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Review article

Application of environmental life cycle assessment (LCA) within the space sector: A state of the art

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ABSTRACT

The space industry generates pressures on the environment and strives towards more sustainable activities. Several actors of or related to the European space industry, such as ArianeGroup or and the European Space Agency (ESA), have identified the life cycle assessment methodology (LCA) as the most appropriate methodology to measure and then support the reduction of their environmental impact. While the use of the LCA is being established within the sector, only a limited number of peer-reviewed publications are available. Most of the documents released by the stakeholders can be considered to be grey literature. As the topic has not been properly discussed in the literature, there is an opportunity to bring the initiatives carried out by the space sector in recent years to the public domain. Thus, the present work aims to provide a comprehensive overview of past and present studies following the LCA framework. The review compiles 11 papers, conferences proceedings or technical reports that address the development of the LCA framework and good practices in the sector and 27 documents dedicated to LCA studies. On the one hand, the results highlight the emergence of a common framework regarding LCA practice in Europe. On the other hand, the analysed LCA case studies show a highly heterogeneous goal and scope definition. In this review, research needs and methodological challenges are identified and discussed. Finally, recommendations on how to implement and develop the use of LCA within the space industry are given in view of designing more sustainable space systems and associated missions.

1. Introduction

Space applications provide a unique and essential data collection service with regard to Earth observation and climate monitoring [1]. As highlighted during the COP21 in Paris, of the 50 essential variables used to assess Earth's climate, 26 are monitored via satellite observations [2]. On the one hand, space applications help to protect the environment. On the other hand, as space activities continuously grow, an increasing number of actors want to gain access to space. The environmental burdens related to the space sector should be extensively investigated and minimised in a manner similar to what has been already done in the information and communications technology (ICT) sector [3]. The industrial stakeholders of the space sector are not targeted by specific UN-level binding commitments regarding environmental legislation.

Nevertheless, in June 2019, the member states of the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) reached an agreement adopting the guidelines for the long-term sustainability of outer space activities [4]. Guideline 27 refers to the development and promotion of technologies that minimise the environmental impact of manufacturing and launching space assets by maximising the use of renewable resources to enhance the long-term sustainability of space activities. France is currently the only nation with a binding national legislative framework. The French Space Operations Act provides a national legislative framework concerning all the space operations launched from the French territory (i.e., Guiana Space Centre). With full entry in force in 2020, the act aims to make operators responsible for the prevention of risks to people, property, public health and the environment [5]. Its article 8 states that impacts on public health and the environment related to a potential operation shall be addressed within a dedicated impact study.

Finally, in the case of the European Union, industrial stakeholders and agencies in the space sector are affected by a set of non-sector-specific environmental directives or regulations. The RoHS directive, short for the *Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment* should be noted. The

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Directive restricts the use of ten substances, mainly heavy metals such as lead or mercury. In parallel, one of the most important is the European Commission Regulation concerning the *Registration, Evaluation, Authorization and Restriction of Chemicals* (REACH). In terms of production rates, the space industry is small in comparison to other industrial sectors. While a major part of the materials is highly specific, the space sector is a minor consumer in terms of volume. That situation could lead to a lack of anticipation in terms of vulnerability and the substitution of materials. There is a high concern on the part of the European space manufacturing industry about the management and mitigation of the long-term risks of 'obsolescence' and supply risk disruption [6]. This was particularly the case when REACH regulation came into force in 2007. Furthermore, particular attention should be given to the use of the critical raw materials (CRMs) targeted by the European Commission [7,8].

Space sector industries sometimes claim to develop "green" or "eco-friendly" technologies when fulfilling specific regulations (such as avoiding substances from the candidate list of REACH), which is typically the case for the so-called "green propellants" [9]. However, the industry's environmental compliance does not capture the full environmental footprint because the technologies are not assessed holistically. In response to this issue, several actors of the space industry have identified life cycle assessment (LCA) as the most appropriate methodology to address and reduce their environmental impact [10,11].

The space sector, including in-orbit activities, is a new area of development for the LCA research. In Europe, the European Space Agency is leading the development of LCA practices within the frame of the *Clean Space Initiative*, which was launched in 2012 [12]. Today, an LCA community involved in space activities is emerging as indicated by the presence of LCA and ecodesign sessions within aerospace conferences, particularly in the context of CEAS conferences [13,14] or in the participation of Airbus Defence & Space within the Organizing Committee of the LCM conference 2015 in Bordeaux [15]. Clean Space Industrial Days (2017, 2018, 2020) now include a specific ecodesign theme with dedicated sessions on LCA [16]. While the use of LCA is being established within the sector, only a limited number of peer-reviewed publications are available. Most of the documents released by stakeholders can be considered to be grey literature. As the topic has not been properly discussed in the literature, we believe there is an opportunity to bring the initiatives carried by the space sector in recent years to the public domain.

Thus, the present work aims to provide a comprehensive overview of past and present studies following the LCA framework [17]. After mapping the LCA initiatives in the space sector, a detailed state of the art is provided. Case studies are selected and analysed using criteria from the 4 phases described in the LCA international standards: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. Finally, means of improvement, challenges and opportunities are presented and discussed.

2. Methods

2.1. Selection of LCA papers addressing space activity

The present review aims at compiling papers presenting a special interest in the application of LCA related to the space sector. According to ISO 14040 [17], life cycle assessment (LCA) compiles and evaluates the inputs, outputs and potential environmental impacts of a product system throughout its life cycle. As a multi-criteria methodology, LCA studies identify the 'burden shifting pollution', which consists in transferring the impact from one environmental impact category to another or from one life-cycle stage to another.

We chose to select papers, conference proceedings or technical reports addressing at least one step of the methodology as follows: (i) definition of goal and scope, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA) and (iv) interpretations of the results. The present review also compiles relevant publications defining a framework or a methodological development linked to sustainability for space activities, which could be a good starting point in the harmonisation of life-cycle applications within the space sector.

The papers, proceedings and technical reports come from various channels: (i) the Scopus database with the following query: *[TITLE-ABS-KEY("Launcher*") OR TITLE-ABS-KEY("satellite*") OR TITLE-ABS-KEY ("spacecraft") OR TITLE-ABS-KEY("rocket") OR TITLE-ABS-KEY("space mission*") OR TITLE-ABS-KEY("space sector")) AND (TITLE-ABS-KEY ("LCA") OR TITLE-ABS-KEY("life cycle assessment") OR TITLE-ABS KEY ("ecodesign")]*; (ii) NASA's technical library's public search engine 'TechDoc' (https://tdglobal.ksc.nasa.gov/); (iii) several conference proceeding publications, which are directly available on the conference website (CEAS, LCM and IAC conferences, ESA Clean Space Industrial Days) and (iv) elements collected within the space industry from different sources (e.g., final reports of environmental studies).

2.2. Analysis grid of the selected papers

We define two separate grids of analysis to analyse two types of papers reviewed here: a-papers related to framework and good practices, b- LCA studies. For each grid, a set of qualitative criteria was established allowing for the classification and analysis of the papers. The criteria are described in the followings sections (§2.2.1; §2.2.2).

2.2.1. Criteria for 'framework and good practices' analysis grid

The papers taken into account within this grid are generic publications discussing the relevance of applying LCA to space activities. Here, the analysis addresses the goal of the selected papers. The following questions were used as qualitative criteria:

- (i) Do the papers provide a complete framework and/or good practices for LCA application within the sector?
- (ii) Do the papers discuss the possible integration of LCA studies during the design phase of new materials, products or processes?
- (iii) Do the papers consider a broader scope than environmental LCA with the aim of integrating other sustainability concerns?
- (iv) Do the papers present a coupling solution between LCA and design tools/methodologies for space systems?

2.2.2. Criteria for 'LCA studies' analysis grid

The case studies were selected and analysed using criteria from the 4 phases described in LCA international standards (see Table 1).

i. First, we focus on the *Goal and Scope* of the space LCA studies. The methodological framework provided by the ESA LCA Working Group [18] in the ESA LCA Handbook proposes to adapt the life-cycle phases of the European-standardized space project management system to better describe the life-cycle steps of a large-scale system [19]. The results are presented in Table 2 for each specific

Table 1
Description of criteria reviewed for LCA studies.

