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ORIGINAL PAPER

Formulating life-cycle-sustainability assessment indicators for space activities from a systematic review and evaluation-based selection process

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Abstract
Sustainability is an objective that permeates more and more activities and has also begun to enter into spaceflight. Although attention is mainly put towards the environmental impacts of space activities, economic and social aspects also need to be included for sustainability assessments. To measure sustainability impacts in all three dimensions on a product scale, Life-Cycle-Sustainability Assessment (LCSA) is a typical method in many industries. However, it has not been standardized or regularly implemented for space activities. Aiming at collecting suitable indicators for LCSA for space activities, this paper presents a systematic review about LCSA as applied for space activities and other fields of activities to accommodate all dimensions of sustainability. After obtaining a list of indicators for each sustainability dimension, these were evaluated by actors from the space field for application for space activities and recommended for further use. The results are presented and discussed in this paper.

Keywords Sustainability · Spaceflight · Satellites · Space missions

Abbreviations

CF	Characterization factor
EC	European commission
ESA	European space agency
DLR	German aerospace center
JRC	Joint research council of the European commission
LCA	Life-cycle assessment
LCC	Life-cycle costing
LCE	Life-cycle engineering
LCSA	Life-cycle sustainability assessment
LEO	Low earth orbit
LCIA	Life-cycle impact assessment
MCDA	Multi-criteria decision analysis
OECD	Organisation for economic cooperation and development
UNEP	United nations environment programme
SCC	Social cost of carbon
SDG	Sustainable development goals
SETAC	Society of environmental toxicology and chemistry
S-LCA	Social life-cycle assessment
TBL	Triple bottom line

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1 Introduction

Sustainability and sustainable development are concepts that have captured greater attention in the past decades in all areas of life, including politics and technology. Sustainable development has been defined formally in the Brundtland Report of 1987 as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [47]. On a path of combining the need for sustainability and development of developing and emerging countries, that concept eventually became the guideline for the Agenda 2030 in the form of the Sustainable Development Goals (SDGs) [36]. From the Brundtland Report's definition already, the time element of sustainable development becomes clear: The ability to meet needs has to be maintained over time (between generations),

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i.e. sustainability is a condition to be achieved and is time sensitive. While some might only regard sustainable development as an activity towards sustainability for developing countries, the Organisation for Economic Cooperation and Development (OECD) argues that all countries have to conduct sustainable development [36]. Similarly, progress on achieving the SDGs is reported on by all UN nations, e.g. in the form of Voluntary National Review such as Germany's from 2025 [14], indicating it is seen as a global mandate and not specific to developing and emerging nations. Looking, for instance, at planetary boundaries, such as climate change or ozone depletion, it can be seen that the global, human society, has not achieved sustainability [38], as the current activities of humanity cannot be maintained in the same manner indefinitely without destroying our livelihood on Earth. Humanity's activities have progressed 70% of the so-called "vital signs" of Earth (e.g., ocean acidity, minimum arctic sea ice, sea level change) into levels, which describe conditions perilous to the human existence on individual and societal levels and the Earth's ecosphere in general [39].

Typically, the concept of sustainability is described as resting on three equally relevant pillars: the economic, ecological or environmental, and social dimensions [16]. The differentiation of the three dimensions is also referred to as Triple Bottom Line (TBL) Approach [9]. These dimensions are interdependent, i.e. usually a measure affecting one dimension is positively or negatively affecting at least one other [31]. Consequently, sustainable development and determining sustainability impact(s) are complex subjects [16], and thus need holistic approaches.

1.1 Sustainability and space activities

The number of objects launched into space, as shown in Fig. 1, has increased by a factor of 12, from 210 in the year 2013 to 2,664 in the year 2023 [34]. Further increases are to be expected from installing satellite mega-constellations onto Earth orbits. Sustainability impacts of space activities can be expected to scale up as well and thus can no longer be neglected. An example of such non-negligible impact has been given by Miraux et al. [30], by showing e.g. significant global warming and ozone depletion due to space transportation activities in planned, future mission scenarios.

At the same time, previous work has shown that space technologies can also have a positive impact on sustainability, by either providing new technologies or being a driver for technology development in general [29]. Especially human spaceflight is often facing, on a mission scale, what Earth faces on a global scale: maintaining stable conditions suitable for human life [29]. Technologies addressing power generation, energy harvesting, and circularity of resource utilization are examples of the potential for adoption to terrestrial application and thus contributing to sustainability [29]. Yet, such technology adoption and transfer are no trivial tasks and require careful planning and effort [29].

Research has further shown that such positive impact can be perceived in developing and emerging nations [27, 35]. This is achieved e.g. by globalized supply chains as well as established space research programmes in such nations [35]. Furthermore, major contributions to sustainable development in such nations stem from technologies and services

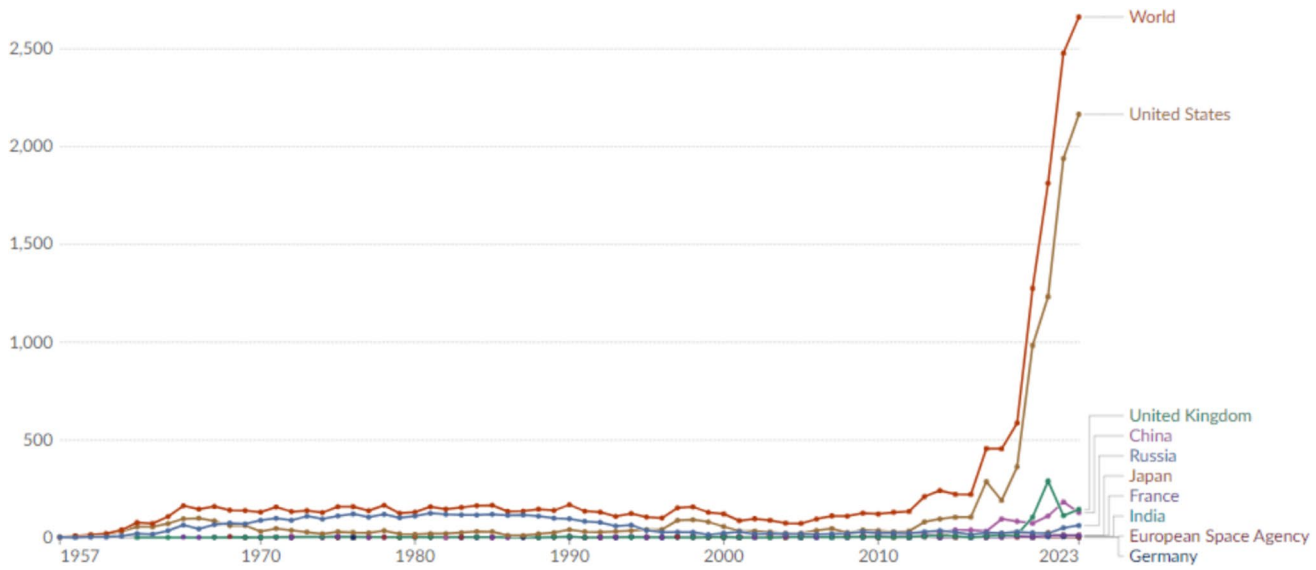

Fig. 1 Satellites, probes, landers, crewed spacecraft, and space station flight elements launched into Earth orbit or beyond [34]. CC BY 4.0: https://creativecommons.org/licenses/by/4.0/

and impact is regarding infrastructure build-up (e.g. for communication or Earth observation), education and international cooperation [27]. Yet, deliberate incorporation of space activities and their positive impacts into national sustainable development strategies is missing, but would likely improve the positive impacts while at the same time formalize accounting for negative impacts [27].

While sustainability has been understood as an important subject within the space community, the comprehension and interpretation of the term is typically not congruent with the term as used in the sustainability sciences as such. Often, sustainability is reduced to a single aspect, e.g. space debris mitigation [28].

To ensure sustainability is not reduced to a buzzword, a generally agreed framework for analyzing sustainability impacts is necessary. Such a framework has to clearly define methods and indicators to be used for assessing sustainability impacts. It has to be ensured that potential impacts are regarded throughout the whole life cycle on Earth and orbit. A common method for the environmental dimension is Life-Cycle Assessment (LCA), part of Life-Cycle Engineering (LCE) [6].

Wilson et al. [53] have used the formalized method of LCA and applied it to a space mission design concept in early phases (i.e. 0/A, see below). Social and economic dimension were considered by single composite indicators, but were not further elaborated on. This study was a first attempt to cover sustainability impacts of space mission design, but did not cover later phases of the space mission design and mainly focused on the environmental aspects [53].

In front of this backdrop and the need for a formalized framework of analysing sustainability impacts of space activities, the German Aerospace Center (DLR) has launched an initiative to establish a metric for evaluating the impacts of space activities onto all three sustainability dimensions.

1.2 Research goal

The overall goal of this research is to find a comprehensive metric for sustainability impacts of space activities, on a mission scale, e.g. for Earth observation, but also larger scale activities, such as the ARTEMIS programme or the installation of mega-constellations. Specifically, for the work reported on in this paper, the focus is on the space mission scale. For the mission scale, LCA and Life-Cycle Sustainability Assessment (LCSA), which incorporates all sustainability dimensions, are typical methods outside the space sector. LCA has been used for the space sector as well.

LCA and LCSA require suitable indicators for providing useful information for decision-makers in the design process. Indicators for sustainability in all three dimensions need to be meaningful enough to generate a purposeful overview on sustainability impacts in reality, caused by – in this case – space activities and at the same time require reliable and available data to be filled with.

