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FROM LIFE CYCLE ASSESSMENT OF SPACE SYSTEMS TO ENVIRONMENTAL COMMUNICATION AND REPORTING

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Abstract

Within the European space sector, heightened interest in Life Cycle Assessment (LCA) has been stimulated by an increased motivation and urgency on quantifying environmental consequences of space activities. The associated growth in the application of this method places a greater emphasis on obtaining high levels of transparency, reliability and validity of all ensuing environmental claims. As such, the purpose of this study is to present a potential pathway for effective space-specific environmental communication and reporting. The paper outlines the results of a scoping exercise designed to map the specificities of the space sector against the ISO 14025:2006 standard on environmental labels and declarations. This was based on a literature review conducted to obtain the current state of knowledge within the space industry whilst drawing upon the procedures and experiences of other sectors, with particular consideration to Product Environmental Footprint Category Rule (PEFCR) development. The findings from this activity have been used to formulate a harmonised framework for environmental communication and reporting purposes in the context of the European space sector. The framework provides a comprehensive set of voluntary operating procedures which intend to act as preliminary guidance for European industrial stakeholders and national agencies. The paper goes on to discuss potential future framework refinements and provides a list of recommendations to advance sectoral practices further. This includes a call for the establishment of an industry-specific platform to enhance the harmonisation of LCA development and ensure rigorous verification and validation of environmental claims.

Keywords: life cycle assessment; space systems; environment; communication; reporting; conceptual framework

Acronyms & Abbreviations

B2B	Business-to-Business
B2C	Business-to-Consumer
CEN	European Committee for Standardization
EC	European Commission
ECSS	European Cooperation for Space Standardization
EPD	Environmental Product Declaration
ESA	European Space Agency
EU	European Union
FU	Functional Unit
ILCD	International Reference Life Cycle Data System
ISO	International Organization for Standardization
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
OEF	Organisation Environmental Footprint
PCR	Product Category Rule
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rule
REACH	Registration, Evaluation, Authorisation & Restriction of Chemicals
RoHS II	Restriction of Hazardous Substances in Electrical & Electronic Equipment
SC	Steering Committee
SSR	Space Sustainability Rating System
TAB	Technical Advisory Board
UNOOSA	United Nations Office for Outer Space Affairs
WEEE	Waste, Electrical & Electronic Equipment Recycling

1. Introduction

Over the last decade, the application of Life Cycle Assessment (LCA) as a method for assessing environmental impacts of space missions and technologies has been growing in importance amongst European industrial stakeholders and national agencies. To date, space LCA studies have predominantly been used to scientifically quantify and reduce adverse impacts, rather than for comparative assertions. However, there is a strong possibility that LCA results may eventually become part of external business communication within the sector. For this reason, it is important that an appropriate mechanism is put in place to promote accurate and verifiable impact quantification for regulatory and economic purposes, thereby avoiding greenwashing and other false environmental claims.

This issue is particularly relevant since recent findings from the European Commission (EC) and national consumer authorities screening of websites exercise found that 42% of environmental claims made by companies were exaggerated, false or deceptive and could potentially qualify as unfair commercial practices under European Union (EU) rules [1]. As such, Palmroth et al. [2] advocates for the development of an LCA-based eco-labelling scheme for measuring and reporting the sustainability footprint of space missions, based on metrics such as the carbon footprint per unit of service delivery. Implementing such an approach will not be without its difficulties, but it does have the potential to create a measurable concept which could be used in policies to enhance the sustainable use of outer space.

In an attempt to tackle this issue, the European Green Deal states that "companies making 'green claims' should substantiate these against a standard methodology" [3]. In this regard, the environmental product declarations (EPDs) [4] and EC product environmental footprint (PEF) [5] methodologies provide standardised approaches for declaring environmental impacts of products over their entire life cycle, based on LCA calculations. Their applicability towards space systems should, therefore, be properly investigated as a means for ensuring high standards of transparency and accountability in environmental reporting. At a minimum, this would require the production of a harmonised set of guidelines to regulate services and programmes in the context of the execution and preparation of space-specific PEFs or EPDs.

Therefore, the aim of this paper is to present a new preliminary conceptual framework for environmental communication and reporting in the context of the European space sector. The framework will be formulated based on a scoping exercise designed to map the specificities of the space sector against relevant international standards on environmental labels and declarations. The key issues identified during the scoping exercise will be used to inform the development of the framework based on the current state of knowledge within the space industry, whilst drawing upon the procedures and experiences of other sectors. As a result, this framework is expected to act as a method for best practice for environmental communication and reporting of space systems from a European perspective and provide recommendations for areas of further refinement.

2. Background

2.1 Legislative & regulatory issues

Environmental impacts of space activities have historically been omitted from leading legislative and regulatory requirements globally. This has meant that key impacts arising within the sector have traditionally been overlooked or ignored. For example, when the Montreal Protocol on Substances that Deplete the Ozone Layer was introduced in 1987, it completely left out the space industry despite rocket propulsion being the only source of anthropogenic emissions to inject ozone destroying compounds directly into all layers of the atmosphere [6]. At a European level, space technologies are currently exempt from several EU directives which cover environmental protection, including Directive 2012/19/EU on waste electrical and electronic equipment (WEEE) and Directive 2011/65/EU on the restriction on the use of certain hazardous substances in electrical and electronic equipment (RoHS II), among others [7]. The space sector strongly relies on these exclusions since some of the restricted substances such as lead are considered to be essential components for space hardware production without suitable alternatives. Although the current position of the European space sector is to maintain existing exclusions from the scopes of WEEE and RoHS II, there is a growing realisation that a more coherent application of each directive is required. It has been suggested that this could be supplemented by more stringent coverage within the Waste Framework Directive (Directive 2008/98/EC) and the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Regulations (Regulation (EC) No 1907/2006), particularly relating to space-specific end-of-life scenarios for launched hardware and the production of propellants [8]. Much will depend on how these are amended and harmonised in the coming years. Despite this, although the EU's RoHS III Directive (which was adopted in 2019), sets expiry dates for most of the current exemptions, again this does not include space technologies [9].

Such oversight had left the space sector with an inability to accurately and scientifically account for its environmental impacts. For this reason, the European

Space Agency (ESA) has been pioneering the application of LCA within the space sector since 2009 to support the required evolution of space missions in response to current environmental regulations and global challenges. The application of LCA is, therefore, expected to assist stakeholders to scientifically quantify and reduce the life cycle environmental impacts of space missions for the first time. This has the potential to create a competitive advantage for businesses due to increasing customer demands for green products, whilst also enabling compliance with current and future legislation.

2.2 LCA in the context of aerospace

LCA is a systematic methodology which compiles and evaluates the inputs, outputs and potential environmental impacts of a product system (i.e. product, process or service) throughout its life cycle. The method is internationally standardised through the International Organization for Standardization (ISO) 14040:2006 [10] and 14044:2006 [11] environmental management standards which provide a globally accepted framework to which all LCA studies should adhere to. This framework consists of four distinct steps which are outlined in Figure 1 below.

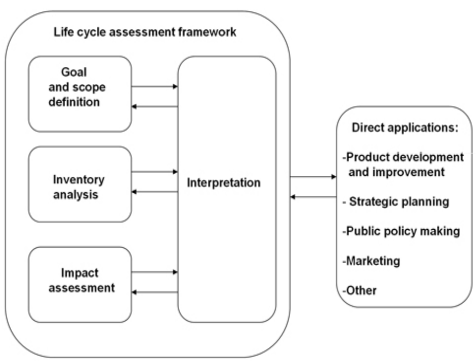

Figure 1: Life cycle assessment framework [7]

However, within the space sector, implementing LCA is not a straightforward process due to the industry's unique characteristics. In particular, space technologies have low production volumes, long research & development cycles, intensive testing and use specialised materials and industrial processes with an extremely high cost per weight ratio [12]. This differs significantly from traditional, common, and/or mass-produced products by comparison, for which LCA is more practical. By extension, this means that the datasets necessary to run an LCA on a space product are generally not captured within traditional process-based LCA models, thereby reducing their relevancy for space missions and technologies [13]. As well as this, the space industry has a unique and unusual set of environmental impacts (such as direct emissions into each layer of the atmosphere from rocket launches) which also cannot be quantified by traditional LCA models [12]. Additionally, monetary flows are vastly different than in other sectors as the industry does not fulfil the requirements of a completely free market due to state financing schemes and limited players. This adds further complexity, virtually eliminating the use of environmentally-extended input-output models as method of analysis due to the high inaccuracies produced when applied to space systems [14]. As such, these issues place many constraints on how LCA can be applied to space missions and technologies.

