University of Stuttgart
Institute of Space Systems

Recommendations for the development of space systems life cycle assessment methodology for space transportation systems

Results of the 2nd Workshop on Life Cycle Assessment of Space Transportation Systems

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Executive Summary of the recommendations

The present document serves to contribute to the discussion on the development of European Life Cycle Assessment (LCA) methodologies regarding ESA LCA Handbook update and PEFCR for the space sector. It gives an overview over the need for space transportation specific guidelines as well as available methodologies and databases for LCA.

Furthermore, gaps in the current methodologies are evaluated and suggestions are made for further development of LCA methodology for a comprehensive and high-quality LCA of launchers in the future. These points are specifically:

- 1. Implementation of impacts on the environment of launch emissions into LCA with characterisation factors for high atmospheric emissions
- 2. Implementation of impacts on the environment of re-entry emissions into LCA with characterisation factors for high atmospheric emissions
- 3. Required discussion about useful metrics for implementation of launch and re-entry emissions into Life Cycle Inventories.
- 4. Definition of a common functional unit for comparison of different launch vehicles and their specific targets
- 5. Setting new system boundaries and formulating guidelines for consideration of re-usable systems and recyclable materials.
- 6. Implementation of development phase of the space transportation system and production and launch infrastructure into LCA
- 7. Addition of three additional indices for data availability, data uncertainty and methodological uncertainty
- 8. Definition of common prospective scenarios for materials, processes regarding changing energy mixture and development of new technologies

Workshop on Life Cycle Assessment of Space Transportation Systems

This whitepaper is intended to give an overview of the results from the 2nd workshop on Life Cycle Assessment of Space Transportation Systems. During a three-day workshop from 4th – 6th July 2023 a group of 30 experts from academia, agencies and industry came together at the Space Center Baden Württemberg to access the status of research on “Life Cycle Assessment of Space Transportation Systems” in order to identify necessary measures for a better understanding of the environmental impacts. In the following, on 5th February 2024, 34 experts discussed online the results of the workshop and further worked on the whitepaper.

Based on a series of presentations where the participants presented their expertise three working groups discussed the status of knowledge and further measures. These working groups were: LCA methodology, launch emissions and re-entry emissions. In these groups, a discussion about the knowledge gaps, key questions and already known answers from other departments as well as possible solutions was conducted. At the end of the workshop, measures for dedicated implementation concepts were defined These conclusions are summarised in the following.

List of acronyms

CSG	Guiana Space Centre
ESA	European Space Agency
GWP	Global Warming Potential
IAM	Integrated assessment models
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
PB	Planetary Boundaries
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
SSSD	Strathclyde Space Systems Database
WMO	World Meteorological Organization

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1. Sustainability, environmental impacts, and LCA in the space sector

“Meeting the needs of the present without compromising the ability of future generations to meet their own needs.” [1]

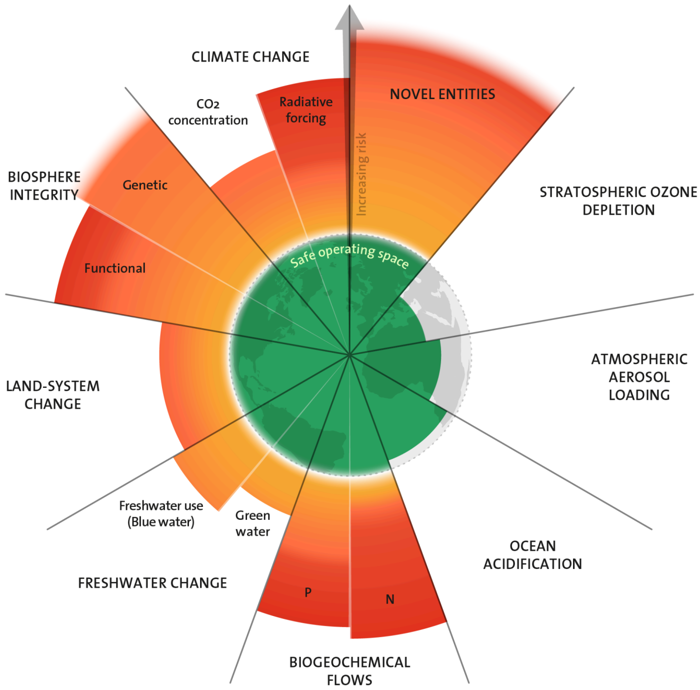


Fig. 1: 6 of 9 planetary boundaries are currently out of the safe operating space [2]

The definition of sustainability from the United Nations' Brundtland Report makes it clear that we must also keep future generations in mind in our activities.

The Planetary Boundaries show against it that in 6 of the 9 areas we have already gone beyond the boundaries that have allowed us to evolve as a human species. Among them, climate change is a problem that is already outside the safe zone. Ozone depletion, on the other hand, is currently still in the safe zone, as the measures of the Montreal Protocol have largely reduced emissions of ozone-depleting CFCs [3].

However, there are "heightened concerns about influences on 21st century ozone include impacts of: ... increased frequency of civilian rocket launches ... ." [3]. The lack of knowledge regarding the effects of rockets during launch and re-entry represents a major risk. Atmospheric aerosol loading as well as stratospheric ozone depletion are both influenced by space flight and could be shifted outside the safe operating space. The influences on the climate and the environment in general are also too poorly understood at the moment. Against the background of increasing rocket launches, it should be understood what effects occur and whether these are potentially significant [4].

A quantitative methodology must therefore be used to record the environmental impact to allow ecodesign for mitigating the environmental impact. Life Cycle Assessment is the method which allows for quantification of environmental impacts related to the full life cycle of a product or service. With regard to space transportation systems, there are large gaps in the method to cover all aspects. Therefore, this paper presents the state of the art and suggests possible improvements to the LCA methodology.

2. Why LCA in the space sector?

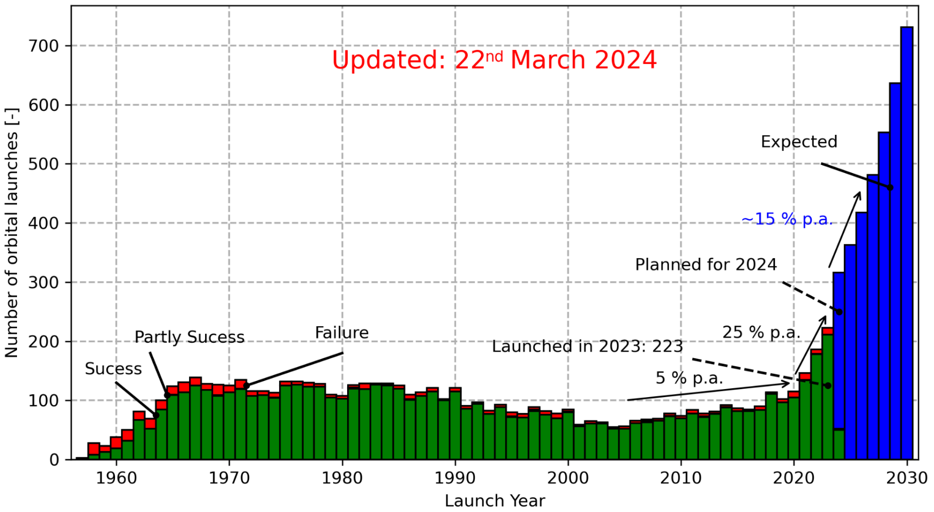


Fig. 2: Historical and expected future orbital launches (data from [5])

2023 is the third year in a row with a new record in orbital launches after a record in 2022 with 223 attempts and 211 successful missions [5]. At the same time, humanity faces the challenge of maintaining the planetary boundaries that have allowed it to evolve. Climate change and ozone depletion are two examples that are affected by rocket launches as they are the only human source of direct emissions into all atmospheric layers.

