the results were be done quickly. While relevant conclusions are shown in the sections below, the Master Thesis[1] for which this work is primarily done, is expected to contain a few more data points and slightly more in-depth analysis, as some participants still need to submit their answers at the time of writing.

3.4 Recruitment of the expert panel

The size of the expert panel was decide based on suggestions from literature on the DELPHI method. Most sources advise a minimum panel size of 7 experts [43, 45], while the recommended upper-bound of a DELPHI research is most often placed at 20 to 25 [43]. Occasional sources suggest a panel in excess of a hundred experts [45], which, for the purposes of this survey, was deemed impractical and non-productive. Considering the subjectiveness of the questions to be asked, a larger panel size was preferred, to provide a sufficient significance and acceptance of the results for the wider space industry. Thus the maximum total panel size was 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 to the survey were recruited with care, based on their knowledge level. It was 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 were shortlisted based on on the individuals' reputation (e.g. the relevance of their publications or the relevance of their

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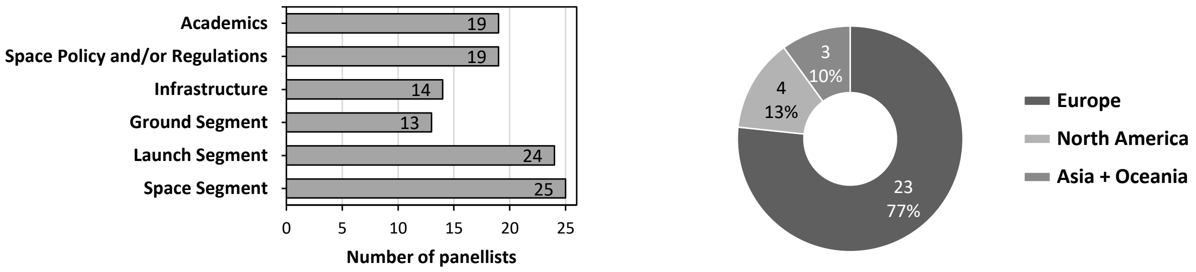
current or past professional position) and their knowledge level in space sustainability and LCA - a solid knowledge therein was preferred, with a handful of exceptions. Where possible, an introduction through a common acquaintance was used instead of cold emailing.

The results of the knowledge distribution within the final panel of experts can be seen in Figure 1a. Note that the figure also shows, for completeness' sake, the number of participants knowledgeable or experience 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 = 30 answers).

(b) Distribution in the location of the workplace (n = 30 answers). The top number is the number of panellists, while the bottom one is the percentage of them.

Figure 1: Information on the panelists' knowledge and experience in each segment, and 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), as described in Section 3.1, panellists from elsewhere were also recruited. Figure 1b shows that nearly one fourth of the final panellist are from Asia and North America. Nevertheless, the lack South American and African representation could be critiqued, since those continents have a rising - or well-established - space industry [47, 48]

While the participation to the survey is completely anonymous, some participants 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. While the list below shows the company or institutions where those panellists work, or their profession, it is important to underline that the survey's answers of the vast majority of the panellists are based on personal experience and expertise, as opposed to being based on the company's policies or practices. The survey's results should therefore not be considered a direct reflection of the company or institution. Moreover, note that this list is non-exhaustive.

- 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

3.5 Conception of the questionnaires

As mentioned in Section 3.3, the survey is split up in three questionnaires, each reiterating the questions pertaining to the secondary goals discussed in Section 3.1, giving feedback on the average answers to the preceding questionnaire. The space mission's environmental hotspots identification is asked for in the first questionnaire and a reflection on the average answers is requested through the feedback in the second one. No further questions are asked in later questionnaires, as the outcome was quite clear and the limited questionnaire time required prioritisation on the second primary objective.

Alongside this, the importance ranking of each impact indicator is asked in all three questionnaires for the case where two mission designs are to be compared. In the first one, only the internationally recognised impact indicators discussed in Section 2.2 are to be ranked. The second questionnaire adds the impact categories of "Mass left in Space" and "Al_2O_3 emissions in air," based on the majority of suggestions to add them. The final questionnaire adds all the other impact categories suggested in literature[49]: 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).

