Frameworks of sustainability and sustainable development in a spaceflight context: A systematic review and critical analysis

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A B S T R A C T
Continuous missions to Low-Earth Orbit, Moon and even Mars missions are the prospect for the coming decades of especially human spaceflight. The actors in these missions are commercial and institutional, public and private. The bandwidth of planned missions is wide, ranging from scientific exploration to commercial exploitation. In-situ resource utilization is planned to support such missions and thus reduce the amount of effort needed for transportation of goods to mission regions, e.g. by supplying water or fuel on the lunar or Martian surface. In the past decades the concept of sustainable development and sustainability has been evolved and became more and more relevant for many aspects of human life and society. These terms have also migrated into more specialized fields such as spaceflight. This paper systematically reviews the concepts of sustainable development and sustainability which have been formulated in a spaceflight context implicitly and explicitly. For this purpose, four perspectives are defined which originate from either Earth or space and alternate with the addressed object between Earth and space as well. It is explained and discussed how these concepts manifest in a spaceflight context, how they evolved over time and which implications result from the respective point of view. Subsequently, the formulation of space in-situ sustainable development is coined and an outlook is given how to further evolve this centric idea to enable a comprehensive evaluation of mission scenarios and roadmaps with regard to their sustainability.

Keywords: planetary sustainability, ISRU, sustainable development, space treaty

Nomenclature

BLSS	Bio-regenerative Life-Support Systems
CSA	Canadian Space Agency
ESA	European Space Agency
GDP	Gross Domestic Product
ILRS	International Lunar Research Station
ISECG	International Space Exploration Coordination Group
ISRU	In-situ Resource Utilization
ISS	International Space Station
LEO	Low Earth Orbit
MDG	Millennium Development Goal
MOXIE	Mars Oxygen ISRU Experiment
NASA	National Aeronautical and Space Administration
UN	United Nations
SDG	Sustainable Development Goal

1. Introduction

About fifty years ago, humans last set foot on the lunar surface during *Apollo 17* in late 1972. Up to this point, this marked the last time humans have left Earth's immediate vicinity during spaceflight. In the following decades, human missions focused on Low Earth Orbit (LEO) with space stations such as *Salyut*, *Skylab* and *Mir*. The United States also developed the *Space Shuttle* and more than two decades ago, the international space community began the operation of the *International Space Station* (ISS). In recent years, China introduced an own space station program, which culminated in the launch and operation of the *Tiangong* station, whose assembly was finished in November 2022. Not all mentioned stations have been occupied during their complete operations duration, which e.g. influences resupply need.

Since the beginning of the 21st century, planning of missions beyond LEO became more concrete in the sense that programs were formulated that targeted the Moon, Mars and asteroids, e.g. in the *Constellation* program of the National Aeronautical and Space Administration (NASA) or the European Space Agency's (ESA) *Aurora* program.

Constellation was dropped but the ideas behind it eventually evolved into the *Artemis* program [1], which comprises landing humans on the lunar surface once more – in difference to *Apollo*, this time in cooperation with international partners – as well as establishing and operating the *Gateway* station in lunar orbit. ESA has its own idea of a long-term stay on the lunar surface, labeled *Moon Village* [2]. It is further one partner in the *Artemis* program, e.g. providing the service module for the *Orion* spacecraft, facilitating the return to the Moon. With the exception of Russia's Roscosmos, all partners of the *ISS*, e.g. the Canadian Space Agency (CSA), return as partners for *Artemis*, resp. *Gateway*. The former announced together with China the plan to establish the *International Lunar Research Station* [3]. The interest in Moon missions is broad.

However, this interest is aiming at more permanent and long-term missions than the previous excursions of the *Apollo* program. For instance, ESA's Terrae-Novae Roadmap that describes space exploration in the next decades, specifies the goal of "enabling sustainability" [4, p. 22], for which ESA regards "advanced environment control and life-support system" [4, p. 17] as decisive. Similarly, the International Space Exploration Coordination Group's (ISECG) Global Exploration Roadmap defines closed-loop-life-support as "key technology" [5, p. 25] for future human space exploration, as it is required for mission sustainability.

The concept of sustainable development is not only relevant for human spaceflight, but for uncrewed spaceflight as well. However, the resource demand is higher for crewed than uncrewed missions, since additional resources, e.g. water, oxygen and food, are required to sustain the crew. Also, uncrewed missions lack the social dimension which is typical for sustainability, resp. sustainable development (see Chapter 2).

Furthermore, e.g. automated In-situ Resource Utilization (ISRU) in a scale to autonomously support uncrewed missions, is more difficult to realize, because collecting material, extracting resources and then utilizing them requires complex processes, which profit from at least human supervision if not operation. For fully exploiting ISRU capability and for extending human presence in space to settlements, space logistics are required in between settlements and between settlements and Earth.

Sustainability and sustainable development are concepts which evolved in a terrestrial setting (see Chapter 2) and sustainable development on Earth can benefit greatly from spaceflight technologies and did so in the past, e.g. with the development of solar cells [6].

1.1 Motivation and Research Question

Sustainability and sustainable development are evidently linked to spaceflight in various ways, but their spaceflight related definitions are often obscure and usage of these terms in this context is ambiguous. Therefore, this paper investigates the question of what the general relation of sustainable development is to spaceflight. How is it addressed by the space community?

This is motivated by the need to evaluate missions and space activities on their sustainability, especially since long-term missions become more and more relevant. Evaluating mission scenarios and systems for such scenarios requires indicators and figures of merit, which need to be defined, if not yet existing in a standardized manner. To understand if such indicators exist, a clear idea of what sustainability is in the context of space activities has to be established, which is the purpose of this paper. Future research will focus on establishing indicators and evaluation processes. Indicators and frameworks present in sustainability science (on Earth) can possibly be adapted to use for spaceflight application, but for this it has to be understood as well, what the understanding of sustainability and sustainable development is within the space community. From this it can be derived, which indicators, data and information is relevant and useful to determine sustainability of spaceflight activities. Therefore, this paper reviews the concepts of sustainability and sustainable development present among space actors.

1.2 Paper Outline

The following chapter provides an overview of the concept of sustainable development, beginning with its history and definition. Furthermore, the dimensions relevant for sustainable development, the relevance of governance and participation are summarized and the terms weak and strong sustainability are explained.

Chapter 3 describes the method of how the review has been conducted. Subsequently, Chapter 4 elaborates the concepts that exist in the space community, how they evolved and which perspectives exist and have to be regarded. These results are discussed in the fifth chapter, before Chapter 6 formulates the conclusion.

A short summary of preliminary results has been presented at the 73rd International Astronautical Congress in Paris and led to a number of discussions [7]. This paper extends the contents further, describes more details and more concepts and the discussion is more extensive.

This paper aims at setting a common ground in the form of definitions for future research in the field of sustainability and sustainable development for spaceflight.

2. Meaning of Sustainability and Sustainable Development

This section summarizes the concept of sustainability and sustainable development in their original application. It is important to have a firm understanding of these original concepts to evaluate the fit of spaceflight related sustainability frameworks to these, which is the goal of this paper.