Type of papers	LCA phase	Qualitative Criteria
LCA studies	Goal & Scope	Goal of the study
		System boundaries
		Functional unit
	LCI	Source of foreground data
		Source of background data
	LCIA	Mono or multi-criteria analysis
		Selected LCIA methodology/indicators
		Weighting and normalisation (yes/no?)
	Interpretation	Environmental hotspots
		Conclusions: added value of the study

Table 2
Goal and Scope: system boundaries according to the specific segments of a space mission as presented in the ESA's Handbook for large-scale space systems [18].

	Space Segment	Launch Segment	Ground Segment	Support segment (Infrastructures)
Phase A - Feasibility	Office work and travelling			Design facilities
Phase B - Preliminary Definition	Qualification and testing			
Phase C - Detailed Definition	Production and development testing of critical elements and engineering models	Production of launcher components and propellants		Production & Testing facilities
Phase D - Qualification and Production	Production of spacecraft components Qualification, testing and verification Spacecraft assembly	Stage assembly		
Phase E –Utilisation	Launch campaign	Launch campaign Launch event (launch pad operations and lift-off)	Launch and early operation phase + Commissioning Mission control	Spaceport Telemetry, Tracking and Command Ground Station(s) Flight Operation Control centre(s) Payload Datacenter
Phase F – Disposal	Disposal of the spacecraft	Disposal of the launcher stages	Ground operations for the end of life of the spacecraft	

segment of a space mission (e.g., Space segment, Launch segment, Ground segment), which are defined as a set of elements or a combination of systems that fulfil a major, self-contained, subset of the space mission objectives [20]. Based on this framework, we discuss the system boundaries (§3.3.1) and the functional unit (§3.3.2) of each study.

ii. For each targeted study, the analysis of the *life cycle inventory* (LCI) *phase* addresses the issue of the source of the data and its quality, differentiating the data coming from the foreground and background systems (§3.3.3). As explained by Bjorn et al. [21], on the one hand, the data from the foreground system, i.e., all the specific processes that are under control, should be directly collected by the practitioners. On the other hand, LCI databases can be used to source data for the background system, i.e., not under direct control of the decision makers involved in the study, and for the parts of the foreground system for which more specific data cannot be obtained.

iii. Then, the *life cycle impact assessment* (LCIA) proceeds through two mandatory steps: selection of impact categories and characterisation of the impacts. In this review, we identify the selection of a mono- (e.g., carbon footprint) or multi-criteria approach for the assessment of the system under study. Concerning multi-criteria analysis, the chosen LCIA methods with associated indicators at midpoint and/or endpoint levels are described (§3.3.4). The presence of normalisation and weighting, which are optional elements (ISO) based on value choices (i.e., not science-based), is also discussed.

iv. Considering the *interpretation phase*, the environmental hotspots are identified based on the analysis of the relative contributions of the sub-systems. In addition, the added value of the studies is discussed focusing on their conclusions (§3.3.5).

3. Results of the review

3.1. Analysis of the selected documents

Fifty-two documents were collected. After a first screening within the document list, a substantial number of documents (14) were considered to be out of the scope and disregarded. This was the case for papers discussing the benefits of applying ecodesign in the space sector without a concrete reference to LCA applications or addressing a limited scope. Publications referring to “life cycle assessment” or “analysis” without including an environmental dimension were removed. This was especially the case for several of NASA's studies that do not match with the standardised LCA methodology (ISO 14040/44) because they consider only economic costs and no environmental impacts. Finally, we selected eleven papers addressing the aspects of “framework and good practices” (11) and twenty-seven papers regarding LCA studies (27), which came to a total of thirty-eight papers (38). Table 3 shows the complete list of the selected documents.

Of the thirty-eight remaining documents, 84% are from conference proceedings (32) whereas only 8% are peer-reviewed papers (3) and 8% are technical reports or dissertations (3). Those figures show the confidential nature of the LCA practice in the space sector. The geographical distribution shows that Europe is by far the leader in applying LCA within the space sector with 87% of the selected documents, followed by North America with 5 studies. The European Space Agency is the major actor in this field, being associated with 74% (28) of the documents. Other actors include industries (such as ArianeGroup) or academia (such as the University of Austin). The temporal distribution of the publications is addressed in the following section (§3.2).

3.2. Framework and development of the LCA practices within the space sector

Fig. 1 shows the breakdown of the topics addressed in each document.

Table 3
Classification table of the selected documents in terms of temporal range, geographical orientation, type, scope and topic distribution. (P.rev: peer-reviewed; ConfP: conference proceedings; Report: Technical report or dissertation. Inf and GS: Infrastructures and Ground stations; Launch seg: launch segment; S.mission: space mission; Mat: materials; Integ. w/i design: integration within the design phase).

Reference	Year	Europe/ESA	Europe	N. America	Type	LCA study	Framework	Clusters	Topics
Castiglioni et al. [22]	2015	x			P.rev	x		Inf and GS (III)	*Facility management*
Chanoine [23]	2017	x			ConfP	x		Launch seg. (IV) and S.mission (VI)	*European launchers and mission (Earth observation, Communication)*
De Santis [24]	2018	x			ConfP	x		Inf and GS (III)	*Ground stations*
De Santis et al. [25]	2013	x			ConfP	x		S. mission (VI)	*Missions (Astra 1 N and MetOp-A)*
Gallice et al. [26]	2018	x			ConfP	x		Launch Seg. (IV)	*Ariane 6*
Geerken et al. [27]	2018	x			ConfP	x		S. mission (VI)	*Greensat ecodesign (Proba V)*
Geerken et al. [28]	2013	x			ConfP	x		S. mission (VI)	*Mission (Proba II)*
Izagirre et al. [29]	2017	x			ConfP	x		Mat. and process (I)	*Passivation process*
Kurstjens et al. [30]	2018	x			ConfP	x		Mat. and process (I)	*Germanium use in space sector*
Meusy [31]	2009	x			ConfP	x		S. mission (VI)	*CDF ecosat mission*
Neumann [32]	2018			x	Report	x		Launch Seg. (IV)	*Expendable/Reusable launchers*
Pettersen et al. [33]	2018	x			ConfP	x		Mat. and process (I)	*ESA Space LCI database*
Pettersen et al. [34]	2015	x			Report	x		Mat. and process (I)	*ESA Space LCI database*
Pettersen et al. [35]	2015	x			ConfP	x		Mat. and process (I)	*ESA Space LCI database*
Pettersen et al. [36]	2017	x			ConfP	x		Mat. and process (I)	*ESA Space LCI database*
Pettersen et al. [37]	2016	x			Report	x		Propellants (II)	*ESA Space LCI database*
Pettersen et al. [38]	2017	x			ConfP	x		Propellants (II)	*ESA Space LCI database*
Pourzahedi et al. [39]	2017			x	P.rev	x		Mat. and process (I)	*Material replacement*
Remy et al. [40]	2018	x			ConfP	x		S. mission (VI)	*Greensat ecodesign (Proba V)*
Romaniw et al. [41]	2013			x	ConfP	x		Mat. and process (I)	*Material replacement*
Saint-Amand et al. [42]	2013		x		ConfP	x		Mat. and process (I)	*Solid rocket motorcase (materials)*
Silva [43]	2015	x			ConfP	x		Mat. and process (I)	*Photovoltaic system*
Soares et al. [44]	2012	x			ConfP	x		Launch Seg. (IV)	*European Launchers, Ariane 5*
Sydnor et al. [45]	2011			x	ConfP	x		Inf and GS(III)	*Facility management*
Thiry et al. [46]	2017	x			ConfP	x		S. mission (VI)	*Greensat ecodesign (Sentinel 3)*
Thiry et al. [47]	2018	x			ConfP	x		S. mission (VI)	*Greensat ecodesign (Sentinel 3)*
Vercalsteren et al. [48]	2017	x			ConfP	x		S. mission (VI)	*Greensat ecodesign (Proba)*
Austin [10]	2015	x			ConfP		x	Harmonisation	*Guidelines for space sector*
Chanoine [49]	2015	x			ConfP		x	Integ. w/i design	*ESA CDF design*
Chanoine [50]	2017	x			ConfP		x	Integ. w/i design	*ESA CDF design*
Durrieu et al. [11]	2013		x	x	P.rev		x	Position paper	*Possibility of LCA use in space sector*
Huesing [51]	2015	x			ConfP		x	Harmonisation	*Guidelines for space sector*
Morales et al. [52]	2017	x			ConfP		x	Harmonisation	*ESA LCA framework*
Ouziel et al. [53]	2015		x		ConfP		x	Integ. w/i design	*TRL scale - LCA for new techno.*
Saint-Amand [54]	2015		x		ConfP		x	Integ. w/i design	*TRL scale LCA for new techno.*
Soares [55]	2012	x			ConfP		x	Harmonisation	*ESA LCA framework*
Wilson. et al. [56]	2018		x		ConfP		x	Sust. Assessment	*Concurrent design*
Wilson et al. [57]	2017		x		ConfP		x	Sust. Assessment	*Concurrent design*

Fig. 1. Distribution of the documents related to the LCA framework and good practices applied within the space sector. Eleven documents were selected.