If the goal is a comprehensive image of sustainability impacts of space activities, all three dimensions need to be regarded. Therefore, indicators for social and economic impacts need to be included in LCSA in addition to those from the environmental dimension, which are already used by e.g. Wilson et al. [53] and proposed by the European Space Agency Clean Space Initiative [10].

As LCSA has not yet been conducted within the space sector sufficiently to establish a common standard, the first step to such a metric is reviewing existing indicators in *other sectors*, evaluating these and selecting them for further trial use. The basic question was: how are other sectors attacking the problem of surveying economic and social impacts of their respective activities? At the same time, when searching for the potential indicators, it is also relevant to find methods that are used by LCSA actors to select indicators, which have been a further goal of the work presented in this paper.

The scope for the intended LCSA is supposed to be as open as possible concerning space missions, enabling assessment of all relevant parts of a space mission, e.g. production, launch, operation and subsets of processes and flows within these. Summarizing, the goal of the presented work is to survey within the space sector, but especially outside the space sector existing indicators for LCSA of space activities on a mission scale and evaluate their suitability for initial application on LCSA of space activities.

2 Theoretical background

2.1 Life-cycle-sustainability assessment

Life-Cycle Assessment typically involves only environmental aspects, yet sustainability requires consideration of economic and social aspects, either [52]. This combination of assessments is typically labelled as Life-Cycle Sustainability Assessment (LCSA) [22]. It can be achieved by combining the results of LCA, Social-Life-Cycle Assessment (S-LCA), and Life-Cycle Costing (LCC) [52]. The combination of these three paths is achieved by applying – subsequently – Multi-Criteria-Decision Analysis (MCDA) [52, 56]. In literature, this process is often summarized as [23]:

$$\text{LCSA} = \text{LCA} + \text{SLCA} + \text{LCC}$$

This simplified summary should not be mistaken as a summation of results. It is an integration of results for a comprehensive assessment. An important aspect is to apply identical system boundaries for the respective analysis [23]. The method is, however, currently still evolving [2].

In the following, each of the three methods will be shortly introduced.

2.2 Life-cycle assessment

Life-Cycle Assessment has existed for several decades and is defined by ISO 14040 and 14,044 [18, 19]. It is separated into four iterative steps, i.e. [6, 32]:

Definition of Goal and Scope,
Life-Cycle Inventory Analysis,
Life-Cycle Impact Assessment and finally,
Interpretation.

LCA can be applied for product development and improvement (hot spot analysis vs. comparison), strategic planning, public policy making, marketing, and other tasks [18, 19]. The following paragraphs only contain a cursory description of that method. More comprehensive descriptions can be found in the respective standards of [18] and [19] as well as in [6], p. 45ff), Olalekan et al. [32] and ESA LCA Working Group [10]. A very detailed description of the LCA process and its history can be found in Diemer [7].

2.2.1 Definition of goal and scope

The goal and scope phase of LCA is a crucial step as it influences the actual calculation and interpretation of the LCA's results. The goal of an LCA defines the application, purpose of the LCA [6], p. 45ff) as well as the intended audience to whom the results will be communicated [18, 19]. The scope comprises several aspects such as the product system to be studied with its functions, the functional unit, and the system boundaries (i.e. which activities are in- or excluded). With the system boundaries the in- and outputs of each activity/process that is involved along the life cycle are also set.

Also, the definition of the functional unit is a crucial step in the goal and scope phase as it is the reference to which all material and energy flows (cf. life-cycle inventory analysis) are related. The functional unit describes the main benefit of a product (system).

2.2.2 Life-cycle inventory analysis

This step generally involves setting up in- and outputs [6], p. 71ff), associating the respective data to material and energy flows for each process throughout the life cycle [6], p. 71ff). The materials are associated with production, process emissions, waste products. As per definition in the previous step, the data is collected [6], p. 71ff) for each activity. The flows can be categorized as either "emissions to" or "resource extraction from nature" [8], and are named as elementary flows, which are extracted from and released to the environment without modifications by human actions [18, 19].

2.2.3 Life-cycle impact assessment

The life-cycle impact assessment (LCIA) aims for determining the environmental impacts of the considered product system over its complete life cycle. Using the assembled data, indicators specific to certain categories [6], p. 101ff), e.g., CO_2-equivalent, are classified, i.e. related, to the flows defined in the Life-Cycle Inventory. Classification Factors (CF) translate substances' impact to a specific impact category. Different LCIA methods exist. The most recent LCIA method is the Environmental Footprint 3.1 recommended by the European Commission's (EC) Joint Research Council (JRC).

2.2.4 Interpretation

Within this step, the accumulated data is evaluated and interpreted, including, e.g. sensitivity analysis [6], p. 121ff). Depending on the study objective (i.e. goal and scope) recommendations can be derived regarding potential environmental hot spots and potential improvements [6], p. 101ff).

2.3 Life-cycle costing

Secondly, LCC intends to cover the economic dimension of sustainability impacts. Even though the LCC method is older than the S-LCA, no commonly accepted standard has been introduced and thus different standards (with yet different aspects) in various industry sectors exist, such as VDI 2884 or ISO 15686–5, for instance [21, 49]. However, LCC generally considers all costs along the life cycle, including all production, operational, and end-of-life costs throughout the service life of a product.

Yet, LCC assessments can be misleading, as economic impacts are not only associated to costs [2]. Heide et al. [15] point out that for determining the absolute, not only relative, impact on sustainability—which is the goal of the work discussed in this paper—absolute data has to be compiled. Generally, LCC is also not accounting for externalities, i.e. "value changes caused by a business transaction that are not included in the price or are side effects of the economic activity" [41]. This is caused e.g. by lack of clarity which externalities to consider or difficulty of detecting externalities [41].

Wood & Hertwich [54] report that LCC and LCA have similar structures and concepts of functional units, for which the assessment is conducted, but differ in details of how the assessment is conducted and in which scope. They note that LCCs can include different aspects depending on the context as no universal standard exists and thus the understanding of

what an LCC includes differs between sectors. One relevant aspect of LCC is the stakeholder perspective on costs that influence the actual analysis. Further, LCC often does not incorporate future costs [54].

SETAC also published a code of practice about life-cycle costing, as Swarr et al. [43] report. While they point out that only LCA has been standardized, the presented code is intended to be facilitate LCC conducted concurrently with LCA and create a standard akin to [18]. Since only costs are considered, which all have the same unit, based on the respective monetary system, they explain that impact assessment, i.e. "characterization or weighting of inventory data" is obsolete for LCC [43].

2.4 Social-life-cycle assessment

Thirdly, LCSA relates to the social aspects of sustainability. Different methods exist to assess the social aspects, but in the life-cycle thinking context to assess product systems, services, or organizations, the S-LCA was introduced as described in the guidelines of UNEP/SETAC (2009). The principal idea of S-LCA is to align with the well-established LCA method and to assess different social aspects along the life cycle. Thereby, the method provides systematically which stakeholders, each with different impact (sub)categories, can be assessed. Thus, the guidelines of UNEP/SETAC [45] & UNEP [46] recommend aligning the S-LCA as far as possible with the LCA methodology following the ISO 14040/14044, even though details, e.g., data sources will be different. Lie & Qian (2019) also mention that these guidelines are the only standardized approach for S-LCA. A similar standard for S-LCA as for LCA was only introduced at the end of 2024 [20] and consequently, experiences on its applications are still lacking.

2.5 Space mission phases: life-cycle and value chain

For the purpose of this work, we have adopted a life-cycle as described by the "life cycle of space projects" [13] as laid out by the seven phases of the ECSS standard [13]:

1) Phase 0: Mission analysis
2) Phase A: Feasibility
3) Phase B: Preliminary Definition
4) Phase C: Detailed Definition
5) Phase D: Qualification and Production
6) Phase E: Utilization
7) Phase F: Disposal

The phases 0 and A and early part of Phase B (often called Phase B1) mostly involve preliminary work without involving hardware, i.e. computer work and exchange of information. The later phases can involve hardware, i.e. can be influenced by flows associated to production. Phase D is also comprising testing of subsystems and the overall system, which requires space mission specific testing equipment (e.g. thermal vacuum chambers) and mission specific equipment, typically designated as Ground-Support-Equipment (European Cooperation for Space Standardization, 2009). Either activity up to this point could also incorporate Phase E means operation along with launch, which involves mostly impacts associated with the launch itself (e.g. emission from the launch vehicle), computer work (e.g. controlling the spacecraft) and space debris (e.g. returning launch vehicle parts). Utilization usually, also means making the mission purpose available for the respective customer. This could be a service for consumers, e.g. telecommunication, or scientific measurements for a science mission. Finally, Phase F involves disposal of the spacecraft, i.e. again mostly computer work on ground for controlling the spacecraft and either space debris on orbit (e.g. a spacecraft remaining on a graveyard orbit) or returning to Earth.

Space missions typically involve three segments: Launch segment, ground segment and space segment (European Cooperation for Space Standardization, 2009). Depending on the selected scope for the respective LCSA, a permutation of these segments can be involved. The scope also has to define the cut-off point, e.g. which upstream flows of products, i.e. the flows that occur before the product (e.g. a heater, reaction wheel, or computer processor) is used in the space mission, are to be incorporated into the assessment.

Other standards exist, e.g. the phases as labelled by NASA, yet typically, differences occur in details, whereas the general systematic is similar. While this could influence the model used for conducting LCSA, it should not affect the impact assessment as such.