The terms "sustainability", "sustainable development" or "sustainable" are often found with regards to fields of work by now exceeding their original applications. Consequently, the terms' usage has become inconsistent in their meaning, e.g. "sustainable" is often used with regards to bio-regenerative life-support systems (BLSS), yet the meaning is not uniform, i.e. there exists a "lack of coherence" [8].

Generally speaking, “sustainable” is mixed in meaning with “continuous”, even though this is not the same, even if a time-component is relevant for the idea of sustainability. A continuous operation of a system can occur even though it is not sustainable, e.g. by supply of relevant input from outside. Not only is that sustainability dependent on the respective time frame, such consideration often leaves out the societal, environmental or even economical costs of such continuous operation.

Therefore, this chapter summarizes the definition of sustainable development and what “sustainable” entails or should entail to be correctly regarded as such. Exact definitions may differ from field to field, e.g. depending on the involved time-scales, but the definition of sustainable development is – while broad – also very clear. This is not to say, that there have not been adaptations or refinements of the term over the past decades.

2.1 Definition, history and concept of sustainable development

The concept of sustainable development on Earth has been worked on for several decades, including research on how to best achieve its goals. The term was initially coined by the Brundtland report, which defines it as [9]:

“Sustainable Development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs.”

The idea of development policy after World War II had been to focus on economic growth and everything else would fall in place subsequently. However, by the 1980s, this was shown to be erroneous, because the development efforts of the United Nations (UN) were ineffective in the long run, with rising debts of many developing nations [9].

This eventually led to the United Nations Conference on Environment and Development in Rio de Janeiro in 1992, often referred to as Rio92, which agreed e.g. about the Agenda 21, setting a strategy improving development in the twenty-first century, especially in the global south (i.e. developing and emerging nations). As a consequence, the Millennium Declaration and the Millennium Development Goals (MDGs) were formulated, setting new targets for development, instead of staging a strategy as in previous years. With the help of these goals, nations could find their individual path for reaching them. Sustainability concerning ecology has been one goal of the MDGs, the remaining goals focused on social issues, e.g. health. [10]

Follow-up conferences defined further steps, e.g. Rio + 20 in 2012, which eventually led to the official formulation and ratification of the UN Sustainable Development Goals (SDGs) [11] in 2017. The basic premise was similar to the SDGs, i.e. goals for which each nation could find their own path. But the formulations were wider and encompassed more aspects. Especially also concerning ecological sustainability. These goals combined aspects of development and sustainability rather than separating both.

By now the awareness for the need of sustainable development, resp. achieving sustainability, is spreading more into the public, although the subject has been discussed for several decades. Humanity, especially people in industrial nations, realize only now that resources on Earth are not without limitations and that the exploitation of Earth’s resources is threatening ecosystems worldwide, which further threatens our own basis for survival [3].

The SDGs are the most recent policy regarding the progression of the Agenda 2030 and were adopted in 2015 by the UN Resolution 70/1, replacing the previously active Millennium Development Goals [12]. The resolution explicitly mentions the term ‘sustainable development’ along with its associated three dimensions (see below) and aims at achieving it by “a revitalized Global Partnership (…) based on a spirit of strengthened global solidarity, focused in particular on the needs of the poorest and most vulnerable and with the participation of all countries, all stakeholders and all people” [12, p. 2].

The SDGs are given along with their targets in [12, p. 14ff]. They cover different aspects of sustainable development, such as health, employment and pollution mitigation. The concept requires international cooperation and also coordination. Mostly, however, it requires the acknowledgement that others, e.g. future generations, have the same rights to fulfill their needs as oneself. This is an idea, which is familiar in spaceflight, which relies substantially on international cooperation and lasting commitments by the respective partners. Sustainable development is focused on needs, also similar to human spaceflight, which often can grant basic needs to be fulfilled, but lacking in comfort for those involved. It is the development, which ultimately reaches sustainability – a theoretical condition, where everyone’s needs, including those of people not yet born, are fulfillable.

2.2 Dimensions and indicators

The dimension of time is already included in sustainable development by the regard of “present” and “future” generations (see above definition). Sustainability automatically has a quality of time, otherwise being sustainable is pointless and cannot even be measured. Past aspects are not regarded in the concept, there is a focus on the progress from a current to a future condition. Past generations’ needs can no longer be met, therefore they are not part of sustainable development. Since “time” is an inert dimension of sustainable development, it is not regarded explicitly.

When talking about the dimensions of sustainable development, typically three dimensions are named [13]:

- Ecological,
- Economical,
- Social.

These three dimensions are strongly interdependent. Activities concerning one often also affect another or even two other dimensions. For instance, building a factory in a region boosts its economy, by creating jobs and products for a company to sell. This can affect social aspects as well, e.g. when the improved economy leads to better education in the region. However, pollution and resource exploitation can negatively impact the region's ecology. One factory affects three dimensions.

These interdependencies are often difficult to assess and predict, especially since the related systems are complex as are their links. This makes realizing sustainable development challenging. Careful consideration, review, analysis, possibly modelling and study are required to understand the interdependencies and expertise from numerous disciplines are required, including participation of all stakeholders.

Governance is sometimes considered a fourth dimension and participation is an important aspect of sustainable development as well, to ascertain all needs are even known, as stated previously, quoting the UN Resolution 70/1 [12, p. 2].

Evaluation methods are, e.g. for accounting ecological effects the Material Flow Analysis [22], for the sustainability within cities the City Prosperity Index [23], and for resource usage are indicators like the Domestic Material Consumption [24].

2.3 Weak, Strong and Balanced Sustainability

There are different qualities of sustainability, typically weak, strong and balanced sustainability. Weak sustainability originated in the neoclassical economy and its premise is that natural goods can be substituted by produced goods [14], which is also known as Hartwick's Rule, because John Hartwick initially formulated it [15]. Three assumptions are the basis for the paradigm of weak sustainability [16]:

- Natural resources are regarded as infinitely available
- Natural capital can be replaced by produced capital
- Resource scarcity can be balanced out by technological advancement

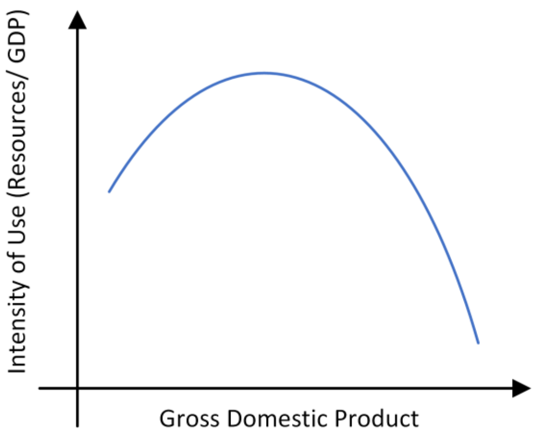

Figure 1. An example of an Intensity-of-Use-Curve, i.e. the ratio of resources used to gross domestic product (GDP) over GDP.