3.2.1. *European LCA framework for space activities*

As far as we know, the first attempt to consider environmental impacts through a complete LCA study came from an ESA pilot Concurrent Design Facility (CDF) study called 'Ecosat' [31]. That study's conclusions highlighted the need to develop a harmonised LCA framework within the European space sector as well as to develop specific datasets related to the space industry. Today, the European space industry is well-structured on this topic, mainly due to the strong efforts of the ESA in the frame of the ecodesign activities of the *Clean Space Initiative* [12]. We did not find any equivalent programme in North America or Asia, as underscored by the analysis of the geographical distribution in section 3.1. The French space agency (CNES) also carried out LCA, particularly focusing on the launch pad system in French Guiana; however, no scientific communication was published on the topic [58].

An important task of the ESA's *Clean Space Initiative* is to raise environmental awareness and to establish a complete network with the European space community as explained by the ESA [51,52,55]. Austin, Huesing and Pettersen et al. [10,35,51] highlight the difference between the space sector and a more conventional consumer-oriented industry. They underscore the need to adapt the conventional LCA methodology to fit with the specific needs of the space sector. Priority has been given to the harmonisation of the LCA approach and practices within the European space sector. The main goal is to establish a common framework to be used by national space agencies and industries when performing spacecraft design. This framework is composed of three main pillars [52]:

1) Guidelines and good practices to aid in LCA studies were released by the ESA with a dedicated handbook: *Space System Life Cycle Assessment guidelines* [18]. This handbook aims to establish the methodological rules for how to correctly perform space-specific LCAs at the complete system level (i.e., space mission) or for dedicated space sub-systems, e.g., a specific component, equipment or technology.
2) A dedicated space LCI database was developed that included specific materials and advanced manufacturing processes [34] as well as space propellants [37]. Current LCA studies for space rely on this database, which covers more than 1.000 space specific datasets [33].
3) An ecodesign platform called OPERA and coupled with a concurrent design facility (CDF) tool was developed to systematically implement environmental LCA in the early-design phase of ESA space missions [49,50].

3.2.2. Integration of the LCA during the design phase

As mentioned by Chanoine [49], the environmental performance of systems, similar to cost performance, is highly driven by design elements that are defined at an early stage in the design process. Consequently, coupling LCA with design tools seems particularly relevant in the case of space missions due to the high complexity of such systems. It is expected that the above-cited OPERA platform will be implemented in the frame of the concurrent design process of the ESA. Hence, the platform will provide instant feedback to the design team related to the environmental performance of the system under study. At the industrial level, Ouziel and Saint-Amand [53,54] discuss the integration of LCA during the development of new technologies. They recommend adapting the completeness level for a given LCA study based on the technology readiness level (TRL) scale of the studied technology. It should be noted that systematic integration of LCA information with existing product life cycle management (PLM) solutions or computer-aided design (CAD) software has already been successfully applied outside of the aerospace community [59,60].

3.2.3. Sustainability assessment

The ESA mentions the fact that their LCA framework may also help actors in the space sector to address European environmental legislation, particularly REACH and the RoHS directives but also to flag the use of critical raw materials. Complementary use of the LCA approach lies in the understanding and monitoring of the supply chain to support pro-active and coordinated measures to avoid potential disruptions [51]. This task can be addressed at the inventory level, once the elementary flows are mapped, or *via* the development of dedicated indicators addressing supply risk during the impact assessment stage [61]. A preliminary ESA-funded study that is headed in this direction was recently presented [62,63]. In that study, the conventional scope of LCA is broadened with the integration of criticality assessment, which is more in line with the life cycle sustainability assessment (LCSA) framework [64,65]. Durrieu and Nelson [11] also suggest the use of social life cycle assessment. An attempt to consider the economic and social dimensions of LCSA is currently being conducted [56,57]. That work aims at developing an LCSA platform coupled with an internal CDF tool to address potential impacts during the early-design of the space missions.

3.2.4. Framework development

Fig. 2 shows the temporal distribution of LCA papers in the space sector. The first range of complete LCA studies was carried out in Europe from 2012 to 2015. Communications in the year 2015 emphasise the efforts made to implement, develop and harmonise the LCA practices in the European space industry. This first phase resulted in the release of the ESA LCA Handbook for space systems in 2016 and the ESA space LCI database in 2017. Since 2017, several new studies have been launched by the ESA capitalising on the good practices and knowledge inherited from the previous studies. Today, new perspectives are emerging based on this established framework: LCA is being applied to many European Earth Observation satellites [66] while the scope is being broadened with the aim of integrating new sustainability concerns, first and foremost regarding space debris proliferation [67].

LCA has mostly been applied for ecodesign purposes; however, in their position paper Durrieu and Nelson [11] explain that LCA methodology is particularly relevant in the field of Earth observation to benchmark and identify the best technological options (among (i) full series of short-lifetime satellites, (ii) a solution based on a long lifetime observation satellite coupled with airborne systems, and (iii) the use of airborne systems alone).

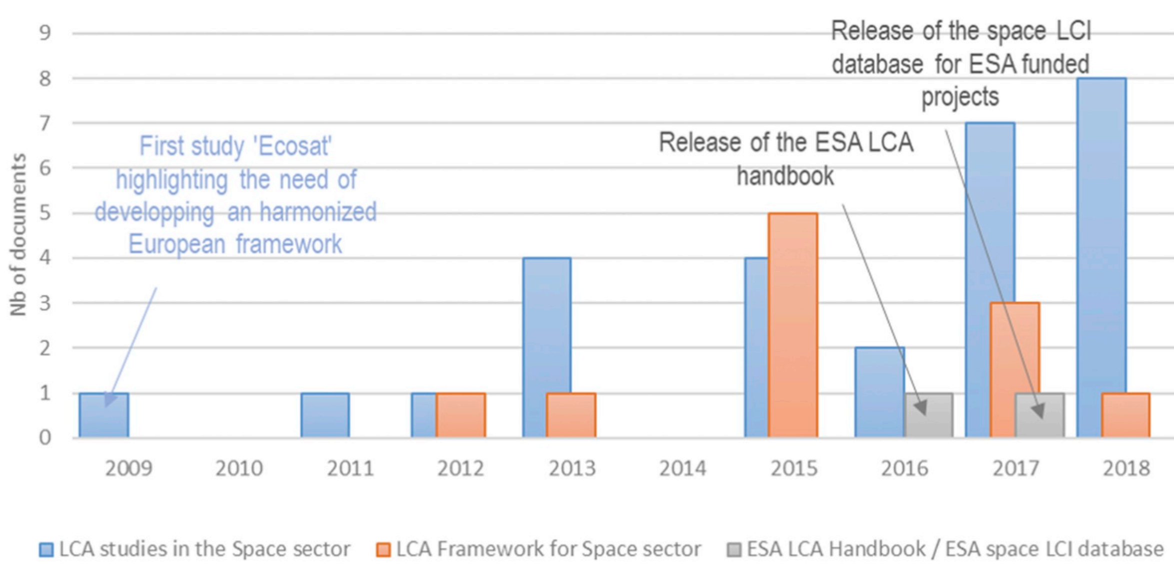

Fig. 2. Temporal distribution of LCA communications in the space sector according to specific LCA studies and “framework and good practice” documents; elements composing the European framework (i.e., ESA LCA Handbook and ESA LCI database) are mentioned.

