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1 Application of environmental Life Cycle 2 Assessment (LCA) within the space sector: a state 3 of the art

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13 **Abstract**

14 The space industry generates pressures on the environment and strives towards more
15 sustainable activities. Several actors of or related to the European space industry, such as
16 ArianeGroup or and the European Space Agency (ESA), have identified the life cycle
17 assessment methodology (LCA) as the most appropriate methodology to measure and then
18 support the reduction of their environmental impact. While the use of the LCA is being
19 established within the sector, only a limited number of peer-reviewed publications are

20 available. Most of the documents released by the stakeholders can be considered to be grey
21 literature. As the topic has not been properly discussed in the literature, there is an opportunity
22 to bring the initiatives carried out by the space sector in recent years to the public domain.
23 Thus, the present work aims to provide a comprehensive overview of past and present studies
24 following the LCA framework. The review compiles 11 papers, conferences proceedings or
25 technical reports that address the development of the LCA framework and good practices in
26 the sector and 27 documents dedicated to LCA studies. On the one hand, the results highlight
27 the emergence of a common framework regarding LCA practice in Europe. On the other
28 hand, the analysed LCA case studies show a highly heterogeneous goal and scope definition.
29 In this review, research needs and methodological challenges are identified and discussed.
30 Finally, recommendations on how to implement and develop the use of LCA within the space
31 industry are given in view of designing more sustainable space systems and associated
32 missions.

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37 **1. Introduction**

38 Space applications provide a unique and essential data collection service with regard to Earth
39 observation and climate monitoring [1]. As highlighted during the COP21 in Paris, of the 50
40 essential variables used to assess Earth's climate, 26 are monitored via satellite observations
41 [2]. On the one hand, space applications help to protect the environment. On the other hand,
42 as space activities continuously grow, an increasing number of actors want to gain access to
43 space. The environmental burdens related to the space sector should be extensively
44 investigated and minimised in a manner similar to what has been already done in the
45 information and communications technology (ICT) sector [3]. The industrial stakeholders of
46 the space sector are not targeted by specific UN-level binding commitments regarding
47 environmental legislation.

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

60 Finally, in the case of the European Union, industrial stakeholders and agencies in the space
61 sector are affected by a set of non-sector-specific environmental directives or regulations. The

62 RoHS directive, short for the *Directive on the restriction of the use of certain hazardous*
63 *substances in electrical and electronic equipment* should be noted. The Directive restricts the
64 use of ten substances, mainly heavy metals such as lead or mercury. In parallel, one of the
65 most important is the so-called European Commission Regulation concerning the
66 Registration, Evaluation, Authorization and Restriction of Chemicals (REACH). In terms of
67 production rates, the space industry is small in comparison to other industrial sectors. While a
68 major part of the materials is highly specific, the space sector is a minor consumer in terms of
69 volume. That situation could lead to a lack of anticipation in terms of vulnerability and the
70 substitution of materials. There is a high concern on the part of the European space
71 manufacturing industry about the management and mitigation of the long-term risks of
72 ‘obsolescence’ and supply risk disruption [6]. This was particularly the case when REACH
73 regulation came into force in 2007. Furthermore, particular attention should be given to the
74 use of the critical raw materials (CRMs) targeted by the European Commission [7,8].

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

82 The space sector, including in-orbit activities, is a new area of development for the LCA
83 research. In Europe, the European Space Agency is leading the development of LCA practices
84 within the frame of the *Clean Space Initiative*, which was launched in 2012 [12]. Today, an
85 LCA community involved in space activities is emerging as indicated by the presence of LCA
86 and eco-design sessions within aerospace conferences, particularly in the context of CEAS

87 conferences [13,14] or in the participation of Airbus Defence & Space within the Organizing
88 Committee of the LCM conference 2015 in Bordeaux [15]. Clean Space Industrial Days
89 (2017, 2018, 2020) now include a specific eco-design theme with dedicated sessions on LCA
90 [16]. While the use of LCA is being established within the sector, only a limited number of
91 peer-reviewed publications are available. Most of the documents released by stakeholders can
92 be considered to be grey literature. As the topic has not been properly discussed in the
93 literature, we believe there is an opportunity to bring the initiatives carried by the space sector
94 in recent years to the public domain.

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

101 **2. Methods**

102 **2.1. Selection of LCA papers addressing space activity**

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

109 We chose to select papers, conference proceedings or technical reports addressing at least one
110 step of the methodology as follows: (i) definition of goal and scope, (ii) life cycle inventory

111 (LCI), (iii) life cycle impact assessment (LCIA) and (iv) interpretations of the results. The
112 present review also compiles relevant publications defining a framework or a methodological
113 development linked to sustainability for space activities, which could be a good starting point
114 in the harmonisation of life-cycle applications within the space sector.

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

125 **2.2. Analysis grid of the selected papers**

126 We define two separate grids of analysis to analyse two types of papers reviewed here: a-
127 papers related to framework and good practices, b- LCA studies. For each grid, a set of
128 qualitative criteria was established allowing for the classification and analysis of the papers.