It is obvious that these assumptions break down in the real world, which gives the concept of weak sustainability an unrealistic quality. Produced capital has wear-off, so e.g. even if products can replace "services" that natural capital usually provides, e.g. producing food or generating oxygen, their function will eventually cease. A bio-regenerative-life-support system, i.e. a greenhouse, can replace the services an Earth ecosystem for a while. However, it will take repairs, replacement of components even, and even with all that eventually will be unable to continue functioning and thus no longer be able to offer the services a natural good or ecosystem can, e.g. transforming carbon dioxide into oxygen and carbohydrates. Hartwick's Rule, is based on the presumption of machines that do not "depreciate" [15]. This presumption is untrue and any machine has wear-off. Most natural resources are not infinitely abundant and can run out and in a space environment typically have to be harvested with great effort and technologies that still need to be properly developed.

The premise of technology advancements, which reduce resource drains and pollution is related to the idea behind Economic Kuznets Curves. These curves relate degradation of the environment (e.g. due to production) to a nation's income and are shaped like a turned over U [17]. Their theory says that the ratio of environmental degradation to national income increases as economies advance from rural to industrial and technological advances, enabled by the growing economy, reduce the natural costs as does externalization of natural degradation to other nations, e.g. because production parts are outsourced [17]. Reality does not confirm this hypothesis, e.g. when analyzed emissions are shown to increase and when considering economic dynamics, the curve is in fact N-shaped and not U-shaped, i.e. after a drop in ecological degradation, it increases again, e.g. caused by rebound effects [17]. Rebound effects occur when e.g. a new technology reduces the amount of resources needed for a given production, but the production is subsequently increased on a level, because of reduced costs, which exceeds the original resource drain.

Similarly, the concept of "intensity of use" is based just as well on a turned over U-curve – an example is given in Figure 1. This concept relates the ratio of resource usage to the gross domestic product (GDP) over GDP and after an initial increase it is hypothetically reduced [18], because heavy industry is transformed over to a services-bases economy over the course of a nation's development [19]. The concept can be misleading, however, as it only relates the ratio of the resource usage over GDP, which means that the absolute resource usage can still increase. Recent studies provide evidence that the intended and hypothesized decoupling is not detectible [20]. Decoupling is prevented by e.g. insufficient recycling, resources efficiency not being the target of technology advancement and incomplete replacement of industrial production with services, i.e. resource usage still occurs [20].

Especially since a replacement of resource usage for production, e.g. of goods needed for survival or further built-up of a space settlement, for services is unlikely, the concept of weak sustainability is not regarded as applicable for human space exploration.

The concept of strong sustainability states that natural capital cannot be substituted and consequently must be preserved [21]. Balanced sustainability assumes that natural capital can be replaced partially. Critical functions supplied by natural means have to be secured by preserving the responsible natural capital, e.g. the rainforest. Other forms of natural capital, e.g. limited resources can be replaced. For instance, water regeneration can e.g. be technologically enhanced and thus replace or improve regeneration relying exclusively on natural means. [21]

For this work, the concept of balanced sustainability is assumed to be the minimum necessary to be regarded for sustainable development.

3. Review Method

For this review and analysis four steps have been undertaken. First, a systematic review of scientific papers has been conducted with the search terms:

- Sustainable development space exploration
- Sustainable development human spaceflight
- Sustainability space exploration
- Sustainability human spaceflight

Second publications by NASA, ESA, ROSCOSMOS and UN have been reviewed concerning topics related to sustainable development and sustainability, including regulations, with similar terms as before.

Third, resulting publications have been analyzed and filtered based on their titles and abstracts concerning their fit to the subject, i.e. sustainable development in a space context and not how space activities can support sustainable development on Earth. Overall 45 publications were regarded as fitting, although several contained doubling information and therefore less were actually used as references.

Fourth, for sorting the results an analysis of the perspectives of the found concepts was conducted as the system borders of the concepts varied. Some concepts were concerning or containing Earth, others were containing other celestial bodies, some only regard Earth. This categorization was formalized by the author.

4. Concepts of Sustainability and Sustainable Development in Spaceflight

This chapter reports the results of the found concepts, sorts them chronologically and it explains the perspectives defined for the analysis.

4.1 Perspectives

Generally, sustainability and sustainable development in the context of spaceflight, can have several perspectives, which are sketched in Figure 2. While the before mentioned principles, i.e. meeting needs and sustainability dimensions (see Chapter 2) remain similar, the scope differs depending on the system borders relevant for the respective consideration.

For instance, the perspectives can regard sustainable development on Earth supported by space activities, e.g. via spin-off applications of space technologies on Earth [6] or by exploiting resources from space for use on Earth [22] [23]. The environmental dimension is regarded when regulations from the *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies* (Article IX) [24, p. 3ff], typically just named Space Treaty, dictate that no element that is transferred from space to Earth may pollute its environment [24, p. 3ff].

For all of these examples, the perspective is directed at Earth. Using space technology on Earth as spin-offs is actually also originating from Earth, because the technologies have been developed and funded there, but its original application had been space. This is akin to perspective (1) in Figure 2. For the second and third example the direction is coming from space, but also pointing at Earth, i.e. perspective (3) in Figure 2: Earth shall be protected against pollution from space and space resources shall be used for Earth. Using space resources on Earth is not straightforward and has to overcome certain hurdles, technologically and legally, this concerns e.g. technology transfer between nations or corporations or nations and corporations, which limits the potential for capital yield [25]. Moon and Near-Earth Objects (NEOs) have significant prospects for space resource harvesting [22] [26].

Earth supporting space missions is another perspective and labeled (2) in Figure 2. It comprises support with technology, resources, funding and public support. The costs associated with space missions, often funded publicly, require public support so that programs are not discontinued before space has become an actual part of the human sphere of existence [25]. Maintaining such support is difficult as immediate benefit for people are not immediately recognizable for the public [25]. One goal of space programs therefore typically is to strengthen such support [27].

Broniatowski & Weigel [28] researched the dynamics of funding for space activities and found that the required condition for funding is a benefit for the stakeholders, but it is not a sufficient condition. The sufficient condition is the threat of losing a certain capability in case of a loss of funding and the benefit-cost-ratio is sufficiently high. [28]

The perspective of space being used to sustain space missions is designated (4) in Figure 2. Currently, such missions do not exist, although harvesting solar energy for power supply of spacecraft is routinely effected, spacecraft are still built exclusively on Earth. ISRU is envisioned to support future missions and tests have been conducted successfully with the Mars-Oxygen-ISRU-Experiment (MOXIE) [29] as part of NASA's *Perseverance* mission, but cannot actually support in a meaningful way. However, estimates show that this will change and then ISRU can become an important step towards sustainability of space missions, e.g. by supplying water or minerals cheaper than they could be transported from Earth [22].

Sustainability and sustainable development of space is limited by the space environment, just like on Earth. Space debris pollutes the space environment close to Earth substantially, endangering its utility [22], i.e. just like on Earth the space environment can only sustain a certain amount of activity before becoming unusable.

4.2 Implicit Concepts and Mentions

Typically, the perspective of the reviewed concepts is Earth-centered, either for developing space to enhance Earth's supply of resources or for including the activity of spaceflight in the overall sustainability of Earth. Space is usually not in the center of considerations, e.g. for actually making a mission self-sustainable. This is the case despite the fact that for many space-nations it is an important goal to "extend human presence" [27] in space. Ehrenfreund & Peter [27] refer to sustainability of space programs, e.g. keeping the momentum of activities and defining objectives such as obtaining space resources, but they do not discuss sustainability as such. Instead they concentrate on key figures like "return" and "performance" [27]. However, they also advertise using space technologies for "global challenges" [27] without referencing sustainability explicitly.