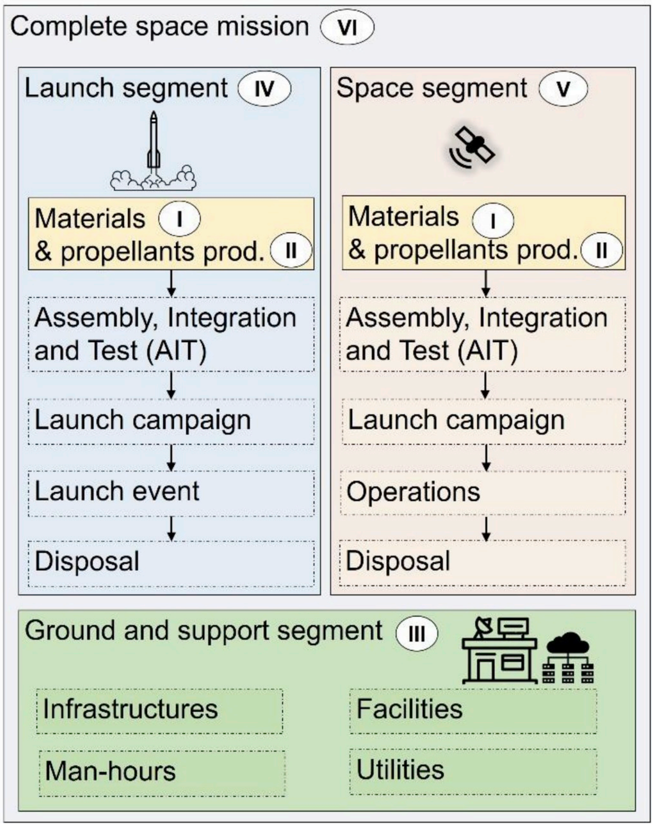

Fig. 3. Goal and system boundaries of the selected LCA studies. Six clusters were identified: (I) components, materials and manufacturing processes; (II) propellants manufacturing; (III) ground and support segments; (IV) launch segments; (V) space segments; (VI) completed space mission.

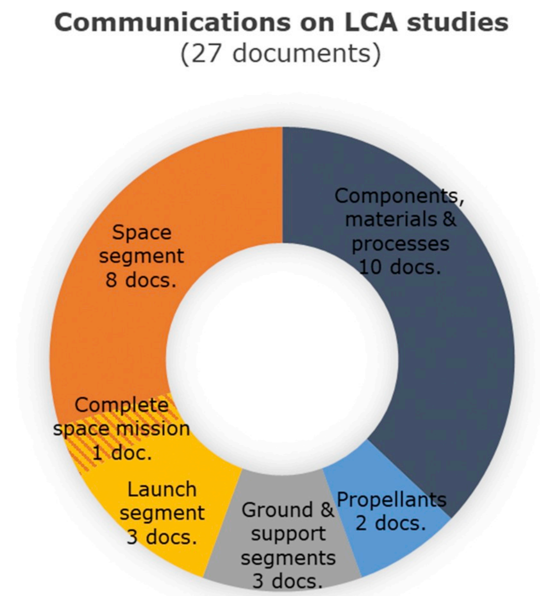

Fig. 4. Distribution of the LCA studies documents according to the six clusters related to the LCA applications within the space sector. Twenty-seven documents were selected.

3.3. Description of the LCA studies

3.3.1. Goal and system boundaries

The goal and system boundaries of each LCA study were identified and classified according to six main clusters as defined in.

Fig. 3: (I) components, materials and manufacturing processes; (II) propellants manufacturing (III); ground and support segments (IV); launch segments; (V) space segments; (VI) completed space mission. It should be noted that 'Materials' and 'Propellants' are addressed in dedicated sub-sections because of the large number of studies found addressing those two industrial clusters. These latter clusters are the core of the ESA space LCI database [33].

Fig. 4 provides the repartition of the LCA studies according to these clusters. For each cluster, a description of the relevant studies is obtained through the analysis grid provided in Table 1.

Components, Material and Processes (I). We identified ten publications addressing specific components, materials and processes for space applications. The components for space applications differ from standard applications [27]: (i) they are produced in very small quantities based on highly advanced processes; (ii) they must operate in extreme conditions and environments and thus require particular properties to be controlled during long testing and qualification steps to comply with space industry standards.

Half of the documents (5) are related to the creation of datasets for the ESA Space LCI database mentioned in section 3.2 above [33–35,43]. This database was designed by the 'Eco-design Alliance for Advanced Technologies' managed by the consultancy *Asplan Viak* with the industrial support of the ArianeGroup. The dataset mostly covers material and manufacturing processes, with some notable exceptions such as manpower and logistics, waste treatments or specific electricity mixes. The system boundaries of each component or sub-system must be addressed separately. Most of the time, the data cover a 'cradle to gate' scope for which the product chain is directly managed by the manufacturer.

In one of the first LCA studies on space sub-systems conducted at the European level, Saint-Amand et al. [42] compare the environmental impacts of several materials (composites, thermal protection, metal) with the associated assembly phases for a Solid Rocket Motor Case. Another study focuses on the Germanium (Ge) use for photovoltaic (PV) systems [30]. Another study addresses the comparison of two steel passivation processes (i.e., surface treatment) [29]. Finally, two studies explore the material substitution of traditional metallic components with polymer composites in the case of electromagnetic interference shielding [39] or with carbon fibre reinforced polymers for structural elements [41].

Space propellants (II). The question of the toxicity of space propellants is a highly discussed topic in the space sector under the umbrella of the terms 'Green propulsion' or 'Green propellants' [9,68–70]. However, the environmental burden of propellants is usually assessed only through the health risks related to the legislation of toxic compounds without matching with an LCA perspective. Only two documents focusing on the LCA of propellants and in line with the ISO 14040/44 were selected [37,38]. They refer to the ESA-funded study on the LCA of space propellants that makes a significant contribution to the field. A large dataset of approximately thirty (current and potentially future) space propellants is implemented in the ESA space LCI database with a 'cradle-to-gate' approach for chemical production and the adding of processes up to the point of launch depending on data availability or judgements on the relevance for environmental impacts assessed in LCA studies.

Ground and support segments (III). According to ESA Clean Space [71], a segment that deserves investigation for space missions is that related to ground activities. The latter is based on the management of the communications between in-orbit satellites and mission control centres as well as the archiving and processing of the mission-specific scientific data collected. Three documents were found [22,24,45]. The ESA-funded study [24] was recently launched with the aim of fully determining the related environmental impacts of those activities. The scope of this study focuses on the characterisation of various "generic families” of ground segment representatives for telecommunication, navigation, scientific earth observation and CubeSat missions, covering their specific infrastructures and operations. Four major ground segment typologies were identified as follows: mission operations centres, science operation centres, data processing centres and other ground stations (i.e., optical, radio-frequency or radar terminal). The scope of the study includes infrastructure and building construction as well as operational phases including transportation phases and facilities. In addition, two studies addressing utility management and infrastructures were previously conducted by Castiglioni et al. [22] at the European Astronaut Centre and Sydnor et al. [45] regarding NASA's high-energy ground test facilities. While the first study mainly discusses energy solutions, water and waste management, the second includes in its scope ground test facilities (excluding the construction and demolition phases).

Launch segment (IV). Three studies focusing on launch segments were identified [26,32,55]. Additionally, a document was identified that covers the complete scope of a space mission, which is included because a dedicated section of the document exclusively considers the launch segment [23].

An ESA LCA study was carried out in 2012 focusing on the European Launcher network (Ariane 5, Vega, Soyuz) [23,44]. The scope of the study follows the ‘Launch segment’ as detailed in Fig. 3. The study highlights the difficulty of including the R&D and testing stages in the scope as well as infrastructures as their impacts are highly dependent on the number of launches. Consequently, the ongoing LCA study of the new Ariane 6 launcher performed by ArianeGroup [26] disregards R&D and feasibility activities, focusing on the exploitation phase. The stages related to end-of-life should also be part of the study's scope. For the first time in the space industry, this LCA study is being performed during the early development of a new launcher system with the goal of providing a complete environmental profile of the launcher at the time of its early production. Another study related to the launcher system was identified: Neumann [32] compares expendable and reusable launchers.