129 The criteria are described in the followings sections (§2.2.1; §2.2.2).

130

131

132 **2.2.1. Criteria for ‘Framework and Good practices’ analysis grid**

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

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

144 **2.2.2. Criteria for ‘LCA studies’ analysis grid**

145 Table 1 - Description of criteria reviewed for LCA studies

Type of papers	LCA phase	Qualitative Criteria
b- 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

146

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

149 i. First, we focus on the *Goal and Scope* of the space LCA studies. The methodological
 150 framework provided by the ESA LCA Working Group [18] in the ESA LCA Handbook
 151 proposes to adapt the life-cycle phases of the European-standardized space project
 152 management system to better describe the life-cycle steps of a large-scale system [19]. The
 153 results are presented in Table 2 for each specific segment of a space mission (e.g., Space
 154 segment, Launch segment, Ground segment), which are defined as a set of elements or a
 155 combination of systems that fulfil a major, self-contained, subset of the space mission
 156 objectives [20]. Based on this framework, we discuss the system boundaries (§3.3.1) and
 157 the functional unit (§3.3.2) of each study.

158 Table 2 - *Goal and Scope*: system boundaries according to the specific segments of a space mission
 159 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 Phase B - Preliminary Definition	<i>Office work and travelling Qualification and testing</i>			<i>Design facilities</i>
Phase C - Detailed Definition Phase D - Qualification and Production	<i>Production and development testing of critical elements and engineering models Production of spacecraft components Qualification, testing and verification Spacecraft assembly</i>	<i>Production of launcher components and propellants Stage assembly</i>		<i>Production & Testing facilities</i>
Phase E –Utilisation	<i>Launch campaign</i>	<i>Launch campaign Launch event (launch pad operations and lift-off)</i>	<i>Launch and early operation phase + Commissioning Mission control</i>	<i>Spaceport Telemetry, Tracking and Command Ground Station(s) Flight Operation Control centre(s) Payload Datacenter</i>

Phase F – Disposal	Disposal of the spacecraft	Disposal of the launcher stages	Ground operations for the end of life of the spacecraft
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160

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

169 iii. Then, the *life cycle impact assessment* (LCIA) proceeds through two mandatory steps:
 170 selection of impact categories and characterisation of the impacts. In this review, we
 171 identify the selection of a mono- (e.g., carbon footprint) or multi-criteria approach for the
 172 assessment of the system under study. Concerning multi-criteria analysis, the chosen LCIA
 173 methods with associated indicators at midpoint and/or endpoint levels are described
 174 (§3.3.4). The presence of normalisation and weighting, which are optional elements (ISO)
 175 based on value choices (i.e., not science-based), is also discussed.

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

179 **3. Results of the review**

180 **3.1. Analysis of the selected documents**

181 Fifty-two documents were collected. After a first screening within the document list, a
 182 substantial number of documents (14) were considered to be out of the scope and disregarded.

183 This was the case for papers discussing the benefits of applying eco-design in the space sector
184 without a concrete reference to LCA applications or addressing a limited scope. Publications
185 referring to “life cycle assessment” or “analysis” without including an environmental
186 dimension were removed. This was especially the case for several of NASA’s studies that do
187 not match with the standardised LCA methodology (ISO 14040/44) because they consider
188 only economic costs and no environmental impacts. Finally, we selected eleven papers
189 addressing the aspects of “framework and good practices” (11) and twenty-seven papers
190 regarding LCA studies (27), which came to a total of thirty-eight papers (38). Table 3 shows
191 the complete list of the selected documents.

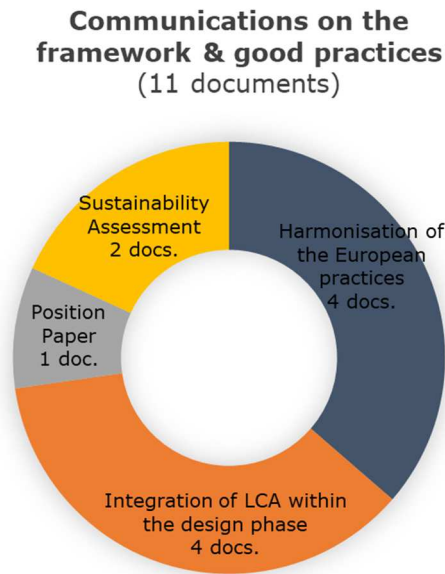
192 Of the thirty-eight remaining documents, 84% are from conference proceedings (32) whereas
193 only 8% are peer-reviewed papers (3) and 8% are technical reports or dissertations (3). Those
194 figures show the confidential nature of the LCA practice in the space sector. The geographical
195 distribution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

201 Table 3 – Classification table of the selected documents in terms of temporal range, geographical
 202 orientation, type, scope and topic distribution.
 203 (P.rev: peer-reviewed; ConfP: conference proceedings; Report: Technical report or dissertation. Inf
 204 and GS: Infrastructures and Ground stations; Launch seg: launch segment; S.mission: space mission;
 205 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 1N 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