3 Materials and methods

The foundation of the presented work has been a literature review. The literature search was conducted in two steps:

1. The literature was reviewed regarding the state-of-the-art in the space sector and other sectors focusing on the used LCSA indicators.
2. The approaches used for indicator selection were reviewed, that might be applicable for further evaluation and to select indicators in the planned preliminary LCSA.

As the initial state of the art review at the beginning of the overall work already had established that sustainability impact analysis is focussing on the environmental part, i.e. LCA, it was clear from the beginning that other sectors have

to be included in the survey for indicators (see Sects. 1.1 and 1.2).

Subsequently, the resulting indicators were subjected to evaluation by experts for selection.

3.1 Literature review on potential indicators

The search part of the literature review did not differentiate indicators used for a large scale such as programmes (see Sects. 1.2), internally referred to as top-down indicators, and LCSA indicators. The former includes indicators, which are proposed by national or international organizations. Here, organizations' websites with a sustainability association, e.g. the United Nations (UN), the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA). These have been searched for documents concerning indicators for sustainability impacts in general and LCSA for space missions especially.

Additionally, Science-Direct and ResearchGate have been searched for publications, comprising indicators that were used in scientific studies. The time interval applied has been 1990–mid-2024, when the search was conducted.

The search queries used for all sources were:

Life-cycle (sustainability) assessment space missions
Life-cycle sustainability assessment indicators
Social life cycle assessment indicators
Life-cycle sustainability indicator selection

The first iteration on space sector related LCSA search did identify only a few articles that included all sustainability dimensions. Thus, the search strings were extended to identify potential indicators used in the LCSA research field in general, without targeting specific sectors of technical nature. Subsequently, the literature findings have been analysed regarding the fit to the intended use, sorted, and then deriving lists of indicators and selection methods for subsequent utilization for answering the research questions.

The decision for inclusion was based on whether or not a paper was addressing a similar goal, i.e. analyzing indicators for LCA, LCC, S-LCA or LCSA in a technical field or was addressing LCA, LCC, S-LCA or LC(S)A for space missions. Research papers addressing fields of activity without a clear technical part, were excluded as too far removed from our own intended application.

3.2 Indicator selection approach

After collecting the indicators for LCSA in the space sector and other LCSA related research, the question arose which indicators should be used for the assessment of space activities across all mission phases. Despite the literature search identified several different reasons for selecting indicators (cf. Table 4 and Sect. 4), the actual selection depends on the study purpose. Focusing on space activities, which is in terms of LCSA a rather young and very specific research field (i.e. lack of data and experience), it was decided to focus on three main selection criteria data availability, relevance and influenceable. The reasons "data availability" (i.e. if adequate data is available and accessible) and "relevance" (i.e. important for the study purpose) were selected as the review of Wulf et al. [55] has shown it. The reason "influenceable" (i.e. are the indicators possible to change by mitigation actions) was selected due to the final purpose of the study to propose different space mission designs for which the influence is a relevant aspect.

Next, five experts of whom three responded (two from the space research field, one from the sustainability research field) were asked to rank each indicator with points ranging from zero (low) to five (high). Finally, the given scores were summed up. Indicators with a score ranking more than ten were selected for further evaluation to keep the number of indicators for initial trials manageable. For the social dimension, an additional threshold for the data availability of three (out of five) was defined because data for social aspects is usually rare but should be included in the LCSA.

Relevance and fit for application in the space sector was not thought to be related to the number of occurrences in the literature; therefore, this issue has not been included in the selection process.

4 Results

4.1 Potential indicators and selection methods

The outcome of the literature review is presented in this section, whereas the outcome of the selection process will be presented in the next section.

In summary, 29 publications, such as reviewed book chapters, journal articles, or official organizational documents, were preselected as described in Sect. 3.1 and subsequently analyzed. The majority of the publications dealt with work in fields outside the space sector because LCSA related to space activities is rare.

4.2 Literature review: space-sector findings

Generally, the literature review identified multiple indicators that can be used in the context of the space sector. Although LCSA would require considering all three sustainability dimensions, the assessment of environmental impacts is the most advanced dimension for space activities. In contrast, the social and economic dimensions have received less attention so far.

One document, which is addressing social and economic elements of space activities in terms of evaluation is ESA's report on the Space Economy [11]. Herein several aspects, e.g. revenue vs. space budget, employment factor, science benefit (e.g. measured by number of papers/ year), are used to evaluate impact of ESA's activities a-posteriori, such as [11]. However, the indicators in that report are not part of an LCSA methodology, but targeting the key figures on a national scale of ESA's member states, ESA as a whole, results of its programmes and are generally on a large scale. Indicators in that report are e.g. the ratio of revenue over space budget, how many jobs outside the space sector are created for each job inside the space sector, or inspirational value, e.g. followers on social media. These indicators are a mix of a-posteriori quantitative evaluation (e.g., economic growth, talent attracting) and qualitative (e.g., scientific leadership, provide information for European citizens), which were applied on an organizational level and not space mission level within the report. Since the scale of the indicators is not fitting the purpose of application in an LCSA, these indicators are not fully reported or further regarded within this work.

Concerning the space mission scale, ESA has a working group dedicated to LCA of space systems, which published guidelines about their method in 2016 [10] that are under revision by the Technical Task Force. These guidelines contain a series of environmental indicators, which are listed in Table 1 [10].

Wilson & Vasile [52] are spearheading research concerning LCE in the space system context. They refer to the ESA guidelines (2016) concerning the environmental dimension, yet point out that sustainability requires three dimensions [53]. They specify that LCSA is similarly conducted to LCA and use Multi-Criteria Decision Analysis (MCDA) to combine LCA, S-LCA, and LCC into LCSA [52]. However, they do use indicators for the environmental dimension as described in the ESA guidelines, but do not specify indicators for the social or economic dimensions, only generally express social impact and costs [52] and use one indicator for each, "social impact" and "whole life cost" respectively [53]. The environmental indicators are reported in Table 1. Wilson and colleagues also investigated using a single score for evaluating sustainability, based on the Product Environmental Footprint weighting as introduced by JRC [50] aggregating several environmental indicators from Table 1.

Osoro et al. [33] looked at the carbon dioxide emissions from satellite mega-constellations for communication. They use the indicator of "Social Cost of Carbon" (SCC) [37] as a number to evaluate the economic and thus also social impact of CO_2 emissions by satellite missions. Due to its dual nature, the SCC is added in both Table 2 and Table 3. Subsequently, Osoro et al. [33] also use several environmental indicators, as reported in Table 1.

4.3 Literature review: non-space-sector findings

As explained, due to the limited published material within the space sector, papers addressing indicators in other sectors have been used to find indicators with potential application in the space sector. It has to be noted that it was not aimed at a complete literature review of general LCSA studies (thus, some studies were selected as these seemed to have the most comprehensive perspective on LCSA by including different dimensions and research fields of a technical nature), but to find articles which aimed at indicators specifically.

In a report to the OECD, Berkhout & Hertin [5] listed a number of categories, but no actual indicators, for evaluation within the computer industry, such as: Manufacture, Transport, Use, Disposal. For instance, they state that only 2% of materials used for computer production constitute the product; the remaining 98% become waste [5].

Konraré et al. [24] conducted their own systematic literature review for LCSA publications within the gold mining sector intending to create a guideline for LCSA sources, methods, and data search. They list 48 indicators for environmental categories, 12 for social categories, but none for economic [24]. They are also listed in Table 1 and Table 2.

Luthin et al. [26] describe their methodology about circular life-cycle sustainability assessment, which they define as a combination of LCSA and circularity assessment concerning circular economy. Aside from indicators concerning circularity directly, they also address especially social indicators, which partly can be applied to non-circularity related assessment, see Table 2. Some indicators are sorted into social categories by Luthin et al. [26], but apply to an economic category, see Table 3.

Backes & Traverso [3] investigated addressing SDGs with LCSA. For that purpose, they have investigated which LCSA indicators have been used in literature about LCSA to analyze adherence to the SDGs [3]. These indicators are reported on in Table 1 to Table 3.

Arulnathan et al. (2023) identified 21 economic indicators after an intensive search for improving the economic evaluation within LCSA, as the economy is influenced by more than just costs. These indicators are listed in Table 3 [2].

The guideline of UNEP/ SETAC [45] suggest using S-LCA similarly to LCA. Furthermore, they define categories based on stakeholders (workers, consumer, local community, society and value chain actors w/o customers) and subsequently subcategories. These subcategories are partially similar to indicators given in other publications, e.g. "Fair salary". [45] Due to the similar nature of these indicators/ subcategories, they are included in Table 2.