Space segment (V) and complete space mission (VI). Most of the studies addressing the LCA of complete space missions (8 documents) mainly focus on ‘space segment’ whereas one compiles the topics of ‘space segment’, ‘launch segment’ and ‘ground and support segments’, taking into account the entire scope of a space mission [23]. These studies present the work funded by the ESA Clean Space initiative through several past projects [23,28,46] and a recent ecodesign study entitled ‘Greensat’ [40,46,48].

3.3.2. Functional unit

Components, Material and Processes (I). Most of the functional units related to the datasets created in the frame of the Space LCI database are defined to fit with the engineering and ecodesign perspective, often including the mass of the incorporated materials, the mass of the formed materials, or the mass of the removed materials. In the case of surface treatment processes, the use of an area unit (e.g., per square metre) seems appropriate whereas a length unit (e.g., metre) fits well for welding processes.

Propellants (II). Each propellant obtains specific density and heating values that make the comparison on a mass-oriented basis irrelevant. When comparing two types of propellants for a given propulsion system, the specific impulse (I_{sp}) that measures the efficiency of the propulsion system has been identified as an appropriate functional unit [37]. In the case of the comparison of different propulsion systems, the I_{sp} is not a sufficient parameter to be taken into account as the thrust level also plays a major role. However, the latter greatly influences the design at the system level, which implies an extension of the scope of the whole study.

Ground and support segments (III). In De Santis [24], the chosen functional unit is the following: “the fulfilment of requirements of Ground Segment for one year for the following mission types: navigation, Earth observation, science, Telecommunications or CubeSat”. Castiglioni et al. [22] and Sydnor et al. [45] also chose one year of facility operations as a functional unit.

Launch segment (IV). According to the ESA's Handbook, the functional unit of large-scale systems shall be differentiated between complete space missions and launchers. For launcher systems, the following functional unit is proposed: “To place a payload of X tons maximum [in single launch configuration and Y tons maximum in dual launch configuration] into orbit Z”. This functional unit allows for the comparison of launchers' environmental performance for the same mission domain. For instance, the comparison between the Ariane 5 and the new Ariane 6 launcher is mentioned in the ESA's contractual requirement regarding the environmental impact study [26]. In this case, the scope and the functional unit should be the same for both product systems to allow for a fair comparison. When comparing expendable and reusable solutions, a temporal dimension must be added related to the launch rates. The yearly equivalent payload mass delivered in orbit may be a good option. Neumann [32] proposes a launch rate of one launch every two weeks.

Complete space missions (VI). Unlike launcher systems, the design of a satellite is highly specific, usually serving a unique purpose through a dedicated space mission. Hence, the ESA's Handbook recommends the following functional unit: “One space mission in fulfilment of its requirements”; however, this functional unit may be subject to debate due to the impossibility of comparison between space missions. An option suggested in the ESA Handbook is to consider the amount of data generated by different space missions to compare the associated environmental impacts of each mission on the same basis. Additionally, Geerken et al. [27] highlight that a specific functional unit could be determined for a generic platform design to be used for multiple missions. This option seems particularly relevant in the case of the mass production of satellite platforms for mega-constellation systems, e.g., the OneWeb Arrow Platform [72]. In this particular case, the R&D activities and infrastructures related impacts could be allocated according to the expected production rate.

3.3.3. LCI

Source of foreground data. Over the twenty-seven papers, twenty-one mention that the study is performed or supported by industrial stakeholders. In the case of complex systems including ‘launch segment’, ‘space segment’ or ‘complete space mission’, data collection is a critical component due to the high number of involved industrial partners from suppliers through the final assembly stage on the launch pad. In the frame of the ESA-funded studies**,** system integrators are involved in the collection of foreground-data-specific questionnaires because they have a good understanding of the full industrial value chain: Thales Alenia Space for the Sentinel-3B mission [46,47], Deimos for study related to ground stations [24], and QinetiQ space with the Proba-II and Proba-V missions [27,28,40,48]. The dataset obtained from those studies is expected to be implemented in the ESA space LCI database.

The ESA-funded study on the European launchers’ network resulted in the creation of a specific dataset collected from fifteen industrial stakeholders over the forty contacted [23]. In the case of the Ariane 6, the data gathered are based on preliminary design status and available information from internal and external partners: more than ten internal focal points and eighteen external focal points among the industrial partners support the data collection step [26]. The ESA Handbook mentions that at least two full iterations are necessary for inventory analysis. Therefore, another iteration and an evaluation of the collected data will be completed at the time of the first Ariane 6 launch.

Regarding direct emissions at the full system level, the ESA handbook recommends the calculation of flow indicators corresponding to the mass left in space, the mass disposed in the ocean, as well as the atmospheric Al_2O_3 emissions corresponding to the burning of propellant.

For facility management, Sydnor et al. [45] compile foreground data for each facility involving both the facility personnel and central utilities. For the study, the data for three years of operations are averaged to obtain a better idea of a typical year for each facility's usage. In Castiglioni et al. [22], the data from the European Astronaut Centre are provided or estimated by the ESA for energy, water and waste management.

Several studies identify specific issues related to data collection within the space sector. According to Pettersen et al. [36], the specific needs of the space sector lead to the production of materials or chemicals not used elsewhere and with very small production rates. Thus, only very little pre-existing literature for processes and precursors can be found. For instance, the confidentiality and specificity of the synthesis routes for the chemicals are responsible for major uncertainties during data collection. Those uncertainties are mainly linked to the chemical reactants and associated reaction yields as well as to the use of solvents or metal catalysts. Moreover, the highly variable TRL levels hamper the data collection for potential alternatives up-scaled at a potential industrial level.

The study performed by Neumann [32] emphasises the difficulty of the data collection stage in the space sector. The limitation encountered during the inventory phase, i.e., the exclusive use of data coming from a generic database for the materials and propellant parts, prevents studies from reaching robust conclusions on the comparison between expandable and reusable launcher systems. In addition, in its conclusions, a study addressing telecom and meteorological missions (respectively ASTRA 1 N and MetOp-A spacecraft), even performed with the support of *Airbus Defence and Space*, highlights the difficulties of collecting input data [25].

However, Petersen et al. showed that a simplified LCI could lead to an overestimation of impacts compared to full and accurate LCI data collection. They modelled the same component (i.e., a spacecraft reaction wheel) from two perspectives: that of a detailed inventory versus that of a simplified inventory. The simplified LCI led to higher impacts than the complex one in four of the five selected impact categories.

Source of background data. The ecoinvent database [73] is used in almost all the studies (23). The US-EI life cycle inventory database (Earthshift, Huntington, VT) is used by Pourzahedi et al. [39]. For studies addressing the carbon footprint of materials and propellants [39,41], the embodied CO_2 is obtained from the Granta Design database (Granta Design Limited, Cambridge, United Kingdom).

Nevertheless, the conventional commercial databases face difficulties in depicting the specificities of the space sector [42]. Hence, the ESA space LCI database (gathering ~1000 space specific datasets) should play a major role in the further growth of the LCA applications within the space sector. Half of the documents selected (14) refer to this database, which provides a helpful basis for data that can be modified according to the specificity of each space project. According to Geerken et al. [27], a limitation of this database lies in the transportation processes for space applications. On the one hand, the high complexity of the supply chain for space activities results in a very broad distance travelled, particularly in Europe where the production and assembly phases and launch events are geographically fragmented. On the other hand, due to the particularity of space structures and components, the transportation step is usually a specific one compared with those of common logistics circuits. Thus, specifically dedicated transportation datasets should be used instead of conventional ones.

Further, the database proposed by the University of Strathclyde, in addition to coupling design and sustainability aspects, is expected to improve the automatic data collection during the early phases of space mission design [56,57].

Finally, a hybrid LCA approach with environmentally extended input/output economic data coupled with the foreground data is performed by Geerken et al. [28]. Space applications differ from conventional industrial applications because the price is mainly not driven by the materials but rather by the number of man-hours including energy consumption, travel, and construction in addition to office equipment and supplies. Consequently, the authors retrieved data for man-hours from the US Input-Output database [74] taking into account several types of workers: office workers, computer system designers and programmers, and scientific researchers.

3.3.4. LCIA methods

Among the twenty-seven (27) selected documents, 22 (i.e., 80%) rely on multicriteria analyses whereas 4 studies calculate only the carbon footprint. One study remains at the inventory level, providing only the flows of utilities [22].