206 **3.2. Framework and development of the LCA practices within the space sector**

207 Figure 1 shows the breakdown of the topics addressed in each document.



208

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

211 **3.2.1. European LCA framework for space activities**

212 As far as we know, the first attempt to consider environmental impacts through a complete
213 LCA study came from an ESA pilot Concurrent Design Facility (CDF) study called ‘Ecosat’
214 [31]. That study’s conclusions highlighted the need to develop a harmonised LCA framework
215 within the European space sector as well as to develop specific datasets related to the space
216 industry. Today, the European space industry is well-structured on this topic, mainly due to
217 the strong efforts of the ESA in the frame of the eco-design activities of the *Clean Space*
218 *Initiative* [12]. We did not find any equivalent programme in North America or Asia, as
219 underscored by the analysis of the geographical distribution in section 3.1. The French space
220 agency also carried out LCA, particularly focusing on the launch pad system in French
221 Guiana; however, no scientific communication was published on the topic [58].

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

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

243 **3.2.2. Integration of the LCA during the design phase**

244 As mentioned by Chanoine [49], the environmental performance of systems, similar to cost
245 performance, is highly driven by design elements that are defined at an early stage in the
246 design process. Consequently, coupling LCA with design tools seems particularly relevant in

247 the case of space missions due to the high complexity of such systems. It is expected that the
248 above-cited OPERA platform will be implemented in the frame of the concurrent design
249 process of the ESA. Hence, the platform will provide instant feedback to the design team
250 related to the environmental performance of the system under study. At the industrial level,
251 Ouziel and Saint-Amand [53,54] discuss the integration of LCA during the development of
252 new technologies. They recommend adapting the completeness level for a given LCA study
253 based on the technology readiness level (TRL) scale of the studied technology. It should be
254 noted that systematic integration of LCA information with existing product life cycle
255 management (PLM) solutions or computer-aided design (CAD) software has already been
256 successfully applied outside of the aerospace community [59,60].

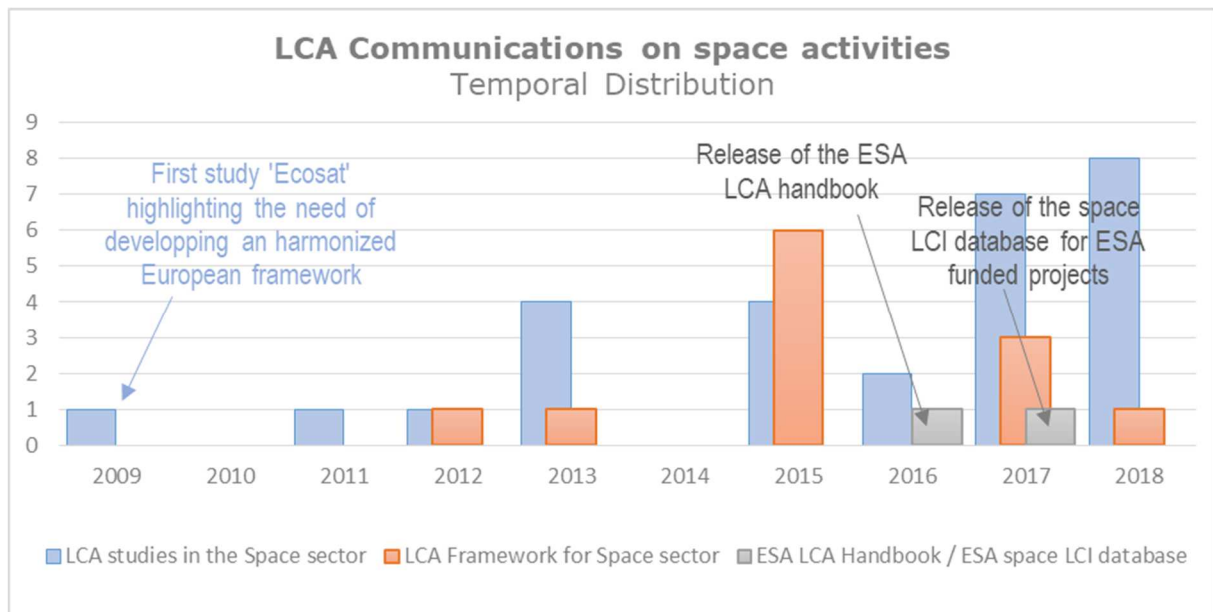
257 **3.2.3. Sustainability assessment**

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

272 **3.2.4. Framework development**

273 Figure 2 shows the temporal distribution of LCA papers in the space sector. The first range of
274 complete LCA studies was carried out in Europe from 2012 to 2015. Communications in the
275 year 2015 emphasise the efforts made to implement, develop and harmonise the LCA
276 practices in the European space industry. This first phase resulted in the release of the ESA
277 LCA Handbook for space systems in 2016 and the ESA space LCI database in 2017. Since
278 2017, several new studies have been launched by the ESA capitalising on the good practices
279 and knowledge inherited from the previous studies. Today, new perspectives are emerging
280 based on this established framework: LCA is being applied to many European Earth
281 Observation satellites [66] while the scope is being broadened with the aim of integrating new
282 sustainability concerns, first and foremost regarding space debris proliferation [67].