Spaceflight is obviously at a turning point, entering maybe a new era with an expected large increase in launches per year due to plans to increase the number of satellites and constellations in orbits largely. Thus, it is mandatory to understand and mitigate potential environmental impacts of space activities in general and of space transportation systems in particular, in a best-case scenario hopefully before increasing the activities by at least one order of magnitude and risking irreversible damages. The environmental impacts of running ships, cars and aircraft fuelled by fossil fuels were not recognized until decades later, after they had become commonplace [6]. In the case of air transportation, impacts on climate change are still not yet fully understood (e.g. [7]). With space transportation systems, the understanding of potential impacts in a timely manner seems achievable, opening the opportunity to then counteract them with more environmentally friendly technical solutions, or give decision makers the basis for regulatory actions to decrease the number of launches, rebound effects, and the environmental impacts related to these.

All human activities and certainly also space flight have an impact on the environment. For some decades now, we have begun to understand the impacts our actions have on us and the environment, and that the Earth's resources are not inexhaustible. To quantitatively assess the environmental impact, there are different approaches. Besides the GHG protocol, which addresses only the climate impact, Life Cycle Assessment (LCA) became the standard approach to calculate the environmental impact of a product or service over its whole life cycle, covering a variety of environmental indicators. International standards are given for example in ISO 14040 and 14044 [8,9], on the basis of which ESA has been proposing a space sector specific LCA methodology since 2012. The EU is also currently developing regulations to standardise LCA in the space industry and possibly make it mandatory.

3. Specifics of LCA in the space sector

The aerospace industry is fundamentally different from other sectors. This includes long development cycles, small production volumes, highly specific materials and impacts on the environment that are so far not considered in traditional LCA.

Launchers are usually individually manufactured systems that are extensively tested beforehand. A development could take up to several decades. Production is also characterised by a large number of special materials and processes that are not included in the standard databases. Another speciality of the LCA of space systems is the characterization of environmental influences in the upper atmosphere and in space. For example, rockets are the only human technology to emit into all atmospheric layers. Currently, no methodology exists to implement those impacts. There are also questions regarding the consideration of space debris, as this must also be included in the impact of space systems. When talking about sustainability and the environmental impact of space flight, three distinctions must be made. Sustainability on Earth, which takes into account the environmental impact on humans, living creatures, the atmosphere and the Earth system. Sustainability in space, which primarily considers space debris and thus the use of space as a resource, but also planetary protection in the context of exploration. Thirdly, sustainability from space, as satellites make an important contribution to understanding weather and climate through Earth observation.

Therefore, the development of a suitable LCA method as well as own data sets is of great importance. All life phases must also be taken into account in an LCA to find the environmentally best solution. In order to carry out an impact analysis of a system currently under development, prospective databases are furthermore necessary, which take into account the constant development in all sectors against the background of the green transition. This paper presents a basis for the discussion.

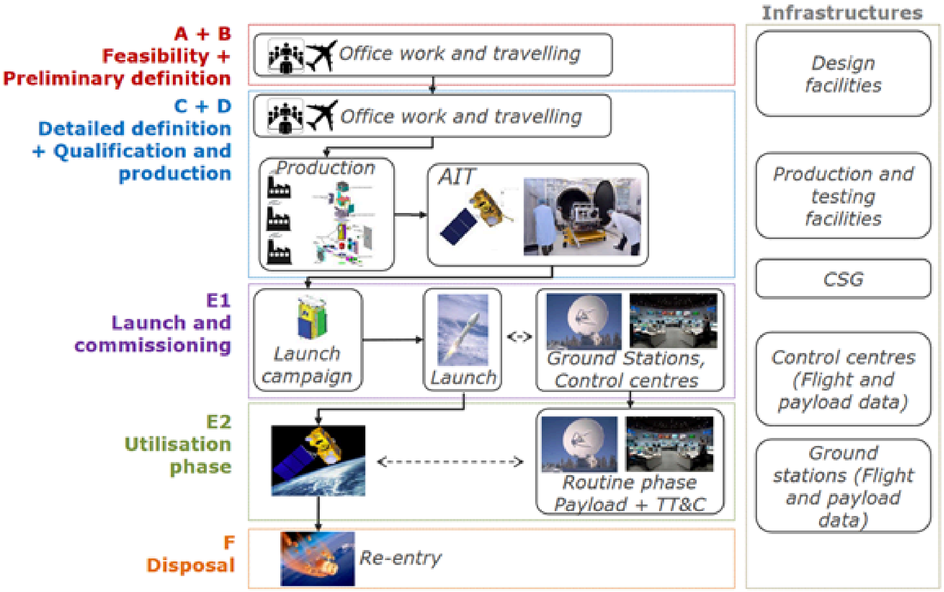


Fig. 3: Life cycle phases of a typical space mission (Credit: ESA)

4. State-of-the of the art in the field

The status quo regarding the application and methodology of Life Cycle Assessment is presented below. To this end, the users, indicators, methods and software are examined.

4.1. LCA practitioners

There are many players in the European space industry who carry out LCAs. Based on the studies presented at the Clean Space Industry Days, Table 1 provides a non-exhaustive overview of these players and the methodology they use.

Table 1: Overview over LCA practitioners and their used methodology

Institution	**Focus**	**Methodology**	**Branch**
Airbus DS	Satellites	ESA LCA	Industry
ArianeGroup	Launchers	ESA LCA	Industry
Deloitte	Satellites & Launchers	ESA LCA	Consulting
DLR Institute of Space Systems	Launchers	SSSD	Research
Space Sustainability Rating	Satellites (and constellations)	Space Sustainability Rating	Consulting
EPFL	Satellites & Launchers	ESA LCA	Research
MaiaSpace	Launchers	ESA LCA	Industry
Metasat UK	Satellites	SSSD	Consulting
OHB	Satellites	ESA LCA	Industry
Orbex	Launchers	ESA LCA	Industry
Paul Scherrer Institute (PSI)	Satellites & Launchers, developers of Brightway2/premise	ESA LCA	Research
Thales Alenia Space	Satellites & Space Transportation Systems	ESA LCA	Industry
TU Delft	Propellants	ESA LCA	Research
Università degli studi di Trieste	Satellite Materials	ESA LCA	Research
Glasgow Caledonian University	Satellites & Launchers	SSSD	Research
University of Stuttgart	Launchers	ESA LCA/PEF	Research
Vito	Satellites	ESA LCA	Consulting

4.2. Existing guidelines / methodology

Europe is at the forefront of implementation of LCA in the space sector. Efforts were started by the European Space Agency 2012 to create and disseminate a common methodology that can be applied by all, facilitating comparison and reproducibility of LCA studies. A first version of the ESA LCA handbook “Space system Life Cycle Assessment (LCA) guidelines” prepared by the ESA LCA Working Group was published in 2016 [10].