The selected LCIA indicators for ESA-funded studies are broadly described in the ESA Handbook. They are based on the ILCD 2011 recommended methods [75] in association with the ReCiPe Midpoint *metal resources depletion potential* [76]. The latter impact indicator is suggested due to the large number of alloys and metallic components used in the space sector, even if it leads to a “double-counting” issue with the *mineral resources depletion potential* [77]. The *ozone depletion potential* (ODP) is a key indicator in the space sector as space activities are responsible for the direct emissions within the ozone layer. The impact category, the *marine aquatic ecotoxicity potential* (CML 2002), is also suggested in the Handbook and aims to characterise the impact of launcher parts falling into the ocean. The related midpoint indicator could be updated using the more recent methodologies that cover *marine ecotoxicity* as LC-impact [78] or ReCiPe 2016 [79].

The ESA also recommends the addition of flow indicators as the cumulative energy demand and water consumption of the ecoinvent database v.3 [73]. They can be appropriate when the LCA study covers the scope of the facility management system. Furthermore, two flow indicators are designed to account for the use of potentially targeted substances: on the one hand, by the REACH legislation (‘candidate list’ and ‘authorisation list’) and, on the other hand, the EU critical raw material list [7]. Ongoing studies are being conducted by the ESA regarding those specific obsolescence or supply risks [62,63].

Concerning the weighting between the impact categories, a score expressed in ‘points’ was designed in the frame of the ‘GreenSat’ study [47]. The ecodesign options are ranked based on the score obtained in combining a single environmental score coming from the LCA results and an industrial score based on techno-economic considerations. Furthermore, the topic of weighting indicators through a panel-based approach has already been debated during a ‘round table session’ of the *Clean Space Industrial Days 2017*. The goal was to prioritise the definition of the most important environmental indicators and to discuss the weighting factors between them to compute a ‘single score for space’ agreed upon by space sector actors. However, no consensus was reached because of a potential arbitrary selection based on ‘value choices’.

Finally, the current LCIA framework faces the methodological limitations of covering the disposal stage and the associated end-of-life of both launcher parts and spacecraft systems as underscored by Chanoine [23] and Geerken et al. [28]. The impacts related to the atmospheric emissions during the launch event also require future investigation [23,26]. For instance, aluminium oxide (Al_2O_3), which is the main substance emitted during the combustion of solid propellant, does not have a characterisation factor in terms of toxicity-related impacts.

3.3.5. Results and interpretation

Components, Material and Processes (I). According to Pettersen et al. [35], the environmental impacts of space missions are distributed across a large number of processes and activities; furthermore, that study highlighted the complexity of space systems and offered a large range of options for methods of improvement.

First, metal alloys must include all elements for proper evaluation, especially with the aim of covering the overall *metal depletion* aspects. Even the smallest measure of a mineral element can have a great effect on comparisons among metal alloys. Analogous to alloys, the electronic components embedded in spacecraft contain minor quantities of specific metals (often neglected in technical documents) that may contribute greatly to the final LCIA results. This is mainly the case for indicators related to the resource depletion issue. The PV system modelled in the ESA space LCI database is composed of triple junction solar cells comparable to the type of gallium indium phosphide/gallium arsenide (GaInP/GaAs) semiconductors found on Ge wafers [34,43]. The gold and silver layers in PV systems and interconnectors are the most important contributors to the metal depletion impacts of the whole space segment. The Ge wafer is also a notable hotspot for metal depletion and contributes to 75% of the PV score on *global warming potential.* Since germanium is the most important semiconductor material, in weight, of space missions, the use of recycled Ge associated with a more efficient industrial processing can generate substantial environmental savings [30,80]. An alternative to GaAs solar cells is also discussed within the 'Greensat' project by Thiry et al. [47] considering triple-junction solar cells manufactured based on the epitaxial lift-off (ELO) process, which results in mass reduction, the use of recycled germanium and higher cell efficiency. Perovskite solar cells are also an option; however, the currently low TRL is an issue. Going further, heavy metals, such as platinum or rhodium, appear to be important sources for *human toxicity* and *freshwater aquatic ecotoxicity* [23,40]. Nevertheless, the impacts related to metal compounds are not well represented by the existing models [81]. For example, the characterisation factors related to those substances are classified as interim by the USEtox consensus model due to the high uncertainties related to the fate, the exposure and the effect of those substances [82].

Moreover, thermoplastics for space show tendencies to differ from conventional thermoplastics regarding energy-related impacts (e.g., *global warming*) and can contribute to greater toxicity or ozone depletion impacts. Hence, the accurate representation of the chemical precursors used during synthesis is particularly important to capture the full environmental profile of a material. One specific thermoplastic, Polytetrafluoroethylene (PTFE), has been identified as being responsible for substantial environmental impacts [40,47]. This thermoplastic, which is used as a cable coating in harness systems, represents approximately 30% of the space segment's *ozone depletion potential* impact. Consequently, its replacement is considered to be an ecodesign option in the frame of the 'GreenSat' project.

Pettersen et al. [34,35] showed that the production of advanced materials generates more impacts than conventional materials. Therefore, material efficiency becomes especially important. Nevertheless, the space industry relies on production processes facing a very low buy-to-fly ratio, particularly for tank production (i.e., the weight ratio between the raw material used for a component and the weight of the component itself). Hence, the recycling of scrap materials could be an interesting means of improving resource efficiency. Innovative processes such as 'friction stir welding' are also a promising option to increase the buy-to-fly ratio [83]. This is also the case of additive layer manufacturing (ALM), for which the potential environmental benefits are widely investigated within the space sector [36,47,84] and in the aeronautic industry [85,86].

Surface treatment processes using chemical baths should be deeply investigated since the chemicals used (e.g., nitric acid or Cr VI) present environmental disadvantages in term of toxicity and can be targeted by specific legislation such as the REACh regulation. This topic is discussed by Izagirre and Zimdars [29] and Pettersen et al. [34]. However, the heavy qualification procedures represent a limiting factor in finding less impacting alternatives. Additionally, the results of the LCA study performed by Izagirre and Zimdars [29] mentioning a potential environmental gain using citric acid passivation must be confirmed with full-scale industrial data. If the LCA approach is well suited to evaluate products or processes that are already mature, it faces practical and methodological difficulties when applied to emerging technologies. This topic is currently being debated in the LCA community [87–89].

Finally, mass and volume reduction due to technology evolution (e.g., miniaturisation) or linked to the use of lightweight materials has been targeted by several space environmental studies. Vercalsteren and Holsters [48] highlight the mass reduction occurring between two generations of similar scientific instruments: 34 kg for the current embedded Vegetation instrument on the PROBA-V mission against 150 kg for the previous instrument on the SPOT5 mission. The following advantages regarding mass and volume savings can be listed: (i) from a resource efficiency perspective, less raw materials are used and associated wastes (including spacecraft with a casualty risk of burning during atmospheric re-entry) are limited; (ii) from a launch segment perspective, more space missions (or more satellites of the same constellation system) can be launched at the same time, allowing for the allocation of the environmental burdens related to the launch operations; (iii) regarding the utilisation phase into the orbital environment, the mass and volume reduction of a spacecraft for a given space mission allows for the reduction of the probability of encounter with debris and thus limits the potential release of fragments into the orbital environment. Mass and the associated potential environmental savings are also studied in explorations of the material substitution of traditional metallic components with composites such as carbon nanotube composites in the case of electromagnetic interference shielding [39] or the carbon fibre reinforced polymers used for structural elements [41]. By reducing the mass of the components, substantial propellant savings may be expected. According to the Tsiolkovsky rocket equation, the delta-V parameter (which determines how much propellant is required for a vehicle of a given mass and propulsion system) increases exponentially with respect to the mass ratio of the wet and dry mass.

Space propellants (II). The trade-off between the lightening of the mass and the reduction of propellant consumption is a key element regarding the ecodesign for space activities. The mass of the propellant represents the majority of the mass breakdown (e.g., approximately 87% of the lift-off mass for Ariane 5 ECA), and its production is a major contributor regarding the environmental profile of the launcher-related segment [26].

