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Sustainability goals for space settlement concept evaluation and development and results of their trial application

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ABSTRACT

Comprehensive sustainability assessment of space activities is still a fledging undertaking. Current consensus is that it is most effective to initiate analysing and addressing sustainability impacts as early as possible during a mission or program as most impacts stem from decisions made during the design phase. If future space settlements are to be (nearly) in-situ sustainable they need to be drafted to that purpose as early as possible. Evaluation of sustainability impacts due to space activities is in its infancy, even more so for in-situ outside the boundaries of Earth. This situation is associated with significant knowledge gaps concerning e.g. adaptation of assessment methods to the space context, or sustainability impact data of space engineering specific processes. These gaps significantly limit the ability to determine sustainability impacts and thus formulate mitigations. To bridge these knowledge gaps, within this paper it is shown how an adapted set of sustainability goals has been derived from the Sustainable Development Goals (SDG) via adaptation, a review process with an expert board, and trial application. These Space-In-Situ Sustainability Goals are meant to provide guidelines for designing large scale missions, human settlements, sustainably and to evaluate mission concepts accordingly, drawing from the heritage of the SDGs. Furthermore, the results of their application on four test cases are shown and ultimately their final iteration, based on that trial application.

1. Introduction

Space has become a relevant field of activity, when concerning sustainability in recent years. Looking at the number of objects launched into space there has been a significant increase in the past two decades [1]. As can be seen in the diagram of Fig. 1, twenty years ago, the number of launched objects was still below 100, the numbers increased to about 4000 in 2025. Within just two decades the numbers leaped up by a factor of about 40, after remaining quite stable for previous decades.

This increase is attributed to improved accessibility, e.g. due to reduced launch costs [2] and miniaturization of space systems [3], but also an increased demand in activities, e.g. services using the space environment for communication, which can be satisfied due to reduced costs. With planned activities like several mega-constellations or interplanetary human exploration missions, it can be expected that these numbers will increase even further. This will subsequently also affect possible sustainability impacts associated with them.

Miraux et al. [4] have shown that the impacts of space transportation can be significant. For instance, the plans of establishing a Mars settlement from 2031 to 2050 would require launches with emissions reaching the planetary boundary of greenhouse gas emissions just for this purpose. When launching 1000 Starship-like vessels per launch window to Mars, the planetary boundary for ozone depletion would be exceeded by a factor of 8 due to emissions of particles, such as black carbon [4].

For the year 2050, Miraux et al. [4] expect satellite numbers, mainly attributed to mega-constellations, to reach about 100.000 satellites, which would be an increase by a factor of about 30 compared to today's numbers, again contributing primarily to global warming potential by reaching half of the emissions due to aviation today in 2040. At the same time, they point out the lack of data and thus need for projection, calling for detailed analysis in the future to ascertain the numbers and impacts [4].

The increase in launch numbers resp. launched objects is accompanied by the need to ascertain the sustainability impacts of such activities. Without the ability to properly determine the sustainability impacts, it is open which consequences they will have. Thus, mitigations can only be determined, once impacts come into effect and apparent, i.e. they are delayed. Mitigating impacts before they manifest, is likely more cost effective. Analysing and addressing sustainability impacts in the design

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Nomenclature

EU	European Union
EUR	Euro
ESA	European Space Agency
HLS	Human Landing System
ISRU	In-Situ Resource Utilization
ISS	International Space Station
LCSA	Life-Cycle Sustainability Assessment
UN	United Nations
MDG	Millennium Development Goal
PEFCR	Product Environmental Footprint Category Rules
SD	Sustainable Development
SDG	Sustainable Development Goal
SISG	Space In-Situ Sustainability Goal
SXS	SpaceX Starship

phase is most cost effective as 80% of all impacts are attributed to choices during the design phase [5]. Thus, setting guardrails for mission and program design aimed at sustainability should begin as early as possible. Even more so for large-scale and thus costly and impactful activities such as space settlements.

1.1. Space's sustainable development

1.1.1. Frameworks

Sustainability is typically described resting on three pillars, usually referred to as dimensions: environmental, social and economic [6] (see Section 2.1.1 for details). While there is a growing understanding of environmental impacts on Earth due to space activities and the need to analyse these, the other two sustainability dimensions, i.e., the social and economic domain are often overlooked [7]. This is possibly – among other reasons – due to the fact that there is no common definition of sustainability in a space context [7], not even about the boundaries within which sustainability is to be defined, e.g. including Earth, or planetary environments or both. Matters of sustainability are rarely addressed in a perspective comprising the respective mission environment as well, if it is not Earth [7]. In consequence, what sustainability means in the frame of space activities has not yet been uniformly defined by space actors, such as industry, agencies or nations in general [7]. Yet as any human endeavour space activities have a relation to sustainability and sustainable development (SD), e.g. by supporting sustainable development on Earth or being conducted with guardrails of sustainable development with the respective mission environment in mind when planning and executing space missions.

As discussed previously by the author [7] four perspectives can be distinguished when regarding space activities with regard to sustainable development:

- Earth-to-Earth
- Earth-to-Space
- Space-to-Earth
- Space-to-Space

These perspectives reflect the boundaries of the system that is to be developed in a sustainable manner. In an Earth-to-Earth perspective, technologies or scientific results in the form of a spin-off are applied directly for sustainable development on Earth. For instance, advancing renewable energy generation with the help of solar cells, which originally were developed to a use-ready status for space application, would be such an activity. The perspective Earth-to-Space is regarding space missions, which need to be sustained with support from Earth, such as ISS' operation. If missions are advancing sustainable development on Earth, e.g. by providing Earth observation data, which is used for improving agriculture efficiency, the perspective is Space-to-Earth. Space-to-Space is the perspective for when a mission is independent of Earth resupply and has to sustain itself in a space environment, e.g. by applying In-Situ-Resource-Utilization (ISRU) techniques [7].

Addressing sustainable development in space as extension of humanity's sphere of activity is e.g. proposed to be extended from its current framework in the form of the Space Treaty to a formulation of an 18th United Nations Sustainable Development Goal (SDG) by Galli & Losch [8]. Yet, this is addressing the topic with Earth in mind and not focussed on evaluating or guiding a mission design in-situ, i.e. in a space-space situation.

This is similar to the essentially only existing legal framework, the Outer Space Treaty of 1967, which describes responsibilities and rights of space actors with a perspective, which is Earth-centered. It can be found at [9].

Irons & Irons [10] describe a very top-level theory on the limitations placed on sustainability of human settlements. They discuss boundaries for settlements based upon the evolution of humans, without specificity to assess missions, but providing general thoughts on sustainability from an environmental perspective. This includes a definition of different levels of sustainability and evaluation based on e.g. available power sources. While they do acknowledge the link between the environmental impacts and social impacts, their theory does not specifically address the

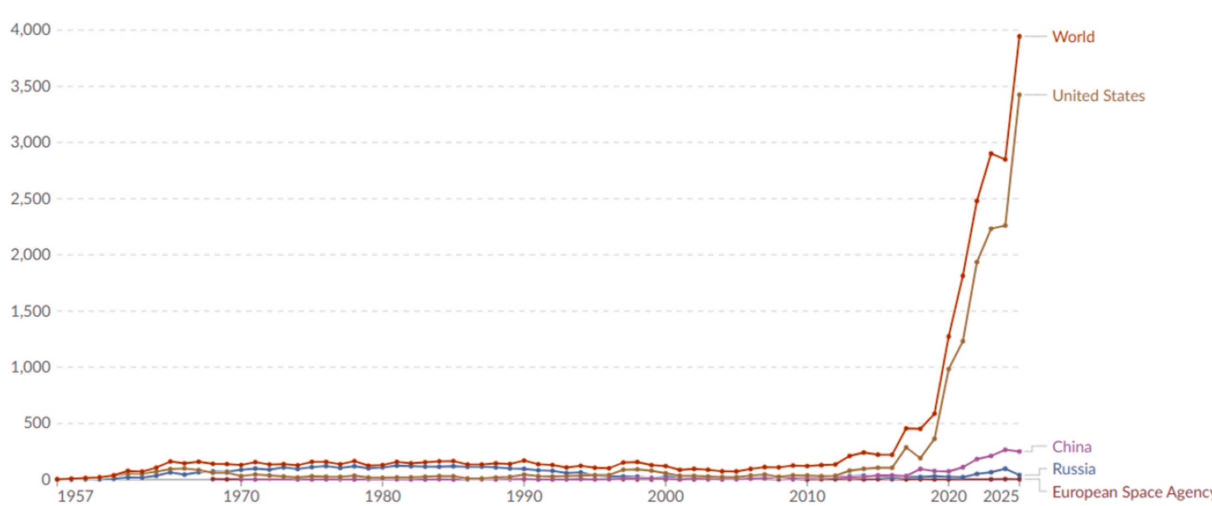

Fig. 1. Number of objects launched into space over launch year [1]. CC BY 4.0.

sustainability dimensions aside from the environmental one [10].

Yap & Truffer [11] talk especially about the connection between Earth and space for sustainability, especially also for terrestrial sustainability, including benefits and risks associated to space activities, such as impacts on climate change or space debris. They specifically point out how sustainability monitoring and implementation should be realized by international cooperation concerning governance and compare the associated obstacles with other non-traditional fields of activity, such as "deep sea, Antarctica, or cyberspace" [11, p. 6]. The recommend interlinking the fields of sustainability transition and global governance, to overcome such obstacles and ensure sustainability of space activities.

1.1.2. Need for sustainable development of space

At a first glance, it might appear as if environmental and even more so social and economic impacts are not relevant within space environments, due to the small number of activities in such environments, yet, this is a non-sequitur. For assessing the relevance of impacts and thus activities, we need to have a thorough understanding of the respective environment, which is not the case for non-terrestrial environments. Furthermore, the microcosm of a space settlement is possibly more susceptive to social and economic impacts, due to the smaller size and thus lack of buffering.

At the same time, there is a plethora of mission plans to e.g. Moon and Mars, even if just counting human exploration missions, which would have social and economic dimensions to consider for sustainability. For instance, there is ESA's scenario for a Moon Village, which can have multiple contributors acting in a collaborative community [12]. Then there is the International Lunar Research Station headed by China and intended to be a collaborative effort as well [13] and to be placed in the vicinity of the lunar south pole [14]. There is NASA's Artemis program, which intends to land on the lunar surface [15], possibly with the landing vehicle being a derivative of SpaceX′ Starship (SXS), labelled Human Landing System (HLS) [16]. Starship is also part of current intentions for a human Mars mission as envisioned for the late 2020s or early 2030s [17,18]. For establishing a human settlement on Mars, SpaceX plans to launch up to 1000 to 2000 per launch window [19]. As pointed out earlier, this would likely have severe impacts on the terrestrial environment [4].

Actual implementation of long-duration human space exploration missions has just occurred twice: Operation of the space stations *Mir* and the International Space Station' (ISS). The former operated for about 15 years from 1986 onwards and the latter's operation began in 1998 and is anticipated to last until at least 2028 [20]. While both have been operated in a space environment, this operation did not occur independently of Earth, relying on regular resupply flights as a cornerstone for sustaining their operation. Sustainability considerations for any of the prospected missions have not been published yet to the author's knowledge. This means, the question remains, how to ascertain sustainability or a sustainable development of these mission concepts and eventually settlements?

1.2. Research goal

1.2.1. Motivation

Previous research has shown that space activities can facilitate sustainable development on Earth [11], e.g. via technologies [3,21] and services [3]. Yet, to achieve best results, a coordinated effort for actively planning space activities as measures for sustainable development is required [3]. It is conclusive that for achieving sustainable development in space, i.e. of space settlements, such careful planning is also required.