To tackle this issue, the ESA created a new framework to orientate the ISO LCA standards to be more appropriate to space products and streamline its application within the European space industry. The framework consists of a handbook, LCA database and ecodesign tool, all of which were developed based on the knowledge acquired from various studies conducted under the scope of the ESA Clean Space Initiative. A previous critical review of the literature [15] highlighted the central role that this framework has had on the ESA and the European space industry in the application and development of good practice relating to space LCA. Recent efforts have been made to expand and develop this framework further [13,16] but nonetheless, it continues to be the first and only framework for space LCA in existence. In this regard, as far as is known, no other initiatives or attempts to develop a harmonised methodological framework for space LCA has been pursued elsewhere, including North America or Asia.

Although the application of LCA is currently voluntary within the European space sector, many ESA projects already include mandatory contractual requirements for evaluating environmental footprints, including Ariane 6 and the Copernicus expansion missions. Beyond this, the importance of public-sector procurement and research programmes expenses (from states, European institutions and agencies) coupled with a limited number of large system operators and integrators in the sector may foster the generalisation of such practices. Consequently, in the future, there is a distinct possibility that such an approach may grow to become an integral part of the development and procurement process across the entire European space industry. Under such a scenario, it is extremely important that all environmental communication and reporting on space projects achieve acceptable levels of focus, reproducibility, comparability, consistency, relevancy and efficiency. Therefore, to realise this goal, it is necessary to develop a single set of industry-wide requirements as a guide to best practice on the disclosure of space-specific life cycle environmental impacts in Europe.

2.3 Approaches for substantiating green declarations

Compliance systems are vital for ensuring that information on the life cycle of a product is presented in a quantified manner which enables comparisons between products fulfilling the same function, paying due attention to the level of awareness of the target audience. In this regard, the ISO 14020:2000 [17] standard on environmental labels and declarations establishes the guiding principles for the development and use of environmental labels and declarations. Under the ISO 14020 standard series, three label types exist which are governed by their own respective standards, as outlined in Table 1 below. Collectively, these ISO standards provide internationally recognised non-binding rules which can be used in the preparation of environmental labels, claims and declarations.

Table 1: ISO standards on environmental labels [18]

Denomination	**Not verified by third party**	**Verified by third party**
Environmental labels	14021:2016 (Type II)	14024:2018 (Type I)
Self-declared environmental claims	14021:2016 (Type II)	-
Environmental product declarations	-	14025:2006 (Type III)

From a life cycle perspective, of particular relevance is the ISO 14025:2006 standard [19] which establishes the principles and procedures for developing Type III environmental declarations and programmes, based on the ISO LCA standards. These types of declarations are defined by ISO 14025:2006 as quantified environmental information on the life cycle of a product to enable comparisons between products fulfilling the same function. They are primarily intended for use in business-to-business (B2B) communication, but their use in business-to-consumer (B2C) communication is not precluded under certain conditions. Additionally, Type III environmental declaration programmes are defined as being voluntary programmes for the development and use of Type III environmental declarations, based on a set of operating rules. An overview of the Type III environmental declaration programme development and operation process, as defined within the ISO 14025:2006 standard, is outlined in Figure 2 below.

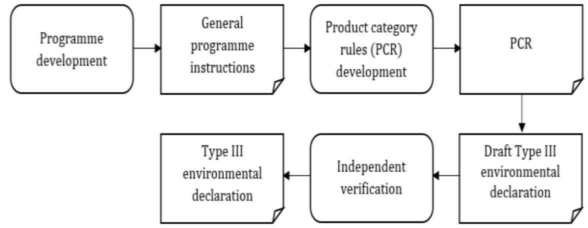

Figure 2: Type III programme development and operation scheme (adapted from [19])

In accordance with the ISO 14025:2006 standard [19], two approaches have materialised as viable methods for making Type III environmental declarations: EPDs and PEFs. EPDs are a simple way of providing environmental information on the life cycle of a product to enable comparisons between products fulfilling the same function [4]. There are five basic steps involved with creating an EPD, which are outlined in Figure 3 below. The technique has been adopted reasonably widely in the EU and Japan, with many regulators beginning to set requirements for EPDs on consumer goods [20].

Figure 3: Phases of a EPD study (derived from [4])

The PEF approach was created to provide specific guidance for calculating and reporting life cycle environmental impacts of products in accordance with ISO 14040:2006 and 14044:2006, as part of the EC's work on harmonising E-LCA across European industries [21]. In this regard, the EC launched the Single Market for Green Products Initiative in 2011, in which the PEF and the Organisation Environmental Footprint (OEF) approaches were introduced. These new methods were proposed as a common way for measuring the environmental performance of products and services based on the principles of reliability, reproducibility, comparability and verification. The basic phases involved with a PEF study are outlined in Figure 4 below. Moreover, the EC published a recommendation on the use of the PEF and OEF methods in 2013 [22] in response to invitations of the Council to develop a harmonised method for calculating the life cycle environmental performance of products under the scientific and technical lead of the Commission's Joint Research Centre (JRC) [23]. The PEF and OEF methods then entered a pilot phase involving 26 screening studies from 2013 to 2018 [24]. It is currently in a transition phase until the end of 2022 where adoption into policies for implementing the PEF/OEF methods are being considered [25]. In particular, the PEF method is already the European selected scheme in the frame of the European Green Deal [3] and Circular Economy Action Plan of the EU [26].

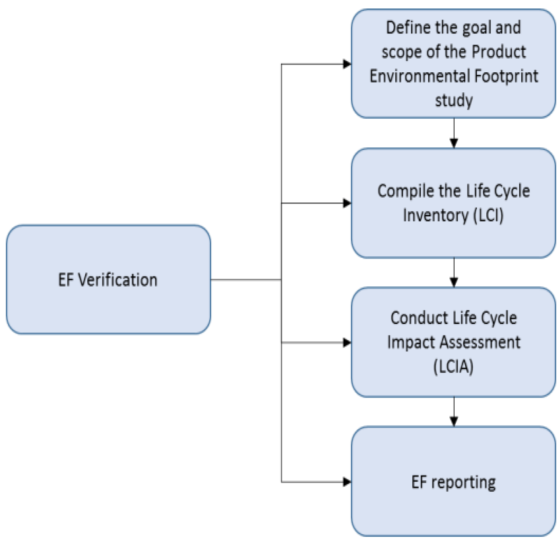

Figure 4: Phases of a PEF study [21]

Despite sharing similar goals, EPDs and PEFs can actually be seen as competing schemes. Nevertheless, formally comparing the two approaches is not so relevant since the context for which they are used is not the same [27,28]. In this regard, EPDs seemingly evolved from the ISO 14025:2006 standard whilst the PEF approach is based on legislative text [22]. However, both schemes have drawn criticism which is important to highlight. In terms of EPDs, the existence of overlapping and duplicate PCRs supervised by different program operators is highly problematic because these program operators are generally private sector entities that do not need to coordinate activities [29]. Such differences in the general requirements and methodologies diminish the comparability of environmental claims [30]. Additionally, the regionalisation of PCRs means there is an absence of coordination on an international level as well. In fact, there is no current structure for PCR alignment or harmonization [31]. Ultimately, this has led to the PCR and EPD framework to be used less than was initially expected [32]. In comparison, the PEF seemingly evolved from the concept of EPDs based on an EC recommendation. Although recommendations are a non-binding legal act, it does provide a certain level of political validation since it is negotiated and voted between Member States. The main difference is that under the PEF approach, the EC takes the place of the program operator in the EU [20], with PEFCRs guiding the development of PEF studies. However, one particular criticism of the PEF approach is that it adds further confusion and lacks harmonization with the ISO standards on LCA due to the embodiment of more stringent rules [33,34].