The propellants synthetized from generic chemicals generate high impacts because of their high purity. For instance, the space-grade liquid hydrogen produced for launches in Kourou (French Guyana) generates one order of magnitude more environmental impacts than conventional liquid hydrogen [38]. This increase is due to the purification steps that are necessary to guarantee a high purity grade of the propellants (> 99%). It results in the additional use of solvents and electricity: a similar quantity of energy is used in the purification step to obtain pure hydrazine (99%) from conventional hydrazine (64%) and to obtain an ultrapure hydrazine (99.9%) from pure hydrazine (99%). As the majority of propellants present toxicity risks, the decontamination and waste treatment steps (such as purges with helium or nitrogen and solvent flush) lead to environmental hotspots in all the impact categories.

In Pettersen et al. [37], three propulsion systems are compared: monopropellant hydrazine, bi-propulsion mixed oxides of nitrogen (MON)/monomethyl hydrazine (MMH), and chemical-electric propulsion hydrazine/xenon. The chemical-electric propulsion system with xenon/hydrazine has the highest environmental impact for all impact categories in comparison with the two other systems except for *freshwater ecotoxicity potential.* This is mainly due to the production of xenon that requires 1400 kWh per kg when extracted using a cryogenic air separation process (according to the ecoinvent database). However, it should be noted that electric propellants have higher I_{sp} values (by approximately 4–8 times) than the other propellant types and thus require lower weight and volume storage, which should modify the propulsion system.

Ground and support segments (III). As the specific ESA-funded study on the ground segment (i.e., related to the on-ground activities during the satellite operational phase) has not yet been completed, the available results are still very limited [24].

For the support segment, most of the impacts on *global warming* *potential* stem from electricity and natural gas consumption in the case of the NASA's ground test facilities [45]. Approximately half of the contribution to the *global warming* impact is driven by coal-fired electricity alone. Therefore, the use of renewable energy coupled with an optimised facility management now seems to be a key element in decreasing the impact of space activities on *climate change.* This means of improvement has been identified in the frame of the ‘GreenSat’ project [46,47].

In addition, Sydnor et al. [45] emphasise the carbon footprint of specialised facilities using refrigerant (e.g., R-134 or R-14) due to their high global warming potentials (GWP). In facilities that use refrigerants, the loss of refrigerant gas by leakage usually dominates the carbon footprint of the facility. Gallice et al. [26] also mention the issue of refrigerant fluid for air conditioning. This issue should be investigated in the next iteration of the Ariane 6 LCA study.

Launch segment (IV). Regarding the Ariane 5 study [23], electricity and heat consumption from the propellant production, stage production, and launcher integration are the three main contributors to *global warming potential*. The activities that happen at the Guiana Space Centre (spaceport), mainly propellant production, contribute less to *global warming potential* than *primary energy consumption* due to the Guianese electricity mix, which is composed of 47% of renewable energy. The transport stage is also a non-negligible contributor to *global warming potential*, specifically maritime transport, which is also an important contributor to *terrestrial acidification, marine eutrophication* and *photochemical oxidation potential.*

The production of the stages, driven by the structure of two boosters and the main cryogenic stage, are identified as the main contributor to the categories of *metal depletion, human toxicity* and *freshwater ecotoxicity* mainly due to the use of stainless steel. The impact on *ozone depletion potential* is dominated by the ‘launch event’ due to the direct emissions of alumina and chlorine occurring in the high atmosphere. Hydrogen chloride is also emitted during the ‘launch event’ and is responsible for one-third of the *terrestrial acidification* impact.

Regarding propellant production, the environmental impacts are mainly generated by solid propellant, which represents more than 70% of the propellant's loaded mass. The solid propellant contributes to 65% of the impact regarding overall propellant production for the *global warming potential* impact and approximately 90% of the impact for *toxicity* and *freshwater ecotoxicity* due to CrVI emissions as well as *metal depletion* due to platinum use. Considering the mass of the propellant loaded, liquid H_2 (~5% of the propellant mass) represents approximately 15% of the impact on the *global warming potential* for the propellant component.

The interim results for Ariane 6 presented by Gallice et al. [26] at the ESA Clean space industrial days may confirm that the ‘production and assembly stages’ and ‘propellant manufacturing’ are the main contributors for both Ariane 5-ECA and the future Ariane 6. However, in both cases, the contributions of the R&D and preliminary testing phases were not taken into account while they should influence the energy-driven impact categories. According to Soares et al. [44], the allocation of the impact of these phases presents several difficulties, which are mainly linked to the ‘technology heritage’ issue, i.e., the identification of which parts or components are inherited from a previous launcher design.

Complete space missions (VI). The launcher represents 99%, and the spacecraft 1%, of the mass of a complete space mission. Therefore, the environmental impacts related to the launcher (production, launch campaign, launch event) is a major hotspot on all the impact categories, e.g., from 50% to 70% of the *global warming potential* depending on the launcher's dry mass [23]. The use phase (control centres and ground stations) contributes to most of the impact categories *via* the energy consumption for operations, particularly the *toxicity/ecotoxicity potentials* (~50%) and to a lesser extent the *global warming potential* (~25%). The ‘Launch event’ (propellant burning) is the most impacting phase regarding *ozone depletion potential*: nearly 100% of the impact. The production of the PV system (for solar cells) also generates approximately 100% of the impact on the *mineral resource depletion potential.*

When the launch segment is not considered within the scope, the utilisation phase of the spacecraft contributes to 40%–60% of the environmental impacts for the overall categories in the particular case of the Proba-V mission [40]. During this use phase, the electricity consumption of the data centre and servers are majors contributors [40,46]. The design and the production phase of the spacecraft accounts for more than 30% of the overall environmental impacts [40].

Within the design and production phase, the office work is by far the major contributor (> 50% for most of the impact categories) with the exception of the *mineral resource depletion* driven by the materials used for satellites [40,46]. During the production stage, the scores related to the *toxicity/ecotoxicity* categories are also driven by the production of the electronic components embedded in the payload that account for approximately 30% [23]. These results are in line with the conclusions of Geerken et al. [28], which are also mentioned by Vercalsteren and Holsters [48] who highlight the environmental importance of the phases that include a large number of man-hours. The production and testing of satellites accrue most of the working time; therefore, the corresponding phases are responsible for a large portion of the environmental impacts. The R&D man-hours are a major contribution to the environmental impact of the satellite mission. Their impacts are mainly generated by the consumption of energy and the infrastructure.

4. Discussion and perspectives

Based on the results of this review, we identified several methodological and operational challenges for the use of LCA within the space sector. The methodological challenges are classified according to the three phases of LCA: (i) goal and scope, (ii) LCI, and (iii) LCIA. Finally, we discuss the opportunities to apply LCA within the space sector.

4.1. Extending the goal and scope of LCA studies in the space sector

Today, the space industry is experiencing an innovation-driven paradigm shift, leading to the “democratisation” and “industrialisation” of space [91]. The emergence of new space systems such as large satellite constellations will result in new technological capacities. However, the breakthrough allowed by space applications should also be judged through the scope of the sustainability assessment. LCA appears to be the most relevant tool to holistically address the comparison of the environmental footprint among conventional, Earth/space hybrid and stand-alone space systems [11].

Communication and internet networks are also a topic of interest as space applications are expected to play a major role in this field. A preliminary work assessing the carbon footprint of a hybrid telecommunications network is proposed by Faulkner et al. [92]. Environmental benefits were also discussed in the case of space solar power generation from a life-cycle perspective [93–95]. Recently, an attempt to apply the LCA methodology to the emerging topic of ‘asteroid mining’ was proposed by Hein et al. [96]. More generally, future applications of LCA in space, following the technological advancements in space exploration and travel, are discussed by Ko et al. [97]. They highlight the need to extend the scope of future LCA in space taking into account outer space exploration and the potential environmental impacts associated with that activity.

4.2. Improving inventory collection

The review of the selected documents highlights the necessity to include industrial stakeholders to enhance the robustness of LCA studies within the space sector. The quality of and access to the inventory data remain the major issue regarding these studies. This is mainly due to the complex supply chain for the large-scale systems as well as the inherent confidential nature of the space sector. The lack of a peer-reviewed process is also illustrated by the nature of the retrieved documents, which include only three scientific peer-reviewed articles.

Contrary to the belief that a detailed and accurate data collection would result in less favourable results compared with those derived from a simplified inventory, it has been shown that a truncated collection might lead to an overestimation of the impacts [33]. This example should encourage industrial stakeholders to carefully address the inventory stage by providing as much foreground data as possible.