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



288

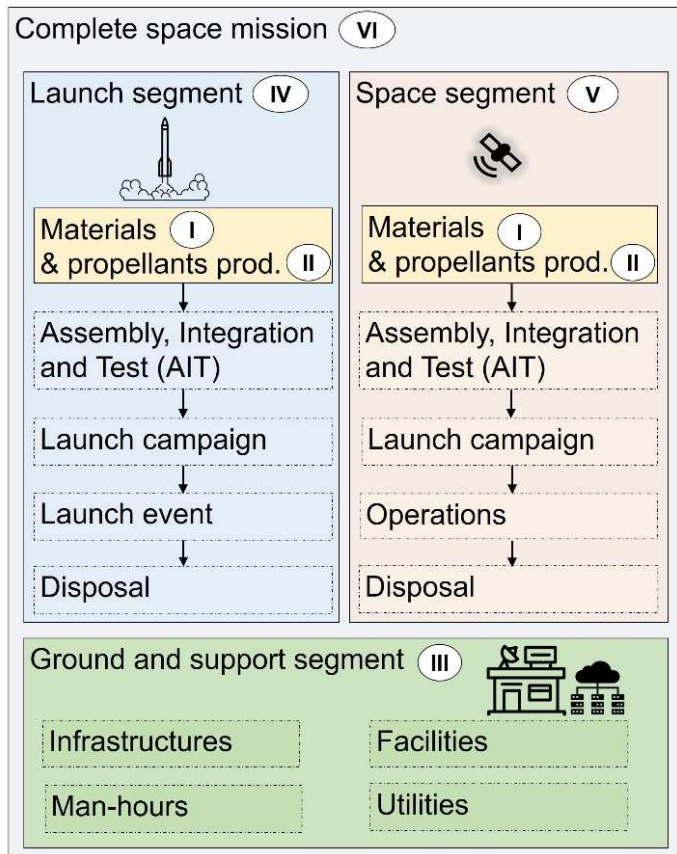
289 Figure 2 - Temporal distribution of LCA communications in the space sector according to specific
 290 LCA studies and “framework and good practice” documents; elements composing the European
 291 framework (i.e., ESA LCA Handbook and ESA LCI database) are mentioned.

292 3.3. Description of the LCA studies

293 3.3.1. Goal and system boundaries

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

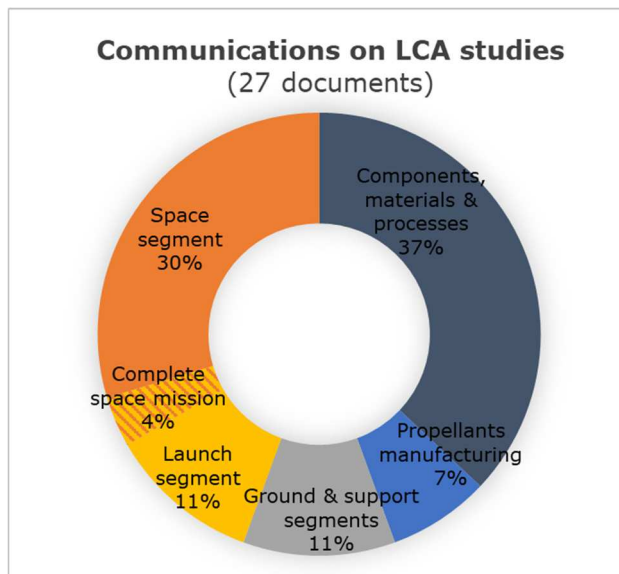
296 Figure 3: (I) components, materials and manufacturing processes; (II) propellants
 297 manufacturing; (III) ground and support segments; (IV) launch segments; (V) space segments;
 298 (VI) completed space mission. It should be noted that ‘Materials’ and ‘Propellants’ are
 299 addressed in dedicated sub-sections because of the large number of studies found addressing
 300 those two industrial clusters. These latter clusters are the core of the ESA space LCI database
 301 [33].



302

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

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



309

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

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

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

326 In one of the first LCA studies on space sub-systems conducted at the European level, Saint-
327 Amand et al. [42] compare the environmental impacts of several materials (composites,
328 thermal protection, metal) with the associated assembly phases for a Solid Rocket Motor
329 Case. Another study focuses on the Germanium (Ge) use for photovoltaic (PV) systems [30].
330 Another study addresses the comparison of two steel passivation processes (i.e., surface
331 treatment) [29]. Finally, two studies explore the material substitution of traditional metallic
332 components with polymer composites in the case of electromagnetic interference shielding
333 [39] or with carbon fibre reinforced polymers for structural elements [41].