Inspired by the definition of (terrestrial) sustainable development (see Section 2.1 for details), the formulation for space in-situ sustainable development has been proposed [7]:

> *"Space missions are realizing Space In-Situ Sustainable Development if they are conducted and designed to enable not just the current crew but future crews and populations as well as all those affected by the mission to fulfil their needs in the economic, social and ecological dimensions."*

Yet, such a formulation is not sufficient for beginning careful planning and design of space missions facilitating their sustainable development. To achieve that, further details and indicators to measure the extent of fulfilling the above definition are needed.

1.2.2. Formulating Space In-Situ Sustainability Goals and their intended application

Facilitating in-situ sustainable development of space missions can possibly profit from an approach similar to that of the United Nations Sustainable Development Goals (SDGs) [22], i.e. a set of Space In-Situ Sustainability Goals (SISGs), which help realize the above definition of space in-situ sustainable development.

The aim is to formulate a means for application on large scale missions, such as establishing permanent or long-duration lunar or Martian bases, to:

i. Act as guardrails for mission concept definition and development in a sustainable manner
ii. Allow evaluating mission designs on their fit for sustainable development

Evaluation should be possible even when information is limited, either because detailed information is not available, such as typically in early mission phases, or when a system is so complex that accumulating all relevant information is exhaustive and not feasible.

2. Theoretical background

2.1. The concept of sustainable development

The paradigm of sustainable development has been defined first in the Brundtland report [23] as:

> *"Sustainable development is the development that meets the need of the present without compromising the ability of future generations to meet their own needs."*

It addresses quite generally needs of the sum of all humans with a time-perspective: now and future. Future is for all intents and purposes indefinite here, i.e. sustainability is not a short-term endeavour. Implicitly, this formulation also establishes that all humans within one generation and across generations have a similarly weighted right of fulfilling their needs.

Development strategies (for the global south) have addressed the connection between sustainability and prospering for several decades, shifting from a mere regard of economic growth towards a more holistic approach, after the former did not establish lasting effects. This culminated in the United Nations Conference on Environment and Development in Rio de Janeiro in 1992, (usually abbreviated as Rio92), which defined the Agenda 21 as a strategy for reaching sustainability in the 21st century. Subsequent conferences defined further specific steps, e.g. Rio+20 in 2012, which eventually led to the official formulation and ratification of the SDGs in 2017 [22] as part of the Agenda 2030.

2.1.1. Sustainability dimensions

Sustainable development is typically modelled in its expressions in the three so-called sustainability dimensions, explains e.g. Hilser [6]. These three dimensions are economic, social and environmental (or sometimes ecological). They are interdependent towards each other. A single activity is usually not only affecting one of these dimensions, which makes evaluating activities with regard to sustainability a complex undertaking [6].

Each dimension has to be sustained, just like a three-legged stool requires each of its legs to not topple over, to fulfil sustainability. Yet, there is a certain hierarchy for these dimensions, especially for an in-situ space perspective. The most important dimension is the environmental. Without a working environment, human life cannot exist and thus the social and economic dimensions are void. Without a society (of whatever size), rules (e.g. for conflict management, aligning conflicting interests) and governance do not exist thus no economy is possible. Economy requires rules, e.g. for exchange of commodities. Yet, economy can also not to be neglected. Economy is a means to ensure e.g. access to resources. Progress and development necessitate some form of economy, even if not monetary based.

Understanding the an activity's sustainability impact is complex and has multiple facets. For instance, a communication satellite designed to connect remote areas to more densely populated areas via communication, can improve their access to education and thus enable better jobs. This improves the social and economic situation in the area. Better jobs also facilitate affording better health care, again affecting the social dimension. Yet, production of the satellite and launching also cause emissions, which affect the environment. Depending on the propellant or other components used, e.g. toxicity could also cause health and environmental problems, affecting the social and environmental dimensions. An economy, which is based on consumerism, will suffer from high poverty rates as people will not be able to afford buying products. Similarly, damages from e.g. climate change, reduce economic outcomes.

2.1.2. Current state of terrestrial sustainability

Generally, when regarding planetary boundaries, such as climate change or ozone depletion, it is evident that the human society has not achieved sustainability [24], because the current activities of humanity are not maintainable similarly to now without destroying our livelihood on Earth. Human activities have progressed 70% of Earth's so-called "vital signs" [25], such as ocean acidity, minimum arctic sea ice, or sea level change, into areas marked as perilous to the human existence on individual and societal levels and the Earth's ecosphere in general [25].

For the European Union, the European Environment Agency determined that the economic damages from weather and climate extremes for the years 1980 to 2024 have been 822 billion EUR, a quarter of which occurred just in the years 2021 to 2024, showing a measurable trend upwards [26].

The World Economic Forum [27] lists among the ten short-term (2yrs) and long-term (10 years) risks a variation of risks associated with the environmental and societal dimensions of sustainability, such as "extreme weather events", "biodiversity loss and ecosystem collapse", "Inequality", "Societal polarization" and "Erosion of human rights and/or civic freedoms" [27].

Specific action and long-term strategies are necessary to achieve sustainable development and eventually sustainability.

2.2. Sustainable Development Goals

The SDGs are the core of the Agenda 2030 aiming at making Earth sustainable by 2030. They have been agreed on by the United Nations General Assembly in 2017 [22]. The goals are intended to be non-specific concerning the means for achieving them, but describe an aim, such as eliminating hunger (Goal No 2, [22]).

There are in total 17 SDGs, see Fig. 2, which implicitly address all three dimensions of sustainability. The environmental dimension is addressed by e.g. Goal 13, Climate Action, the social dimension is addressed by e.g. Goal 5, Gender Equality, and the economic dimension is addressed by e.g. Goal 8, Decent Work and Economic Growth. Some address more than one dimension, e.g. Goal 1, No Poverty, addresses the economic and the social dimensions.

The SDGs have been agreed on per resolution by the UN General Assembly and are goals for all countries and not just developing countries. Each goal has several indicators to evaluate progress towards achievement, grouped for specific targets, e.g. Target 1.1 (Goal 1): "By 2030, eradicate extreme poverty for all people everywhere, currently measured as people living on less than $1.25 a day" [22], with the indicator: "Proportion of population below the international poverty line, by sex, age, employment status and geographical location (urban/rural)" [22].

Means for achieving those goals (via targets) are not specified intentionally, to allow each nation finding their own specific measures. Progress is reported voluntarily to the so-called High-Level Political Forum [29]. With the help of the indicators, the SDG progress can be

Fig. 2. Graphical representation of the 17 SDGs as defined by the UN [28]. (The content of this publication has not been approved by the United Nations and does not reflect the views of the United Nations or its officials or Member States).

monitored and developments assessed, allowing measures to be taken. It is a common language available to all participants of Agenda 2030, which allows comparing results and development as well as exchange about measures.

Listing all goals with all targets and indicators would exceed the limitations of this article, but they can all be accessed here [22]. The basic paradigm of the SDGs is comprising the five principles People, Planet, Prosperity, Peace and Partnership [30].

3. Method

The derivation of the SISGs formulation was conducted in three phases. Initially, the SDGs were reviewed and adapted with a perspective changed to that of an in-situ space mission, and not that of Earth. This created a first iteration of the SISGs, the X_0. Subsequently, a review board was asked to provide feedback on that first iteration, after information about the purpose and goal of their formulation. The review occurred in two steps, with each step resulting in a further iteration, leading to a version X_2 in the end. This version was then applied in trials of case studies, investigating their usefulness and subsequently modified into a final iteration X_3. This process is illustrated in Fig. 3.

3.1. 1st iteration: SDG adaptation

For the first iteration, the SDG formulations have been used as basis as well as the basic paradigm comprising People, Planet, Prosperity, Peace and Partnership with a viewpoint shifted towards space settlements:

- PEOPLE: Inhibit poverty, thirst and hunger in all their forms and dimensions to ensure that all human beings can fulfil their potential in dignity and equality and in a healthy environment. In accordance with the Outer Space Treaty [9] the benefit of all people should be the aim of any settlement.
- PLANET: Protect the planet from degradation, including through sustainable consumption and production, sustainable managing of its natural resources, especially water, so that it can support the needs of the present and future generations. This principle is applied for the immediate living environment (e.g. Moon or Mars) as well as the whole solar system, including Earth.
- PROSPERITY: Ensure that all human beings can enjoy prosperous and fulfilling lives and that economic, social and technological progress occurs in harmony with nature.
- PEACE: Foster peaceful, just and inclusive societies which are free from fear and violence. There can be no sustainable development without peace and no peace without sustainable development.
- PARTNERSHIP: Mobilize the means required for implementing sustainable development, based on a spirit of strengthening interplanetary solidarity, focused in particular on the needs of the poorest and most vulnerable and with the participation of all countries, planets, stakeholders and people.

The SDGs with their individual indicators have been scanned and analysed concerning necessary adaptations for a fit to a space environment. Specifically, it was ensured that the perspective which for the SDGs is a future perspective of a current situation (e.g. reducing poverty to zero from an existing poverty rate) was shifted for the SISGs to preventing the situation from occurring in the first place when regarding future space settlements. The adaptation of the SDGs was intended as a starting point of an iteration, the X_0, for further modification.

3.2. 2nd and 3rd iterations: review board revisions

Subsequently, the first iteration was subjected to a review bord. The purpose of the review was to include relevant expertise into the SISGs' formulation. To get the most out of the reviewers' involvement with limited available time, it was regarded as most effective to use a first iteration as starting point and inquire about changes from the reviewers.

Reviewers were selected with backgrounds in space engineering, programmatic and sustainability, addressing relevant areas for mission programs comprising space settlements in addition to sustainability. Of in total eight people asked, five agreed to comprise the review board. Their backgrounds are listed in Table 1. One reviewer with a background as a space systems engineer was selected to provide insight into technical aspects of the task. Another reviewer was also a space engineer, but with significant experience in the role of a space agency member, providing programmatic insight.

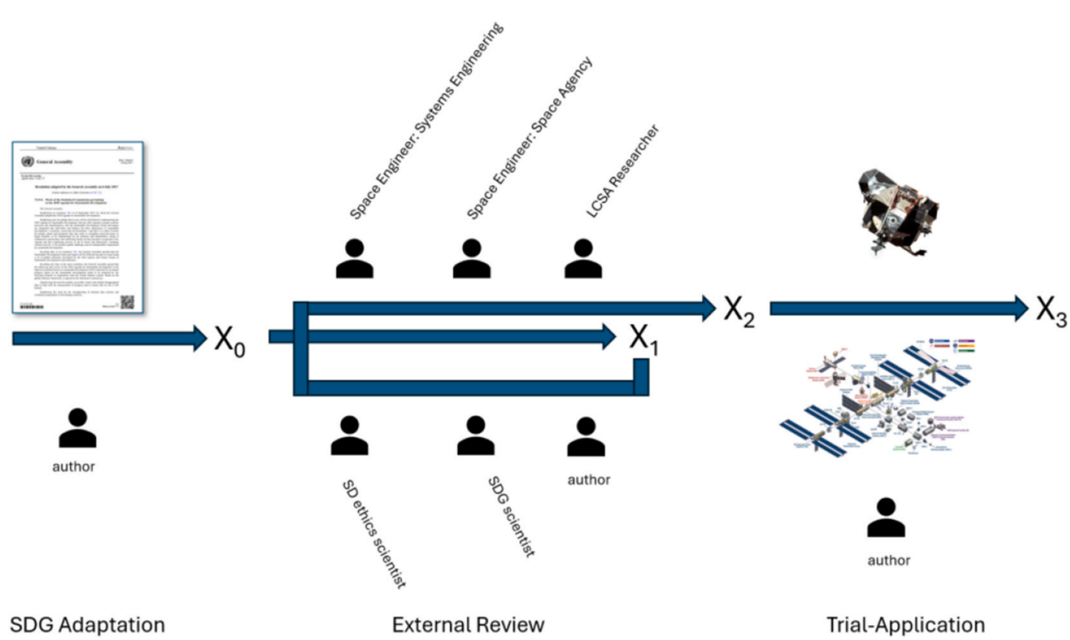

Fig. 3. Method of deriving the current version (X_3) of the SISGs, based on initial adaption of the SDGs, double revision via a review board and trial application on four cases. (Apollo Lunar Excursion Module and ISS images: NASA, public domain).