Generic good practices regarding data collection are addressed in the ESA Handbook. A cut-off rule based on a mass criterion can be used to ease the completion of the inventory phase. According to the ESA Handbook, material or sub-assembly inputs that collectively constitute less than 5% of the total mass of the components considered can be neglected. However, we also recommend paying particular attention to metals and chemicals as follows: (i) a low amount of scarce metals used in a life cycle can significantly affect the metal depletion score; (ii) any substance listed as an EU critical raw material or targeted by the Reach regulation (i.e., REACH Annex XIV) cannot be excluded.

Regarding the end-of-life stage, the ESA Handbook states that no environmental benefit is obtained due to recycling or energy recovery when material is sent to a recycling plant. If conventional inventory data for the end-of-life is to be collected (e.g., transport to waste management plant, ratio between landfill and incineration processes), the "cut-off at recycling" approach is applied for recycling and recycled materials. However, we recommend following general LCA guidelines concerning allocation rules such as those found in Schrijvers et al. [98].

4.3. Towards a better characterisation of the space industry's specific related impacts

When addressing the comparison of conventional and space applications, a fair characterisation of the environmental impacts shall be performed. However, space systems engage a strong particularity that complicates the use of LCA: space missions are the only human activity that crosses all stages of the atmosphere and stays "out" of the natural environment and ecosystems [11]. As highlighted by the results of the review (see section 3.3.4), the current gaps in the life-cycle impact assessment framework must be addressed to cover the full scope of space activities.

The atmospheric impacts during the launch event are commonly perceived as the major environmental hotspot. However, the specific impacts related to the launch phase require future research efforts to be fully considered in LCA studies. Gaseous launcher emissions due to propellant burning include CO, N_2, H_2, H_2O, and CO_2 whereas solid rocket motors (SRM) generate aluminium oxide (Al_2O_3) particles, black carbon (i.e., soot) and gaseous chlorine species into the atmosphere [99]. According to an ESA-funded study [100], uncertainties affect the characterisation of launchers' impacts on the atmosphere. The main areas of uncertainties are related to (i) the aerothermodynamics of rocket plumes, which include the combustion and expansion process; and (ii) climate modelling including the insertion of small-scale plumes into relatively large scale climate models.

A particular focus has been given to ozone depletion concerns, mainly because the emissions associated with the launch are the only human-produced source of ozone-destroying compounds emitted directly into the middle and upper stratosphere [99,101–104]. To a lesser extent, the climate change impacts related to rocket plumes are also discussed [99,104,105]; even if, they are often considered in these papers to be marginal in comparison with the aircraft's carbon footprint. However, emissions of greenhouse gas in high altitudes can have a higher radiative force than emissions in low altitudes [106]. New propellants are also being proposed by the space industry, particularly liquid oxygen/methane solution. New models of ozone depletion should be adapted to anticipate future environmental impacts. Finally, the question of toxicity related to chemical compounds should be more deeply investigated [107].

With an expected increase of the flight rate of space transportation in the next decades, the burdens on *ozone depletion*, *global warming* or *toxicity* could become critical and change the perception of 'marginality' associated with the contribution of the space sector compared to other industries [105,108].

The question of space debris is also a crucial issue in terms of the sustainability of space activities. Colombo et al. [109] developed a preliminary index while a comprehensive framework was published by Maury et al. [110]. These initial studies led to the creation of dedicated characterisation factors to include the space-debris related impacts within the LCAs of space missions [111]. Once developed, this characterisation model was successfully applied in [67] to compare two mission design scenarios based on Sentinel-3 parameters and retrieved from the previous GreenSat study. In this way, the burden shifting between the Earth and the orbital environment could be characterised. Furthermore, the end of life of space missions should also consider the environmental impact due to the atmospheric re-entry in the high atmosphere as well as the presence of non-demised materials or launcher stages in the oceans. An ongoing ESA-funded study is being carried out on the topic of the environmental impact related to atmospheric re-entry [112] while the previous work funded by the French Space Agency [113,114] could represent a first step in the elaboration of dedicated characterisation factors respectively covering the atmospheric re-entry and fall of materials on the ground or in the oceans.

As LCA is a versatile methodological framework, future investigations on emerging environmental burdens could be implemented in the LCA of space missions as long as new indicators and associated characterisation factors are developed in compliance with the ISO standard [17]. For instance, if the trend concerning the impacts of acoustic waves on the ionosphere [115,116] is confirmed, the latter impact could be considered in the frame of the LCA of space missions. In this way, the paper published by Cucurachi et al. [117] provides general guidance for deciding on the inclusion of emerging impacts in life-cycle impact assessment.

4.4. Opportunities for further developing LCA practice in the European space context

At the European level, the tools and methodologies developed in recent years present a great opportunity to implement and develop the use of LCA within the industry. They will facilitate the identification of the environmental hotspots along a company's supply chain of its products, reinforcing the knowledge of upstream and downstream activities. Regarding facility management, LCA is a powerful tool to map the flows of utilities (e.g., electricity, water, waste) and to identify means of improvement adopting a so-called *Lean and Green* approach [118].

Additionally, the application of LCA in the space industry can be regarded as a proactive process to anticipate future risks due to public concerns and legislation. The current issue of plastic marine debris and associated legislative efforts is a good example of this issue. LCA provides a harmonised response regarding environmental impact assessment along the life-cycle. The communication of the obtained results can be understood as a central element in response to a legislative framework (e.g., the French space act), to public concerns expressed by NGOs, or to a client's contractual requirement. Furthermore, as the environmental concern is a new topic in the space community, environmental life cycle management (LCM) appears to be a differentiating factor among competitors [119].

The LCA methodology currently faces limitations at low TRL levels as highlighted through the ex-ante LCA concept [88]. Nevertheless, the integration of LCA in the early design phase seems to be a promising option for improving the sustainability of space systems. In this way, a new dimension related to environmental performance could be included in the concurrent engineering of new projects through the inclusion of LCA-based indicators. This approach would represent a substantial improvement with regard to the ecodesign procedure of the

ISO 14062 [120] standard addressing the integration of environmental aspects into product design and development. The inclusion of environmental performance criteria from the beginning of development could foster the rethinking of design from a different perspective towards more efficient systems.

Finally, the recognition of LCA as a science-based methodology can also strengthen the environmental reporting in the frame of corporate social responsibility (CSR). Quantitative environmental disclosures adopting a life-cycle perspective could be provided through monitored key performance indicators (KPI). According to Stewart et al. [121], the LCA stands for an indication of sustainability management practices in the industry among investors or the evaluation approaches of external ranking agencies. For example, the sustainable finance action plan launched in 2018 in the European Union requires companies to strengthen their nonfinancial information disclosures.

5. Conclusion

This paper reviews the current application of environmental LCA in the space sector. It shows that the existing peer-reviewed literature is scarce. The majority of the work done using an LCA approach in the space sector comes from Europe and particularly the ESA in the frame of its *Clean Space initiative*. The review highlights the emergence of a common framework regarding LCA practice in Europe.

The analysed LCA case studies show highly heterogeneous goal and scope definitions. While some papers addressed large-scale systems such as launch segments or space missions, others focus on space-specific materials or processes. This review emphasises the fact that LCA application in the space sector is not straightforward, mainly due to the completion of the LCI phase in which the collection of foreground data is a key element and a current challenge. Access to a space-specific database for the background data is a need considering the particular properties of the materials and chemicals used. At the European level, substantial efforts have been made in this regard by the ESA through the achievement of the space LCI database, which must be maintained and improved by future LCA studies in the sector.

This review also paves the way for future research with the aim of developing the use of LCA and life cycle management at the industrial level while assessing the environmental performance of space missions. The complete implementation of these approaches would facilitate the undertaking of coherent ecodesign actions along the whole value chains of space systems. However, methodological limitations regarding the LCIA phase remain. They should be approached to reinforce the credibility and robustness of LCA studies in the space sector. Among others, two topics seem to be of prime importance. On the one hand, ozone-depletion-related impact appears to be a major issue, especially as the emissions of ozone-depleting substances have unexpectedly increased in recent years [122,123]. On the other hand, the impacts occurring in the orbital environment due to the lack of space traffic management and through space debris proliferation represent a current dire issue that should be fully integrated into LCA studies to ensure a more sustainable design of space systems.

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