Wood & Hertwich [54] determined indicators for the economic assessment of LCSA in a general field. They distinguish between indicators referring to "value added" (in m€/

Table 1 List of environmental indicators used in reviewed references. Where applicable, the number of mentions as reported in the respective review of the specific article is given. n/a means, no number was given

Indicator	References	# of mentions reported per reference
Global Warming Potential	[3, 10, 24], [33]	6, 6, n/a, n/a
Climate Change	[24, 40, 50, 53]	6, n/a, n/a, n/a
Photo-oxidant creation potential	[24]	1
Photochemical oxidation	[24]	3
Particulate matter	[24]	4
Ozone depletion potential	[10, 24, 40], [33], [50]*	5, n/a, n/a, n/a, n/a
Human toxicity	[24, 50, 53]*	7, n/a, n/a
Water use	[3, 24]	4, 7
Ecotoxicity	[24]	1
Terrestrial ecotoxicity	[3, 24]	2, 4
Marine ecotoxicity	[24]	3
Fresh-water ecotoxicity	[24, 50, 53]	4, n/a, n/a
Marine eutrophication	[3, 24, 50]	5, 6, n/a
Fresh-water eutrophication	[3, 24, 50]	5, 6, n/a
Terrestrial eutrophication	[24, 50]	1, n/a
Acidification potential	[24, 50]*	1, n/a
Terrestrial acidification	[3, 24]	3, 4
Mineral resource depletion	[24], [33], [53]	1, n/a, n/a
Land use	[24, 50]	2, n/a
Agricultural land occupation	[24]	3
Urban land occupation	[24]	3
Natural land transformation	[24]	3
Terrestrial eutrophication potential	[24]	1
Ecological services	[24]	1
Emergy	[24]	2
Environmental loading ratio	[24]	1
Emergy yield ratio	[24]	1
Emergy sustainability index	[24]	1
Emergy inversion ratio	[24]	1
Emergy exchange ratio	[24]	1
Product unit emergy value	[24]	1
Imported resource	[24]	1
CEnD-indicator	[24]	2
CexD-indicator	[24]	1
Embodied energy	[24]	1
Water depletion	[24]	4
Metal depletion	[24], [33]	3, n/a
Fossil depletion	[24]	3
Resource depletion	[24]	3
Ionizing radiation	[24, 50]*	5, n/a
Human health	[24]	4
Energy use	[24, 50]*	3, n/a
CO_2 emissions	[24]	1
Greenhouse gas emissions	[24]	2
Toxicity	[24]	1
Solid wastes	[24]	1
Water waste	[24]	1
Ecosystem quality	[24]	2
Aquatic ecotoxicity	[3]	7

Table 1 (continued)

Indicator	References	# of mentions reported per reference
Terrestrial acidification potential	[3]	6
Terrestrial ecotoxicity potential	[3]	6
Energy consumption	[3]	5
Human toxicity potential	[10], [33]	n/a, n/a
Abiotic resource depletion potential (fossil & mineral resources)	[10]	n/a
Photochemical ozone formation potential	[10]	n/a
Particulate matter formation potential	[10]	n/a
Freshwater eutrophication potential	[10]	n/a
Marine eutrophication potential	[10]	n/a
Metal resources depletion potential	[10]	n/a
Ionizing radiation potential	[10]	n/a
Freshwater ecotoxicity potential	[10], [33]	n/a, n/a
Marine aquatic ecotoxicity potential	[10]	n/a
Fossil resources depletion potential	[10]	n/a
Mineral resources depletion potential	[10]	n/a
Air acidification potential	[10]	n/a
Renewable Energy	[40]	n/a
Recycled/ reused materials	[40]	n/a
Noise pollution	[40]	n/a
Energy efficiency	[40]	n/a
Risk management	[40]	n/a
Recycled water	[40]	n/a
Sensitive land protection	[40]	n/a
Public health and safety	[40]	n/a
Particulate Matter	[50]	n/a
Photochemical Ozone Formation	[50]	n/a
Resource use: metals and minerals	[50]	n/a
Resource use: fossile fuels	[50]	n/a
Mass left in space	[50]	n/a
Al_2O_3 emissions into air	[50]	n/a
Orbital resource depletion	[50]	n/a
Critical raw material use	[50]	n/a
Re-entry smoke particle generation	[50]	n/a
Total mass disposed in ocean	[50]	n/a
Restricted substance use	[50]	n/a

GWh) and those concerning productivity (in m€/m€) [54]. These are added to Table 3.

Rodrigues et al. [40] investigated indicators for the construction industry. They point out that the nomenclature is not universal and even the term "indicator" is used differently by different actors. They surveyed various articles for the listing of indicators. The different meanings of terms make it especially difficult to determine indicators; universality is not apparent for them [40].

A number of indicators are specific to buildings-, e.g. "thermal comfort", and are thus not reported here. The indicators fitting an application to space missions are reported in Table 1 to Table 3 as they are sorted into all three dimensions by the authors.

Liu & Qian [25] conducted a survey for indicators of S-LCA. Elements typically named as "indicators" are labelled "subcategory" in their report, whereas they find further indicators to describe these. Their review results are summarized in Table 2. To measure the health and safety of workers, they used the non-fatal and fatal occupational injuries per 100k workers. Fair salary is measured by them via the ratio of average sector wage and living wage in the respective community. Working hours are rated by weekly working hours exceeding 48 per person. Discrimination is

Table 2 List of social indicators used in reviewed references. Where applicable, the number of mentions as reported in the respective review of the specific article is given. n/a means, no number was given. *indicates a different exact term with similar meaning in the respective reference

Indicator	References	# of mentions reported per reference
Fair salary	[3, 24], [45], [25]	1, 5, n/a, n/a
Working conditions	[24, 40]	1, n/a
Freedom and autonomy	[24]	1
Delocalization and migration	[24]	1
Productivity	[24]	1
Social benefits and security	[24], [45]	1, n/a
Health and safety of workers	[24, 25]	1, 8
Education	[3, 7, 24]	1, 5, n/a
Social insurance	[24]	1
Transportation infrastructure	[24]	1
Legality and formalization	[24]	1
Environment	[24]	1
No. of accidents	[26]	1
No. of jobs created	[26]	1
No. jobs lost	[26]	1
Job related accidents	[26]	1
Campaigns for social acceptance	[26]	1
Trainings for students	[26]	1
Health and Safety	[3], [45], [7, 25]	6, n/a, 9, n/a
Discrimination (gender)	[3], [45], [7, 25]	5, n/a, n/a, n/a
Discrimination (indigenous people)	[3], [45]*, [7]*	5, n/a, n/a
Working hours	[3] [45], [7, 25]*	4, n/a, n/a, n/a
Employee Satisfaction	[2]	2
Freedom of Association and Collective Bargaining	[45]	n/a
Child Labour	[45], [7, 25]	n/a, n/a, n/a
Equal Opportunities/ Discrimination	[45]	n/a
Social Benefits/ Social Security	[45]	n/a
Feedback mechanism (consumer)	[45]	n/a
Consumer Privacy	[45]	n/a
Transparency	[45], [7]	n/a, n/a
End of life responsibility	[45]	n/a
Access to material resources	[45], [7]	n/a, n/a
Access to immaterial resources	[45]	n/a
Delocalization and Migration	[45]	n/a
Cultural Heritage	[45]	n/a
Safe & healthy living conditions	[45]	n/a
Community engagement	[45]	n/a
Local employment	[45], [7, 25]	n/a, 6, n/a
Secure living conditions	[45]	n/a
Public commitments to sustainability issues	[45], [25]	n/a, n/a
Contribution to economic development	[45], [7]	n/a, n/a
Prevention & mitigation of armed conflicts	[45], [7]	n/a, n/a
Technology development	[45]	n/a
Corruption	[45], [7]	n/a, n/a
Fair competition	[45], [7]	n/a, n/a
Promoting social responsibility	[45], [7]	n/a, n/a
Supplier relationships	[45], [7]	n/a, n/a
Respect of intellectual property rights	[45]	n/a
Acoustic and noise control	[40]	n/a

Table 2 (continued)

Indicator	References	# of mentions reported per reference
Employment	[40]	n/a
Infrastructure improvement	[40]	n/a
Public acceptance of the project	[40]	n/a
Stakeholder engagement	[40]	n/a
Social Cost of Carbon	[33]	n/a
Forced labor	[7, 25]	n/a, n/a
Functionality and Usability	[25]	8
Health and Comfort	[25]	14
Accessibility	[25]	6
Feedback Mechanism	[25]	n/a
Integration and Interaction	[25]	7
Technology development	[25]	3
Employment	[7]	n/a
Labor/ Management Relations	[7]	n/a
Occupational Health & Safety	[7]	n/a
Training & Education	[7]	n/a
Diversity & Equal Opportunity	[7]	n/a
Non-discrimination	[7]	n/a
Freedom of Association & Collective Bargaining	[7]	n/a
Security Practices	[7]	n/a
Human Rights Assessment	[7]	n/a
Local Communities	[7]	n/a
Supplier Social Assessment	[7]	n/a
Public Policy, Customer Health & Safety	[7]	n/a
Marketing & Labeling	[7]	n/a
Customer Privacy	[7]	n/a
Socioeconomic Compliance	[7]	n/a
Social Benefits	[7]	n/a
Safe and Healthy Living Conditions	[7]	n/a
Migration	[7]	n/a
End of Life Responsibility	[7]	n/a

measured by the gender inequality index. Forced labour is quantified by the rate of the population in modern slavery. Child labour is defined by the rate of children between 5 and 14 years of age working. Safety and health are measured by reliability of police services, burden of disease and dealing with construction permits. Accessibility is measured by access to water, sanitation facility and quality of roads. Integration and Interaction are measured by government transparency, policymaking and public trust in politicians. Local employment is measured by unemployment rate and local supplier quantity. It should be noted that the authors took a number of indicators, e.g. fair salary or public commitments to sustainability issues, directly from the UNEP guidelines [25].

Diemer [7] reported several indicators, respectively. subcategories, from different sources, e.g. the Global Reporting Initiative, the JRC and the Product Social Impact Life-Cycle Assessment Database (PSILCA). Once more, subcategory and indicator are mixed here in comparison to other publications. For instance, they used the subcategory "Child labour", but use as indicator e.g., Children in employment as % of all children ages 7–14 [7].