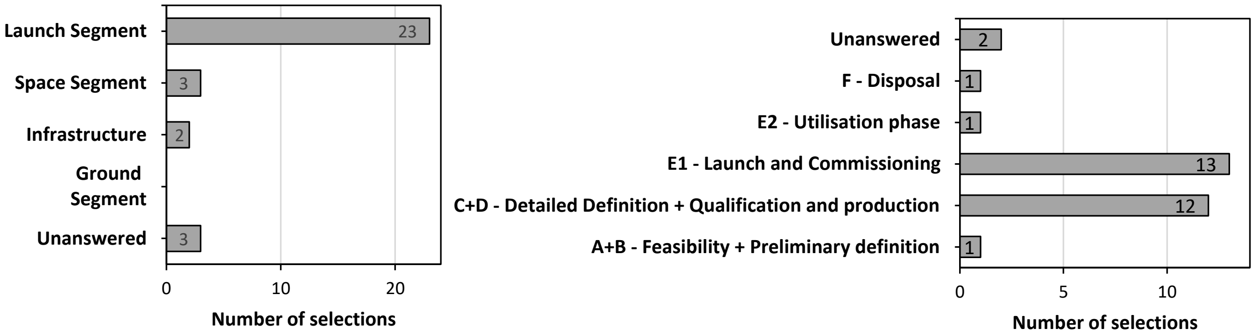
Besides pursuing the primary objectives, each questionnaire also dives into the secondary objectives and other topics. A portion of the first questionnaire is dedicated to obtaining personal information on the panellists, including their geographic location and their field of expertise, needed for a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

4. Outcomes

This section outlines the findings from the survey. The space mission phases and segments with the estimated highest impacts are shown in Section 4.1. The outcomes of the ranking of environmental impact categories based on their impacts levels is disclosed in Section 4.2. The estimated reasons to do or not to do a LCA in the space industry are detailed in Section 4.3 and a reassignment of the weights for the SSR modules is laid-out in Section 4.4

4.1 Hotspots identification of space mission phases and segments with highest environmental impact

As discussed in Section 3.1, during the first questionnaire, the panellists were asked to indicate which phase and segment of a space mission have the highest environmental impact. They could select only one of each, based on their experience. The number of times each segment and phase was selected Figure 2a and Figure 2b, 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 2: Aggregation of the number of selections of the phase and segment with the highest impact.

The main arguments for the phase C+D selection were the length of the design phase, the manufacturing and the use of aerospace-specific material and related minerals. A remark was also put forward 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 were the emissions related to the launch event, including those in the upper atmosphere. Overall, it was mentioned 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. Alike the choice between the phases of a space mission, some panellists mentioned that more information should have been provided on which environmental impact category one is looking at.

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4.2 Prioritization of environmental midpoint indicators during a design

Assuming two similar designs for space missions are to be compared on an environmental impact point of view, the expert panel was asked to indicate which midpoint indicators they think are most important to look at. In the first questionnaire, the space mission was defined as a "generic space mission", but based on feedback, this was 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 were added, as described in Section 3.5. Moreover, while the first two questionnaires did not indicate how the impacts are assessed, the third questionnaire specified 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 were 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 were asked to provide a relative ranking, assigning a score of 100 to the impact indicator they consider one should look at most. 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 3. 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 resulted 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 saw a reduction of the average standard deviation to 28.7 and 27.1 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 17.6, 22.5, 23.5, 24.8, 21.1 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 36.3, 35.3 and 34.2.

Some aspects are worth observing from the scores in Table 3. 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 weights proposed by PEF. In the case where no space-specific impact categories are looked at, the general trends of PEF is 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.