Even before the formulation of the concept of sustainable development, synonymously formed ideas existed, e.g. in the Space Treaty [24, p. 3ff], usually referred to as the Space Treaty, from 1967. The treaty has been adopted and ratified by all major spacefaring nations, especially Russia, United States, China and all members of ESA, declares mutual cooperation and prescribes that "exploration and use of outer space should be carried on for

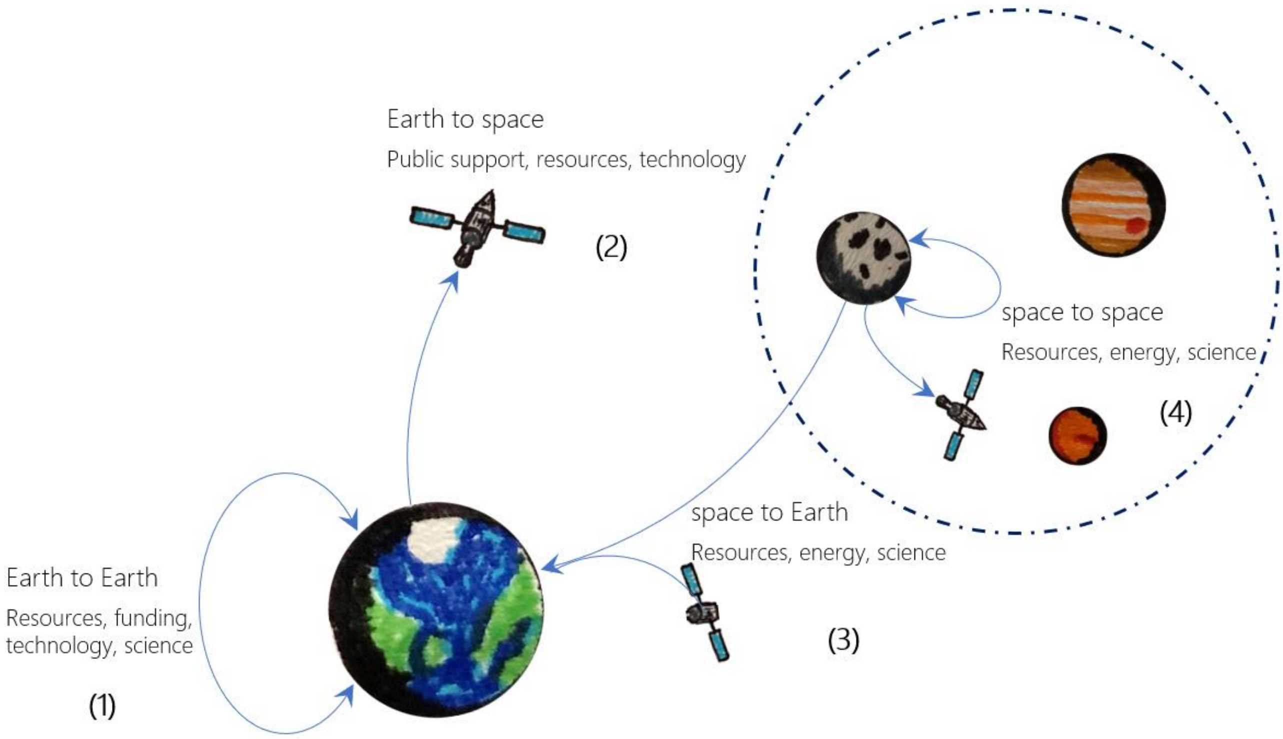

Figure 2. Perspectives for sustainable development concerning spaceflight. Technology spin-offs can make resources, funding, technology and science from Earth available for sustainable development on Earth (1). Public support is required to sustain space missions from Earth, as well as resources and technology (2). Similarly, resources, energy and science from space can support sustainable development on Earth (3). Resources, energy and science attained in space can also support sustainable development of space (4). This last concept is the one in the focus of this research, marked with a dashed circle.

the benefit of all peoples irrespective of the degree of their economic or scientific development" [24, p. 3ff]. This is important as a singular exploitation of space resources should not occur according to the treaty. While this does not exclude exploitation as such, it includes reference to the needs of all contemporary humans. Similarly, Article II of said treaty prevents establishing property on celestial bodies or outer space. And while exploitation is not prevented, Article IX of the treaty specifies protection of the lunar environment against pollution of any kind. Further, Article XI requires that the Secretary-General is apprised of any space activity and distributes such notice to all other treaty members, which is a form of participation even for nations, which are not involved in the mission itself.

The so-called Moon Treaty, formally named *Agreement Governing the Activities of States on the Moon and Other Celestial Bodies* [24, p. 30ff], was agreed upon by the General Assembly in 1979 and refers to resources more explicitly than the Space Treaty and demands protection of other celestial bodies' environment (Article 7) [24, p. 30ff]. Article 11 further demands that environmental protection has to be observed when resources are extracted and stresses once more that all resources should be used for the benefit of all people. The treaty was not adopted as universally as the Space Treaty, however, which makes it hardly relevant for current space activities.

4.3 Explicit Concepts and Mentions

Several concepts name "sustainability" explicitly, defining e.g. paradigms for future mission designs. NASA defined a concept called "planetary sustainability" [30]. This concept refers to Earth but considers space as belonging to Earth's environment.

It prescribes three points. First, it defines that everyone should be supplied necessities such as water and food. Second, economic growth is set as a goal with renewable resources and third, resources from space are to be used for the "people of Earth" [30], which is compatible with formulations focused on Earth alone, such as the Sustainable Development Goals. However, NASA's idea also includes space, as their concept of planetary sustainability comprises "a multi-planetary society, where the resources of the solar system are available to the people of Earth" [30].

NASA has also a definition of sustainable human space exploration [31], which however is focused on technology, culminating in missions to be "Earth independent" [32], i.e. reaching locations beyond Earth orbit like *ISS*. This is however not formulated in a uniform sense, comprising all relevant aspects of sustainability, but focusses on a development approach how to shift from an Earth centered spaceflight strategy to interplanetary missions.

Losch [33] picked up the definition of sustainable development and extended it towards the overall solar system, demanding that "later generations should be able to meet their own needs without perishing due to events in our Solar System" [33]. In difference to NASA's view on sustainability, he elaborates on the need to restrain ourselves in the use of resources to not repeat similar mistakes as on Earth, leading to exhaustion of ecosystems, and warns that "Not all changes that are and that will be technically possible are good" [33].

Galli and Losch also discuss the frame in which sustainability should be addressed concerning spaceflight and opt for two alternatives: either adding it as a further Sustainable Development Goal or use spaceflight as one means to fulfil the SDGs as they have been currently formulated [22]. They also point out that guidelines on how to achieve NASA's idea of planetary sustainability do not exist yet [22] and further explain that the Space Treaty of 1967 does regulate that the space environment is not property of one nation, but it has to become part of humanity's sphere of influence to use its resources enhancing sustainability of humanity on Earth [22].