The handbook provides guidelines to perform LCA for space-specific products, at system level including ground, launch, and space segments, and at equipment level.

A planned update of the handbook is in preparation at ESA.

Furthermore, the European Union developed the PEF methodology, which should provide a standardised framework for LCA in Europe (C(2021) 9332 final) [11]. Currently it is discussed that ESA aims to adapt their methodology towards PEF or replacing the ESA LCA Guidelines by the PEFCR [12].

Moreover, the University of Strathclyde developed a methodology to assess the environmental impact as well as the economic and social impact [13]. A comparison between the environmental indicators of different LCA methods is given in Table 2.

Table 2: Environmental impact indicator category of space related LCA methods

Indicator	Unit	ESA	PEF	SSSD	LCIA method
Climate Change (PB)					
Global Warming Potential (100 y)	kg CO2 eq.	X	X	X	IPCC2013
Stratospheric Ozone Depletion (PB)					
Ozone Depletion Potential	kg CFC-11 eq.	X	X	X	WMO 2014 + integrations
Human Health					
Human toxicity, cancer	CTUh	X	X	X	USEtox2.1
Human toxicity, non-cancer	CTUh	X	X	X	USEtox2.1
Ionising Radiation Potential	kg U235 eq.	X	X	X	Frischknecht et al., 2000
Resource depletion					
Abiotic resource depletion potential (metal and mineral resources)	kg Sb eq.	X	X	X	CML 2002 (ultimate reserve)
Abiotic resource depletion potential (metal and mineral resources)	kg Sb eq.	X	-	X	CML2002 (reserve base)

Abiotic resource depletion potential (fossil fuels)	MJ	X	X	X	CML2002
Land system change (PB)					
Land use	Dimensionless (pt)	X	X	X	LANCA
Freshwater Use (PB)					
Water use	m3 water eq. of deprived water	X	X	X	AWARE
Energy consumption					
Energy Consumption - Total Cumulative Energy Demand	MJ	X	-	X	Cumulative Energy Demand
Biochemical Flows (PB)					
Freshwater eutrophication potential	kg P eq.	X	X	X	ReCiPe
Marine eutrophication potential	kg N eq.	X	X	X	ReCiPe
Terrestrial Eutrophication potential	mol N eq.	X	X	X	Accumulated Exceedance
Atmospheric Aerosol Loading					
Particulate matter formation potential	PM10 eq.	X	X	X	PM UNEP 2016
Ecotoxicity					
Freshwater ecotoxicity potential	CTUe	X	X	X	USEtox model 2.1
Marine ecotoxicity potential	kg 1.4-DB eq.	X	-	X	CML 2002
Atmospheric Impact					
Photochemical ozone formation potential	kg NMVOC eq.	X	X	X	ReCiPe 2008
Air acidification potential	mol H+ eq	X	X	X	Accumulated Exceedance
Air acidification potential	kg SO2 eq.	X	-	X	CML 2002

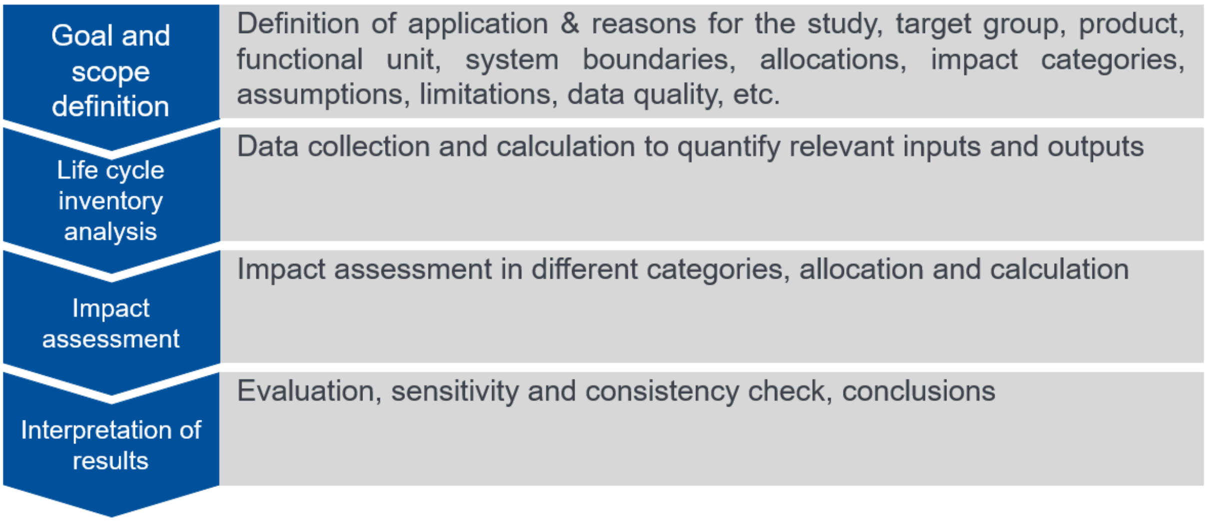
(Al2O3 particle emissions)	kg	X	-	X	Calculated from primary data
Re-entry Smoke Particles - RSP Creation Potential	kg RSP eq	-	-	X	SSSD 2019
Space Debris					
(Mass left in space flow indicator)	kg	X	-	-	ESA (2016)
Orbital Risk - Space Debris Risk	Index Score	-	-	X	Politecnico di Milano et al (2017)/SSSD 2019
Orbital Space Use - Orbital Resource Depletion Potential	objects.m3.year/potential fragments*years/k$	-	-	X	Maury et al (2018/2019)
(Mass disposed in ocean flow indicator)	kg mass	X	-	X	ESA (2016)
Policies					
Critical Raw Materials - CRM Use Potential	kg mass	-	-	X	SSSD 2019
REACH Substances - Restricted & SVHC Use Potential	kg mass	-	-	X	SSSD 2019

ESA = ESA database 1.2.0f e3.9.1., PEF = Product Environmental Footprint, SSSD = Strathclyde Space Systems Database v1.0.3, PB = Planetary Boundary

4.3. LCA of space transportation systems

ESA methodology is derived from ISO 14040 & ISO 14044 [8,9] and consists therefore of the four steps “Goal and scope definition”, “Life cycle inventory analysis”, “Impact assessment”, “Interpretation of results”. The content of each phase is shown in Fig. 4.

The analysis starts with a functional breakdown: a space system is in general divided into space segment (payload), launch segment, and ground segment according to ECSS-S-ST-00-01 RD. In this paper we focus on the launch segment with the launch vehicle. If the entire system is considered, i.e. launch system with the required ground-segment and infrastructure it’s called a level 1 study.