4.3 Drivers and inhibitors of a LCA for the space industry

As mentioned in Section 3.5, the expert panel was questioned on the reasons why they think the space industry does or doesn't do a LCA. They were given a number of statements to which they could answer that they "disagree," "somewhat agree" or "agree". The statements were 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 [14]. This study is a part of the European Joint Research Centre's (JRC) development of Europe's weighting approach for the Product/Organisation Environmental Footprint (PEF) [15]. Section 3 and Section 4.3.2 show respectively the drivers and inhibitors of LCA for a space mission.

4.3.1 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 3. All panellists either agree or somewhat agree that a LCA would drive environmental im-

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	PEF	Questionnaire 1: Generic mission (*n* = 30 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* = 17 answers)	
Midpoint impact indicator	Adapted PEF Weight	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.	14.28	95.6	9.88	87.4	8.29	91.1	8.28	95.3	6.59	92	6.33	82.7	6.29
Ozone depletion.	6.18	89.6	9.26	87.2	8.27	90.9	8.27	90.3	6.24	87.2	6	45.5	3.46
Human Toxicity - cancer effects.	7.53	65.7	6.79	65.2	6.18	52.6	4.78	65.7	4.54	58.3	4.01	68.4	5.21
Human Toxicity - non-cancer effects.	6.51	60.4	6.24	56.5	5.36	49.9	4.54	57.3	3.96	44.2	3.04	57.3	4.36
Particulate matter.	6.08	63.9	6.61	63.5	6.02	63.8	5.8	67.6	4.67	63	4.33	52.7	4.01
Ionizing radiation - human health.	6.31	58.3	6.03	53.7	5.09	60.4	5.49	55.7	3.85	52.8	3.63	53.2	4.05
Photochemical ozone formation - human health.	5.27	53.7	5.55	45.8	4.34	53.4	4.86	54.4	3.76	43.5	2.99	44.3	3.37
Acidification.	5.47	55.1	5.7	46.1	4.37	50.1	4.56	44.3	3.06	36.5	2.51	38.8	2.95
Eutrophication - terrestrial.	3.27	48.2	4.98	42.7	4.05	44.5	4.05	38	2.63	33.3	2.29	35.5	2.7
Eutrophication - freshwater.	3.53	49.5	5.12	41.5	3.94	43.9	3.99	38.5	2.66	32.9	2.26	36.6	2.79
Eutrophication - marine.	3.25	48.9	5.05	40.2	3.81	44.1	4.01	37.6	2.6	36.5	2.51	38.8	2.95
Ecotoxicity - freshwater.	6.77	61.8	6.39	50.4	4.78	47.9	4.36	44.5	3.08	39.5	2.72	45.2	3.44
Land use.	10.01	55.8	5.77	53.1	5.04	48.6	4.42	45.5	3.15	47.1	3.24	42	3.2
Resource use: metals and minerals.	7.39	82.7	8.55	84.3	8	92.4	8.4	83	5.74	87.5	6.02	79	6.01
Resource use: fossil fuels.	8.16	78.2	8.08	80.4	7.63	83.6	7.6	75.8	5.24	72.6	5	62.7	4.77
Mass left in space	NA	NA	NA	79.8	7.57	96.9	8.81	73.7	5.09	99.1	6.82	80.2	6.1
Al2O3 emissions in air	NA	NA	NA	76.6	7.26	85.5	7.78	84	5.81	91.9	6.32	42.1	3.2
Orbital resource depletion	NA	NA	NA	NA	NA	NA	NA	77.9	5.38	97	6.67	80.8	6.15
Critical raw material use	NA	NA	NA	NA	NA	NA	NA	69.7	4.82	75.6	5.2	70.9	5.4
Re-entry smoke particle generation	NA	NA	NA	NA	NA	NA	NA	61.1	4.22	66	4.54	66.9	5.09
Cumulative energy demand	NA	NA	NA	NA	NA	NA	NA	66.1	4.57	66.8	4.6	63.7	4.85
Total mass disposed in ocean	NA	NA	NA	NA	NA	NA	NA	54.5	3.77	56.5	3.89	54.1	4.12
Restricted substance use	NA	NA	NA	NA	NA	NA	NA	66.2	4.58	73.5	5.06	72.6	5.53

Table 3: Average of the scores given to each midpoint indicator throughout the three questionnaires, based on a specific given space mission type, an indication on how the impacts are computed and on which segments are considered. The color 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.