2.4 Applicability to the space sector

Intrinsically, it can be seen that both the EPD and PEF method are equally valid for the communication and reporting of life cycle environmental impacts of space missions. However, it could be argued that the PEF approach is more suitable in a European context. In this regard, whilst the EC has not committed to creating a PEFCR for space, they strongly encouraged the development of the ESA 'Space system Life Cycle Assessment (LCA) Guidelines' [35]. Published in 2016 as part of the ESA LCA framework for space, these act as the only guidance on space LCA. As such, they are already orientated as closely as possible with the PEFCR approach, allowing the ESA to align more closely with the strategic goals of the EC.

Therefore, due to the orientation of the ESA LCA guidelines with the PEF compliance system, the focus of this paper will be on PEF approach. Based on this, given that PEF reports must be made public (unlike EPDs), this means that by design this approach is capable of preventing false and/or unsubstantiated environmental claims from being made. Additionally, its use should also encourage the sharing of information, which to date has been a major hinderance to the advancement of space LCA. As such, it is envisaged that the following applications could be possible if the PEF method is applied to space studies:

- **In-house applications:** support for environmental management through the identification of environmental hotspots and the implementation of environmental performance improvement and tracking, which may implicitly include cost-saving opportunities through ecodesign.
- **External communication:** provision of product environmental information publicly in response to consumer demands, to maintain compliance with environmental regulation at European or Member State level, for marketing and environmental labelling purposes, which may also focus on sustainable supply chains and green procurement.
- **Benchmarking:** measuring the environmental prowess of a product according to its performance in comparison to a benchmark value or alternative.

3. Approach & scoping exercise

3.1 Aim & methodology

The purpose of this study is to create a preliminary framework for environmental communication and reporting of space products and technologies. This framework will be based upon the PEF approach and present a new set of voluntary operating procedures as an interim guide for European industrial stakeholders and national agencies to ensure accurate and verifiable impact quantification for communication and reporting purposes. As such, in order to achieve this goal, the framework will principally concentrate the general programme development, with a particular focus on the formulation of PEFCRs for space systems in order to refine the process for external results disclosure within the sector.

The methodological approach for producing this framework for Type III programme development and operation was formed using a ten-step procedure based on the scheme presented in Figure 2. This method has been adapted from the combined experience of guideline development [36,37,38], guidance for PCR development [39] and from the experience of developing the ESA LCA framework [35]. These steps are outlined below:

1. Select & refine the subject area of the framework.
2. Identify & assess the evidence.
3. Translate evidence into preliminary practitioner operating procedures with recommendations.
4. Establish a consortium of interested parties.
5. Develop a draft that meets market needs.
6. Share the draft for comments & discussion through framework development groups.
7. Integrate comments & suggestions.
8. Further modification until consensus is reached.
9. Panel review of final draft for approval.
10. Publish framework & continue to update.

It is the aim of this study to reach and conclude the third step. In this regard, the first two steps will be fulfilled through a scoping exercise designed to map the specificities of the space sector against the ISO 14025:2006 standard [19] on environmental labels and declarations, thereby identifying important issues or gaps which need to be addressed. This is based on the framework for scoping studies proposed by Arksey & O'Malley [40]. In particular, step one will align the research topic selection with the overall aim of this study. It will also develop a decision plan relating to the method of search for relevant literature and criteria. As such, this will provide a roadmap for the scoping exercise in the subsequent step. After this, a qualitative synthesis of the ISO 14025:2006 standard [19] and associated PEF documents will be conducted as part of step two, to determine pertinent issues relating to general programme and PEFCR development. This systematic review of evidence will also seek to obtain the current state of knowledge within the space industry, including any gaps which need to be addressed in respect to the issues identified. Following on from the completion of the first two steps, step three will then use the findings of these activities to develop and formulate a harmonised framework for environmental communication and reporting purposes in the context of the European space sector, drawing upon the procedures and experiences of other sectors, with particular consideration to PEFCR development. The completion of these three steps is expected to act as a strong foundation for the development of more official PEF guidance on space products and technologies. The remaining steps (which are not addressed as part of this study) refer to the initiation of a more official process for general programme and PEFCR development.

3.2 Selecting & refining the subject area

The subject area of this study is the space systems due to the lack of environmental regulation covering the industry. This issue was catapulted to the forefront of public attention when two privately funded spaceflights of billionaires Jeff Bezos and Sir Richard Branson made headlines around the world in 2021 [41]. The public perception was not generally positive, with many seeing privately funded space travel and exploration trips as vanity projects. Moreover, this has also inadvertently placed a heavy focus on the potential environmental impact of the space sector. With this in mind, it is anticipated that this could propel the use of space LCA as a method for making environmental claims. As such, it is extremely important that a mechanism is put in place to ensure high levels of transparency, reliability and validity of all ensuing environmental claims to avoid potential greenwash.

As outlined within Subsections 2.3 and 2.4, the PEF approach was selected as the most appropriate method for this purpose from a European perspective. For this reason, the scoping exercise will focus primarily on developing a framework for effective environmental communication and reporting, based on the PEF approach. It will map the specificities of the space sector against the ISO 14025:2006 standard [19] and associated PEF guidance to produce a list of issues and gaps which need to be addressed within the framework. To achieve this, a wide range of literature was obtained, which came from various channels including online internet searches and resources collected directly from stakeholders within the space industry. To be considered relevant for the purposes of the scoping exercise, the following questions were used as qualitative criteria:

(1) Does the evidence provide guidance and/or advice on good practice relating to making Type III environmental declarations, with a particular focus on PEFs (but not excluding EPDs)?

(2) Does the evidence provide guidance and/or advice on good practice relating to LCA, with a particular focus on studies conducted within the space sector?

A complete list of all the evidence and criteria that was reviewed during the scoping exercise is outlined in Table 2 below, with the findings from the most pertinent aspects from this material detailed in Subsection 3.3. It should also be noted that this table excludes additional literature sources used in the development of the new framework for environmental communication and reporting, outlined in Section 4.

Table 2: Full list of evidence and criteria reviewed during the scoping exercise

Reference	**Year**	**Type**	**Content**
EC JRC [22]	2018	Report / guidance	Current PEFCR guidance.
EC JRC [42]	2016	Report / guidance	PEFCR guidance during the pilot phase.
EC JRC [43]	2012	Report / guidance	ILCD recommendations on LCIA methods and characterisation factors.
Elsen et al. [44]	2019	Report / guidance	Potential labels for communicating the Environmental Footprint profile of products.
ESA LCA Working Group [35]	2016	Report / guidance	Guidelines on space LCA.
Fazio et al. [45]	2018	Report / guidance	Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods.
Fazio et al. [46]	2019	Report / guidance	Guide for EF compliant data sets.
ISO 14020 [17]	2000	Standard	General principles for environmental labels and declarations.
ISO 14025 [19]	2006	Standard	Principles and procedures for Type III environmental declarations.
ISO 14040 [10]	2006	Standard	Principles and framework for LCA.
ISO 14044 [11]	2006	Standard	Requirements and guidelines for LCA.
Manfredi et al. [5]	2012	Report / guidance	Current PEF guidance.
Minkov et al. [47]	2020	Journal article	Proposal of a characterisation scheme for ecolabels and to provide recommendations for the enhancement of existing ecolabel classification, questioning the current sufficiency of ISO standards.
Nissinen et al. [48]	2019	Report / guidance	Review on the possibility for common information and coordination between environmental information sources for the various product policy instruments and the PEF.
Sala et al. [49]	2019	Report / guidance	Suggestions for the update of the Environmental Footprint Life Cycle Impact Assessment.
The International EPD® System [4]	2019	Report / guidance	Current EPD guidance according to the rules of the International EPD® System.
Wade et al. [50]	2017	Journal article	Lessons learned during the development of PEFCRs for PV modules.
Zampori and Pant [21]	2019	Report / guidance	Suggestions for updating the PEF method.