4.4 Literature review: indicator selection methods and selected method

The definition of indicators depends on the purpose that these indicator sets should fulfil. Thus, the goal of the assessment should be clarified by the stakeholders because it lays the foundation for a common understanding and fostering in the end their accepted use. Besides the user's acceptance, several other selection criteria exist that can be applied to choose the "correct" indicators. Hirschberg et al. [17] summarized the potential reasons why indicators can be selected.

Table 3 List of economic indicators used in reviewed references. Where applicable, the number of mentions as reported in the respective review of the specific article is given. n/a means, not number was given

Indicator	References	# of mentions reported per reference
No of patents for innovative technologies	[26]	1
No. of innovation meetings	[26]	1
Cost efficiency/ effectiveness	[2]	4
Gross margin/ Net income	[2]	24
Net present value (NPV)	[2]	18
Internal Rate of Return (IRR)	[2]	13
Risk Aspects	[2]	7
Contribution to GDP/ GNP	[2], [54]	5, n/a
Import/Export ratio	[2]	7
Capital productivity	[2], [54]	6, n/a
Labor productivity (return on labor)	[2], [54]	16, n/a
External finance	[2]	5
Diversification (income sources, markets, business, products)	[2]	9
(Relative) Market share	[2]	4
Innovation (product, frequency)	[2]	10
Customer satisfaction	[2]	5
Payback Period	[2]	12
Ratio between net Income and initial Investment	[2]	n/a
Invested Capital Generated in the Activity	[2]	2
Return on Investment (ROI)	[2], [40]	5, n/a
Return on assets, equity, costs and sales	[2]	6
Gross operating surplus	[2]	2
Subsidies	[2]	11
Added value: Labour	[54]	n/a
Added value: Capital	[54]	n/a
Added value: Tax	[54]	n/a
Added value: Surplus	[54]	n/a
Innovation management	[40]	n/a
Use of regional resources	[40]	n/a
Costs (production)	[40]	n/a
Costs (operation)	[40]	n/a
Regional workers & personnel	[40]	n/a
Marketing price	[40]	n/a
Job opportunities (direct)	[40]	n/a
Job opportunities (indirect)	[40]	n/a
Social Cost of Carbon	[33]	n/a

They differentiated the reasons into scientific, pragmatic, and functional characteristics that are shown in Table 4.

The multitude of potential reasons clearly indicates the need of involving stakeholders for selecting "suitable" indicators as the final selection of indicator sets always depends on the study purpose and stakeholder preferences (Wigger et al., 2025). Thus, depending on the setting and actual stakeholder involvement, different indicators can be selected for the same study purpose. Consequently, different final indicator sets can be applied for the same study. However, the literature review identified further articles addressing indicator selection.

For example, Luthin et al. [26] have set up a method to define "circularity indicators". The parameters for evaluation after a review of possible indicators have been: Levels, Performance, Loops, Units, Dimension, and Transversality. "Levels" can differ between city (micro), region (meso), and nations (macro). They state that LCSA should typically only address "micro"-level indicators. "Performance" and "Loops" are specific to the concept of circularity. "Units" determine if indicators are quantifiable, and the authors recommend just using quantitative indicators. Furthermore, the "Dimension" indicator specifies if the origin of its value was transparent and—if several

Table 4 Summary of potential criteria for selecting indicators sorted by scientific, pragmatic and functional characteristics. (based on [17, 51])

Scientific	Pragmatic	Functional
measurable	*manageable*[1]	*relevant*[+]
qualitatively and quantitatively	adequate number of indicators	for most stakeholders involved
meaningful[*+]	*understandable*[*]	*compelling*
reflects the users' needs	possible to comprehend	interesting and suggestive for actions
clear in value[*]	*feasible*	*leading*
clear positive or negative denotation	possible to collect within time and cost constraints	basis for the decision about actions
clear in content[*]	*timely*	*influenceable*
understandable units	easy and quick to calculate	indicators are able to influence actions
appropriate in scale[#1]	*coverage of the intended aspects*[#*+]	*comparable*
suitable dis-/aggregation scale	purpose is covered	if applied in different systems, the comparison should be possible
no redundancy		*comprehensive*[+]
avoid double counting		describes the relevant aspects of the system under study
robust/reproducible		
transparent and sound indicator calculation method		
sensitive/specific		
sensitive to changes during the time scale considered		
verifiable		
verifiable by third persons		
hierarchical[*]		
adjustable levels of detail		

components were used (as the authors recommend)—their weighting clear. Finally, "Transversality" describes whether the indicator is unique to a specific field or universally applicable [26].

Arulnathan et al. 2023 [2] have searched and selected indicators for an economic assessment for LCSA aside from LCC. They explain their method of literature search and analysis of the found papers. They further defined criteria for evaluation, such as (Arulnathan, et al., 2023):

General Information

- o Number of occurrences
- o Scale (Macro-economic, Micro-economic)
- o Type (Leading, Lagging, both)

Indicator Measurement

- o Quantification (Quantitative, Qualitative)
- o Variables (Number)
- o Method (Formula for calculation)
- o Complexity (low, medium, high)
- o Reliability (strong, average, weak)
- o Data availability (Mostly, Some, None)

Indicator Use

- o Comprehensibility (easy to understand, understandable with supporting information, hard to understand)
- o Reproducibility
- o Comparison
- o Trends

Use in LCSA

- o Data (Most data available, some data available, no data available)
- o Functional unit
- o Application
- o Specificity
- o Impact category (Profitability, Productivity, Stability, Autonomy, Customers, Innovation)

The indicators were evaluated with these criteria and subsequently selected by the authors [2].

Heide et al. [15] set up a methodology for identifying social indicators for LCSA. They aimed at representing the social domain for addressing the Sustainable Development Goals (SDG) and wanted to address adherence to the SDGs by use of indicators in a SLCA. Their method follows the guidelines published by the United Nations Environment Program (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC) [45] and is based on the fact

that the social dimension is often overlooked in absolute evaluations of sustainability [15].

Heide et al. [15] recommend the usage of a six-step process for selecting indicators, which contains the process steps as given in Table 5. Additionally, they defined "validation criteria for indicators", which have to be fulfilled for an indicator to be acceptable. These criteria are summarized in Table 6.

Rodrigues et al. [40] reported that after the initial indicator review, an industry survey can be used to set up indicator lists. They also reported that several other authors have used a separation into the three sustainability dimensions for indicator grouping [40].

4.5 Indicator selection: results of expert ranking and final list of indicators

The indicator selection followed the approach described in Chapter 3.2. For the environmental dimension, the recommended indicator set of ESA's LCA working group was selected because it is the current standard accepted by the community. Also, most of the environmental indicators can be calculated by a standardized method as long as data are available.

The indicators, along with the evaluation by experts as described in Chapter 3.2, are listed in Table 7 for the social and Table 8 for the economic dimension. To the economic dimension, only 4 out of 29 indicators were assigned for further analysis. These indicators address the microeconomic aspects of space activities, which are a feasible effort for setting up a new LCSA method. Three indicators are cost-oriented, such as the total cost of ownership, cost of production, and cost of operation. In order to consider non-cost effects, the indicator of cost efficiency, relating cost and benefits for further analysis, is added to the list. The social dimension included 65 potentially relevant indicators, which were mainly based on the UNEP guidelines. The experts scored eight indicators as being relevant, influenceable, or available data. The latter criterion was additionally defined with an upper threshold where the minimal score of three has to be reached for further consideration (cf. Table 8).

Summarizing, the following indicators are recommended to be used for further trials:

Environmental (based on ESA LCA guidelines [10]):

- Global Warming Potential (GWP 100)
- Ozone depletion
- Ionizing Radiation
- Photochemical Ozone Formation
- Particulate Matter
- Human Toxicity, non-cancer
- Human Toxicity, cancer

Table 5 Steps for identifying and selecting social indicators for SLCA, based on Heide et al. [15]

Step-#	Step Name	Step Description
1	What?	Definition of study goal (purpose, sector, type of product), functional unit, main need addressed by product
2	Where?	Identification of phases of the product's life cycle phases and the region where respective activities occur
3	Who and how?	Identification of stakeholders, for each life cycle phase their risks, opportunities, burdens and benefits and derive from that sub-goals and indicators
4	Validate	Participate stakeholders as validation of the sub-goals and indicators
5	Formulate	Refine the indicators based on the validation and formulate them in a form, which is quantifiable
6	Set targets	Target values need to be assigned for the indicators

Table 6 Validation criteria for indicator selection, based on Heide et al. [15]

No	Name	Description
1	Relevance	Representative of the respective issue within that sector
	Ability	The sector should be able to affect the indicator
	Responsibility	Is the sector responsible and who else is?
	Materiality	Significant effect comes from this sector
	Representativity	Must be addressing respective issue
2	Measurable	Must be a quantifiable property
3	Reliability	The data acquisition must be well documented
4	Accept	The indicator is accepted by the industry and researchers
5	Additionality	Are additional indicators required for evaluating side effects?
6	Data availability	Required data should be obtainable easily
7	Resources	Quantifying the indicator should require "reasonable" effort concerning time and finances