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provements 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 highlighted 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.

There are some noteworthy similarities and differences in the prioritisation by the panellists of the drivers and those of the full European industry [14]. The European industry's first, third and fourth drivers are also found somewhat high in the ranking of the expert panel, namely (in their respective European order) the statement that LCA increases awareness of employees in environmental issues, that it improves the reputation of the organisation and that it would improve the organisation's reputation. The idea that LCA would improve customer satisfaction - ranked as the second most important in Europe - 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.

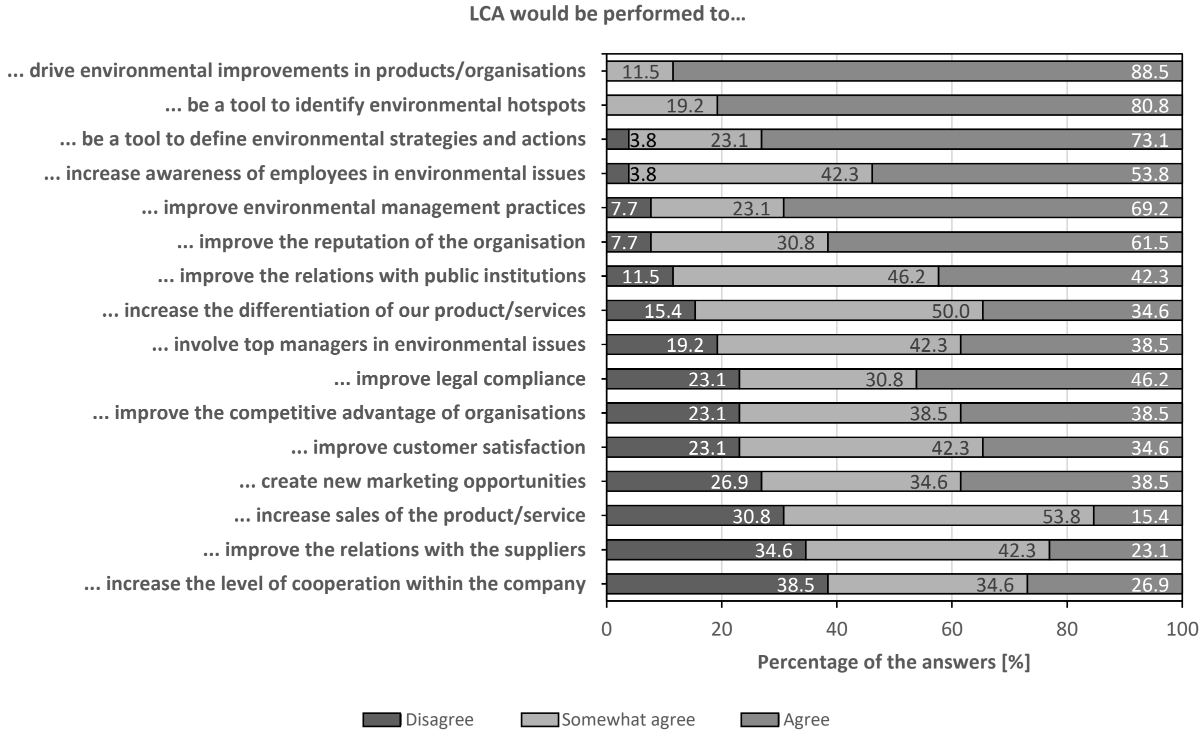

Figure 3: LCA drivers as given by the expert panel ($n = 26$ answers)

4.3.2 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 4. As seen from the percentage of panellists choosing the "disagree" option, 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 disagreed 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 [14]. 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 than by the European study.