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

345 **Ground and support segments (III).** According to ESA Clean Space [71], a segment that
346 deserves investigation for space missions is that related to ground activities. The latter is
347 based on the management of the communications between in-orbit satellites and mission
348 control centres as well as the archiving and processing of the mission-specific scientific data
349 collected. Three documents were found [22,24,45]. The ESA-funded study [24] was recently
350 launched with the aim of fully determining the related environmental impacts of those

351 activities. The scope of this study focuses on the characterisation of various “generic families”
352 of ground segment representatives for telecommunication, navigation, scientific earth
353 observation and CubeSat missions, covering their specific infrastructures and operations.
354 Four major ground segment typologies were identified as follows: mission operations centres,
355 science operation centres, data processing centres and other ground stations (i.e., optical,
356 radio-frequency or radar terminal). The scope of the study includes infrastructure and building
357 construction as well as operational phases including transportation phases and facilities. In
358 addition, two studies addressing utility management and infrastructures were previously
359 conducted by Castiglioni et al. [22] at the European Astronaut Centre and Sydnor et al. [45]
360 regarding NASA’s high-energy ground test facilities. While the first study mainly discusses
361 energy solutions, water and waste management, the second includes in its scope ground test
362 facilities (excluding the construction and demolition phases).

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

367 An ESA LCA study was carried out in 2012 focusing on the European Launcher network
368 (Ariane 5, Vega, Soyuz) [23,44]. The scope of the study follows the ‘Launch segment’ as
369 detailed in Figure 3. The study highlights the difficulty of including the R&D and testing
370 stages in the scope as well as infrastructures as their impacts are highly dependent on the
371 number of launches. Consequently, the ongoing LCA study of the new Ariane 6 launcher
372 performed by ArianeGroup [26] disregards R&D and feasibility activities, focusing on the
373 exploitation phase. The stages related to end-of-life should also be part of the study’s scope.
374 For the first time in the space industry, this LCA study is being performed during the early
375 development of a new launcher system with the goal of providing a complete environmental

376 profile of the launcher at the time of its early production. Another study related to the
377 launcher system was identified: Neumann [32] compares expendable and reusable launchers.

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

384 **3.3.2. Functional unit**

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

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

398 **Ground and support segments (III).** In De Santis [24], the chosen functional unit is the
399 following: “the fulfilment of requirements of Ground Segment for one year for the following

400 mission types: navigation, Earth observation, science, Telecommunications or CubeSat”.
401 Castiglioni et al. [22] and Sydnor et al. [45] also chose one year of facility operations as a
402 functional unit.

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

415 **Complete space missions (VI).** Unlike launcher systems, the design of a satellite is highly
416 specific, usually serving a unique purpose through a dedicated space mission. Hence, the
417 ESA’s Handbook recommends the following functional unit: “One space mission in
418 fulfilment of its requirements”; however, this functional unit may be subject to debate due to
419 the impossibility of comparison between space missions. An option suggested in the ESA
420 Handbook is to consider the amount of data generated by different space missions to compare
421 the associated environmental impacts of each mission on the same basis. Additionally,
422 Geerken et al. [27] highlight that a specific functional unit could be determined for a generic
423 platform design to be used for multiple missions. This option seems particularly relevant in
424 the case of the mass production of satellite platforms for mega-constellation systems, e.g., the

425 OneWeb Arrow Platform [72]. In this particular case, the R&D activities and infrastructures
426 related impacts could be allocated according to the expected production rate.

427 **3.3.3. LCI**

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

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

446 Regarding direct emissions at the full system level, the ESA handbook recommends the
447 calculation of flow indicators corresponding to the mass left in space, the mass disposed in the
448 ocean, as well as the atmospheric Al₂O₃ emissions corresponding to the burning of propellant.

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

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

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

471 However, Petersen et al. showed that a simplified LCI could lead to an overestimation of
472 impacts compared to full and accurate LCI data collection. They modelled the same
473 component (i.e., a spacecraft reaction wheel) from two perspectives: that of a detailed

474 inventory versus that of a simplified inventory. The simplified LCI led to higher impacts than
475 the complex one in four of the five selected impact categories.

476 **Source of background data.** The ecoinvent database [73] is used in almost all the studies
477 (23). The US-EI life cycle inventory database (Earthshift, Huntington, VT) is used by
478 Pourzahedi et al. [39]. For studies addressing the carbon footprint of materials and propellants
479 [39,41], the embodied CO₂ is obtained from the Granta Design database (Granta Design
480 Limited, Cambridge, United Kingdom).

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

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

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

505 **3.3.4. LCIA methods**

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

509 The selected LCIA indicators for ESA-funded studies are broadly described in the ESA
510 Handbook. They are based on the ILCD 2011 recommended methods [75] in association with
511 the ReCiPe Midpoint *metal resources depletion potential* [76]. The latter impact indicator is
512 suggested due to the large number of alloys and metallic components used in the space sector,
513 even if it leads to a “double-counting” issue with the *mineral resources depletion potential*
514 [77]. The *ozone depletion potential* (ODP) is a key indicator in the space sector as space
515 activities are responsible for the direct emissions within the ozone layer. The impact category,
516 the *marine aquatic ecotoxicity potential* (CML 2002), is also suggested in the Handbook and
517 aims to characterise the impact of launcher parts falling into the ocean. The related midpoint
518 indicator could be updated using the more recent methodologies that cover *marine ecotoxicity*
519 as LC-impact [78] or ReCiPe 2016 [79].