3.3 Identifying & assessing the evidence

For a specific product category (which is defined by ISO 14025:2006 as a group of products that can fulfil equivalent functions [19]), PEFCRs can be developed to complement and further specify methodological guidance for PEF studies. According to Annex A of [21], the development of a PEFCR should take into account, to the furthest extent possible, already existing technical documents and PCRs from other schemes. The goal of this is to identify particular aspects and parameters that matter the most and for calculating products' life cycle potential environmental impacts [22]. These guidelines on how to develop PEFCRs are based on the minimum content of a PCR document as required by ISO 14025:2006 [19]. Following ISO 14025:2006 requirements for PCRs, this includes, but is not limited to:

- Identification of the product category for which a PCR is to be developed, including a description of, for example, the product's function(s), technical performance and use(s).
- Definition of the goal and scope for the LCA of the product, according to the requirement of the ISO 14040 series in terms of, for example, functional unit (FU), system boundary, data quality requirements.
- Description of the Life Cycle Inventory (LCI) analysis, with special focus on the data collection phase, calculation procedures, and allocation rules.
- Choice of the Life Cycle Impact Assessment (LCIA) impact category indicators to be included in the LCA.
- Description of any eventual predetermined parameter for the reporting of LCA data, for example, certain predetermined inventory data categories and/or category indicators.
- If not all life-cycle stages are included in the LCA, information / justification on which stages are not covered.
- Time validity of the PEFCR being developed.

However, as space LCA is still an extremely novel topic, very limited guidance material was uncovered. In this regard, the ESA LCA guidelines [35] are the only real authoritative source on this aspect. For this reason, the other sources were discarded, and a critical review of the ESA LCA guidelines was conducted to map the list of minimum content of a PCR to its contents. Where data was considered to be missing or in need of refinement according to this criteria, it was listed as an issue in Figure 5. These data issues are areas which need to be addressed as part of the new framework for environmental communication and reporting of space systems in Section 4.

On review of the ESA LCA guidelines [35], it was found that information relating to product categories at system level have not been defined. The goal and scope (including the FU and system boundaries) are covered extensively, although there is a need for further consolidation of these aspects, particularly if new product categories are to be developed. Data quality requirements were not considered to be covered in a sufficient manner. As such, it is recommended that this aspect should be addressed in the next update of the guidelines. Details on the LCI are provided thoroughly within the ESA LCA guidelines, particularly on data collection and calculation procedures, with examples datasets also provided within the annex. This is largely based on the International Reference Life Cycle Data System (ILCD) format [43]. Allocation rules are somewhat defined, but could be more detailed, particularly in relation with dedicated space LCA databases. The LCIA impact category indicators outlined in the guidelines require updating to fully align with the impact categories outlined in [21]. However, those impact categories will need to be adapted to better suit the specificities of the space sector. Despite this, details on what or how to update these is not provided within the guidelines. Additional impact categories which could be used (including flow indicators) have also been outlined, but similarly, no details have been provided on the development of these new flow indicators. No predefined parameters for the reporting of LCA data is provided within the ESA LCA guidelines. In terms of cut-offs, the ESA LCA guidelines states that any omissions of life-cycle stages or process outlined within the system boundary, including data needs, assumptions about electricity production, use and end-of-life stages, needs to be fully justified within the goal and scope of the study. And finally, the time validity of the PEFCR is not directly relevant to the ESA LCA guidelines, which are reviewed and updated on a continual basis. It is foreseen that the time validity would be set by the consortium of parties involved with developing the category rules (called the Technical Secretariat). In this regard, there is a need to consider what parties should be invited to participate in this process and who should lead it.

Lastly, the findings from this review were further examined during the virtual ESA Clean Space industrial days 2021 through some initial discussions with interested parties on the main challenges facing space LCA in terms of PEFCR development. Although an update to the ESA LCA guidelines is due to take place, the following issues were commonly quoted by conference attendees in relation to the current version:

- How to select of an appropriate FU for different mission classifications.
- Confidentiality issues leading to large data gaps and a lack of useable data.
- Data selection and the differentiating between both primary and secondary datasets based on their different degrees of granularity, which at system level could significantly impact the amount of detail which can be achieved within a given study.
- Tracing the supply chain during the data collection phase due to the large number of suppliers and sub-suppliers involved.
- The level of adaptation required for environmental impact categories indicators and the lack of guidance on this.
- The level of detail required to adapt and comply with the PEF format when space LCA itself is still finding its feet.

3.4 Translating the evidence into guidelines

Developing a framework or standard can be a long and laborious process, typically lasting about 3 years from first proposal to publication. However, given the consensus already established through the ESA LCA guidelines, the process for establishing a new framework for the environmental communication and reporting of space products and technologies has the potential to be drastically reduced. Coupled with the findings of the scoping exercise (which have been charted on a mind map in Figure 5 below), this provides a basis for developing preliminary guidance. In particular, this diagram outlines the main issues which will be used to formulate a harmonised framework for environmental communication and reporting purposes in the context of the European space sector. This will be achieved by drawing upon the procedures and experiences of other sectors in the development of EPDs and PEFs. This framework is outlined in Section 4.