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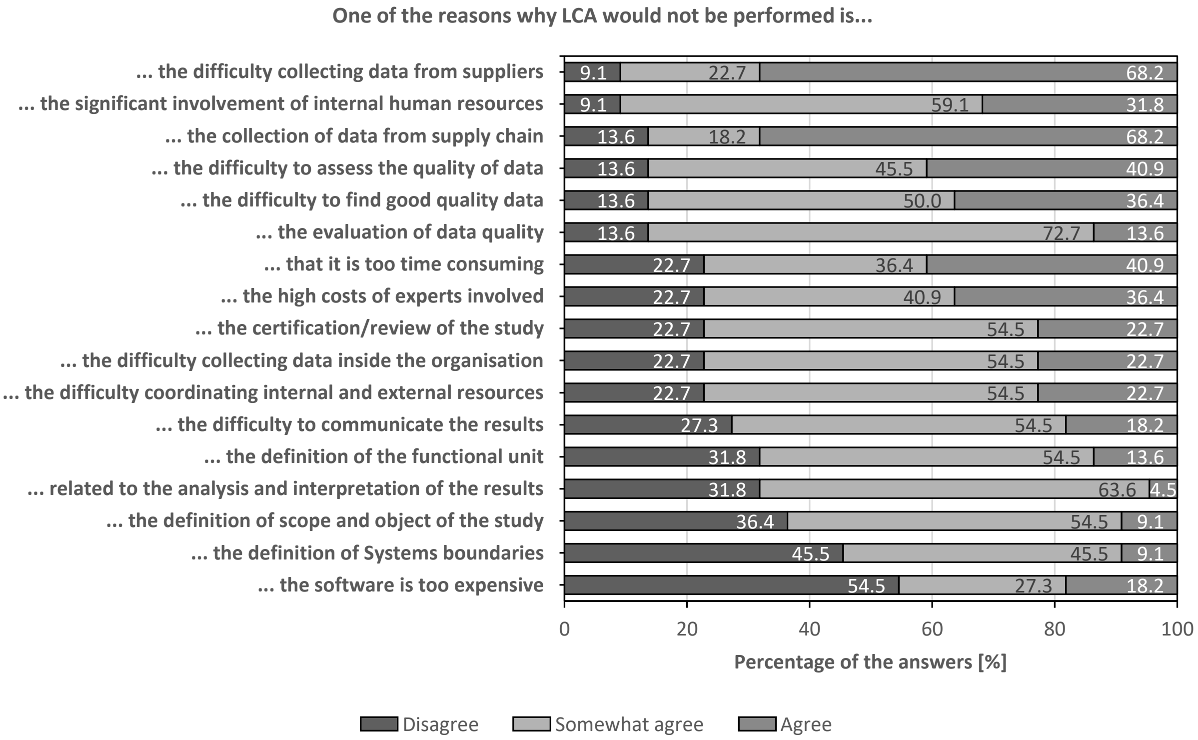

Figure 4: LCA inhibitors as given by the expert panel (n = 26 answers)

4.4 Reassignment of the weigths for the current and new SSR modules

During the third questionnaire, the panellists were asked to rank the modules assessed and proposed by SSR. A first ranking of only the current modules was asked for, after which a new ranking combining both the current and the future modules was done. The panellists were asked to provide a relative ranking, identical the one of the midpoint indicators, as described in Section 4.2. The weights computed from the average final scoring of the current modules and the current and future modules can be seen in Table 4, 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.

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 too 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.

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	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	16.5	18.7	16.4	9.3
COLA	16.5	19.7	17.2	10.7
Data Sharing	12	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

Table 4: 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.

5. Discussion

While interesting conclusions can be drawn, the results shown are only a preliminary analysis of the data and more work would arguably need to be done to draw definite conclusions. The thesis [1] for which this research is performed will contain a more detailed look at the outcomes, including answers from a slightly greater number of panellists and subdividing the answers per expertise level and geographical location.

This Section provides a discussion on the drivers and inhibitors for a LCA in the space sector in Section 5.1, on the computed weights for the SSR modules in Section 5.2 and on the midpoint impact category's weights in Section 5.3. A future outlook on work still to be done is provided in Section 5.4.