520 The ESA also recommends the addition of flow indicators as the cumulative energy demand
521 and water consumption of the ecoinvent database v.3 [73]. They can be appropriate when the

522 LCA study covers the scope of the facility management system. Furthermore, two flow
523 indicators are designed to account for the use of potentially targeted substances: on the one
524 hand, by the REACH legislation ('candidate list' and 'authorisation list') and, on the other
525 hand, the EU critical raw material list [7]. Ongoing studies are being conducted by the ESA
526 regarding those specific obsolescence or supply risks [62,63].

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

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

543 **3.3.5. Results and Interpretation**

544 **Components, Material and Processes (I).** According to Pettersen et al. [35], the
545 environmental impacts of space missions are distributed across a large number of processes

546 and activities; furthermore, that study highlighted the complexity of space systems and
547 offered a large range of options for methods of improvement.

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

570 the USEtox consensus model due to the high uncertainties related to the fate, the exposure and
571 the effect of those substances [82].

572 Moreover, thermoplastics for space show tendencies to differ from conventional
573 thermoplastics regarding energy-related impacts (e.g., *global warming*) and can contribute to
574 greater toxicity or ozone depletion impacts. Hence, the accurate representation of the
575 chemical precursors used during synthesis is particularly important to capture the full
576 environmental profile of a material. One specific thermoplastic, Polytetrafluoroethylene
577 (PTFE), has been identified as being responsible for substantial environmental impacts
578 [40,47]. This thermoplastic, which is used as a cable coating in harness systems, represents
579 approximately 30% of the space segment's *ozone depletion potential* impact. Consequently,
580 its replacement is considered to be an eco-design option in the frame of the 'GreenSat'
581 project.

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

592 Surface treatment processes using chemical baths should be deeply investigated since the
593 chemicals used (e.g., nitric acid or Cr VI) present environmental disadvantages in term of
594 toxicity and can be targeted by specific legislation such as the REACH regulation. This topic

595 is discussed by Izagirre and Zimdars [29] and Pettersen et al. [34]. However, the heavy
596 qualification procedures represent a limiting factor in finding less impacting alternatives.
597 Additionally, the results of the LCA study performed by Izagirre and Zimdars [29]
598 mentioning a potential environmental gain using citric acid passivation must be confirmed
599 with full-scale industrial data. If the LCA approach is well suited to evaluate products or
600 processes that are already mature, it faces practical and methodological difficulties when
601 applied to emerging technologies. This topic is currently being debated in the LCA
602 community [87–89].

603 Finally, mass and volume reduction due to technology evolution (e.g., miniaturisation) or
604 linked to the use of lightweight materials has been targeted by several space environmental
605 studies. Vercauteren and Holsters [48] highlight the mass reduction occurring between two
606 generations of similar scientific instruments: 34 kg for the current embedded Vegetation
607 instrument on the PROBA-V mission against 150 kg for the previous instrument on the
608 SPOT5 mission. The following advantages regarding mass and volume savings can be listed:
609 (i) from a resource efficiency perspective, less raw materials are used and associated wastes
610 (including spacecraft with a casualty risk of burning during atmospheric re-entry) are limited;
611 (ii) from a launch segment perspective, more space missions (or more satellites of the same
612 constellation system) can be launched at the same time, allowing for the allocation of the
613 environmental burdens related to the launch operations; (iii) regarding the utilisation phase
614 into the orbital environment, the mass and volume reduction of a spacecraft for a given space
615 mission allows for the reduction of the probability of encounter with debris and thus limits the
616 potential release of fragments into the orbital environment. Mass and the associated potential
617 environmental savings are also studied in explorations of the material substitution of
618 traditional metallic components with composites such as carbon nanotube composites in the
619 case of electromagnetic interference shielding [39] or the carbon fibre reinforced polymers

620 used for structural elements [41]. By reducing the mass of the components, substantial
621 propellant savings may be expected. According to the Tsiolkovsky rocket equation, the delta-
622 V parameter (which determines how much propellant is required for a vehicle of a given mass
623 and propulsion system) increases exponentially with respect to the mass ratio of the wet and
624 dry mass.

625 **Space propellants (II).** The trade-off between the lightening of the mass and the reduction of
626 propellant consumption is a key element regarding the eco-design for space activities. The
627 mass of the propellant represents the majority of the mass breakdown (e.g., approximately
628 87% of the lift-off mass for Ariane 5 ECA), and its production is a major contributor
629 regarding the environmental profile of the launcher-related segment [26].

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

641 In Pettersen et al. [37], three propulsion systems are compared: monopropellant hydrazine, bi-
642 propulsion mixed oxides of nitrogen (MON)/monomethyl hydrazine (MMH), and chemical-
643 electric propulsion hydrazine/xenon. The chemical-electric propulsion system with
644 xenon/hydrazine has the highest environmental impact for all impact categories in comparison

645 with the two other systems except for *freshwater ecotoxicity potential*. This is mainly due to
646 the production of xenon that requires 1400 kWh per kg when extracted using a cryogenic air
647 separation process (according to the ecoinvent database). However, it should be noted that
648 electric propellants have higher I_{sp} values (by approximately 4-8 times) than the other
649 propellant types and thus require lower weight and volume storage, which should modify the
650 propulsion system.