Goal and scope definition	Definition of application & reasons for the study, target group, product, functional unit, system boundaries, allocations, impact categories, assumptions, limitations, data quality, etc.
Life cycle inventory analysis	Data collection and calculation to quantify relevant inputs and outputs
Impact assessment	Impact assessment in different categories, allocation and calculation
Interpretation of results	Evaluation, sensitivity and consistency check, conclusions

Fig. 4: Life Cycle Phases and required steps according to ISO 14040 & 14044

For the assessment of only a subsystem as well as the required equipment, components and material it's level 2. In Fig. 5 the system boundaries, i.e. all phases considered in the LCA for a level 1 launcher study are shown. The system boundaries exclude the R&D phase with office work and travelling, testing as well as qualification flights and infrastructure. The reason for this is twofold: on the one hand, it is difficult to attribute in a LCA a defined amount of R&D work to a specific product or component, and on the other hand, it is challenging to estimate the remaining work in an ongoing R&D phase.

The construction, operation and end-of-life of infrastructure is also difficult to assess, as existing structures are often reused, for example. Moreover, both impacts are difficult to assign to one single launch. So far in Europe there exist only a limited number of launch pads for A5 and VEGA at CSG, but with the emergence of small launchers a huge amount of new launch pads are developed at CSG but also in Europe in Norway, Sweden and other countries. Therefore, the assessment of launch infrastructure will be more meaningful.

The main focus of the system boundaries are production and assembly of the launcher, production of the propellant, as well as the launch campaign. These initially include the extraction of raw materials as well as the subsequent production of base materials. The next step is the production of components and propellants as well as consumables and stage integration. During the production and assembly phase, there is also employee travel considered and other related activities such as the testing of stages and components. The launch phase includes launcher integration, satellite integration and final launcher integration, and fuelling. This is accompanied by launch platform preparations and employee travel to the launch site. The launch event phase is included in the system boundaries, but not characterised. This includes burned fuel, space debris and stage disposal. The ESA methodology further recommends the functional unit, which is defined as "place a payload of x tons maximum into orbit z".
In addition to common environmental indicators, ESA also proposes the usage of flow indicators. These represent besides energy and water consumption, also a method for taking into account space debris, burned-out launcher stages and Al2O3 emissions without characterising them.

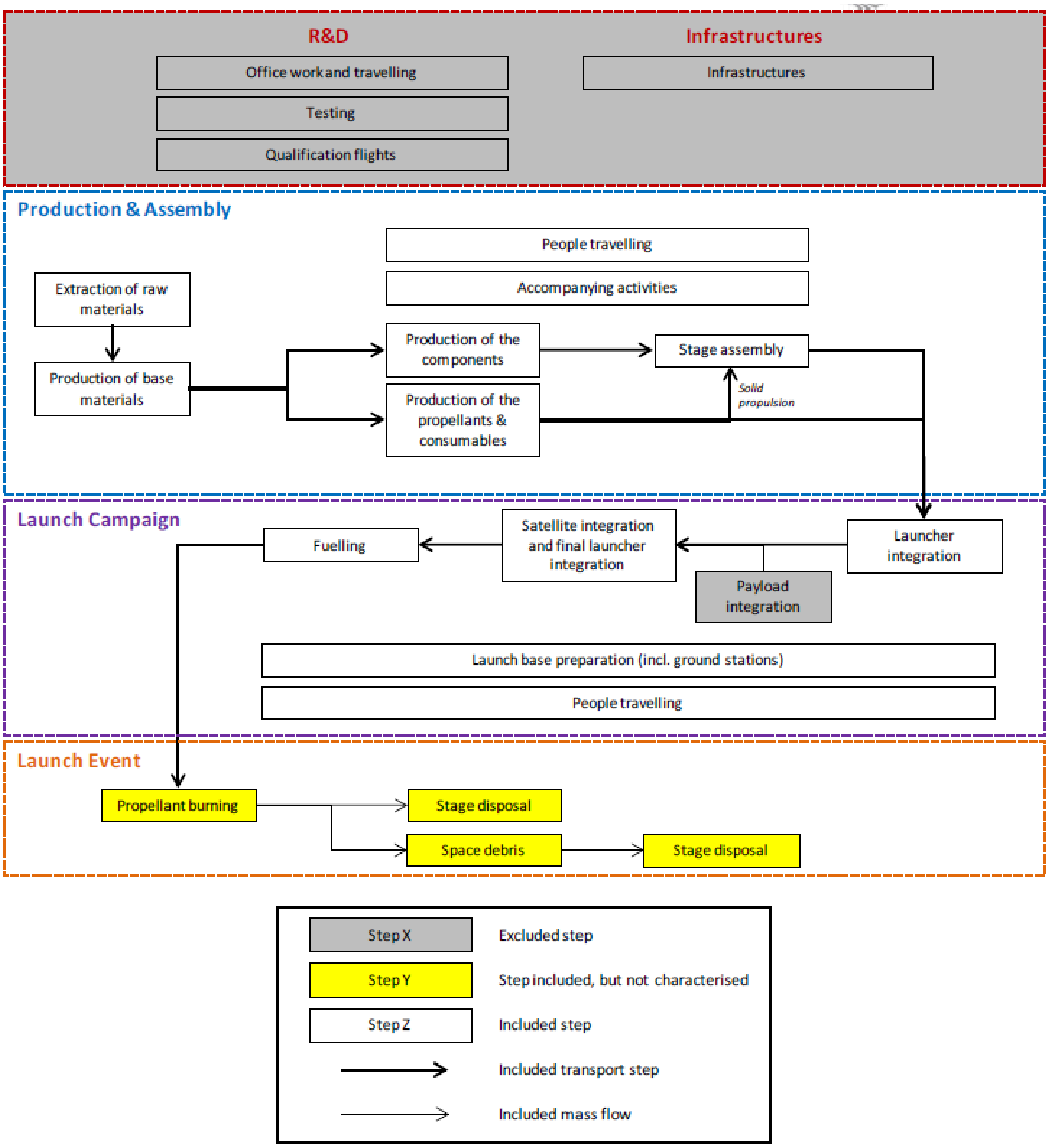


Fig. 5: System boundaries of an LCA of the launch segment as proposed by ESA LCA Handbook [10]

4.4. Available tools for LCA

To conduct LCA, multiple tools are available. For LCA in space, SimaPro, openLCA and Brightway are the most used tools due to their compatibility to the databases.

Table 3: Available LCA tools for full LCA

Tool	Version	Developer	Licence
SimaPro	9.5.0.1	PRé Sustainability	Commercial and Educational
openLCA	2.0.3	GreenDelta	Free
Brightway	2.5	PSI Chris Mutel/open source/PSI	Open source
GaBi	10.6.1	sphera	Commercial
Umberto		iPoint	Commercial

Table 4: Known simplified LCA / ecodesign tools

Tool	Version	Developer	Licence
Assessment and Comparison Tool	0.2.24	EPFL Space Center with consortium	In development, expected to be open-source

4.5. Available Life Cycle Inventory databases

In Table 5 a list of available datasets is listed which are relevant for LCA in space.