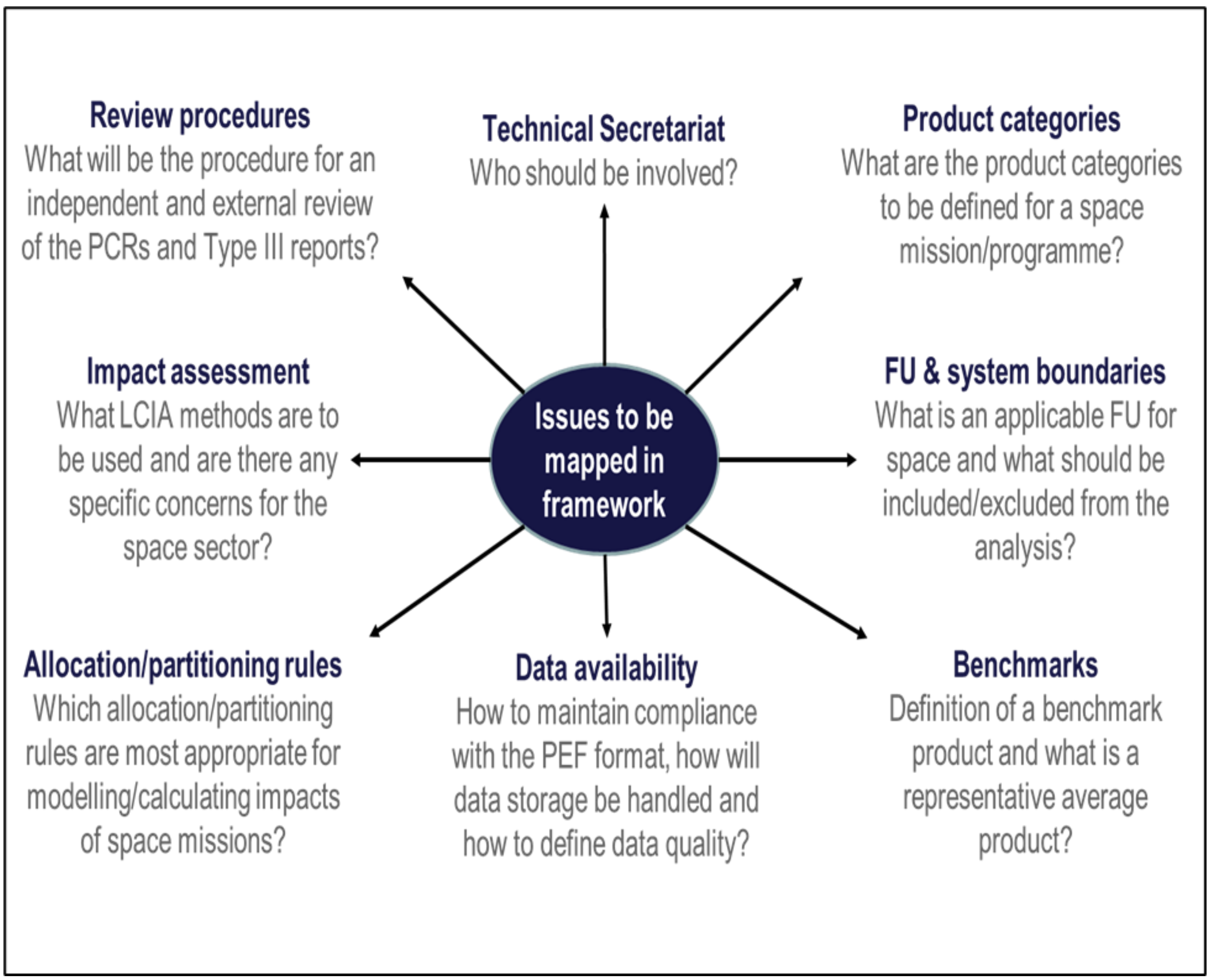

Figure 5: Main issues identified during the scoping exercise to be mapped in the framework

4. A framework for environmental declarations

4.1 General programme development

Type III environmental declaration programmes are voluntary and have a set of rules guiding their overall administration and operation. These rules, managed by a programme operator, are referred to as general programme instructions [19]. The PEF guide stipulates that a Technical Secretariat will be set up to develop a PEFCR, which can be comprised of a single entity or a mix of entities [5]. Given that the literature review identified in Subsection 2.2 of this study [15] highlighted the central role that the ESA LCA framework has had on the European space industry in the application and development of good practice relating to space LCA, the ESA would be an ideal candidate to lead a consortium for general programme and PEFCR development as technical secretariat. Based on the approach of other PEF pilot programmes [50], to ensure market representativeness, the full technical secretariat should include a variety of different stakeholders, with an ideal scenario being:

- A minimum of 75% of EU market players being invited to participate in the Technical Secretariat.
- All EU market players contributing >10% of the market being invited to participate in the Technical Secretariat.
- A minimum of at least 51% of EU market players actively participating in the Technical Secretariat.
- Besides large commercial entities, participation of a wide range of stakeholders must also be ensured, including (but not limited to) EC/ESA Member States, national space agencies, the United Nations Office for Outer Space Affairs (UNOOSA), small-medium enterprises, industrial associations, non-governmental organisations, academia and select scientists.

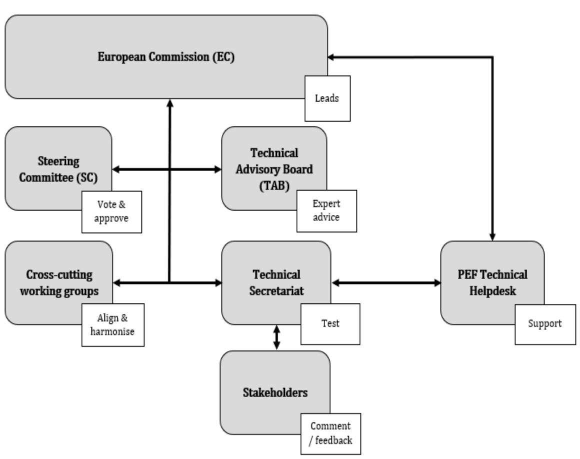

Figure 6: Governance structure based on the PEF pilot phase (derived from [42])

The Technical Secretariat could also be supported by a wide range of different groups, as depicted within Figure 6. This provides an overview of the PEF governance structure which was implemented by the EC across the 26 PEF pilot projects. However, it is currently unclear how the governance structure will be constructed following the conclusion of the PEF pilot phase. For this reason, it is important to define what the role of these different groups were during the PEF pilots.

In this regard, the EC provided an overall lead for general programme development, with the Directorate-General for Environment being responsible for its coordination and political direction whilst the JRC Institute for Environment and Sustainability taking the methodological lead. This is highly unlikely to change going forward [42].

The Steering Committee (SC) and Technical Advisory Board (TAB) were responsible for officially scrutinising and approving the work undertaken during the pilot phase. In particular, the main responsibility of the SC was to approve documents submitted by the Technical Secretariat such as draft PEFCRs. The SC was comprised of one member from each pilot, one official from each EU member state, one individual from key stakeholder groups and other representatives of the EC. Similarly, since an approval body is necessary for PEFCRs, it is envisaged that the SC will also be applicable for the development of dedicated PEFCRs for space. The TAB provided technical support and advice to SC members that had appointed them. Each member of the SC could appoint one expert to be a member of the TAB. The TAB expressed its opinion and input to the EC on technical issues that were of cross-cutting relevance to several PEF pilots [42].

Additionally, there was a number of cross-cutting working groups established in the pilot phase which aim at creating horizontal rules for issues that are common to several pilots. As such, the lessons learned by the TAB and cross-cutting working groups could provide vital input in the development of PEFCRs for space, particularly given the difficulties in applying LCA within the sector. On this aspect, a technical helpdesk was also established so that pilots could direct any technical questions they may have had to experienced LCA practitioners who were well-informed about ongoing developments in the pilot phase [42]. This would also prove to be highly beneficial.

Lastly, it should be noted that anyone was able to register as a stakeholder and submit comments during PEF pilot phase, widening participation in the process. It was also compulsory that these comments were addressed [42]. The encouragement of such an approach again would be advantageous.

4.2 Product environmental footprint category rules

The unique operating sphere of the space industry makes it critically important to define a pathway with regards to how PEF studies might be conducted within the sector. In this regard, PCRs are a necessary tool to define the rules and requirements for Type III environmental declarations [19]. Moreover, PEFCRs can be seen as the PEF version of PCRs and are typically developed in an open and collaborative manner, much like industry standards [23,27], based on the process outlined in Figure 7 [51]. The ESA LCA guidelines [35] act as an excellent basis for the development of PEFCRs, and as such, much of the current rules can be defined based upon them. In line with the space system breakdown defined within the ECSS-S-ST-00-01 standard [52], these guidelines provide the primary guiding principles which should be applied when conducting a space LCA study at system level or equipment, component and material level. They are based on the ISO 14040:2006 [10] and 14044:2006 [11] standards which provide a globally accepted framework to which all LCA studies should adhere to. The ESA LCA guidelines tailor the methodological rules contained within the ISO framework to be more appropriate to the space sector without risking non-compliance. As such, they should be seen as an extension of the ISO framework rather than an alternative to it.

In terms of product categories, the focus of this framework is on system level analyses rather than equipment, component and material level analyses. The reason for this is because several PEFCRs already exist on a wide range of products which are applicable within the space sector, including IT equipment (storage) [53], rechargeable batteries [54], PV modules [55], uninterruptible power supply [56] and metal sheets [57]. For this reason, from a system level perspective, it makes sense to create product categories based on mission classification. This approach allows product categories to be developed based on the function of a space mission and its potential use, providing a more attractive basis for comparison in terms of technical performance. Examples of mission classifications are outlined below:

- Earth Observation
- Satellite Navigation
- Telecommunications
- Science
- Exploration
- Space Telescopes
- Launch Vehicle
- …

Defining the goal and scope definition as part of the PEFCRs is also extremely important. Of particular relevance within the goal and scope definition is the FU and system boundary. The FU is a quantified performance of a product system for use as a reference unit [10,11]. It defines what all inputs and outputs of the PEF study should be related to. However, due to varying requirements and specifications of different space missions, an applicable FU can be hard to define, particularly if results are to be used for comparison. Currently, the ESA LCA guidelines provide a generic FU, namely 'one space mission in fulfilment of its requirements' [35]. As new product categories have been defined within this framework, there is potential to update this FU or select something which is more specific to different mission classifications. Possible FUs which could be used are outlined below. The first two are relevant for a telecommunications mission whilst the last two are for a launcher:

- 1 MB of data transferred over a distance of x km.
- Space mission per kg mass.
- One launch of a launch vehicle.
- One kg of payload placed into orbit.