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

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

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

667 **Launch segment (IV).** Regarding the Ariane 5 study [23], electricity and heat consumption
668 from the propellant production, stage production, and launcher integration are the three main

669 contributors to *global warming potential*. The activities that happen at the Guiana Space
670 Centre (spaceport), mainly propellant production, contribute less to *global warming potential*
671 than *primary energy consumption* due to the Guianese electricity mix, which is composed of
672 47% of renewable energy. The transport stage is also a non-negligible contributor to *global*
673 *warming potential*, specifically maritime transport, which is also an important contributor to
674 *terrestrial acidification*, *marine eutrophication* and *photochemical oxidation potential*.

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

682 Regarding propellant production, the environmental impacts are mainly generated by solid
683 propellant, which represents more than 70% of the propellant’s loaded mass. The solid
684 propellant contributes to 65% of the impact regarding overall propellant production for the
685 *global warming potential* impact and approximately 90% of the impact for *toxicity* and
686 *freshwater ecotoxicity* due to CrVI emissions as well as *metal depletion* due to platinum use.
687 Considering the mass of the propellant loaded, liquid H₂ (~5% of the propellant mass)
688 represents approximately 15% of the impact on the *global warming potential* for the
689 propellant component.

690 The interim results for Ariane 6 presented by Gallice et al. [26] at the ESA Clean space
691 industrial days may confirm that the ‘production and assembly stages’ and ‘propellant
692 manufacturing’ are the main contributors for both Ariane 5-ECA and the future Ariane 6.
693 However, in both cases, the contributions of the R&D and preliminary testing phases were not

694 taken into account while they should influence the energy-driven impact categories.
695 According to Soares et al. [44], the allocation of the impact of these phases presents several
696 difficulties, which are mainly linked to the ‘technology heritage’ issue, i.e., the identification
697 of which parts or components are inherited from a previous launcher design.

698 **Complete space missions (VI).** The launcher represents 99%, and the spacecraft 1%, of the
699 mass of a complete space mission. Therefore, the environmental impacts related to the
700 launcher (production, launch campaign, launch event) is a major hotspot on all the impact
701 categories, e.g., from 50% to 70% of the *global warming potential* depending on the
702 launcher’s dry mass [23]. The use phase (control centres and ground stations) contributes to
703 most of the impact categories *via* the energy consumption for operations, particularly the
704 *toxicity/ecotoxicity potentials* (~50%) and to a lesser extent the *global warming potential*
705 (~25%). The ‘Launch event’ (propellant burning) is the most impacting phase regarding *ozone*
706 *depletion potential*: nearly 100% of the impact. The production of the PV system (for solar
707 cells) also generates approximately 100% of the impact on the *mineral resource depletion*
708 *potential*.

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

715 Within the design and production phase, the office work is by far the major contributor (>
716 50% for most of the impact categories) with the exception of the *mineral resource depletion*
717 driven by the materials used for satellites [40,46]. During the production stage, the scores
718 related to the *toxicity/ecotoxicity* categories are also driven by the production of the electronic

719 components embedded in the payload that account for approximately 30% [23]. These results
720 are in line with the conclusions of Geerken et al. [28], which are also mentioned by
721 Vercajsteren and Holsters [48] who highlight the environmental importance of the phases that
722 include a large number of man-hours. The production and testing of satellites accrue most of
723 the working time; therefore, the corresponding phases are responsible for a large portion of
724 the environmental impacts. The R&D man-hours are a major contribution to the
725 environmental impact of the satellite mission. Their impacts are mainly generated by the
726 consumption of energy and the infrastructure.

727 **4. Discussion and perspectives**

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

732 **4.1. Extending the goal and scope of LCA studies in the space sector**

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

740 Communication and internet networks are also a topic of interest as space applications are
741 expected to play a major role in this field. A preliminary work assessing the carbon footprint
742 of a hybrid telecommunications network is proposed by Faulkner et al. [92]. Environmental

743 benefits were also discussed in the case of space solar power generation from a life-cycle
744 perspective [93–95]. Recently, an attempt to apply the LCA methodology to the emerging
745 topic of ‘asteroid mining’ was proposed by Hein et al. [96]. More generally, future
746 applications of LCA in space, following the technological advancements in space exploration
747 and travel, are discussed by Ko et al. [97]. They highlight the need to extend the scope of
748 future LCA in space taking into account outer space exploration and the potential
749 environmental impacts associated with that activity.