Table 5: Available databases for space specific LCA

Input database	**Origin / Licence**	**Version**	**Content**	**Format**
ecoinvent	ecoinvent Association. Licence required	v3.10 (released 2023)	Worldwide leading and most transparent LCI background database existing today. Contains LCI datasets for: ● Materials ● Processes ● Energy ● Transport ● Waste treatment	Ecoinvent ecospold 2
ESA in-house space LCI database	ESA Cleanspace . External version without confidential datasets available under request. Ecoinvent licence required	V1.2 (based on ecoinvent v3.9.1)	Datasets specific to the European space sector: ● Materials ● Processing ● Spacecraft components ● Propellants	SimaPro Database csv export file openLCA zolca file and zip file
Strathclyde Space Systems Database	University of Strathclyde	v1.0.3	Datasets for Life Cycle Sustainability Assessment specific to the space sector: ● Ground segment ● Launch segment ● Space segment ● Infrastructures ● Organisations	openLCA zolca file
European reference Life Cycle Database	Joint Research Center	v3.2	Datasets specific to the European industry for: ● Energy carries and technologies ● Materials production ● Systems ● Transport services ● End-of-life treatment	openLCA zolca file

4.6. Interfaces with other methods

The methodology presented here only considers ecological aspects of the Life Cycle Assessment. For a meaningful consideration of all sustainability criteria, however, the economic and social dimensions must also be taken into account in accordance with the three pillars of sustainability. In this so-called Life Cycle Sustainability Assessment (LCSA) ecologically sensible options can also be evaluated economically and socially [14]. In the long term, assessments should be expanded in this direction in order to enable a holistic assessment of spatial transport. Further assessments like Life Cycle Costing (LCC) or Social Life Cycle Assessment (sLCA) as well as Techno-economic assessment (TEA) are often used. This means that in the case of space flight, for example, the environmental impact of a mission to send an earth observation satellite can be significantly different from that of a space tourism flight, despite the same launch system.

5. Gaps and opportunities identified

In the following, gaps in the existing ESA LCA methodology will be presented and possible measures for closing these gaps and making improvements will be discussed.

5.1. Gaps

Based on the system boundaries in chapter 4.3, the missing components are now discussed following the life cycle of a launcher.

5.1.1. Research and development phase

The research and development phase is currently excluded from LCA. The space industry, and the space transportation industry in particular, is characterised by development cycles lasting years to decades. The current development of Ariane 6 started in 2014 and was also the conclusion of various studies. In Europe, in the past there was one large system development taking several decades. With the emergence of small launchers, the development cycle will most certainly be reduced but still spreads around 5-10 years. The design of systems as technically complex as launchers requires a large number of experts and work hours. This is accompanied by a corresponding environmental impact due to energy consumption and transportation. Furthermore, the development of launcher systems is usually linked to the development of new materials or manufacturing processes, which require novel designs. The extensive testing of the new developments also requires a high input of materials, energy and time. For this reason, excluding these influences when considering the entire life cycle of launchers can significantly bias the results. Studies on the environmental impact of satellites showed that this phase is smaller compared to production, but not negligible [15].

5.1.2. Infrastructure

Infrastructure is currently excluded from LCA. Infrastructure for space projects is needed during all phases. When developing launchers, design and testing facilities are needed. During production and verification, offices, test and production facilities, and transportation systems are needed. For launch preparation, equipment is needed to assemble the launcher and integrate the satellite and for refuelling. The launch itself takes place on a launchpad with a launch tower specially built for the launcher, which provides all the necessary interfaces with the ground stations and tank systems. Furthermore, for tracking and data processing as well as control during launch and flight, telemetry and ground stations as well as a flight operation centre are required. All this infrastructure has to be built, rebuilt or maintained depending on the project. In sum, this infrastructure can contribute significantly to the environmental impact of launch systems, even if it is divided over many flights.

5.1.3. Impact of launch emissions

The implementation of launch emissions into LCA is a challenge, as there is not enough research available to date. Launcher emissions affect all atmospheric layers, with about 1/3 of the mass emitted in the troposphere and 2/3 above [16]. Details on these emissions are not yet known with regards to substances emitted at the various atmospheric layers, reaction with atmosphere, and their impacts on the environment. Further, common LCIA characterization factors are only available for impacts happening on Earth (soil, water, biosphere) or the lower atmosphere.

The impacts on climate change from emissions from Earths' surface are commonly calculated based on the radiative forcing of substances as published by the IPCC. Applying them to launchers would be not sufficient as the complex non-CO2 effects such as soot and cloud formation and impact by rocket specific species on ozone are not considered. Furthermore, not enough knowledge exists on high atmospheric impacts. For emissions from aircraft which usually emit in the higher troposphere to lower stratosphere, Lee et al. (2018) [7] published characterization factors for this, which are shown in Table 6. In a first and rough approach, launcher emissions can be characterised using these factors, at least for the 1/3 propellant burned in the early phases of flight in the troposphere and venting of tanks.
But climate and ozone metrics have not yet been determined for many launcher specific emissions. These include, for example, Al2O3 with a possible impact on climate and ozone or other ozone-depleting substances. There are no characterisation factors for black carbon, stratospheric and mesospheric water and other pollutants which are discussed to contribute to climate change or ozone depletion [17].

Furthermore, the given characterization factors, including CO2 emitted at the stratosphere or mesosphere, are provided with large uncertainty ranges, since the current state of climate research does not have a high confidence level for many emissions. This is especially the case for emissions in the higher atmospheric layers. For emissions in the high stratosphere and mesosphere, no metrics are available yet to consider launch emissions in a comprehensive assessment. This is also applicable for all other environmental factors. Only CO2, NOx and Cl2 characterization factors already exist in the PEF methodology as GWP100 CO2-eq. These are intended for emissions in the troposphere or lower stratosphere. Therefore, the impacts in the higher atmospheric layers might well be different. Some emissions will not harm the environment or humans on earth, others might have yet unknown effects especially considering vertical transport of pollutants in atmospheric layers or e.g. have a higher impact on radiative forcing.

A further discussion point is whether the GWP100 is the right metric to characterise the impact of launch emissions. As all of them have a relatively short lifetime (up to a few years) compared to CO2, the impact of those emissions is mainly of short but maybe significant impact. GWP20 for example leads to different impacts [18,19]. Therefore, Megill discussed if other metrics like GTP or ATR are more useful to assess the impact on climate for emissions from aviation, which could be transferred partly to rockets. Therefore, more research is required and a comparison of the different metrics is necessary to decide, which one represents the real impact the best.

Table 6: GWP100 for common emissions from space transportation systems

GWP100	**IPCC [20]**	**Lee et al. [7]**	**ESA LCA DB**	**Confidence**
Emission from	Surface	Aviation		
CO2	1	1	1	High (for Troposphere/Lower Stratosphere)
CO	1,6-7,6		1.57	
H2O (Vapour)	-	0.06	-	Medium
BC	100-1700	1166	-	Very Low - Low
NOx	-238 - -11	114	0	Low
SO2	-	-226	-	Very Low - Low
Al2O3	-	-	-	-
Clx	-	-	0	-
HOx	-	-	-	-

Besides the mentioned emissions in Table 6, emissions from venting the propellant (e.g. methane or hydrogen) can also have a significant impact [20].