The ESA LCA guidelines already cover the system boundary in great detail. In this regard, space projects have a life cycle, from concept definition to end-of-life (phases A to F) where the suggested system boundary is a sum of the space, launch and ground segment (including infrastructures if considered to be appropriate) [35]. These phases incorporate design work, travel, production, manufacturing, assembly, integration, qualification, testing, verification, launch campaign, LEOP, commissioning, mission control, and end of life. Additionally, it should be noted that the issue of space debris is not currently included within the system boundary, despite previous work on the topic, including the developing a debris label for spacecraft based on the evaluation of the consequences of fragmentations on operational satellites [58]. This is because fully characterising space debris in terms of end of life procedures is a lengthy and complex task. However, the ESA Space Debris Mitigation Compliance Verification Guidelines [59] could act as a complementary metric on this topic. In the future, the ESA hopes to be able to integrate space debris into LCA through a bespoke indicator that aims to quantify the risks associated with the creation of space debris.

Despite all of the issues identified within Figure 5 being relevant for PEFCR development, the rest of these be addressed in other subsections of this paper. However, for any issue considered relevant but not covered by this framework, the ESA LCA guidelines, ISO 14025:2006 standard and/or the PEF guide should be consulted.

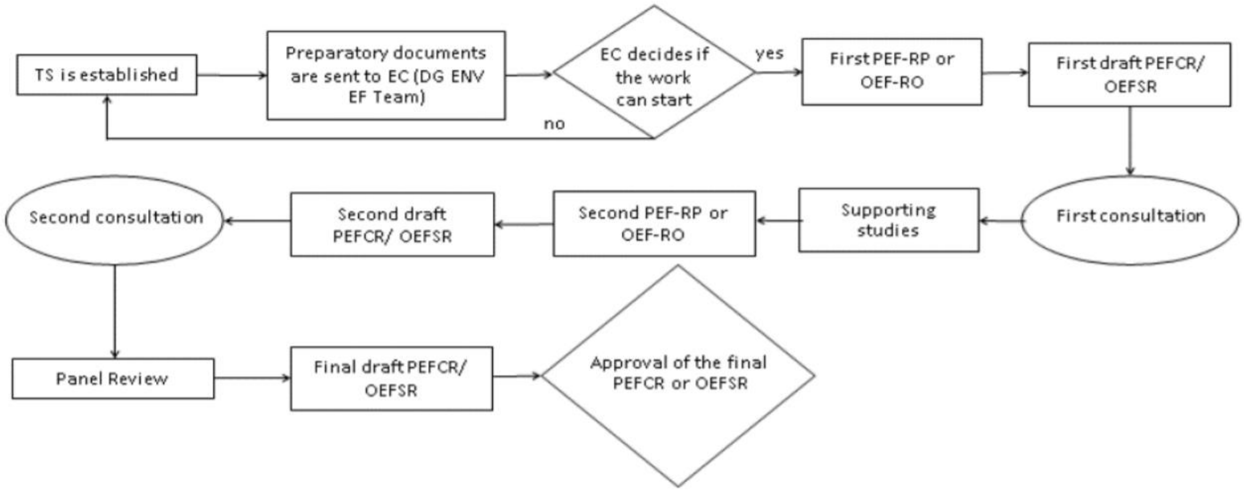

Figure 7: Process for developing new PEFCRs [51]

4.3 Life cycle assessment

Besides ensuring conformity of the methodological approach to the predefined PEFCRs, the inventory data used within any LCA study should also be equally as transparent and robust [10,11]. In this regard, dataset validation will be critical even in established space LCA databases. This is because space missions can often host components, technologies or materials that are unique to a particular spacecraft. As such, the datasets required to model two space missions can differ significantly in comparison to one another [35] (even under the same product category). As such, it is a distinct possibility that new datasets will have to be created specifically for a given PEF study. This places an added importance on data collection and calculation procedures, allocation and partitioning rules and data quality requirement aspects during the LCI phase.

Data collection and calculation procedures should comply with the various PEF guidance. This includes providing a description and documenting all primary data collected, including data gaps and assumptions. Only EF compliant or ILCD compliant background datasets may be used, with only a maximum of 10% of the total environmental impact derived from the latter [21]. The PEFCR will determine the specific data which needs to be collected, based on the life cycle stages included within the system boundary and impact categories the LCA will need to assess [22]. Additionally, the cut-off rule outlined within the ESA LCA guidelines should be followed. Based on this, only inputs constituting less than 5% of the total mass of the component considered can be excluded from the scope due to a lack of data, negligible environmental or health risks, it is not included on the REACH 'Authorisation List' and/or identified by the EU as critical raw materials (CRM). By default, space debris is also excluded [35]. It should also be noted that the LCI itself can be kept confidential during B2B and B2C communication, but it must be visible for validation purposes by the PEF study reviewer.

Allocation/partitioning rules still need to be determined for space LCA as the ESA LCA guidelines do not provide detailed advice on this other than mass criterion is to be used and monetary allocation avoided [35]. At present, the use of both cut-off and allocation at the point of substitution are used in space LCA tools used by industry. Overall, it could be considered that cut-off may be more appropriate as it is simpler for non-LCA experts to understand, whilst its use can be easily justified as recycling of waste adds even more complexity due to the additional information required, leading to further tracing of material across the supply chain. This means the primary producer does not receive any credit for the provision of any recyclable materials in model calculations. However, it is common practice within industry to use allocation at the point of substitution and it could be argued that this is more aligned with the PEF approach. As such, this framework does not necessarily preclude the use of the allocation at the point of substitution approach. Therefore, it is recommended that the Technical Secretariat addresses this point once formed. However, to ensure transparent impact quantification, the LCA should be based on a burden-based approach using a process-based attributional methodology for the reasons outlined in Subsection 2.2, as emphasised within the ESA LCA guidelines [35].

In terms of data quality requirements, setting a minimum data quality level for datasets to be included within space databases was considered critical. At present, the ESA are in the process of developing data quality requirements according to the PEF data quality criteria [21]. It is expected that this will be released within the next update of the ESA LCA guidelines. However, based on this criteria, only datasets with a basic data quality level (i.e. an overall DQR ≤3.0) shall be considered valid to use within a life cycle inventory. It is therefore recommended that only the ESA LCA database and other space LCA databases which have gone through a validation process such as the Strathclyde Space Systems Database [13] are used for this purpose.

A default list of impact categories and related assessment methods is provided for PEF studies [21], formed around ILCD recommendations [43]. These are at midpoint level, which is a problem-oriented approach used to translate impacts into environmental themes, and are outlined in Table 3. According to the PEF approach, all of these impact categories shall be applied, without exclusion. However, due to sector specificities, some adaptations may need to be made. For example, CML [60] is potentially a better LCIA method than the source indicated for acidification, whilst the 'reserve base' horizon is more representative for resource use (minerals and metals) in the space sector as it refers to resources that have reasonable potential to become economically and technologically available. Additionally, specific characterisation factors will need to be added to these LCIA methods for launch and re-entry processes, as well as for certain chemicals and substances for which no characterisation factor is defined (e.g. chlorine). A full list of required adaptations is not yet available and should be outlined in any newly developed PEFCRs. Several other newly developed impact categories and flow indicators could be considered within a space LCA in the future with further development, which are outlined in Table 4.

In addition to completeness, sensitivity and consistency checks, the interpretation phase of an LCA should also seek to identify hotspots. To support the identification of hotspots in the life cycle of a space mission, the ESA have identified six impact categories as key environmental hotspots, based on average LCIA results across a variety of different missions (product categories). These include climate change (total), ozone depletion, human toxicity (cancer), human toxicity (non-cancer), ecotoxicity (freshwater) and resource use (minerals and metals).