Newman [34] further points out that human exploration of the Moon should not hinder its future exploration nor damage its environment (which he mainly links to generation of space debris, such as impact probes). This is a relevant fact, because it provides another aspect, which goes even further than described in his paper. Not only does it state that even science, while not intended to be exploitive, can actually result in exploitation. It states that science is a worth-while goal, which should be kept up sustainably. If followed through to the end, any destructive methods used should not erase the object of scientific interest and preserving the lunar environment should be more important than studying it. This is a concept that can be extended to all space. Newman also states that the Moon does not have a self-regulating property as Earth's ecosystems have, e.g. it has no atmosphere, which can burn up space debris. Any debris will remain in the lunar orbit or on its surface.

The relevance of space debris mitigation and protection against it, as well as the need for regulations concerning Mars' environment have also been recognized, e.g. by Suchantke et al. [35]. Hofman et al. [36] have shown in an extensive study of the International Astronautical Academy that environmental protection on celestial bodies in general is relevant and currently insufficiently realized. Newman [34] points out as well the need to avoid mistakes from our exploitation of Earth resources or the space environment, concerning space debris.

As mentioned before, ESA's Terrae-Novae Roadmap declares "enabling sustainability" [4, p. 22] one goal, to be achieved with technological means. This is not considering a social dimension in the long run for the space perspective. However, Earth-centered considerations are addressing e.g. the economic and social dimensions of sustainable development by describing job potential by investment in space activities [4, p. 10]. Focused on a space environment further dimensions are not mentioned and a clear definition of principles or qualities are not specified for a concept of sustainability.

Similarly, the International Space Exploration Coordination Group's (ISECG) Global Exploration Roadmap defines "sustainability principles" [5]:

- Affordability
- Exploration benefit
- Partnerships
- Capability Evolution and Interoperability
- Human-Robotic Partnerships
- Robustness

Generally, the document uses the term "sustainable", but actually only means "long-term". The principles are Earth centered. They do regard the economical dimension, but only with a view at Earth, e.g. demanding an exploration benefit for those on Earth. An environmental dimension is not considered in their principles and space-centered principles are also non-existent.

The Secure World Foundation has its own definition of sustainability concerning space. It states: "Space sustainability is ensuring that all humanity can continue to use outer space for peaceful purposes and socioeconomic benefit now and in the long term. This will require international cooperation, discussion, and agreements designed to ensure that outer space is safe, secure and peaceful" [37]. This definition differs again, from previous ones. It includes all humanity and stresses the need for collaboration, but it does not define all people as equal and entitled to the resources found in space environments. It leaves out especially those peoples, which are unable to use space at the moment. The definition however allows including people or groups of people that are not living on Earth.

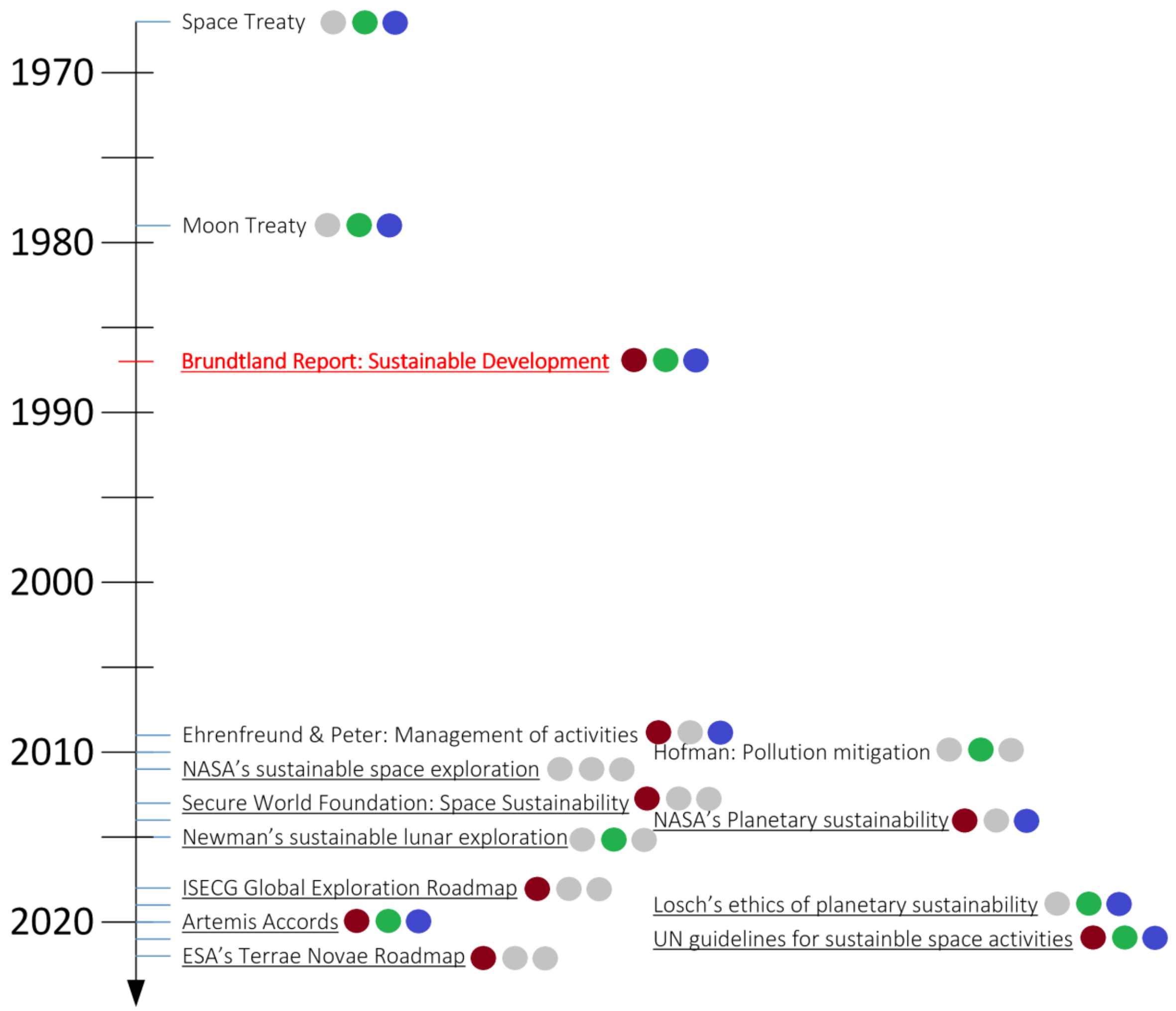

Figure 3. Timeline from 1967 to 2022 of investigated concepts regarding sustainability in a spaceflight context. Underlined elements have an explicit regard to "sustainability", non-underlined only regard it implicitly. Marked are also the dimensions concerned with circles. If greyed-out the respective dimensions are not regarded in the concept. Red (left) is the economic dimension, green (center) the ecological dimension and blue (right) the social dimension. Marked is also the Brundtland report, which originally defined "sustainable development" in 1987, but has no relation to space activities per sé.