Table 7 Social indicator selection list and expert ranking outcome

Main category	Subcategory/Indicator	Expert 1			Expert 2			Expert 3			Total
		Relevance (1–5)	Access to data (1–5)	Influencable (1–5)	Relevance (1–5)	Access to data (1–5)	Influencable (1–5)	Relevance (1–5)	Access to data (1–5)	Influencable (1–5)	
Children	Training and Education (incl. Students)	0	0	0	0	0	0	1	1	1	**1.0**
Consumer	Feedback mechanism (consumer)	0	0	0	0	0	0	1	1	1	**1.0**
Consumer	Consumer Privacy	0	0	0	0	0	0	1	1	1	**1.0**
Consumer	Transparency	0	0	0	0	0	0	3	1	5	**3.0**
Consumer	End of life responsibility	0	0	0	0	0	0	0	0	0	**0.0**
Consumer	Functionality and Usability	0	0	0	0	0	0	4	1	5	**3.3**
Consumer	Health, Safety and Comfort	0	0	0	0	0	0	3	1	5	**3.0**
Consumer	Accessibility	0	0	0	0	0	0	1	1	1	**1.0**
Consumer	Marketing and Labeling	0	0	0	0	0	0	1	1	1	**1.0**
Local community	Integration and Interaction	0	0	0	0	0	0	1	1	1	**1.0**
Local community	Safe and Healthy Living Conditions	0	0	0	0	0	0	1	1	1	**1.0**
Local community	Migration	0	0	0	0	0	0	1	1	1	**1.0**
Local community	Discrimination (indigenous people)	5	3	4	5	2	5	1	1	1	**9.0**

Table 7 (continued)

Main category	Subcategory/Indicator	Expert 1			Expert 2			Expert 3			Total
		Relevance (1–5)	Access to data (1–5)	Influencable (1–5)	Relevance (1–5)	Access to data (1–5)	Influencable (1–5)	Relevance (1–5)	Access to data (1–5)	Influencable (1–5)	
Local community	Access to material resources	0	0	0	0	0	0	3	1	5	**3.0**
Local community	Access to immaterial resources	0	0	0	0	0	0	1	1	1	**1.0**
Local community	Delocalization and Migration	0	0	0	0	0	0	1	1	1	**1.0**
Local community	Cultural Heritage	0	0	0	0	0	0	1	1	1	**1.0**
Local community	Safe and healthy living conditions	0	0	0	0	0	0	3	1	5	**3.0**
Local community	Community engagement	0	0	0	0	0	0	1	1	1	**1.0**
Local community	Local employment	0	0	0	0	0	0	1	1	1	**1.0**
Local community	Secure living conditions	0	0	0	0	0	0	1	1	1	**1.0**
Other	Transportation infrastructure	0	0	0	0	0	0	1	1	1	**1.0**
Other	Environment?	0	0	0	0	0	0	5	3	4	**4.0**
Other	Acoustic and noise control	0	0	0	0	0	0	5	4	4	**4.3**
Other	Infrastructure improvement	0	0	0	0	0	0	1	1	1	**1.0**
Other	Public acceptance of the project	0	0	0	0	0	0	3	1	3	**2.3**

Table 7 (continued)

Main category	Subcategory/Indicator	Expert 1			Expert 2			Expert 3			Total
		Relevance (1–5)	Access to data (1–5)	Influencable (1–5)	Relevance (1–5)	Access to data (1–5)	Influencable (1–5)	Relevance (1–5)	Access to data (1–5)	Influencable (1–5)	
Other	Social Cost of Carbon	0	0	0	0	0	0	1	1	1	**1.0**
Other	Security Practices	0	0	0	0	0	0	1	1	1	**1.0**
Other	Socio-economic Compliance	0	0	0	0	0	0	1	1	1	**1.0**
Society	Legality and formalization	0	0	0	0	0	0	1	1	1	**1.0**
Society	Public commitments to sustainability issues	0	0	0	0	0	0	1	1	1	**1.0**
Society	Contribution to economic development	0	0	0	0	0	0	1	1	1	**1.0**
Society	Prevention and mitigation of armed conflicts	0	0	0	0	0	0	1	1	1	**1.0**
Society	Technology development	0	0	0	0	0	0	1	1	1	**1.0**
Society	Corruption	3	4	2	3	5	4	1	1	1	**8.0**
Society	Stakeholder engagement	0	0	0	0	0	0	1	1	1	**1.0**
Society	Technology development	0	0	0	0	0	0	4	4	3	**3.7**
Value chain actor (exkl. Consumer)	Fair competition	0	0	0	0	0	0	1	1	1	**1.0**

Table 7 (continued)

Main category	Subcategory/Indicator	Expert 1			Expert 2			Expert 3			Total
		Relevance (1–5)	Access to data (1–5)	Influencable (1–5)	Relevance (1–5)	Access to data (1–5)	Influencable (1–5)	Relevance (1–5)	Access to data (1–5)	Influencable (1–5)	
Value chain actor (exkl. Consumer)	Promoting social responsibility	0	0	0	0	0	0	1	1	1	**1.0**
Value chain actor (exkl. Consumer)	Supplier relationships	0	0	0	0	0	0	1	1	1	**1.0**
Value chain actor (exkl. Consumer)	Respect of intellectual property rights	0	0	0	0	0	0	1	1	1	**1.0**
Value chain actor (exkl. Consumer)	Human Rights Assessment	5	4	2	5	4	2	1	1	1	**8.3**
Value chain actor (exkl. Consumer)	Supplier Social Assessment	0	0	0	0	0	0	1	1	1	**1.0**
Worker	Fair salary	4	2	4	5	4	4	1	1	1	**8.7**
Worker	Freedom and autonomy	0	0	0	0	0	0	1	1	1	**1.0**
Worker	Delocalization and migration	0	0	0	0	0	0	1	1	1	**1.0**
Worker	Productivity	0	0	0	0	0	0	1	1	1	**1.0**
Worker	Social benefits and security	0	0	0	0	0	0	1	1	1	**1.0**
Worker	Health and safety of workers	5	1	4	5	3	4	3	1	3	**9.7**
Worker	Social insurance	0	0	0	0	0	0	1	1	1	**1.0**
Worker	No. of accidents	5	2	4	5	4	4	1	1	1	**9.0**
Worker	No. of jobs created	4	1	3	4	1	3	1	1	1	**6.3**
Worker	No. jobs lost	0	0	0	0	0	0	1	1	1	**1.0**

Table 7 (continued)

Main category	Subcategory/Indicator	Expert 1			Expert 2			Expert 3			Total
		Relevance (1–5)	Access to data (1–5)	Influencable (1–5)	Relevance (1–5)	Access to data (1–5)	Influencable (1–5)	Relevance (1–5)	Access to data (1–5)	Influencable (1–5)	
Worker	Job related accidents	4	2	3	4	2	3	1	1	1	**7.0**
Worker	Campaigns for social acceptance	0	0	0	0	0	0	1	1	1	**1.0**
Worker	Discrimination (gender)	5	4	4	5	2	4	1	1	1	**9.0**
Worker	Working hours	0	0	0	0	0	0	1	1	1	**1.0**
Worker	Employee Satisfaction	0	0	0	0	0	0	1	1	1	**1.0**
Worker	Freedom of Association and Collective Bargaining	0	0	0	0	0	0	1	1	1	**1.0**
Worker	Child Labour	5	2	4	5	4	4	1	1	1	**9.0**
Worker	Equal Opportunities/ Discrimination	0	0	0	0	0	0	1	1	1	**1.0**
Worker	Forced labour	0	0	0	0	0	0	1	1	1	**1.0**
Worker	Employment	0	0	0	0	0	0	1	1	1	**1.0**
Worker	Labor/Management Relations	0	0	0	0	0	0	1	1	1	**1.0**
Worker	Occupational Health and Safety	0	0	0	0	0	0	3	2	3	**2.7**

Table 8 Economic indicator selection list for and expert ranking outcome

Indicator		Expert 1			Expert 2			Expert 3			Total
		Relevance (1–5)	Access to data (1–5)	influencable (1–5)	Relevance (1–5)	Access to data (1–5)	influencable (1–5)	Relevance (1–5)	Access to data (1–5)	influencable (1–5)	
Cost efficiency/ effectiveness	5	3	3	4	3	3	2	3	4	10.0	
Gross margin/ Net income	0	0	0	0	0	0	2	3	4	3.0	
Net present value (NPV)	4	3	3	4	3	3	0	0	0	6.7	
Total cost of ownership (TCO)	5	3	3	5	3	3	5	3	4	11.3	
Internal Rate of Return (IRR)	0	0	0	0	0	0	2	1	3	2.0	
Capital productivity	0	0	0	0	0	0	1	1	3	1.7	
Labor productivity (return on labor)	0	0	0	0	0	0	1	1	3	1.7	
External finance	0	0	0	0	0	0	1	1	3	1.7	
Diversification (income sources, markets, business, products)	0	0	0	0	0	0	1	1	3	1.7	
(Relative) Market share	3	2	3	1	2	3	1	0	0	5.0	

Table 8 (continued)

Indicator		Expert 1			Expert 2			Expert 3			Total
		Relevance (1–5)	Access to data (1–5)	influencable (1–5)	Relevance (1–5)	Access to data (1–5)	influencable (1–5)	Relevance (1–5)	Access to data (1–5)	influencable (1–5)	
Cost efficiency/ effectiveness	5	3	3	4	3	3	2	3	4	10.0	
Innovation (product, frequency)	5	3	4	4	3	4	0	0	0	7.7	
Customer satisfaction	0	0	0	0	0	0	5	1	5	3.7	
Payback Period	3	3	4	1	2	4	1	1	3	7.3	
Ratio between net Income and initial Investment	0	0	0	0	0	0	1	1	3	1.7	
Invested Capital Generated in the Activity	2	2	2	0	0	0	1	1	3	3.7	
Return on Investment (ROI)	0	0	0	0	0	0	1	1	3	1.7	
Return on assets, equity, costs and sales	0	0	0	0	0	0	1	1	3	1.7	
Gross operating surplus	0	0	0	0	0	0	1	1	3	1.7	