Table 1
Overview about the Review Bord and its input into the adaptation, per revision.

Reviewer Number	Background	No of Remarks Rev 1 (for iteration X_1)	No of Remarks Rev 2 (for iteration X_2)
1	Space Engineer: Systems Engineering	3	5
2	Space Engineer: Space Agency	41	58
3	Life-Cycle Sustainability Assessment Researcher	25	11
4	Sustainability Scientist: SDGs	1	0
5	Sustainability Scientist: Ethics in Sustainable Development	1	0

Third, a reviewer with knowledge about Life-Cycle-Sustainability Assessment (LCSA), a typical method for evaluating sustainability impacts of products over their whole life cycle, e.g. from resource harvesting to disposal of the product, was included to make use of their knowledge about sustainability evaluation in a technical area. Further information about LCSA can be found here [31].

One further reviewer with research activities concerning the SDGs was included to ascertain that enough knowledge about a large-scale framework as the SDGs is available. The last reviewer had a research focus concerning ethical questions about sustainable development, ensuring the social domain was represented as well, considering the technical expertise of the author. All participants were experienced researchers, with at least 4 years (Reviewer 2) of experience in the respective background and up to two decades (Reviewers 4 and 5). The participant with 4 years of experience in space agency work, had previous work experience of a decade as space systems engineer. All except reviewer 1 had at least a doctorate, members 4 and 5 had a professorship.

The board's size allowed timely handling of reviews and the diversity of backgrounds ensured that relevant aspects could be introduced into the SISG formulation. The reviewers conducted the review remotely in written form, aware of further reviewers, but unaware of their identity. They received a document with the formulation of the SISGs and for each SISG also a rationale for their formulation. An introductory text explained the purpose of the SISGs and the review.

The reviewers responded with a collection of comments on their suggested changes within the document. Review duration depended on the availability of the reviewers and comprised several weeks. A tentative deadline of four weeks was given as guideline, but not enforced, to ensure completeness of the review while encouraging timeliness. The responses' adaptations were incorporated into the SISGs and accompanying text. After the first revision, i.e. iteration X_1, an identical approach was implemented for a second revision, leading to an iteration X_2.

3.3. 4th iteration: trial application

Subsequently to the formulation of the SISGs leading to iteration X_2 a trial application was set up. The goal was to generation another iteration based on "lessons learned" and to test if the SISGs were fulfilling their intended purpose. The trial application was conducted using test cases based on real missions. While it was investigated to also apply speculative mission scenarios, e.g. a Mars mission applying SXS, this was ultimately decided against.

For instance, a Mars mission scenario with SXS as described in Ref. [32], is still speculative in many aspects, regarding key indicators, such as power supply, crew size, or settlement governance, as SpaceX has not published own information about these key elements of such a mission's design. This means that these gaps would have to be filled by assumptions, extrapolations and estimates or several if not many SISGs cannot be applied for such an analysis, thus reducing the extend and usefulness of the trial application. Whether or not the described SISG method is suitable for early design analysis is already a significant uncertainty. Introducing another significant uncertainty into the trial by using speculative data, multiplies these uncertainties. Furthermore, making assumptions to evaluate a methodological fit always has the risk of either selecting assumptions, possibly without being aware of it, that lead to a certain outcome of the method's evaluation. An outcome of the evaluation then needs to be further analysed whether it is an artifact associated with unknowns of the mission scenario, filled with assumptions, or if it is a genuine outcome based on the method's properties.

Therefore, while the intended application of the SISGs would fit analysing a future Mars mission scenario with SXS, for the method evaluation it was decided to limit the trials to test cases based on existing mission scenarios, reducing the uncertainty as much as possible on the data side. These missions, by changing the boundaries/background were varied to "provoke" expected results and thus evaluate the SISGs concerning their intended purpose, i.e. *to determine whether or not the test case can be sustained for the defined mission duration in-situ.*

The four cases have been defined based on the Apollo 11 mission, a well-documented human exploration mission in a quasi-planetary (here lunar) environment and the ISS, a well-documented long-duration human exploration mission (with resupply from Earth), which has lasted for several decades. For both missions, an "as is" scenario has been defined, labelled here A-1 and I-1. These scenarios are representative for the actual missions flown. Yet, it is not expected that they necessarily provide all elements necessary for sustainability. However, as they were successfully implemented failure in sustainability fit cannot be attributed to mission failure but has to stem from mission design.

For both of these "as is" scenarios a theoretical alteration of the mission scenario has been used to determine a scenario fitting the long-duration in-situ perspective of the SISGs, which are labelled here A-2 and I-2. They are described in detail in the following and summarized in Table 2.

3.3.1. Case A-1: Apollo 11 actual implementation

For A-1, the Apollo 11 mission was selected in the actual implementation on the lunar surface in 1969, i.e. the same mission duration and the actual system were considered for the case. A-1 is selected as an example for an in-situ human exploration mission in a non-terrestrial environment, here the lunar surface. It is well documented, i.e. data availability is expected to be high.

Table 2
Summary about the test cases for the trial-application of the SISGs as well as the expected outcome concerning the Sustainability evaluation via SISGs.

Test Case	Background	Description	Expected Result & Rationale
A-1	Apollo 11 actual implementation	Actual mission as happened on the lunar surface as in-situ environment	FAIL: mission could be sustained for the intended mission duration, but no measures for extension were implemented, i.e. basis for sustainability is missing.
A-2	Apollo 11 mission in a theoretical 10 year mission duration	10 years of operation on the lunar surface, w/o any changes to mission or system design	FAIL: mission was not designed to last 10 years
I-1	ISS operation for 10 years w/resupply	Earth resupply (once outside Earth's atmosphere) is part of the system, 10 years of ISS missions as is	PASS: Operation lasted 10 years and longer, sustained by Earth resupply
I-2	ISS operation for 10 years w/o resupply	No Earth resupply	FAIL: Without resupply operation is not sustainable

The original mission design did not include any measures for extending the operation to an indefinite interval, i.e. a necessary strategic element for sustainable development is missing. Therefore, it is expected that this scenario fails the sustainability evaluation via the SISGs.

3.3.2. Case A-2: Apollo 11 for 10 years

For A-2, the Apollo 11 mission was selected but not with its original duration, but assuming a ten-year operation on the lunar surface. Yet, no system or operational changes are assumed.

The original mission could not operate for 10 years on the lunar surface, i.e. failing the sustainability evaluation via the SISGs is expected to be even clearer for this scenario.

3.3.3. Case I-1: ISS for 10 years, w/resupply

For I-1, the ISS was selected. The boundary of the condition is assumed to be the Earth's atmosphere so that the system includes the ISS but also resupply activities, such as crew flights and cargo flights. The mission duration considered is ten years and the conditions are the actual conditions for that ten-year operation. The boundaries have been selected specifically as close as possible to the ISS, but including resupply. Resupply is essential for the sustainability of the ISS' mission. The resupply originates on Earth and thus Earth is actually part of the operational environment of the ISS. Yet, if all of Earth would be included to evaluate the overall ISS mission, the effects due to the ISS would be minimal and not distinguishable. Therefore, the system boundaries were selected as described here, without Earth as a whole, but including resupply flights.

The ISS has been successfully operated for more than 10 years utilizing resupply flights. Activities also contained extension of the ISS' capabilities, e.g. with added modules. It is therefore assumed, that the case I-1 will pass the sustainability evaluation with the SISGs.

3.3.4. Case I-2: ISS for 10 years, w/o resupply

For I-2, the ISS was also selected, but with the assumption that no resupply from Earth would happen. Only the unaltered system and operation of the ISS have been assumed without any means of resupply, neither crew nor cargo.

The actual design of the ISS' mission requires resupply of e.g. food and crew. It is therefore expected that for this case, the SISG evaluation would indicate failure.

3.3.5. Generating the final iteration of the SISGs

Subsequent to the trial application, its outcome was analysed, drawbacks and possible improvements identified and implemented, leading to the final iteration, X_3, of the SISGs. This iteration is considered to be the set of SISGs useable for the purpose described in Section 1.2.

4. Results

The SISGs, including their explanation and rationale, is comprising about 10 pages of documentation. Reporting on all text iterations fully, is beyond the scope of a single paper. The reader is referred to supplemental documentation in combination to this article, containing each iteration.

A summary of the formulations is given in Table 4, with a documentation of the evolution between iterations. It should be noted that the numbering of the SISGs is here used in the final version, established in X_2, for clarity, changes are indicated by providing the original number in brackets. This way, the reader can follow more easily the evolution of the individual SISGs. The full version, including introductory texts are found in the supplementals, yet the introductory texts' information is also reported on in this article's introduction.

The subsequent sections will explain the results based on the individual steps taken and provide an overview about the evolution. Also, the results of the trial-application are reported on, leading to the final iteration X_3 of the SISGs' formulation.

4.1. First iteration X_0 from SDG adaptation

Post SDG adaptation the SISGs comprise 13 goals, with between four and seven indicators associated to them, in total 70 and on average 5.4.

The sequence of the goals was based on the SDGs and not a content-prioritization. For that reason, the first SISG has been "Inhibit poverty in all forms for all sexes and ages" (this became SISG No 3 in the final version, see Table 4).

Goals, which aim at improving a present situation in the context of the SDGs have been generally formulated to prevent formation of such situations. For instance, the first SDG aims to "end poverty in all its forms everywhere" [22], abbreviated to "no poverty" in the UN graphic depicted in Fig. 2. The second SDG, similarly aims to "end hunger" [22]. Such formulations have been transformed into "inhibit" for the SISGs, e.g. "inhibit poverty in all forms for all sexes and ages" for the originally first SISG (later No 3). Currently no settlements in space exist, with such prevalent conditions that need to be addressed, but they have to be prevented in the first place.

Similarly, to ensure equity for all involved, formulations for the SISGs specifically mention inclusiveness based on e.g. sex or age. Indicators have been labelled as such to pick up the nomenclature of the SDGs as well.

The SISGs comprise formulations which allow quantitative evaluation, e.g. "Energy harvesting rate" (Goal-ID 6 (4)), cut-off criteria, such as "All crew must have access to sufficient and fair sanitation and hygiene" (Goal-ID 1 (3)), and measures, such as "implement disaster risk reduction strategies on local, regional and planetary scale" (Goal-ID 3 (1)).

4.2. Iterations X_1 and X_2 from reviews

For both review cycles, about 70 remarks have been produced by the reviewers, see Table 1. The remarks of reviewers 4 and 5 have been general and overarching, providing insight into the general scheme. These remarks led to clarifications concerning the intended application of the SISGs and renumbering to prioritize certain aspects such as the relevance of water supply in the awareness of the respective user of the SISGs. A more thorough introduction of the SISGs (see supplementals), was established, which containing the information presented in this article, e.g. the reference to the five principles upon which the SDGs have been built (see Section 3.1). Furthermore, a specific definition of the SISGs application has been formulated between X_1 and X_2, similar to Section 1.2.2.