The Artemis Accords also address "sustainability" [38] at several points. Meant mostly as an agreement of common rules for cooperative space exploration, the document reaffirms the Space Treaty in several instances, e.g. concerning the need for transparency of activities [38, p. 3]. It addresses not only governance, but also economic aspects of sustainability, e.g. by prescribing commonality of systems in the sense that the can be commonly used, e.g. for refueling

The accords [38] address the social dimension also e.g. concerning sites of cultural relevance, e.g. landing sites. They also refer to resources, and even regard them in a context for support space activities, i.e. with a space-to-space regard. [38]

The United Nations have also attempted to address the topic of sustainability, e.g. with the United Nations' *Guidelines for the Long-term Sustainability of Outer Space Activities* [39], but have not developed a specific definition. The guidelines address various points, e.g. space debris or socio-economic development, but are also focused on Earth.

4.4 Evolution

Figure 3 provides an overview of the timeline of the previously mentioned concepts, starting in 1967 with the Space Treaty and ending in 2022 with ESA's Terrae-Novae-Roadmap. The figure also marks, with underlines, which concepts explicitly mention sustainability and as a reference gives also the Brundtland report's position in the timeline (1987). It can be seen that after 2010 all concepts explicitly refer to sustainability. Their regard of the dimensions of sustainable development is marked as well by colored circles. Red (left) signifies relating to the economic dimension, green (center) to the ecological and blue (right) to the social dimension. Grey circles mean the dimension was not regarded.

No clear trend in the regard of dimensions can be seen. Just two concepts affect all three dimensions. As described in the previous Chapter, their regard is however very limited and not comprehensive of the dimensions. The most recent concept in ESA's roadmap is only addressing the economical dimension. Therefore, a trend to more regard of dimensions cannot be stated with confidence.

4.5 Governance

Benz et al. [40, p. 13] summarize that governance is the label for all processes to cope with interdependencies between public, economic and societal stakeholders on various levels. Government is one form of governance, another can be an economical market with its respective rules and mechanisms. Any mechanism that regulates societal interaction is part of governance. [40, p. 13]

Currently, mission crews on ISS are organized in a hierarchy, which is akin to military crews [41]: The crew commanders are responsible for effective teaming (even before launch) and harmony among the crew. It is also their mandate to ensure achievement of mission objectives, crew safety and avoidance of damaging equipment. A change of command is possible and occurs based on preformulated regulations, which e.g. give each crew member a clear position in the chain of command. Commanders "have the authority to use any reasonable and necessary means to fulfill" [41] their duties, which is rather absolute onboard the station. The crew commander is subordinate to the Flight Director on ground. [41]

There are no governance strategies yet for how to handle off-planet bases, e.g. on the lunar surface differing from such military inspired rules. This is especially complicated when private entities can conduct missions on their own with various purposes, including economic profit e.g. based on resource harvesting. Currently, governance is still lacking concerning e.g. private property and in general handling and using resources from stellar bodies [23].

According to Ehrenfreund & Peter [27], the landscape of stakeholders and actors in human space exploration has changed over the past years and the number of actors is increasing as e.g. private entities, universities and NGOs participate in space exploration, including human space exploration. The interests of these groups vary, e.g. profit or science, which makes it necessary to align agendas and roadmaps. This is a more complex task than in early phases of human space exploration, which basically was conducted by two players, i.e. the Soviet Union and the United States of America. [27]

Ehrenfreund & Peter [27] explain that space programs require new forms of cooperation and communication to be aligned and form a global program, which can sustain human space exploration. A major part of forming a strong governance is in their ideas the formulation of common and smart objectives. [27]

As Newman describes the problem of governance: "Sustainability requires the political will to first acknowledge what the limits of commercial activity should be and where the responsibility for determining this should lie" [34]. A similar attitude is given by Williamson, who also suggests that humanity has to define rules for using the Moon [42].

Kramer proposes the introduction of standards e.g. for the handling of resources and extra-terrestrial life, if it should ever be encountered. Generally, he suggests that environmental impact should be assessed prior to any action taken in a space environment and e.g. data about the undisturbed situation before such action, should be collected and stored, available to all. This requires international cooperation. [43] Hofmann et al. [36] suggest to establish new international law for protecting celestial bodies from environmental damage, without limiting unnecessarily the ability for their exploration.

At the moment, a vague, global form of governance does exist in the form of the Space Treaty, which prescribes in Article XI that the UN General Secretary has to be informed about space activities [24, p. 7]. There are also guidelines to coordinate company activities via national agencies, which in turn are responsible for international coordination [39]. The Artemis Accords confirm the concepts of common governance in space activities, e.g. “registration of space objects” [38, p. 3] p.3 or open access to research results [38, p. 4].

5. Discussion

The presented concepts relate to sustainability of space activities. The majority explicitly refers to sustainability in some form (see Figure 3), but also the majority is only addressing – in various perspectives – an inadequate amount of aspects, i.e. dimensions. While the Artemis Accords and the UN guidelines do regard aspects of all three dimensions, they are still not sufficient, as many aspects are left out.

The accords do relate to a space perspective, which few concepts do, from space, i.e. sustainability provided for space from space (e.g. via ISRU) and even regard the social aspect of cultural significance of historical sites, e.g. the remains of the *Apollo* landings, yet, other cultural aspects are not even mentioned. For instance, the effect of changes to the lunar surface may have for people on Earth [42], especially when not part of the cultural hegemony of people aware of spaceflight, i.e. people in isolation. This is a very complicated subject, because they may have cultural needs, which they cannot express or see regarded to due to their isolation or political status. Yet, in such cases contacting them is prohibitive as even that could already mean cultural contamination.

Some concepts, e.g. the Space Treaty, do regard people as having rights to benefit from space activities even if they are not capable of own activities. However, this is in no case addressing cultural or social aspects, but e.g. economic exploitation of resources.

It can be seen that the topic of sustainability has become even more relevant as a conceptual element in the most recent decades after several decades where it was not addressed at all (see Figure 3). There is a cluster of sustainability concepts, more than 20 years after the definition of sustainable development. It can be seen that the idea of sustainability is present in space activities on various levels, but a common understanding, which is comprehensively affecting all dimensions is not existent.

5.1 Perception of Space in Sustainability Concepts

Recent years have shown a certain focus on economic aspects of long-term human space exploration strategies. Examples for mission ideas focused on asteroid mining [26], the dearMoon-mission [44], a private mission using SpaceX’s Starship aiming for lunar orbit, or the by now defunct MarsOne mission proposal, are focused on the economic dimension, mean to support mission by commercialization. MarsOne comprised a one-way mission to Mars as seeding point for the planet’s settlement, financed with broadcasting rights sells and which could not establish a technical feasibility for a closed-loop life support system [45], among other problems.

Technical analyses for mission studies are often advanced and entail concepts for closed-loop systems [6], i.e. using recycling capabilities to reduce the need of resupply to a minimum (theoretically to 0). This has environmental and economic relevance. The technological solutions of long-term settlements on Moon and Mars are elaborated in numerous studies, e.g. about the ESA’s Moon Village [46] or NASA’s studies about Mars reference missions, e.g. in [47]. Their simulation has achieved a complex level and allow high-fidelity models of close-loop systems from a technical/ biological point of view [49]. Closed-loop systems and human factors, i.e. aspects concerning crew welfare, are considered in technical designs, e.g. [47, p. 67], but this typically is not considering long-term effects, societal aspects or an integrated view of all sustainability dimensions. Sustainable development of such missions is also not considered in these studies, the view of closed-loop and human factors is limited to the immediate situation and not extended to e.g. the planetary environment, building of societies (and their rights), resource use on Earth to develop and built such closed-loop systems. The short-term hurdles to be overcome are clearly dominated by technical challenges, therefore their dominance is conceivable, but still insufficient, if the human presence in space is intended to be long-term or even permanent.