Table 8 (continued)

Indicator		Expert 1			Expert 2			Expert 3			Total
		Relevance (1–5)	Access to data (1–5)	influencable (1–5)	Relevance (1–5)	Access to data (1–5)	influencable (1–5)	Relevance (1–5)	Access to data (1–5)	influencable (1–5)	
Cost efficiency/ effectiveness	5	3	3	4	3	3	2	3	4	10.0	
Subsidies	2	2	1	2	2	1	0	0	0	3.3	
Added value: Labour	0	0	0	0	0	0	0	0	0	0.0	
Added value: Capital	0	0	0	0	0	0	0	0	0	0.0	
Added value: Tax	0	0	0	0	0	0	0	0	0	0.0	
Added value: Surplus	0	0	0	0	0	0	0	0	0	0.0	
Innovation management	0	0	0	0	0	0	0	0	0	0.0	
Use of regional resources	3	1	5	3	1	5	0	0	0	6.0	
Costs (production)	5	3	4	5	3	5	3	3	5	12.0	
Costs (operation)	5	3	4	5	3	5	3	3	5	12.0	
Regional workers & personnel	4	2	2	4	2	2	1	1	1	6.3	
Marketing price	0	0	0	0	0	0	0	0	0	0.0	

- Acidification (potential expressed as kg SO_2 equivalent)
- Acidification (accumulated exceedance)
- Euthrophication Freshwater
- Eutrophication Marine
- Eutrophication Terrestrial
- Ecotoxicity Freshwater
- Land Use
- Water Use
- Resource Use, Energy Carriers
- Resource Use, Mineral & Metals
- Ecotoxicity, marine aquatic
- Primary energy consumption

Social:

- Child Labour
- Corruption
- Discrimination (Gender)
- Discrimination (Indigenous)
- Fair Salary
- Health & Safety of Workers
- Human Rights Assessment
- Number of Work Accidents

Economic:

- Total Cost of Ownership
- Cost of Production
- Cost of Operation
- Cost Efficiency

Due to the nature of the search results, no generally applicable definition for these indicators can be given, as the articles do not provide these. This is further discussed in the next section.

5 Discussion

5.1 Discussion of space-sector findings

ESA's socio-economic reports [11] [12] use large scale categories, based on data available a-posteriori. Since the evaluation occurs on ESA and not mission level, they are not analogously applicable to future space activities. Furthermore, the respective parameter's value, e.g. the economic benefit and return on investment for space transport activities, would have to be updated regularly. It is beneficial to have a single number e.g. to evaluate the economic impact (e.g. growth outside space economy), yet the data will be specific for each nation and be difficult to obtain for other nations, which do not specify such evaluations. Thus, the indicators as described in the ESA space economy reports are not recommended for use in LCA or LCSA. ESA itself does have guidelines for LCA application on space systems, but focusses only on environmental aspects and there are no guidelines concerning other dimensions, i.e. LCSA is not conducted.

Sustainability is typically defined incompletely by actors in the space industry, e.g. by limiting sustainability to issues of space debris, independent of the actor's nature [28]. Thus, the dominance of the environmental dimension within the ESA guidelines is not surprising, yet nonetheless insufficient to assess sustainability. Thus, the LCA guidelines of ESA can be a valid starting point for establishing LCSA (and have been, e.g., for the University of Strathclyde [52]), yet are no complete method. Research for a more widespread consideration of sustainability in the form of LCE or LCSA is currently limited in the space community to this research group [52], which has published several papers—other entities active in that field could not be identified.

5.1.1 Single-number evaluations

Osoro et al. [33] use the SCC for their evaluation. The SCC "is an estimate, in dollars, of the economic damages that would result from emitting one additional ton of greenhouse gases into the atmosphere" [37]. While it quantifies economic damages, this is still an indicator also linked to social repercussions, e.g. less funding available for public activities such as education or health care. Yet, it attempts to use one number for all these impacts. Inherent in the SCC is a level of uncertainty, which usually would require an interval of values, which however is usually not applied [37]. The SCC is typically used in the US and not in Europe. It is not a universal figure. Also, it only links one value with economic and social implications to one environmental value, which already is understood to be hugely negative: CO_2 equivalent emission. Therefore, its use is questionable on such a small scale as mission planning. It does not fundamentally improve the understanding of the negative impact exceeding that of the total amount of CO_2-equivalent emissions, especially not due to the uncertainty involved. While the CO_2 (or equivalent) emissions are a number, which can be measured, or based on measurements (e.g. from previous satellite launches), the SCC is an interval of estimates.

Using single scores for an overall evaluation of sustainability seems to be simplifying a complex activity, but has a number of drawbacks, some of which Verkammen et al. [50] identify, e.g., reducing the problem to some main impacts such as climate change. Furthermore, it is not helpful if one wants to identify drivers for sustainability impacts of a specific mission and mitigate them by redesign – essentially, the resolution of information is insufficient. While it can help with quick decisions by picking a mission design with the best score, it still might have specific impacts, which

are detrimental to important aspects, e.g., climate change, and only appear better performing by "averaging". Also, the compensation of a bad performance in one dimension by a performance in another dimension does not seem to be useful, as in a balanced interpretation of sustainability such inequalities should be identified, reduced, or avoided if possible.

If one were to reduce the sustainability impact to one number, one could assume a representation would be given by launch mass. Materials to be used for production or the production itself, launch emissions, etc. are proportional to the launch mass. Not similarly for each spacecraft, as processes differ, but these details get lost with a single score anyway.

5.1.2 Incorporating end-of-life scenarios into LCSA

Verkammen et al. [50] have also included several indicators specific to space missions, such as "mass left in space", "orbital resource depletion", "re-entry smoke particle generation" and "total mass disposed in ocean". These are also helpful to conduct trade-offs between different space missions, yet they are difficult to assess. The time interval, for instance, concerning "mass left in space" would be interesting, as satellites can re-enter even after hundreds of years. Additionally, re-entry and burning are still not well understood, so it is difficult to determine how much mass is actually returned to the Earth [50].

On average 10 to 40% of a spacecraft mass survive re-entry and reach ground [1]. The exact demise behaviour of individual components has been tested for only few components [42], i.e. there is a considerable lack of data concerning such behaviour which needs to be remedied. Simulations of such re-entry lack accuracy [42]. One could assume that any emission from a spacecraft into the environment either ocean, land or atmosphere, is negative, and thus it might help to only regard the re-entry mass. In turn, this would make it advantageous to keep satellites in orbit, even though this would be detrimental to future missions, e.g. by increasing collision risks with dysfunctional, de-commissioned satellites, or blocked orbits. A thorough assessment of end-of-life scenarios is required to provide basis for a trade-off.

5.2 Discussion of non-space-sector findings

5.2.1 UNEP/SETAC guidelines

The first version of UNEP/SETAC (2009) guidelines does not provide indicators suitable to the LCSA for space activities context, even though some of their sub-categories have been used as indicators by other publications. In 2020, the guidelines were updated, and also in 2022, several examples of applications were given in a follow update [4] [44]. Generally, their considerations are very exhaustive and thus would provide a useful overall expression of the social dimension in a comprehensive metric. It is therefore recommended to carefully check and adapt the guidelines for LCSA of space activities in the coming years.

5.2.2 Selection method: stakeholder involvement

The method presented by Heide et al. [15] relies heavily on stakeholder feedback. While participation is an important step for evaluating sustainability (especially, in the social dimension), this is difficult for LCSA for space missions, especially in early phases, where design work happens fast. Since for the active stakeholder involvement, longer time intervals are needed and consequently would lead to delays. The scope of the work of Heide et al. [15] has, however, been targeted at SDGs and thus is not totally congruent with the purpose of the LCSA as envisioned within the context of the presented work.

It should be discussed how—in general—industry can be involved in selecting indicators, without the risk of watering down the amount of potentially critical information. At the same time, if we want to acquire the respective data and create a standard method, acceptance of the respective actors in the field is also required.

5.2.3 Clarity of indicator sorting

The list of Rodrigues et al. [40] is extensive but at times incomprehensible regarding how they are sorted. For instance, several indicators are used in one category, when they should be at least in another one as well. One example is "public health and safety" as an environmental indicator. The reference to the "public" also indicates a connection to the social dimension. While environmental aspects, e.g., pollution, can have an impact on public health, this indicator is not linked to the environment as such, but rather the other way around—the environment a person is living in, including emissions from human activity, influences their health. Similarly, "noise pollution" appears only as an environmental indicator. While noise can have environmental aspects, e.g., on wildlife, it is also very relevant for a human population's health. Careful analysis is needed to appropriately assign indicators to dimensions, which is also dependent on whether an indicator is a midpoint or endpoint indicator.

5.3 Overarching discussion

5.3.1 Indicator nomenclature

The varying use of the term indicator, sometimes designating concepts, which are referred to as categories by other parties, complicates the actual analysis regarding which

"indicators" are being used in the field of LCSA. Particularly, the environmental dimension is straightforwardly defined due to the existing ISO standard. This also applies to the term indicator, which is related to the impact category. According to [19] for instance, climate change represents the impact *category*, whilst the global warming potential is the characterization factor (measured in kg CO_2-equivalents) to be applied to each emitted substance. The impact *indicator* is the radiative forcing [18]. There is no single set of indicators to be used for LCSA. Furthermore, nomenclature differs within the LCA or LCSA community, some referring to subcategories, some not. The wording is not universal, possibly due to lack of standardization. Yet, standardization also risks being not specific enough for a certain field, such as space activities. Nonetheless, it should be attempted to use universal indicators where possible to be comparable and comprehensible to activities of other fields as well as to ensure accessibility of existing databases.