Reviewer remarks also indicated typos, the need of clarification of wording to avoid ambiguity, and addressed the explanatory text. A major part of the discussion also concerned avoiding overlap, e.g. between SISG's 3 last two indicators in X_1, which both specified protection against economic, social and environmental shocks, but the last indicator was focussed on the different scales of the measures (local, regional and planetary), whereas the third was already establishing the equal protection against these shocks.

A major outcome of the second revision has been the separation of indicators into actual indicators, which provide quantifiable properties, and measures, which essentially can only be evaluated as being implemented or not. This resulted in the separation visible in Table 4 in column 3 for the iteration X_2.

4.3. Trial application leading to iteration X_3

Table 3 provides an overview about the outcome of the test cases evaluation, where F indicates failing an SISGs and P indicates passing, a detailed file can be found in the supplementals as it is prohibitively large for a single article. It is apparent that the majority of evaluations is

Table 3
Overview about the trial outcome of the SISGs, with added tags as short descriptors. "F" indicating Failing an SISGs and "P" indicating Passing it.

SISG/ Test Case	1 Warter & Sanitation	2 Water reservoir conservation	3 Inhibit poverty in all forms	4 Inhibit hunger & achieve Food Security	5 Health & well-Being	6 Sustainable energy for all	7 Adequate education opportunities	8 Prevent Inequality	9 Inclusive economy & decent work for all	10 Infrastructure, sustainable industrialization & innovation	11 Equity in & between settlements	12 Inclusive, safe & resilient settlements	13 Circular economy	14 Peaceful & inclusive societies	15 Strong partnerships
A-1	F	F	P	F	F	F	F	F	F	F	P	F	F	F	F
A-2	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
I-1	P	n.a.	P	F	F	P	F	F	F	F	P	F	F	F	F
I-2	F	n.a.	F	F	F	P	F	F	F	F	F	F	F	F	F

negative. The expected outcomes of failure have occurred as expected, yet for case I-1, the expected result was that that scenario would pass the evaluation, which did not occur.

4.3.1. Cases A-1 and A-2

Filling the indicators with data led to challenges. For instance, focussing on oxygen is not necessarily sufficient. While data is present for the cases, a clear number was missing for A-1 and A-2. Yet, in any case, oxygen is not the only prerequisite for breathability of air, therefore the indicators require adaptation.

The test cases selection proofed effective in the sense that A-1 and A-2 lacked for instance recycling capability for air and thus failed the fourth indicator for SISG 1. Generally, the always planned-for temporal nature of Apollo, makes it lack recycling and long-term measures, which are required for sustainability. As expected, case A-1 therefore fails the sustainability evaluation and even more so A-2, because a design aiming at a mission duration of days, has to fail for a projected duration of 10 years.

Crew provisions were planned similarly, e.g. concerning food or water. Other indicators, e.g. concerning births or life expectancy (SISG 5) are not applicable, measures for hygiene and health, such as vaccination applied. At the same time, provisions were not depending on any hierarchy, fulfilling requirements of a discrimination free supply within the boundaries (possible discriminations outside the boundaries used here, notwithstanding).

Energy efficiency of the overall system (SISG 6) turned out to be impossible to determine for any of the systems investigated, which suggests a modification is necessary. If even well documented missions cannot provide such a number, it is unlikely that an early concept can provide such numbers for evaluation.

For SISG 8, a modification concerning the "property distribution" is clarified to "private property", as property did exist, but was not part of the individuals' belongings, but institutional. This special case meant that the indicator was failed, even though no actual discrimination was in place, suggesting the modification. Private property was equally distributed (as all had none) and not depending on e.g. age or ethnicity within the mission boundaries.

Other indicators and goals, e.g. Measure 2 of SISG 8 fail, due to the military equivalent hierarchy during the mission. A major drawback for A-1 and A-2 is the non-redundant nature of the infrastructure, which only existed in the form of the lunar excursion module. Also, no production capabilities, allowing self-sufficiency were present. Similarly, no extension of the infrastructure (especially not in a sustainable manner) was planned for on the lunar surface during Apollo 11, failing SISG 12.

SISG 13 address waste management and resource usage. No in-situ resources were used, which leaves indicator 2 unapplicable and efficiency is not definable for lack of use (0 outcome divided by 0 effort is not defined). Therefore, this indicator should only be applied if there is use of resources, a modification implemented for that indicator. Waste did occur during Apollo 11, e.g. human waste and equipment parts, yet was not recycled, but left on the lunar surface [34].

SISG 14's indicators are identified as difficult to determine a-priori, especially during early phases, where such numbers are likely not addressed and more technical issues are in the foreground, focussing on the mission feasibility. Yet, they are relevant to ensure sustainability and to foster awareness and so it is considered to be prudent of leaving these indicators in, addressing even death rates as well, likely only applicable for evaluation of implemented scenarios.

4.3.2. Cases I-1 and I-2

Evaluation of indicators with a technical background was facilitated with detailed data, e.g. concerning reserves of water and oxygen as well as their recovery rates (SISG 1). As expected, I-1 passed these indicators, whereas I-2 failed them, because reserves and recovery measures would fail without resupply. The special on-orbit nature of the ISS' operation,

Table 4
Summary of the results for the SISG iterations. Documentation occurs on basis of the final numbering, to ease following the evolution of the individual goals, with original numbering (up to X_2) appears is brackets to allow comparisons with supplemental materials. The distinction between Indicators and Measures occurred between X_1 and X_2.

Goal-ID	Description
1 (3)	X_0: Ensure availability of water and sanitation for all and their sustainable management. X_1: Ensure availability of water and sanitation for all and their sustainable management. X_2: Ensure availability of oxygen, water and sanitation for all and their sustainable management. X_3: Ensure availability of oxygen, water and sanitation for all and their sustainable management.

Indicators X_0	**Indicators X_1**	**Indicators X_2**	**Indicators X_3**
All crew/population must have access to a sufficient and fair amounts of safe drinking water All crew must have access to sufficient and fair sanitation and hygiene Water pollution must be avoided and when not avoidable water treatment must be available Water use efficiency must be maximized to near closed-loop Water management must occur at all levels Amount of cooperation between missions for water management	All crew/population must have access to a sufficient and fair amounts of safe drinking water All crew must have access to sufficient and fair sanitation and hygiene Water pollution must be avoided and when not, avoidable water treatment must be available Water use efficiency in relation to (near) closed-loop Water management must occur at all levels Amount of cooperation between missions or settlements for water management at the same location	Amount of oxygen available per crew Amount of water available per crew Water recycling rate Oxygen recovery rate Amount of cooperation between missions or settlements for water management at the same location **Measures X_2** All population must have access to a sufficient and fair amounts of safe drinking water All population must have access to sufficient and fair sanitation and hygiene Water pollution must be avoided and when not, water treatment must be available Water management must occur at all levels of operational management	Amount of breathable air reserves (in days) available per crew Amount of water reserves (in days) available per crew Water recycling rate Oxygen recovery rate Amount of cooperation (e.g. number of cooperation agreements/settlement) between missions or settlements for water management at the same location **Measures X_3** All population must have access to sufficient and fair amounts of safe drinking water and oxygen All population must have access to sufficient and fair sanitation and hygiene Water pollution must be avoided and where not possible, water treatment must be available Air pollution must be avoided and where not possibly, air treatment must be available Water management must occur at all levels of operational management Air management must occur at all levels of operational management

Goal-ID	Description
2 (11)	X_0: Conserve and sustainably use water reservoirs, protect any form of potential ecosystem and life. X_1: Conserve and sustainably use naturally occurring water reservoirs and protect any form of potential ecosystem and life. X_2: Conserve and sustainably use naturally occurring water reservoirs and protect any form of potential ecosystem and life. X_3: Conserve and sustainably use naturally occurring water reservoirs and protect any form of potential ecosystem and life.

Indicators X_0	**Indicators X_1**	**Indicators X_2**	**Indicators X_3**
Prevent pollution of all kinds of water reservoirs Protect potentially existing ecosystems from adverse effects Regulate use and exploitation of possibly existing life to avoid its extinction and avoid suffering of life and allow its natural evolution Conserve at least 50 per cent of water reservoirs, based on the best available scientific information and establish legal protection of these reservoirs Promote fair and equitable sharing of the benefits arising from the utilization of possible genetic resources and promote appropriate access to such resources, as internationally agreed, especially it should be shared with population of a settlement Protection of ecosystems and water reservoirs has to be included in development and processes of settlements.	Prevention of pollution of all kinds of natural water reservoirs in the respective mission's or settlement's environment Protection of potentially existing ecosystems from adverse effects Regulations in place for use and exploitation of possibly existing life to avoid its extinction and avoid suffering of life and allow its natural evolution Conserving at least 50 per cent of water reservoirs, based on the best available scientific information and establish legal protection of these reservoirs Legal regulations for fair and equitable sharing of the benefits arising from the utilization of possible genetic resources and promote appropriate access to such resources, as internationally agreed, especially it should be shared with population of a settlement Protection of ecosystems and water reservoirs has to be included in development and processes of settlements.	Rate of acceptance of regulations for use and exploitation of possibly existing life over number of settlements Ratio of protected water reservoirs over total number Ratio of benefit share of genetic resources usage of present life (if applicable) **Measures X_2** Prevention of pollution of all kinds of natural water reservoirs in the respective mission's or settlement's environment Protection of potentially existing ecosystems from adverse effects Regulations in place for use and exploitation of possibly existing life to avoid its extinction and avoid suffering of life and allow its natural evolution. Conserving at least 50 per cent of water reservoirs, based on the best available scientific information and establish legal protection of these reservoirs. Legal regulations for fair and equitable sharing of the benefits arising from the utilization of possible genetic resources (e.g. if life is discovered) and promote appropriate access to such resources, as internationally agreed, especially it should be shared with population of a settlement Protection of ecosystems and water reservoirs has to be included in development and processes of settlements.	Rate of acceptance of regulations for protection of possibly existing life over number of settlements Ratio of protected water reservoirs over total number Ratio of benefit share of genetic resources usage of present life (if applicable) Regulations in place for use and exploitation of possibly existing life to avoid its extinction and avoid suffering of life and allow its natural evolution. **Measures X_3** Prevention of pollution of all kinds of natural water reservoirs in the respective mission's or settlement's environment as well as protection of all existing ecosystems from any adverse effects Conserving at least 50 per cent of water reservoirs, based on the best available scientific information and establish legal protection of these reservoirs. Legal regulations for fair and equitable sharing of the benefits arising from the utilization of possible genetic resources (e.g. if life is discovered) and promote appropriate access to such resources, as internationally agreed, especially it should be shared with population of a settlement Protection of ecosystems and water reservoirs has to be included in development and processes of settlements.

Goal-ID	Description
3 (1)	X_0: Inhibit poverty in all forms for all sexes and ages. X_1: Inhibit poverty in all forms non-discriminatorily for all. X_2: Inhibit poverty in all forms non-discriminatorily for all. X_3: Inhibit poverty in all forms non-discriminatorily for all.