5.1.4. Stage disposal

The effect of re-entering upper stages on the environment has been investigated in some studies but still has a very uncertain impact. During re-entry, the formation of thermal NOx is expected; a study by Park and Rakich (1980) [21] calculated a formation rate of 17.5% of the spacecraft mass, which is used as a basis in today's studies. Ryan et al. calculated a large impact (45%) on ozone depletion. The magnitude is questionable, but should be further investigated. Furthermore, the ablation of the structural materials produces a variety of different emissions. Metallic structures are likely to consist mainly of aluminium. It has been shown that aluminium emissions from launcher and satellite re-entry are already larger compared to meteoroids without understanding the impacts [22, 23]. This is the case for other metals as well and might well increase dramatically in the future [23]. Additionally, for CFRP structures, carbon-containing emissions such as CO2 or black carbon could also be generated. A large portion of the overall material might be injected as aerosols, however a considerable vapour portion exists [22, 23]. It is not known yet what the lifetime and impact of all these emissions are, but various effects on all parts of the higher atmosphere including ozone loss, cloud formation, and climate effects are possible [4]. Emissions might even have impacts that we are not aware of at the moment, even in small concentrations. Same as for launch emission calculation, this comes with no characterisation factors for the higher atmosphere, where normally all processed during disposal happen.

5.1.5. Reusability

The reuse of core stages for orbital launches was first demonstrated by SpaceX in 2015. Before that, only the Space Shuttle and Buran were known as partially reusable systems, but they turned out not to be as economically attractive as planned. In the meantime, there are numerous concepts (Starship, New Glenn, Vulcan), including European ones (Themis, Callisto, Space Rider, Polaris), which want to reuse parts, stages or the complete system. However, the ESA methodology presented does not provide a basis for assessment for reusable systems. There are many questions about how the influence of the research and development phase as well as the infrastructure but especially the influence of the component and stage production as well as their integration and transport should be characterised. The requirements for re-entry also change, since reusable systems usually use heat shields or perform a re-entry burn. Furthermore, the maintenance or refurbishment phase as well as partly reuse of components need to be considered.

5.2. Prospective aspects

Launchers have a long development cycle. Still, LCA is used today to already give an insight into expected environmental impacts of a launcher under design. As the actual launcher will only be built and launched in future, both the foreground data (i.e. technical design data such as material amounts or types used) as well as the background data (taken from the databases as listed in Table 5 modelling e.g. supply chains) have to be adapted to represent that future state.

Engineers may use scaling laws, their expertise, or other data to estimate future conditions when building a launcher in a few years’ time.

Background databases usually represent the state of the data in the past with regards to technologies, supply chains, technological efficiency values, or energy sources. For instance, the energy mixes data of the countries are not always up to date and are in reality subject to constant updating, especially against the background of the ongoing and expected large energy system transformation in the context of the Paris Climate Agreement. The latter additionally affects many industrial sectors, such as technologies used for steel production or chemicals. Further, circular economy and with that circular design are gaining importance.

Since launchers have a long development cycle, it is worthwhile to develop scenarios now to take such aspects into account when modelling production processes happening in the future. Integrated assessment models (IAMs) are numerical models which represent potential evolution of the world's economic sectors under given constraints. Interactions between society, the biosphere and the climate system are quantified, and the results can be used to support decision making. The Intergovernmental Panel for Climate Change (IPCC) uses a variety of IAMs to explore potential changes in the economic sectors of the world under different climate change reduction pathways and goals. Historically, IAMs have a strong focus on direct CO2 emissions or greenhouse gas emissions as well as costs, running optimization problems for those parameters. As such, changes in the energy sector and industries heavily related to it (e.g. steel or chemical production) are best represented in IAMs. Regulations with regards to aspects such as toxicity, stratospheric ozone depletion, or eutrophication are usually not yet considered. IAM modellers are however starting to include such aspects.

Usually, such prospective LCA studies are run exploring various scenarios as provided by different IAMs to show potential ranges of LCA results. The latter need to be interpreted with care depending on how well a certain impact category is represented by such scenarios. Note that LCIA methods so far do not adapt characterisation factors to potential future conditions.

5.3. Suggestions for LCA methodology in space

Possible improvements to the ESA LCA methodology are presented and discussed below.

5.3.1. Functional units

The comparison between two launcher systems is currently difficult. It must be guaranteed that the same system limits and functional units have been taken into account for both systems. In particular, a comparison between heavy-lift launchers and microlaunchers is difficult because they serve different markets and payloads. However, a uniform functional unit should be defined for better comparability. A suggestion for this is to calculate the results for 1t payload into a LEO, SSO, MEO, GTO, TLI or TMI with precisely defined Δv.

This offers the possibility to compare different launch systems with regard to their different performance (different stage architecture, structure and payload mass ratios as well as propellants) with a uniformly defined target velocity, taking into account their respective launch situation (different gravitational acceleration due to different latitudes). In other words, a well-chosen functional unit provides the possibility to compare the environmental performance of various options by choosing various reference flows fulfilling an identical functional unit.

5.3.2. System boundaries

To ensure comparability and the reliability of the validity of studies, a proposal for uniform system boundaries for studies on the Life Cycle Assessment of (reusable and expendable) launchers will be discussed below. Like in the ESA LCA guidelines, the system boundaries are divided into space launch vehicle (i.e. the launcher and possibly the kick-stage for transporting the payload into space), ground segment (i.e. the facilities that are necessary for monitoring and controlling the launcher during the flight) and infrastructure (i.e. the buildings, machines, means of transport, roads, etc.). This should distinguish the individual phases from each other and enable a detailed analysis. The life cycle is divided into four new phases for this purpose.

First, the development phase. This includes all activities that are necessary for the development of a type of launcher system. This applies in particular to pre-development with office work and travel as well as qualification and testing of technologies. The next step is the detailed development with office work, travel, construction, testing and qualification as well as verification of the necessary models (structural and thermal model, structural model, qualification model and protoflight model) including the necessary propellants and test flights until flight readiness. In the second phase, the production phase, all the necessary activities are carried out to produce the dry mass of the launcher system. In particular, this includes raw material extraction and base material production, component production, subsystem integration and stage integration, followed by the necessary qualification and verification tests, as well as the transport of the flight model stages to the launch pad. The third phase is the operation phase, which includes all the necessary steps to carry out the mission. This includes propellant production, launcher assembly, payload integration, roll-out and refuelling, as well as launch, space transport, re-entry of reusable stages and systems, landing and maintenance to restore flight capability.

Stages and subsystems that are disposed of after their mission, whether in a graveyard orbit or in the atmosphere, are finally assigned to the fourth and final phase (disposal). Disposal after multiple reuses also falls under this category. In the case of expendable systems, phases two to four coincide.

5.3.3. Uncertainty and robustness of results

Uncertainty estimation plays an important role in the calculation of environmental impacts. Thus, calculated environmental factors only represent an average value of all estimates and assessments that are carried out within the framework of a LCA. A statistical distribution of the value (lognorm or constant) is usually given for each value in the LCA, from which the uncertainty for the finally determined value is calculated by means of a Monte Carlo simulation. For a more precise uncertainty assessment, we have to differentiate uncertainty related to three aspects when conducting a LCA: Data availability, data uncertainty (e.g. with regards to future scaling up) and methodological uncertainty.

It is of importance that LCA results are shown such that they show potential ranges of results values, acknowledging not only uncertainties but also sensitivities. Especially when LCA is applied to early launcher development phases, being able to judge the robustness of the results is crucial when interpreting the results.

5.3.3.1. Data availability

In order to obtain values that are as accurate as possible, ideally only primary data from the manufacturer itself and its supply chain should be used. In general, suppliers and the industry should provide as much data as possible to allow for a detailed LCA. This would accelerate our common efforts in assessing the environmental impact of systems and counteracting them. In many cases, however, there is no specific data available for each process, material and energy used. Therefore, secondary data such as the ESA or ecoinvent database is used during a LCA. If these also do not give data, proxy data is necessary from similar processes and materials, potentially adapted to the process.