5.1 Drivers and inhibitors of a space LCA

One should evaluate the conclusions draw from the drivers and inhibitors with care, given the limited size and the bias of the expert panel demography. As mentioned in Section 3.1, the main objective of the survey pertained to the rating of the midpoint indicators, for which the DELPHI method would be ideal. The estimation of space LCA's drivers and inhibitors is one that should be given to 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 so 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 procy data is regularly mentioned.

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5.2 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 4 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 [50], and some iterations on it [40].

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 Quite 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 [39], 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.

5.3 Weighting of the environmental midpoint indicators

The fact that few participants chose 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 indications on how to compare these within a life cycle framework. In addition to this, 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

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14044 [12], 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.

5.4 Future work

The conclusion of this paper are only preliminary and should be used as a basis to build upon. A refined version of the conclusions is shown in the Master Thesis for which this work is done (not yet published at the time of writing) [1]. It contains a further subdivision of the proposed weights, in function of the panellists exact sector of expertise within the space industry and their knowledge level of each impact categories. Moreover, it includes the impact category of Water Use, omitted in the survey thus far.

Overall, the current early stage of the adoption of environmental practices in the space sector worldwide, the uncertainties in the environmental LCA of space missions and the lack of international agreements on the methodology of a single-score calculation, should incite the reader to pursue further research in the topic. A more detailed survey could be done regarding the weighting of the environmental impact, which also specifies the exact normalisation method to be considered in order to reduce any ambiguity in that regards. Similarly, a further division in mission types could be proposed to investigate any clear differences and more participants from diverging backgrounds should give their opinions on the drivers and inhibitors behind space LCA. More insights should be given on the workings and meaning of each of the SSR modules, in order for a conclusive consensus-based weighting of the SSR score to be attained. Such a survey could be performed much more internationally, including parts of the world and countries not addressed in for this survey, to assess any differences in perception of space sustainability.

In general, life cycle assessments should be be performed on various types of space missions and the single-scores should be computed for each, using the weights proposed in this paper, as well as those given by PEF and suggested by other sources. With this, a fine-tuning of the values ought to be performed and an assessment of their usefulness during a space mission's design process should be investigated.

6. Conclusion

The preliminary findings from the survey show that space missions require different weights for the impact categories of a LCA compared to the weights defined by the European Product Environmental Footprint (PEF) guidelines. The expert panellists in the survey have indicated that climate change should have a lower weight, while ozone depletion and resources use should be taken more into consideration. Besides this, very little differences were found between the assigned weights for a single satellite space mission's and a constellation mission's impact categories. The main differences pertain to the additional impact categories of mass left in space, Al_3O_2 emissions and orbital depletion, which all were considered to need a higher weight for the constellation mission.

Moreover, the survey shows that there are similarities and differences behind the drivers and inhibitors of doing a LCA in the space industry as compared to the general European industry. Some points that stand out are the fact that the idea that LCA would increase competitiveness seems not to be such a driving reason to perform a LCA and that environmental awareness and reputation rank high among the drivers. Similar to the European industry, the space sector seems to find the difficulty of collecting data and assessing their quality as some of the main reasons not to perform a LCA, while defining the LCA system boundary and scope appear not to be problematic. Although, one should note that the last answer could be biased, due to the level of LCA expertise of the panellists.

Regarding SSR's weighting of their modules, the panellist have agreed on an evenly distribution of weights, reducing drastically the relative weight of the Mission Index. For the newly proposed modules, the one on LCA and the one on Dark and Quite Skies seem to dominate, although a panellists' bias in favour of LCA was likely present.

Further work ought to be done to reach a more unanimous consensus, to verify the calculation process and to reduce the subjectivity of the single-score. This would give the space industry a new tool to simplify LCA, in order to incorporate it easily as part of new space missions' eco-design. This would allow the space industry world-wide to increase its efforts towards sustainability.

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