Indicators X_0	Indicators X_1	Indicators X_2	Indicators X_3
No population below poverty line Protection of all by social systems, without any discrimination, e.g. by sex, disability, ethnic Equal protection of all against natural disasters Implement disaster risk reduction strategies on local, regional and planetary scale (where applicable)	No population below poverty line Protection of all by social systems, without any discrimination, by e.g., sex, disability, ethnicity. Equal protection of all against natural, social and economic shocks and disasters Implement disaster risk reduction strategies on local, regional and planetary scale (where applicable) protecting all equally from economic, social and environmental shocks and disasters	No population below poverty line Amount of effort (e.g. by crew-time, assigned crew members) spend on social systems and equity measures **Measures X_2** Protection of all by social security systems, without any discrimination, by e.g., sex, disability, ethnicity Equal protection of all against natural, social and economic shocks and disasters Implement disaster risk reduction strategies on local, regional and planetary scale (where applicable) protecting all equally from economic, social and environmental shocks and disasters, based on established standards, where possible and on new standards where necessary	No population below poverty line Amount of effort (e.g. by crew-time, assigned crew members) spend on social systems and equity measures **Measures X_3** Protection of all by social security systems, without any discrimination, by e.g., sex, disability, ethnicity Equal protection of all against natural, social and economic shocks and disasters Implement disaster risk reduction strategies on local, regional and planetary scale (where applicable) protecting all equally from economic, social and environmental shocks and disasters, based on established standards, where possible and on new standards where necessary

Goal-ID	Description
4 (2)	X_0: Inhibit hunger, achieve food and nutrition security and sustainable agriculture. X_1: Inhibit hunger, achieve food and nutrition security for all and sustainable agriculture. X_2: Inhibit hunger, achieve food and nutrition security for all and sustainable agriculture. X_3: Inhibit hunger, achieve food and nutrition security for all and sustainable agriculture.

Indicators X_0	Indicators X_1	Indicators X_2	Indicators X_3
No presence of undernourishment No food insecurity in the population/ crew Number of plant and animal genetic resources for food and agriculture secured in either medium- or long-term conservation facilities Total resources allocated to agriculture	No presence of undernourishment No food insecurity in the population/crew by establishing redundancy Number of plant and animal genetic resources for food and agriculture secured in either medium- or long-term conservation facilities Total resources allocated to agriculture	No presence of undernourishment No food insecurity in the population by establishing redundancy Number of plant and animal genetic resources for food and agriculture secured in either medium- or long-term conservation facilities Total resources allocated to food production **Measures X_2** Implement in-situ food production Provide emergency food supplies as redundancy and food safety procedures	No presence of undernourishment No food insecurity in the population by establishing redundancy Number of plant and animal genetic resources for food and agriculture secured in either medium- or long-term conservation facilities Total resources allocated to food production **Measures X_3** Implement in-situ food production Provide emergency food supplies as redundancy and food safety procedures

Goal-ID	Description
5 (n.a.)	X_0: *did not exist* X_1: Ensure healthy lives and promote well-being for all at all ages. X_2: Ensure healthy lives and promote well-being for all at all ages. X_3: Ensure healthy lives and promote well-being for all at all ages.

Indicators X_0	Indicators X_1	Indicators X_2	Indicators X_3
n.a.	Avoid maternal mortality and limit mortality ratio to 70/100,000 per live births Neonatal and deaths of children under 5 years should be at least below 25 per 1000 live births. Adequate measures against any epidemic should be taken, e.g. vaccines and hygiene products should be available Prevent substance abuse and make treatment available. Prevent deaths through accidents or injuries by safety measure to similar values on Earth. Provide universal health coverage and access to quality essential health-care, medicine and treatment concerning physical and psychological illness Establish means for early warning and risk management of all-out health risks.	Maternal mortality and infant mortality ratios Neonatal and deaths of children under 5 years should be at least below 25 per 1000 live births. Vaccination rates for typical illnesses Cases of substance abuse Ratio of medical personnel to overall population Average life-expectancy over income, gender, ethnicity, occupation **Measures X_2** Avoid maternal mortality and limit mortality ratio to 70/100,000 per live births Adequate measures against any epidemic should be taken, e.g. vaccines and hygiene products should be available Prevent substance abuse and make treatment available. Prevent deaths through accidents or injuries by safety measure to similar values on Earth. Provide universal health coverage and access to quality essential health-care, medicine and treatment concerning physical and psychological illness, with a special focus on the effects caused by the non-terrestrial living environment	Maternal mortality ratio Neonatal deaths should be at least below 25 per 1000 live births. Deaths of children under 5 years should be at least below 25 per 1000 live births. Vaccination rates for typical illnesses Cases of substance abuse Ratio of medical personnel to overall population Average life-expectancy over income, gender, ethnicity, occupation for settlements, for shorter missions: death rates or fatal accidents **Measures X_3** Avoid maternal mortality and limit mortality ratio to max. 70/100,000 per live births Adequate measures against any epidemic should be taken, e.g. vaccines and hygiene products should be available Prevent substance abuse and make treatment available. Prevent deaths through accidents or injuries by safety measure to similar values on Earth. Provide universal health coverage and access to quality essential health-care, medicine and treatment concerning physical and psychological illness, with a special focus on the effects caused by the non-terrestrial living environment

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Table 4 (*continued*)

Goal-ID	Description
5 (n.a.)	X_0: *did not exist* X_1: Ensure healthy lives and promote well-being for all at all ages. X_2: Ensure healthy lives and promote well-being for all at all ages. X_3: Ensure healthy lives and promote well-being for all at all ages.

		Establish means for early warning and risk management of all-out health risks. Ensure that life expectancy is not reduced in comparison to Earth's population with similar occupations, income, gender and ethnicity. Ensure universal access to sexual and reproductive health and rights	Establish means for early warning and risk management of all-out health risks. Ensure that life expectancy is not reduced in comparison to Earth's population with similar occupations, income, gender and ethnicity. Ensure universal access to sexual and reproductive health and rights

Goal-ID	Description
6 (4)	X_0: Ensure access to sufficient, reliable and sustainable energy. X_1: Ensure access to sufficient, reliable and sustainable energy for all and its sustainable management. X_2: Ensure access to sufficient, reliable and sustainable energy for all and its sustainable management. X_3: Ensure access to sufficient, reliable and sustainable energy for all and its sustainable management.

Indicators X_0	Indicators X_1	Indicators X_2	Indicators X_3
All crew/population must have access to sufficient amounts of energy Energy efficiency must be maximized Renewable energy share must be maximized Energy storage must occur with sufficient margins Energy harvesting rate	All crew/population must have access to sufficient amounts of energy of all relevant types (e.g. thermal, electrical) and the relevant power levels Energy efficiency must be optimized considering the overall system Renewable energy share must be maximized Energy storage must occur with sufficient margins Rate of energy harvesting vs. stored energy and stored energy from Earth (e.g. chemical fuel) Fair energy management, based on equity, must occur at all levels	Energy efficiency of the overall system Ratio of renewable energy usage (e.g. as opposed to (nuclear) fuel-based energy use) Energy storage margin Rate of energy harvesting vs. stored energy, and stored energy from Earth (e.g. chemical fuel) Fair energy management, based on equity, must occur at all levels **Measures X_2** All population must have access to sufficient amounts of energy of all relevant types (e.g. thermal, electrical) and the relevant power levels Implement redundant energy supply concept Fair energy management, based on equity over the whole population, must occur at all levels of operation	Energy efficiency of the primary energy supply system (e.g. solar panels) Ratio of renewable energy usage (e.g. as opposed to (nuclear) fuel-based energy use) Energy storage margin above expected energy demand over mission (if finite mission duration) or average demand during mission (for missions without finite duration) Rate of energy harvesting vs. stored energy, Rate of energy harvesting vs. stored energy from Earth (e.g. chemical fuel) **Measures X_3** All population must have access to sufficient amounts of energy of all relevant types (e.g. thermal, electrical) and the relevant power levels Implement redundant energy supply concept Fair energy management, based on equity over the whole population, must occur at all levels of operation

Goal-ID	Description		
7 (n.a.)	X_0: *did not exist* X_1: Ensure inclusive and equitable quality education, lifelong learning opportunities and child-care in adequate manner for the duration of stay. X_2: Ensure inclusive and equitable quality education, lifelong learning opportunities and child-care in adequate manner for the duration of stay. X_3: Ensure inclusive and equitable quality education, lifelong learning opportunities and child-care in adequate manner for the duration of stay.		
Indicators X_0	**Indicators X_1**	**Indicators X_2**	**Indicators X_3**
n.a.	Provide, independent of gender, ethnicity, age or other criteria, free quality primary and secondary education fitting the time-scale of the mission Ensure preparation of children for primary education for settlements All adults should have access to tertiary education for technical, vocational and other education, including university level, where necessary with remote means Ensure that all have literacy and numeracy	Time spent on education vs. overall mission time, OR ratio of personnel hrs spent on education over overall personnel hrs Literacy and numeracy rates of settlement population Ratio of occupations, which can be in-situ trained vs. which are necessary for maintaining the settlement **Measures X_2** Provide, independent of gender, ethnicity, age or other criteria, free quality primary and secondary education fitting the duration of the intended mission or planetary presence. Ensure preparation of children for primary education in settlements, e.g. by child-care measures. All adults should have access to tertiary education for technical, vocational and other education, including university level, where necessary with remote means Ensure that all have literacy and numeracy or have the opportunity to obtain it by the measures mentioned before	Time spent on education vs. overall mission time, OR ratio of personnel hrs spent on education over overall personnel hrs Literacy and numeracy rates of settlement population Ratio of occupations, which can be in-situ trained vs. which are necessary for maintaining the settlement **Measures X_3** Provide, independent of gender, ethnicity, age or other criteria, free quality primary and secondary education fitting the duration of the intended mission or planetary presence, if uneducated population is present. Ensure preparation of children for primary education in settlements, e.g. by child-care measures, if children are present. All adults should have access to tertiary education for technical, vocational and other education, including university level, where necessary with remote means, fitting the expected stay duration Ensure that all have literacy and numeracy or have the opportunity to obtain it by the measures mentioned before

Goal-ID	Description
8 (5)	X_0: Prevent inequality e.g. - but not exclusively - due to ethnicity, age, gender. X_1: Prevent inequality and inequity e.g. - but not exclusively - due to ethnicity, age, gender. X_2: Prevent inequality and inequity e.g. - but not exclusively - due to ethnicity, age, gender. X_3: Prevent inequality and inequity e.g. - but not exclusively - due to ethnicity, age, gender.

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Table 4 (*continued*)

Goal-ID	Description
8 (5)	X_0: Prevent inequality e.g. - but not exclusively - due to ethnicity, age, gender. X_1: Prevent inequality and inequity e.g. - but not exclusively - due to ethnicity, age, gender. X_2: Prevent inequality and inequity e.g. - but not exclusively - due to ethnicity, age, gender. X_3: Prevent inequality and inequity e.g. - but not exclusively - due to ethnicity, age, gender.