4.4 Product environmental footprint reporting

Evidently, as part of this framework, the Type III environmental report should conform to the specified PEF standard format [5. 21]. The PEF report is a vital accompaniment of a public environmental declaration as it provides details about the LCA methodology, including any assumptions made. The minimum sections of a PEF report are a summary, a main report, an annex and a confidential report (the latter of which is an optional element) [21].

For clarification purposes, the summary is a stand-alone report used to summarise the key points of the main report. In that regard, the main report provides information on the LCA in accordance with the ISO 14040:2006 and ISO 14044:2006 standards, including all predetermined parameters outlined within the PEFCR. The Annex serves to document supporting elements to the main report which are of a more technical nature. The confidential report is an optional reporting element that shall contain confidential or proprietary data and information that may not be externally available (such as raw data contained within the LCI). Regardless, the confidential report should be made available for the verification and validation procedure of the PEF study.

Despite this, it is clear that many environmental declarations are made purely to showcase the environmental performance of a product. As such, a recent study was launched to gather insight into the most effective ways of communicating the PEF profile of products to consumers. One method explored was the used of optional PEF labels within PEF reporting [44]. All the developed PEF labels used in this experiment displayed the single performance score on the following a three-level scale:

- Performance information as a percentage relative to the average.
- Information on the three most relevant impact categories.
- Information on the product's performance on the three most relevant impact categories (on three-level scales).

Such an approach makes defining a benchmark for space systems imperative. Although some results are slowly becoming available, confidentiality issues surrounding space LCA has meant that there is little information or data that can be used for this purpose. To add further complexity, unlike other PEFs, space missions are not directly comparable even under the same product category (see Subsection 4.2). For this reason, should benchmarking is to be attempted, it is recommended that it only takes place for products within same product category. In this regard, the following criteria has been considered as being potentially representative of an average product:

- Historical ESA missions
- Averages based on a number of missions
- Selection of a particular mission

Table 3: Suggested EF impact categories with their respective indicators and characterization models [21]

Impact category	Indicator	Reference
Climate change, total	Radiative forcing as global warming potential (GWP100) [kg CO_2 eq.]	[61]
Ozone depletion	Ozone depletion potential (ODP) [kg CFC-11 eq.]	[62]
Human toxicity, cancer	Comparative toxic unit for humans [CTUh, c]	[63]
Human toxicity, non-cancer	Comparative toxic unit for humans [CTUh, n-c]	[63]
Particulate matter	Impact on human health [disease incidence]	[64]
Ionising radiation, human health	Human exposure efficiency relative to U^{235} [kBq U^{235} eq.]	[65]
Photochemical ozone formation, human health	Tropospheric ozone concentration increase [kg NMVOC eq.]	[66]
Acidification	Accumulated exceedance (AE) [mol H^+ eq.]	[67,68]
Eutrophication, terrestrial	Accumulated exceedance (AE) [mol N eq.]	[67,68]
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P) [kg P eq.]	[69]
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N) [kg N eq.]	[69]
Ecotoxicity, freshwater	Comparative toxic unit for ecosystems [CTUe]	[63]
Land use	Soil quality index [Dimensionless (pt)]	[70,71]
Water use	User deprivation potential (deprivation-weighted water consumption) [m^3 world eq.]	[64]
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves) [kg Sb eq.]	[60]
Resource use, fossils	Abiotic resource depletion – fossil fuels (ADP-fossil) [MJ]	[60]

Table 4: Extra impact categories and flow indicators to be considered with appropriate development (at a minimum)

Impact category	Indicator	Reference
Al_2O_3 emissions	Al_2O_3 emissions in air (flow indicator) [kg Al_2O_3 eq.]	[35]
Critical raw material use	TBC: Supply risk (flow indicator) [TBD]	[72]
Cumulative energy demand	Primary energy consumption potential (flow indicator) [MJ]	[73]
Mass disposed in ocean, total	Total mass disposed in ocean (flow indicator) [kg mass]	[35]
Mass left in space, total	Total mass disposed in ocean (flow indicator) [kg mass]	[35]
Orbital resource depletion	Space debris crossing the orbital resource (flow indicator) [objects.m^3.year]	[74]
Re-entry smoke particle generation	Re-entry smoke particle generation potential (flow indicator) [kg RSPs]	[13]
REACH substance use	TBC: Risk assessment (flow indicator) [TBD]	[75]

Alternatively, benchmarks could also be formed on something else entirely, such as normalisation factors (e.g. planetary boundaries [76], global consumption data [77], annual global ecospheric impacts of space activities [13]). However, the development of benchmarks for space missions could allow for the development of a Type III PEF label similar to the one outlined below. Additionally, it is envisaged that as more space PEF studies are conducted, more data may become available. Under such a scenario, averages/percentiles from other PEF studies on space missions within the same product category could be used to compare and contrast results, including impact/kg.

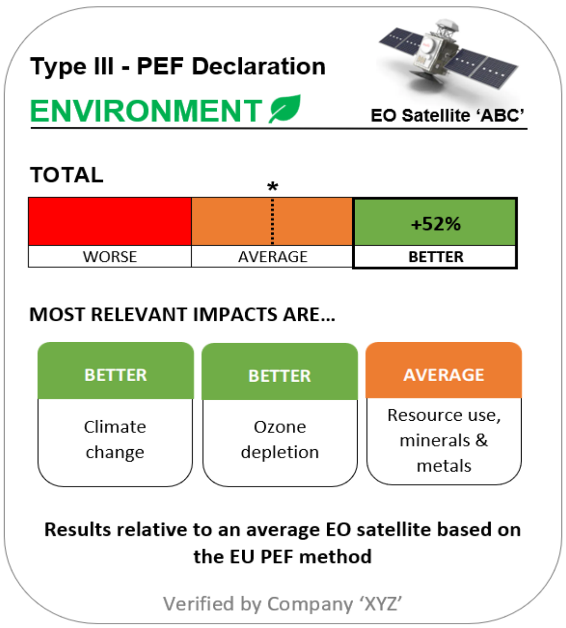

Figure 8: A simplified example of a potential PEF label for space missions (adapted from [44])

Despite this, the ESA LCA guidelines advise against performing environmental comparisons between different space missions. For this reason, at present, this framework does not recommend that product comparisons are attempted until more appropriate benchmarks become available.

4.5 Third party validation & verification

An independent and external third party review of the PEFCR procedure and Type III environmental report is mandatory before it can be published [19]. This ensures the verification and validation of all PEF studies, reports and communication vehicles intended for external communication. In this regard, verification refers to a conformity assessment carried out by an environmental footprint verifier to check whether a given PEF study complies with the most updated version of the PEF method and PEFCRs [21]. Validation refers to confirmation by the environmental footprint verifier who carried out the verification that the information and data included in the PEF study and report, including all associated communication, is reliable, credible and correct. This also incorporates the LCI inventory data according to data quality requirements.

According to ISO 14025:2006 [19], the programme operator shall establish minimum requirements for the competence of verifiers. Under the PEF method [21], this has already been set in line with the ISO/IEC 17020:2021 standard [78] on the requirements for the operation of various types of bodies performing inspection. In this regard, it is specified that all reviewers should be sufficiently qualified according to the PEF scoring system for eligible reviewers/review teams [21]. Based on this, unless otherwise specified, the minimum score required for verifier qualification is six points, including at least one point for each of the three mandatory criteria of verification and validation practice, PEF/LCA methodology and practice, and knowledge of technologies or other activities relevant to the PEF study. A minimum score for the review of PEFCRs and Type III environmental reports has not yet been set within this framework since space LCA is a very novel topic and still developing. Instead, at a minimum, reviewers are expected to have a sufficient knowledge in either LCA or space systems (but preferably both), including relevant experience with verification and validation, process and product knowledge of the relevant product category and a high familiarity with the ISO 14025:2006 standard, PEF method and ESA LCA guidelines. Additionally, the verification and validation may be performed by a single verifier or by a verification team who are external to the organisation that conducted the PEF study. However, to algin more closely with the ISO 14044:2006 standard [11], when intended for external communication, this would require a review by a panel with a minimum of three reviewers. All verifiers must also have had no involvement in the development of the general programme development, as defined by the governance structure outlined in Figure 6.