Although this contains uncertainty factors, it is not representative of the process in question in all cases. Therefore, the most accurate data possible or derived processes should be used before resorting to a standard process from the databases. This should be as well documented as possible. An additional calculation of how much data in percent is derived from primary, secondary and proxy data should be included and reported as standard in a LCA.

Another factor is the confidentiality of data in the supply chain. Not every supplier wants to deliver a digital representative model of his own processes including uncertainties and assumptions. Therefore, a standardised approach with e.g. black boxes that contain information about the uncertainty of data and the ability to change e.g. the energy mixture of these process steps needs to be defined and implemented into the databases. There are already some examples in the ecoinvent and ESA database.

Data availability can also be a problem when assessing future systems early in the design phase. An (eco)design decision is easier and less costly to take in phase 0 to B, before the system definition is too advanced. It is therefore interesting to assess the expected environmental impacts as early as possible to guide the design choices towards solutions with less impacts. Of course, this is complicated by the lack of data and that is where heritage and proxies will help make acceptable assumptions before more detailed data can be collected in subsequent iterations of the LCA.

5.3.3.2. Data uncertainty

Even data from own supply chains or measurements are usually prone to some uncertainty. For instance, assumptions on the exact input value of a material have to be taken, or seasonal fluctuations in energy and heat demand exist. Therefore, also this needs to be implemented into the LCA process and make available an uncertainty calculation for each set of data.

5.3.3.3. Methodological uncertainty

Furthermore, there are also uncertainties in the LCIA characterization factors that need to be taken into account. The characterization factors' uncertainty should be calculated and reported in addition to the data availability and uncertainty. This would make it easier to evaluate results from LCAs and also show where further research and detailing would be worthwhile. An example are the emission characterization factors.

5.3.4. Regionalisation

Regionalisation is particularly important when considering production processes and the use of secondary data. Linking LCA data with a definition of the geographic region would simplify the calculation of the influence of energy production and transport processes. In this way, a region-specific energy mix can be assigned and taken into account in the assessment. In addition, transport routes and local emissions criteria could be taken into account to obtain more accurate results in the inventory assessment (LCI). Furthermore, a regional characterisation of impacts is sometimes also necessary to consider specific local impacts of a technology (LCIA).

5.4. Development of (new) guidelines

Guidelines need to be constantly under development and review to establish the best result possible. The current discussion of implementing PEF as PEFCR for space systems comes with the unique possibility to uniform LCA efforts in Europe and define a common standard. The ESA guidelines provide therefore an optimal basis on which the discussed gaps could be closed and further recommendations could be implemented then defining a new PEFCR. Therefore, the authors are calling for ESA and the planned technical secretariat of the PEFCR to collaborate and build together a new standard methodology for the European space industry.

5.5. Labels like the Space Sustainability Rating

Right now, the use of LCA is not standardised and is mostly pushed by public entities like ESA. But some companies in the space sector have started to analyse and communicate on the environmental impacts of their products / services.
An identified opportunity is for the creation and adoption of a rating system for space missions or systems that could help companies and agencies communicate on their impacts without disclosing confidential information. A widely accepted label could also encourage spacecraft operators and other stakeholders to make more efforts in terms of environmental sustainability.

Such a rating is being deployed by the Space Sustainability Rating (SSR) association with a scoring system made of six modules, each of them assessing the impacts of space missions regarding different aspects of sustainability in space. Right now, this means the rating is focused on space debris risks, with assessment of the use of orbital capacity (mission index module), detectability and trackability from ground, collision avoidance capability, but also data sharing, compliance to existing guidelines, and how well the mission is adapted for external services like in-orbit servicing or active debris removal.

The rating in its current version was developed by a consortium which included the World Economic Forum (WEF), the European Space Agency, the Massachusetts Institute of Technology, BryceTech and the University of Texas at Austin. In 2021, the EPFL Space Center was selected to operationalize the rating, which ultimately saw the foundation of the SSR association.
The SSR is still supported by the EPFL Space Center with research projects to develop new modules that could be added to the existing ones, or new rating methodology, to have them better adapted to different systems. For instance, an LCA module using a single score (see below), or a “Dark and Quiet Skies” module, being investigated with the help of the Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference (CPS). [24, 25]. Research on the development of a Launch Vehicle Sustainability Rating (LVSR) is under way [26], which could ultimately include the LCA module mentioned above.

The SSR was recently presented in front of the European Parliament’s Panel for the Future of Science and Technology (STOA), with a session named “The Future of Space - the Sustainable Path”.

5.6. LCIA and results representation: Single score

When performing an LCA, the LCA practitioner needs to decide for LCIA methods, and whether to make use of midpoints only (as presented partially in table 2), or if subjective normalisation and weighting of the various midpoint impact categories is used to show so-called single score “endpoints”. After identification of hotspots the mitigation of impacts comes with the challenge to find new processes or material which have a lower impact for the environmental indicators. However, a reduction in one indicator may lead to an increase of another indicator, in a process called “burden shifting”. This poses challenges to engineers when it comes to ecodesigning a space system, as burden-shifting can sometimes occur in unexpected or unintuitive ways. A single score, which reduces all the LCA environmental indicators into a single number or figure, could therefore simplify the ecodesign process.

However, such a simplification ought to be based on a scientifically founded system as some indicators cover the same characterisation factors and there are also overlaps of different impact categories. The subjective nature of the assignment of weights to each indicator calls for a consensus-based approach, which is being investigated in several projects [27,28]. It is noteworthy that these projects mainly investigate a single-score for a full space mission (i.e. not only including the launch vehicle, but also the satellite) and that the discussion is still open on the need for a single-score dedicated solely to space transportation systems. Further meta-studies ought to be performed to compare these single-score methodologies and assess their soundness.

5.7. Include LCA in continuous education and at university level

The more LCA is performed the more personnel will be required which is capable of performing an environmental assessment of technical systems. Therefore, universities and other institutions training people need to implement courses on space specific LCA and ecodesign. The more employees are capable of considering the environment in development of new technologies and data acquisition, the more the topic will become important in industry. Some examples are presented in 6.2.

6. Ongoing activities

Initiatives and training to better understand the environmental impact of rockets are presented below.

6.1. The Stuttgart LCA workshops

The workshops are intended to promote the exchange of interested parties from research, agencies (ESA, DLR, CNES) and industrial partners to jointly assess the state of research and discuss measures to close knowledge gaps.

The first Stuttgart workshop on "Life Cycle Assessment of Space Transportation Systems" took place in 2022 in the frame of Jan-Steffen's thesis work. With the organising help of the Institute for Space Systems (IRS), the workshop was attended by more than twenty experts from academia, agencies and industry, mostly from western European countries, and produced a first whitepaper on the "Measures for an improved understanding of the environmental impacts of space transportation systems". Working groups were created to focus on questions about LCA methodology, emissions in the atmosphere, and re-entry impacts.

Two online sessions were held in late 2022, these meetings allowed sharing updates between attendees and to invite more experts to connect to a larger network.