Concepts such as NASA’s planetary sustainability contain the exploitation of space resources for Earth’s purposes, possibly including but not exclusively meaning for Earth’s space activities. The focus is specifically on usage for Earth and not e.g. for a non-Earth-based society (e.g. a future Mars settlement). Just like in the before mentioned ideas of e.g. asteroid mining, space resources are seen as an element to be exploited for purposes of Earth. The before mentioned mission studies also consider ISRU, a concept which can support sustainability of a mission in the economical dimension, but negatively affects the environmental dimension.

It has to be noted that NASA’s definition, or any Earth-centered concept, does not include a justification, why the resources of the solar system should be available to humanity on Earth, whereas the Space Treaty does not mention resources explicitly, only states that space should be used for all humanity’s advantage. A risk of contradicting and abuse of the definition of planetary sustainability exists. First of all, creating a multi-planetary society where resources are transferred back to Earth is difficult to maintain in a sustainable manner. For instance, transport of these resources and infrastructure need to be maintained at a cost, which has societal, economic and ecological components. The concept does e.g. not acknowledge the

Figure 4. Polarity of the overall spectrum of sustainability as expressed for sustainability concepts regarding human spaceflight, with the priorities shifting between exploiting the space environment's resources (economical dimension) and protection of the space environment even at the expense of science (ecological dimension).

fact that a society on another planet, once set up, should be able to determine what happens with the respective resources on that planet, especially if they are vital to its own prospering. This definition also does not regard the – not yet excluded – possibility of an existing ecosystem on another planet or moon. Such an ecosystem could require resources on its own for its continued existence, e.g. water.

The idea of planetary sustainability for Earth, enabled by resource from space, is similar to the Space Treaty's formulation of using outer space and celestial bodies for the advantage of all people. Yet, there is a small, but significant difference. The Space Treaty speaks of "all peoples" [24, p. 3ff], NASA's definition only regards "people of Earth" [30]. Currently the meaning is synonymous, but the Space Treaty could also regard people on another location, if they should ever form and be recognized as such. Furthermore, the acknowledgement of the resource usage for the "people of Earth" [30] is more aligned with the Moon Treaty, even if it is not legally binding.

On the other hand, there are considerations, such as those of Newman [34], which suggest that environmental aspects should be regarded stricter than at the moment, possibly even limiting scientific exploits, which could harm future activities (including further science). Hofman et al. [36] have shown that environmental protection for celestial bodies is relevant and insufficiently realized at the moment. Thus, there is the risk of repeating environmental exploitation in space as we have done on Earth with similar results.

These different views show a certain polarity of sustainability considerations concerning space (be it in the perspective from space to Earth or from space to space), which is expressed in Figure 4, showcasing the existing spectrum of sustainability concepts for human spaceflight. None of the mentioned concepts, or mission studies, contain any aspect which concerns the social dimension of sustainability that exceeds basic needs of a human crew to uphold their functionality.

Thus, it can be seen that here also no comprehensive consideration of sustainability exists, which contains all dimensions and formulations diverge on a polarity spectrum between resource exploitation and environmental protection.

This relates to the concepts of weak and strong sustainability as introduced in Chapter 2.3. Exploiting resources, especially via ISRU to support space missions, implicitly assumed that produced goods can replace natural goods and technology advancement can reduce resource demands. For instance, limited oxygen supply could be enhanced with ISRU. For the development and application of this technology, considerations on available amount and thus limited produce, is not considered nor the justification for using these resources is discussed. The stance of e.g. Newman [34] links more to a strong sustainability, where natural goods cannot be replaced at all and thus have to be protected vigorously.

If long-term missions use ISRU, the amount of resources used has to be carefully reviewed if not to limit mission durations based on that amount. A combination of ISRU and closed-loop technologies can however reduce the amount of resources needed. This amount will not only depend on the efficiency, but also reliability of the applied technology. The resources can be used to drive machines which provide "services" normally linked to an ecosystem (i.e. life-support), but machines have wear-off and therefore will eventually always fail. Thus, there is a resource drain, e.g. to replace such machines. While natural ecosystems are not stable or permanent either, the time scales – if not affected by human intervention or disaster – are usually larger than for a machine.

5.2 The Role of Governance

Governance is needed to successfully implement sustainable development in human spaceflight, especially since most undertakings in that regard involve multi-national groups of stakeholders. In addition to a global scale, which governance e.g. in the form of the United Nations can have, a new level is added, including space itself and its actors, which have interdependencies with Earth. These interdependencies can be linked to a state, a company, but also Earth or humanity as a whole, e.g. when regarding resources accessible in space. Also, governance describes how mission crews themselves regulate themselves. A governance supporting sustainability has to be active on all these levels and ensure that the participation of all stakeholders, e.g. mission crews, supporting organizations on Earth, local ecosystems, companies, are regarded with their needs for planning and conducting space activities. The Space Treaty provides some high-level elements of communication for space actors, the Artemis Accords also set some ideas for a high-level governance, e.g. common support in case of disaster, but are not addressing governance on all levels nor for the purpose of sustainability.

5.3 Fit to the original definition

The initial concept of sustainable development was introduced with the dimensions of sustainability, which have to be regarded and are interlinked. As discussed before, the concepts presented in this work are not regarding the three dimensions sufficiently. However, are those dimensions even fitting for a space perspective? Are they all relevant?

Relevance of the environmental dimension

On the first glance, lacking any known ecosystem, the ecological dimension does not apply on human space exploration. However, this is not true for two reasons. First of all, it has not been shown that indeed there is no natural ecosystem containing life on any other body. It is possible, even if only in primitive form, that life-forms exist on other planets or moons and such possible ecosystems need to be protected. Emissions and pollution by space missions, exploiting resources in an amount, which threatens such life, have to be prevented. This demand is grounded in the "intrinsic value of all living species and natural environments" [48]. Further value could stem from possible application of such life-forms for societal challenges, e.g. concerning health care or recycling of resources.

Second, human spaceflight involves artificial ecosystems provided by space habitats for their crews. These have to be protected similarly as on Earth to guarantee their function in enabling human life. These systems are far less advanced than the Earth ecosystem and therefore are typically more vulnerable. Pollution of space is also affecting orbits due to space debris and can e.g. occur during mining operations, via gas exhaust, which pollutes regolith or atmosphere [42], which subsequently cannot be used for e.g. life-support (for instance when using CO_2 from an atmosphere to enable plant growth in a space greenhouse).

Already the Space Treaty acknowledges implicitly the relevance of the environmental dimension for space activities, e.g. in Article IX, which prohibits pollution in space, resp. celestial bodies [34] [24, p. 3ff]. This consideration is rather weak and only concerns contamination in case it causes damages, which has to be determined by the involved nations [34]. This means, clearer regulations needed to not endanger the environment, but also not exclude any activity including science from occurring in the first place [36], i.e. negotiating the poles as seen in Figure 4.