Indicators X_0	**Indicators X_1**	**Indicators X_2**	**Indicators X_3**
Existence of regulatory frameworks to prevent all forms of discrimination Existence of regulations and means to ban all forms of violence, harmful practices or exploitation Recognize care and domestic work through services provided Ensure equal opportunity for leadership positions Ensure universal access to sexual and reproductive health and rights Ensure equal opportunity to access resources and obtain property, financial services	Existence of regulatory frameworks to prevent all forms of discrimination Existence of regulations and means to ban all forms of violence, harmful practices or exploitation Recognize care and domestic work through services provided Ensure equal opportunity for leadership positions Ensure universal access to sexual and reproductive health and rights Ensure equal opportunity to access resources and obtain property, and financial services	Existence of regulatory frameworks to prevent all forms of discrimination Existence of regulations and means to ban all forms of violence, harmful practices or exploitation Recognize care and domestic work through services provided Ratio of leadership positions per ethnicity, age & gender over their local prevalence Ratio of resources availability per ethnicity, age & gender over their local prevalence Ratio of property per ethnicity, age & gender over their local prevalence **Measures X_2** Recognize care and domestic work through services provided Ensure equal opportunity for leadership positions Ensure equal opportunity to access resources and obtain property, and financial services Ensure social, economic and political inclusion of all, irrespective of age, sex, disability, race, ethnicity, origin, religion or economic or other status Ensure equal opportunity and prevent inequalities of income, including by preventing discriminatory laws, policies and practices and promoting appropriate legislation, policies and action in this regard Adopt policies, especially fiscal, wage and social protection policies to maintain equality	Existence of regulatory frameworks to prevent all forms of discrimination Existence of regulations and means to ban all forms of violence, harmful practices or exploitation Ratio of leadership positions per ethnicity, age & gender over their local prevalence Ratio of resources availability per ethnicity, age & gender over their local prevalence Ratio of private property per ethnicity, age & gender over their local prevalence **Measures X_3** Recognize care and domestic work through services provided Ensure equal opportunity for leadership positions Ensure equal opportunity to access resources and obtain property, and financial services Ensure social, economic and political inclusion of all, irrespective of age, sex, disability, race, ethnicity, origin, religion or economic or other status Ensure equal opportunity and prevent inequalities of income, including by preventing discriminatory laws, policies and practices and promoting appropriate legislation, policies and action in this regard Adopt policies, especially fiscal, wage and social protection policies to maintain equality

Goal-ID	Description
9 (6)	X_0: Promote a sustained and inclusive economy, full and productive employment and decent work for all as well as participation on resource efficiency improvement. X_1: Promote a sustained and inclusive economy, full and productive employment and decent work for all as well as participation on resource efficiency improvement. X_2: Promote a sustained and inclusive economy, full and productive employment and decent work for all as well as participation on resource efficiency improvement. X_3: Promote a sustained and inclusive economy, full and productive employment and decent work for all as well as participation on resource efficiency improvement.

Indicators X_0	**Indicators X_1**	**Indicators X_2**	**Indicators X_3**
Achieve higher levels of resource efficiency through diversification, technological upgrading and innovation, including through a focus on high-value added and labour-intensive sectors and distribute the gains equivitly Promote development-oriented policies that support productive activities Decouple economic growth from environmental degradation Achieve full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal compensation for work of equal value Take effective measures to prevent any form of forced labour Protect labour rights and promote safe and secure working environments for all	Level of resource efficiency through diversification, technological upgrading and innovation, including through a focus on high-value added and labour-intensive sectors and distribute the gains equivitly Amount of development-oriented policies that support productive activities Rate of decoupling economic growth from environmental degradation in-situ Rate of achieving full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal compensation for work of equal value Effectiveness and Efficiency of measures to prevent any form of forced labour Amount of labour rights, means of their protection and rate of ensuring safe and secure working environments for all vs. unsafe working environments	Level of resource efficiency through diversification, technological upgrading and innovation, including through a focus on high-value added and labour-intensive sectors and distribute the gains equitably. Amount of development-oriented policies that support productive activities Rate of decoupling economic growth from environmental degradation in-situ Rate of achieving full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal compensation for work of equal value Effectiveness and Efficiency of measures to prevent any form of forced labour Amount of labour rights, means of their protection and rate of ensuring safe and secure working environments for all vs. unsafe working environments **Measures X_2** Establish overall review and improvement process, with participation of all stakeholders Establish an economy, which is oriented on needs of the population vs. profit	Amount of development-oriented policies that support production activities Rate of decoupling economic growth from environmental degradation in-situ Rate of achieving full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal compensation for work of equal value Effectiveness and Efficiency of measures to prevent any form of forced labour Amount of labour rights, means of their protection and rate of ensuring safe and secure working environments for all vs. unsafe working environments **Measures X_3** Establish overall review and improvement process, with participation of all stakeholders Establish an economy, which is oriented on needs of the population vs. profit

Goal-ID	Description

(*continued on next page*)

Table 4 (*continued*)

Goal-ID	Description		
10 (7)	X_0: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation. X_1: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation. X_2: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation. X_3: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.		
10 (7)	X_0: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation. X_1: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation. X_2: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation. X_3: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.		
Indicators X_0 Develop quality, reliable, sustainable and resilient infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all Promote inclusive and sustainable industrialization on a scale fitting the required population and mission duration Increase the access of small-scale enterprises to financial services, including affordable credit, and their integration into value chains and markets for (near-)permanent settlements ensure industries to be sustainable, with high resource-use efficiency and adoption of clean and environmentally sound technologies and industrial processes Enable research and development in a sufficient number of research hours per total work hours, to avoid just maintained the status quo. Ensure access to information and communications technology in a universal and affordable manner.	**Indicators X_1** Number of effective measures to develop quality, reliable, sustainable and resilient infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all Resources assigned for inclusive and sustainable industrialization on a scale fitting the required population and mission duration Amount of financial services, including affordable credit, small-scale enterprises have access to and their integration into value chains and markets for (near-) permanent settlements Resource-use efficiency of present industries and Rate of regulations for clean and environmentally sound technologies and industrial processes to overall regulations Number of work hours dedicated for research and development in a sufficient to total work hours for avoiding just maintaining the status quo. Ensure access to information and communications technology in a universal and affordable manner. Level of redundancy in all infrastructure elements Ability to maintain and repair infrastructure without help from outside	**Indicators X_2** Number of effective measures to develop quality, reliable, sustainable and resilient infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all Resources assigned for inclusive and sustainable industrialization on a scale fitting the required population and mission duration Amount of financial services, including affordable credit, small-scale enterprises have access to and their integration into value chains and markets for (near-) permanent settlements Resource-use efficiency of present industries Rate of regulations for clean and environmentally sound technologies and industrial processes to overall regulations Number of work hours dedicated for research and development in relation to total work hours for avoiding just maintaining the status quo. Ensure access to information and communications technology in a universal and affordable manner. Level of redundancy in all infrastructure elements **Measures X_2** Establish redundancy in all relevant infrastructure elements Establish the ability (e.g. concerning expertise, production) to repair and maintain infrastructure without outside help	**Indicators X_3** Number of effective measures to develop quality, reliable, sustainable and resilient infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all Resources assigned for inclusive and sustainable industrialization on a scale fitting the required population and mission duration Amount of financial services, including affordable credit, small-scale enterprises have access to and their integration into value chains and markets for (near-) permanent settlements Resource-use efficiency of present industries Rate of regulations for clean and environmentally sound technologies and industrial processes to overall regulations Number of work hours dedicated for research and development in relation to total work hours for avoiding just maintaining the status quo. Least level of redundancy in all infrastructure elements, which are required for operation **Measures X_3** Establish redundancy in all relevant infrastructure elements Establish the ability (e.g. concerning expertise, production) to repair and maintain infrastructure without outside help Ensure access to information and communications technology in a universal and affordable manner.
Goal-ID	Description		
11 (8)	X_0: Ensure equality within and among settlements and towards Earth. X_1: Ensure equality within and among settlements and towards Earth. X_2: Ensure equality in settlement governance, among settlements, including settlements on different planetary bodies, and towards Earth. X_3: Ensure equality in settlement governance, among settlements, including settlements on different planetary bodies, and towards Earth.		
Indicators X_0 Ensure social, economic and political inclusion of all, irrespective of age, sex, disability, race, ethnicity, origin, religion or economic or other status Ensure equal opportunity and prevent inequalities of outcome, including by preventing discriminatory laws, policies and practices and promoting appropriate legislation, policies and action in this regard Adopt policies, especially fiscal, wage and social protection policies to maintain equality Ensure equal representation and voice for all settlements in decision-making regarding inter-settlement aspects and in dealing with topics addressing the	**Indicators X_1** Ensure social, economic and political inclusion of all, irrespective of age, sex, disability, race, ethnicity, origin, religion or economic or other status Ensure equal opportunity and prevent inequalities of outcome, including by preventing discriminatory laws, policies and practices and promoting appropriate legislation, policies and action in this regard Adopt policies, especially fiscal, wage and social protection policies to maintain equality Ensure equal representation and voice for all settlements in decision-making regarding inter-settlement aspects and in dealing with topics addressing the	**Indicators X_2** Rate of governance participation between settlements per settlement & population size Rate of migration between settlements, and between settlements & Earth Democracy Indexes such as e.g. the Freedom House Index, Fragile State Index **Measures X_2** Ensure equal representation and voice for all settlements in decision-making regarding inter-settlement aspects and in dealing with topics addressing the relation between settlements and Earth. Facilitate orderly, safe, regular and responsible migration and mobility of people, including through the implementation of planned and well-	**Indicators X_3** Rate of governance participation between settlements per settlement & population size Rate of migration between settlements, and between settlements & Earth Democracy Indexes such as e.g. the Freedom House Index, Fragile State Index **Measures X_3** Ensure equal representation and voice for all settlements in decision-making regarding inter-settlement aspects and in dealing with topics addressing the relation between settlements and Earth. Facilitate orderly, safe, regular and responsible migration and mobility of people, including through the implementation of planned and well-

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Table 4 (*continued*)