The second Stuttgart workshop happened in July 2023, with more participants and the presence of honourable guests: Vera Pinto from the European Commission to discuss the definition of a Product Environmental Footprint Category Rule (PEFCR) for space systems (see section PEFCR guidelines by the European Commission), and Sebastian Eastham from the MIT Laboratory for Aviation and the Environment.

A third on-site workshop is planned in 2024 and more online meetings will be organised in between to maintain the network and progress on different topics.

Concrete outcomes of the workshops are already visible, with the start of several research activities with ESA and between entities attending the workshop (see sections Projects by ESA and Activities by workshop participants).

6.2. Available training

Training on LCA in the space sector is currently rare, but there are multiple options listed in Table 7, and education efforts should increase to prepare the next generation of engineers, managers and policy-makers, and generalise the life-cycle thinking mindset in the industry.

6.3. Data and guidelines by ESA Cleanspace

Currently, ESA is in continuous development of their database, which is available for every ESA member state citizen with an ecoinvent database. ESA is also working on an update of the ESA Handbook with foreseen updates of the environmental indicators to align them with PEF and add additional indicators which are needed for the implementation of the launch- and disposal phase. The update of the guidelines is expected for 2024.

Table 7: Available trainings for space specific LCA

Training	Conductor	Duration	Target audience
Space Sustainability Course, including a lesson and exercise on LCA	EPFL Space Center	3 days, spring	Professionals
Space Sustainability Course, including a lesson on LCA	EPFL Space Center	1 semester, 2 ECTS, spring	EPFL Master students
Clean Space Training Course	ESA Academy	4 days	Students (Ph.D. or Master)
Training for Environmental Life-Cycle Assessment for Space Missions	ESA & Deloitte	4 days	Professionals (SME)

6.4. Space Law and PEFCR guidelines by the European Commission

The European Commission is working on implementing PEFCRs for the space sector and its own foreseen space projects within Copernicus and IRIS2. Furthermore, a European Space Law is currently developed considering LCA in the development of space systems. The PEFCR are based on the general PEF methodology, but can be adapted to the specific sector. Therefore, it would make sense to add additional indicators for the launch phase of rockets. EC DG DEFIS was conducting some workshops on a green transition path for the aerospace sector and is now working in the next step on the implementation of a technical secretary.

6.5. Further projects by ESA

ESA works with its Cleanspace Office since 2011 on the implementation of environmental aspects in ESA technical projects. From 2021 all signed ESA projects need to conduct an LCA. Furthermore, ESA Cleanspace Team is working on the further development of ESA LCA guidelines and database.

The ESA Corporate Social Responsibility team works on climate and sustainability at corporate level to induce changes and transitions to mitigate the impacts of ESA’s activities. This scope more than just the space missions, introducing sustainability criteria in the procurement process, are reducing emissions from ESA sites. ESA CSR is also organising an ecodesign workshop with several subgroups tackling amongst others:

- Guidelines, Database, Data collection improvement
- Simplified ecodesign tools
- The eco-design approach
- Commonly agreed list of top-level Hotspots for space products
- An LCA communication Plan

In addition, ESA Future Launcher Preparatory Programme (FLPP) is also looking at the environmental impact of (future) space transportation vehicles, conducting projects to measure and calculate their impacts in support of new launcher designs with lower impacts and risks.

6.6. Activities by workshop participants

As mentioned above, the development of the Assessment and Comparison Tool (ACT) as part of project REACT for ESA Future Launcher Preparatory Programme (FLPP) is ongoing. A consortium led by EPFL, supported by IRS Stuttgart, ISAE SUPAERO, The Paul Scherrer Institute (PSI), Ateleris GmbH, and WaysEhead, has been working on the project since November 2023. In 2025, it is expected to deliver a tool for simplified LCA of space transportation vehicles. The tool is based on ecoinvent and ESA database, and offers an interface for users to build their models, and space-specific impact assessment such as space debris risks, and high-altitude atmospheric emissions. The tool will allow comparisons between architectures and systems when they fulfil the same functional unit, and is intended to be used in the early design phases of a future system.

Glasgow Caledonian University is conducting activities on carbon accounting approach for the UK space sector. Furthermore, it is involved in several consortium-based space LCA bids.

Activities within ArianeGroup regarding LCA are conducted on civil projects by the development of a database including internal processes inventory data. Furthermore, ArianeGroup is involved in several ESA projects including environmental impact analysis: e.g. PROTEIN, VOLARE (reusability of launcher) as well as LCA projects on Human Space Flight.

IGEP (Institute of Geophysics and Extraterrestrial Physics), Technische Universität Braunschweig is continuing and refining research on spacecraft re-entry emissions through ablation.

Metasat is a company which has now taken over management of the SSSD. It will remain open-source for those with an Ecoinvent licence but looking into commercial development opportunities.

Paul Sherrer Institute (PSI) offers training on the use of brightway (including temporalis and regionalisation), activity browser, and premise, which allows for prospective and flexible LCA in the space sector.

The University of Stuttgart is conducting a multi-year research project looking at the ecological balance of space transportation. To this end, the environmental impact of the production, operation and re-entry of rockets and the necessary propellants are being researched. The project is also developing a methodology for calculating the environmental impact. In a cooperation between DLR and IRS, first measurements of emission signatures of rocket plumes have successfully been conducted.

In addition to the actors mentioned, there are many other research activities in the field of LCA, sustainable space transportation systems and atmospheric effects.

7. Conclusions

The space transportation industry is currently undergoing a great change in the business model as new commercial players enter the market and the demand for launches has risen enormously in the last few years. It is expected that we will soon reach a new order of magnitude of space launches.

This poses an environmental risk that needs to be quantified during the development of new launch systems. Life Cycle Assessment (LCA) is the standard methodology to calculate the impact of technologies considering all life cycle phases.

In this paper we presented practitioners of LCA, LCA methodologies and their gaps and suggestions for further developments. This paper is intended to support the discussion for the further development of the ESA guidelines as well as the PEFCR for the space sector.

We highlighted the state of the art regarding available methodologies, tools and system boundaries. Furthermore, we identified gaps that the current methodology has.

Especially, the development phase, infrastructure, launch phase and disposal are not well covered. Therefore, we suggest a methodology for implementing the development phase and infrastructure.

Assessing the impact of the launch phases presents a challenge in characterising the impacts as the emissions occur in each layer of the atmosphere. Therefore, scientific well-based factors are missing. Furthermore, the current methodology with a GWP100 might not be the proper methodology to calculate the impact of short living rocket emissions

Also characterising the re-entry poses a challenge as first, it is unknown which emissions do occur and second which effect they might have even in small concentrations on the radiative balance, cloud formation and ozone. Furthermore, characterisation factors are also missing here.

In this paper we discuss furthermore the implementation of indicators for uncertainty in data, data availability and methodological uncertainty. We propose therefore the addition of three indicators to give the user an insight into the accuracy of this data.

Furthermore, we were discussing the implementation of a standardised procedure with black boxes to ease the exchange of foreground data, considering prospective changes in the background, e.g. energy mixture for activities in the future.

We hope to give a guide to implement the missing pieces of the puzzle for a comprehensive and prospective LCA for launchers. The implementation of this into the ongoing update of LCA guidelines on European level is being sought.

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