A full list of verification and validation techniques and requirements are outlined within [21]. The output of this process is a verification and validation report with a validation statement. This is used to reach a final conclusion whereby it is determined whether the study, report and associated communication is either 'compliant', 'not compliant' or 'complementary information needed'. Once completed, to fall in line with the PEF approach, the maximum validity of the verification and validation report and of the validation statement should not exceed three years starting from the first issue date [21].

In order to enhance harmonisation, it is recommended that an industry-specific PEF platform is created for PEF verification and validation within the space sector. This could be run in a similar manner to the ECO Platform for the European construction industry [79], whereby EPDs run by program operators are audited by the platform to ensure that they are following the EPD pathway outlined in Figure 3. This platform was developed following the adoption of the EN 15804 standard relating to the calculation of the environmental impacts of construction products by the European Committee for Standardization (CEN) in 2012, which has since been used as the basis for publishing EPDs on construction works and services [80]. Therefore, based on the underlying function of the ECO Platform, the new industry-specific platform proposed as part of this framework could maintain a list of approved reviewing bodies to ensure that submitted PEF studies and reports are aligned with the quality and verification criteria outlined within this framework and the 'Suggestions for updating the Product Environmental Footprint (PEF) method' document [21]. This will guarantee a high level of robustness and quality in PEFs of space systems, thus creating a globally recognised standard. For heightened visibility, such PEFs could brandish a platform verified logo to showcase their adherence to this standard, which would provide much higher levels of recognition across the European space sector. In this regard, only once the PEF study has been accredited through the platform can it use the verified logo.

4.6 Report publication

Although not strictly part of the PEF approach, it is still important to consider the potential audience of any environmental declaration under development and its provision according to ISO 14025:2006 [19]. In this regard, the method by which PEF reports will be used externally has not yet been specified. In comparison, EPDs with their extensive detailed information, are indispensable for B2B communication. However, one big difference between the two approaches is the requirement for PEF reports to be made public, whilst the declaration is public in the case of EPDs, but the report may be confidential. Therefore, PEF reports are designed to provide heightened levels of transparency in reporting and communication, thereby allowing direct product comparisons to be made. Despite this, although it can be anticipated that the vast majority of PEF declarations on space systems will be developed for B2B communication, some may still be used in B2C communication. In this respect, given that Type III environmental reports are complex and require considerable documentation, it is important to also take into account both the content and availability of a PEF declaration in both B2B and B2C communication in order to ensure transparent information is conveyed at all times.

In terms of content, according to ISO 14025:2006 [19], no part of a Type III environmental report shall be omitted or simplified for B2C communication in comparison to B2B communication. However, since the EC specifies that PEF reports must be made public [5,21], this eliminates all risk concerning the possible issuing of a diluted public PEF declaration. Despite this, ISO 14025:2006 also specifies that the organisation making the environmental declaration should provide extra explanatory material upon request (when used in B2C communication) to facilitate consumer understanding of the data [19]. For this reason, it is also important that contact details are clearly stated within the PEF report to afford all interested parties the opportunity to communicate with the organisation and obtain any extra explanatory material or further clarification.

Regarding availability, ISO 14025:2006 states that Type III environmental reports which are intended for B2C communication shall be available to the consumer at the point of purchase [19]. However, since the space sector does not act as a traditional market where products can be readily purchased by consumers, it is recommended that this information should become freely available at Phase E1 (i.e. prior to 'use'). This is because although a critical design review will occur at the end of Phase C, data from Phase D production, manufacturing and testing may not be fully accounted for at this point due to a lack of measurement or knowledge. For this reason, making a PEF report available at Phase E1 was considered to be more appropriate. No upper limit has been defined for issuing a PEF report beyond Phase E1 due to potential retrospective legacy reporting of many space missions. However, it is essential that a PEF report becomes available as soon as any kind of a public environmental declaration is made.

Finally, there is no guidance available on the process for placing PEF reports in the public domain, unlike with EPDs [4]. In this regard, once an EPD has been verified by an independent third party, an organisation may wish to place this into the public domain via publication. To do this, the EPD document is submitted to the program operator, who will process, register and then publish the EPD. As such, it is recommended that an industry-specific PEF platform for space is developed for the registration and publication of PEF reports in a similar manner to the International EPD System [4]. This could act as a single consolidated and centralised location for holding European PEF reports on space activities and could be tied into the verification and validation platform outlined in the previous subsection. In the future, this could even be expanded to include the aviation industry as well. However, in the meantime, it is proposed that all verified and validated PEF reports on space systems are published directly online through the website of the organisation responsible for making the environmental declaration.

5. Discussion

5.1 Intended application & future vision

The industry-leading work conducted by the ESA on space LCA over the past decade has undoubtably led to environmental concerns becoming a much more prominent and widely considered topic within the European space sector. The proliferation of this technique has led to an elevation in perceived importance for developing environmentally benign space products, technologies, facilities and resources. Conversely, this has unintentionally led to the emergence of vague, unclear and potentially misleading environmental claims, for which there is already ample evidence. Therefore, in order to prevent other false, deceptive or unsupported environmental claims from surfacing, this paper has presented a new framework for environmental communication and reporting on space systems. The developed framework provides a comprehensive set of voluntary operating procedures, consistent with the PEF approach, which intend to act as preliminary guidance for European industrial stakeholders and national agencies. As such, it complements the ESA LCA guidelines (rather than replacing them) and should be used as a basis for any pursuant environmental declarations.

The specific rules outlined within the framework are expected to act as a placeholder until more detailed (or official) guidance is issued. In that regard, through its design, the scope of the developed framework is somewhat restricted. This is because the study was limited by what it could address and the decisions/rules that could be defined without wider market consultation. Although it should still be used wherever possible, it can be considered that the framework requires further refinement, focussing particularly on creation of dedicated PEFCRs (using the ESA LCA guidelines as a basis). This includes the need to enhance LCA/PEF development within the European space sector. However, additional work could also be formed around this, including the adaptation of this framework into the newly developed space sustainability rating (SSR) system and the creation of a new protocol/directive to strengthen environmental regulation on space activities.

5.2 List of recommendations

Based on the intended application and future vision outlined above, seven high-level recommendations have been established to advance this work further:

- Another critical review of the ESA LCA guidelines should take place with a goal of updating them, taking into account potential alignment with the PEF method.
- The developed framework should act as a method for best practice in the absence of dedicated PEFCRs for space.
- A consortium should be created to develop PEFCRs for space (based on the ESA LCA guidelines) and improve on this framework by addressing all of the gaps identified in this paper, with the ESA leading the Technical Secretariat.
- Heightened knowledge transfer on space LCA is required within the European space sector, including the development of better benchmarks, to expand the application of LCA studies and establish a better understanding of environmental performance characteristics through comparison.
- An industry-specific platform should be established to act as consolidated and centralised location for European PEF studies on space activities, whose primary purpose is to enhance the harmonisation of LCA development and ensure rigorous verification and validation of environmental claims.
- A protocol or directive should be produced on mandatory environmental reporting requirements for space activities to better regulate the industry, regardless of current exemptions already granted to the sector.
- Based on this framework, LCA should be integrated as an entirely new module within the SSR system, where conformity with a compliance system is treated as an essential component for an environmental claim to be globally recognised or considered valid.

6. Conclusion

A scoping exercise was conducted to map the specificities of the space sector against the ISO 14025:2006 standard, based on the PEF approach. As a result, a new harmonised framework was presented as a potential pathway for the communication and reporting of environmental declarations in the context of the European space sector. Although further refinement will be required to convert this into a draft that meets market needs, the voluntary operating procedures proposed within this paper intend to act as preliminary guidance to ensure rigorous verification and validation of environmental claims. In the interim, conducting a simplified PEF based on this framework should ensure good sectoral practice, thereby avoiding greenwashing and other false environmental claims.

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Disclaimer

The views expressed in this paper are those of the authors and do not necessarily reflect the views of the organisations they represent. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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