750 **4.2. Improving inventory collection**

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

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

763 Generic good practices regarding data collection are addressed in the ESA Handbook. A cut-
764 off rule based on a mass criterion can be used to ease the completion of the inventory phase.
765 According to the ESA Handbook, material or sub-assembly inputs that collectively constitute
766 less than 5% of the total mass of the components considered can be neglected. However, we
767 also recommend paying particular attention to metals and chemicals as follows: (i) a low

768 amount of scarce metals used in a life cycle can significantly affect the metal depletion score;
769 (ii) any substance listed as an EU critical raw material or targeted by the Reach regulation
770 (i.e., REACH Annex XIV) cannot be excluded.

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

778 **4.3. Towards a better characterisation of the space industry’s specific related** 779 **impacts**

780 When addressing the comparison of conventional and space applications, a fair
781 characterisation of the environmental impacts shall be performed. However, space systems
782 engage a strong particularity that complicates the use of LCA: space missions are the only
783 human activity that crosses all stages of the atmosphere and stays “out” of the natural
784 environment and ecosystems [11]. As highlighted by the results of the review (see section
785 3.3.4), the current gaps in the life-cycle impact assessment framework must be addressed to
786 cover the full scope of space activities.

787 The atmospheric impacts during the launch event are commonly perceived as the major
788 environmental hotspot. However, the specific impacts related to the launch phase require
789 future research efforts to be fully considered in LCA studies. Gaseous launcher emissions due
790 to propellant burning include CO, N₂, H₂, H₂O, and CO₂ whereas solid rocket motors (SRM)
791 generate aluminium oxide (Al₂O₃) particles, black carbon (i.e., soot) and gaseous chlorine
792 species into the atmosphere [99]. According to an ESA-funded study [100], uncertainties

793 affect the characterisation of launchers' impacts on the atmosphere. The main areas of
794 uncertainties are related to (i) the aerothermodynamics of rocket plumes, which include the
795 combustion and expansion process; and (ii) climate modelling including the insertion of
796 small-scale plumes into relatively large scale climate models.

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

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

811 The question of space debris is also a crucial issue in terms of the sustainability of space
812 activities. Colombo et al. [109] developed a preliminary index while a comprehensive
813 framework was published by Maury et al. [110]. These initial studies led to the creation of
814 dedicated characterisation factors to include the space-debris related impacts within the LCAs
815 of space missions [111]. Once developed, this characterisation model was successfully
816 applied to compare two mission design scenarios based on Sentinel-3 parameters and
817 retrieved from the previous GreenSat study. In this way, the burden shifting between the Earth

818 and the orbital environment could be characterised. Furthermore, the end of life of space
819 missions should also consider the environmental impact due to the atmospheric re-entry in the
820 high atmosphere as well as the presence of non-demised materials or launcher stages in the
821 oceans. An ongoing ESA-funded study is being carried out on the topic of the environmental
822 impact related to atmospheric re-entry [112] while the previous work funded by the French
823 Space Agency [113,114] could represent a first step in the elaboration of dedicated
824 characterisation factors respectively covering the atmospheric re-entry and fall of materials on
825 the ground or in the oceans.

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

834 **4.4. Opportunities for further developing LCA practice in the European space** 835 **context**

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

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

852 The LCA methodology currently faces limitations at low TRL levels as highlighted through
853 the ex-ante LCA concept [88]. Nevertheless, the integration of LCA in the early design phase
854 seems to be a promising option for improving the sustainability of space systems. In this way,
855 a new dimension related to environmental performance could be included in the concurrent
856 engineering of new projects through the inclusion of LCA-based indicators. This approach
857 would represent a substantial improvement with regard to the ecodesign procedure of the ISO
858 14062 [120] standard addressing the integration of environmental aspects into product design
859 and development. The inclusion of environmental performance criteria from the beginning of
860 development could foster the rethinking of design from a different perspective towards more
861 efficient systems.

862 Finally, the recognition of LCA as a science-based methodology can also strengthen the
863 environmental reporting in the frame of corporate social responsibility (CSR). Quantitative
864 environmental disclosures adopting a life-cycle perspective could be provided through
865 monitored key performance indicators (KPI). According to Stewart et al. [121], the LCA
866 stands for an indication of sustainability management practices in the industry among
867 investors or the evaluation approaches of external ranking agencies. For example, the

868 sustainable finance action plan launched in 2018 in the European Union requires companies to
869 strengthen their nonfinancial information disclosures.

870 **5. Conclusion**

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

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

885 This review also paves the way for future research with the aim of developing the use of LCA
886 and life cycle management at the industrial level while assessing the environmental
887 performance of space missions. The complete implementation of these approaches would
888 facilitate the undertaking of coherent eco-design actions along the whole value chains of
889 space systems. However, methodological limitations regarding the LCIA phase remain. They
890 should be approached to reinforce the credibility and robustness of LCA studies in the space
891 sector. Among others, two topics seem to be of prime importance. On the one hand, ozone-

892 depletion-related impact appears to be a major issue, especially as the emissions of ozone-
893 depleting substances have unexpectedly increased in recent years [122,123]. On the other
894 hand, the impacts occurring in the orbital environment due to the lack of space traffic
895 management and through space debris proliferation represent a current dire issue that should
896 be fully integrated into LCA studies to ensure a more sustainable design of space systems.

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