Relevance of social dimension

The social dimension is relevant for all well-being of e.g. crews and people involved in space activities, but also those, who are just affected. This can concern e.g. physical health, mental health or culture. For instance, space activities can be detriment of cultural aspects, e.g. mining of the moon can have visible changes on the surface, which can alter its cultural importance for people on Earth [42], including non-contacted tribes of indigenous people. Similarly, activities such as resource harvesting but also tourism can damage historical sites, even leading to scavenging of historical parts [42], which has to be prevented, e.g. to maintain peaceful coexistence between people and actors in space, but also within a crew of a mission.

Relevance of economic dimension

Economy is relevant, e.g. as motivator for certain space activities. However, the resources which can be harvested are limited and access is challenging and the economic viability is not clear at the moment [34]. ISRU is regarded as one means to reduce transport costs and launch costs for missions by reducing the amount of resupply needed from Earth. Resource harvesting is also seen as motivation, however, for obtaining resources for Earth or general commercial activities. Kramer [43] estimates the economic profit from mining the Near-Earth-Object *Anteros* at 5.5 trillion US dollars [43]. Yet, an economy, a market, or rules for such an economy in space do not exist yet.

Summarizing it can be said that usually, the presented concepts do not have an orientation on all three dimensions, even though all three dimensions have relevance for space activities.

The term sustainability is used in a "watered down" manner, often just in the meaning of "long-term" activities and if at all only addressing one dimension, e.g. Ehrenfreund & Peter [27] talk about the sustainability of space programs, but actually only mean their long-term implementation. If at all, they address the social dimension in the form of politics. The ISECG's roadmap considers only technical aspects, which basically aim at making missions affordable, i.e. regarding the economic dimension [5]. While, e.g. the Artemis Accords [38] do regard aspects of all three dimensions, the regard is very limited in the social and ecological dimensions and only contain elements directly affecting space operations.

A comprehensive understanding entailing all three dimensions does not exist in any concept. There is no strategy for conducting sustainable development in space, even though it is clear that space has to be developed to become a relevant, meaningful and useful element for the human sphere of existence. The majority of considerations have an Earth-centered view, which is not sufficient to allow sustainable space missions. Some regard how sustainable development on Earth can be supported by space activities, which is relevant and useful addition of space benefits, but essentially this means only a shift of borders for the system that needs to be sustained. However, the resources in space, although possibly abundant, are not limitless and their extraction can have non-economic costs, i.e. simply harvesting such resources is not a means to sustainability without considering these other costs. An analysis for break-even points has to be conducted to find valid, sustainable mission scenarios and strategies, which exceed technical and economic feasibility. Other aspects, e.g. cultural relevance, legal issues, health issues for affected people and more, have to be regarded.

5.4 Space In-Situ Sustainable Development

As all three dimensions have relevance for spaceflight, it is imperative that such comprehensive considerations also become part of roadmaps and strategies. Such planning should not be limited to technical feasibility, otherwise the risk of repeating past mistakes as on Earth, e.g. during the age of colonization, which was coined by exploitation, caused by not considering every entry on the "bill" really make activities unsustainable. The current dominance of technology regard concerning sustainability is likely to be attributed to the technology-heavy subject, spaceflight. It is a driver for technology development, often reaching limits of technological performance [6]. Technological fit alone, possibly supplemented by legal frameworks, is however insufficient from a sustainability point of view. Fitting technology is a necessary condition for sustainability, but not a sufficient one.

Regarding space as an element for sustainable development in its own right is not a current idea present in any of the described concepts. However, the risks mentioned before make it mandatory to not just regard an Earth-centered view and the idea of sustainable development should be adapted to space missions. Therefore, an adaption of the definition of a space context is suggested:

"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."

This form of sustainable development is subordinate to the general expression given in [9]. The original formulation is containing all elements of human existence, i.e. Earth and space, along with all possible future settlements. Yet, a space-focused formulation as given here, can help to underline a self-sufficiency associated with more than just technical feasibility. The space in-situ sustainable development does not need to contain needs of people e.g. on Earth, although they are relevant, because this definition is viable only for the system borders marked in Figure 2 by the dashed circle, yet for an increase awareness, these needs are still mentioned.

The original definition does not contain an explicit mention of the dimensions. They are added here, again, to increase the awareness of space actors for these dimensions as that awareness, as can be seen in Figure 3 and as explained in the previous discussion, is not currently widespread.

A definition as given here is not sufficient to conduct a sustainable development for or in space. Strategies, roadmaps and activities must be evaluable on their adherence to principles of sustainable development. Such evaluation needs methods and indicators, key figures to be used for evaluation. These need to be defined and developed.

Sustainable development is the path to sustainability. As systems change, naturally but also through artificial means, e.g. by disaster or introduction of new activities, so measures of sustainable development have to be adapted and changed. Thus, sustainable development in reality is never completed, but a continuous process that has to be monitored. Adaptation is easier in case activities are investigated beforehand regarding their effect on sustainability so to improve their implementation and therefore not hindering the sustainable development.

5.5 Outlook

It has been shown what the current, lacking, understanding of sustainability and sustainable development is in the context of human space exploration. There are still further questions to be answered: How can the concept of sustainable development be applied to human space exploration? How do the concepts as applied on Earth have to be modified for human space exploration? Which aspects are relevant for space exploration and how can sustainability be developed for space missions or settlements?

As a next step, indicators for evaluation of sustainable development fit of space missions and strategies are to be developed and tested. These indicators will be calibrated by applying them to known missions, e.g. the *Apollo*-missions, which have not been sustainable, or *ISS* and also to future mission scenarios, which at least have been planned with more sustainability in mind. That calibration will likely result in modification and adaptation. Subsequently, it will be further researched, which methods can be used for enhancing sustainability for space missions and drive the sustainable development of space with recommendations based on the found key figures.

For instance, the *resource curse*, an effect precipitating in poor development in all dimensions, caused by economic dependence on resource exports [50], could be a risk also faced by future space settlements, specializing in that. This has to be prevented, e.g. by adapting strategies from Earth [51].

6. Conclusion

This work investigated which concepts exist that regard sustainability in a spaceflight context, explicitly and implicitly, reviewing what the current understanding of sustainability and sustainable development within the space community is and that its fit to the original concepts is insufficiently. It has been shown that the same dimensions that are relevant for terrestrial sustainable development are relevant for such in space and thus should be regarded when sustainability is to be achieved in space. The presented concepts have shown an incomplete consideration, possibly understanding, of what sustainability contains.

Sustainability has become more relevant as a concept in the past two decades for strategies and will likely even increase in importance with more challenging missions and with commercial space applications becoming available. Therefore, a space-centered formulation of what sustainable development entails has been formulated.

A comprehensive view of all dimensions and their interdependencies is required to establish truly sustainable mission concepts and scenarios and to avoid especially non-technical damages, i.e. social or environmental impairments. For this purpose, a comprehensive set of indicators and analysis tools have to be developed, which will be the focus of future research.

For avoiding mistakes, which have been made by disregard of all dimensions of sustainability in the age of colonization, must be avoided. Not space colonization, term still present in the current space community [55] [56], but sustainable settlement must be the goal.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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