When reviewing the literature, it became evident that there is no strict differentiation of these terms and so the results regarding indicators used in LC(S)A, is additionally complicated by the different LCIA methods that use different terms in this context for similar aspects. Consequently, the listings of indicators contain indicators with similar names, e.g., "Ionizing Radiation" and "Ionizing Radiation Potential", see Table 1. It is unclear whether these different labels actually refer to the same and have only been shortened or refer to (if so slightly) different indicators (e.g., using different units). Since, this cannot be determined and several sources use a mix of terms with and without the addition of "potential", they are listed as such. Another example is the term "Human Toxicity", which is ambiguous to "Human Toxicity Potential" and can have a similar or different meaning. For the sake of selection, the terms are regarded as similar even if reported separately. Such identification of differences or overlap could be approached with generalized descriptions, which at this stage do not exist and have not been used in the reviewed papers. This is problematic as the same term might be understood differently, by different research groups.

Furthermore, several indicators are overlapping in meaning. For example, "transparency" exists as an indicator, but "Integration and Interaction" is also linked to the transparency of government [25]. Thus, for an evaluation and for developing an LCSA indicator set, it is important to precisely define each indicator and avoid overlapping/double counting or ambiguity in meaning.

5.3.2 Indicator definition

The overall analysis shows that neither within the space field, nor outside of it, LCSA or its indicators are uniformly defined. Social and economic indicators are far from being implemented within the space sector, but also outside there are a number of variations. Differences in formulation also hinder uniformity and clarity within the analysis. The reasons for these huge differences lie in the fact that indicators and their selection always relate to specific purpose, which should be defined by stakeholders or users of the indicator sets. Thus, different indicators sets can serve the same purpose, but complicate the inter comparison of different studies [51]. A standard for each industry is currently not existing and probably requires lessons learned from application to be implemented. Considering the long-term effects that e.g. a space mission potentially has it will be difficult to actually assess these, as e.g. data of effects is lacking and has to be accumulated over long times to understand effects, e.g. from launch vehicle emissions or lingering space debris. Especially also, because the individual mission's contribution, e.g. to climate change, is nearly impossible to identify in the aftermath. This makes evaluations of whether a specific indicator selection has been correct after the fact difficult. Selection a priori has thus to occur very carefully.

Several publications refer to certain standard publications, such as UNEP/SETAC (2009) for their own analysis and thus reported in Table 1 to Table 3 can appear to be regarding indicators twice. Yet, at the same time this reuse shows their relevance and thus they are still regarded as separate mentions.

Concerning methods, there is no specific approach on how to define indicators, which is especially relevant for the space industry concerning the social and economic dimensions as they are not regarded in the ESA guidelines.

Differentiating between mid-point and end-point indicators is important as well. Mid-point indicators, i.e., immediate effects, are often more accurate as they require, e.g., no translation via models into further effects like life-span reduction. Being more accurate, they can be used effectively to relate different designs to each other and see which performs best. End-point indicators provide aggregated impacts, yet typically need to be calculated via models from mid-point indicators. So, to receive a specific impact or effect of a system, end-point indicators might be more helpful. This should be regarded when selecting indicators for specific purposes.

5.3.3 Costs as indicator for economic sustainability

Costs, indicated by their rare usage, actually are a rather uninformative indicator measure. Costs as "spent funding" at first glance appear to be necessary to be minimized. Especially for space activities, but not exclusively, costs can however also be regarded as investment, e.g. into innovation, patents, and thus create a return, which is reduced if the costs, i.e. investment, are reduced. Therefore, other indicators should be preferred as costs are not resolved enough concerning

their positive impacts and are per sé connotated negatively. For instance, patents and investments in ESA's ISS activities had a revenue of 80% for each Euro spent, in ESA's launcher program, it was a revenue of 220%, both reported in the year 2016 [11]. If the costs would have had been simply reduced, the economic repercussions, even losses in the form of costs of opportunity costs could have been severe. When regarding only costs for an economic evaluation, the apparent solution would be to do not a conduct a mission at all, i.e. reducing the apparent costs to zero. Yet, this would mean also losing the benefits of the investment. Typically, however, LCSA indicators do not consider positive impacts, e.g. benefits from patents. This needs to be considered during assessments.

5.3.4 Adherence to principles of LCSA

Valdivia et al. [48] have published a guideline containing principles on how to generally conduct LCSAs. While several, e.g., No. 1 (understanding of the areas of protection and impact pathways), are very specific to an actual LCSA, which is not part of the work presented in this paper, some are general enough to also have relevance for said work.

Principle No 2 calls for "alignment with the phases of ISO 14040" [48]. As described previously, the indicators presented here, are intended to be used in a framework akin to that standard. This is not only affecting the LCA part, but the goal is to also apply the phases, e.g. goal and scope, to the LCC and SLCA parts of analysis. This is essential to ensure that the same system is addressed in all parts of the LCSA and thus create a consistent assessment.

Principle No 3 recommends completeness concerning the sustainability dimensions [48], which is the goal of this work as well as the reason for reviewing indicators outside the environmental dimension. Furthermore, completeness is also aimed at conducting LCSAs over the whole space mission life cycle, i.e. covering all mission phases from 0 to F.

Principle No 4 addresses the need to receive stakeholder feedback [48]. At this stage, the initial selection has incorporated some stakeholder feedback in the form of evaluating relevance; further feedback is planned for future steps in this work.

Principle No 5 is more specific and demands regard for co-benefits from activities, resp. the functional unit [48]. While this is yet outside of the scope of this work, the implementation of LCSA for space missions is planned to incorporate such co-benefits. Previous research conducted within the team shows that space activities have significant potential for co-benefits [29] [27].

Principle No 6 encourages setting system boundaries in a way that all relevant processes, which could affect any or all sustainability dimensions [48]. The indicators selected here are meant to ensure that. At the final production site of a spacecraft, it is likely that e.g. no child labour will occur. Yet, upstream processes, e.g. concerning material harvesting could include such activities and thus indicators should be able to map that.

Consistency in all aspects of the LCSA is relevant according to principle No 7 [48]. This is also applicable for utilizing the selected indicators, as e.g. they can only provide informative data if they are e.g. applied on a system with the same boundaries for the LCA, LCC and SLCA.

Principle 8 and 9 are regarding "transparency" and "communication of trade-offs" [48]. One of the major goals of the LCSA method for space missions, intended to be developed, is to allow such trade-offs allowing for a space mission design and development which is more sustainable, but identifying hot spots and drivers for sustainability impacts.

Weighing of positive and negative impacts on sustainability, as described in Principle 10 [48], is likely outside the method presented here. Indicators at this stage only address negative impacts. It will be necessary to evaluate a mission's purpose and expected results against such negative impacts.

5.4 Literature review method and indicator selection method

Due to the lack of familiarity with LCSA in a space context, the initial review was set up expecting a more standardized procedure for defining and selecting indicators for conducting an LCSA in sectors other than the space sector. For this purpose, e.g., articles only presenting LCSA results in non-technical fields were excluded. Depending on the results acquired from trial runs with the presented indicators, further review could be necessary with other queries and exclusion criteria.

Similarly, the lack of data, experience and precedence also limited the ability for evaluation, i.e. it can be expected that further iterations will lead to other evaluations of the indicators and thus a modification of the set. This is also affected by enhancing the stakeholder group.

Overall, the explained method provided a solid and grounded first trial base set of indicators, which, however, is expected to only be a first iteration.

5.5 Outlook

The selected indicators are to be tested further on all phases of a space mission. From lessons learned concerning data in all stages of space mission development and operation, the set will be refined. This will enable identification of hot spots and drivers concerning sustainability impacts of space missions. Additionally, further stakeholder feedback is required to align the indicators with experience, needs, and data from stakeholders and improve acceptance as well as usefulness of LCSA results.

6 Conclusion

During the course of the here presented survey, it became clear that LCSA is not yet an established process for the space sector. While LCA has some precedence, the social and economic dimensions are still largely untagged. Therefore, the presented work can be a first step in making assessments in these dimensions available as well. Trial applications will provide information on the validity of that assumption.

The field of potential indicators is large and currently not very space activity specific. A clear, defined method for adopting new indicators does not exist across sectors, only criteria for evaluation, which are recommended to be used for selecting indicators for further work.

A list of indicators has been created from the conducted survey and based on an initial stakeholder evaluation. In a next step, trial runs with these indicators will be conducted and iteratively further stakeholder feedback and lessons learned will be incorporated into the set of indicators, where necessary, depending on e.g. mission phase, data availability and mission type.

It is further recommended to use universal indicators where possible and relevant, but space activity-specific ones, e.g. "mass left in orbit", where necessary to address space activity-specific impacts and needs. This would enable inter-mission comparison and thus allow identifying best practices.

In any case, indicators, especially in the social and economic domains, are required to identify hot spots of impacts in these areas. Regarding only costs can be detrimental to sustainability in the economic and social dimensions as it risks losing positive impacts of investments such as patent creation or employment. Using similar indicators as in other fields, such as construction, also eases the comparison of the impacts associated with space activities and other human activities for decision makers.

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Declarations

Conflict of interest The authors declare no competing interests.

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