Goal-ID	Description		
11 (8)	X_0: Ensure equality within and among settlements and towards Earth. X_1: Ensure equality within and among settlements and towards Earth. X_2: Ensure equality in settlement governance, among settlements, including settlements on different planetary bodies, and towards Earth. X_3: Ensure equality in settlement governance, among settlements, including settlements on different planetary bodies, and towards Earth.		
relation between settlements and Earth. Facilitate orderly, safe, regular and responsible migration and mobility of people, including through the implementation of planned and well-managed migration policies	relation between settlements and Earth. Facilitate orderly, safe, regular and responsible migration and mobility of people, including through the implementation of planned and well-managed migration policies	managed migration policies, concerning migration between settlements and between settlements and Earth	managed migration policies, concerning migration between settlements and between settlements and Earth
Goal-ID	Description		
12 (9)	X_0: Make missions and human settlements inclusive, safe, resilient and sustainable. X_1: Make human habitats and settlements inclusive, safe, and resilient. X_2: Make human habitats and settlements inclusive, safe, and resilient. X_3: Make human habitats and settlements inclusive, safe, and resilient.		
Indicators X_0 Ensure access for all to adequate, safe and affordable housing and basic services Provide access to safe, affordable, accessible and sustainable transport systems and for settlements green, public spaces for all, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons Enhance inclusive and sustainable settlement and capacity for participatory, integrated and sustainable settlement planning and management Avoid adverse per capita environmental impact, including especially air quality and waste management	**Indicators X_1** Access for all to adequate, safe and affordable housing and basic services Access to safe, affordable, accessible and sustainable transport systems and for settlements green, public spaces for all, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons Enhance inclusive and sustainable settlement and capacity for participatory, integrated and sustainable settlement planning and management Avoid adverse per capita environmental impact, including especially air quality and waste management	**Indicators X_2** Average housing volume Ratio of people with housing volume below BVAD [33] recommended $30m^3$ Average living costs for housing vs. average income **Measures X_2** Access for all to adequate, safe and affordable housing and basic services Access to safe, affordable, accessible and sustainable transport systems and for settlements green, public spaces for all, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons Enhance inclusive and sustainable settlement and capacity for participatory, integrated and sustainable settlement planning and management Avoid adverse environmental impact, including especially air quality and waste management	**Indicators X_3** Average housing volume Ratio of people with housing volume below BVAD [33] recommended $30m^3$ Average living costs for housing vs. average income **Measures X_3** Access for all to adequate, safe and affordable housing and basic services Access to safe, affordable, accessible and sustainable transport systems and for settlements green, public spaces for all, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons Enhance inclusive and sustainable settlement and capacity for participatory, integrated and sustainable settlement planning and management Avoid adverse internal environmental impact, including via measures like especially air quality and waste management
Goal-ID	Description		
13 (10)	X_0: Ensure sustainable consumption and production patterns. X_1: Ensure sustainable consumption and production patterns in a circular economy. X_2: Ensure sustainable consumption and production patterns in a circular economy. X_3: Ensure sustainable consumption and production patterns in a circular economy.		
Indicators X_0 Achieve the sustainable management and efficient use of natural resources Allow in-situ production of food, enable self-sufficiency. Prevent food waste at production and consumer levels, including post-harvest losses, by enabling a (near-)closed loop production cycle. Achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, and prevent their release to minimize their adverse impacts on human health and the environment Enable prevention, reduction, recycling and reuse of waste Integrate sustainability information into reporting cycles Ensure that all mission participants or settlement populations have the relevant information and awareness for sustainable development	**Indicators X_1** Achieving sustainable management and efficient use of natural resources. Rate of in-situ production of food, air and other consumables and equipment required for maintaining operation to enable self-sufficiency. Prevent food, air and resource waste at production and consumer levels, including post-harvest losses, by enabling a (near-)closed loop production cycle. Achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, and prevent their release to minimize their adverse impacts on human health and the environment Enable prevention, reduction, recycling and reuse of waste materials Integrate sustainability information into reporting cycles Ensure that all mission participants or settlement populations have the relevant information and awareness for sustainable development	**Indicators X_2** Rate of in-situ production of food, air and other consumables and equipment required for maintaining operation to enable self-sufficiency. Efficiency of natural resource use Recycling rate of waste **Measures X_2** Achieving sustainable management and efficient use of natural resources. Prevent food, air and resource waste at production and consumer levels, including post-harvest losses, by enabling a (near-)closed loop production cycle. Achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, and prevent their release to minimize their adverse impacts on human health and the environment Enable prevention, reduction, recycling and reuse of waste materials Integrate sustainability information into reporting cycles Ensure that all mission participants or	**Indicators X_3** Rate of in-situ production of food, air and other consumables and equipment required for maintaining operation to enable self-sufficiency. Efficiency of natural resource use, if there is use Recycling rate of waste **Measures X_3** Achieving sustainable management and efficient ($\geq$90%) use of natural resources. Prevent food, air and resource waste at production and consumer levels, including post-harvest losses, by enabling a (near-)closed loop production cycle. Achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, and prevent their release to minimize their adverse impacts on human health and the environment Enable prevention, reduction, recycling and reuse of waste materials Integrate sustainability information into reporting cycles Ensure that all mission participants or

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Table 4 (*continued*)

Goal-ID	Description
13 (10)	X_0: Ensure sustainable consumption and production patterns. X_1: Ensure sustainable consumption and production patterns in a circular economy. X_2: Ensure sustainable consumption and production patterns in a circular economy. X_3: Ensure sustainable consumption and production patterns in a circular economy.

		settlement populations have the relevant information and awareness for sustainable development	settlement populations have the relevant information and awareness for sustainable development

Goal-ID	Description
14 (12)	X_0: Establish peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels. X_1: Establish peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels. X_2: Establish peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels. X_3: Establish peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels.

Indicators X_0 Prevent all forms of violence and related death rates End abuse and exploitation and all forms of violence against children Promote the rule of law at all levels and ensure equal access to justice for all Prevent corruption and bribery in all forms and establish effective, accountable and transparent institutions Ensure responsive, inclusive, participatory and representative decision-making at all levels Ensure public access to information and protect fundamental freedoms Promote and enforce non-discriminatory laws and policies for sustainable development	**Indicators X_1** Prevent all forms of violence and related death rates ….Prevent abuse and exploitation and all forms of violence against children. Promote the rule of law at all levels and ensure equal access to justice for all Prevent corruption and bribery in all forms and establish effective, accountable and transparent institutions Ensure responsive, inclusive, participatory and representative decision-making at all levels Ensure public access to information and protect fundamental freedoms Promote and enforce non-discriminatory laws and policies for sustainable development	**Indicators X_2** Rate of personnel hrs spent on violence sanction and prevention over total personnel hrs. Number of resources spent on mental health over total resources **Measures X_2** Prevent all forms of violence and related death rates Prevent abuse and exploitation and all forms of violence against children Promote the rule of law at all levels and ensure equal access to justice for all Prevent corruption and bribery in all forms and establish effective, accountable and transparent institutions Ensure responsive, inclusive, participatory and representative decision-making at all levels Ensure public access to information and protect fundamental freedoms Promote and enforce non-discriminatory laws and policies for sustainable development	**Indicators X_3** Rate of personnel hrs spent on violence sanction and prevention over total personnel hrs. Number of resources spent on mental health over total resources Death rate from violence **Measures X_3** Prevent all forms of violence and violence induced deaths Prevent abuse and exploitation and all forms of violence against children Promote the rule of law at all levels and ensure equal access to justice for all Prevent corruption and bribery in all forms and establish effective, accountable and transparent institutions Ensure responsive, inclusive, participatory and representative decision-making at all levels Ensure public access to information and protect fundamental freedoms Promote and enforce non-discriminatory laws and policies for sustainable development

Goal-ID	Description
15 (13)	X_0: Strengthen the means of implementation and establish strong partnership. X_1: Strengthen the means of implementation and establish strong partnership. X_2: Strengthen the means of implementation and establish strong partnership for all. X_3: Strengthen the means of implementation and establish strong partnership for all.

Indicators X_0 Mobilize financial and personnel, technical and technological resources for developing missions and settlements from multiple sources Enhance mission or settlement cooperation with Earth and among each other and access to science, technology and innovation and enhance knowledge sharing on mutually agreed terms Promote the development, transfer, dissemination and diffusion of environmentally sound technologies to settlements on favourable terms, including on concessional and preferential terms, as mutually agreed Promote a universal, rules-based, open, non-discriminatory and equitable multilateral trading system between settlements and Earth and mong each other	**Indicators X_1** Mobilize financial and personnel, technical and technological resources for developing missions and settlements from multiple sources Enhance mission or settlement cooperation with Earth and among each other and access to science, technology and innovation and enhance knowledge sharing on mutually agreed terms Promote the development, transfer, dissemination and diffusion of environmentally sound technologies to settlements on favourable terms, including on concessional and preferential terms, as mutually agreed Promote a universal, rules-based, open, non-discriminatory and equitable multilateral trading system between settlements and Earth and mong each other	**Indicators X_2** Ratio of resources leaving the settlement over resources entering the settlement through own activities Ratio of resources leaving the settlement over resources delivered to the settlement from another party **Measures X_2** Mobilize financial and personnel, technical and technological resources for developing missions and settlements from multiple sources Enhance mission or settlement cooperation with Earth and among each other and access to science, technology and innovation and enhance knowledge sharing on mutually agreed terms Promote the development, transfer, dissemination and diffusion of environmentally sound technologies to settlements on favourable terms, including on concessional and preferential terms, as mutually agreed Promote a universal, rules-based, open, non-discriminatory and equitable	**Indicators X_3** Ratio of resources processed within the settlement leaving the settlement over resources entering the settlement through own activities Ratio of resources leaving the settlement over resources delivered to the settlement from another party **Measures X_3** Mobilize financial and personnel, technical and technological resources for developing missions and settlements from multiple sources Enhance mission or settlement cooperation with Earth and among each other and access to science, technology and innovation and enhance knowledge sharing on mutually agreed terms Promote the development, transfer, dissemination and diffusion of environmentally sound technologies to settlements on favourable terms, including on concessional and preferential terms, as mutually agreed Promote a universal, rules-based, open, non-discriminatory and equitable

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Table 4 (*continued*)

Goal-ID	Description		
15 (13)	X_0: Strengthen the means of implementation and establish strong partnership. X_1: Strengthen the means of implementation and establish strong partnership. X_2: Strengthen the means of implementation and establish strong partnership for all. X_3: Strengthen the means of implementation and establish strong partnership for all.		
		multilateral trading system between settlements and Earth and among each other. Ensure that all countries on Earth and all people can benefit from settlements, e.g. from products, scientific or technological results.	multilateral trading system between settlements and Earth and among each other. Ensure that all countries on Earth and all people can benefit from settlements, e.g. from products, scientific or technological results.

essentially made SISG 2 obsolete and not applicable, as e.g. there are no local water reserves and no potential ecosystem or life.

SISG 3 is a major difference for cases I-1 and I-2. For I-1 it is not problematic, but since the mission design did foresee resupply flights, which is void for I-2, the lack of resupply would eventually lead to poverty of the crew in terms of available resources and the crew would even perish likely, due to lack of life-supporting resources.

SISG 4's food supply is ensured by e.g. resupply flights, but again, this is failing for I-2. Yet, e.g. ISS does not contain resources to start producing food onboard in a sufficient amount, neither does the system boundary artificially created to contain resupply flights. So, while resupply exists, a resource which is deemed to be necessary within the system for that is lacking, causing SISG 4 to fail even for I-1.

Similarly, SISG 5 is passed for I-1 in all entries, except the last measure. The fact that reproduction is not possible on ISS (neither technically, medically nor regulatory), violates the last measure of SISG 5 and thus even I-1 is failing that SISG. The capability to allow children in a long-term settlement is required to ensure a stable population as well as provide fundamental human rights to the respective settlement's population.

Generally, SISGs aiming at creating a self-sufficient system are failed, even in the specially generated case I-1. This happens despite “flow” of resupply is present, because no effort to “generate” supply in-situ is made as this is not necessary within the system of I-1. For instance, there are no policies for developing production (2nd indicator of SISG 9), nor are there resources for creating industrialization (2nd indicator of SISG 10).

For SISG 10 it became clear that the redundancy of infrastructure elements was difficult to determine with the formulation of X_2, therefore for X_3 a formulation including “least” was introduced, allowing the “least” level of redundancy to be the determining factor. This way it is sufficient to identify elements, which are least redundant vs. defining some form of overall redundancy.

SISG 12 aims at planning and organizing settlements inclusively. These are elements, which are also not fulfilled by the ISS, as e.g. crew members with disability are currently not eligible for mission participation.

For SISG 15 it is clear that exchange with Earth, especially concerning science exists. While measures for scientific input have increased, fulfilling the “enhance” statements, more appropriate is “establish”, which would also be fulfilled if such connections already exist. Therefore, this modification was implemented for X_3. Otherwise “enhancing” from 0 to 1 would perform better than having 10 such measures in place and not enhancing them.

4.4. Final iteration X_3

Adaptations between X_2 and X_3 have been in details and can be seen in Table 4's last column. No new SISGs were added, but some indicators were specified. Overall, 15 SISGs comprise the final iteration and have a sum of 126 indicators and measures, i.e. 8.4 on average. This is a significant increase from the initial iteration with 13 SISGs and 70 indicators.

Details that have been adapted between X_2 and X_3 are found for instance in SISG 1, where “breathable air” replaces “oxygen”, to accommodate also the fact that oxygen is not a sufficient condition as e.g. toxicity or pollution is not reflected by availability of oxygen. Another detail is found in the indicators of SISG 5, where a difference between long-term and short-term missions has been defined or the change between energy efficiency of the overall system to the energy efficiency of the primary energy supply in SISG 6, as the former is unlikely to be determinable without very detailed information.

5. Discussion

The evolution of the SISGs over the iterations is very clear to perceive. The final iteration has an increase of 80% of indicators and measures compared to the initial iteration. This shows that the different means of iterating the SISGs have had meaning and improved the formulations concerning comprehensiveness.

The changes between X_2 to X_3 are small, indicating a convergence of the formulations. The intra-dimensional nature of the SDGs has been further transported over into the SISGs as well ensuring that all dimensions are regarded.

The trial applications also helped to remove ambiguity in the formulations, e.g. in SISG 13's first measure, where the efficiency value signifying “efficient use” was set to 90% to avoid lack of clarity. While the value is arbitrary and can be changed in further iterations, a specific value is needed to specify what is deemed as “efficient”. This differentiates measures and indicators. Indicators provide insight on values, e.g. the efficiency and inform about them, to allow evaluation. Measures to be implemented, can be essentially Booleans, which check on their implementation.

5.1. Fit to purpose

The trial application indicates that the formulations fit the purpose given in Section 1.2.2. Evaluations were possible with cursory review of available information. The separation into indicators and measures allows a clear identification of guidelines, represented by the measures, while the indicators can inform about relevant issues, e.g. efficiency of power supply, and what to design and plan for, e.g. incorporating resources for preventing violence within a settlement, even when specific information is not yet available. In any case, the indicators increase awareness for factors, which might be overlooked otherwise, depending on the background of the respective design or evaluation team.

Generally, the diverse set of indicators and measures also ensures that the variety of needs of crews, as mentioned in the definition for space in-situ sustainable development (see Section 1.2.1), is covered. This decreases the likelihood that an area of needs is overlooked and not addressed.

The large number of indicators further allows tailoring to a specific mission purpose, background, and goal and scope of an evaluation. For instance, mission duration can make certain indicators unnecessary, such as life expectancy related information. On the other hand, tailoring can also occur based on availability of information. As a design or plan evolves, so can the usage of the individual indicators and measures.

5.2. Failing of I-1

With the formulation of I-1's background, it was attempted to artificially generate a scenario, which could represent a sustainable space settlement. ISS is per design not in-situ sustainable, as it requires regular resupply of crew and cargo to remain operational.

Despite the artificial scenario of I-1, it did not proof to be sustainable, which is attributed to the fact that measures for building resilience and sustainability in-situ are not implemented. For instance, ISS does not have the capability to produce food for the crew or generate an economy. While setting the system boundary in a way that resupply flights are included in I-1, this does not include the means to generate the resupply. Even if the flights themselves were regarded as the means, the system boundaries were not containing the generation of launch vehicles and spacecraft to conduct these – in comparison, a lunar settlement could e.g. have the capability to produce machinery needed to use resources in-situ. Therefore, it is in fact expectable that I-1 would also lead to failure.

The alternative would be to incorporate these means in the system for the trial run, but here the purpose is in contradiction. The "in-situ environment" in which ISS is operating is Earth and the low Earth orbit. Earth support is required, e.g. for producing food, providing oxygen, spare parts, and crew training. ISS was always designed for that condition. Therefore, to make a realistic assessment of the sustainability of ISS' operation, one needs to include the whole system for which its operation was planned and that includes Earth. Yet, the inclusion of all of Earth would have diluted the influence of ISS on the results so much that evaluation of the SISGs would not have been possible in a reasonable manner. Not only would the system be large and complex, contradicting the purpose of the SISGs, it would also be essentially an evaluation of sustainability of Earth itself, which is not the application of the SISGs, but SDGs. Furthermore, as pointed out in Section 2.1.2, terrestrial sustainability has not been achieved, development is still necessary, meaning even when including Earth it could not be expected that such a system would produce a "passing" result in a trial application of the SISGs.

In any case, especially I-1 underlines the importance of measures for production to be introduced into a mission design from the start to achieve sustainability.

5.3. Guideline for application

With the SISGs being in a useable iteration, the question remains how to apply them. Especially the case I-1, but also the others have shown the relevance of how to define a system for evaluation.

5.3.1. Relevance of system definition: Goal & Scope

As discussed and as evident in Table 3, the system definition will influence the outcome of the evaluation significantly. Therefore, a system needs to be clearly defined, which is analogously to product scale sustainability assessments based on LCSA [31]. The standards applied are typically the ISO 14040 and ISO 14044 [33,35]. Originally formulated for the environmental assessment, they are recommended to be analogously used for assessments of the other sustainability dimensions as well [31].

This initial phase of LCSA is labelled "Goal & Scope" [33]. For the purpose of the SISGs, this means, the goal should be defined, e.g. is the goal to determine the sustainability of an existing design or a guiding a design process? The stakeholders addressed should also be regarded, e.g. the design team or decision makers.

For the scope, the system needs to be defined. What is part of the respective environment, e.g. a region of the lunar surface and a specific technical system, e.g. a station, needs to be clarified. The temporal, physical and operational boundaries have to be determined, e.g. are ISRU-activities part of the evaluation or not. The scope should also include which SISGs are regarded and how they are tailored, e.g. based on data availability. The scope should also define which sources are used to fill the information in and what quality sources must have, e.g. concerning reliability of data. It also needs to be stated whether if a third party's design is to be evaluated, public data from news articles is acceptable or not.

The relevance of the system definition becomes apparent in SISG 5's evaluation for case I-1. The 8th measure requires reproductive rights, which have been violated by case I-1, but only because within the ISS operation reproduction is not possible, based on the decision of the respective crew members to become the crew. Outside that system those rights are not violated.

5.3.2. Filling indicators and measures

Once the scope is defined, the data can be accumulated, appraised on its fit to the scope and used to conduct the evaluation of the sustainability. This can require an extensive search, especially if a third party's design or mission is to be evaluated, or be a rather straight forward undertaking if e.g. a present, own design is subject of the evaluation. If the design process is to be guided by the SISGs, data will likely only become available with time, i.e. trade-offs or recommendations to the design team need to be formulated based on the SISGs.

5.3.3. Data availability and iterative application

A certain amount of data and especially certainty of that data is required to apply the SISGs for early design evaluation. A technical design and a mission scenario need to exist with reliable data, even if e.g. margins are used to cover uncertainties, to be able to execute an analysis concerning sustainability. At this stage, it is expected that at least a technical analysis similar to a Pre-Phase A (NASA terminology, [36]) or Phase 0 (ESA terminology, [37], i.e. a conceptual design and a feasibility analysis, are required to begin such an analysis. While the SISGs can be used to guide the design process even before that, e.g. by informing what capabilities are needed to achieve feasibility, an analysis concerning fit requires actual data. It is therefore recommended to:

a) Guide the Pre-Phase A/Phase 0 work by the needs imposed via the SISGs
b) Once a sufficiently matured concept has emerged, to analyse that with the help of the SISGs
c) Iteratively modify the concept and re-analyse it with the SISGs until the concept fits the SISGs and has been implemented

It is to be expected that the implementation will also depend on the exact mission, i.e. which data is available, which gaps need to be closed and which data is available with what uncertainty.

5.4. Methodological fit for formulating the SISGs

First of all, it needs to be stated, that the SISGs are likely not to be considered as "finished". These goals are meant to be iterated further, based on application and subsequent lessons learned and best practices.

The SDGs' background ensures covering all three dimensions. Furthermore, the fact that the UN have decided upon them via a general assembly resolution [22], provides them with a relevant justification. Therefore, it seems prudent to use them as a basis for formulating goals with a similar, but not the same, purpose for space in-situ evaluations of settlements.

Naturally, the method presented here, does not grant the same relevance to the SISGs as the SDGs possess. Yet, their purpose is different as well.

The SDGs' purpose is to guide national development worldwide to achieve sustainability on Earth, the other is to allow space mission designers and decision makers evaluating space mission designs involving human settlements on other planets. It can be assumed that the implementation of such settlements is still many years away, so the application will likely remain theoretical for the time being – in much difference to the SDGs. To equip the SISGs with a similar legitimacy as the SDGs, a similar approach would be necessary as well, i.e. to generate a set of goals regulating formally the establishment of space settlements, high-level legitimacy, e.g. on at least national level (for national missions) or international level has to be achieved via common definitions, e.g. a UN General Assembly resolution.

The involvement of technical and non-technical backgrounds in the review board, ensured that relevant viewpoints are considered for the formulation of the SISGs. While during the review and revision it was challenging at times to inform the non-technical board members about the technical application of the SISGs, in the end these viewpoints could be consolidated into a document, containing a thorough introduction, formulations for the SISGs and their rationales. This ensures that the formulations' reasoning can be understood and evaluated by possible users of the SISGs.

The fact that the author of the initial formulation X_0 was also the "editor" during the review process risks a certain bias. At the same time, it also helps to ensure that the formulations would remain fitting to the intended purpose. A possible bias can be alleviated by publishing the SISGs and allow their application by others, producing further data and review of the formulations.

Additionally, the trial-application of the SISGs allowed a first testing of their usefulness and further influenced their formulations, exceeding simple review. It can be expected that additional application cases provide additional improvement as well.

5.5. Outlook

The SISGs are meant as being one tool in a tool box for evaluating space missions' sustainability, here specifically space missions involving human settlements, on a large scale.

It is intended to apply them further in trials, yet trials based on mission designs, such as a Mars mission with SXS, which has been previously evaluated on a technical basis alone [32], to evaluate such scenarios concerning their sustainability.

If human space settlements should be able to be long-lasting, they need to be sustainable and that can be reviewed with SISGs. It is expected that the current formulation's fit to that purpose is certain enough to allow introducing uncertainty by using new mission scenarios with possible gaps in data or generally information and still provide meaningful evaluations.

In addition to human spaceflight systems, it is the author's intention to analyse mission program components like e.g. non-crewed rover missions, concerning their contribution to SISG performance.

For promoting the adoption and application by others, it is the intention to propose them to e.g. space agencies in sustainability related forums, such as the ESA Clean Space Days, an annual conference about implementation of environmental sustainability analyses in space mission design. Both ESA and European Commission representatives concerned with EU's PEFCR4space [38], an initiative aiming at standardized Life-Cycle Assessment for space activities based on Europe's PEFCR (Product Environmental Footprint Category Rules) framework, are in involved in discussing and reviewing results from the project in which the SISGs are developed. Similarly, other forums more international, e.g. space conferences can be used to generate awareness about the SISGs.

Furthermore, further application can generate data to be used by others and thus help sustainability analyses for the space sector and at the same time spread knowledge and awareness about the SISGs. Eventually, if sufficient governance interest has been generated, formalization could be possible in form of a framework, handbook or even regulation.

6. Conclusion

Currently, no tool exists to evaluate large-scale space missions on their sustainability, especially not in-situ in a space environment. This is necessary to ensure prospering of space settlements and therefore, this article presents the SISGs as tool for evaluation and design guidelines.

The SISGs have been derived iteratively based on the SDGs, a review process with an interdisciplinary review board, and trial applications based on existing missions, i.e. Apollo 11 and ISS operation.

15 SISGs have been formulated with 126 indicators and measures providing information about the sustainability of the investigated mission scenarios.

It is not expected that the current iteration of the SISGs as presented here will be the final iteration, but it is regarded a useful enough iteration to publish and thus allow further trials and therefore improvement as well as inform about sustainability of mission concepts and help guide mission designs towards sustainability.

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Declaration of competing interest

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Appendix A. Supplementary data

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